ECE 203

Circuits I

Op-amps

Lecture 5-2

Chapter 5: The Operational Amplifier

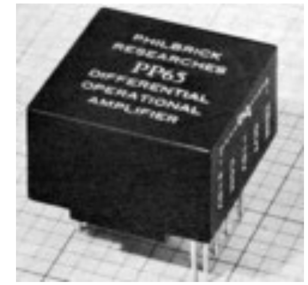
Op Amp = Operational Amplifier

A complex circuit, but for our purposes, can be analyzed using simplifying assumptions.

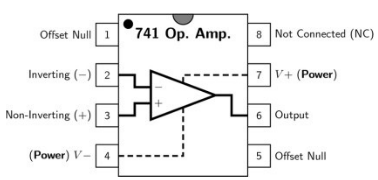
Operational Amplifiers (Op Amps)

1941 Bell Labs Patent

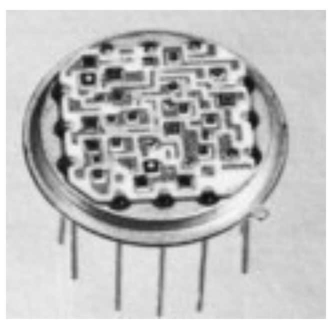
1961



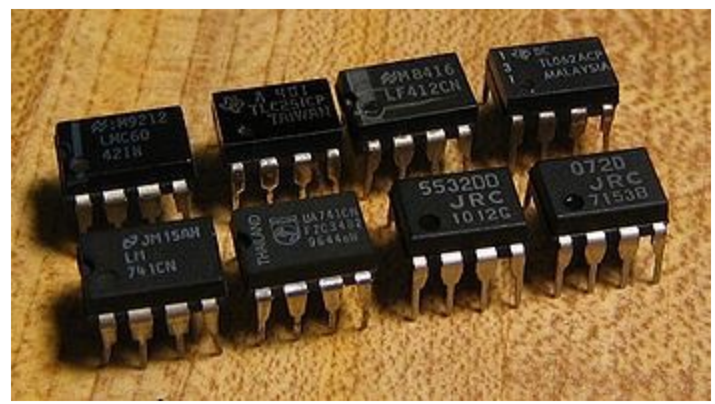
1962



1963



1979



Today

Introduction

☐ What is an Op-Amp?

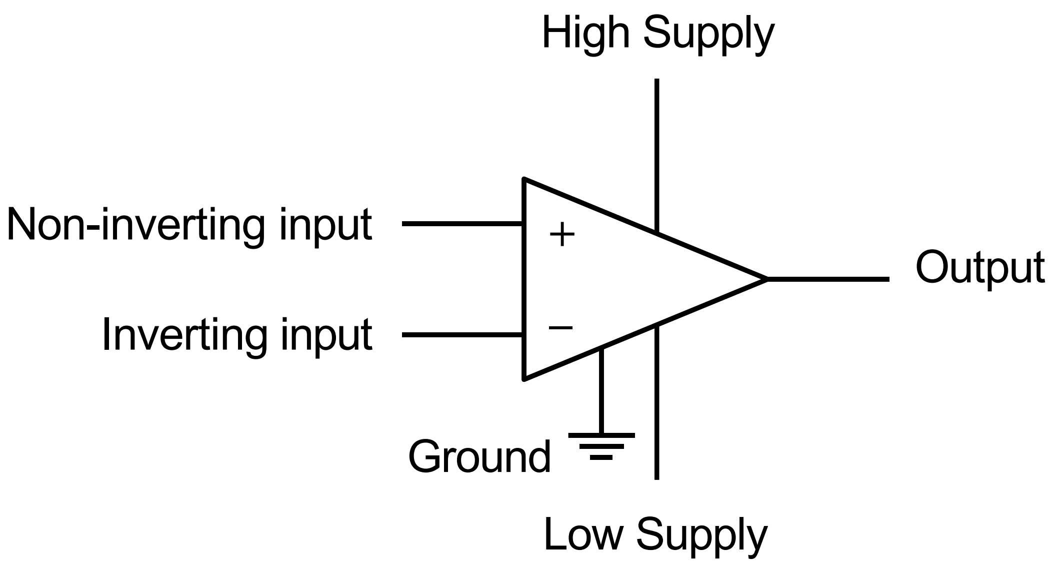
- Op-Amp is short for "operational amplifier".
- It is an integrated circuit (IC) originally used to perform some *mathematical operations*, such as addition, subtraction, differentiation, and integration.
- That's why it is called an operational amplifier!

