Mechatronics

Analog and Digital Electronics: Studio Exercises 1 & 2

There is an electronics revolution taking place in the industrialized world. Electronics pervades all activities. Perhaps the most important technological development in the second half of the 20th century is the development of solid-state electronics and all the technological changes that this development made possible. While the details of the field of electronics are changing very rapidly, the fundamental laws describing the operation of electronic devices and the methods of analysis used to understand electronic circuits change only slowly, if at all, and so the emphasis here is on the fundamentals and the basic vocabulary used in electronics.

A good working knowledge of electronics has four distinct elements:

- knowledge of the basic physical laws that apply to the operation of electronic devices, including basic circuit analysis laws
- knowledge of circuit analysis techniques, i.e., the mathematical techniques used to understand the operation of circuits, including computer simulation of electronic circuits
- knowledge of the state of the art in electronics in order to answer the challenge "design a ..." or "build a ...."
- mastery of the vocabulary of electronics which is essential for reading the electronics literature

Of these four, only the third element changes very rapidly.

The goal in the first two studio exercises is to provide a balanced approach to these elements of electronics as they relate to mechatronic system design.

Studio Exercise #1, Analog Electronics, Part A:
Resistors, Capacitors, DC/AC Circuits, RC (Filter) Circuits, Lead/Lag Controllers, Input/Output Impedance, Loading Effects

Introduction:

This exercise is a review of the two most fundamental electronic components, the resistor and capacitor, together comprising essential building blocks of both analog and digital circuitry. Kirchhoff's and Ohm's laws provide the means of analyzing and constructing analog circuits using these components. The basic circuits covered, voltage dividers, RC (filter) circuits, lead/lag controllers, you will put together in this laboratory exercise. You will learn about input / output impedance and loading effects, two of the most important concepts for any mechatronics engineer to know. You will also begin to learn, through analysis and experimentation, the relationship between the time domain and the frequency domain.

Obviously, much of this is a review in the basics nearly all of you have, at one point or another, already seen. Yet it is precisely for this reason that it is so important that you master these basics, particularly from a design point of view. In addition, as elementary as voltage dividers and RC filters are, they are in fact two of the most useful and applicable circuit fragments to know as a mechatronics engineer, since a host of common electronic devices are based on them.

This exercise will also quickly familiarize you with the use of the following standard electronics equipment: multimeter, function generator, oscilloscope, breadboard.

Procedure:

- Using the multimeter, measure all resistors and capacitors. Note values. Note tolerances.

- Using the multimeter, check +15 V, -15 V, and +5 V on the powered breadboard. Using the multimeter, check the connectivity on the breadboard.

