ECE20007: Experiment 5

RC Circuits and Timing

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1 Application

Capacitors in an RC circuit have the ability to charge at very standard and reliable rate that is dependent on their capacitance, and the resistor that is in series with it. Using this relationship, we can accurately predict how long it will take a capacitor to charge to a certain voltage, and we can use this to monitor, control, and even change a circuit. One of a scientist's or engineer's greatest skills is being able to quickly and effectively create a simple timing circuit to control or monitor a circuit, which will be practiced here.

Since we will be monitoring charge that is changing with time, our classic multimeter probably won't be helpful, especially if we are looking for changes of voltage that takes place in less than a second. In order to help with this, we will be using a piece of equipment called an Oscilloscope, which will allow us to visualize how voltage will change with a graph and other measurement capabilities.

2 Experiment Purpose

As mentioned above, timing circuits are extremely useful to help monitor and control circuits. To get a good image of what is going on, we will be using an oscilloscope, which is a very valuable tool in electronics, as it allows us to see signals that vary with time.

Arguably the most important parts of this lab is learning how to use an oscilloscope. Oscilloscopes are your best friend when working with electronics, but can appear to be temperamental until you get used to them. Getting used to the controls, and different tools available to you on an oscilloscope will be extremely beneficial for future labs, courses, and projects.

3 The Capacitor

A capacitor is a component that can store electrical energy as an electric field, and then release it at a later time when the conditions are right. The ideal model of a capacitor, called a parallel plate capacitor, is simply two conductive plates separated by some amount of distance. The capacitance of the capacitor, measured in Farads, can be defined as a function of the area of the plates, the distance between them, and the material that is inserted into that space called the dielectric. One Farad of capacitance has the equivalent of holding one Coulomb of charge (the amount of charge from $6.24 \cdot 10^{18}$ electrons) per volt applied to the capacitor.

$$C = \frac{\epsilon * A}{d} = \frac{Q}{V} \tag{1}$$

Where A is the area of the plates in the capacitor, d is the distance between the plates, and ϵ is the permittivity of the dielectric, or how well the dielectric holds an electric field.

There are many different types of capacitors on the market, but they generally fall into two main categories, polarized and non-polarized capacitors. Your non-polarized capacitors, generally either ceramic or film capacitors, are close to the ideal parallel plate capacitor as they are just two plates of metal then filled with either a ceramic material, or foil-like films that are rolled around each other, and separated by a thin dielectric film respectively. The ceramic capacitors have the advantage of being very small, as the ceramic dielectric can maintain an electric field quite well and are very stable, but with their area being so small, their capacitance if often very low, not usually exceeding $1\mu F$. The film capacitors allow for a large area and small separation distance of the plates, but with a less effective dielectric, the capacitance is often fairly low as well, but the ranges of film capacitors can vary greatly since size isn't much of an issue. The polarized capacitors, also known as electrolytic capacitors, are similar to construction of a film capacitor, but one of the plates are oxidized, creating an extremely thin dielectric layer that works very effectively and allows the plates to essentially rest on top of each other. The extremely small distance and strong dielectric allows for the capacitors to have a wide range, including large values of capacitance. The only drawback is the charge can only flow in one direction. This is both useful and potentially dangerous if not used properly, as the capacitors can overheat and sometimes explode if they are wired in a circuit incorrectly! Fortunately, to prevent this situation, manufacturers label the anode, or the side of the capacitor that goes to ground with a stripe that is a different color than the main body of the capacitor. In a schematic, polarized and non-polarized capacitors are represented differently too.

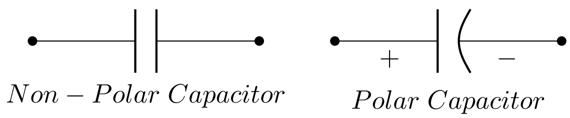


Figure 1: Polar and non-polar capacitor schematic symbols. For a polarized capacitor, the curved side represents the anode, or the side that goes to ground. This will sometimes just be denoted by a "+" sign on the positive side too depending on the designer. European models use two rectangles to show a capacitor, and the filled in rectangle represents the anode.

