Introduction:
In this lab of the course, you will explore the properties of operational amplifiers, one of the most important circuit elements in analog electronics. Make sure you read the section on op amps in the introductory notes. First, you will use the op-amp in a DC circuit and learn how to use it as an amplifier and determine its input and output impedance. In the second part of the lab, you will see how you can do math on sinusoidal AC signals using a simple op-amp circuit. At the end of the lab, you should be able to:

- Understand DC and AC op-amp operation
- Determine input and output resistance/impedance
- Measure the frequency response of an amplifier
- Build and characterize a preamplifier
- Design an op-amp circuit that carries out a desired mathematical operation

Topics from the lecture you need to be familiar with:
- Op-amp circuit model
- Ideal op-amp technique
- Input and output impedance
- Basic op-amp circuits
- Differentiators and integrators

Pre-lab questions (hand in before lab starts):
1. Under what assumptions is the ideal op-amp technique valid?
2. Why are input and output impedance of an op-amp circuit important?
3. How would you measure input and output impedance for DC?
4. What is the amplification of an ideal inverting op-amp amplifier?
5. How can you differentiate or integrate AC signals with an op-amp circuit? (see Hambley ch. 14.10.)
Part 1: Fundamental op amp properties

1. DC amplification
   a) Build the circuit shown below using a 741 op amp:

   ![Circuit Diagram]

   
   b) Apply a DC voltage \( V_1 \) using the power supply. Vary \( V_1 \) between \(-5\)V and \(+5\)V in 1V steps and record the output \( V_2 \).
   c) Draw a graph of \( V_2 \) versus \( V_1 \) and find the relation between \( V_2 \) and \( V_1 \) from your graph. Does this result agree with your expectations? (see prelab question 4)
   d) Now vary \( V_1 \) between \( V_{EE} \) and \( V_{CC} \) in 1V steps. Measure \( V_2 \) and plot \( V_2 \) versus \( V_1 \). What behavior does the circuit exhibit now? Explain.
   e) There is a way to observe the same behavior as seen in d) by replacing one of the resistors with a potentiometer. Which resistor do you need to replace? Verify your assumption by replacing \( R_1 \) or \( R_2 \) with the 10kΩ pot. Set \( V_1 \) to 3V and vary \( R_{pot} \). Measure \( V_2 \) for each \( R_{pot} \) value and plot the amplification \( V_2/V_1 \) as a function of \( R_{pot} \). Explain your graph.

2. Input and output resistance
   a) Put the circuit back in its original state (\( R_1=10k\Omega \), \( R_2=22k\Omega \))
   b) For \( V_1=3V \) measure \( I_1 \) and determine the input resistance of the circuit.
   c) Determine the output impedance \( Z_{out} \) from the load line you get by measuring the open circuit voltage and voltage and current with a load resistor (e.g. 10 kΩ). Do NOT short circuit the output! Can you justify your result for \( Z_{out} \) with the ideal op amp laws? Given this result for \( Z_{out} \), what load resistor would draw the most power from this op amp circuit?

3. AC amplification
   a) Now use the function generator as input. Use a sinusoidal signal with amplitude 1V and frequency 100Hz. Set the oscilloscope to the appropriate time scale to observe a few periods and display both input \( V_1 \) and output signal \( V_2 \). Does the output signal agree with your expectations? Can you measure a phase difference between \( V_1 \) and \( V_2 \)? Why or Why not?
   b) Drive the amplifier into the nonlinear regime found in part 1d) by increasing the amplitude of \( V_1 \). Observe \( V_2 \) on the scope and describe what you see.
   c) Build the following integrator circuit:
R = 39kΩ, C = 10nF, R_{DC} = 10MΩ

**NOTE:** R_{DC} compensates for nonidealities of the op-amp at DC and does not (visibly) affect the AC operation of the integrator circuit. If you’re interested in learning more, see Horowitz and Hill, p.222f.

d) Again, use an amplitude of 1V for V₁ and f=100Hz and observe V₂ on the scope. What are amplitude and phase difference with respect to V₁ of the output voltage? Does this agree with your expectation? **NOTE:** If the shape of your output signal looks strange or is unstable, talk to your TA. You may have a DC offset problem and may have to increase R_{DC}.

e) Vary the frequency between 1Hz and 10kHz in suitable steps (1,2,5,10,20,50,…,10000 Hz). Measure the amplification V₂,max/V₁,max and the phase difference φ at each frequency. Plot 20log(V₂,max/V₁,max) versus log(f). Do your results agree with your expectations? Compare with theory.

f) Using your oscilloscope traces, explain why this circuit acts as an integrator in the time domain.

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**Part 2: Design of an integrator/differentiator**

In this part of the lab, you will design a circuit which is able to carry out mathematical operations you know from calculus: differentiation and integration. Make sure you have read and understood section 14.10 in the textbook which explains how these circuits work.

Decide whether you want to build an integrator or differentiator. Call this circuit ‘C’.

1. **Fixed frequency operation**
   a) Draw a circuit diagram of the circuit ‘C’ of your choice. Identify the circuit elements you can vary in your design.
   b) We want to carry out integration/differentiation on a sinusoidal AC signal with frequency f=1kHz and amplitude V₁,max=1V. Depending on your choice for ‘C’, design a circuit which carries out your operation and leads to an output signal with the same amplitude V₂,max=1V. **NOTE:** Show your design to the TA to have it approved before you build it. If you build a differentiator, choose C<=1nF to avoid running into op amp nonidealities!
   c) Build the circuit. Apply the correct input signal with the function generator. Monitor input and output voltage simultaneously on channels 1 and 2, respectively. Draw a graph of the scope images and verify the circuit does what you designed it to do.
   d) Vary the frequency of the input signal. Describe qualitatively what happens to the output signal. Explain.
2. Tunable differentiator/integrator

a) Modify your design such that you will be able to obtain an output signal with 1V amplitude for all frequencies between 1kHz and 10kHz. You will need to use a variable circuit element (potentiometer) in order to do this. Pick your capacitor such that the required resistor values at the lowest and highest frequencies are within the potentiometer range. Draw a circuit diagram of your design and show your calculations.

b) Build the new circuit and try it out. Change the input signal frequency from 1kHz to 10 kHz in 1kHz steps. Adjust your pot to obtain the correct output amplitude. Measure R\text{pot} for each frequency. Make a plot of R\text{pot} versus f. Also add the graph you would expect theoretically. Do your measurements agree with theory?

3. Noninverting operation

a) You found in part II.1. that your circuit ‘C’ inverts the signal, i.e. \( V_2 = -\int V_1(t) \, dt \) (integrator) or \( V_2 = -\frac{dV_1}{dt} \) (differentiator).

b) Expand your circuit to obtain an output signal that is given by \( V_2 = \int V_1(t) \, dt \) (integrator) or \( V_2 = \frac{dV_1}{dt} \) (differentiator). You will need to add another op amp stage as shown below. (amplitude at output: 1V)

\[ \begin{align*}
1\text{st op amp stage:} & \quad \text{circuit ‘C’} \\
2\text{nd op amp stage:} & \quad \text{inverter, voltage gain 1} \\
\end{align*} \]

c) Draw a circuit diagram, build the circuit and monitor input and output signals on the scope. Draw input and output signals and verify the circuit operation. Run the circuit at f=1kHz.

d) If you have time: Design your output stage such that you can vary the gain \( \frac{V_2,\text{max}}{V_1,\text{max}} \) between 1 and 5.