

Basics of Electrical Circuitry

Instructor: Steve Cox, steve.cox@nmmc.edu, 505-579-4550

Place: TRK Building: 195 East Road, Los Alamos. (TA 00, BLDG 1355 – Classroom # 1009).

Dates: October 27 - December 15.

Times: Wednesdays, 8-9:15am (Class), and 9:15-9:45am (Office Hours), 10/27-12/8.

Course Topics:

- The nature of electricity: charge, current, voltage and power.
- Harnessing electricity: the roles played, and laws obeyed, by resistors, capacitors and inductors.
- How these components interact in electrical circuits.
- How to build and test electrical circuits in both virtual and physical environments.

Student Outcomes: At the end of this course students will demonstrate knowledge of Basic electrical circuit components and instruments and know how to identify, create and test simple circuits.

Text: [Practical Electronics for Inventors](#), by Paul Scherz and Simon Monk, 4th edition, McGraw-Hill, 2016

Lab Work: We will build and test circuits at tinkercad.com. You will log in, everytime, by following our [class link](#) followed by your first name in all lower case when queried for your nickname. There will be hands-on physical class demonstrations of each circuit.

Grade: Seven Quizzes at 5% each. Seven Labs at 5% each. One Final Examination at 30%.

Schedule:

Lesson 1. 10/27. Volts, Amps, Ohms and Watts. Quiz 1 due at Blackboard midnight 11/1. Lab 1 due at tinkercad midnight 11/1.

Lesson 2. 11/3. Resistors in Series and Parallel. Quiz 2 due at Blackboard midnight 11/8. Lab 2 due at tinkercad midnight 11/8.

Lesson 3. 11/10. Capacitors. Quiz 3 due at Blackboard midnight 11/15. Lab 3 due at tinkercad midnight 11/15.

Lesson 4. 11/17. RC filters. Quiz 4 due at Blackboard midnight 11/22. Lab 4 due at tinkercad midnight 11/22.

Lesson 5. Monday 11/22. 7:30-9am. Inductors. Quiz 5 due at Blackboard midnight 11/29.
Lab 5 due at tinkercad midnight 11/29.

Lesson 6. 12/1. RL filters. Quiz 6 due at Blackboard midnight 12/6. Lab 6 due at tinkercad
midnight 12/6.

Lesson 7. 12/8. RLC filters. Quiz 7 due at Blackboard midnight 12/13. Lab 7 due at tinkercad
midnight 12/13.

Final Exam. Due at Blackboard 12/15.

Lesson 1. 10/27. Volts, Amps, Ohms and Watts

Reading. Chapter 2. Pages 5-17 and Pages 49-50

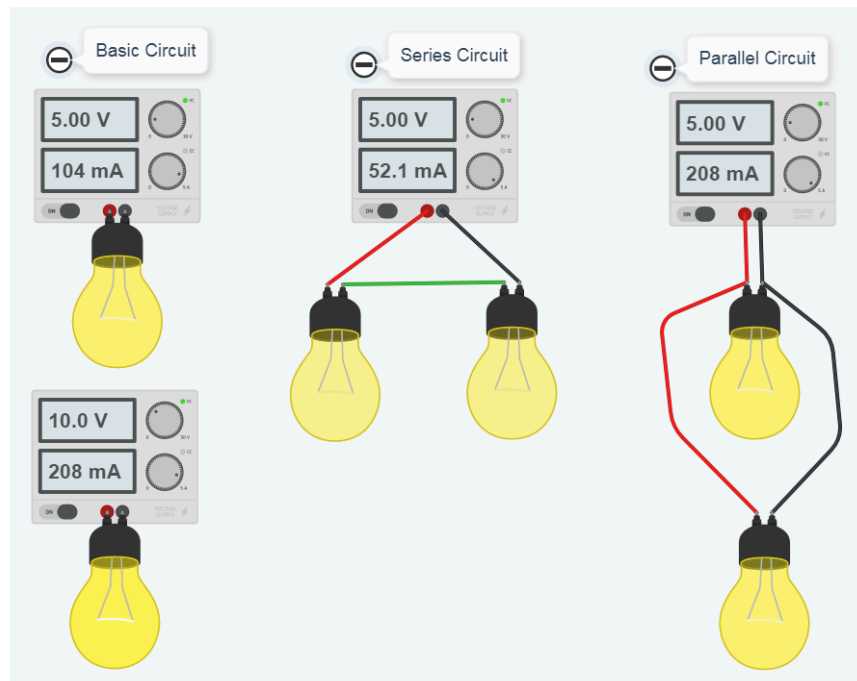
Objectives:

1. Explore the Tinkercad Circuit Dashboard
2. Wire power supplies to light bulbs in three standard configurations
3. Deduce Ohm's Law as well as laws for series and parallel resistances from these experiments.

Content:

From this tinkercad simulation we observe that,

- 1) The single bulb draws 104 milliAmperes (or 0.104 Amps) at 5 Volts and 208 milliAmps at 10 Volts.
- 2) The 2 bulbs in series draw half the current of one bulb.
- 3) The 2 bulbs in parallel draw twice the current of one bulb.



Let's take up these observations one at a time. Our power supply delivers a prescribed Voltage and then reveals the associated current drawn by the load. The load in our case is a light bulb rated at 12 Volts and 3 Watts. The small filament in the bulb offers a certain resistance to current flow.

Does it make sense that this resistance just depends on the filament and not the applied voltage and current?

Let us then attempt to discover a relationship between Voltage, Current and Resistance. Do you see in our two instances of the Basic Circuit that doubling Voltage merely doubles the Current? This observation leads to the fact that Voltage/Current does not change (do you see how the 2s cancel?) In fact this unchanging thing is merely the resistance of the bulb. That is

$$\text{Voltage} / \text{Current} = \text{Resistance}$$

This is known as **Ohm's Law** and strictly speaking only holds for "resistive" loads. We will discover and exploit the laws for the common no-resistive loads as we proceed. This law permits us to determine the resistance of our bulb to be

$$10 \text{ Volts} / 0.208 \text{ Amps} = 48.08 \text{ Volts/Amps}$$

As Volts/Amps show up so often we give it a name, in honor of our Lawgiver, Ohm. Hence, we find that our bulb has a resistance of about 48 Ohms.

You note that when buying bulbs we rarely, if ever, are informed of their resistance. In this case our bulb was rated at 12 Volts and 3 Watts. This would be a decent interior light for your car. Your headlamps are typically in the range of 30 to 60 Watts. So what is a Watt?

A Watt is a measure of **power**. While resistance is the ratio of voltage to current, power is their product

$$\text{Power} = \text{Voltage} \times \text{Current}$$

So just as Ohm is short for Volt/Amp. Watt is short for Volt x Amp.

Looking back at our two Basic Circuits we see that the top is consuming **0.52 Watts** while the bottom circuit consumes **four times that much**. It looks like the bulb is a little brighter on the bottom too.

For many this still leaves the questions What is a Volt and what is an Amp. Both rely on the fundamental concept of charge, as measured in Coulombs.

An Amp measure the speed of the charges, in Coulombs/second

A volt measures the Energy of a charge in Joules/Coulomb.