4 Capacitor Characteristics

4.1 Charging a Capacitor

When using a capacitor in a circuit, as a charge is applied to the capacitor say from a battery, the charge is built up on one plate. As the charge builds, the opposite charges are attracted to the other plate and forms an electric field between the plates. This creates a voltage difference across the plates of the capacitor which can eventually equal the voltage that is being applied to the capacitor. The cool thing here is that once the charge is applied to the capacitor, you can actually remove the capacitor from the circuit, and it will remain charged! Depending on how the charge is used, this means you essentially have a very small capacity battery at your disposal.

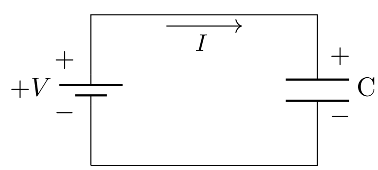


Figure 2: A capacitor in series with a voltage source.

Capacitors are known as **reactive** components, which means that their behavior in a circuit will depend on different parts of the circuit, and the type of current supplied to a circuit. When a capacitor is charging, it builds up charge in a fashion where the positive charge is attached to the positive side of the voltage source. This makes sense, as that is the plate that is being directly charged by the source, but it does cause the sign of the charge to play an important role. Once the capacitor is "fully charged" (quotation marks explained in RC section), the charge on the capacitor pushes back equally onto the source, preventing current to flow. Simple nodal analysis will show us that the if the two components in figure 2 have the same potential facing each other, there will be a net voltage of 0V in the circuit, which means there will be no current flowing. Another way to say this is that as a capacitor charges, it becomes more and more like an open circuit, and when it is "fully charged," it will act as an open circuit until it is discharged. This allows us to take rather choppy signals, or even a DC signal that isn't as DC as the user would like, and help smooth them out, known as **decoupling**. It is very common to use decoupling capacitors as a parallel path to ground from a source to help make a DC signal steadier, and helps protect more sensitive circuits from unwanted fluctuations in voltage.

4.2 Series and Parallel capacitors

Just like resistors, capacitors can be placed in series and parallel with each other, but the relationships of series and parallel are flipped for capacitors when compared to resistors. This means that capacitors in parallel increase the total capacitance of a circuit to the sum of the parallel capacitors, and capacitors in series will decrease their total capacitance in the same inverse relationship as parallel resistors.

$$C_{parallel} = C1 + C2 + C3 + ... \tag{2}$$

$$\frac{1}{C_{series}} = \frac{1}{C1} + \frac{1}{C2} + \frac{1}{C3} + ... \tag{3}$$

It is a good thought experiment to think about why these relationships are what they are. Think about what it would mean to put a capacitor in parallel with another, the direction of the charge buildup, and how capacitance is determined. On the other side, think about how putting capacitors in series would cause the total capacitance to decrease.

4.3 Resistor-Capacitor (RC) Circuits

Arguably one of the most effective ways capacitors are used in electronics is by making an Resistor-Capacitor (RC) circuit. An RC circuit has great applications in both DC and AC systems, and can allow for both control and monitoring of a circuit, all based around how fast or slow the capacitor charges in the system.

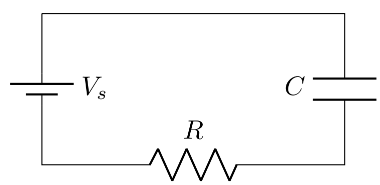


Figure 3: A classic RC circuit.

