# Introduction to Analog Electronics

**Preparation: Before coming to lab, read this guide and *Melissinos* Chapter 3 sections 3.1 – 3.4 (downloadable). Then do the Pre-Lab. Important: note you are required to come to the lab prior to class for several hours and familiarize yourself with the test equipment! <u>Answer pre-lab questions and hand in at the beginning of your lab.</u> Bring to lab: this guide, your lab notebook, calculator. Explore various RLC circuit behaviors using the Java applet (instructive and fun).**

**Background:** *Resistors*, *capacitors*, and *inductors* are ubiquitous components in practically every electronic circuit. Their combinations and applications are endless and limited only by your imagination. Two very common applications are (1) filters and (2) oscillators. Electronic filters can be used to let only high frequency signals pass through while suppressing the low frequencies, to let only low frequencies through while suppressing the high ones, and to remove noise from an electrical signal (sometimes call noise suppressors). Electronic oscillators are analogous to the mechanical simple harmonic oscillators you have come to know. Both are described mathematically by the same differential equation. The phenomenon of resonance is a behavior common to both, and there are countless applications that use this phenomenon to select a particular frequency (radio and TV signals, for example). When you select a radio station or TV channel, you are using electronic oscillators. In this lab you will use resistors, capacitors, and inductors in circuits to create some filters and oscillators.
At the end of this analog electronics lab, and before you start the pulse propagation electronics lab, you will be given a 20-400 pF variable capacitor and a 150 μH inductor with which you will build a tunable filter of the sort you have in a radio in the AM band.

**Experimental Setup:** A function generator (with 50 Ohm load) will supply square-wave and sinusoidal voltages to RC, and RLC circuits. This function generator is tunable over a wide range of frequencies. The oscilloscope (with X1 probe) will be used to measure the voltage across a resistor and thus monitor the instantaneous current flowing in the circuits as a function of time.

**Objective:** In these experiments you will study RC and RLC circuits in the frequency domain and time domain. You will learn to use an oscilloscope, a powerful and versatile tool used to study electrical circuits. <u>ENTER ALL DETAILS AND RESULTS IN YOUR LAB BOOK.</u>

**Circuit 1: RC "low pass" filter, or "integrator"**

The response of analog circuits may be viewed either in the time domain or frequency domain, and they are complementary. In this exercise you will explore both domains for a simple RC circuit. An RC "low-pass" filter circuit is shown in Fig. 1. The term "low pass" refers to its frequency domain behavior (passes AC signals mostly below some characteristic frequency). By symmetry, in the time domain it is an integrator of the input voltage function V(t), if $V_{out} << V_{in}$. Using complex impedances for the components you can show that if the circuit is fed a step input (or low frequency square wave) that the output will show an RC charging curve that

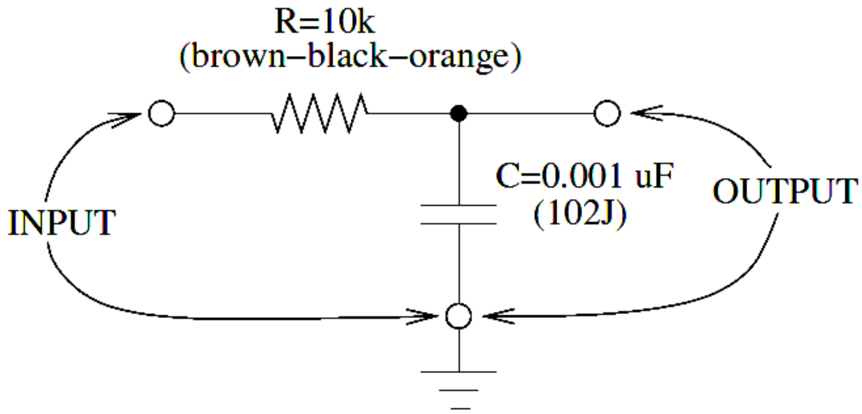



Figure 1: Schematic of the *RC* circuit used in Exercise 1.

