Electronics - PHYS 2371/2

Week #	Lectures	Weekly Topics (Chs.)	Homework (Ch-Problem)	Lab Experiments (always look for latest version)
III Sept 23-25	Wed Lecture Time-Dependent AC Circuits	The Oscilloscope (Ch-17) AC and Elements of Circuits (Ch-7/8) Circuit Analysis (LRC) (Ch-9/12) Resonance (Ch-10)	7-all, 8-3 12-all	Worksheet-3, Worksheet-3 video RC data xls ***Time-Dependent AC Circuits*** (R, RC, LRC)
IV Sept 30-Oct 2	Wed Lecture Semiconductor Devices	Solid State Devices (Ch-40) *p-n* Junction Diodes (Ch-41) Transistors/Circuits (Ch-42-45)	HW Handout	Worksheet-4, ***Say Hello (and Goodbye) to the Transistor***
V Oct 7-9	Wed Lecture Operational Amplifiers	Op-Amp Basics (Ch-28, 31) Basic Op-Amp Circuits (Ch-29)	28-1/3/4, 29-1/2/3/4	Lab-5, *Op-Amps*
VI Oct 14	Wednesday Study for EXAM-1	**Study for EXAM-1** **Basics, AC Circuits, Semiconductors, Op-amps**		No Lab
VII Oct 19, 21-23 MON/WED	MONDAY EXAM-I	Wed Lecture Magnetoelectronics Magnetic induction/flux Transformers (Ch-11)	11-all	Lab-6, *Build a Magnetometer*
VIII Oct 28-30	Wed Lecture Optoelectronics	Photodiode, LED, laser	none	Lab-7, *Optoelectronics* (coupled LED-photodiode)

Due Wednesday, Sept. 25

- Week-III HW (Chs. 7,8,12)
- Worksheet-3 on AC

TODAY

- ☐ **Quick Review-Basics**
- ☐ **Alternating Current, Ch-7**
  - RMS
- ☐ **Elements of AC Circuits, Ch-8**
  - resistor, capacitor, inductors(L)
  - impedance (Z), reactance (X)

(video break)

- ☐ **AC Circuits, Ch-9**
  - Gain in RC and LRC circuits
  - Frequency dependence
- ☐ **Step Function Analysis, Ch-12**
  - RC circuit
- ☐ **LRC Resonance, Ch-10**
  - add inductor (L)
- ☐ **Lab-3, Time-varying AC Voltages**
  - oscilloscope, RC and LRC circuits

Review Basics

- **Kirchhoff's Basic Circuit Laws**
  - **KCL – Kirchhoff's Current Law**
    $\Sigma I = 0$ at node – conservation of charge
  - **KVL – Kirchhoff's Voltage Law**
    $\Sigma V = 0$ around loop – conservative field
- **Adding components**
  - $R_{series} = \Sigma R_i$, $1/R_{parallel} = \Sigma 1/R_i$
  - $C_{parallel} = \Sigma C_i$, $1/C_{series} = \Sigma 1/C_i$
- **Voltage Divider**

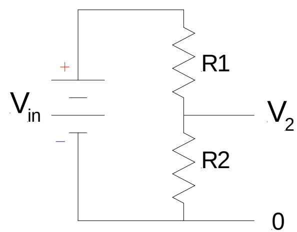
$$V_2 = V_{in} \frac{R_2}{R_1 + R_2}$$

Gustav Robert Kirchhoff (1824 – 1887)

He contributed to the fundamental understanding of electrical circuits.

Kirchhoff formulated his circuit laws, which are now ubiquitous in electrical engineering, in 1845, **while still a student**. He completed this study as a **seminar exercise**; it later became his doctoral dissertation. In 1857 he calculated that an electric signal in a resistanceless wire travels along the wire at the **speed of light**.

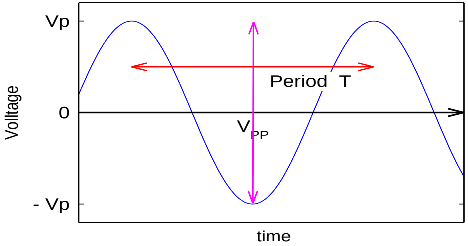
He proposed his law of thermal radiation in 1859, and coined the term **"black body" radiation** in 1862.



