Module 4

Operational Amplifier

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Reference book

- OPAMPS and Linear Integrated Circuits by Ramakanth Gayakwad

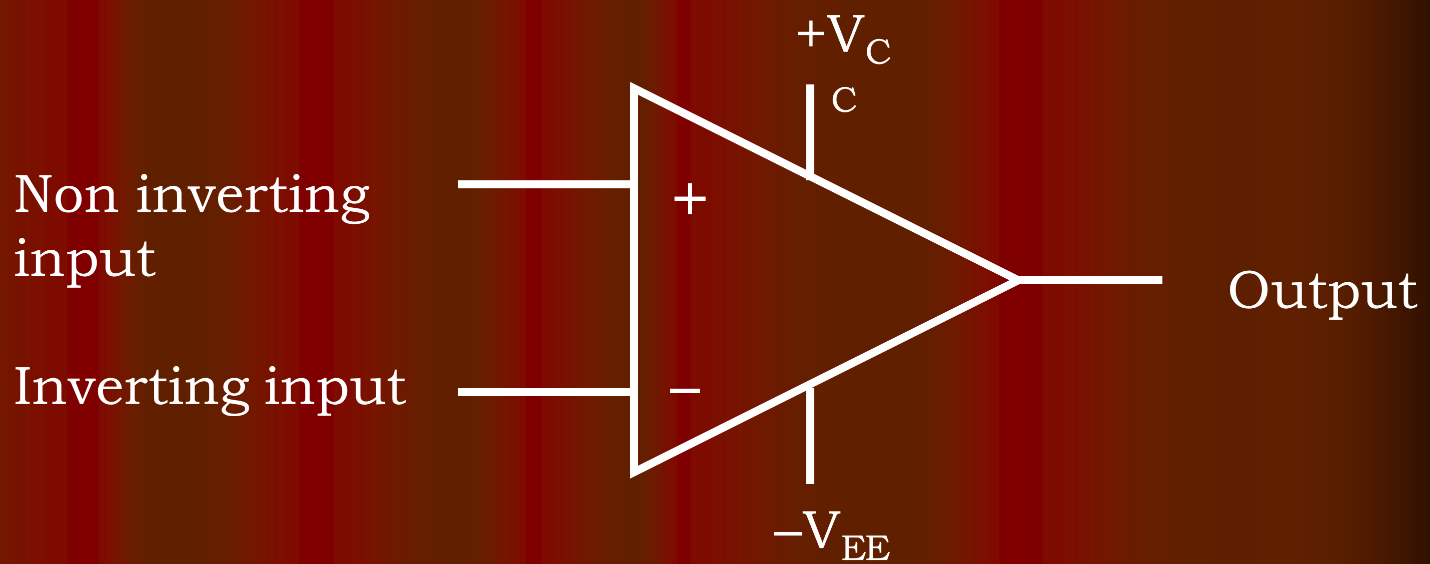
Introduction

- Operational Amplifier (OPAMP) is a very high gain amplifier fabricated on Integrated Circuit (IC)
- Finds application in
  - Audio amplifier
  - Signal generator
  - Signal filters
  - Biomedical Instrumentation
    - And numerous other applications

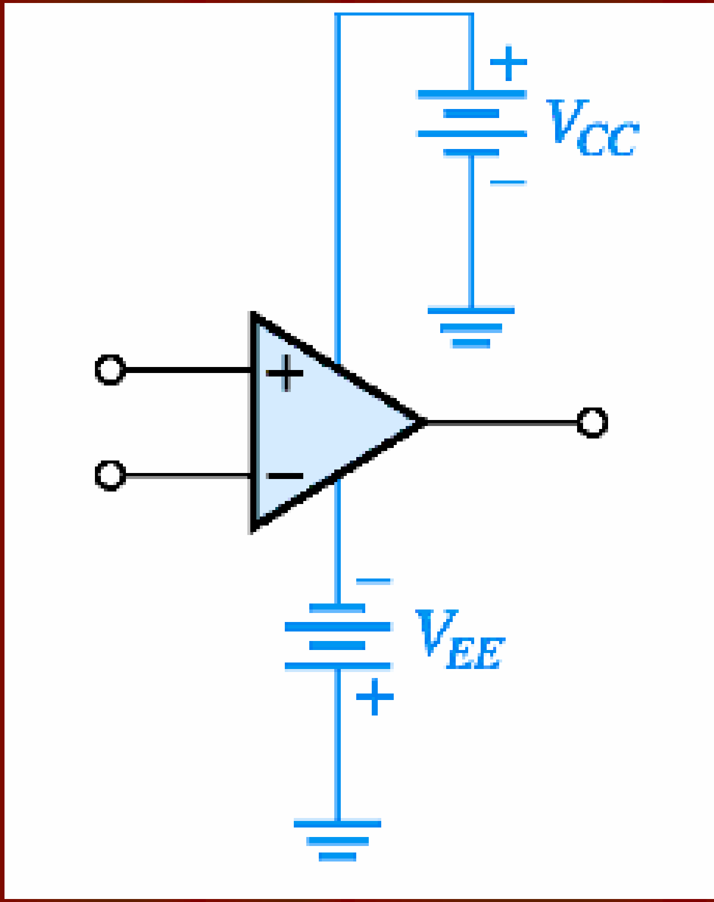
Introduction

- Advantages of OPAMP over transistor amplifier
  - Less power consumption
  - Costs less
  - More compact
  - More reliable
  - Higher gain can be obtained
  - Easy design

OPAMP terminals



OPAMP terminals



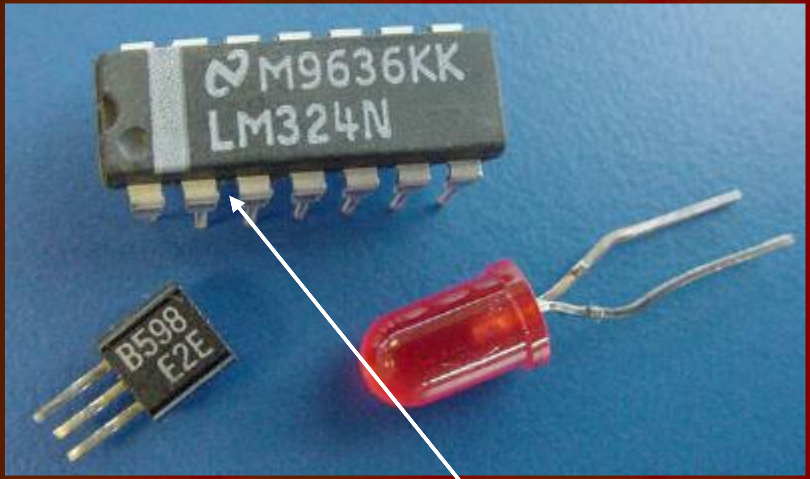
OPAMP terminals

- If input is applied to non inverting input terminal, then output will be in-phase with input
- If input is applied to inverting input terminal, then output will be 180 degrees out of phase with input
- If inputs are applied to both terminals, then output will be proportional to difference between the two inputs

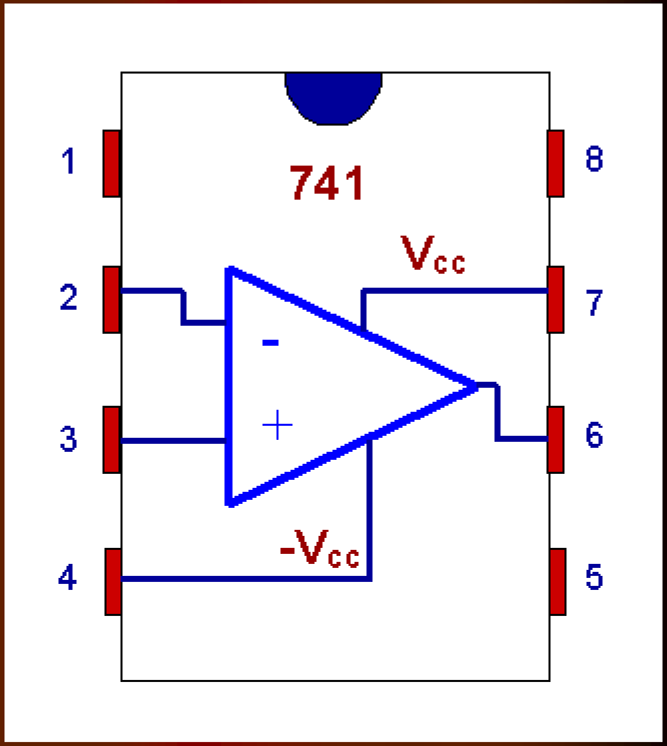
OPAMP terminals

- Two DC power supplies (dual) are required
- Magnitudes of both may be same
- The other terminal of both power supplies are connected to common ground
- All input and output voltages are measured with reference to the common ground