It follows that

$$\text{Watt} = \text{Volt} \times \text{Amp} = (\text{Joule/Coulomb}) \times (\text{Coulomb/second})$$

$$= \text{Joule/second} = \text{Energy/time}$$

If the Joule remains mysterious, note that

$$\text{Energy} = \text{Work} = \text{Force} \times \text{Distance}$$

Now, regarding our series and parallel circuits, we note that

Two bulbs in series present twice the resistance,

While

Two bulbs in parallel present half the resistance.

We shall see in our next lesson that these are instances of common laws of resistor combinations.

Laboratory 1. Build the 5 lightbulb circuits in tinkercad, as above, with detailed annotation. Explore several voltage levels.

[Quiz 1 Solved.](#)

Lesson 2. 11/3. Resistors in Series and Parallel

Reading: Chapter 2. Pages 50-58

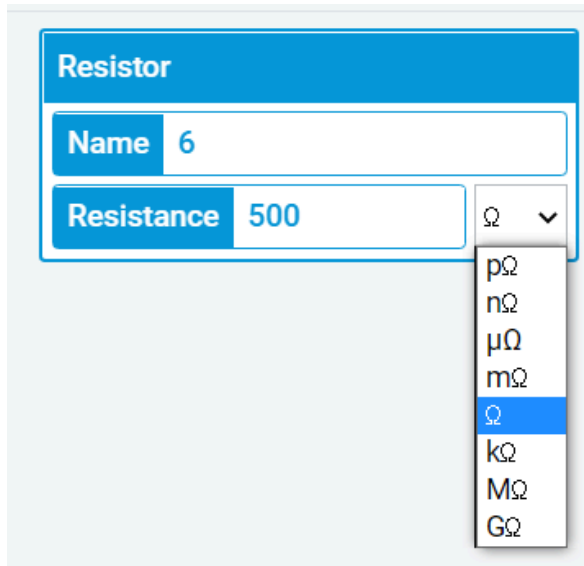
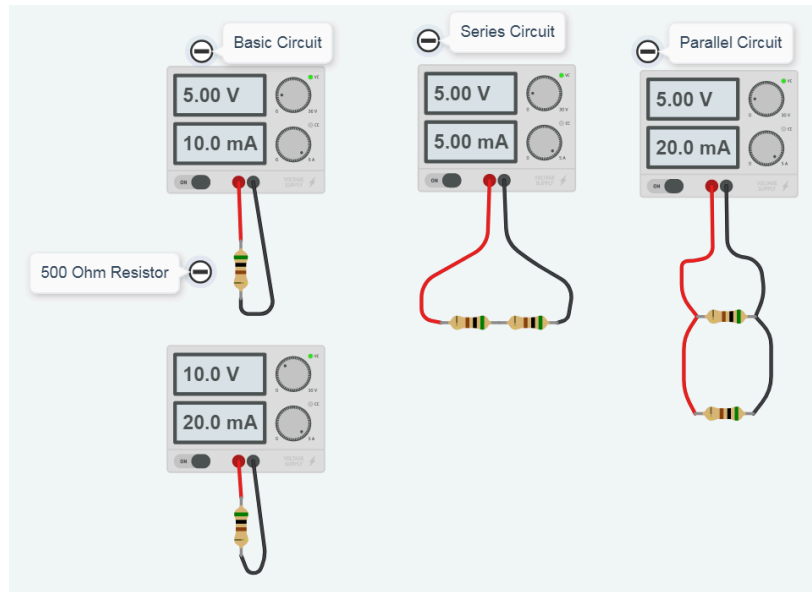
Objectives:

1. Investigate resistors of various values
2. Examine series and parallel connections
3. Build and analyze the Voltage Divider Circuit.

Content: We used light bulbs in Lesson 1 because they are familiar and they permitted us to introduce the notion of resistance. It turns out that resistance is a very very useful tool and as such resistors are manufactured over a wide range of values.

In the circuits to the right we have chosen 500 Ohms, or 500 Ω , for short.

We make the choice by clicking on the resistor and typing in the window provided as below.



This drop-down menu uses the common letter codes for factors of $1000=10^3$

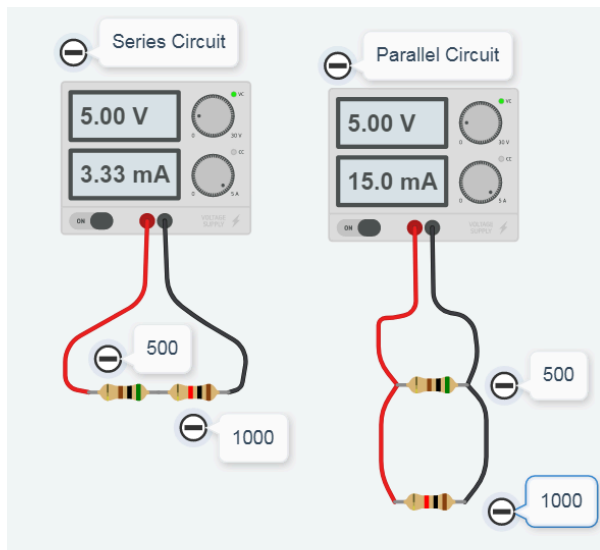
p means 10^{-12} and is pronounced "pico"
n means 10^{-9} and is pronounced "nano"
 μ means 10^{-6} and is pronounced "micro"
m means 10^{-3} and is pronounced "milli"

k means 10^3 and is pronounced "kilo"
M means 10^6 and is pronounced "mega"
G means 10^9 and is pronounced "giga"

Our four circuits should reinforce last week's Lessons

1. Voltage = Current x Resistance
2. Equal Resistances in series, double
3. Equal Resistances in parallel, halve

Now that we have resistors of many possible values we can dig a little deeper into these last two lessons. We return to our earlier circuit and now replace one of the 500 Ω resistors with a 1000 Ω resistor.



Let's let R denote the Combined Resistance in each case.

In the series circuit $5 = 3.33 \times 10^{-3} \times R$ so
 $R = (5/3.33) \times 10^3 = 1.5 \text{ k}\Omega$
 which we recognize as the sum of our two resistances.

In the parallel circuit $5 = 15 \times 10^{-3} \times R$ so
 $R = (5/15) \times 10^3 = 0.333 \text{ k}\Omega = 333 \Omega$
 which we recognize as product of our two resistances, over their sum
 $R = 500 \times 1000 / (500 + 1000)$

This then is the proper generalization of our two earlier observations

The **combined resistance** of resistors R_1 and R_2 in **series** is $R_1 + R_2$

The **combined resistance** of resistors R_1 and R_2 in **parallel** is $R_1 R_2 / (R_1 + R_2)$

One immediate application of these results is that it allows us to construct new resistors from the more common store-bought resistors. Can you see the values that come in this box of 400



Resistors for \$10? What's the smallest? What's the biggest? And what does that ¼ W designate?