Adding a resistor into the circuit with a capacitor and a voltage source allows us to very accurately control the flow of current in this circuit. This control is so accurate in-fact, that we can derive a constant for the circuit known as the RC Time Constant. Multiplying the resistance and the capacitance of the circuit together gives us a value **in seconds** which tells us how long it will take for the capacitor to charge 63.2% of the difference between the charge that is already on the capacitor and the charge applied to the circuit.

$$\tau = R * C \tag{4}$$

For example, say we have an RC circuit with a $10V$ source, a $10K\Omega$ resistor, and a $0.1mF$ capacitor all in series with each other. This would create a time constant of one second. Assuming the capacitor starts discharged, after charge has been applied to the capacitor for one second, there would be $6.32V$ stored in the capacitor. If we were to let the capacitor charge for another second, we would charge 63.2% of the remaining way to $10V$, which would put us at $8.65V$. This process will keep going on as long as there is charge being applied to the circuit. After three time constants have gone by, the capacitor will be about 95% charged, and after five time constants, the capacitor will be over 99% charged. This is a classic example of an exponential growth model, which means we can represent it effectively with an exponential equation. Recall that as a capacitor charges, the current in the circuit approaches $0A$. The relationship of current overtime is the amount of voltage still available to flow through the circuit divided by the resistance in the circuit, which follows an exponential decay model.

$$V(t) = V_s * \left(1 - e^{-(t-t_0)/\tau}\right), \qquad I(t) = \frac{V_s - V(t)}{R} = \frac{V_s\left(e^{-(t-t_0)/\tau}\right)}{R} \tag{5}$$

It is this relationship that does not allow the capacitor to ever fully charge. Since we are always charging an additional 63.2% every time constant, we can get infinitesimally close, close enough for us at least to say that the capacitor is charged, but it will never get quite there. Depending on your application, some will say that three time constants are enough to classify the capacitor as charged, about 95% charged, where others will say it needs to be at least five time constants, or over 99% charged. You will rarely ever need to go beyond five time constants unless you are doing extremely precise measurements or timing.

When a path is available for the capacitor to discharge, like a path to ground was present without a battery, the same exponential relationships from charging can be used, but instead of the voltage starting at 0V and working its way up, it starts at the voltage on the capacitor, and exponentially decays similar to how the current decays when charging.

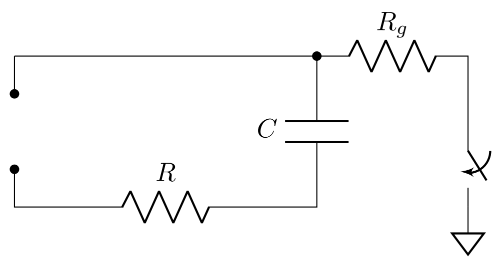


Figure 4: An RC circuit with a path to ground when the switch is closed. The voltage source is removed so no additional charge is being added to the circuit.

$$V(t) = V_C * e^{-(t-t_0)/(R_g*C)} \tag{6}$$

When the capacitor is discharging, it can be treated as a voltage source in the circuit. This means that the current through R_g will follow the same curve shape as the voltage, just divided by the resistance of the circuit.

4.4 Using and Measuring an RC Circuit

When working with reactive devices such as capacitors, there are some extra steps we have to take in order to properly measure what is going on. This is because, as mentioned above, the capacitors potential difference will change with time when attached to a circuit, and is also dependent of the resistance in the circuit. Say we wanted to measure the voltage across the capacitor in Figure 3. We could take our multimeter and just put it across our capacitor like we would with a resistor, but as we know from Lab 1, the resistance of a real multimeter is not infinite, and usually has a resistance around $1M\Omega$. If we were to measure the capacitor with the voltmeter, as in put the meter in parallel with the capacitor, we will give a path for the capacitor to discharge. Take the RC circuit discussed above, if we have a $0.1mF$ capacitor with a $1M\Omega$ resistor (our meter), would a time constant of 100 seconds. While that does seem like a long time, and it would take over a minute to reach a time constant, using equation 6, if we even keep the meter attached for about five seconds, we are already losing about 5% of our charge, and nearly 10% if the meter is attached for ten seconds. This charge dissipation adds up quickly, and while we will lose 63% of our charge after 100 seconds, the majority of that loss is happening much earlier in that 100 seconds, within the first 40 seconds or so. To combat this, we can instead measure the voltage across the resistor in the circuit, and subtract that voltage from the total voltage available in the circuit. Thanks to Kirchhoff's Voltage Law, this will give us the voltage across the capacitor. Using a voltmeter in parallel with the resistor will not give an effective path for charge to dissipate, and it will not change the equivalent resistance of the circuit at a noticeable scale. This method of measuring treats the capacitor as a **Device Under Test** (DUT), which allows us to monitor a component without drastically impacting its performance.