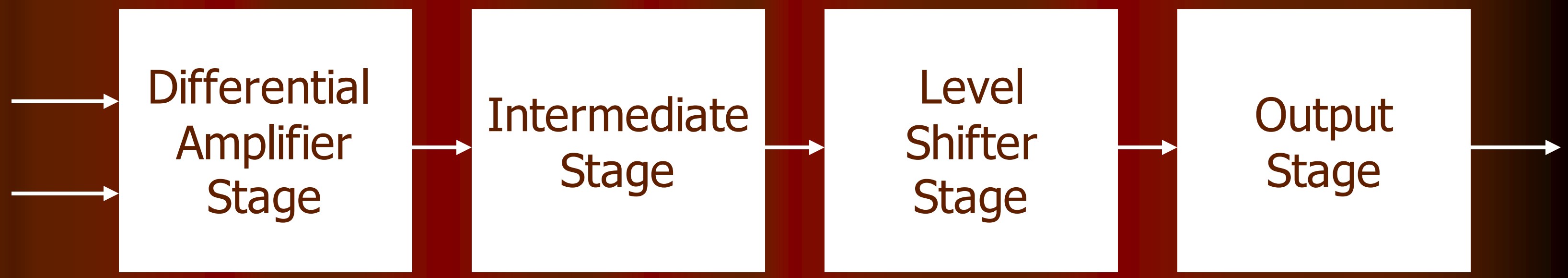
OPAMP terminals



Integrated Circuit



Internal Block Diagram

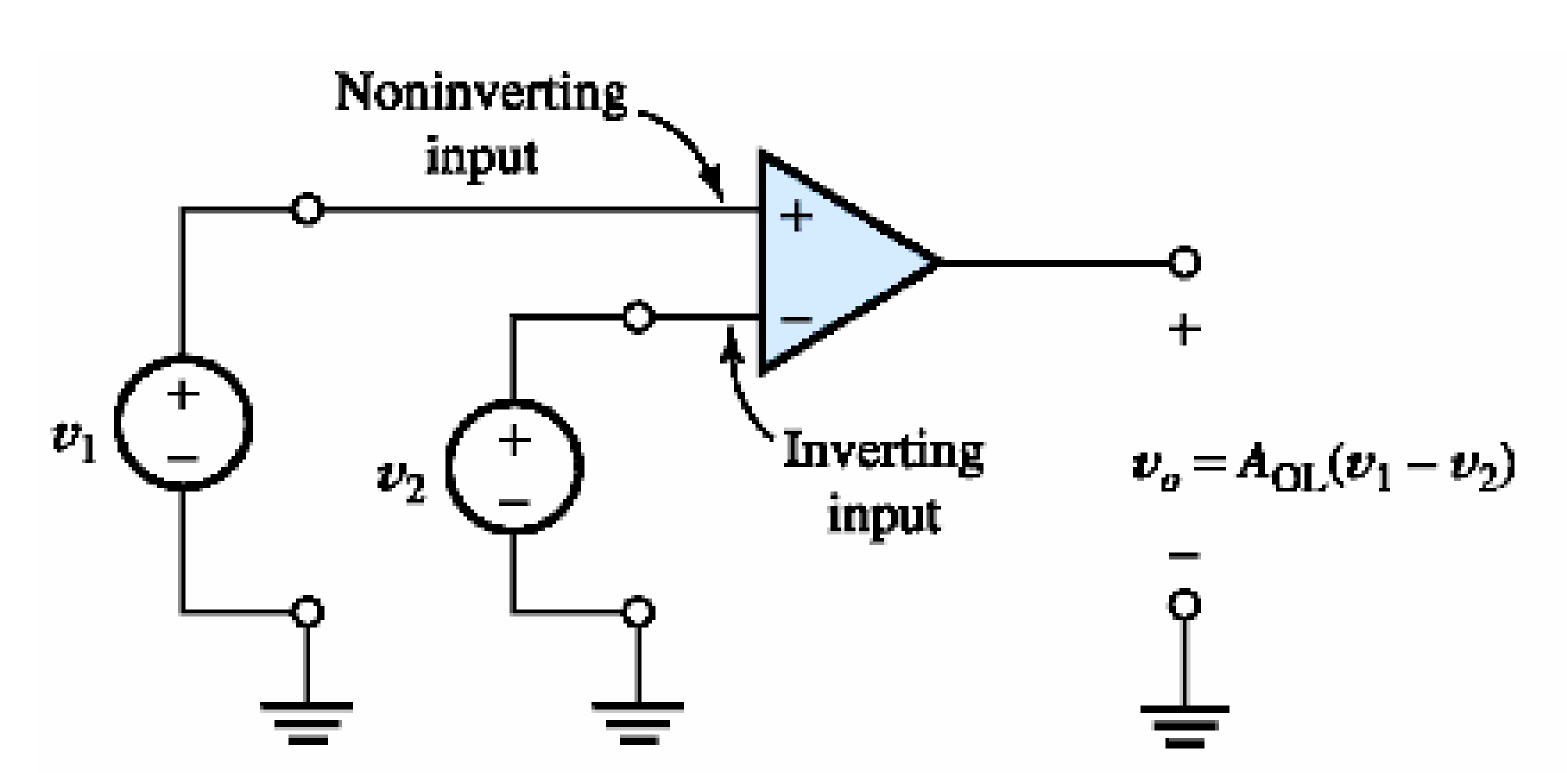


- Four stages can be identified –
- Input stage or differential amplifier stage can amplify difference between two input signals; Input resistance is very high;

Internal Block Diagram

- Intermediate stage (or stages) use direct coupling; provide very high gain
- Level shifter stage shifts the dc level of output voltage to zero (can be adjusted manually using two additional terminals)
- Output stage is a power amplifier stage; has very small output resistance; so output voltage is the same, no matter what is the value of load resistance connected to the output terminal

Open-loop configuration



If $v_1 = 0$, then $v_o = -A_{OL}v_2$ Inverting amplifier

If $v_2 = 0$, then $v_o = A_{OL}v_1$ Non inverting amp

Open-loop configuration

- A_{OL} is the open-loop voltage gain of OPAMP
  Its value is very high
  Typical value is 0.5 million
- So, even if input is in micro volts, output will be in volts
- But output voltage cannot cross the value of power supply V_{CC}
- So, if input is in milli volts, output reaches saturation value $V_{sat} = V_{CC}$ (or V_{EE})

Open-loop configuration

- If $v_1 = v_2$, then ideally output should be zero
- But in practical Op-Amp, output is

$$\upsilon_o = A_{cm}\left(\frac{\upsilon_1 + \upsilon_2}{2}\right)$$

Where, A_{CM} is the common-mode gain of Op-Amp

- So, final gain equation is:

$$\upsilon_o = A_d(\upsilon_1 - \upsilon_2) + A_{cm}\left(\frac{\upsilon_1 + \upsilon_2}{2}\right)$$

$$\upsilon_o = A_d \upsilon_{id} + A_{cm} \upsilon_{icm}$$

Open-loop configuration

- Common-mode rejection ratio
  - It is a measure of the ability of Op-Amp to reject the signals common to both input terminals (noise)
  - Defined as