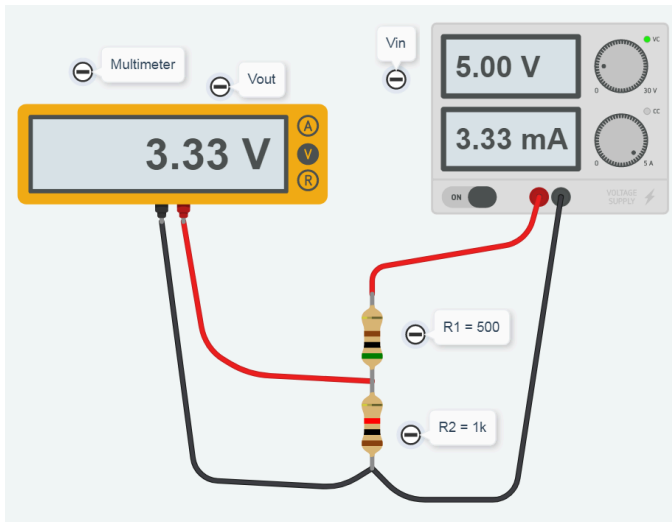
It says that these resistors will smoke and burn your fingers if they receive more than one fourth of a Watt.

This is a common figure for many circuits. For circuits involving higher power you'll need higher ratings on your resistors, and more money.

There are however more cogent reasons for working with series and parallel circuits.

The Voltage Divider

We add to our series circuit an important new instrument, the Multimeter. It is Multi in the sense that it can measure Amps (A), Volts (V) and Ohms (R). These are under \$10 and often free at Harbor Freight.

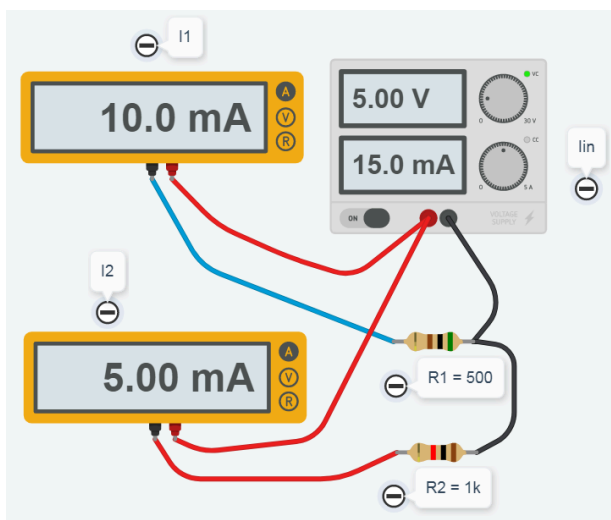


You see that we are using the multimeter to measure the voltage across the 1k resistor.

We call the Voltage delivered by the power supply V_{in} (for input voltage) and we call the voltage at the junction of our two resistors V_{out} (for output voltage) and see that our resistors act as dividers in the sense that

$$V_{out} = V_{in} \times R_2 / (R_1 + R_2) \quad 3.33 = 5 \times 1000 / 1500$$

The Current Divider



Can you see the two loops of current summing to the total input current

$$I_{in} = I_1 + I_2, \quad 15 = 10 + 5$$

We recognize this as **Kirchhoff's Current Law**: The current into a node equals the sum of the currents leaving the node.

The individual currents obey Ohm's Law

$$I_1 = V_{in} / R_1 = 10 \text{ mA} \quad \text{and}$$

$$I_2 = V_{in} / R_2 = 5 \text{ mA}$$

Laboratory 2. In tinkercad

Build a Voltage Divider circuit that produces 2 Volts from an input voltage of 5 Volts. Please label your resistors.

Build a Current Divider circuit that produces currents of 20 mA and 30 mA from an input voltage of 5 Volts. Please label your resistors.

Lesson 3. 11/10. Capacitors

Reading: Chapter 2, pages 94-110

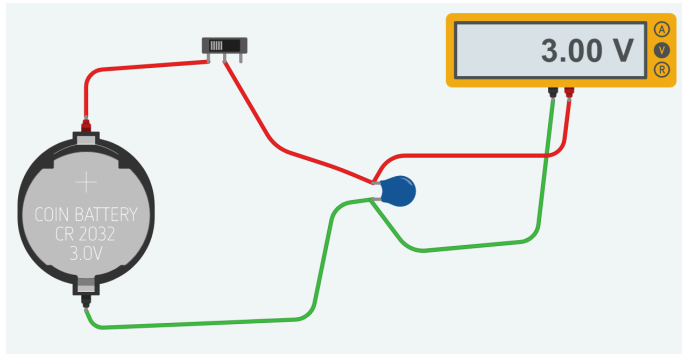
Objectives:

1. Explore discharging of capacitors with switches
2. Explore series and parallel combinations of capacitors
3. Explore charging and discharging of capacitors with a function generator and oscilloscope.

Content:

Capacitors are dynamic charge storage devices. By **dynamic** I mean that they respond to a **change** in voltage rather than to the absolute level of change.

To illustrate this we put a simple switch between our battery and our capacitor. When the switch is to the left we are charging the capacitor to the level supplied by the battery.



When we move the switch to the right we can watch the capacitor discharge by observing the decrease in voltage as a function of the tinkercad simulation time, in milliseconds.

The unit of capacitance is a **Farad**, after Michael Faraday. To understand how the rate of discharge depends on capacitance we run the above simulation for 3 values of capacitance and record how long it takes to descend from 3 volts to 1 volt on the multimeter. I find

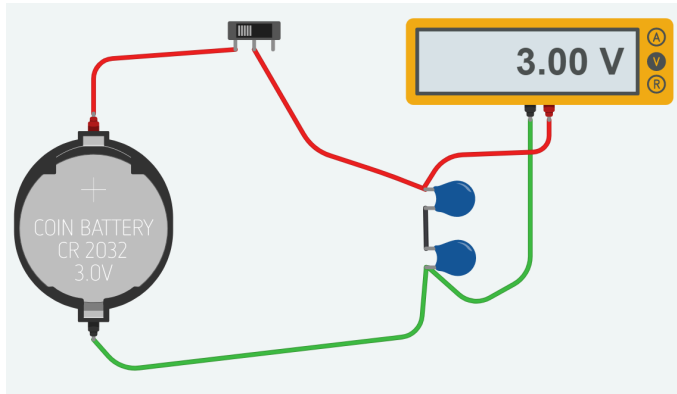
Capacitance	100 nF	200 nF	300 nF
Discharge Time	11 ms	22 ms	33 ms

where ms stands for milliseconds. Do you see that the

Discharge Time is Proportional to the Capacitance

With this observation we can explore whether series or parallel combinations speeds up or slows down this discharge time.

We run the same experiment as above with two 100 nF capacitors in **series** and find that it



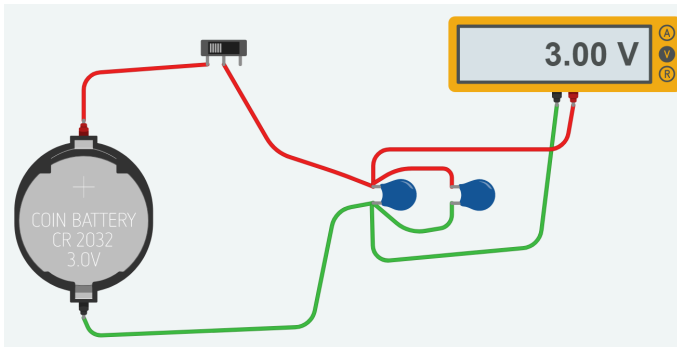
takes only 5.5 ms to discharge 2 volts.

We speculate therefore that **series** capacitances yield a **smaller** combined capacitance.

In fact the series law is

$$\text{Combined series capacitance of } C_1 \text{ and } C_2 \text{ is } C_1 C_2 / (C_1 + C_2)$$

If we now run this same experiment with two 100 nF capacitors in **parallel** we find that it takes



22 ms to discharge 2 volts.