AC – Alternating Current (Ch-7)

Sine wave $V(t) = V_p \sin(\omega t+\phi)$

- ω frequency, units---radians/s
- ϕ phase, units---radians



$f = \omega / 2\pi$ frequency, units - Hz or cycles/s

$T = 1 / f = 2\pi / \omega$ period, units - s

$V_{pp} = 2\ V_p$ peak-to-peak voltage

How do you measure the power for AC?

For DC, **Power = $I_{DC} \times V_{DC}$**
both I and V are constant

With AC, I(t) and V(t)

RMS – root mean square

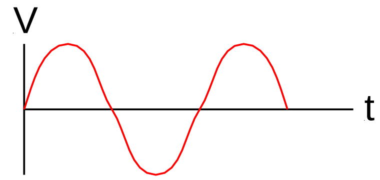
Averaging for AC signals of any waveform

$\langle V_p \rangle = 0$ for sine wave

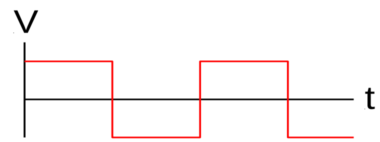
$$V_{RMS} = \sqrt{\frac{1}{T} \int_0^T V^2(t)\, dt}$$

RMS characterizes the average, **independent** of the waveform

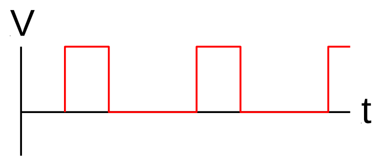
Power $P = V_{RMS}^2 / R$



For sine wave $V_{RMS} = V_p / \sqrt{2} = 0.707\, V_p$



For square wave $V_{RMS} = V_p$



For pulses $V_{RMS} < V_p$

Prob. 7-1 wall plug

f = 60 Hz

V_{RMS} = 115 – 120 V

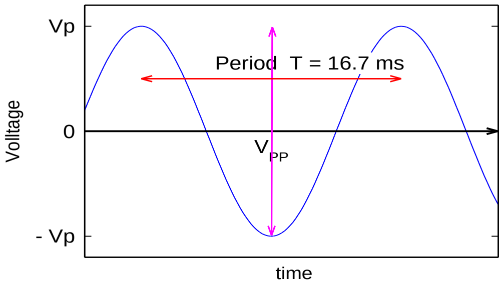
Period

T = 1 / 60 = 16.7 ms

Peak voltage

$V_p = \sqrt{2}\, V_{RMS}$

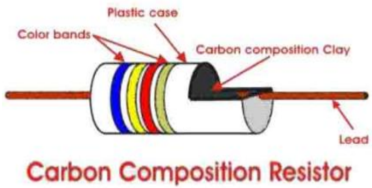
$\approx$ 170 V

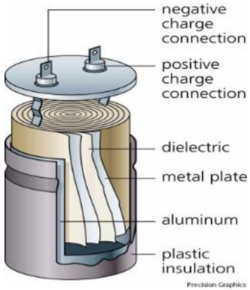


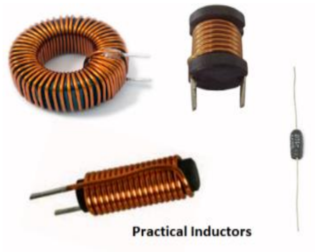
Questions?

Simple AC, RMS

Basic Elements of AC Circuits



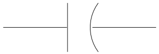




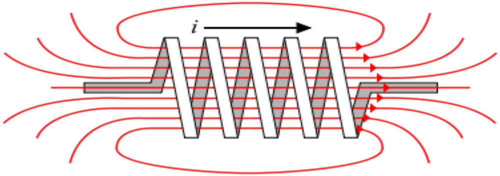
R – **resistor**
carbon, carbon film, metal film
ohm (Ω)

C – **capacitor**
metal + ceramic or plastic film
farad (F)

L – **inductor**
coil of insulated wire
henry (H)

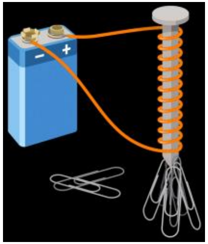


Inductor



An **inductor**,
as an electrical component, is a coil of wire.

