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Chapter 30

Operational Amplifiers

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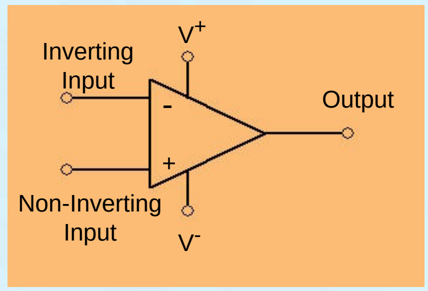
Introduction

- Characteristics
  - High input impedance
  - Low output impedance
  - High open-loop gain
  - Two inputs
  - One output
  - Usually + and – dc power supplies

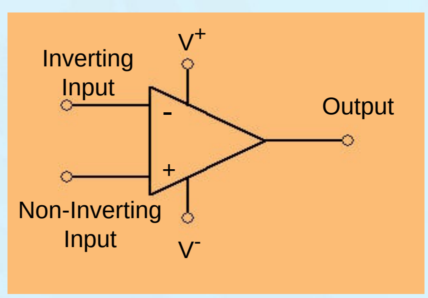
Introduction

- Ideal Characteristics
  - $z_{in\ (inverting)} \approx \infty$
  - $z_{in\ (non\text{-}inverting)} \approx \infty$
  - $z_{out} \approx 0$
  - $A_v \approx \infty$



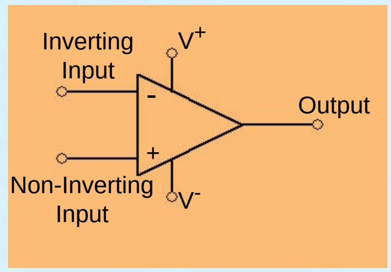
Introduction

- Uses
  - Comparators
  - Voltage amplifiers
  - Oscillators
  - Active filters
  - Instrumentation amplifiers



Introduction

- Single-ended amplifier
  - One input grounded
  - Signal at other input
- Double-ended amplifier/Differential amplifier
  - Signals at both inputs



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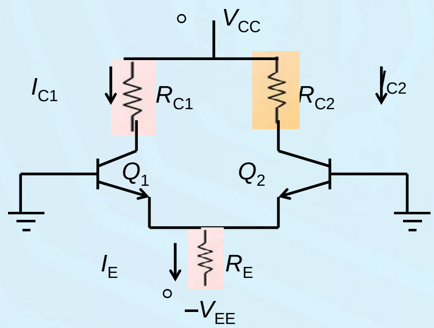
Differential Amplifier and Common-Mode Signals

- Basic differential amplifier
  - Q_1 identical to Q_2
  - $R_{C1} = R_{C2}$
  - $\therefore$ $I_{C1} = I_{C2}$ and emitter currents equal
  - Also, $I_C \approx I_E$ for high β
  - and $V_{BE} \approx 0.7$ V
- Similar calculation of Bias

Differential Amplifier and Common-Mode Signals

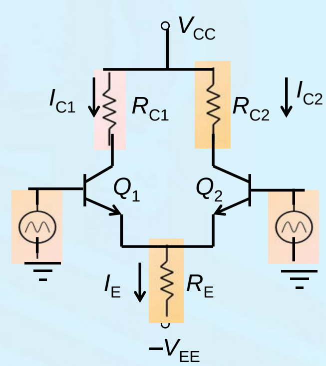


Differential Amplifier and Common-Mode Signals

- Apply same signal to both Bases

  $V_{out} = V_{out1} - V_{out2} \approx 0$

  - Eliminates common-mode signals
  - 60 Hz
  - Noise

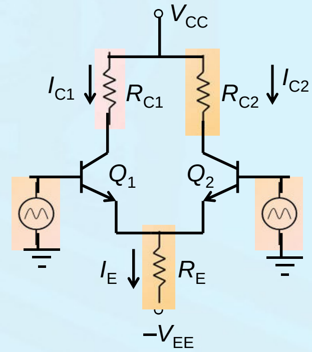


Differential Amplifier and Common-Mode Signals

- Apply sinusoids to both bases:
  - Same amplitude, 180° difference in phase,

  ∴ if $V_{in1} = -V_{in2}$

  $V_{out} = 2V_{in}$



Differential Amplifier and Common-Mode Signals

- Common-mode signals
  - Differential voltage gain

$$A_{vd} = \frac{v_{out}}{v_d}$$

also called open-loop voltage gain

$20{,}000 \le A_V \le 200{,}000$

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Differential Amplifier and Common-Mode Signals