- **RC Low-Pass Filter Circuit**: R = 15 KΩ, C = 0.01 μF
  $\Rightarrow$ Derive the ideal transfer function for this system.
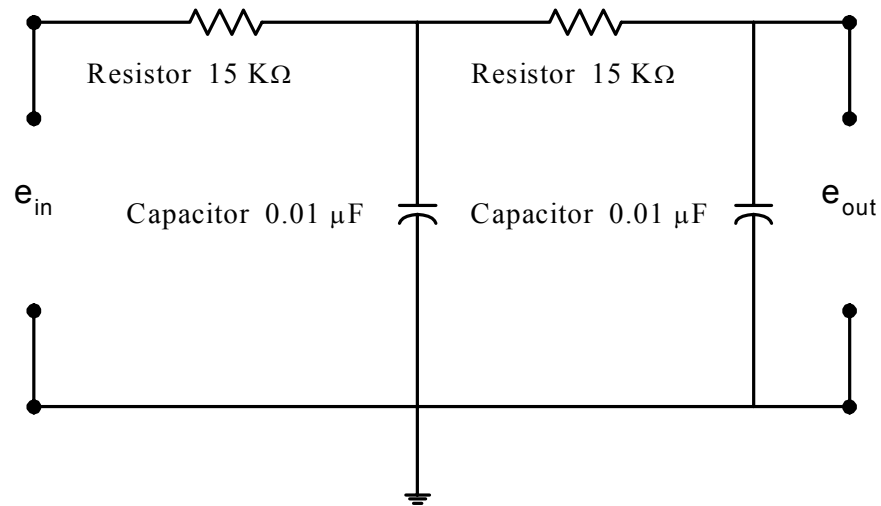 $\Rightarrow$ Perform MatLab Simulations: plot the step response and frequency response.
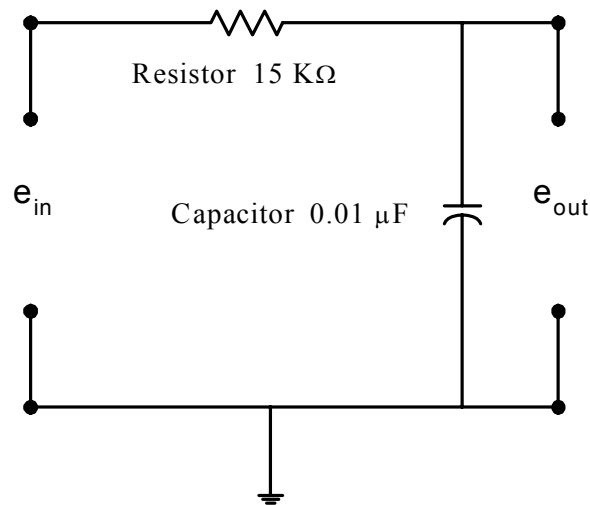
$\Rightarrow$ Build in hardware the RC low-pass filter circuit and use the function generator and digital oscilloscope to validate your step response and frequency response predictions in the MatLab simulations.

Dynamic System Investigation
## of a
RC Low-Pass Filter

1. **Physical System:** Describe the actual physical system. Draw a schematic of the RC circuit.
2. **Physical Model:** Develop a physical model of the actual physical system. State all simplifying assumptions. Describe differences between the physical system and the physical model.
3. **Model Parameter Identification:** Determine the values of the parameters in your physical model. If these parameter values were given to you, state how you would determine them if you had access to the circuit and measuring equipment.
4. **Mathematical Model:** Develop a mathematical model of the physical model by applying the laws of nature to your physical model. Express your model in differential equation form and in operational transfer function form.
5. **Predicted Dynamic Behavior:** Predict the unit step response and the frequency response of the physical model both analytically and using MatLab. Label plots and indicate important parameters, e.g., time constant, steady-state gain, bandwidth, high-frequency slope, low-frequency gain.
6. **Actual Dynamic Behavior:** Describe the experimental procedure performed to measure the behavior of the physical system. Plot the experimental step-response results and frequency-response results. Identify the time constant, steady-state gain, bandwidth, low-frequency gain, high-frequency slope.
7. **Compare the Experimentally-Measured Behavior with the Predicted Behavior:** Compare the analytical predictions with the experimental measurements. Note and explain any differences. Determine if your physical model is adequate to predict the behavior of this physical system.
8. **Conclusions:** Summarize your work and state any important conclusions learned from this exercise.

- **Two identical RC Low-Pass Filters in Series**: R = 15 KΩ, C = 0.01 μF
  ⇒ Derive the ideal transfer function for this system.
  ⇒ Perform MatLab Simulations: plot step response and plot frequency response. Note the effect of the second filter loading the first filter.
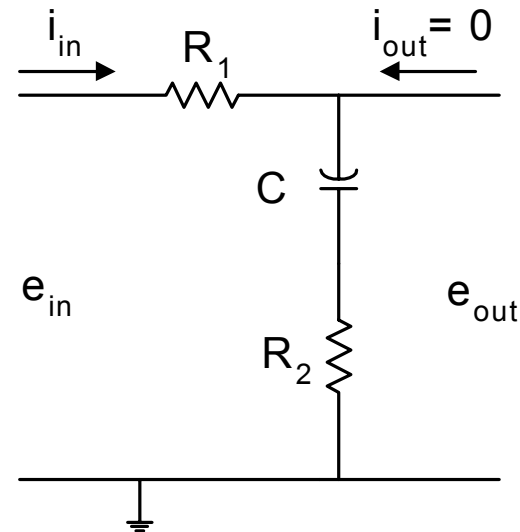

⇒ Build in hardware the RC-RC circuit and use the function generator and digital oscilloscope to validate your step response and frequency response predictions in the MatLab simulations.