$$CMRR = \frac{A_d}{A_{cm}}$$

$$(CMRR)_{dB} = 20\log_{10}\left(\frac{A_d}{A_{cm}}\right)$$

Problems

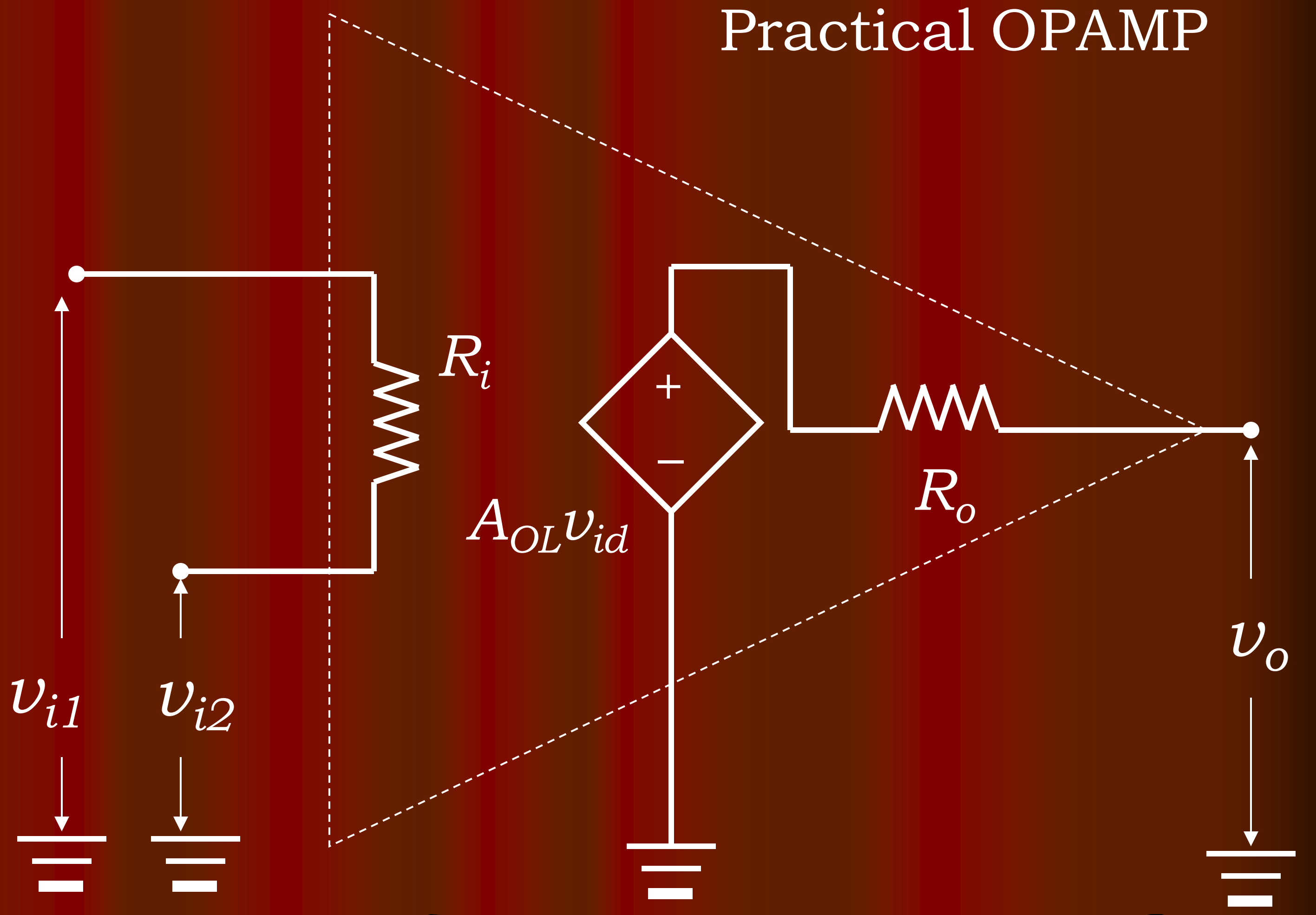
- An OPAMP has differential voltage gain of 100,000 and CMRR of 60 dB. If non inverting input voltage is 150 μV and inverting input voltage is 140 μV, calculate the output voltage of OPAMP

  Ans: 1.01 V

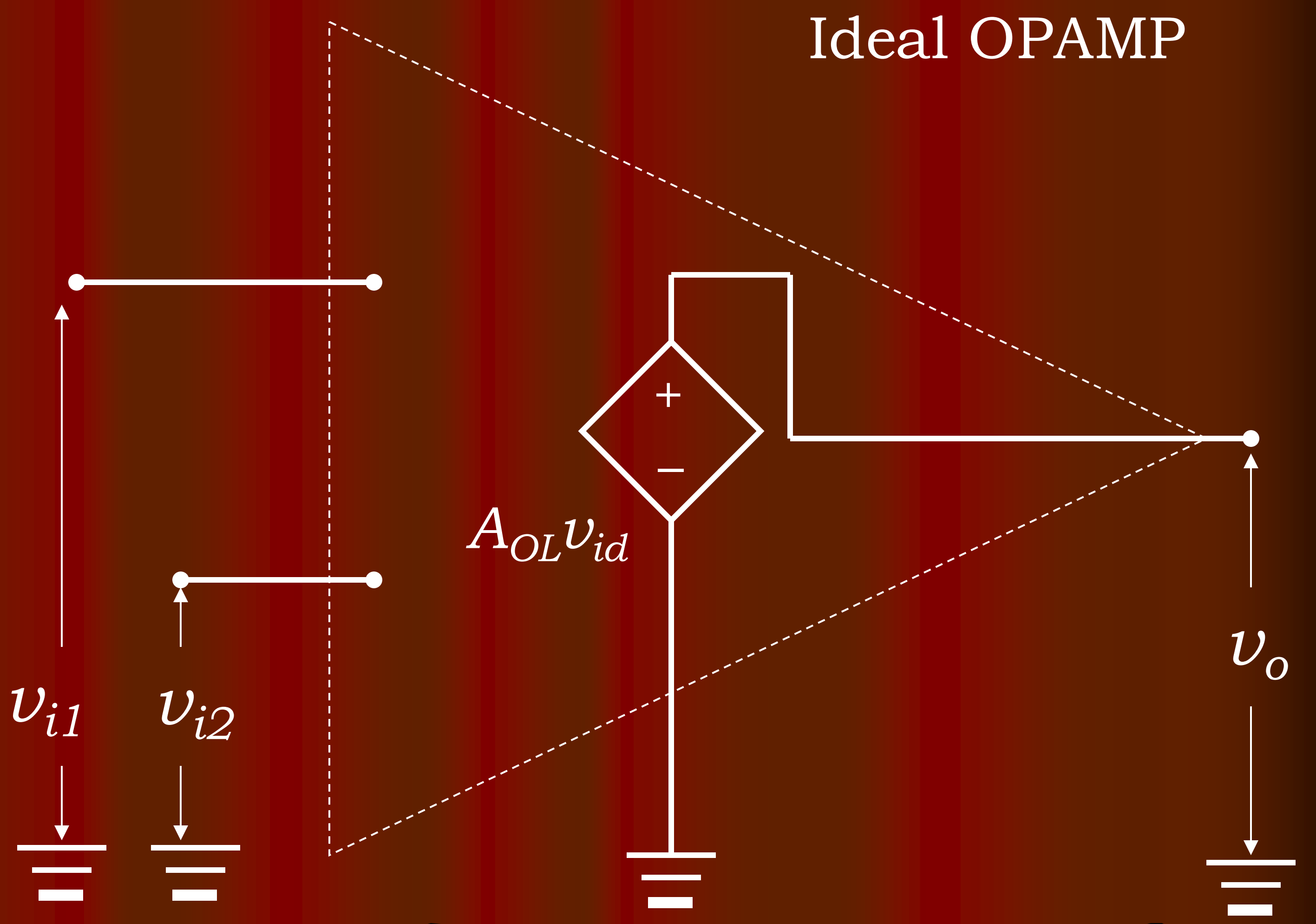
- For an OPAMP, when v1 is 0.5 mV and v2 is –0.5 mV, output voltage is 8 V. For the same OPAMP, when v1 = v2 = 1 mV, output voltage is 12 mV. Calculate the CMRR of the OPAMP

  Ans: 56.48 dB

OPAMP equivalent circuit



OPAMP equivalent circuit



OPAMP Characteristics

- Ideal OPAMP
  - Infinite differential mode gain
  - Zero common mode gain
  - Infinite CMRR
  - Infinite input resistance
  - Zero output resistance
  - Infinite bandwidth
  - Infinite slew rate
  - Zero input offset voltage
  - Zero input offset current
  - Zero output offset voltage

OPAMP Characteristics

- Differential mode gain A_d
  - It is the factor by which the difference between the two input signals is amplified by the OPAMP
- Common mode gain A_{cm}
  - It is the factor by which the common mode input voltage is amplified by the OPAMP
- Common mode rejection ratio $CMRR$
  - Is the ratio of A_d to A_{cm} expressed in decibels

OPAMP Characteristics

- Input resistance R_i
  - It is the equivalent resistance measured between the two input terminals of OPAMP
- Output resistance R_o
  - It is equivalent resistance measured between output terminal and ground
- Bandwidth
  - It is the range of frequency over which the gain of OPAMP is almost constant

OPAMP Characteristics

- Output offset voltage V_{oo}
  - It is the output voltage when both input voltages are zero
  - Denoted as V_{oo}
- Input offset voltage V_{io}
  - It is the differential input voltage that must be applied at the input terminals in order to make output voltage equal to zero
  - $V_{io} = |v_1 - v_2|$ for $v_o = 0$

OPAMP Characteristics

- Input offset current I_{io}
  - It is the difference between the currents in the input terminals when both input voltages are zero
  - $I_{io} = | I_1 - I_2 |$ when $v_1 = v_2 = 0$
- Input bias current I_{ib}
  - It is the average of the currents in the input terminals when both input voltages are zero
  - $I_{ib} = (I_1 + I_2) / 2$ when $v_1 = v_2 = 0$

OPAMP Characteristics

- Slew rate *SR*
  - It is the maximum rate of change of output voltage with respect to time
  - Slew rate has to be very high if OPAMP has to operate efficiently at high frequencies
- Supply voltage rejection ratio *SVRR*
  - It is the maximum rate at which input offset voltage of OPAMP changes with change in supply voltage