approaches the limiting DC voltage exponentially with a time constant of *RC*. In other words, if the initial voltage across the capacitor is some positive voltage $V_0$ and then the input drops to zero volts, the capacitor voltage $V_C$ will decay according to

$$V_C = V_0 e^{-t/RC} \ . \tag{1}$$

If the input were not a step or low-frequency square wave but a sine wave, the ratio of the output amplitude $V_{out}$ to the input amplitude $V_{in}$ would depend on the frequency $f$:

$$\frac{V_{\rm out}}{V_{\rm in}} = \frac{1}{\sqrt{1+(2\pi f RC)^2}} \ . \tag{2}$$

Derive equation 2 by taking the real part of the complex impedance. We can obtain the *RC* constant in two ways: either by measuring the "half-life" of the decay, or by measuring the frequency at which the output amplitude of a sine wave drops by a specific amount. In the following, we'll use the digital scope to try both methods.

1. Build the *RC* circuit shown in Fig. 1 using the supplied RC circuit, a BNC-to-clip cable, and a X1 scope probe. *As a check, first use an ohmmeter to measure your resistor – it may not be exactly 10K ohms.*

2. Attach a 50 ohm load and a BNC tee to the main output of the function generator. Then connect a BNC cable between the one end of tee and CH1 of the scope [to monitor your input voltage]. Connect a BNC-to-clip cable to the other end of the tee, and clip it onto the input of your RC circuit [black = ground].

3. Connect the output of the *RC* circuit to CH2 of the scope (see Fig. 1) using your X1 probe [black = ground].

4. Set up the function generator to produce a 5000 Hz square wave of 8 volts peak-to-peak amplitude, and look at both the input and output signals of the *RC* circuit on the digital scope. You should see something like Fig. 2a. Notice that triggering is on CH1, with a negative slope.

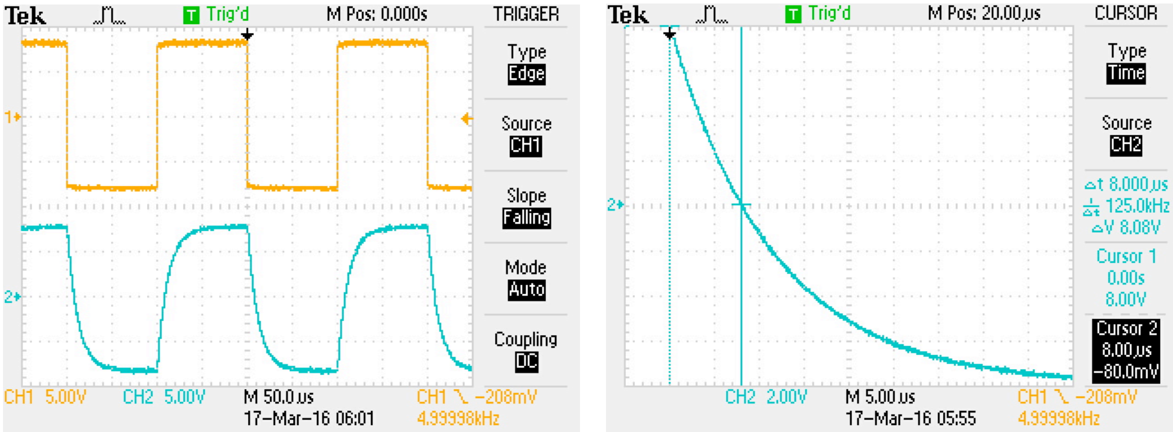



Figure 2: Digital scope measurements of RC decay. (a: *left*) Display showing both the input square wave (CH1) and the output waveform that is rounded due to RC charging (CH2). (b: *right*) Expanded view of the signal in CH2 showing the cursors placed to measure one half-life time of the decay (8µs).

