EEE 3571 Electronic Engineering I

Lecture 8: Operational Amplifiers- Inverting Ckts

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References

Our main reference text books in this course are

[1] Neil S., Electronics: A Systems Approach, 4th edition, 2009, Pearson Education Limited, ISBN 978-0-273-71918-2.

[2] Boylestad R. L., Nashelsky L., Electronic Devices and Circuit Theory, 11th Ed, 2013, Prentice-Hall, ISBN 978-0-13-262226-4.

[3] Smith R. J., Dorf R. C., Circuits Devices and Systems, 5th Ed., 2004, John Wiley, ISBN ISBN 9971-51-172-X.

However, feel free to use pretty much any additional text which you might find relevant to our course.

Learning Objectives

At the end of the lecture 10 on Op-Amps, you ought to:

1) Learn how these versatile amplifiers work and know how we can use them in practical circuits
2) Represent an amplifier by a simple circuit model and use the model to explain the features and behavior of an op amp and to analyze or design basic op-amp circuits for a variety of linear applications.
3) Learn about constant gain, summing, and buffering amplifiers.
4) Understand how an active filter network works.
5) Analyze or design useful circuits that take advantage of the nonlinear operating regions of the op amp, and understand some of the practical considerations in designing op-amp circuits.
6) Describe different types of controlled sources.
7) Arrange op amps to form an analog computer that can solve differential equations.

8.1 Introduction

- The name operational amplifiers was first applied to amplifiers employed in analog computers to perform mathematical operations such as summing and integration.
- With sophisticated integrated-circuit (IC) amplifiers available for less than a dollar, the design of signal processing equipment has been radically altered.
- For linear or analog systems, the IC op amp plays the same basic building block role as do the IC logic and memory elements in digital systems.
- Combinations of op amps and digital devices are widely used in instrumentation and control.

8.2 Operational Amplifier (Op Amp)

- Recall that a multistage amplifier is a complex circuit that combines basic designs (CB, CE, CC, Differential, Darlington, Current Mirror) to achieve optimum performance. It typically has three sections:

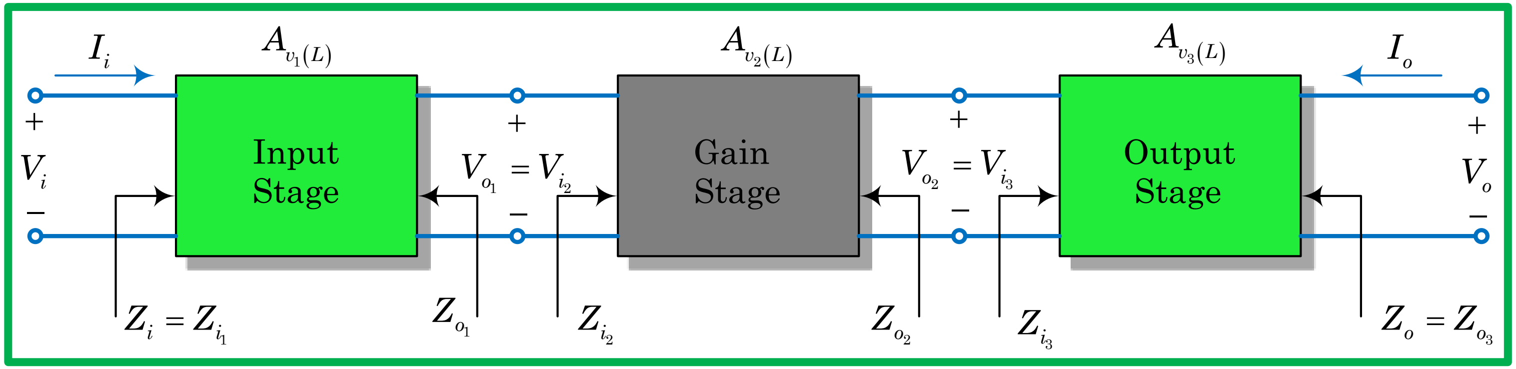


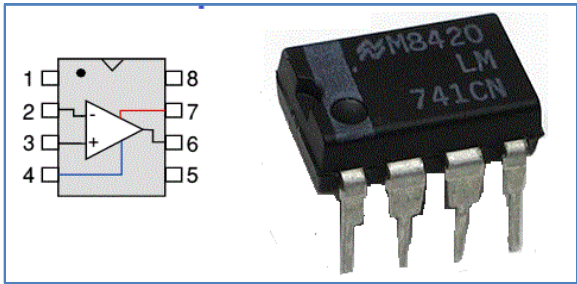
Fig. 1: Typical multistage amplifier.