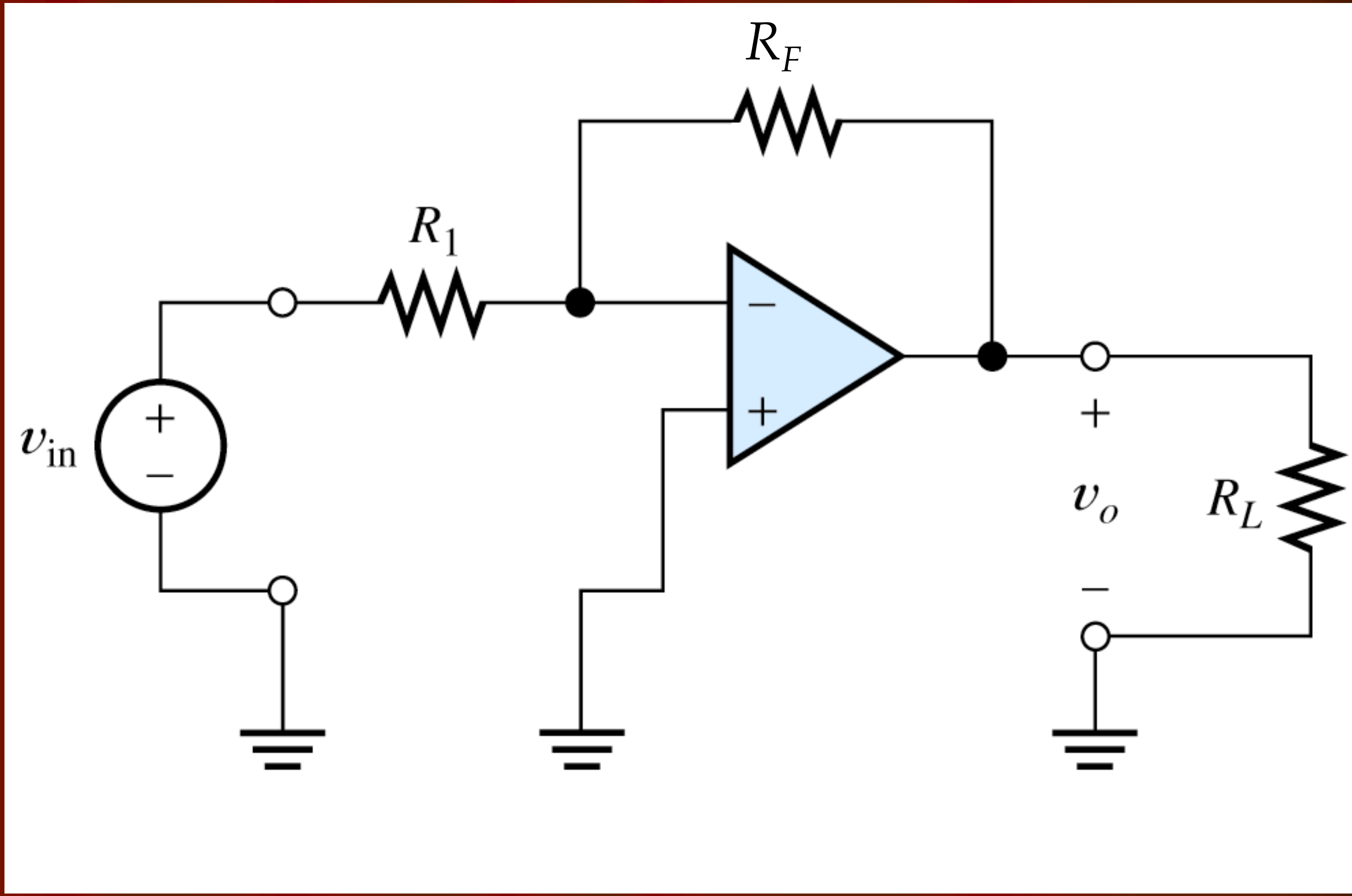
OPAMP Characteristics

- Practical characteristics of 741C OPAMP
  - Differential mode gain is 200,000
  - CMRR is 90 dB
  - Input resistance is 2 MΩ
  - Output resistance is 75 Ω
  - Unity-gain Bandwidth is 1 MHz
  - Slew rate is 0.5 V / μs
  - Output offset voltage is 1 mV
  - Input offset current is 20 nA
  - Input bias current is 80 nA

Closed-loop configurations

- Open-loop voltage gain of OPAMP is very high; such high gain is not required in most applications
- In order to reduce gain, a part of output signal is fed back to the inverting input terminal (called negative feedback)
- Many other OPAMP characteristics are improvised with this

Inverting Amplifier

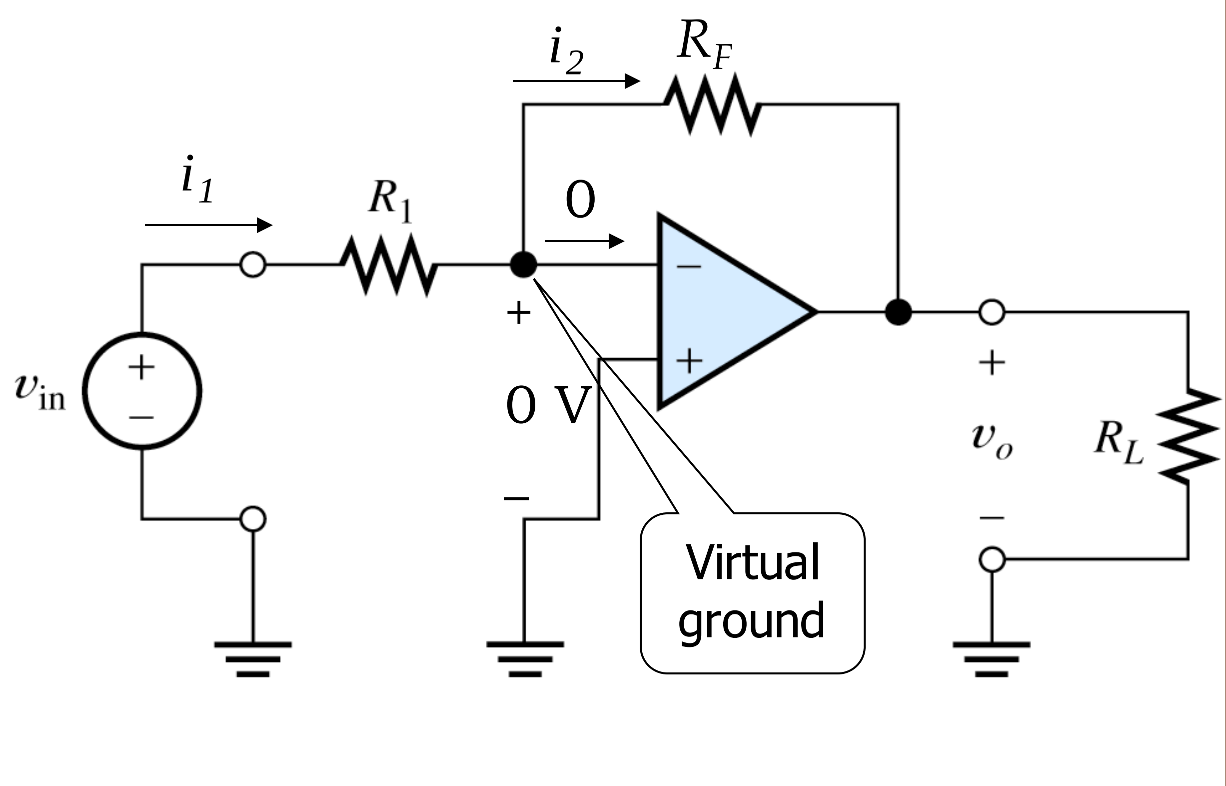


Inverting Amplifier

- Input is applied to inverting terminal
- Non inverting is grounded
- Feedback is given to inverting terminal through resistor R_F
- Assuming v_o is less than V_{CC}

  since A_d is very high, v_{id} should be very small; v_{id} taken as almost zero
- Current entering OPAMP input terminal is almost zero