5. Next, turn CH1 off and use the SEC/DIV knob, the VOLTS/DIV knob and the horizontal and vertical POSITION knobs to zoom into a downward-going part of the RC-circuit output waveform, as is shown in Fig. 2b. Note that the vertical sensitivity on CH2 is 1 V/div, so that an 8 volt peak-to-peak signal takes up the full vertical range of the screen.

6. Now you should be ready to measure the decay "half-life". The half-life time $T_{1/2}$ is defined as the amount of time it takes for the signal to drop by one-half of wherever it was when you started the measurement. So if the full peak-to-peak value is 8 volts, and we start $t = 0$ at the beginning of its drop from +4 volts towards −4 volts it will drop by 4 volts (to 0 volts) at $t = T_{1/2}$, and then it will drop by another 2 volts (to −2 volts) at $t = 2T_{1/2}$, and then by another 1 volt (to −3 volts) at $t = 3T_{1/2}$. These points correspond well with the grid markings on the scope. As shown in Fig. 2b, the cursors are positioned to measure the first $T_{1/2}$ interval of 8µs. Use the cursors to measure $T_{1/2}$ for your circuit.

7. From Eq. (1), it is easy to show that $RC = T_{1/2} / \ln 2$. Calculate RC for your circuit from your measurement, and compare it to the value you expect from the part values. In the example shown in Fig. 2b, we would find that RC = 8/0.693 = 11.5µs. This is close to the expected value of 10µs (10kΩ × 0.001µF), if we remember that capacitor tolerances are typically 10%–20% and resistor tolerances are 5%. Of course Eq. 1 tells us that RC is simply related to the time to decay by a factor of 1/e (37%), and you can do this measurement that way too.

To try the second method of comparing the input to the output using sine waves and Eq. 2, note that when $2\pi fRC = 1$, $V_{out}/V_{in} = 1/\text{sqrt } 2 = 0.707$. Note that this is the half power point, since power goes like voltage squared.

1. Set the function generator to produce a sine wave of 10 volts peak-to-peak amplitude.
2. Turn on both CH1 and CH2 so that you can see the input and the output.
3. Set up automated measurements to make the following: CH1 peak-to-peak amplitude, CH2 peak-to-peak amplitude, CH1 frequency and/or period. You should see that the CH1 amplitude measurement gives close to 10 volts.

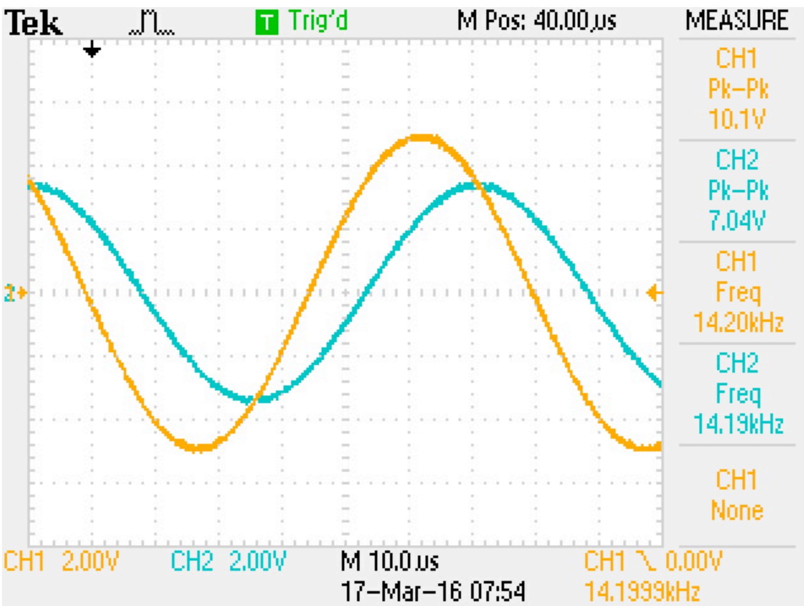



Figure 3: Digital scope measurements of sine wave response of an *RC* circuit. The larger waveform is the signal at the input of the *RC* circuit, and the smaller waveform is the signal at the output. The frequency of the sine wave is set so that the ratio of the output to input amplitude is about 0.7.