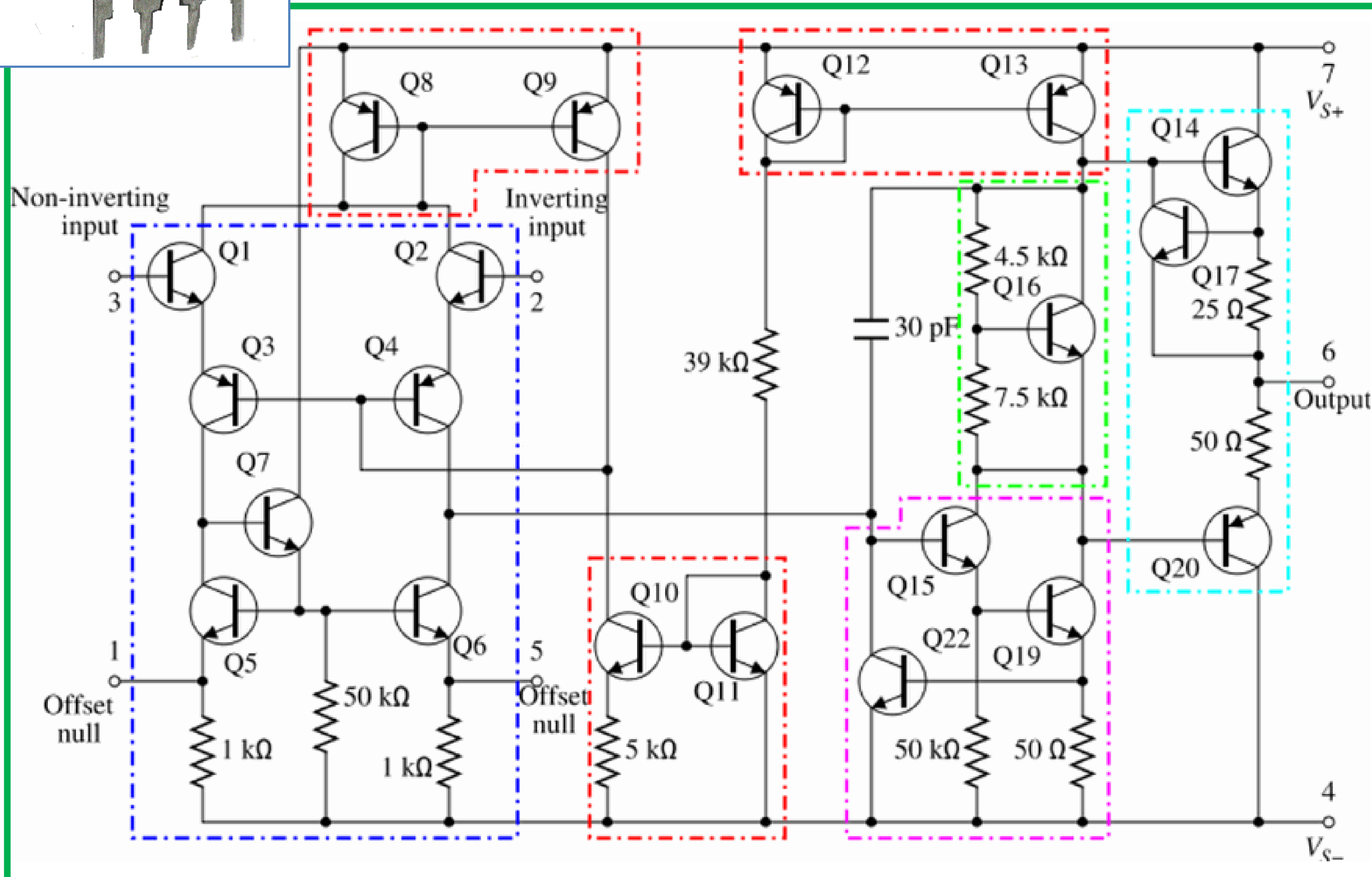
(1) Input Stage – This has one purpose: To provide the multi-stage amplifier with high input impedance e.g. differential amplifier.

(2) Gain Stages – This section consists of one or more amplifiers (**stages**) with high open-circuit voltage gain (e.g. common emitter). This stage provides the required voltage gain.

(3) Output Stage – This one's purpose: To provide the multi-stage amplifier with a low output impedance. This stage is commonly Common Collector (Emitter follower).

An Example a Multistage Amplifier:
Operational Amplifier: 741 (8-pin IC)





Components of 741 Operational Amplifier above

- An Q1, Q2: Differential Amplifier (High input impedance, High voltage gain)
- Q3, Q4: Each forms cascode pair with Q1 and Q2 respectively (high frequency)
- Q8,Q9: Current Mirror for further reduction of Common Mode (CM) gain.
- Q10,Q11: Current Mirror for reference voltage from negative rail. They provide the slight base current needed by Q3 and Q4. Q10 has 5K resistor to limit current to almost zero.
- Q12,Q13: Current Mirror to act as active load to the Class A amplifier (Q15,Q19).
- Q14,Q20: Push Pull pair(Class AB). This is emitter follower and thus provides low output impedance and being a Class AB provides high current driving capability.
- Q16: Level shifting stage. This provides the Push-Pull pair with pre-biasing.
- Q17: Current limiting in Push-Pull's Q14.
- Offset Null (Pins 1 & 5): Zero out the output offset.

Operational Amplifier (Op Amp)

Ideal Operational Amplifiers

- An op amp is a direct-coupled, high-gain voltage amplifier designed to amplify signals over a wide frequency range. Typically, it has two input terminals and one output terminal and a gain of at least 10^5, and it is represented by the symbol in Fig. 3*b*.
- It is basically a differential amplifier responding to the difference in the voltages applied to the positive and negative input terminals. (Single-input op amps correspond to the special case where the +ve input is grounded.)
- Normally we use an op amp with external feedback networks that determine the function performed.
- The characteristics of an ideal op amp are as follows:

Voltage gain $A = \infty$

Input impedance $Z_i = \infty$

Output voltage $v_o = 0$ when $v_n = v_p$

Output impedance $Z_o = 0$

Bandwidth $BW = \infty$

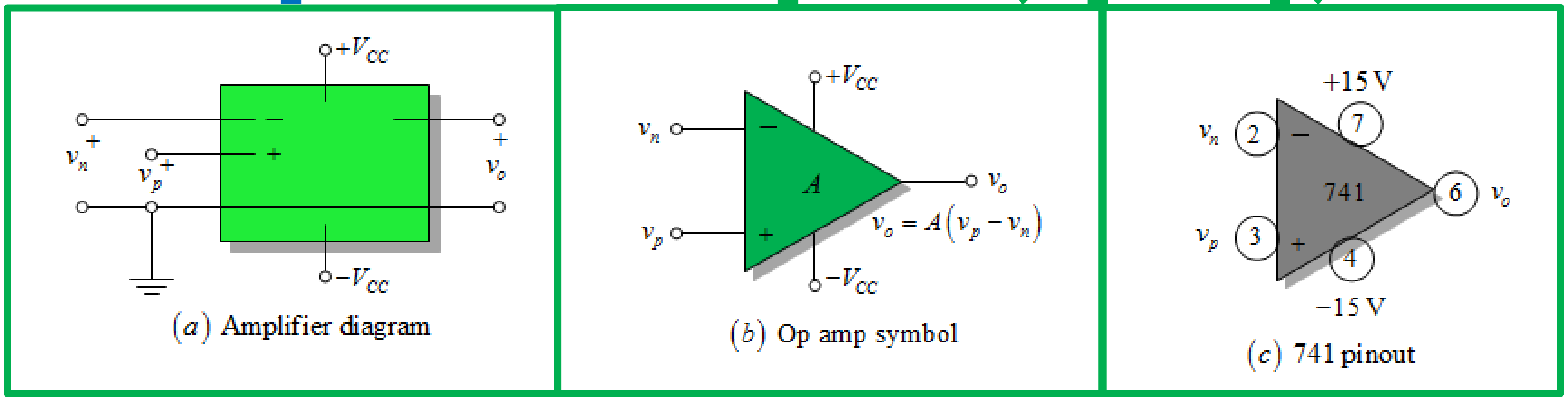


Fig. 3: Operational amplifier diagram, symbol, and pinout.

- Much as the aforesaid specifications are extreme, commercial units approach the ideal so closely that we can design many practical circuits assuming that these characteristics are available.
- One practical limitation that cannot be ignored is that, for linear operation, the output voltage v_o cannot exceed $\pm V_{CC}$.

8.3 Inverting Circuit Applications

- Usually, impedances Z_i and Z_o can be considered to be pure resistances R_i and R_o as shown in the model of Fig. 4*a*.
- The input signal is applied to the negative terminal and the positive terminal is grounded as depicted in the amplifier circuit of Fig. 4*b*.
- The input voltage v_1 is applied in series with the resistance R_1, and the output voltage v_o is fed back through resistance R_F.

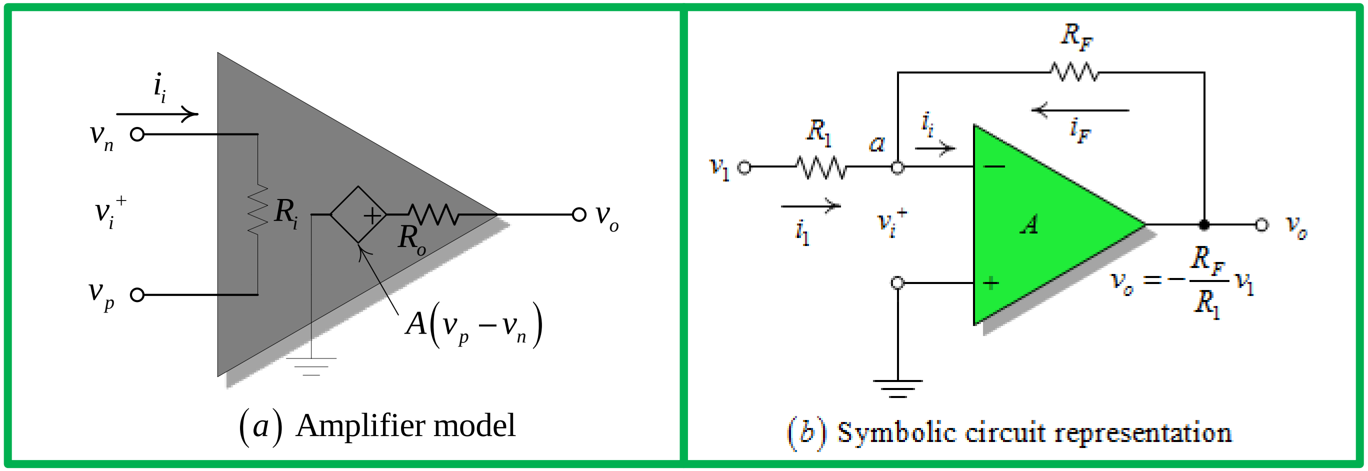


Fig. 4: The basic inverting amplifier circuit.

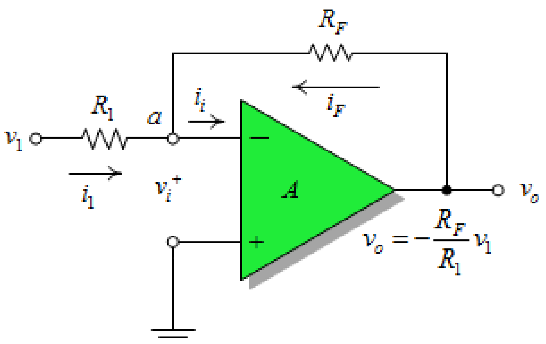
Inverting Circuit Applications

- Since the signal voltage is inverted, the feedback current is of opposite sign and i_F tends to cancel the input current i_1, leaving only a very small difference i_i.
- Another interpretation is that part of v_o fed back tends to cancel the effect of v_1, leaving only a very small v_i; we say that "the gain A drives v_i to zero." (Output attempts to make voltage difference at input zero).
- For an ideal op amp as in Fig. 4 *b*, closely approximated by a commercial unit, $v_i = 0$ and $i_i = 0$; therefore, the sum of the currents into node *a* is

$$i_1 + i_F = \frac{v_1}{R_1} + \frac{v_o}{R_F} = 0 \quad [1]$$

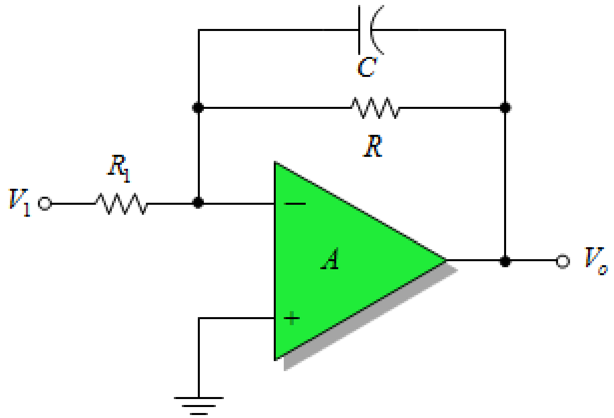
and the gain of the inverting amplifier circuit is