In DC applications, once the capacitor is charged, there needs to be a way to discharge the capacitor if you want current to be able to flow again. There are ways to do this automatically, such as a transistor setup, but discharging the capacitor manually is also an option. As discussed with figure 4, creating a path to ground, or simply shorting out the leads on the capacitor will discharge the capacitor so it can be recharged. This can be done by physically removing the capacitor from the circuit, and then touching the two leads together, or by creating a short path around the capacitor in the circuit with a switch as shown in figure 5. This path can be done with a button, or simply a wire that is added or removed.

Depending on the voltages used and capacitance in the circuit, R_g can be used to limit the current flowing through C. For this lab, where we will be using 5V and capacitors on the μF scale, R_g will not be necessary, but making a

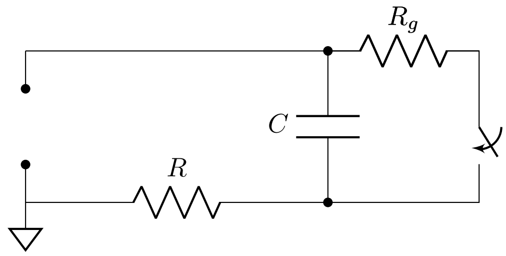


Figure 5: An RC circuit with a short to discharge the capacitor. The voltage source is removed so no additional charge is being added to the circuit.

short like this will be necessary unless you want to remove the capacitor every time. Turning off the supply while manually discharging will also help make sure that the circuit doesn't start charging again until you are ready.

5 Stabilizing a switch

This phenomenon of capacitors helping smooth out signals can be used in places other than just supplies. Anywhere where there are potentially erratic movements in a circuit, like where a human is pressing a button or switch, can cause signals to fluctuate unpredictably. If this switch is attached to a sensitive circuit, such as a memory or state circuit, it can cause data to be overwritten or corrupted.

Taking a look at a switch, we almost always want to set it up with a *pull-up* or a *pull-down* resistor in series with the switch, and the output is between the switch and resistor similar to a voltage divider setup. Starting with

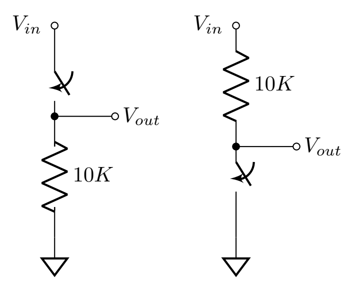


Figure 6: Left: A switch *Pulled Down* with a resistor. Right: A switch *Pulled Up* with a resistor.

a pull-down setup, when the switch is open, V_{out} has a path to ground, and is isolated from power, making the voltage at V_{out} 0V, or often just called "low". Once the switch is closed, V_{out} is directly attached to voltage, and nodal analysis tells us that the voltage on the top of the resistor must be V_{in}, or "high". A pull-up setup works in the opposite way, where the output is "high" when the switch is open, and "low" when the switch is closed. This is also good practice for a number of reasons. First, if the resistor is not in this system, there would be a short circuit between V_{in} and ground which is a dangerous situation no matter the application. This also helps prevent floating voltages, or having a situation where V_{out} is neither high nor low. Depending on what is reading V_{out}, this situation can cause false readings, or again cause corruption. To further prevent this situation, a capacitor can be added in series or parallel with the resistor to allow for a slight charge and discharge as the switch is toggled, allowing for a smoother transition to the opposite state, and preventing other accidental toggles to drastically impact the circuit. There is, of course, limitations to this assistance, which will be examined in the lab tasks.