We speculate therefore that **parallel** capacitances yield a **larger** combined capacitance.

In fact the parallel law is

$$\text{Combined parallel capacitance of } C_1 \text{ and } C_2 \text{ is } C_1 + C_2$$

These illustrations, with humans moving a switch and watching a stopwatch and a voltage meter, brought us real insight but will likely be too fast if we move to smaller capacitors and perhaps too slow for our patience for larger capacitances.

Fortunately there is a common instrument available for automatically switching voltage (the **function generator**) and a second instrument by which we can capture changing voltages (the **oscilloscope**).

This will also give us an opportunity to capture the charging phase as well.

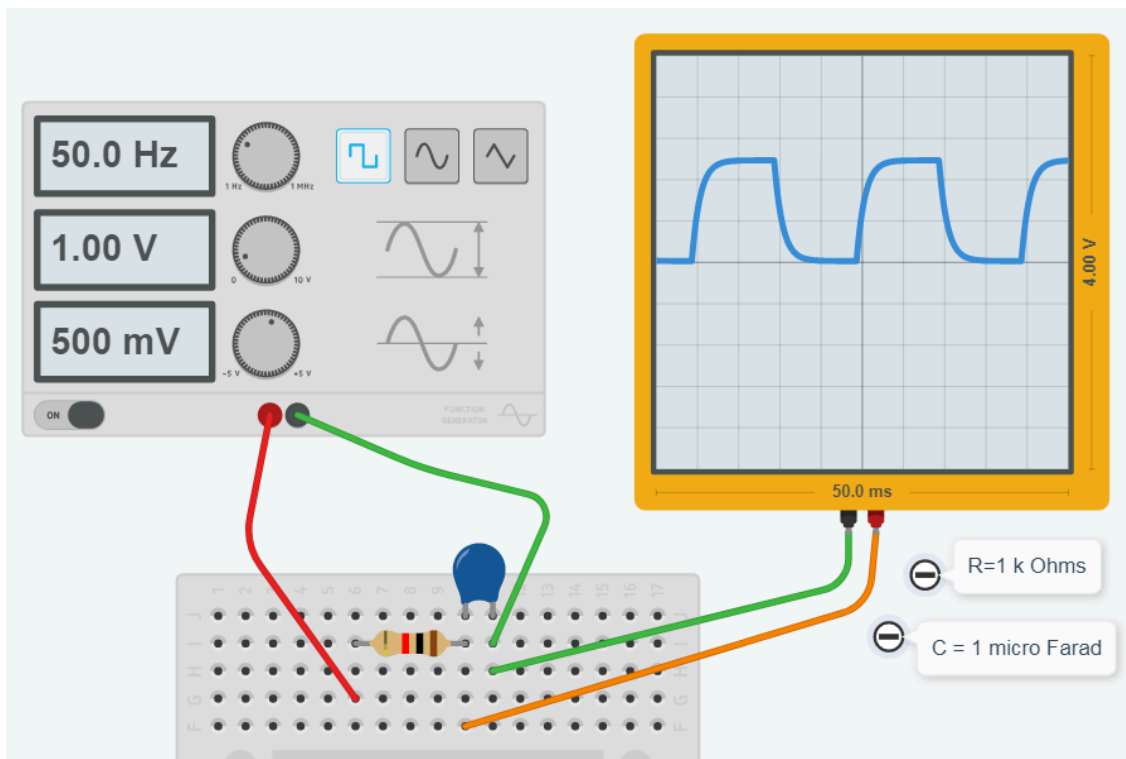
We demonstrate this in the circuit below, with a handy auxiliary resistor, all built on a breadboard rather than in mid-air. If you hover over a black dot on the breadboard, tinkercad will show which dots it is **automatically** connected to.

The function generator can produce square, sine, or sawtooth waves. We have chosen a **square wave** to mimic our on/off switch.

We get to choose the **frequency** of switching. Here we have chosen **50 Hertz (Hz)**, i.e., 50 on/off cycles per second.

We also get to choose the **peak-to-peak amplitude** of our wave, here we have chosen **1 volt**.

Finally, we get to choose the **DC offset** of our wave, and here we have chosen $\frac{1}{2}$ volts, so that the low part of the wave will deliver 0 volts and the high part will deliver 1 volt.



On the right we find the oscilloscope rendering of our output voltage (on the y axis) as a function of time (on the x axis).

Do you see the capacitor **charging** during the **on-stage** of the input wave, and **discharging** during the **off-stage**?

Do you also see that we may quantify this, as the voltage axis is divided into steps of 4/10 volts and the time axis is divided into steps of 5 ms?

Laboratory 3. Build a circuit with a 100 nF capacitor in series with a 200 nF capacitor and report the time it takes to shed 2 Volts and confirm that this agrees with the appropriate combined capacitance formula.

Lesson 4. 11/17. RC filters

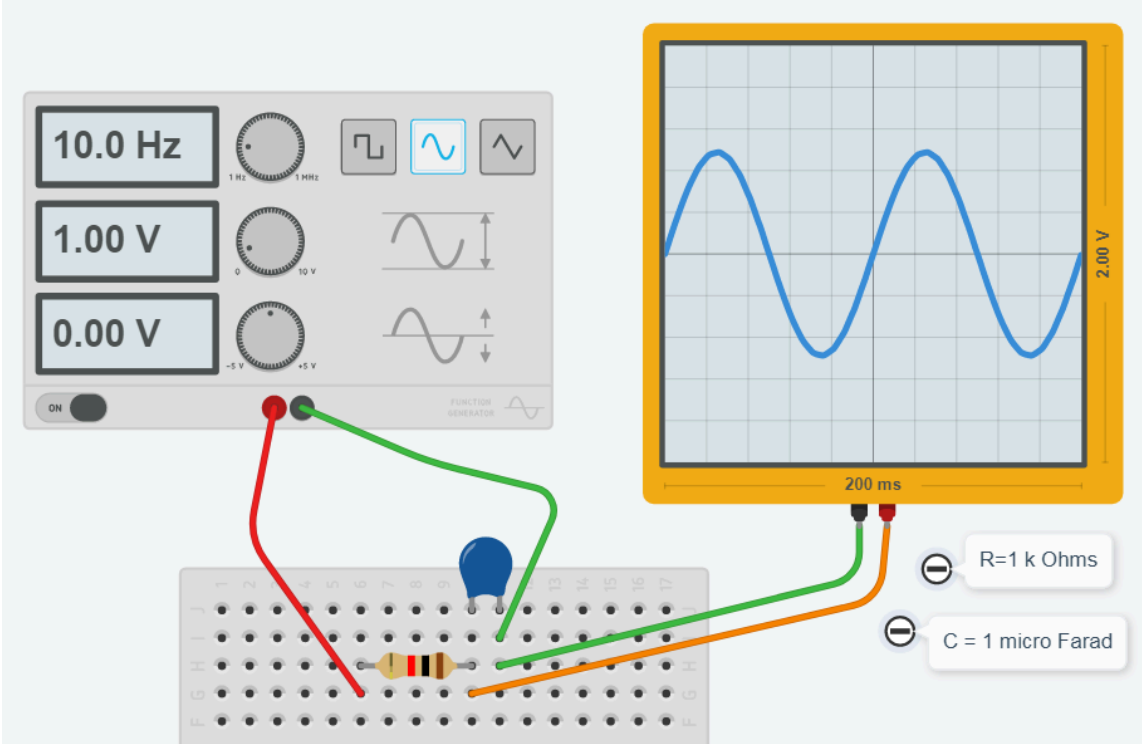
Reading: Chapter 2, pages 204-207 and Chapter 9, pages 663-666

Objectives:

1. Build and study RC filters
2. Record and plot their frequency response
3. Report frequency response as Gain in decibels

Content:

We retain the setting of our previous RC circuit, though we switch from square to sine wave and we explore the size of the output waveform as we vary the input frequency.