$$\frac{v_o}{v_1} = A_F = -\frac{R_F}{R_1} \quad [2]$$

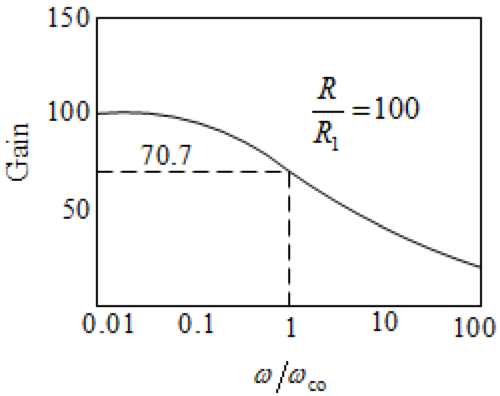


Low-pass Filter

- A passive filter is frequency-selective network consisting of passive resistors, inductors, and capacitors. On the other hand, an active filter is one that incorporates amplifiers.
- They avoid the use of bulky and expensive inductors and have other advantages. Op amps with appropriate properties are used in active filters.



(a) Circuit



(b) Frequency response

Inverting Circuit Applications: Low-pass Filter

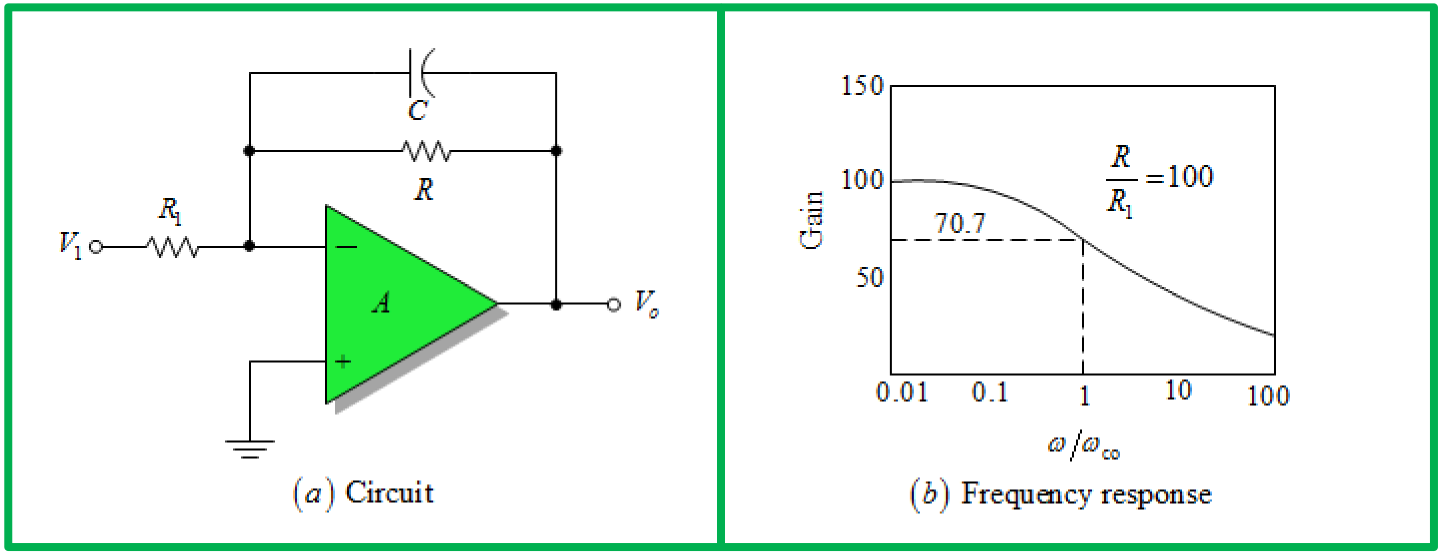


Fig. 5: A simple low-pass filter.

- Consider Fig. 5*a* as a simple example. It is a form of the general inverting amplifier circuit with impedance elements $\mathbf{Z}_F\left(R \| C\right)$ and $\mathbf{Z}_1\left(R_1\right)$ in the feedback network.
- Here $\mathbf{V}_1$ is a sinusoidal signal of variable frequency or a combination of signals of various frequencies. The voltage gain (a function of frequency here) is

$$\mathbf{A}_F = \frac{\mathbf{V}_o}{\mathbf{V}_1} = -\frac{\mathbf{Z}_F}{\mathbf{Z}_1} = -\frac{1/\left[\left(1/R\right) + j\omega C\right]}{R_1} = -\frac{R/R_1}{1 + j\omega RC}$$

[3]

Inverting Circuit Applications: Low-pass Filter

- The cutoff or half-power frequency is defined by $\omega_{co} RC = 1$, or

$$\omega_{co} = \frac{1}{RC}$$ [4]

- The voltage gain decreases rapidly above ω_{co} and this serves as a low-pass filter. The curve of Fig. 5b, drawn for $R/R_1 = 100$, does not exhibit a sharp cutoff.
- More complicated circuits designed by more sophisticated methods and using several op amps can provide sharp high-, low-, or band-pass filtering.
- In designing active filters for high-frequency applications, the frequency response of the op amp itself must be taken into account.
- Here we will assume that the range of frequencies passed is within the frequency response of the chosen op amp.