6 Inductors

Another reactive component out there is the inductor. Inductors are simply a coil of wire, that will charge a magnetic field similar to how a capacitor charges an electric field. Inductors have a value of inductance measured in Henrys which tells us how well they can harness and control an electric field that is dependent on their length, number of coils, their diameter, and what material is inside of the coils, usually iron or ferrite. Inductors have a lot of applications that allow us to boost and step down voltages without losing power, but can be rather dangerous in DC if not controlled properly as the currents can get out of hand quickly, so we will be looking at these closer in AC later on.

Inductors charge and discharge in the opposite way of capacitors when looking at their current and voltage. While a capacitor's voltage increases over time and starts acting as an open circuit, an inductor will become more like a wire, allowing for more current to flow with a minimal voltage drop. This charge and discharge can be managed with a resistor, creating a time constant calculated by dividing the resistance of the circuit by the inductance. This time constant also has a unit of seconds, which is another "fun" derivation.

7 Oscilloscope

Oscilloscopes are the best friend of anyone working with time-varying signals because they allow the user to visualize what is happening in the circuit in real time. Depending on the oscilloscope, you can view multiple waveforms at once, which is helpful if you would like to look at the input and the output signal at the same time. Newer oscilloscopes can even decode signal protocols from a computer, such as the information coming from your keyboard via USB.

That said, oscilloscopes can be rather temperamental at times, or at least we view them that way because they are "not doing what we want them to do." In the grand scheme of things, oscilloscopes are computers, and will do exactly what we tell them to do. If we give an instruction that isn't what we actually want to do, the oscilloscope doesn't care, and will do it anyways. There are many controls, modes, and tools that need to get used properly to best visualize whatever wave you want to view. This takes time to master, and each oscilloscope is a little bit different.

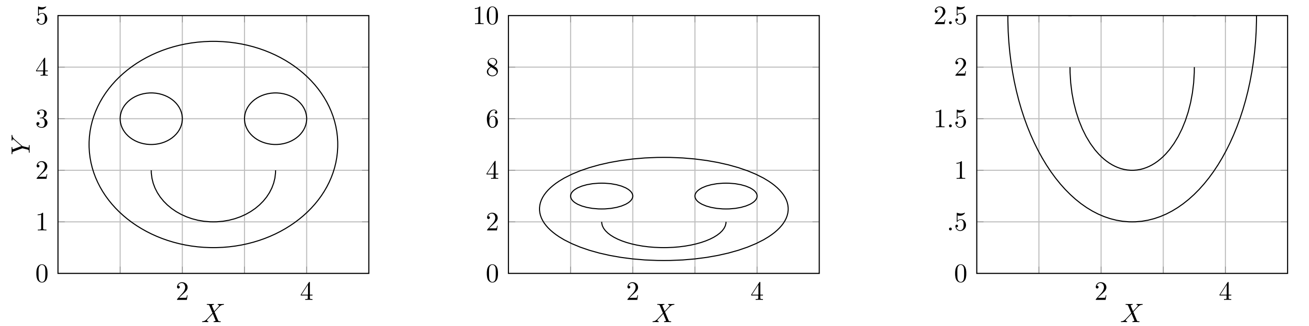
One important thing to note is no matter what, we are always constrained by time when viewing waves on an oscilloscope. Time is often used as the X axis of the plot, but it doesn't have to be. There are modes on an oscilloscope that do not have time on the X axis, but time still greatly affects what the wave looks like!

7.1 Vertical and Horizontal Control

Adjusting the vertical and horizontal components of the viewing window are the first thing someone should try to best visualize the waveform. Most oscilloscopes will have a specific sized graph as a background. Older oscilloscopes used to have these physically painted on, or just behind, the screen. As the controls are adjusted, the graph doesn't change size, but the units associated with each grid line changes. Picture an XY graph with the Y axis labeled at each grid line as "1,2,3,4,..." and then drawing a smiley face on the graph. If we make another grid of the same size, but this time assign each y axis line to "2,4,6,8,..." and map the same coordinates of the face onto this graph, the face would look squished vertically because the units for each line are on a larger scale. If the y axis lines were labeled "0.5,1,1.5,2,..." instead, the face would look stretched, and may not even fit on the graph anymore depending on how large the original face was drawn. This is similar to how the vertical scale works on an oscilloscope. Usually each input will allow you to adjust the vertical scale with an independent dial. This is helpful when you have multiple waves of different sizes, but want to see them equally as large. The horizontal axis, or often the time scale, can also be stretched and squished in a similar fashion, but it will usually affect all inputs. This also makes sense as we want to know what each input is doing when another input is doing something else.