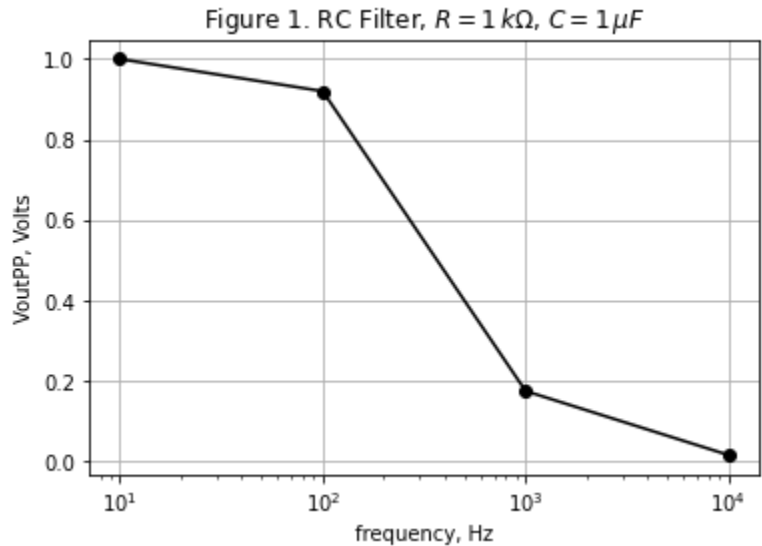
With an input frequency of 10 Hz we record a peak-to-peak output amplitude of 1 Volt. In the table below we record the peak-to-peak output amplitude for increasing values of input frequency.

Frequency, Hz	10	100	1,000	10,000
VoutPP, V	1	0.92	0.175	0.016

On graphing this data we recognize (compare to Fig. 9.1 in our text) that it passes low frequencies (say below 100 Hz) and rejects high frequencies (say above 1000 Hz).

As a result we call it a **low pass filter**.

Note that as our frequency increases over several orders of magnitude we have plotted our response on log-paper. The result is that it gives the same amount of space for every decade (power of ten).



Filter builders often play a similar game on the output side. Let's begin by working with powers of 10 and noting that \log_{10} picks off powers. Namely

$$\log_{10}(10^6) = 6 \quad \text{and} \quad \log_{10}(10^{-3}) = -3$$

With this practice we can define a

$$\text{Bel} = \log_{10}(\text{Output Power} / \text{Input Power})$$

Now as $\text{Power} = \text{Voltage} \times \text{Current}$ and (for our resistor) $\text{Current} = \text{Voltage} / \text{Resistance}$ we find

$$\text{Power} = \text{Voltage squared} / \text{Resistance}$$

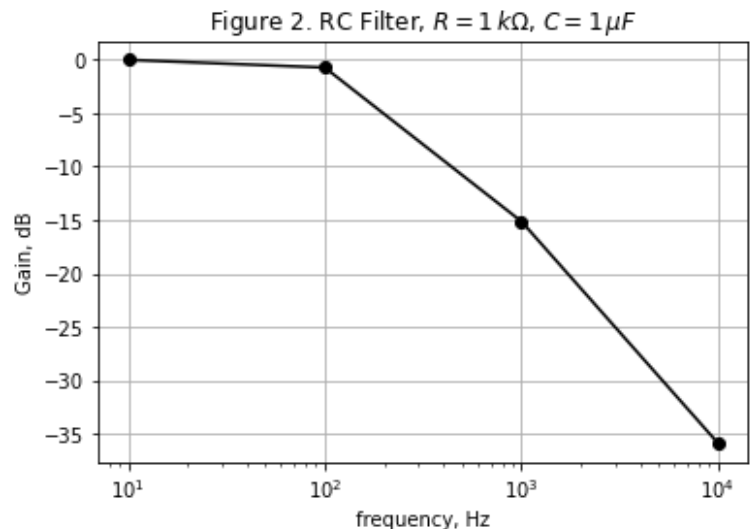
In taking the ratio of output power to input power the common resistance will drop out and we find

$$\text{Bel} = \log_{10}(\text{VoutPP}^2 / \text{VinPP}^2)$$

As exponents become multipliers, and we adopt the common usage of decibels (dB times 10) we arrive at the final form

$$\text{Gain} = 20 \times \log_{10}(\text{VoutPP} / \text{VinPP})$$

When evaluating this on our tabular data we arrive at the Gain vs. Frequency plot at right.



As we compare this to Figure 9.2 in our text we note that the text calls out the -3 dB point in defining our filter's cutoff frequency. This -3 dB marks the point at which the output power is one half of the input power. More precisely,

$$10 \times \log_{10}(1/2) = -3 \text{ dB}$$

And so the **cutoff frequency** of our filter is the frequency at which the output has $\frac{1}{2}$ the power of the input. With a bit more theory we can arrive at the exact determination

$$\text{cutoff frequency} = 1 / (2\pi RC) = 159 \text{ Hz}$$

Laboratory 4. Reverse the order of R and C and record VoutPP for the 7 frequencies

10, 50, 100, 500, 1000, 5000, 10000

and sketch your new gain curve using the same axes and labels found in the Gain curve above. Draw the horizontal -3 dB line. Where this line crosses your Gain curve, drop a vertical line down to your frequency axis and confirm that it hits near the same cutoff frequency. Upload a photo of your new plot to our BlackBoard page.

Lesson 5. 11/24. Inductors

Reading: Chapter 2, pages 113-138.

Objectives:

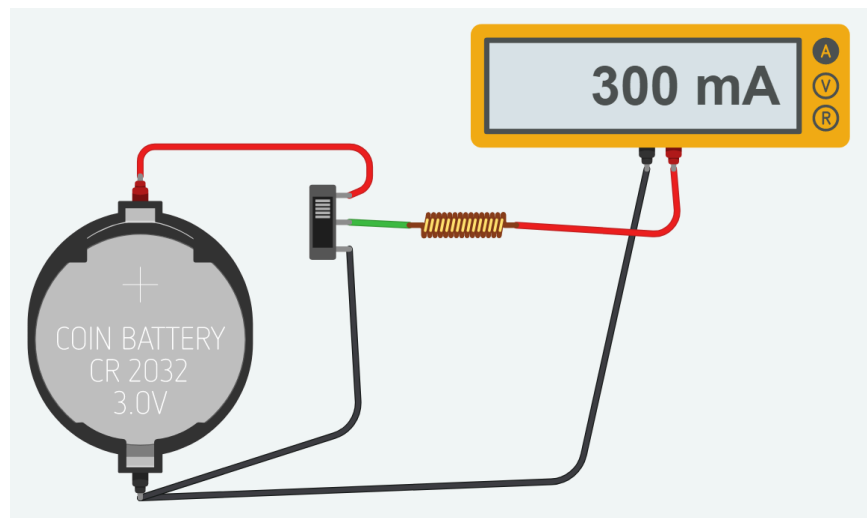
1. Explore charging of inductors with switches
2. Explore series and parallel combinations of inductors
3. Explore charging and discharging of inductors with a function generator

Content:

Inductors are dynamic magnetic storage devices. By **dynamic** I mean that they respond to a **change** in current rather than to the absolute level of current.