- **Passive Lag Controller**: $R_1 = 100\ \text{K}\Omega$, $R_2 = 11\ \text{K}\Omega$, $C = 0.1\ \mu\text{F}$
- **Passive Lead Controller**: $R_1 = 100\ \text{K}\Omega$, $R_2 = 11\ \text{K}\Omega$, $C = 0.1\ \mu\text{F}$
  $\Rightarrow$ Derive the ideal transfer functions for these systems.
  $\Rightarrow$ Perform MatLab Simulations: plot step response and frequency response.
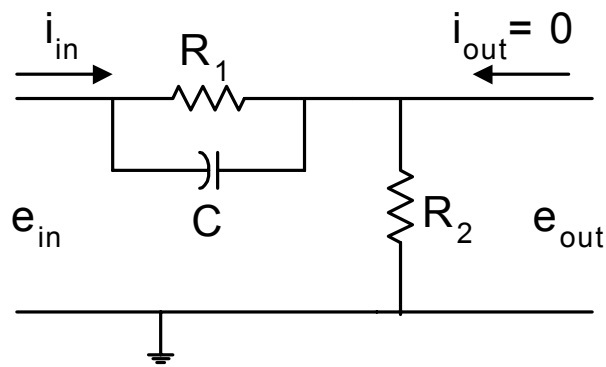
Passive Lead Circuit

Passive Lag Circuit

$\Rightarrow$ Build in hardware the Lead and Lag Controller circuits and use the function generator and digital oscilloscope to validate your step response and frequency response predictions in the MatLab simulations.

Studio Exercise 1A Questions

1. Resistors dissipate power, capacitors do not. Why? Where does the power go?
2. Explain how a passive RC differentiator is exactly the same as a passive RC high-pass filter. What is the criterion for good differentiation? How would you construct a "perfect" differentiator?
3. Explain how a passive RC integrator is exactly the same as a passive RC low-pass filter. What is the criterion for good integration? How would you construct a "perfect" integrator?
4. The following questions apply to the RC Low-Pass filter.
   $\Rightarrow$ Draw the circuit and write the Laplace transfer function e_{out} / e_{in} .
   $\Rightarrow$ Sketch the unit step response of this system. What is the time constant τ of the system in terms of the system hardware parameters and what does it represent in the time domain ?
   $\Rightarrow$ Sketch the frequency response of this system. In the magnitude plot, identify the low-frequency amplitude ratio, the breakpoint frequency and amplitude ratio at that frequency, and the slope of the curve at high frequency. On the phase plot, show the low-frequency value, the high-frequency value, and the breakpoint-frequency value. What is the bandwidth of this system and how is it related to the time constant τ ?
   $\Rightarrow$ What is the input impedance for this circuit?
   $\Rightarrow$ What is the output impedance for this circuit?
5. Using the expressions for the input and output impedance of the RC circuit, write the expression for the overall transfer function e_{out} / e_{in} of two identical RC circuits connected in series. Do not simplify. Identify the term in the expression that represents the loading effect.
6. Why are the passive lead and lag circuits given their names, i.e., lead and lag?
7. The passive lead circuit is an approximate PD (proportional-derivative) controller? Explain.
8. The passive lag circuit is an approximate PI (proportional-integral) controller? Explain.