When a current flows through it, energy is stored temporarily in a **magnetic field** in the coil.



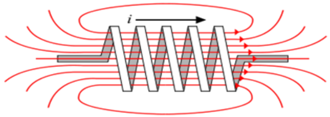
How does it work in an AC Circuit?

It resists changes in current passing through it.

When the current flowing through an inductor **changes**,

the **time-varying magnetic field induces a voltage** in the conductor according to Faraday's law of induction,

which opposes the change in the current that created it.
(Wikipedia)



Inductor in an AC Circuit

- When the **current** changes
- it creates a changing **magnetic** field
- this creates a **reverse voltage**
- thus **opposing** the original changing **current**

An inductor appears to have **inertia**,
as it tries to keep the *status quo*,
or fight any changes in the current.

Questions?

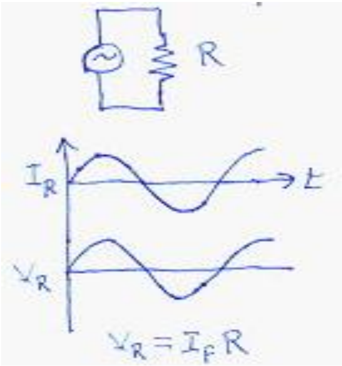
R, C, L in an AC Circuit
→ Phase Shift between V(t) and I(t)

Time dependence of V(t) and I(t)

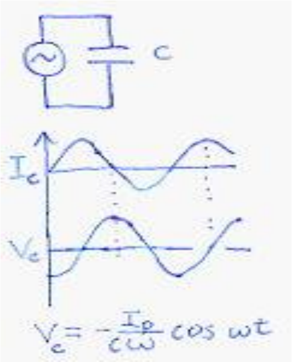
V(t) and I(t) may not be "in phase"

$$I = I_P \sin(\omega t)$$

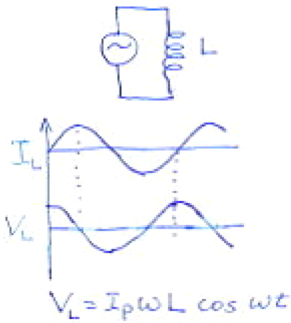
Resistor



Capacitor



Inductor



What are I-V relationships for any time-dependent voltages

R	$V = IR$	$I = V/R$	$(\Omega = volt/amp)$
C	$V = \frac{1}{C}\int I dt$	$I = C\frac{dV}{dt}$	$(farad = coulomb/volt)$
L	$V = L\frac{dI}{dt}$	$I = \frac{1}{L}\int V dt$	$(henry = \frac{volt - s}{amp})$

	R	C	L
I(*t*) =	V(t)/R	C *d*V(t)/*d*t	-1/L ∫V(t)*dt*
V(*t*) =	I(t) R	1/C ∫I(t)*dt*	L *d*I(t)/*d*t
Z =	**R**	**-*i*/ωC**	***i*ωL**
X = |Z|=	R	1/ωC	ωL
φ	0	V lags I by 90°	V leads I by 90°

Properties of R, C, L in an AC Circuit

- **R** dissipates energy in the form of heat
- **C** and **L** only change the flow of current
- **C** and L do not dissipate energy, they store energy
- **C** stores energy in an **electric field**
- **L** stores energy in the form of a **magnetic field**

C and L only "**act**" like resistances (reactance)

In order to use an "*effective resistance*" for C and L, we use the concept of **Impedance** and **Reactance**.