4. Position the 0 volt markers of both channels at the horizontal centerline of the display, so that each trace is symmetric about the center.
5. Now turn the frequency knob up until you see the CH2 amplitude drop to (about) 7.07 volts. This is the frequency at which $2\pi fRC \approx 1$. This is the condition that is shown in Fig. 3.
6. From this frequency, calculate the value of $RC$. In the example of Fig. 3, the frequency of 14,200 Hz, gives $RC = 1/(2\pi \times 14,200)$s or 11.2$\mu$s, which is close to the value obtained through the half-life measurement.

7. Your complex impedance derivation of equation 2 also predicts that at this frequency there should be a phase shift between the input and output of $45^\circ$. You can measure this with the cursors. First use the cursors to measure the time difference for the points at which the two waveforms cross the 0 volt line. Then use the automated measurement of the frequency to find the full period of the sine wave. The ratio of these two values times 360 gives the phase shift in degrees. From Fig. 4 below, one obtains a phase shift of $8.8\mu s/70.4\mu s \times 360 = 45$ deg. What do you get for your circuit?

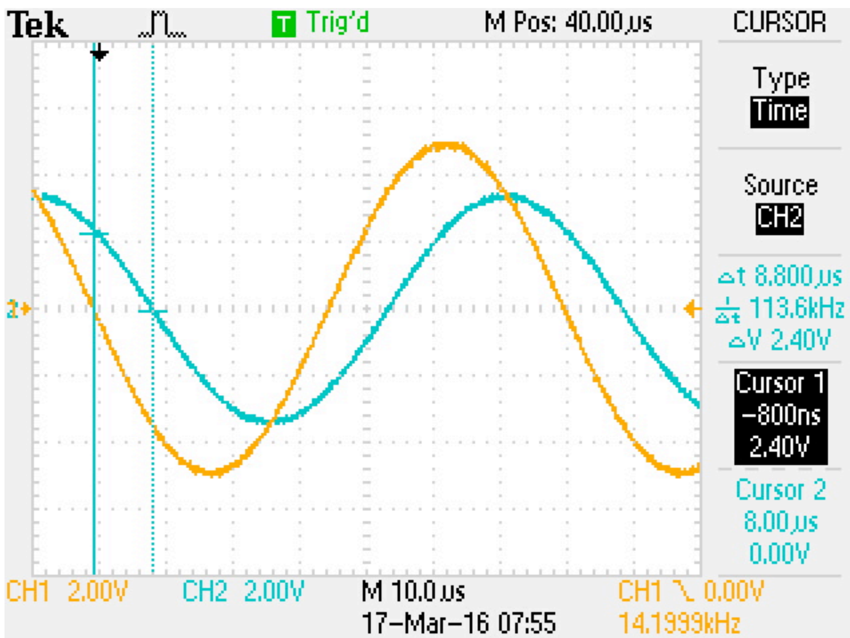



Figure 4: As in fig 3, the frequency of the sine wave is set so that the ratio of the output to input amplitude is about 0.7. The time domain cursors have been placed at the zero volt crossing times of the input and output waveforms, resulting in an automated measurement of the time delay of $8.8\mu s$.