☐ How Op-Amps are built?

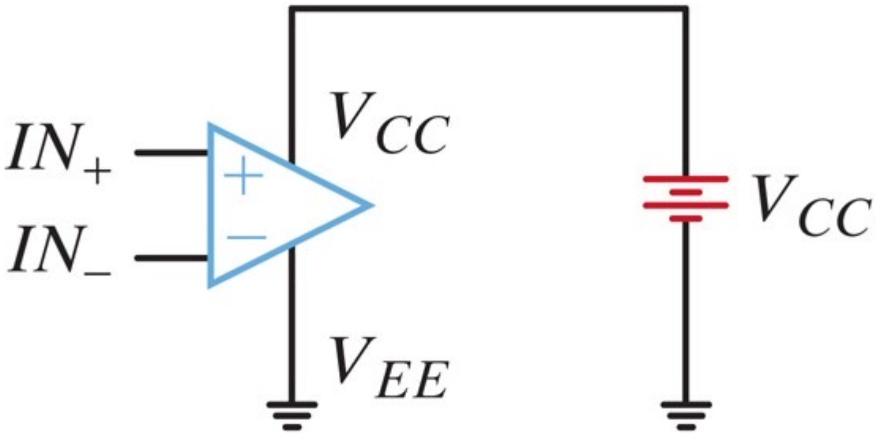
- They are built using transistors in an integrated circuit.

What is an Op-Amp?

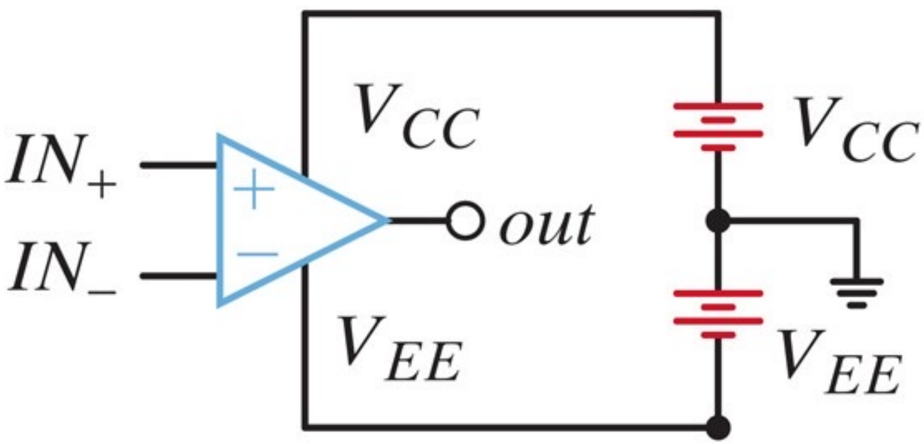
- **The Op-Amp is an "active" element with a high gain that is designed to be used with other circuit elements to perform signal processing operations.**
- **It requires power supplies, sometimes a single supply, sometimes positive and negative supplies.**
- **It has two inputs and a single output.**



