Operational Amplifiers

- Universal analog circuit element --- can design almost anything with them
- Easy to design with since they behave very similar to ideal amplifier model

- Differential input and single output amplifier
- Generally use a positive and negative supply voltage
- dc coupled amplifier
Opamp Model

- System level perspective --- we’ll look at circuits/systems which are built using opamps
- Later we will look at how to design an opamp with transistors, etc.
- But for now we can consider it as a macromodel of the actual circuit behavior
Opamp Terminal Voltages and Currents

- Terminal voltages are specified with respect to the ground of the power supply voltages
Differential Input

- Amplifies the difference between $v_2$ and $v_1$ by a constant gain factor: $A$

$$v_o = A(v_2 - v_1)$$

- A nearly ideal model has infinite input impedance and zero output impedance
Open Loop Gain

- If $A$ is large, any slight difference in $v_2$ and $v_1$ will cause a large output voltage.
- The magnitude of the output voltage is limited by the supply voltages.
- Output voltage is likely to saturate when used in this way.
- To behave like an amplifier, the difference in the input voltages must be really small.

\[ v_o = A(v_2 - v_1) \]

\[-VCC \leq v_o \leq VCC\]
Input-Output Transfer Function

- Opamp open loop gain, $A$, can be as high as $\sim 10^4$ to $10^6$
- $VCC$ is generally no more than 20 volts

- So the linear region of amplifier operation is quite narrow
Open Loop Gain

- But even if our signals are really small in magnitude, we can’t use an opamp in an open loop configuration because the gain cannot be tightly controlled.

\[ v_o = A(v_2 - v_1) \]

- For these reasons (and others that we will soon get to) negative feedback is used to design circuits with accurate/precise gain.

- With negative feedback, the difference between \( v_2 \) and \( v_1 \) becomes very close to zero.
Negative Feedback: Closed-Loop Gain

• Important concept for all types of systems, including electronics
Negative Feedback

- Makes the input voltage to A practically zero when closed loop gain is large

\[ V_f - V_i + V_o = 0 \]

\[-V_f = V_i - V_o \]
Desensitize Loop Gain to Changes in A

- Assuming that feedback factor, $\beta$, can be controlled by elements such as resistors, then the gain (closed-loop) is no longer sensitive to changes in the open loop gain, $A$
Inverting Amplifier

- Resistors can be used to create a controlled, smaller gain
- One of the most common configurations is an inverting amplifier

If it’s operating in the linear region (as an amplifier), $v_o = -A(v_1 - v_2)$
- With really large open loop gain, feedback should force $(v_2 - v_1) \to 0$
- Assume that feedback works, and amplifier is operating in its linear region:
  1) Solve equations; 2) check assumption
Inverting Amplifier with Ideal Opamp Model

- Assume $i_2 = i_1 = 0$
Virtual Ground

- If the open loop gain is infinite, then $v_1$ is a virtual ground
- This can further simplify the analysis
Inverting Amplifier

- For a dc input, the inverting amplifier has a negative output voltage.
- For an ac input, the output is 180° out of phase with the input.
**Opamp Currents and Input Impedance**

- Due to the transistors used to build an opamp, the input currents, $i_2$ and $i_1$ are practically zero --- input resistance of amplifier is huge, especially for MOS!
- For the ideal opamp we assume, $i_2 = i_1 = 0$, and $R_{in}$ of opamp is infinite

- All circuit elements are charge conserving, so $i_o$ is coming to/from the power supplies:
Feedback and Input Impedance

- Feedback can be used to change the input impedance of the amplifier circuit too.
- What’s the input impedance (Thevenin equivalent) of an inverting amplifier?
**Input Impedance**

- Sometimes want large values of $R_1$ for increasing input impedance. Why?

- But then gain is set by $R_2$, and we can’t make it arbitrarily large. Why?
Output Impedance

- We generally want a small output impedance. Why?

- What is the output impedance for the idealized amplifier?
Complex Impedances in Opamp Circuit

- We can analyze the inverting amplifier the same way if the external elements include impedances and admittances (functions of $s$ or $j\omega$)
Example: Integrating Amplifier

- Integrating amplifiers are used in various applications: e.g. analog computing
- We can analyze this circuit in the time domain or the frequency domain:
Example: Integrating Amplifier

- What is the frequency domain response?
- Where’s the pole?
Example: Integrating Amplifier

- What does the frequency response (Bode plot) look like?

- What is the dc gain? What is the unity gain frequency?
Bode Plot
Integrating Amplifier

- Without control over the dc gain, a small dc input voltage can saturate the opamp output
- For this reason a large feedback resistor is added to control the dc gain

- But the circuit is no longer a perfect integrator!
**Summing Amplifier**

- A variety of opamp circuits are based on the inverting amplifier configuration
Noninverting Opamp

- The noninverting amplifier is analyzed in the same manner as the inverting one.

![Noninverting Opamp Diagram](attachment:diagram.png)