- Common-mode signals
  - Common-mode voltage gain

$$A_{vc} = \frac{v_{out}}{v_c}$$

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Differential Amplifier and Common-Mode Signals

- Common-mode rejection ratio (CMRR)
  - Equations

$$CMRR = \frac{A_{vd}}{A_{vc}}$$

$$[CMRR]_{db} = 20\log_{10}(CMRR)$$

  - Values

$$70db \leq CMRR \leq 90db$$

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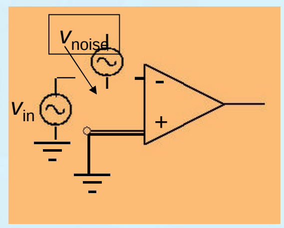
Differential Amplifier and Common-Mode Signals

- Noise
  - Static in audio signal
  - Increases as signal is amplified
  - Common mode signal
  - Significantly reduced by differential amplifier



Negative Feedback

- Op-amp
  - Large differential, open-loop voltage gain
    - $A_{vol} \approx 100{,}000$
  - Small input yields saturated output (V_{CC} or V_{EE})

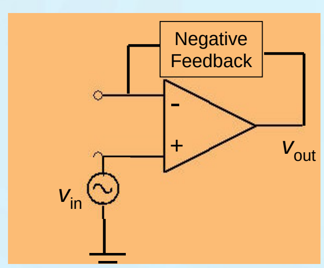
Negative Feedback

- Negative feedback
  - Returns a portion of output signal to the input
  - Open-loop voltage gain decreased

Negative Feedback

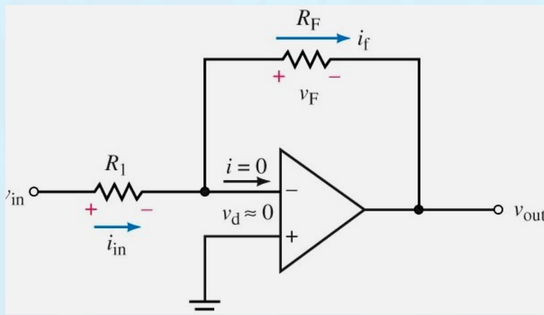
- Input impedance still high
- Output impedance low
- Circuit voltage gain, A_v
  - Adjustable
  - Stable

$$A_v = \frac{v_{out}}{v_{in}}$$



Inverting Amplifier

- Basic circuit



Inverting Amplifier

- Output 180° out of phase with input
- Significant decrease in gain
  - Gain now called closed-loop voltage gain
- Output impedance ≈ 0
- $v_d \approx 0$

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Inverting Amplifier

- Inverting input at virtual ground, $v_{in(-)} \approx 0$
- i_{in} to op-amp ≈ 0
- Input current only dependent on v_{in} and R_1
- A_{vcl} only dependent on input resistor and feedback resistor

$$i_{in} = \frac{v_{in}}{R_1}$$

$$A_{vcl} = \frac{v_{out}}{v_{in}} = -\frac{i_{in} R_F}{i_{in} R_1}$$

$$A_{vcl} = -\frac{R_F}{R_1}$$

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Inverting Amplifier

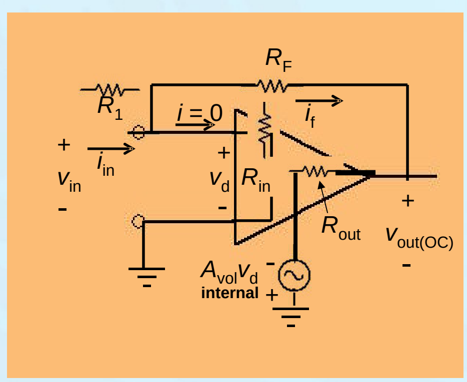
- Model

  $v_d \approx 0$

  $R_{in} \approx \infty$

  $i_{in} = i_f$

  $z_{in} \approx R_1$



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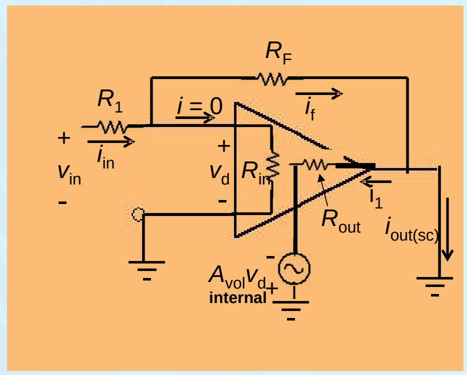
Inverting Amplifier