Inverting Circuit Applications

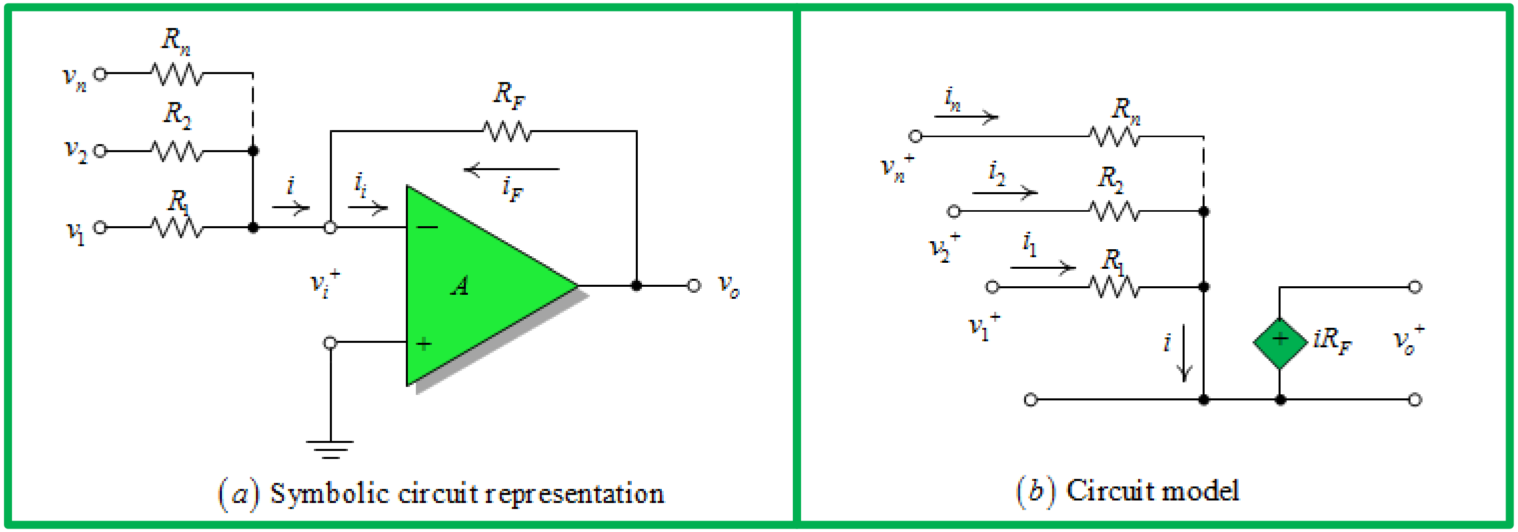


Fig. 6: A summing circuit.

❑ Summing Circuit

- ❑ If the circuit in Fig. 4 is modified to permit multiple inputs, the operational amplifier can perform addition.
- ❑ In Fig. 6, the input current is supplied by several voltages through separate resistances. In the practical case, $v_i = 0$ and $i_i = 0$ and the circuit model is as shown in Fig. 6*b*. The sum of the input currents is just equal and opposite to the feedback current, i.e.,

$$i = i_1 + i_2 + \cdots + i_n = -i_F$$

[5]

Inverting Circuit Applications

- It follows from Eq. [5] that

$$\frac{v_1}{R_1}+\frac{v_2}{R_2}+\cdots+\frac{v_n}{R_n}=-\frac{v_0}{R_F}$$

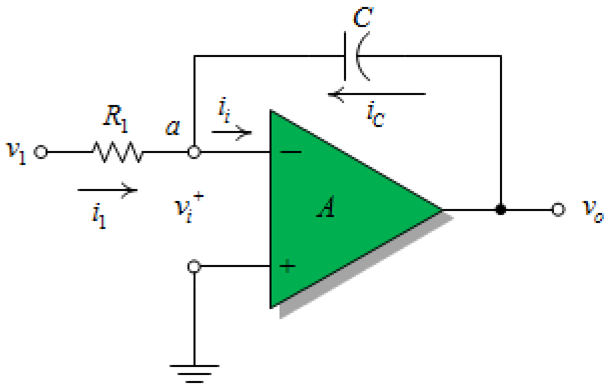
- Thus,

$$v_0=-\left[v_1\left(R_F/R_1\right)+v_2\left(R_F/R_2\right)+\cdots+v_n\left(R_F/R_n\right)\right] \quad \textbf{[6]}$$

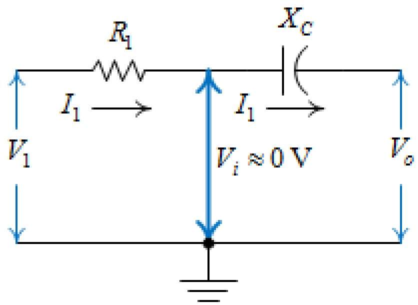
- The output is the weighted sum of the inputs. Note, that a signal can be subtracted using an inverting amplifier with $R_F = R_1$.

Analog Integrator ckt

- So far, the input and feedback components have been resistors. If the feedback component used is a capacitor as shown in Fig 11a, the ckt is called an integrator. The virtual-ground equivalent ckt is shown in Fig 11b.
- Recall that the virtual ground entails the voltage at the junction of R_1 and X_C to be ground, that is, $v_i \approx 0$, but not current goes into the ground at that point.