Studio Exercise #1, Analog Electronics, Part B:
Operational Amplifiers, Active Lead / Lag Controllers, and Active Filters

Introduction:

This exercise is an introduction to the most versatile linear integrated circuit (IC) used: the operational amplifier. You will also become familiar in this lab with active controllers and active filters. In part A you built and tested a low-pass RC filter. In this exercise, you will place two RC low-pass filters in series and observe the loading effect. You will then place a buffer op-amp (high input impedance, low output impedance, unity gain) between the two RC filters and observe the loading effect disappear. You will construct active lead and lag controllers and compare their performance to the passive lead and lag controllers you built and analyzed in part A. You will construct active high-pass and low-pass filters and compare their performance to the passive versions. You will then construct a two-pole Butterworth active low-pass filter and compare the performance to the two RC low-pass filters in series with the buffer amplifier.
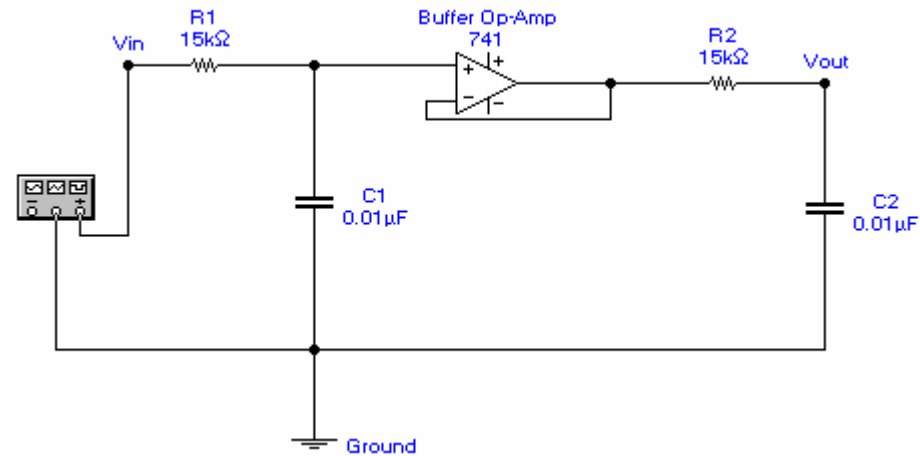
<u>Procedure:</u>

- **Buffer Op-Amp**
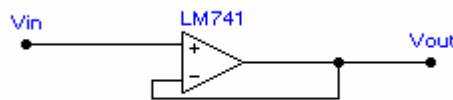
⟹ Build in hardware the buffer op-amp circuit and use the function generator and digital oscilloscope to measure the frequency response and step response.
⟹ Note: Slewing rate limitation vs. frequency response limitation. At very small amplitudes, the frequency response of the op-amp limits the high frequency behavior, while at larger amplitudes, the slewing rate limits its response.
⟹ Question: How would you measure the input impedance (very large) and output impedance (very small) of this circuit?

- **RC - Buffer Op-Amp - RC Circuit**

⇒ The transfer function for this circuit is given by: $\dfrac{V_{out}}{V_{in}} = \dfrac{1}{(RCs+1)^2}$ because of the absence of loading effects as a result of the presence of the buffer op-amp.

⇒ Perform MatLab simulations: plot the step response and frequency response.

⇒ Build this circuit in hardware and use the function generator and digital oscilloscope to validate your step response and frequency response predictions in the MatLab simulations.