Op-Amp Power Supply Configurations



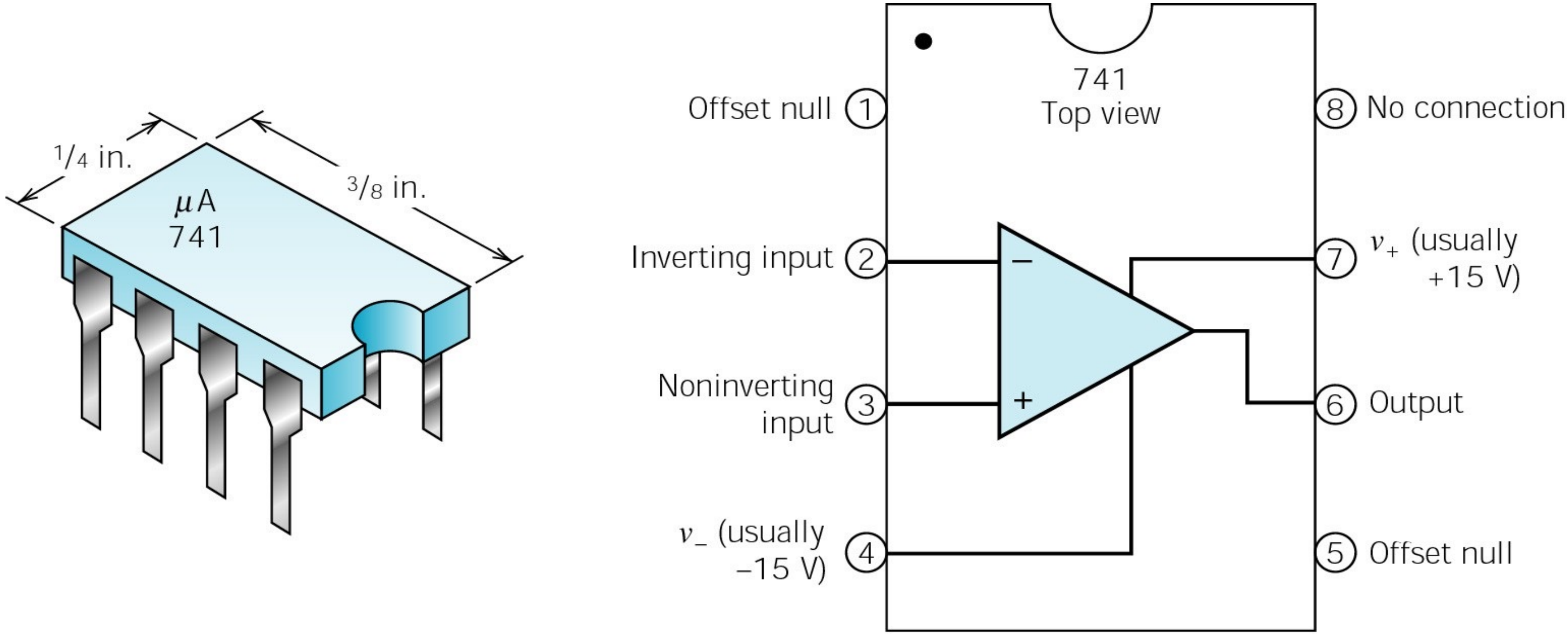
Single-supply implementation



Dual-supply implementation

UA 741: A standard Off-The-Shelf Op-Amp

(*a*) A μA741 integrated circuit has eight connecting pins. (*b*) The correspondence between the circles pin numbers of the integrated circuit and the nodes of the operational amplifier.



(*a*) (*b*)

How Can We Model Op-Amps?

- Op-Amp is an Amplifier.
- So the output voltage is an amplified version of the inputs