Inverting Amplifier



Inverting Amplifier

$$i_1 = \frac{v_{in} - 0}{R_1} = \frac{v_{in}}{R_1}$$

$$i_2 = \frac{0 - v_o}{R_F} = \frac{-v_o}{R_F}$$

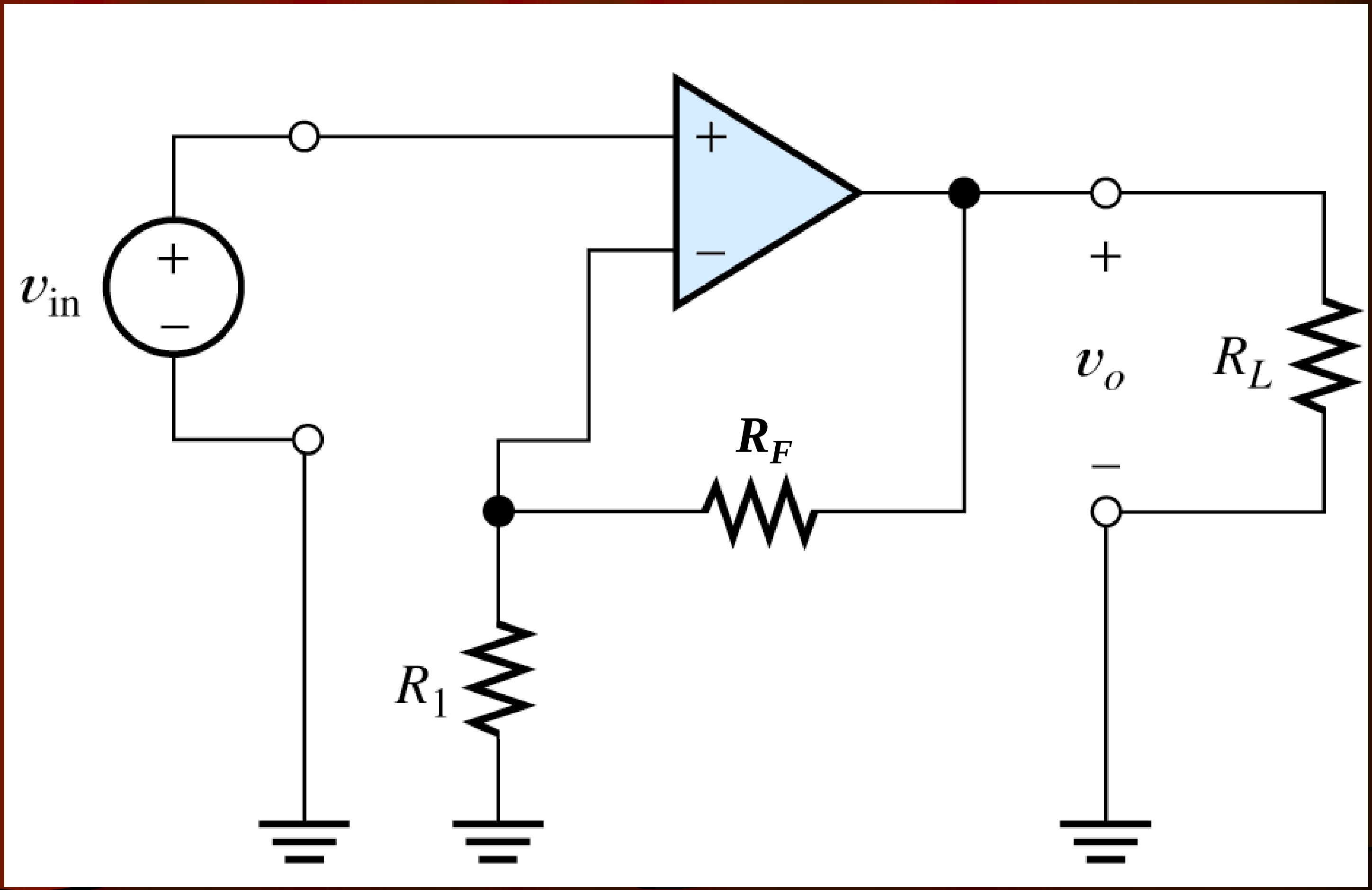
$$i_1 = i_2$$

$$\frac{v_{in}}{R_1} = \frac{-v_o}{R_F}$$

$$v_o = -v_{in}\frac{R_F}{R_1}$$

$$A_V = \frac{v_o}{v_{in}} = -\frac{R_F}{R_1}$$

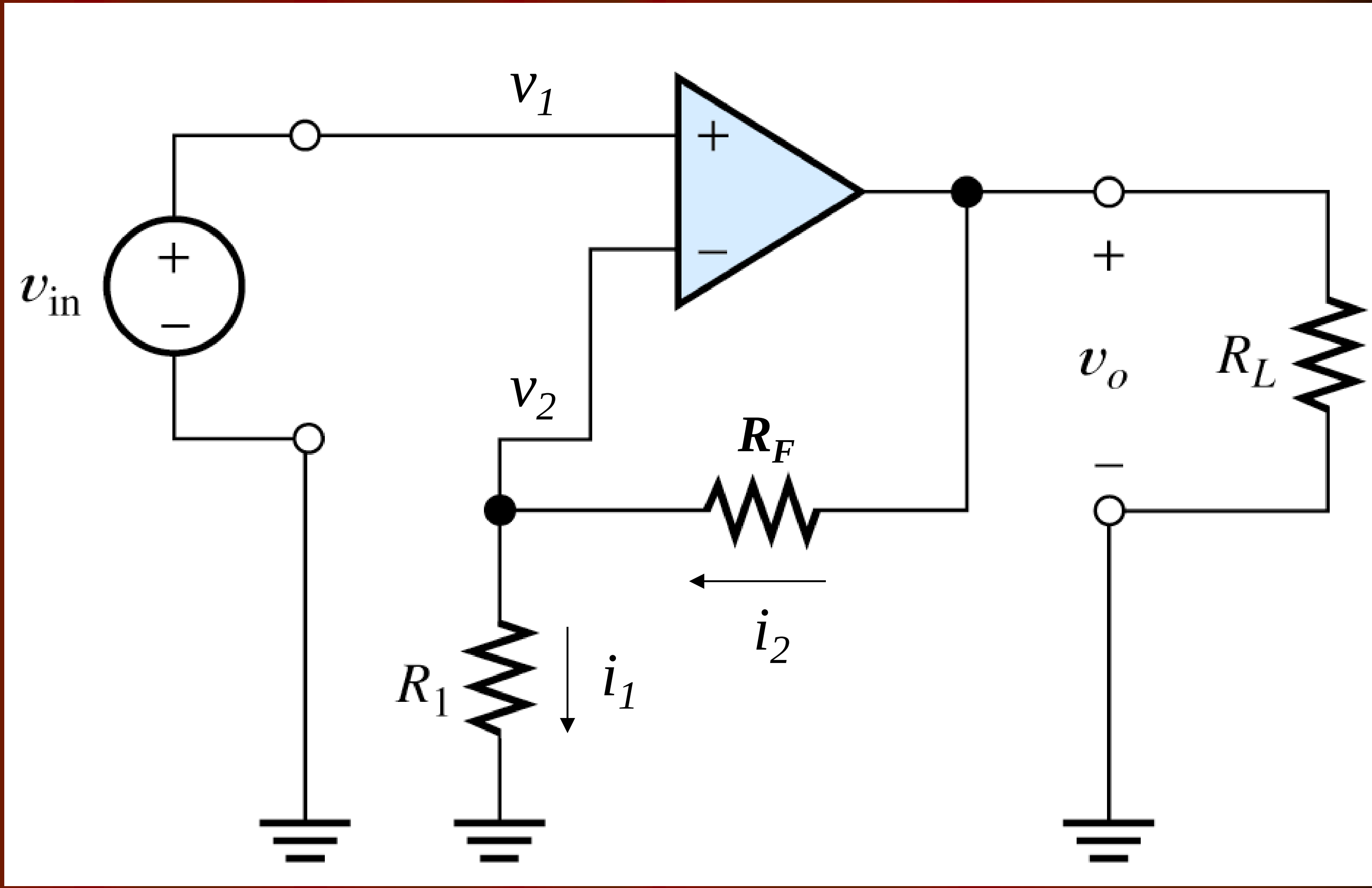
Non Inverting Amplifier



Non Inverting Amplifier

- Input is applied to non inverting terminal
- Feedback is given to inverting terminal
- Output voltage will be in-phase with input voltage
- Here again, the following assumptions are made
  - Since A_d is very high, v_{id} should be very small; v_{id} taken as almost zero
  - Current entering OPAMP input terminal is almost zero

Non Inverting Amplifier



Non Inverting Amplifier

$$v_{id} = 0 \qquad v_1 = v_2 = v_{in}$$

$$i_1 = \frac{v_2}{R_1} = \frac{v_{in}}{R_1} \qquad i_2 = \frac{v_o - v_2}{R_F} = \frac{v_o - v_{in}}{R_F}$$

$$i_1 = i_2$$

$$\frac{v_{in}}{R_1} = \frac{v_o - v_{in}}{R_F} \qquad v_o = v_{in}\left(1 + \frac{R_F}{R_1}\right)$$

Problems

- For an inverting amplifier using OPAMP, R_1=1K, R_F=100K, v_{in}=0.1sin(ωt). Find v_o.