- **Two-Pole, Low-Pass, Active Filter with a 1061 Hz Cutoff Frequency**
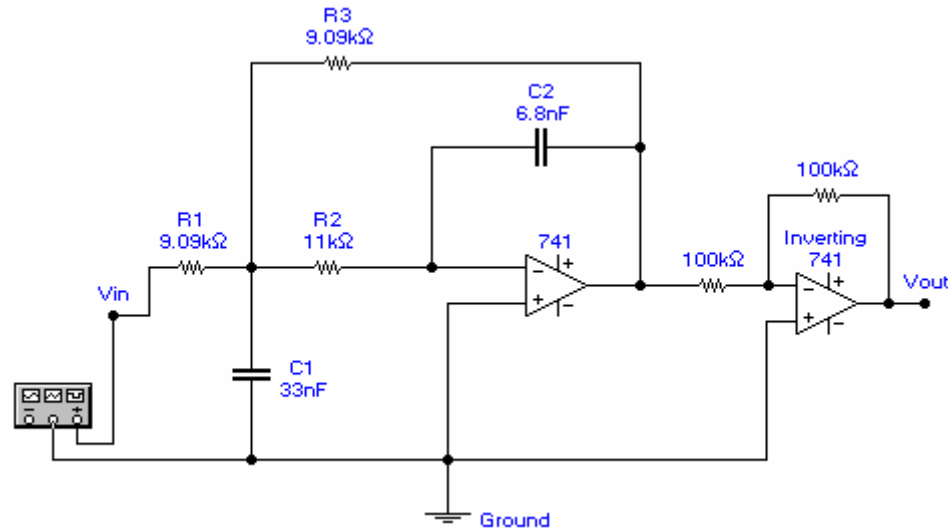
$\Rightarrow$ The transfer function for this active filter is given by: $\dfrac{V_{out}}{V_{in}} = \dfrac{\dfrac{1}{R_1 R_2 C_1 C_2}}{s^2 + \left[\dfrac{1}{R_2 C_1} + \dfrac{1}{R_1 C_1} + \dfrac{1}{R_3 C_1} \right] s + \dfrac{1}{R_2 R_3 C_1 C_2}}$

$\Rightarrow$ Build this circuit in hardware. Using MatLab Simulations and experimental measurements, compare the predicted frequency response and step response with the measured responses. Also compare the frequency response of this filter with the frequency responses of the single RC filter and the RC-Buffer Op-Amp-RC filter circuit already studied.

- **Active Lead / Lag Controller**

Lead / Lag Network:
(R1)(C1) > (R2)(C2)   Lead
(R1)(C1) < (R2)(C2)   Lag
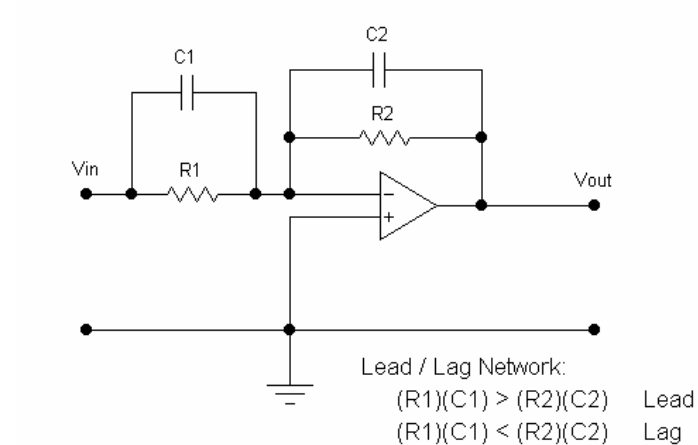
$\Rightarrow$ The transfer function for this circuit is: $\dfrac{V_{out}}{V_{in}} = -\dfrac{R_2}{R_1}\dfrac{R_1C_1s+1}{R_2C_2s+1}$. Pick parameter values to give you first lag behavior and then lead behavior.

$\Rightarrow$ Perform MatLab simulations: plot the step response and frequency response.

$\Rightarrow$ Build this circuit in hardware and use the function generator and digital oscilloscope to validate your step response and frequency response predictions in the MatLab simulations. Compare your results to the passive lag and lead controllers you have already studied.