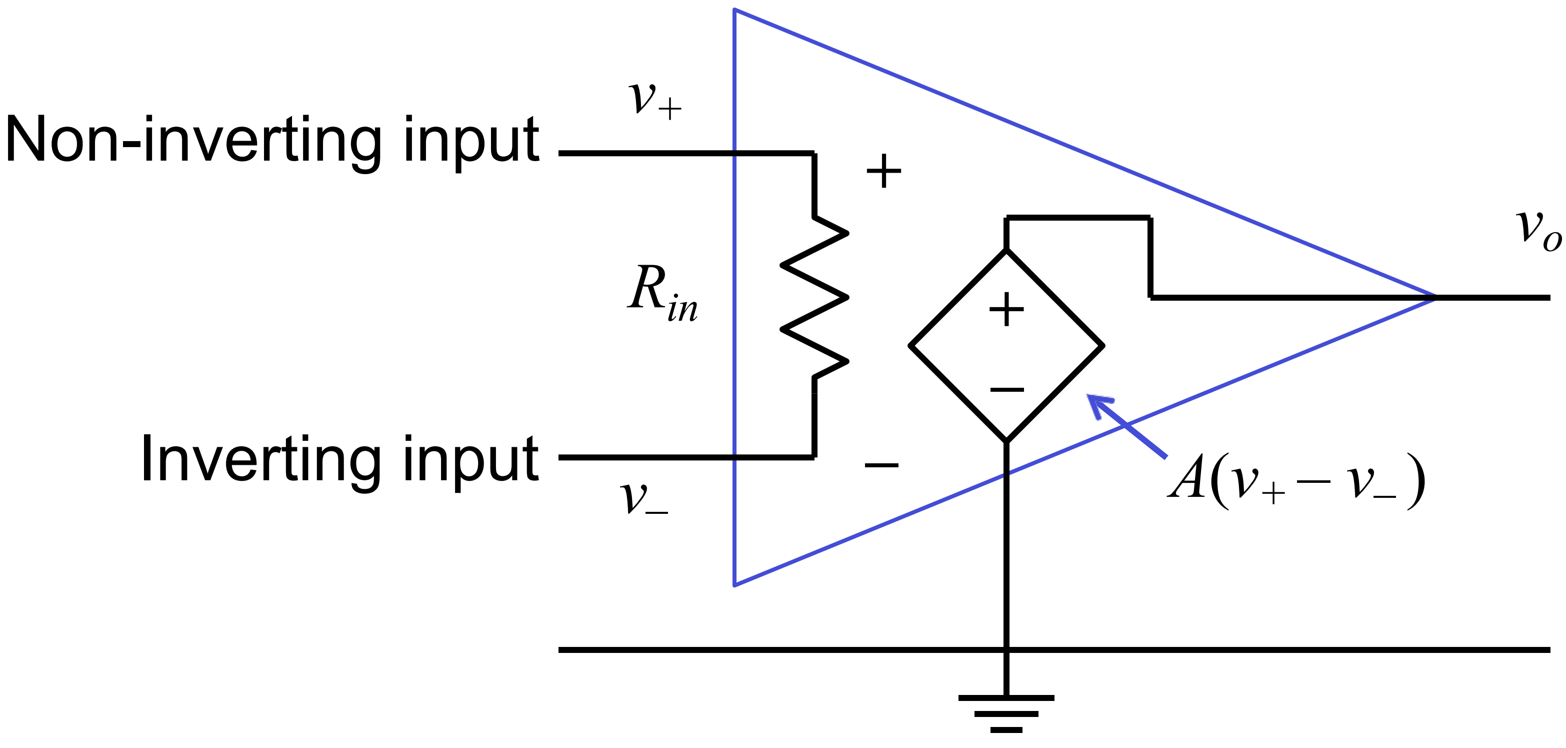
$$V_o = A_o(IN_+ - IN_-)$$

In this equation, A_o is the amplification (or gain), IN_+ is the voltage at the non-inverting input and IN_- is the voltage at the inverting input.

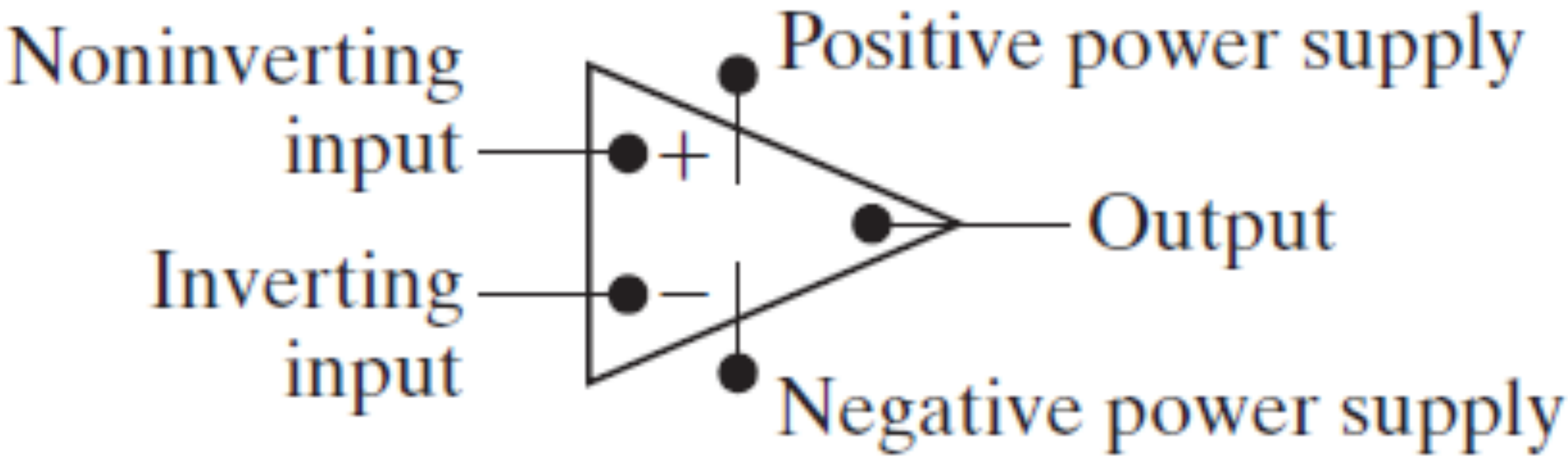
- V_o can be easily modeled with a “dependent voltage source”