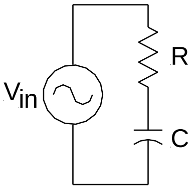
Impedance and Reactance

Similar to resistance – but depends on frequency ω

Impedance Z Complex Number			
Z =	**R**	**$-i/\omega C$**	**$i\omega L$**

Reactance X = |Z| Magnitude of Z			
X =	**R**	**$1/\omega C$**	**ωL**

- Example – **RC Circuit Impedance**



R = 1.0 KΩ
C = 0.10 μF
f = 1.0 kHz

$Z_R = X_R = R = 1.0\ k\Omega$

$Z_C = -iX_C = -i/\omega C$

$= -\,i\,/(2\pi * 10^3\ s^{-1} * 10^{-7}\ F)$

$= -\,i\ 1600\ \Omega$

$Z = (1.0 - 1.6\,i)\ k\Omega$

$X = ZZ^* = [(1.0-1.6\,i)k\Omega*(1.0+1.6\,i)k\Omega]^{1/2}$

$= [(1.0\ k\Omega)^2 + (1.6\ k\Omega)^2]^{1/2}$

$X = 1.9\ k\Omega$ **C conducts more at higher ω**

Combining Impedances

Simple way to derive series/parallel formulas

Series components

$\mathbf{Z_T = \sum Z_i = Z_1+Z_2\cdots}$

Parallel components

$\mathbf{1/Z_T = \sum 1/Z_i = 1/Z_1+1/Z_2\cdots}$

$Z_R = \mathbf{R} \sim \mathbf{R}$

$Z_C = -i/\omega \mathbf{C} \sim 1/\mathbf{C}$

Series components

$\mathbf{R_T} = \sum R_i = \mathbf{R_1+R_2}\cdots$

$\mathbf{1/C_T} = \sum 1/C_i = \mathbf{1/C_1+1/C_2}\cdots$

Parallel components

$\mathbf{1/R_T} = \sum 1/R_i = \mathbf{1/R_1+1/R_2}\cdots$

$\mathbf{C_T} = \sum C_i = \mathbf{C_1+C_2}\cdots$

Formulas are derived without Kirchhoff's laws

Questions?

Video

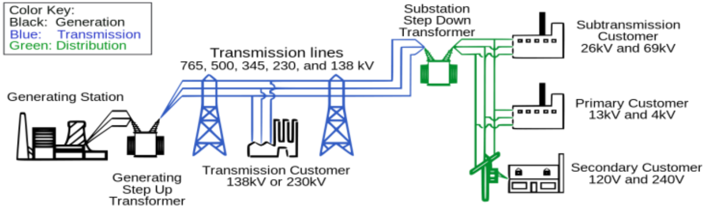
Tesla 8:12 – (17:57)

Tesla Video

Why is AC better than DC for power applications?

For DC, electrons
DO NOT
have to travel a long distance.
The video was **WRONG.**

POWER GRID	Voltage
GigaW Power plant	138-500 kVAC
Large substation	26/69 kVAC
Small substation	13,800 VAC
Street	4,000 VAC
House	120/240 VAC



AC allows for lower transmission losses,

by increasing voltage and reducing current.

Using a few assumptions, the power loss in transmission through power lines with resistance R is $\Delta P = I^2 R$. Thus, the power loss is proportional **to** $\sim I^2$.

You can keep the delivered power (**P=IV**) constant by simply increasing the voltage by the factor η, and reducing the current by the same factor of η.

So increasing the voltage by a factor of 2 and decreasing the current by a factor of 2, keeps the delivered power constant, but reduces the power loss in the power lines by a factor of 4.

Power grids use voltages up to nearly 10^6 volts.

This effect is only useful with AC, as it is very easy to step up and down the voltages with **passive electrical transformers**.

Questions?

Step function analysis of RC circuit

KVL: $V_O - IR - V_C = 0$

$$V_O - I(t)R - \frac{Q(t)}{C} = 0$$

$I = dQ/dt$

$$V_O - R\,\frac{dQ(t)}{dt} - \frac{Q(t)}{C} = 0$$

Guess the solution: $Q = A + Be^{\alpha t}$

$$dQ/dt = \alpha B e^{\alpha t}$$

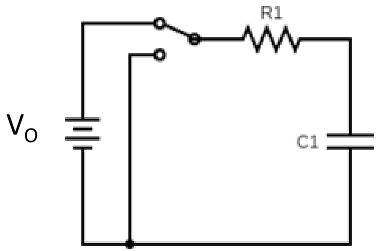
$$\left[V_O - \frac{A}{C}\right] - Be^{\alpha t}\left[\alpha R - \frac{1}{C}\right] = 0$$