Other than adjusting the scale, we can also adjust the offset of the horizontal and vertical settings. This allows us to move the wave on the screen up and down so we can see multiple waves without overlapping, and side to side to look at different parts of the wave we can't effectively see at the same time. The vertical offset again can usually be controlled for each input, but the horizontal offset will affect every input.

There is a tool that many modern oscilloscopes have called "Auto Scale." This is a helpful tool at times where the oscilloscope will try to find the best configuration of scales and offsets to best display the inputs. Note the word "try" in the previous statement. Auto scale doesn't always work, especially with more complicated signals. It sometimes helps to use auto scale to get the wave to a general setting, but almost always the settings will need to get further adjusted to properly see the desired waveform. Use auto scale with reservations. With practice one



(a) Normal Image

(b) Range too large on Y, squished

(c) Range too small on Y, stretched

Figure 7: Plots showing how range adjustments skews image appearance

will never need it, and one day you might find that auto scale doesn't even exist (or disabled) on the oscilloscope that is being used!

7.2 Viewing Modes

In order to best observe the signal coming into the oscilloscope, different viewing modes need to be used. We will focus on the main three.

Normal Mode

Normal mode is the default setting for the oscilloscope. In Normal mode, the oscilloscope will try to fill the screen with whatever data it is getting. This can be adjusted with a trigger event which will get discussed in the next lab. Whenever you press "Auto Scale," the oscilloscope will set itself to Normal mode.

Roll Mode

In Roll mode, the signal moves across the screen much like the stereotypical heart monitor you see in medical shows or cartoons. This mode is very helpful for monitoring signals that have very long periods, or have events you want to monitor that do not happen consistently with time.

XY Mode

XY mode is interesting because it plots one input against another. Input 1 is traditionally the X axis, and input 2 is the Y axis. This helpful when you want to compare two input voltages that change with time and it can make cool shapes, too! Even though time is no longer an axis, it still affects how the oscilloscope pots the data, kind of like the refresh rate of a computer screen.

7.3 Measurement tools

Along with changing how we can view the signal going into an oscilloscope, many oscilloscopes have tools to take measurements of the signal. The three measurement tools that will probably be the most help to you are below.

Cursors

Cursors, much like a mouse on a computer screen, can be used to hover over a point on a signal to determine the X and Y values. For Normal mode and Roll mode, the X value is time and the Y value is voltage. In XY mode, both the X and Y coordinates will be the voltage of their respective input.

Atuo-Measure

Many oscilloscopes can actually measure different parts of a signal automatically, such as the frequency and peak-to-peak voltage. These values can also be adjusted to measure period, peak, and RMS values. There are other measurements available, too, depending on the oscilloscope. Make sure the oscilloscope you are using is capable of the measurements you want, or you will have to do more math.

Math

Most commercial oscilloscopes can perform basic math operations on a signal (such as adding, subtracting and multiplying signals together) and then plot the output on the screen. Again, depending on the oscilloscope, different math functions may be available, but these are pretty common.