A Circuit Model for Op-Amp

- An operational amplifier is modeled as a voltage-controlled voltage source.



The Circuit Symbol for Op-Amp



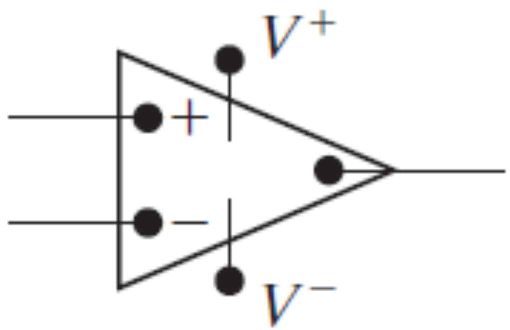
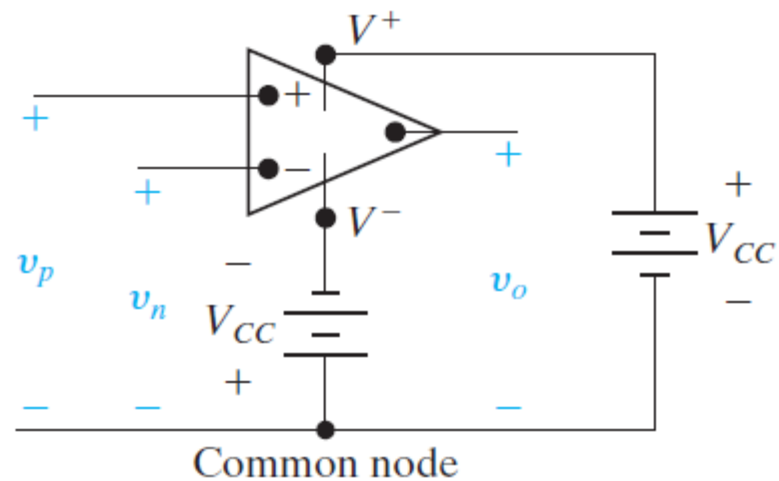


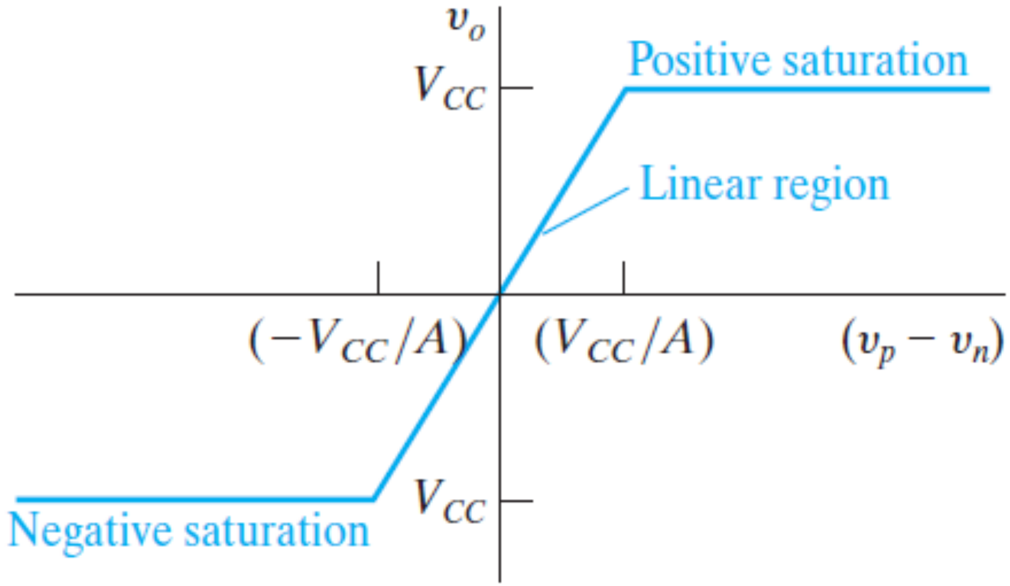
Figure 5.3: A simplified circuit symbol for an op amp.