To illustrate this we put a simple switch between our battery and our inductor. When the switch is down we should read 0 current.

When we move the switch to the up position we can watch the inductor current increase as a function of the tinkercad simulation time, in milliseconds.



The unit of inductance is a **Henry**, after Joseph Henry. To understand the rate of current growth we run the above simulation for 3 values of inductance and record how long it takes to reach 300 mA from 0. I find

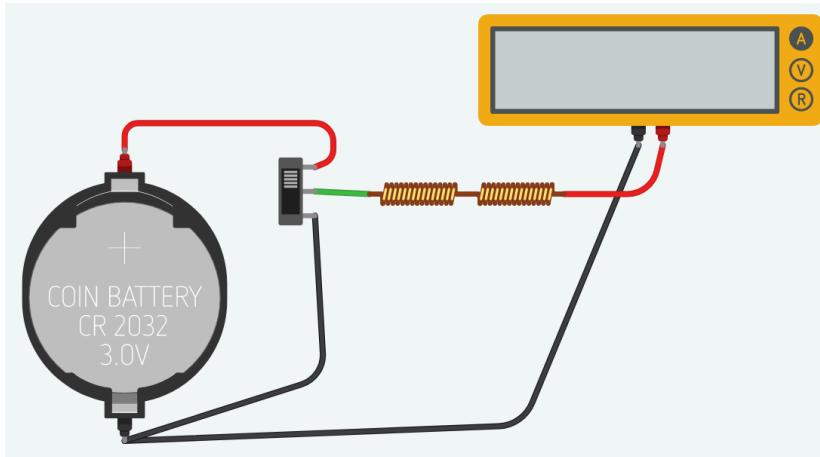
Inductance	1 H	2 H	3 H
Charge Time	1 ms	2 ms	3 ms

Do you see that the

Charge Time is Proportional to the Inductance

With this observation we can explore whether series or parallel combinations speeds up or slows down this charge time.

We run the same experiment as above with two 2 H inductors in **series** and find that it



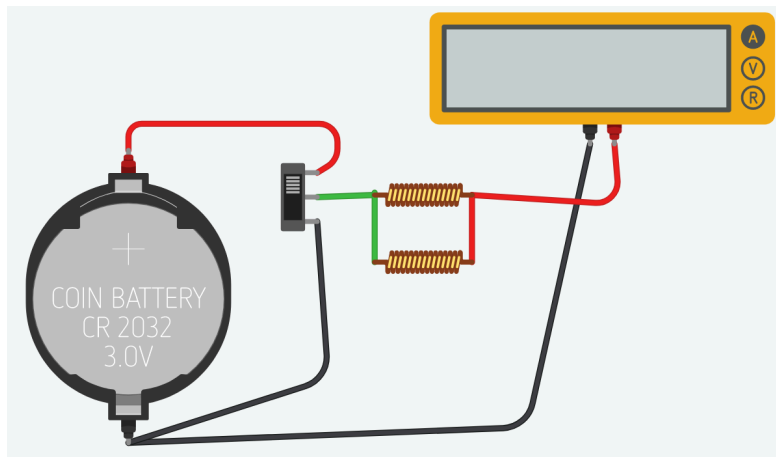
takes 4 ms to charge up.

We speculate therefore that **series** inductances yield a **larger** combined inductance.

In fact the series law is

Combined series inductance of L_1 and L_2 is L_1+L_2

If we now run this same experiment with two 2 H inductors in **parallel** we find that it takes



only 1 ms to charge up.

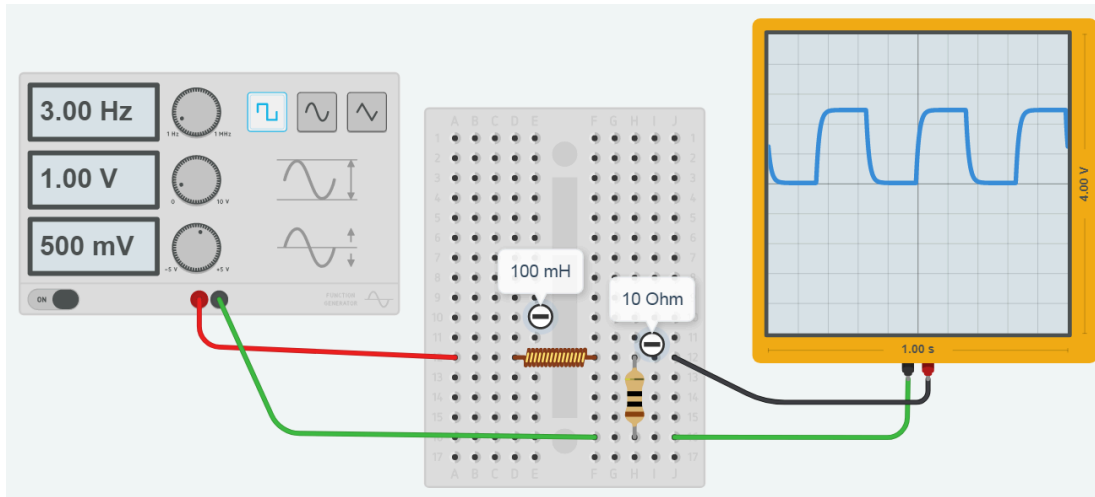
We speculate therefore that **parallel** inductances yield a **smaller** combined inductance.

In fact the parallel law is

Combined parallel inductance of L_1 and L_2 is $L_1 L_2 / (L_1+L_2)$

As with our initial study of capacitors it pays to bring out better instruments.

We breadboard below a simple RL series circuit driven by a function generator and observed by an oscilloscope.



Do you see the inductor **charging** during the **on-stage** of the input wave, and **discharging** during the **off-stage**?

Do you also see that we may quantify this, as the voltage axis is divided into steps of 4/10 volts and the time axis is divided into steps of 100 ms.

Laboratory 5. Build a circuit with a 1 H inductor in parallel with a 2 H inductor and report the time it takes to reach 300 mA and confirm that this agrees with the appropriate combined inductance formula.