(a)



(b)

Inverting Circuit Applications

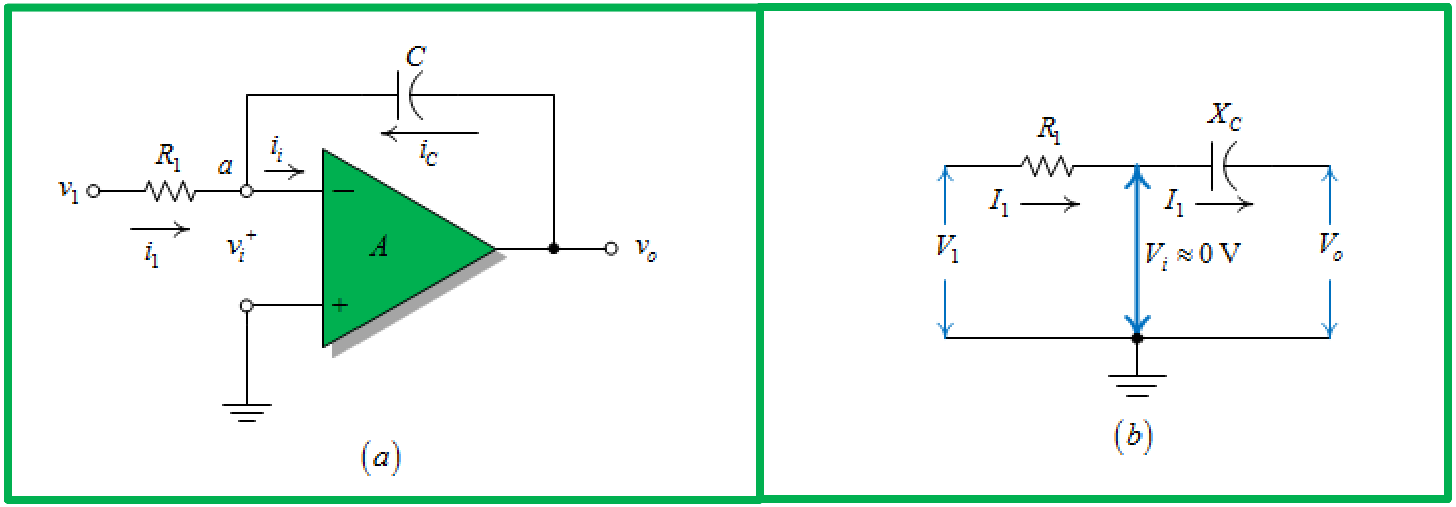


Fig. 11: Integrator circuit.

- The capacitive impedance can be expressed as

$$X_C = \frac{1}{j\omega C} = \frac{1}{sC} \qquad [16]$$

where $s = j\omega$ is in *Laplace notation*. Thus, solving for V_o/V_1 yields

$$I_1 = \frac{V_1}{R_1} = -\frac{V_o}{1/sC} = -sCV_0 \qquad [17]$$

Inverting Circuit Applications

- It follows from Eq. [17] that,

$$\frac{V_o}{V_1} = -\frac{1}{sCR_1} \qquad [18]$$

- Eq. [18] can be rewritten in the time domain by its inverse Laplace transform as

$$v_o(t) = -\frac{1}{R_1 C}\int v_1(t)\,dt \qquad [19]$$

- Eq. [19] shows that the output is the integral of the input, with an inversion and scaled multiplier of $1/R_1C$.

- It is worth noting that more than one input may be applied to an integrator, as shown in Fig. 12, with the resulting operation given by

$$v_o(t) = -\left[\frac{1}{R_1 C}\int v_1(t)\,dt + \frac{1}{R_2 C}\int v_2(t)\,dt + \frac{1}{R_3 C}\int v_3(t)\,dt\right] \qquad [20]$$

Inverting Circuit Applications

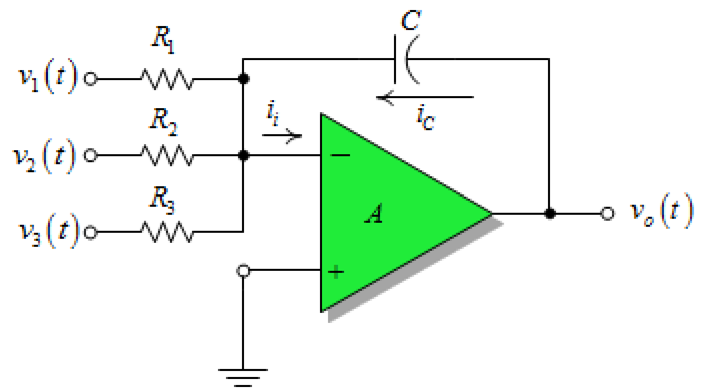


Fig. 12: Summing-Integrator circuit.

[Example 8.3] Inverting Circuit Applications

- Consider the ckt in Fig. 12, let the values of the input resistors and feedback capacitor be, $R_1 = 200\,\text{k}\Omega$, $R_2 = 100\,\text{k}\Omega$, $R_3 = 1\,\text{M}\Omega$, and $C = 1\mu\text{F}$. Find the output voltage when all inputs are unit step voltages, i.e., 1V.

[Solution]

- From Eq. [20] it follows that

[Example 8.3] Inverting Circuit Applications Cont'd

$$-\frac{1}{R_1C} = -\frac{1}{(200\,\text{k}\Omega)(1\,\mu\text{F})} = -5\,, \quad -\frac{1}{R_2C} = -\frac{1}{(100\,\text{k}\Omega)(1\,\mu\text{F})} = -10\,,$$

$$-\frac{1}{R_3C} = -\frac{1}{(1\,\text{M}\Omega)(1\,\mu\text{F})} = -1$$

- Thus, $$v_o(t) = -\left[5\int v_1(t)\,dt + 10\int v_2(t)\,dt + \int v_3(t)\,dt\right]$$
- Given that, $v(t)_1 = v_2(t) = v_3(t) = 1\,\text{V}$, we get

$$v_o(t) = -\left[5\int dt + 10\int dt + \int dt\right]$$

$$= -\left[5t + 10t + t\right]$$

- The final result is the summation of ramp functions scale by factors, -5, -10, and -1.