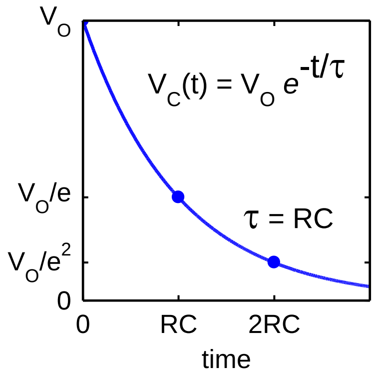
$$A = V_O C \quad and \quad \alpha = -\frac{1}{RC} = -\frac{1}{\tau}$$

$$Q = CV_O + Be^{-\frac{t}{\tau}}$$

$V_C(t) = Q/C = V_O e^{-\frac{t}{\tau}}$ for discharge

τ=RC



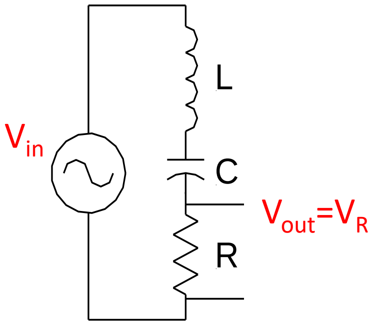


http://www.falstad.com/circuit/e-cap.html

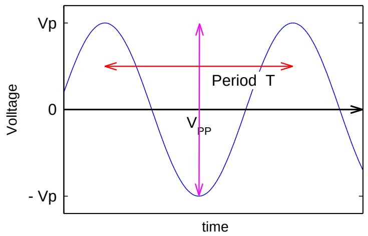
LRC Circuit Analysis (Ch-9)

General Series LRC Circuit

Resonant Circuit



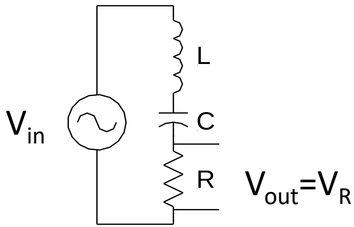
Input $V_{in}(t) = V_P \sin(\omega t)$



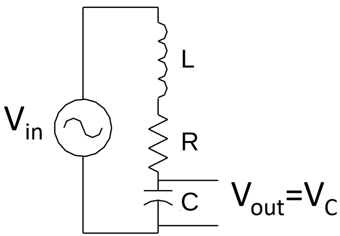
$$\text{Compute Gain} \quad G \equiv \left| \frac{V_{out}}{V_{in}} \right|$$

LRC Circuit Analysis (Ch-9)

Gain on R and C in LRC Circuit



$G_R=|V_R/V_{in}|$



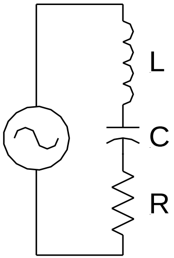
$G_C=|V_C/V_{in}|$

Compute voltages
V_R and V_C
using **Impedances Z**

LRC Gain G(*f*) - Voltage Divider

$$V_J = V_{in}\frac{Z_J}{Z_R + Z_L + Z_C}, \quad J = R, C, L$$

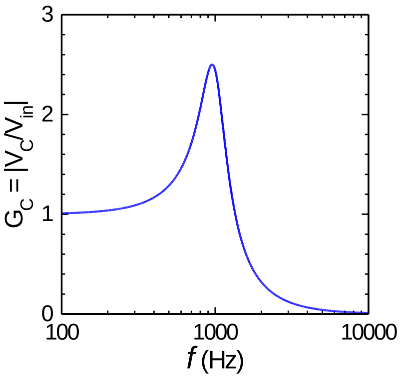
$$Z_R = R, \quad Z_C = -i/\omega C, \quad Z_L = i\omega L$$



$$G_J \equiv \left| \frac{V_J}{V_{in}} \right| = \left| \frac{Z_J}{Z_R + Z_C + Z_L} \right|$$

$$G_C = \sqrt{\left[\frac{-i/\omega C}{(R - i/\omega C + i\omega L)}\right]\left[\frac{i/\omega C}{(R + i/\omega C - i\omega L)}\right]}$$