- Low output impedance

$$z_{out} = \frac{v_{out(OC)}}{i_{out(SC)}}$$

$$z_{out} = (1 - A_{vcl})\left(\frac{R_{out}}{A_{vol}}\right)$$



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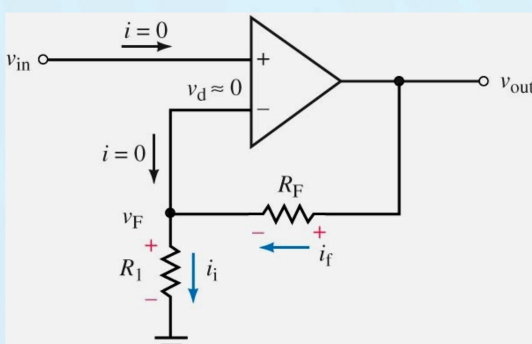
Non-Inverting Amplifier

- Circuit



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The Non-Inverting Amplifier

- Very high input impedance
- Voltage gain related to the two resistors
- Very low output impedance
- Excellent buffer

Non-Inverting Amplifier

- Differential voltage
  - $v_d \approx 0$
- Input current to op-amp
  - $i = 0$
- Closed-loop voltage gain (A_{vcl}) is a resistor ratio

Non-Inverting Amplifier

$$A_v = \frac{v_{out}}{v_{in}}$$

$$A_v = \frac{R_F i_F + R_1 i_F}{R_1 i_F}$$

$$A_{vcl} = \frac{R_F}{R_1} + 1$$

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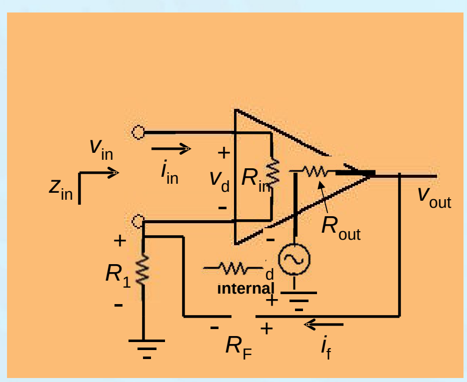
Non-Inverting Amplifier

- Model
- Input impedance

$$i_{in} = \frac{v_d}{R_{in}}$$

$$z_{in} = \left(1 + \frac{A_{vol}}{A_{vcl}}\right) R_{in}$$



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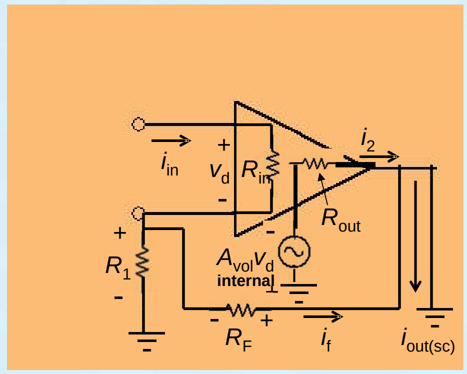
Non-Inverting Amplifier

- Model
- Output impedance

$$i_{out(sc)} = i_2 + i_f$$

$$z_{out} = \left(\frac{A_{vcl}}{A_{vol}}\right) R_{out}$$



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Non-Inverting Amplifier

- Very high z_{in}
- Very low z_{out}
- Good buffer circuit
- Also called voltage follower (gain = 1)
- Or adjustable gain > 1

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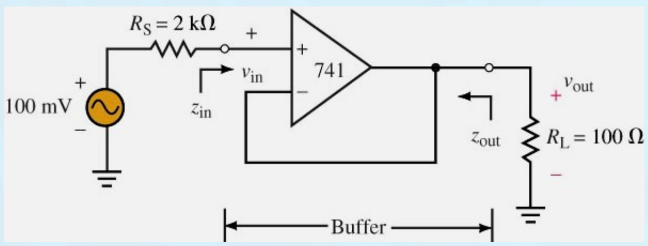
Non-Inverting Amplifier