- **Active Differentiator (High-Pass Filter) and Active Integrator (Low-Pass Filter)**
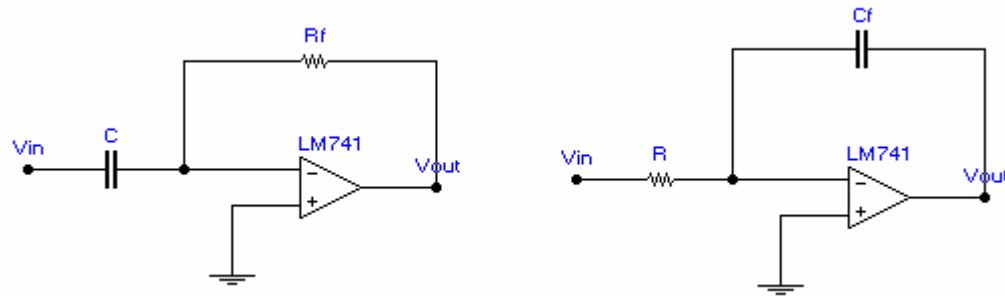

$\Rightarrow$ The transfer functions for these two circuits are: $\dfrac{V_{out}}{V_{in}} = -R_f C s$ and $\dfrac{V_{out}}{V_{in}} = \dfrac{-1}{RC_f s}$, respectively.

$\Rightarrow$ Using MatLab simulations and hardware implementation and measurement of these two circuits, explain the differentiating and integrating functions of these two circuits.

Studio Exercise # 1, Analog Electronics, Part B:
## Operational Amplifiers, Active Lead / Lag Controllers, Active Filters
Questions

1. In studio exercise #1, Part A, you derived and measured the transfer function for two identical RC low-pass filters connected in series. It is given by: $\dfrac{1}{(RCs+1)^2 + RCs} = \dfrac{1}{(RC)^2 s^2 + 3RCs + 1} = \dfrac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$ where $\omega_n = 1/RC$ and $\zeta = 1.5$. Place an buffer operational amplifier between the RC low-pass filters, as shown below, and show that the overall transfer function is given by $\dfrac{1}{(RCs+1)^2}$, as predicted in the absence of loading effects.
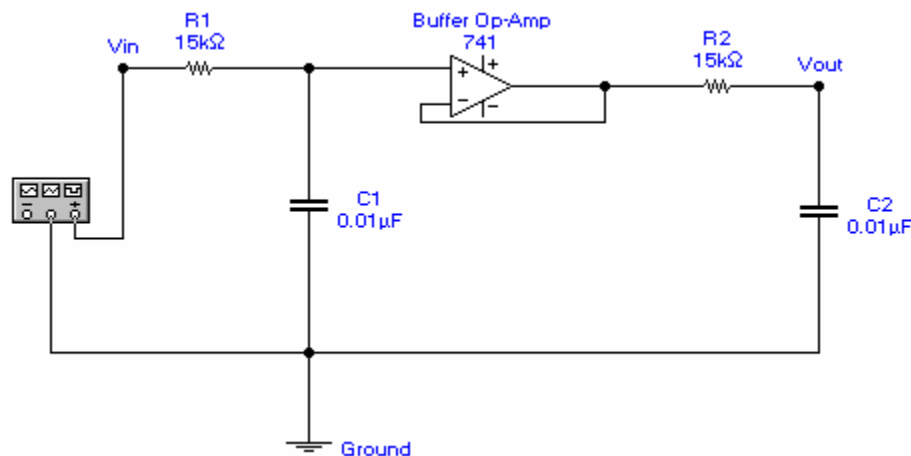
2. A two-pole, low-pass active filter with a 1061 Hz cutoff frequency is shown below. Derive the transfer function V_{out} / V_{in} for this filter. Using MatLab, compare the frequency response of this filter with the frequency responses of a single RC low-pass filter (same cutoff frequency) and two identical RC low-pass filters cascaded and perfectly buffered (same cutoff frequency). What is the purpose of the second op-amp in the circuit?
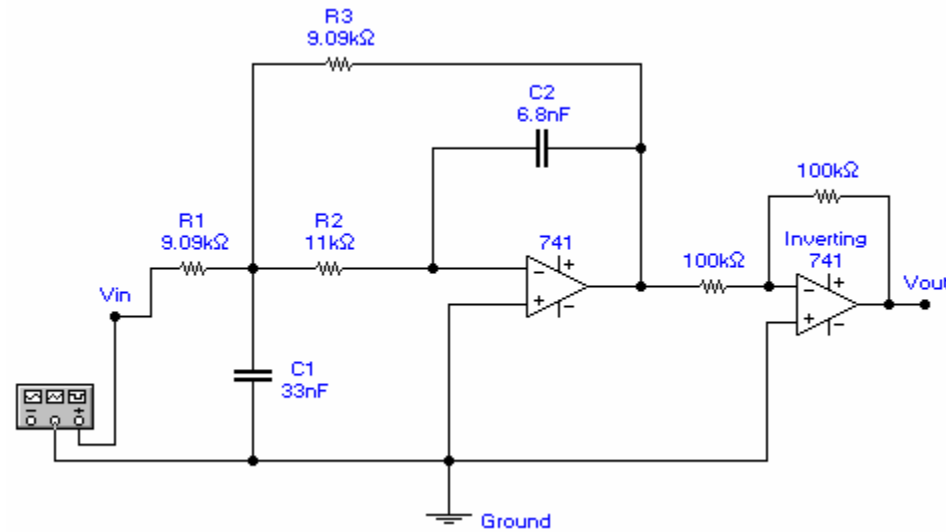
3. An active electronic lead / lag controller is shown below. Derive the transfer function V_{out} / V_{in} and show how this circuit can be used as either a lag controller or a lead controller by the appropriate choice of parameter values.
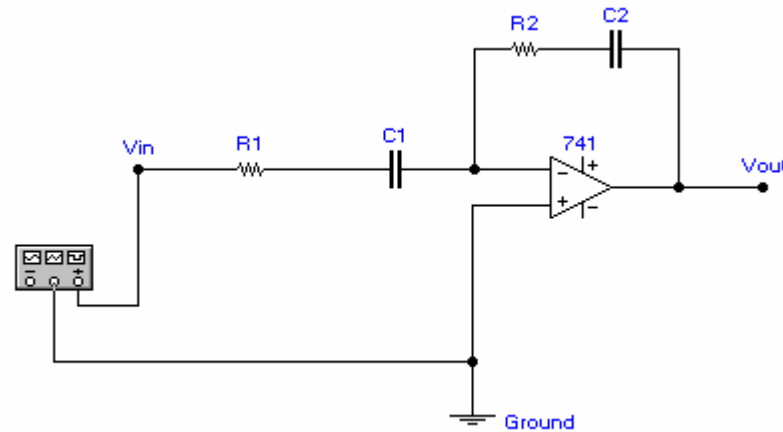