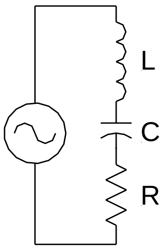
$$G_C = \frac{1/\omega\tau_{RC}}{\sqrt{1 + (1/\omega\tau_{RC} - \omega\tau_{LR})^2}}, \quad \tau_{RC} = RC, \ \tau_{LR} = L/R$$



The resonance maximum occurs in $G_C(\omega)$ *at* ω_o *when the squared term in the denominator is zero.*

$$\boldsymbol{\omega_o = 1/\sqrt{LC}}$$

LRC Circuit Gains G(ω)



Circuit	Gain	Phase
J	G_J , $\tau_{RC} = RC$, $\tau_{LR} = L/R$	Phase between V_J and I
RC	$G_R = (\omega\tau_{RC}) / [1 + (\omega\tau_{RC})^2]^{1/2}$	$\phi_R = \text{atan}(1/\omega\tau_{RC})$
RC	$G_C = 1 / [1 + (\omega\tau_{RC})^2]^{1/2}$	$\phi_C = \text{atan}(-\omega\tau_{RC})$
RL	$G_R = 1 / [1 + (\omega\tau_{LR})^2]^{1/2}$	$\phi_R = \text{atan}(-\omega\tau_{LR})$
RL	$G_L = (\omega\tau_{LR}) / [1 + (\omega\tau_{LR})^2]^{1/2}$	$\phi_L = \text{atan}(1/\omega\tau_{LR})$
LRC	$G_R = 1 / [1 + (\omega\tau_{LR} - 1/\omega\tau_{RC})^2]^{1/2}$	$\phi_R = \text{atan}(1/\omega\tau_{RC} - \omega\tau_{LR})$
LRC	$G_C = (1/\omega\tau_{RC}) / [1 + (\omega\tau_{LR} - 1/\omega\tau_{RC})^2]^{1/2}$	$\phi_C^* = \text{atan}(1/\omega\tau_{RC} - \omega\tau_{LR}) - \pi/2$
LRC	$G_L = (\omega\tau_{LR}) / [1 + (\omega\tau_{LR} - 1/\omega\tau_{RC})^2]^{1/2}$	

Phase Angle

$I \sim \sin(\omega t)$

$V_J \sim \sin(\omega t + \varphi_J)$

φ_J phase angle that V_J LEADS I_{total}

φ_X^* phase angle that V_J LEADS input V_{in}

Questions?

Lab Experiment Week-III

Time-dependent and AC Voltages

General Circuit Instructions

Apply to this lab and all subsequent labs

(1) **Draw the circuit diagram.** This is important for any circuit you build, showing all instrument connections, as well as ground connections and other important information.

(2) **Place the elements physically on the breadboard to mimic the circuit diagram**.

(3) Make sure that **all of the negative (ground/black) instrument connections are connected** to the same point on the circuit whenever possible. Since the negative connections are usually connected together thru the power cables, they can short out a circuit component.

(4) Always set the scope display to enhance the visibility of the important data (for example, peak-to-peak voltages, phase shifts, cycles, etc.).

Worksheet-3, AC and Time-Dependent Voltages

Name:________________

Physics PHYS 2371/2372, Electronics for Scientists

Don Heiman and Hari Kumarakuru, Northeastern University

This lab allows you to explore the behavior of the circuit elements, such as resistors/capacitors/inductors, to time-varying voltages. It also examines more combinations of circuit elements with AC signals.

I. The Oscilloscope

In this exercise you will become familiar with the digital scope.
Using a 5 V peak, 60 Hz **sine wave** from the function generator, view the waveform on the scope.
Use the **Measure** function of the scope.

1. What is the peak-to-peak voltage? V_{pp} = ______________________

2. What is the frequency of the waveform? f = ______________________

3. What is the period of the waveform? P = ______________________

Videos on Oscilloscopes (0-1:45, 0-3:30)

https://www.youtube.com/watch?v=u4zyptPLlJI
http://www.youtube.com/watch?v=LAdEyEOOBjU

II. Time Response of an RC circuit

Here you will explore the response of an RC (resistor/capacitor) circuit to a voltage pulse. Construct a circuit consisting of a C=0.1 μF capacitor and an R=2 kΩ resistor in ***series***, and connect to the function generator. Use a BNC Tee on the **"TTL" output** from the function generator to go to both chnl-1 on the scope and the circuit. (Some function generators have the TTL output on the rear.) The TTL voltage is a ***square wave*** with voltage alternating between +5 V and 0 V. Note that this is equivalent to switching a DC voltage on and off (grounded). View the voltage across function generator on chnl-1 of the scope and the voltage across the capacitor (V_C) on chnl-2. Make sure you consider that the scope has a single ground (outer contact on the BNC connector), so you don't short out one circuit element.