Lesson 6. 12/1. RL filters

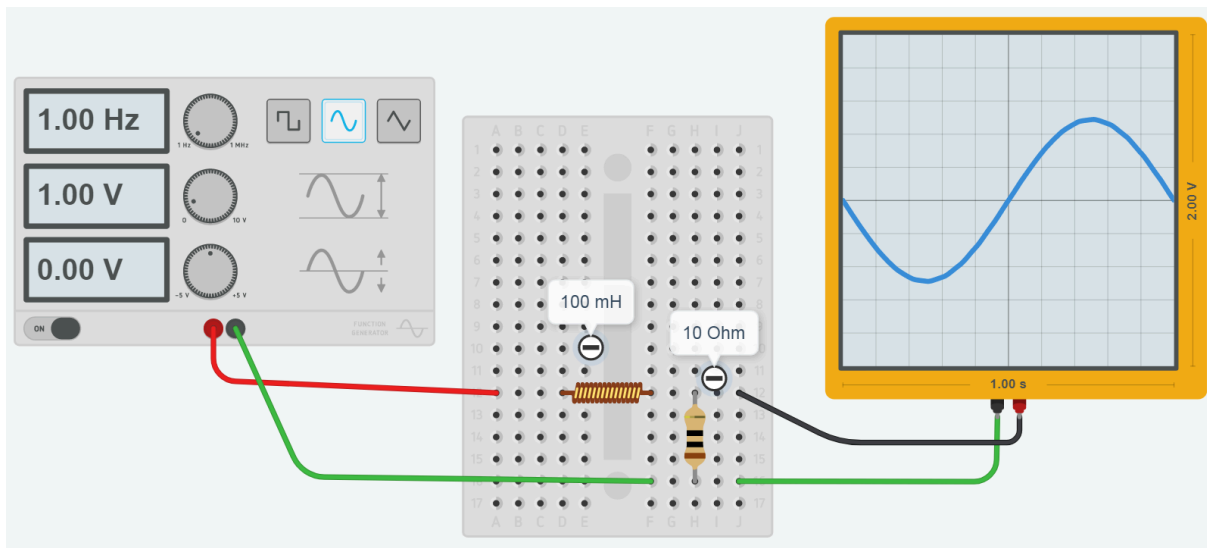
Reading: Chapter 2, pages 204-207 and Chapter 9, pages 663-666

Objectives:

1. Build and study RL filters
2. Record and plot their frequency response
3. Report frequency response as Gain in decibels

Content:

We retain the setting of our previous RL circuit, though we switch from square to sine wave and we explore the size of the output waveform as we vary the input frequency.



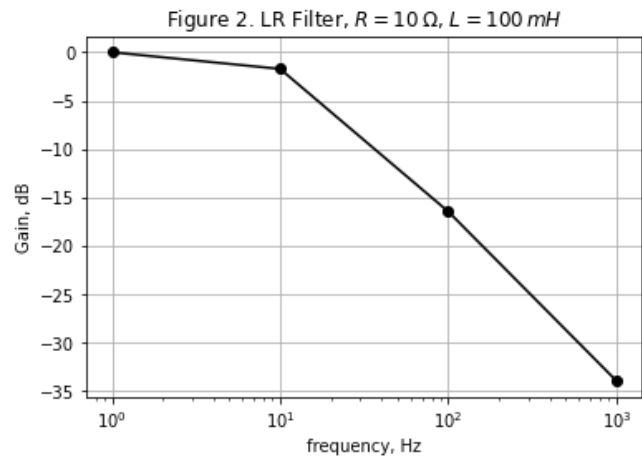
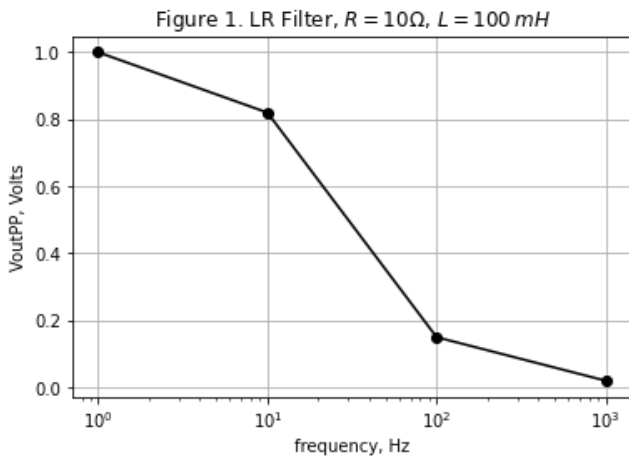
We achieve the following table

Frequency, Hz	1	10	100	1000
VoutPP, Volts	1	0.82	0.15	0.02

This is best “seen” as a graph.

As in our earlier filter work we follow the custom of plotting Gain rather than peak-2-peak output voltage.

$$\text{Gain} = 20 \times \log_{10}(\text{VoutPP}/\text{VinPP})$$



As above we continue to use the half power point, -3 dB, to define our cutoff frequency. In this case a bit more theory reveals that

$$\text{cutoff frequency} = R / (2\pi L) = 15.9\text{ Hz}$$

Laboratory 6. Reverse the order of R and L and record VoutPP for the 7 frequencies

1, 5, 10, 50, 100, 500, 1000

and sketch your new gain curve using the same axes and labels found in the Gain curve above. Draw the horizontal -3 dB line. Where this line crosses your Gain curve, drop a vertical line down to your frequency axis and confirm that it hits near the same cutoff frequency. Upload a photo of your new plot to our Blackboard page.

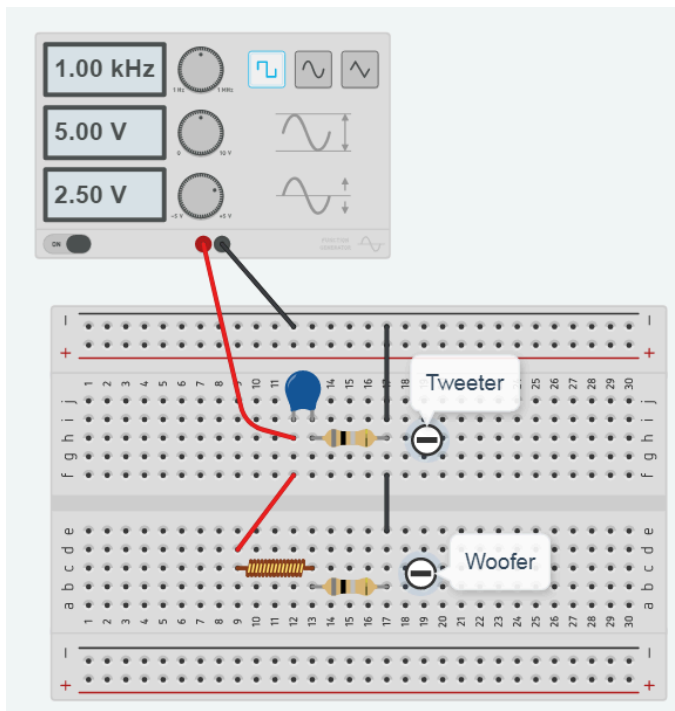
Lesson 7. 12/8. RLC filters

Reading: Chapter 3, page 350, Chapter 2, pages 204-207 and Chapter 9, pages 663-666

Objectives:

1. Combine low and high filters for a speaker crossover network
2. Build and study Bandpass filters
3. Build and study Bandstop filters

Content:



We imagine that our function generator is an audio signal that we wish to direct to an 8-Ohm tweeter and an 8-Ohm woofer.

As their names imply the tweeter is a speaker designed to play high frequencies while a woofer is designed to play low frequencies.

As such we place an LR Low pass filter en route to the woofer and a CR high pass filter en route to the tweeter.

The component values, see Fig 3.75 on page 350 are chosen to yield a common cutoff frequency of 5 kHz.

In this setting it is called a **crossover frequency**.