**Circuit 2: RLC resonant circuit** EXTRA CREDIT

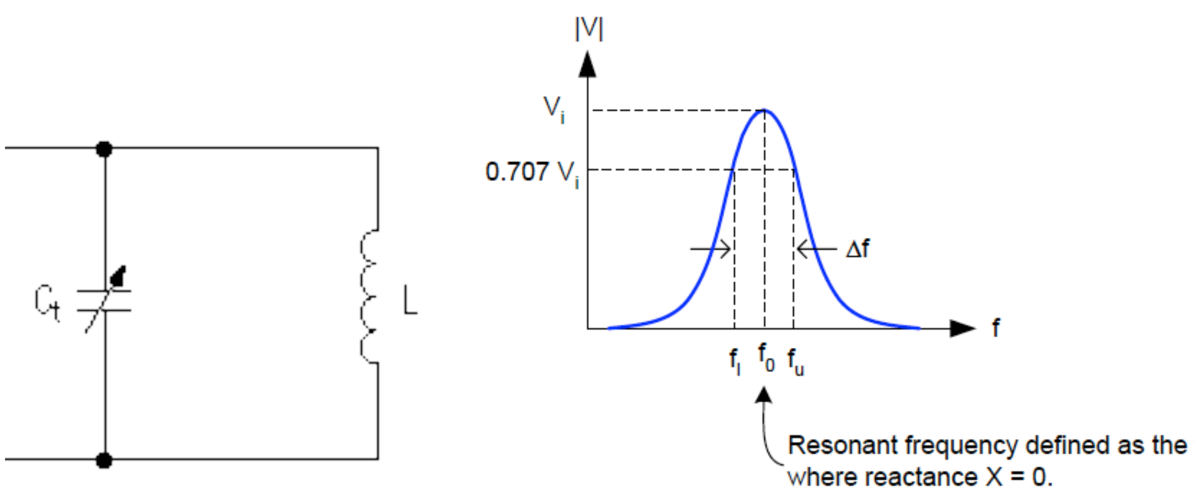
An inductor and capacitor connected either in series or parallel will resonate at a characteristic frequency:

$$f_0 = \frac{1}{2\pi\sqrt{LC}}.$$

Derive this relationship, starting with the complex impedances for the components, for a parallel LC circuit. What does the impedance across the parallel LC circuit do as you approach the resonant frequency? What if there is some loss (consider a parallel high resistance R)?

Using the supplied 150µH ferrite core inductor and 20-400pF variable capacitor ($C_t$ in figure below), construct a LC parallel circuit. What is the expected voltage across this parallel LC circuit vs frequency? Hint: this is related to the impedance vs frequency. In reality, your LC circuit is not completely free of loss. Estimate and list all sources of resistance. Next, excite the LC oscillator. Inductively couple a little oscillator power into this circuit via ~1-2 turns of wire wound around the inductor. (*This is a transformer*). Hook this coupling coil in series with a 50 ohm resistor (so as not to load down your oscillator output amplifier) and apply a small fraction of a volt from your oscillator at a frequency near where you calculate the resonance of your LC circuit will be for an intermediate setting of the variable capacitor (say 250pF).

With your scope switched to high input impedance, measure the voltage across your LC circuit with a X10 scope probe as you "tune" your variable capacitor. You need to use the X10 probe so you don't create extra loss by effectively placing a resistance across the circuit. Observe the resonance. Do the reverse too: set your oscillator to a frequency near your resonance, and then change the oscillator frequency measuring the peak-to-peal voltage as you go, mapping out this resonance. Some of the elective experiments use this kind of circuit. Plot this curve and fit it with an appropriate function (you will do this in some of the elective experiments).




$$Q_p = \frac{f_0}{\Delta f}$$

Figure 5: LC resonant circuit, its response, and Q.

There is an exact analogy between the RLC circuit and a mechanical harmonic oscillator:

$$m\frac{d^2x}{dt^2} + B\frac{dx}{dt} + kx = 0 \quad \text{damped harmonic oscillator}$$

$$L\frac{d^2q}{dt^2} + R\frac{dq}{dt} + \frac{q}{C} = 0 \quad \text{undriven RLC circuit}$$

where x ~ q (charge), L ~ m, k ~ 1/C, and the damping coefficient B ~ R.

The sharpness of this resonance makes the LC circuit ideal for situations where you want to pass only signals in a very narrow range of frequencies (band pass filter) or, if hooked up differently, if you want to reject signals in a narrow range of frequencies (band reject, or "notch" filter).