  Ans: –10sin(ωt)

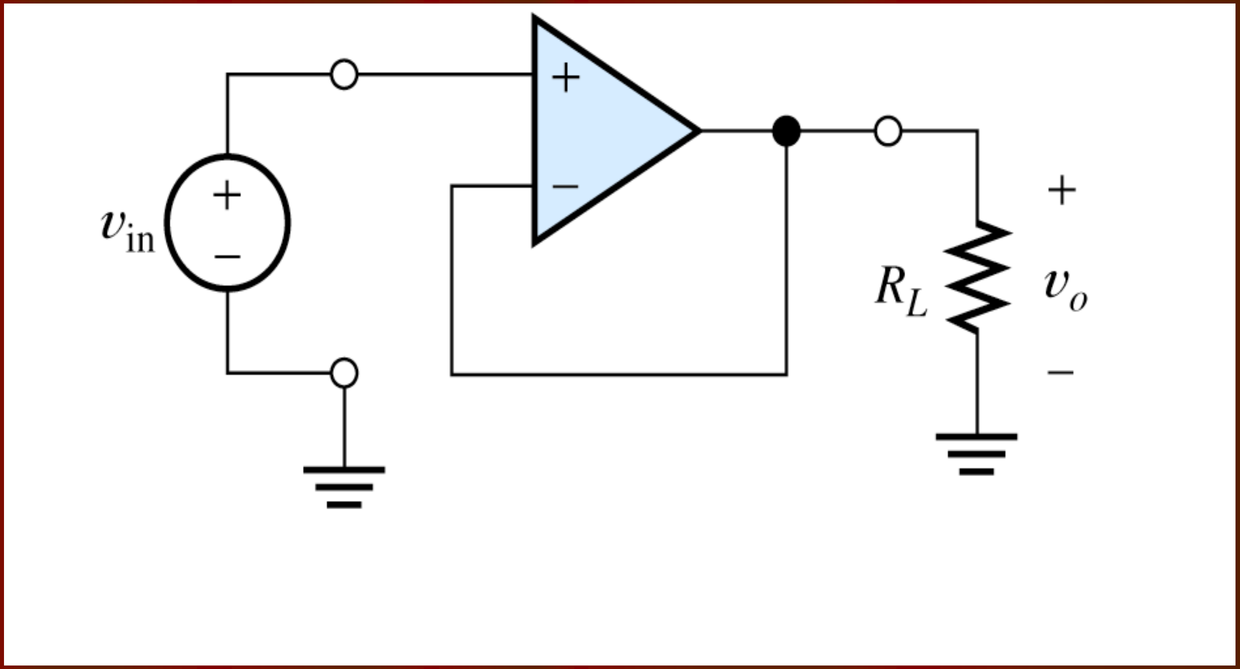
- For a non inverting amplifier, R_1=10K, R_F=100K. Calculate v_o if v_i = 25 mV dc.

  Ans: 275 mV dc

- An ac signal of rms value 2 mV needs to be amplified to 1.024 V rms, 180 degree phase shifted. Design a suitable amplifier choosing R_1=1.2K

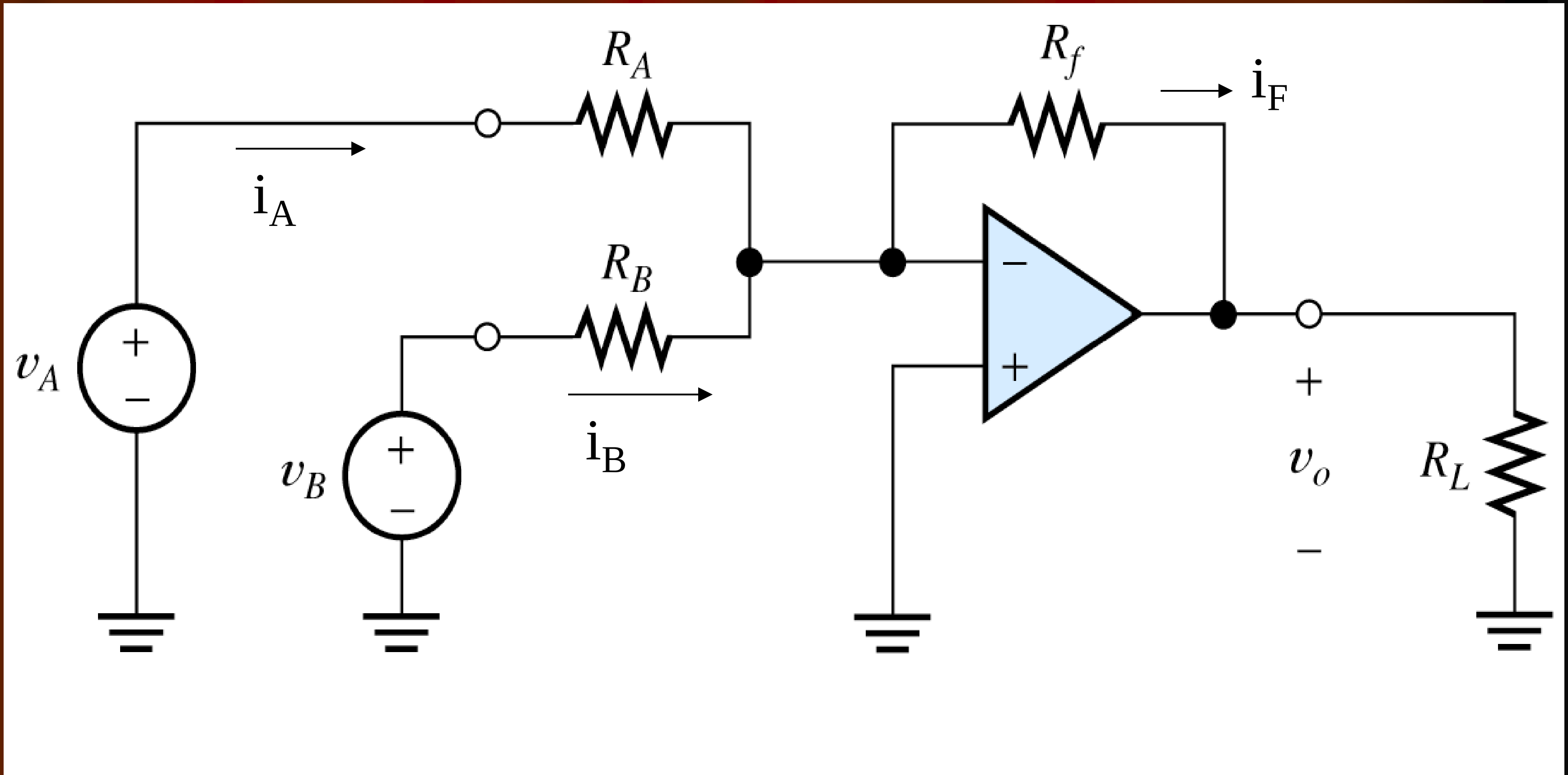
  Ans: Inv amplifier with R_F=614.4K

Voltage Follower



- Special case of non inverting amplifier where $R_F=0$
- Voltage gain is unity. $v_o = v_{in}$
- Has very high input resistance and very low output resistance; Used as buffer for impedance matching

Summing Amplifier (Adder)



Summing Amplifier (Adder)

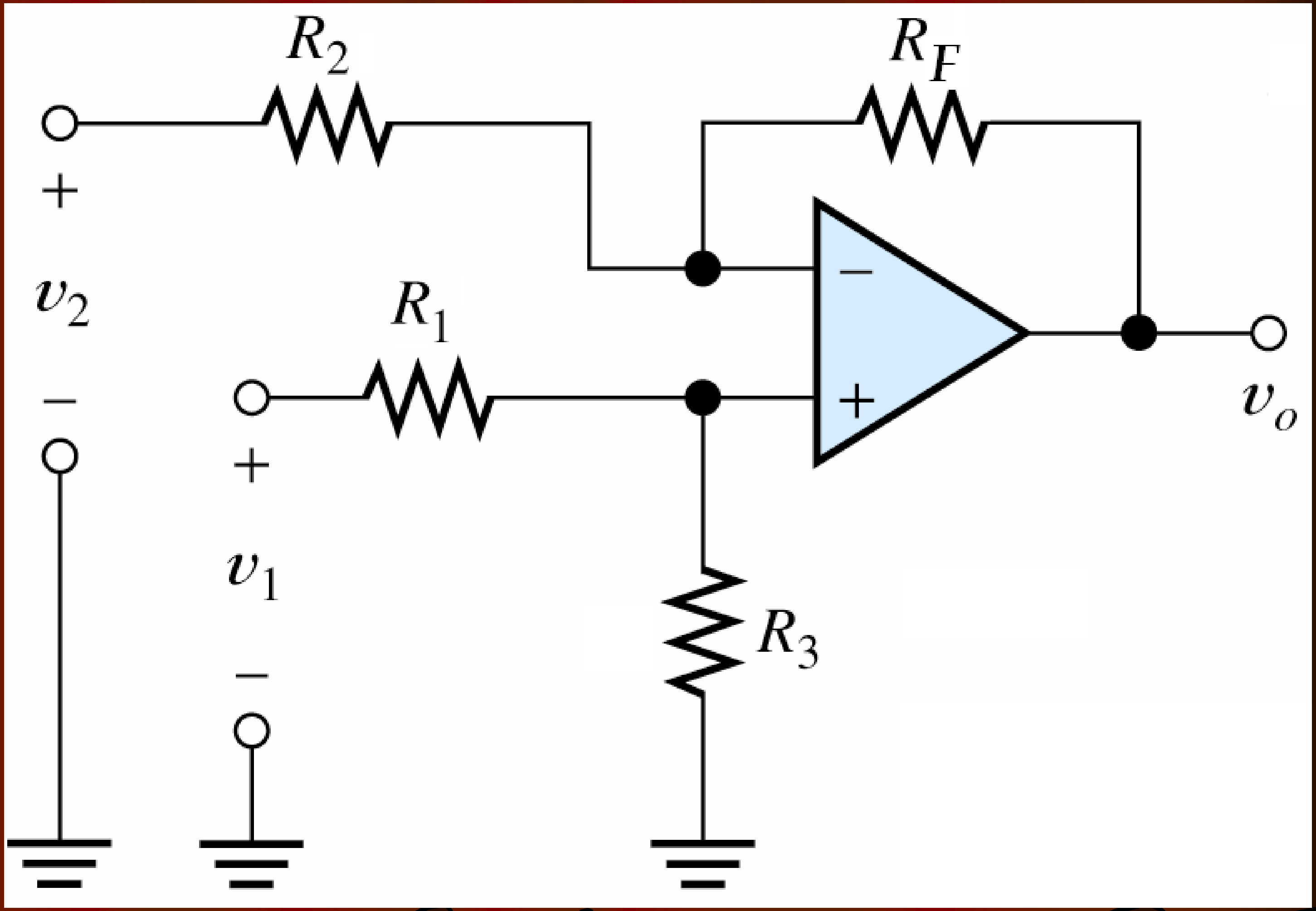
$$i_A = \frac{v_A}{R_A} \qquad i_B = \frac{v_B}{R_B} \qquad i_F = \frac{-v_o}{R_F}$$