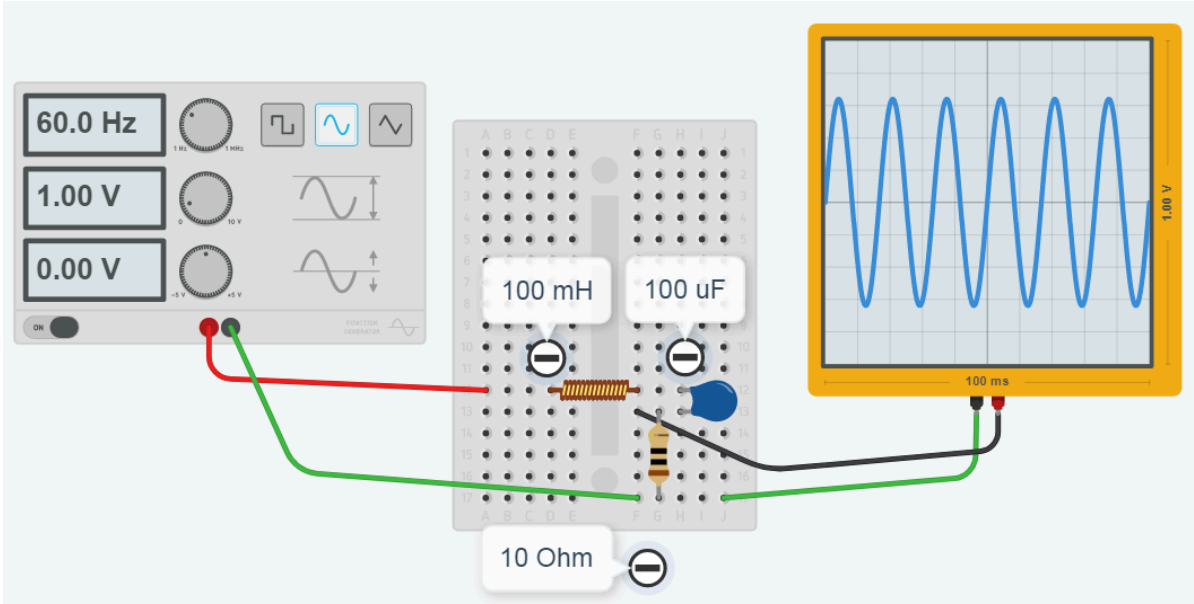
This crossover circuit is a nice application of our existing 2-component Low Pass and High Pass filters.

If we move to true 3-component filters we can be much more selective - in that we can build amazing BandPass and BandStop filters.

We'll do the first type together and then you'll do the second as a final lab assignment.

The Band-Pass Filter

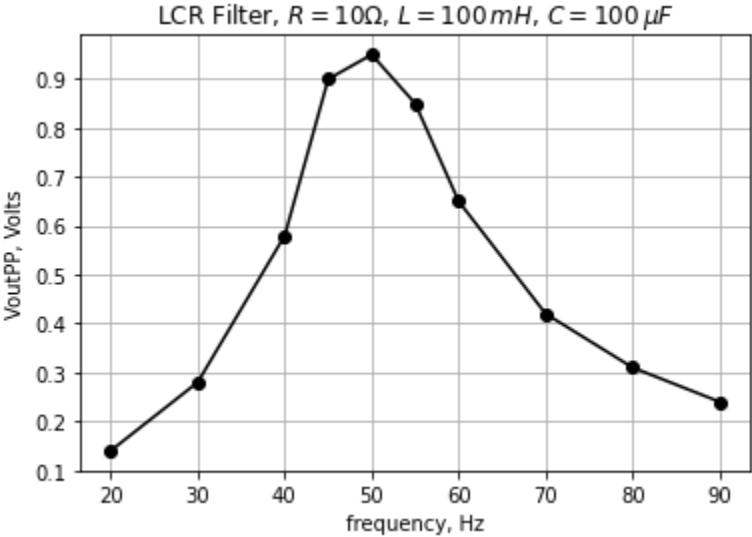
We build the LCR circuit below



and sweep over frequencies and record the associated output peak-2-peak voltage

Freq	20	30	40	45	50	55	60	70	80	90
VoutPP	0.14	0.28	0.58	0.9	0.95	0.85	0.65	0.42	0.31	0.24

As above we see this best in graphical form

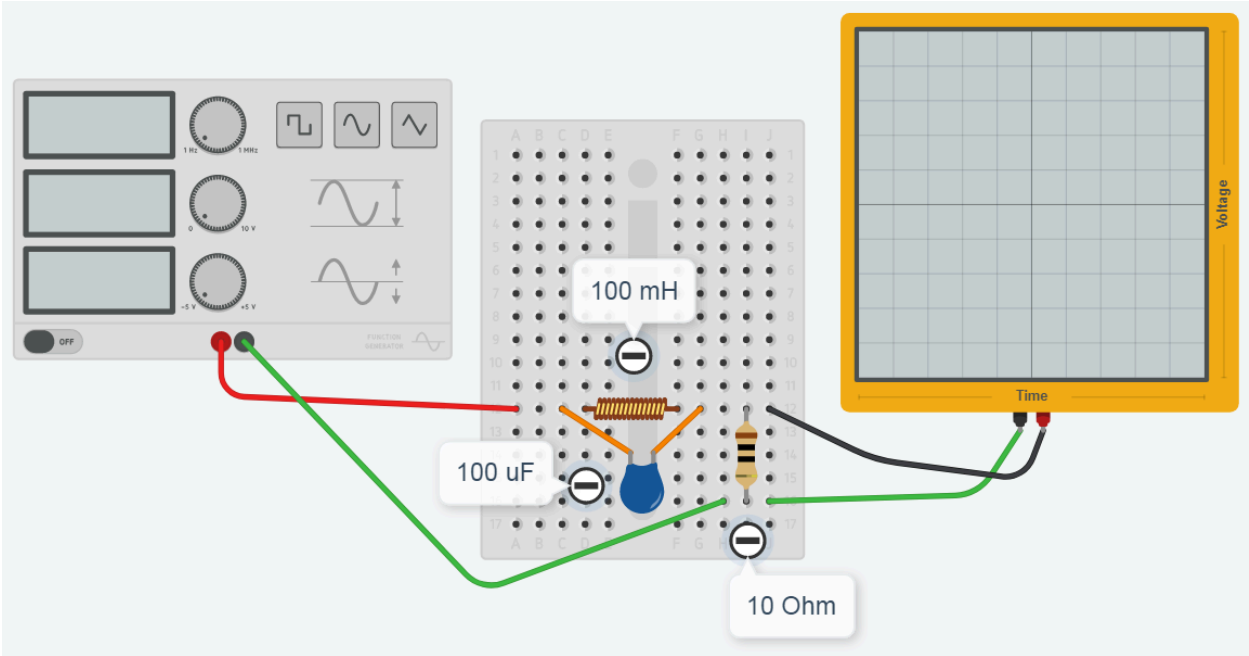


This is indeed passing a band of frequencies, centered about the **resonant frequency**

$$1/(2\pi\sqrt{LC}) = 50.33 \text{ Hz}$$

and a bandwidth determined by R.

Laboratory 7. Build the circuit below



and record the output peak-2-peak voltage for the same frequencies as the table on the previous page. Construct your new table and graph your results. Confirm that you achieve a Band-Stop filter centered at the same resonant frequency. Upload a photo of your new graph to our Blackboard page.