1. Compute time constant τ_C=RC=_______________ and frequency $f_o=1/(2\pi\ \tau_C)$=________________.

2. Adjust the FG to $f \ll f_o$. What is the peak voltage on the capacitor? V_C = ____________________
   (**Note**: "<<" means 5 or more times smaller)

3. Adjust the FG to $f \gg f_o$. What is the peak voltage on the capacitor? V_C = ____________________

4. Adjust the FG to $f < f_o$. Measure the circuit time constant, which is equal to the time it takes for the capacitor voltage, $V_C(t)$, to drop to 1/*e* of any starting value.
   τ_C = ____________________

5. For the three frequency conditions above, **plot $V_C(t)$**.

Video on
Function Generators

https://www.youtube.com/watch?v=Zink6v6TXk4

III. Resonant Response of an RLC Circuit

The RLC circuit is often called a *resonance circuit*.

Construct a circuit with an R, L, and C in series. Connect an **R=100 Ω** resistor, **L~50 mH** inductor, and **C=0.5 μF** capacitor in series across the function generator. Set the sine wave amplitude of the FG to a peak-to-peak voltage of Vo ~ 15 V.

Use the two scope channels to measure V_O across the FG and V_C across the capacitor. Again, make sure that all the negative (black) connections are attached together. For the phase shift, Δt, pay attention to the **sign** of the phase shift (relative time shift where the voltage crosses zero).

1. Measure the voltages V_O and V_C and Δt between V_O and V_C, for frequencies *f*=40 Hz to 100 kHz.

2. Plot the gain for the capacitor ($G_C=V_C/V_O$) as a function of *f* on a semi-log scale. Is G_C greater than 1? Collect additional data points near the resonance region to improve the plot.

4. On the graph, plot the theory for the gain and the phase (points for data, curved line for theory). Do they match reasonably well? Does the inductor have resistance? ______________________

6. Compare the measured and calculated resonance frequency *f*o and maximum gain G_C.

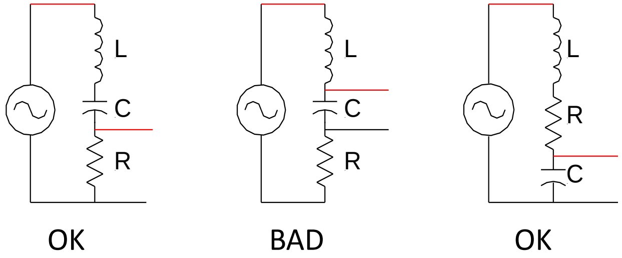
f_o(meas) = ___________________; Gc(meas) = ___________________

f_o(calc) = ____________________; Gc(calc) = ____________________

7. Compute the phase shift ϕ_C from Δt for: $\phi_C(f<<f_o)$=_____________ and $\phi_C(f>>f_o)$=___________________.

Make sure that **<u>all of the negative (ground/black) instrument connections are connected</u>** to the same point on the circuit whenever possible. Since the negative connections are usually connected together thru the power cables, they can short out a circuit component.

Note that I moved C to the bottom



Drawing Circuits (free)

Circuit Diagram - https://www.circuit-diagram.org/
(download/save png file/open in TWINUI, copy/paste file into document)

Digikey – http://www.digikey.com/schemeit#

CircuitLab – https://www.circuitlab.com/
(can only copy whole screen page)

XCircuit – http://opencircuitdesign.com/xcircuit/
(download)

SmartDraw – http://www.smartdraw.com/software/electrical.asp
(sign up)

Teach logic gates and build circuits - http://logic.ly/
(useful for **digital** circuits)

Questions?

Ende