$$i_A + i_B = i_F \qquad \frac{v_A}{R_A} + \frac{v_B}{R_B} = -\frac{v_o}{R_F}$$

$$v_o = -\left(v_A \frac{R_F}{R_A} + v_B \frac{R_F}{R_B} \right)$$

- If R_A=R_B=R_F, then $v_o = -\left(v_A + v_B\right)$

Difference Amplifier (Subtractor)



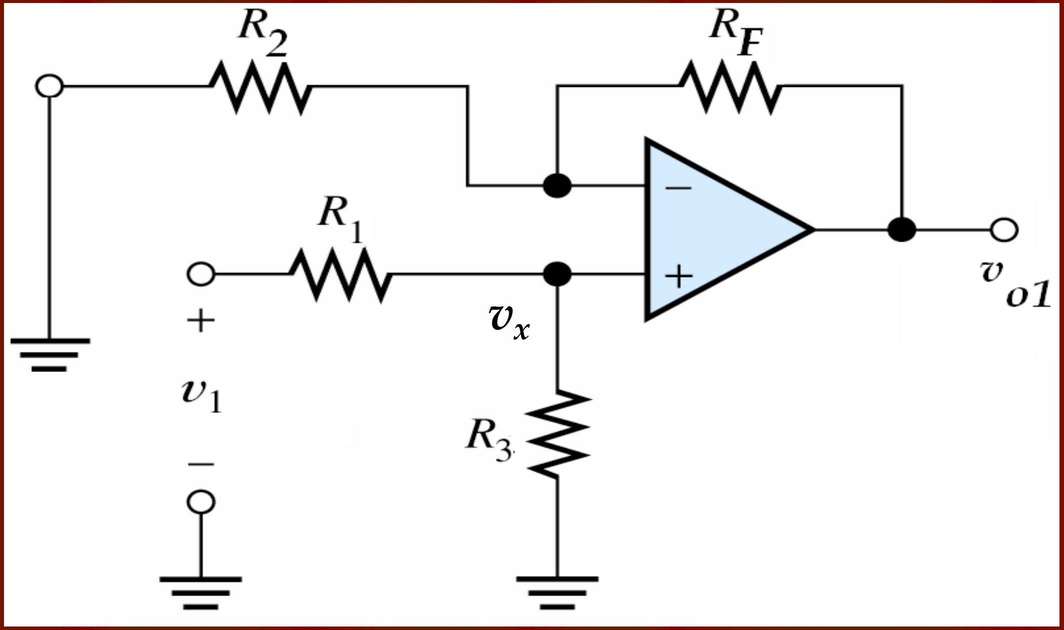
Difference Amplifier (Subtractor)

- The circuit is analyzed using superposition theorem
- Consider only v_1 to be present; $v_2=0$

  Now derive expression for output voltage v_{o1}
- Next consider only v_2 to be present; $v_1=0$

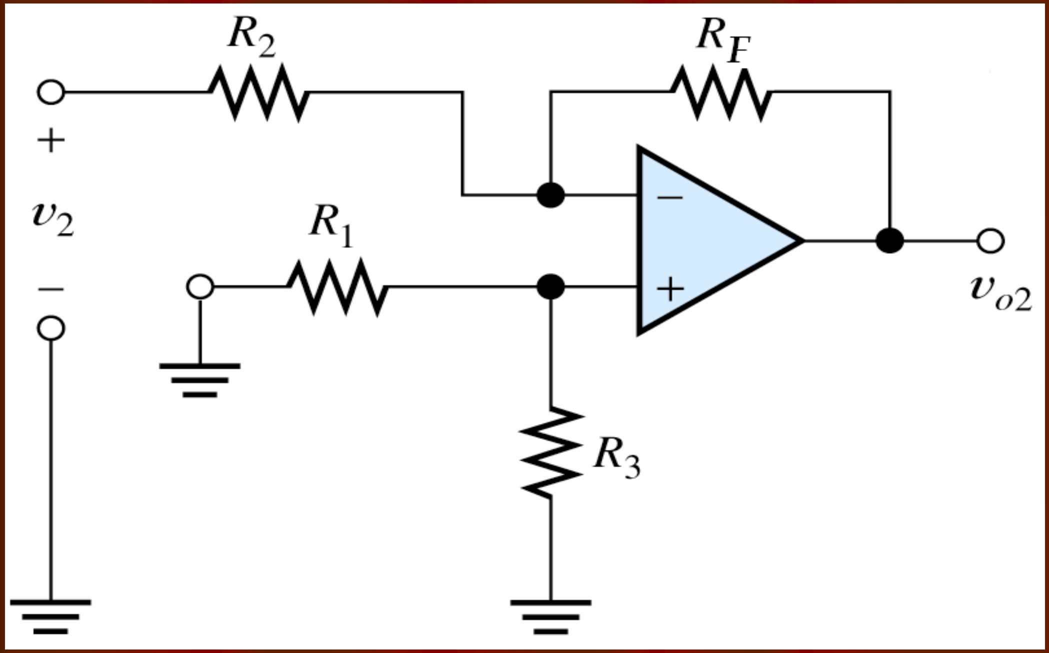
  Derive expression for output voltage v_{02}
- Actual output voltage $v_o = v_{o1}+v_{o2}$

Difference Amplifier (Subtractor)



$$v_{o1} = v_x\left(1 + \frac{R_F}{R_2}\right) \qquad v_{o1} = \left(\frac{v_1 R_3}{R_1 + R_3}\right)\left(1 + \frac{R_F}{R_2}\right)$$

Difference Amplifier (Subtractor)



$$v_{o2} = -v_2 \frac{R_F}{R_2}$$

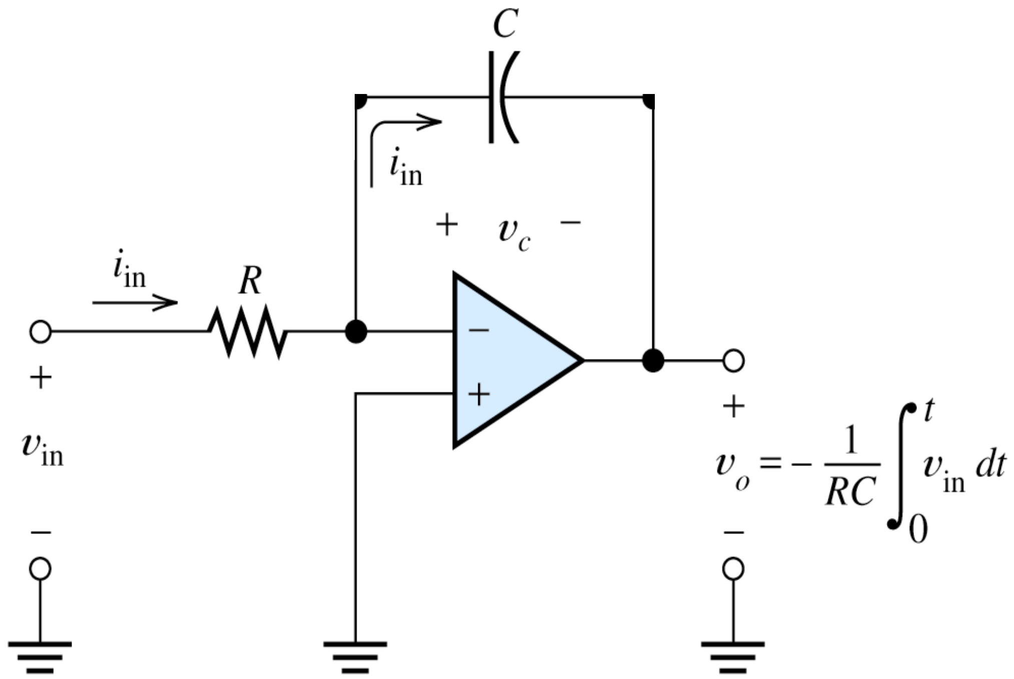
$$v_o = v_{o1} + v_{o2} = \left(\frac{v_1 R_3}{R_1 + R_3}\right)\left(1 + \frac{R_F}{R_2}\right) - v_2 \frac{R_F}{R_2}$$

$$= v_1 - v_2 \quad \text{if } R_1 = R_2 = R_3 = R_F$$

Problems

- Design an OPAMP circuit such that output is given by $v_o = -(0.5v_1 + 0.75v_2)$ where v_1 and v_2 are input voltages. Choose $R_F = 10K$
- Design an OPAMP subtractor to have output given by $v_o = \frac{2}{3}v_1 - v_2$ Choose $R_F = R_2 = 1K$
- Design an OPAMP adder/subtractor to get output voltage $v_o = -\frac{1}{2}v_1 + \frac{2}{3}v_2 - v_3$