Terminal Voltage Variables

- All voltages are considered as voltage rises from the common node, a convention we also used in the node-voltage analysis method.
- A positive supply voltage (V_{CC}) is connected between V^+ and the common node.
- A negative supply voltage ($-V_{CC}$) is connected between V^- and the common node.
- The voltage between the inverting input terminal and the common node is denoted $\mathbf{v_n}$
- The voltage between the noninverting input terminal and the common node is designated as $\mathbf{v_p}$
- The voltage between the output terminal and the common node is denoted $\mathbf{v_o}$



The voltage transfer characteristic of an op amp.



Typical versus Ideal Op-Amp

Typical Op Amp:

1. The input resistance (impedance) R_{in} is very large (practically infinite).
2. The voltage gain A is very large (practically infinite).
3. Output resistance is a few tens of Ohms.

Ideal Op Amp:

1. The input resistance is infinite.
2. The gain is infinite.
3. The output resistance is zero.

Consequences of the Ideal Op-Amp

- Infinite input resistance means the current into the inputs is zero:

$$i_- = 0; \mathrm{i}_+ = 0$$

- Infinite gain means the difference between v_+ and v_- is zero:

$$\mathrm{v_o = A_o\,(v_+ - v_-)}$$

$$\mathrm{v_+ - v_- = v_o/A_o}$$

If A_o = infinity, then:

$$v_+ - v_- = 0$$

This means $\mathrm{v_+ = v_-}$

- Zero output resistance: $R_{out} = 0$

Ideal versus Practical Op-Amp

characteristic	ideal	practical	sample
Bias current	0	> 0	0.012 - 80 nA
Input resistance	infinite	finite	2 - 10^6 MΩ
Output resistance	0	> 0	60 – 1 kΩ
Differential gain	infinite	finite	100-5000V/mV
Current saturation	infinite	finite	2 – 30 mA

Practical Op-Amp Datasheet

TABLE 4.1 A list of commercial op-amps and their model values

MANUFACTURER	PART NO.	A_o (V/V)	R_i (MΩ)	R_o (Ω)	COMMENTS
National	LM324	100,000	1.0	20	General purpose, up to ± 16 V supplies, very inexpensive
National	LMC6492	50,000	10^7	150	Low voltage, rail-to-rail inputs and outputs†
Maxim	MAX4240	20,000	45	160	Micro-power (1.8 V supply @ 10 μA), rail-to-rail inputs and outputs
Apex	PA03	125,000	10^5	2	High-voltage, ± 75 V and high-output current capability, 30 A. That's 2 kW!

†Rail-to-rail is a trademark of Motorola Corporation. This feature is discussed further in the following paragraphs.

---

*Op-amps are available that have input and/or output voltage ranges beyond the supply rails. However, these devices constitute a very small percentage of the op-amp market and will not be discussed here.

These are some of the newer op amps

Op-Amp Circuit Analysis

Assumptions (constraints) when in linear operating region:

1) Since gain is infinite, $V^+ = V^-$
2) No current flowing into the V^+ or V^- inputs, $i^+ = i^-$
3) Output resistance is zero