4. For an inverting op-amp, derive the expression for the transfer function V_{out} / V_{in} in two ways: (a) carry out the analysis for a real op-amp and, at the end of the derivation, replace the parameters of the real op-amp with those of the ideal op-amp, and (b) make the ideal op-amp simplifying assumptions at the very start of the analysis.

5. For a non-inverting op-amp, calculate the input impedance and the output impedance of the circuit.

6. We have seen how a passive RC low-pass filter and a passive RC high-pass filter behave as an integrator and a differentiator, respectively. Construct a "perfect integrator" and a "perfect differentiator" using op-amps and derive the output / input transfer functions. Compare the passive integrator and differentiator with the active integrator and differentiator.

MECHATRONICS
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ANALOG ELECTRONICS QUESTIONS

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   - What is the input impedance for this circuit?
   - What is the output impedance for this circuit?
5. Using the expressions for the input and output impedance of the RC circuit, write the expression for the overall transfer function e_{out} / e_{in} of two identical RC circuits connected in series. Do not simplify. Identify the term in the expression that represents the loading effect.
6. How would you eliminate the loading effect present when the two identical RC circuits are connected in series? Explain.
7. For an inverting op-amp, derive the transfer function e_{out} / e_{in} making the ideal op-amp assumptions at the very start of the analysis.
8. Sketch an active lead/lag controller. Treat the op-amp as ideal and derive the input/output transfer function e_{out} / e_{in} . Show how by proper selection of the hardware parameters this circuit can give either lead or lag behavior.
9. What does the expression "many soft knees do not a hard knee make" mean?