Integrator

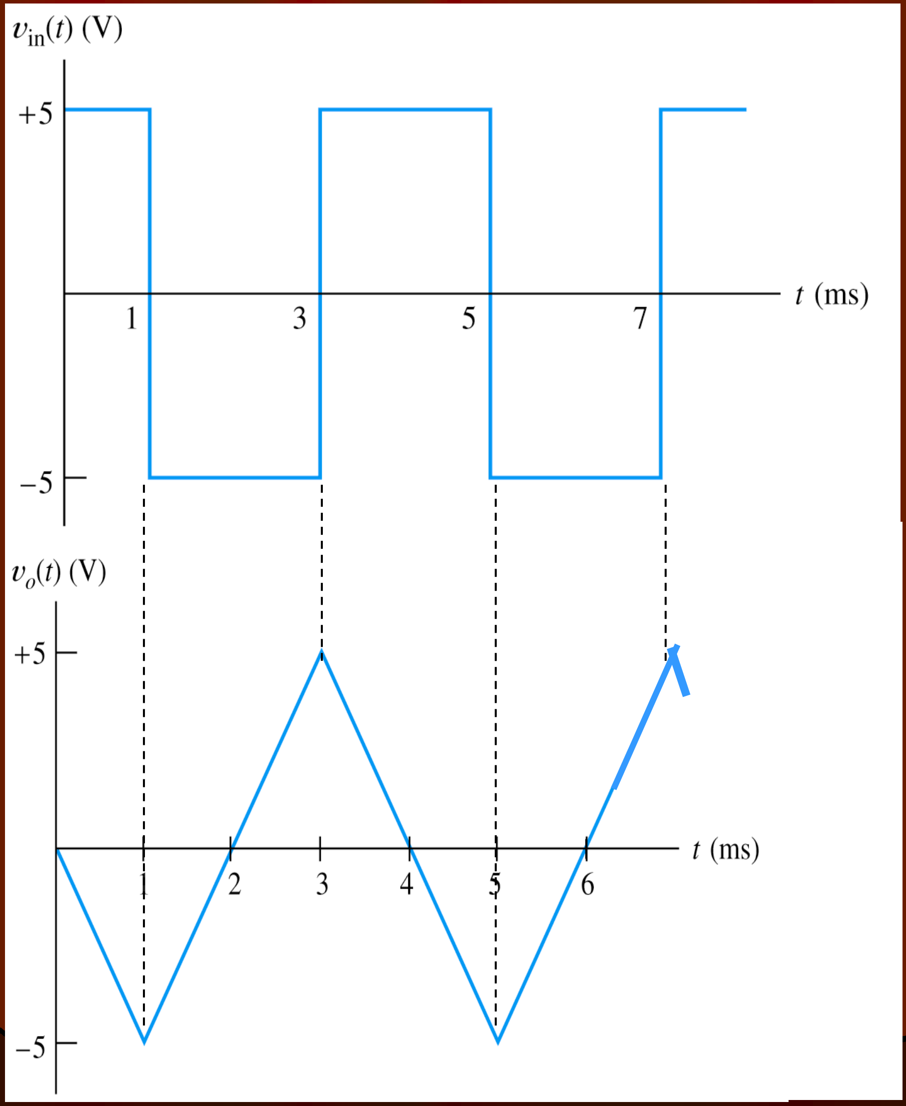


Integrator

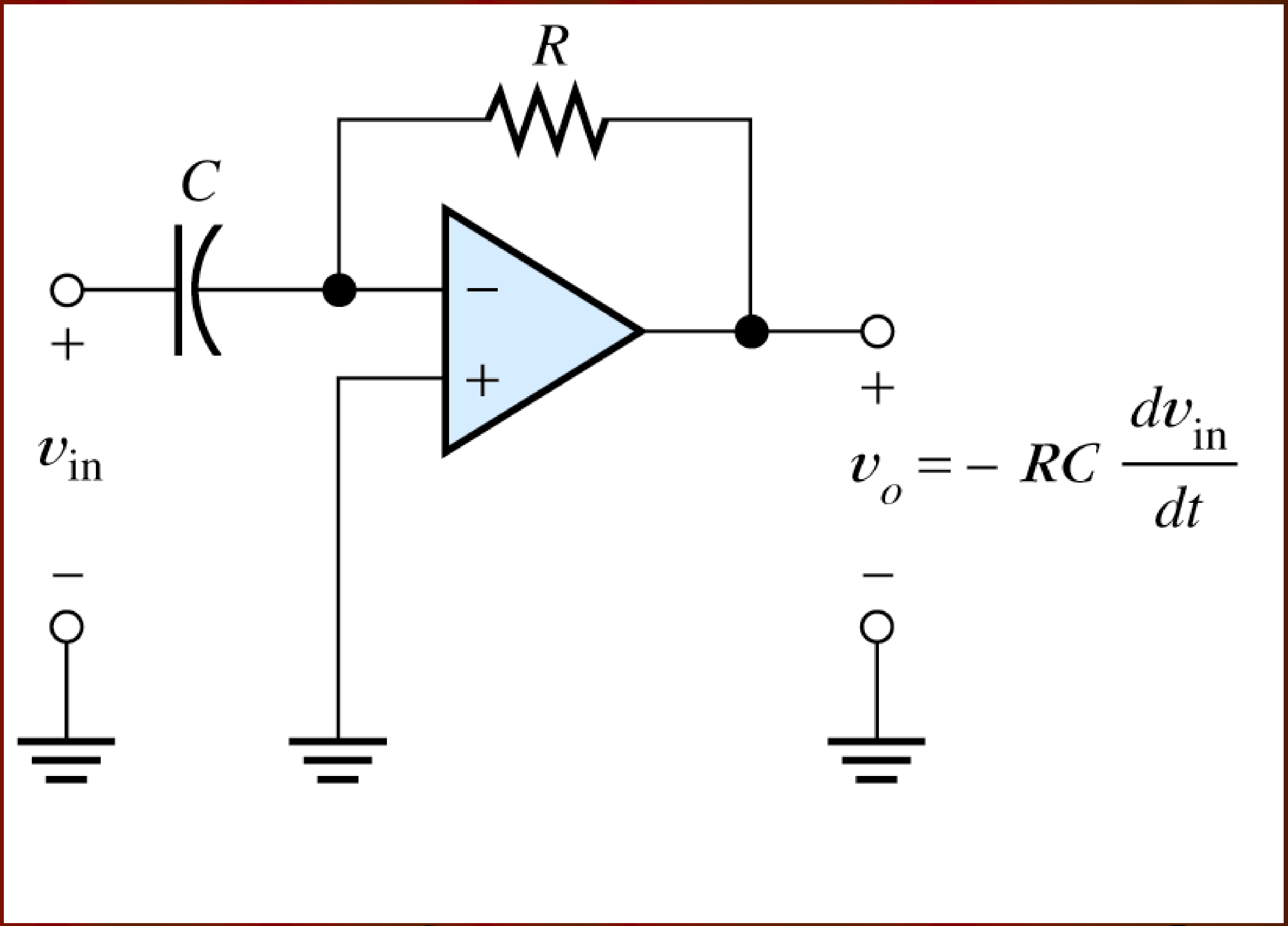
- Integrator is a circuit whose output is proportional to (negative) integral of the input signal with respect to time
- Feedback is given through capacitor to inverting terminal
- Since same current flows through R and C,

$$\frac{v_{in}}{R} = -C\frac{dv_o}{dt} \qquad v_o = \frac{-1}{RC}\int_0^t v_{in}\,dt$$

Integrator



Differentiator



Differentiator

- Differentiator is circuit whose output is proportional to (negative) differential of input voltage with respect to time
- Input is given through capacitor, feedback given through resistor to inv terminal

- Since current through R and C are same,

$$C\frac{dv_{in}}{dt} = -\frac{v_o}{R} \qquad v_o = -RC\frac{dv_{in}}{dt}$$

End of Module 4