- Voltage Follower Buffer Circuit
  - Gain = 1
  - High impedance source drives low impedance load



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Op-Amp Specifications

- LM 741 series
  - Inexpensive
  - Widely used
  - Good general specifications
  - Characteristic of all op-amp specifications
- Provide Minimum, Typical, and Maximum ratings

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Op-Amp Specifications

- Input Offset Voltage, V_{io}
  - LM741C, V_{io} typical is 2 millivolts
  - Model is voltage source with value, V_{io} in series with + input

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Op-Amp Specifications

- Input Offset Voltage, V_{io}
  - Without feedback this would saturate output with no input
  - With negative feedback, output due to V_{io} is closed-loop gain times V_{io}

Op-Amp Specifications

- Input Offset Current, I_{os}
- I_{os} = Difference between bias currents at + and – inputs of op-amp
- 741C typical I_{os} is 20 nanoamps
- Multiplying resistor used to measure I_{os}

Op-Amp Specifications

- Input Resistance
  - 741C: minimum = .3 MΩ, typical = 2 MΩ
- Open-Loop Voltage gain (A_{vol})
  - 741C: A_{vol} = Large Signal Voltage Gain
    - minimum = 20,000, typical = 200,000
  - Closely related to Bandwidth, *BW*

Op-Amp Specifications

- Gain-bandwidth product
  - 741C = 1,000,000 = 10^6 MHz

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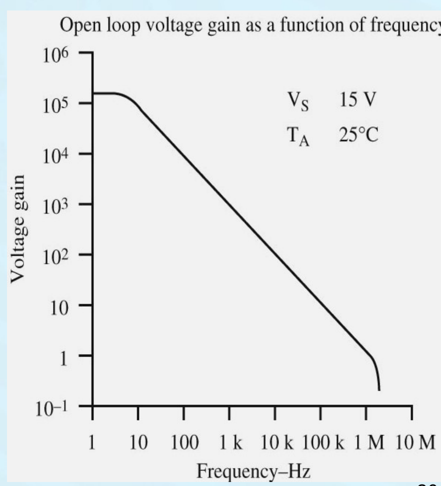
Op-Amp Specifications

- Gain versus frequency curve for op-amp



Op-Amp Specifications

- Slew rate
  - Maximum rate of change of output voltage

$$Slew\ Rate = \frac{\Delta V}{\Delta t}$$

- 741C maximum slew rate = 0.5 V/ μ sec

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Op-Amp Specifications

- Fastest time for output to go from 0 to 10 volts is 20 μ sec
- Can distort waveforms that have too fast a rise time

Op-Amp Specifications

- Slew rate required for Sinusoid with frequency *f* and amplitude *A*
- Maximum amplitude of a sine wave with frequency *f* for a given slew rate

$$v = A\sin(\omega t)$$

$$\frac{dv}{dt} = \omega A\cos(\omega t)$$

$$slew\ rate = 2\pi fA$$

$$f_{\max} = \frac{slew\ rate}{2\pi A}$$

$$A_{\max} = \frac{slew\ rate}{2\pi f}$$

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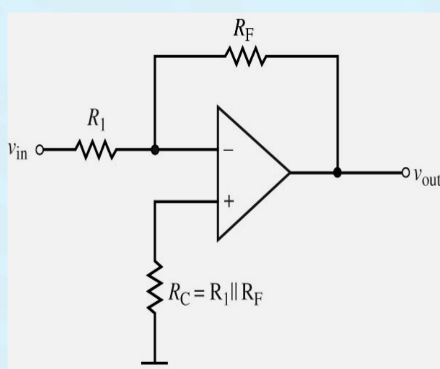
Op-Amp Specifications

- Bias
  Compensation: use
  $R_C = R_1 || R_F$



Troubleshooting an Op-Amp Circuit

- Problems occur when circuit is first built
- Most important
  - Correct connection of dual power supply
- Connecting a – supply to a + input (or vice versa) can burn out an op-amp
- Single earth ground
- Short connecting wires