The measure of the sharpness of the resonance is the Q, defined in Fig. 5. The Q is the resonant frequency divided by the full width of the resonance curve at the half power points (0.707 voltage points). This follows from the definition of the Q as:

Q (quality factor) of a circuit: determines how well the RLC circuit stores energy

$Q = 2\pi$ (max energy stored)/(energy lost) per cycle

From this definition of Q and the expression for stored energy $CV^2/2$, write an expression for Q in terms of L,C, and a small effective series resistance R. Repeat but instead for a large effective parallel resistance R.

How high a Q can you get with your circuit? Try 2-3 different values of your variable capacitor over its whole range, measuring the Q at each of the corresponding resonant frequencies. We'll have a contest! The winner gets their name entered into the PHY Advanced Lab Hall of Fame. What limits the Q of your particular setup? Observe what happens if you switch your probe to X1.

The above definition or Q suggests a complementary way of measuring it – in the time domain. Remember the time domain- frequency domain duality. To measure the Q in the time domain measure how long it takes to ring down by some factor, or equivalently measure the decrease of voltage in one cycle. So you need to shock excite your LC circuit, just as you would strike a tuning fork.

Set up a pulse generator giving a few volts pulse height at a pulse repetition frequency of 1-10 KHz and ~50-100ns pulse widths [explain why so narrow], and feed this into your coupling coil+50ohm resistor. Look at the response by triggering your scope via a BNC Tee on the pulse generator output connected to CH2, measuring the voltage waveform on CH1 with your X10 probe of course. After adjusting trigger and channel gains, you may see something like Fig. 6. Tune the variable capacitor and see the Q change by observing the change in waveform decay. Derive the Q from this time-domain technique, for your best Q setting from the previous frequency domain measurement. What limits your measurement precision in this second method? You might consider measuring the voltage fractional decay over N cycles.

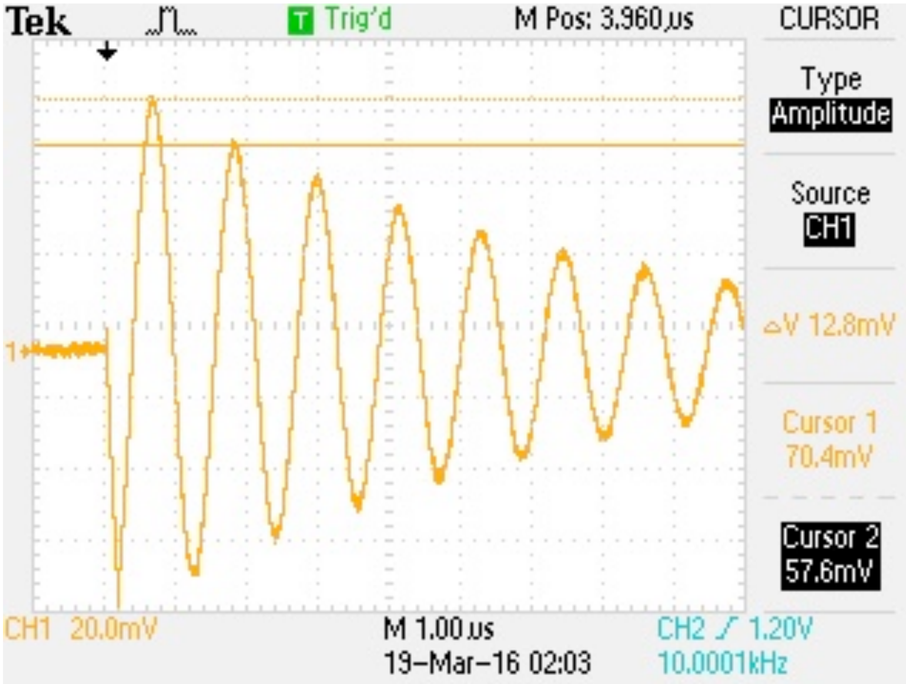



Figure 6: Shock excited oscillator: your LC circuit response to a pulse. Cursors were used in the amplitude mode to measure the decay of voltage in one cycle.