Analog Differentiator ckt

- A differentiator circuit is shown in Fig. 13. Much as it is not as useful as the integrator ckt we just looked at, the differentiator does provide a useful operation. The resulting relation for the circuit is

$$v_o(t) = -RC\frac{dv_1(t)}{dt} \qquad [21]$$

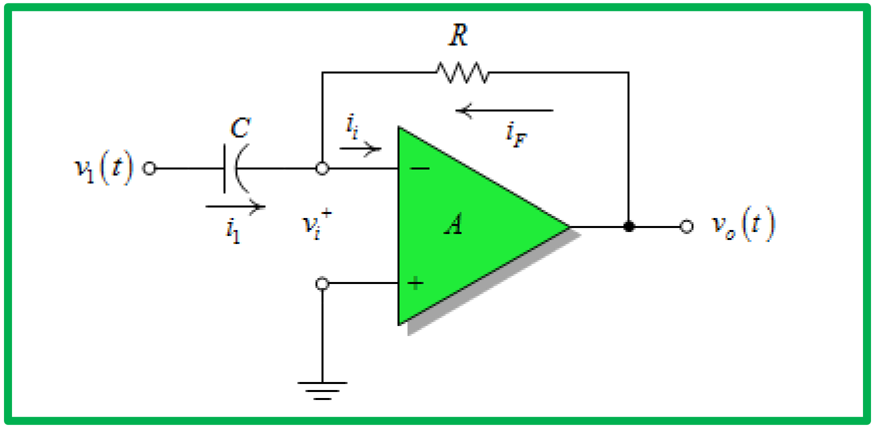


Fig. 13: Differentiator circuit.

OP-Amp Specifications-DC Offset Parameters

- It is worth while to become familiar with some of the parameters used to define the operation of the op-amp. This is critical in practical applications.

Offset Currents and Voltages

- Although the op-amp output should be 0V when the input is 0V, in actual operation there is an offset voltage at the output.
- For instance, if one connected $0\,\mathrm{V}$ to both inputs and then measured $26\,\mathrm{mV}$ (dc) at the output, this an unwanted voltage generated by the ckt and not the input.
- The manufacturer specifies an input offset voltage for the op-amp. The output offset voltage is then determined by input offset voltage and the gain of the amplifier, as connected by the user.
- The output offset voltage is affected by; an input offset voltage V_{IO} and an offset current due to the difference in currents resulting at the +ve and –ve inputs.

Inverting Circuit Applications

Input Offset Voltage

- The manufacturer's specification sheet provides a value of V_{IO} for the op-amp. To determine the effect of this input voltage on the output, consider the connection shown in Fig. 14. Using $V_o = AV_i$, we can write

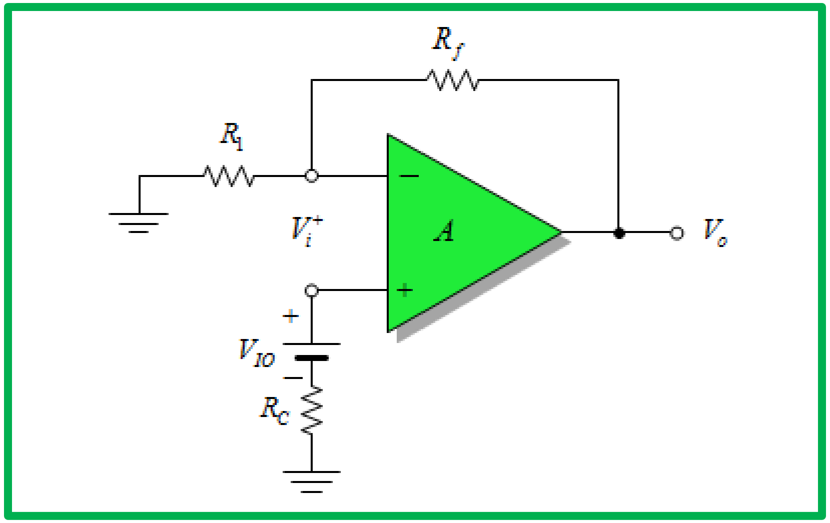


Fig. 14: Input offset voltage effect ckt.

$$V_o = AV_i = A\left(V_{IO} - V_o \frac{R_1}{R_1 + R_f}\right) \quad [22]$$

✓ Solving for V_o , we get

$$V_o = V_{IO} \frac{A}{1 + A\left[R_1 / \left(R_1 + R_f\right)\right]}$$

$$V_o \approx V_{IO} \frac{A}{A\left[R_1 / \left(R_1 + R_f\right)\right]} \quad [23]$$

Inverting Circuit Applications

- From Eq. [23] we can write

$$V_o(\text{offset}) = V_{IO}\frac{R_1 + R_f}{R_1} \quad [24]$$

- From Eq. [24] shows how the output offset voltage results from a specified input offset voltage for a typical amplifier connection of the op-amp.

[Example 8.4]

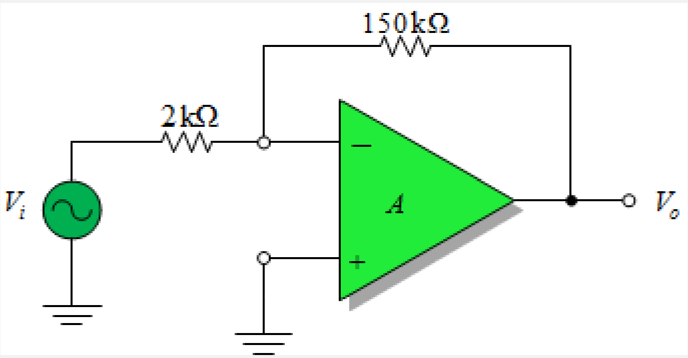


Fig. 15:

- Calculate the output offset voltage of the ckt in Fig. 15. The op-amp spec lists $V_{IO} = 1.2\,\text{mV}$.