8 Important Notes about Oscilloscopes

Here are a few general things to keep in mind when working with oscilloscopes:

- The probes that are used to interface with an oscilloscope are fragile. **DO NOT SHOVE THE PROBES INTO BREADBOARDS!** There are spring-loaded caps on the probe input that protect the main contact. Put a wire in the hook on the cap, and put the wire in the breadboard. This will help the probes and breadboards last longer. That said, **DO NOT TAKE THE CAPS OFF OF THE PROBES!**
- The probes also have 2 different settings, 1x and 10x mode. This changes the input impedance of the probe, essentially putting a signal through a voltage divider. The 10x mode will reduce the size of the input wave by 10x, making the wave look much smaller than it actually is, but will allow you to view high-amplitude waves that might be out of the measurable range of the oscilloscope, or want to keep the signal on a similar scale as other inputs.
- Oscilloscopes do not measure current. Think of oscilloscopes as fancy volt-meters. There are methods we can use to measure current using an oscilloscope. This usually involves using a special probe called a differential probe, or an external circuit that monitors a load resistor, and then performing a math operation. There are also special current probes that will measure the current in a circuit, and then convert that current value to a voltage signal that can be presented on the oscilloscope.
- Internally, every oscilloscope and probe is a little bit different, even if they are the same model. This means that changing probes can sometimes lead to different measurements. This is an important thing to realize with ANY piece of equipment.
- Each probe has a ground cable. Make sure to use this cable to minimize the **ground loop** for the probe. A ground loop describes how far electricity has to travel from an input to ground. The smaller the loop, the less attenuation you will have in the signal. To help with this, all of the grounds on the oscilloscope are coupled together to a common ground. This has is pros and cons. As mentioned, the ground loop stays small for the probes. This also makes taking differential or floating measurements (where we are not measuring from the same common ground) more difficult, which is why we would need to use differential probe or Math Mode to get the proper measurement.
- Every model of oscilloscope (and any piece of equipment for that matter) has its pros and cons, along with its own learning curve to use. Do not get flustered if it takes a few tries to get the right measurement. Once you master a piece of equipment, a new piece will come out that you then need to learn. While the general function may be the same, dials, buttons, and other interfaces might move around or be adjusted for different purposes. Find commonalities with what you are familiar with, and adjust what you know to fit the equipment that is being used.

Pre-Lab

9 Capacitor and RC Characteristics

1. Using resistors and capacitors in your kit, determine a resistor and capacitor value to allow an RC circuit to "Fully charge" (Over 99% charge) in 5 seconds. Determine the error between your calculation and the ideal full charge time of 5 seconds.
   Hint: You have fewer options for capacitors than you do resistors. It might be worth picking a capacitor, and choosing a resistor to go with it instead of the other way around.
   Another Hint: Your oscilloscope, just like a multimeter, has an input impedance, roughly around $1M\Omega$. Make sure to pick a resistor MUCH LESS than $1M\Omega$ for your circuit to work properly!

2. Simulate your circuit in Spice using a 5V source in a **Transient** simulation. There are multiple tutorials on how to do this online. **Take a screenshot** showing both voltage and current across the capacitor. **Note:** The default color settings on LTspice are not ideal for getting good images, it might be worth your time to adjust the color settings to get better images, and just allow you to view things better in general, especially in the transient modes (Looking at an oscilloscope).

   Multisim Hints:
   Hint 1: Setting up your transient system will be done in the document settings. This can be found by selecting the gear in the top right of the screen, or by double clicking on a component in the circuit, and then moving over to document. The main thing that you will need to adjust will be the time duration. It is recommended that you keep the initial time at 0s, and adjust your end time accordingly. You can adjust the resolution of both the x and y coordinates as needed, but start with the default and go more precise if the need arises.
   Hint 2: Since we are doing a transient simulation with a DC circuit, the initial conditions are important. More times than not, transient simulations are used to look at longer trends or AC movement in circuits, so the initial conditions are not as critical. For this task, in your capacitor settings (double click on the capacitor), make sure to set the "IC" or "initial voltage" to 0V. You will also need to set the transient simulation in the document settings to "user defined" in the initial conditions.

   LTspice Hints:
   Hint 1: Setting up your transient system will change depending on your operating system. The general setup will be ".tran [duration in seconds] startup". There are a variety of other options you can do with this, including when you want data to start recording data and your time step. The "startup" command tells the program to start with your power supplies off, and then turn them on once the simulation starts. This is necessary when doing DC operations with capacitors in a transient mode.
   Hint 2: You can also use a pulse supply instead of a DC. This will toggle your supply on and off at a set interval. You can adjust your on voltage, off voltage, period time, and on-time (just like a duty cycle).