[Solution] $V_o(\text{offset}) = V_{IO}\frac{R_1 + R_f}{R_1}$;

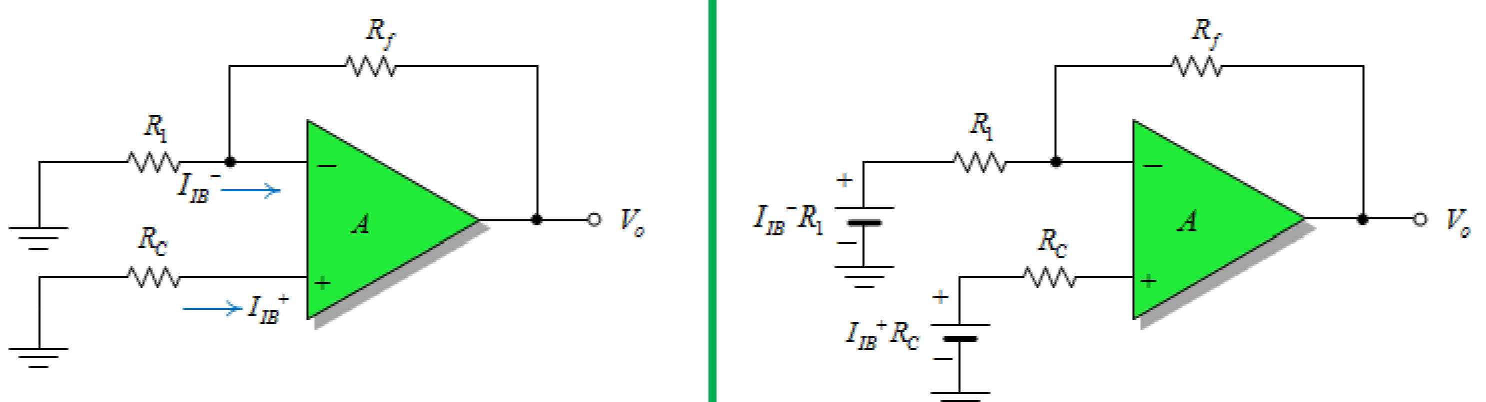
$$\Rightarrow V_o(\text{offset}) = (1.2\,\text{mV})\left(\frac{2\,\text{k}\Omega + 150\,\text{k}\Omega}{2\,\text{k}\Omega}\right)$$

$$V_o(\text{offset}) = 91.2\,\text{mV}$$

Inverting Circuit Applications

Output Offset Voltage Due to Input Offset Current

- An output offset voltage will also result due to any difference in dc bias currents at both inputs.
- Since the two input transistors are never exactly matched, each will operate at a slightly different current.
- Consider a typical op-amp connection in Fig. 16a, an output offset voltage can be determined as follows.



(a) Op-amp ckt showing input bias currents.

(b) Redrawn ckt.

Fig. 16:

Inverting Circuit Applications

- Replacing the bias currents through the input resistors by the voltage drop that each develops as shown in Fig. 14b, we can determine the expression for the resulting output voltage.
- By superposition, we see that the output voltage due to the input bias current I_{IB}^{+} denoted by V_o^{+} is given by

$$V_o^{+} = I_{IB}^{+} R_C \left(1 + \frac{R_f}{R_1} \right) \qquad [25]$$

- whereas the output voltage due to only I_{IB}^{-}, denoted by V_o^{-}, is given by

$$V_o^{-} = I_{IB}^{-} R_1 \left(-\frac{R_f}{R_1} \right) \qquad [26]$$

- Thus, the total offset voltage is

$$V_o \left(\text{offset due to } I_{IB}^{+} \text{ and } I_{IB}^{-} \right) = I_{IB}^{+} R_C \left(1 + \frac{R_f}{R_1} \right) - I_{IB}^{-} R_1 \left(\frac{R_f}{R_1} \right) \qquad [27]$$

Inverting Circuit Applications

- Since the main consideration is the difference between the input bias currents rather than each value, we define the offset current I_{IO} by

$$I_{IO} = I_{IB}^{+} - I_{IB}^{-} \qquad [28]$$

- Since the compensating resistance R_C is usually approximately equal to the value of R_1, using $R_C = R_1$ in Eq. [27], we can write

$$\begin{aligned} V_o(\text{offset}) &= I_{IB}^{+}\left(R_1 + R_f\right) - I_{IB}^{-}R_f \\ &= I_{IB}^{+}R_f - I_{IB}^{-}R_f = R_f\left(I_{IB}^{+} - I_{IB}^{-}\right) \end{aligned} \qquad [29]$$

- Resulting in

$$V_o(\text{offset due to } I_{IO}) = I_{IO}R_f \qquad [30]$$

[Example 8.5] Inverting Circuit Applications

- Calculate the offset voltage of the ckt in Fig. 14 for the op-amp spec listing $I_{IO} = 100\,\text{nA}$.

[Solution] Using Eq. [30], $V_o = I_{IO} R_f = (100\,\text{nA})(150\,\text{k}\Omega) = 15\,\text{mV}$

Total Offset Due to V_{IO} and I_{IO} .

- The total offset voltage due to both factors covered above can be expressed as

$$|V_o(\text{offset})| = |V_o(\text{offset due to } V_{IO})| + |V_o(\text{offset due to } I_{IO})| \quad [31]$$

- The absolute magnitude is used to accommodate the fact that the offset polarity may be either positive or negative.
- **Input Bias Current**, I_{IB} . A parameter related to I_{IO} and the separate input currents I_{IB}^{+} and I_{IB}^{-} is the average current defined as

$$I_{IB} = \frac{I_{IB}^{+} + I_{IB}^{-}}{2} \quad [32]$$

Inverting Circuit Applications

- One could determine the separate input bias currents using the specified I_{IO} and I_{IB}. It can be shown that for $I_{IB}^{+} > I_{IB}^{-}$

$$I_{IB}^{+} = I_{IB} + \frac{I_{IO}}{2} \quad \text{and} \quad I_{IB}^{-} = I_{IB} - \frac{I_{IO}}{2} \qquad [33]$$

End of Lecture 8

Thank you for your attention!