10 Oscilloscope Logistics

1. What viewing mode will likely be the most helpful for this lab, since the scale that we are looking at is in seconds?

2. Using math mode on the oscilloscope will not be necessary in order to determine the time constant of the circuit, but it will help us determine another important value. If we measure the total voltage of the circuit, and **subtract** the voltage across the resistor, what values will we be able to measure?

In-Lab

11 Capacitor and RC Characteristics

1. Using the values calculated in the prelab, construct your RC circuit in the fashion of figure 5. R_g is not necessary for the circuit as long as your total current does not exceed 250mA. Adjust your power supply for 5V, but do not turn on the output yet! Set your current limit of your power supply to 250mA.

2. Setup your oscilloscope so that Chanel 1 is measuring the total voltage in the circuit, and Chanel 2 is measuring the voltage across R. Don't forget about your common grounds!

3. Turn on your output and adjust your oscilloscope to get a full image of the charge in relation to the total voltage, and the voltage **across the resistor**. This may take a few attempts to get a good image. Once you have a good image, use the "Start/Stop" button on the oscilloscope to pause the screen.

4. Using the cursors on the oscilloscope, move the X and Y cursors around on the screen to verify that the time constant is appropriate. Calculate your percent error.

5. Capture a screenshot of your display using BenchVue or using a USB drive that can be plugged into the oscilloscope. **DO NOT take a picture with a camera!** Images like these can cause glare and inconsistent resolution.

6. **Export** your data as a .CSV file. Using your preferred computing platform (Spreadsheet editor, MATLAB, Python...), calculate and plot the voltage across the capacitor. What do you notice about the voltage across the capacitor versus the voltage across the resistor? Does this make sense? Why or why not?

7. Repeat the above steps except with a 2.5V source. What has changed? What can you conclude about changing the input voltage in an RC circuit?

8. **Bonus (+5%): Math Mode:** Instead of exporting the data and using a program to calculate the voltage across the capacitor, you can use math mode on the Oscilloscope to calculate and show the voltage across the capacitor instead. For both the 5V and 2.5V source, capture a screenshot showing the voltage across the capacitor on the oscilloscope using math mode. What benefits does this have over exporting and calculating somewhere else? What drawbacks does it have?

12 Lab Task: De-bouncing a Switch

1. Setup the pull-down setup shown in Figure 6 with +5V as a source voltage. Use a wire you move in and out of the breadboard as a switch. Attach your oscilloscope to V_{out}.

2. Test your switch connecting V_{in} to the node at V_{out}. You should be able to see a toggle between high and low voltage.

3. Toggle your circuit (move the switch back and forth) very quickly. What do you notice about the signal? Those light lines that pop up, are known as "phantom" lines, where the switch appears to be toggled even though it wasn't. Depending on the sensitivity of your circuit, these can cause chaos in your system.

4. Add a ceramic or film (not electrolytic!) capacitor in parallel with your resistor. Try quickly toggling again. Do you see a change? Try different capacitors until you don't see any more phantom lines.

5. Removing these phantom lines comes at a cost. What do you notice about the "reactiveness" of your switch? Try to find a combination that provides a reasonable compromise to minimize the lines, while still allowing the switch to react properly to the toggle.

6. Repeat the above steps with a pull-up system, flipping the location of your resistor and switch.

This process is known as “de-bouncing” since you are trying to remove the unwanted bouncing of the signal. Both pull-up and pull-down setups are used in a variety of places, and will depend on your application on which you use. Just remember that if you want a clear high or low signal, you do need to pull the signal one way or the other. Phantom lines are going to be a hazard that need to be addressed in many settings too, especially high-frequency settings. Phantom lines can be addressed in a program on a microprocessor too. If you know that there should only be one press every second or so, you can prevent the microprocessor from reading the signal until the time is appropriate.