Analyzing a Circuit with an Ideal Op Amp

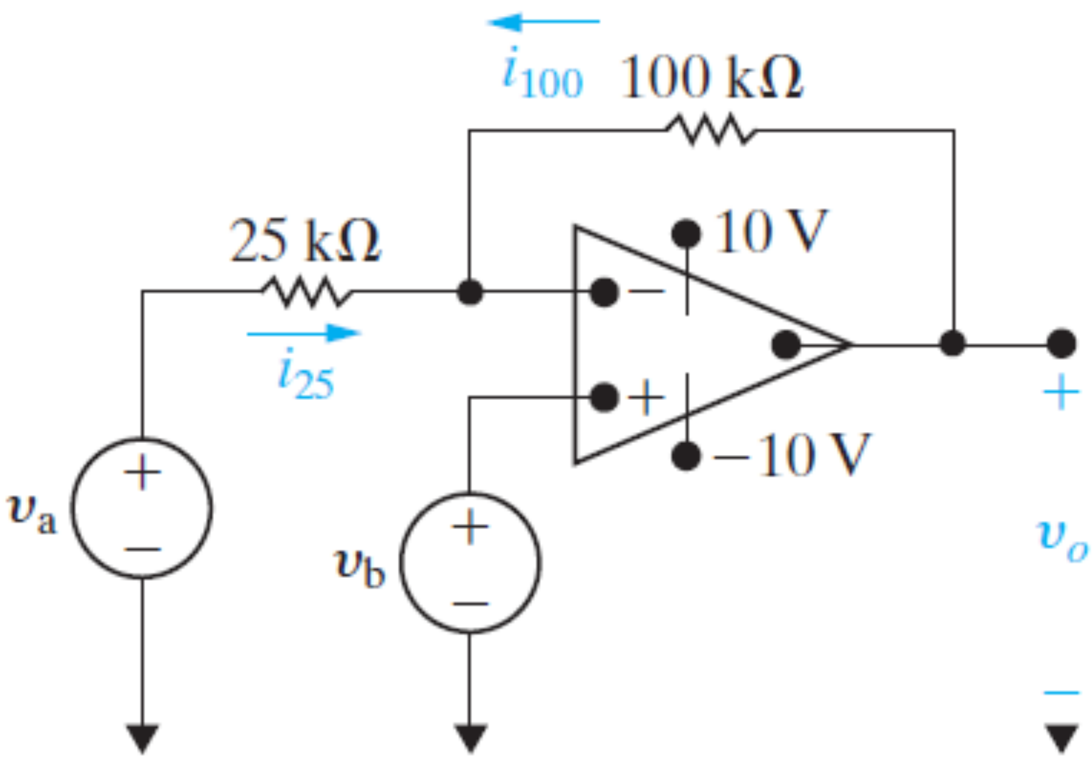
Step 1: Check for the presence of a negative feedback path; if it exists, we can assume the op amp is operating in its linear region.

Step 2: Write a KCL equation at the inverting input terminal, using the input current constraint (Eq. 5.3), the input voltage and Ohm's law to find the currents.
This equation will usually contain the unknown voltage at the op amp's output terminal.

Step 3: Solve the KCL equation and calculate the voltage at the op amp's output terminal.

Step 4: Compare the voltage at the op amp's output terminal to the power supply voltages to determine whether the op amp is actually in its linear region or whether it has saturated.

Op-Amp Example



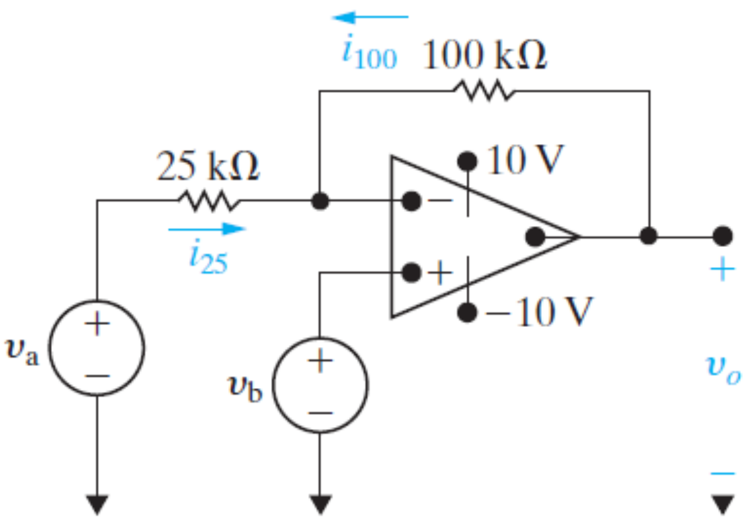
This op amp is ideal.

a. Calculate v_o if $v_a = 1$ V and $v_b = 0$ V.

b. Repeat (a) for $v_a = 1$ V and $v_b = 2$ V.

c. If $v_a = 1.5$ V, specify the range of v_b that avoids amplifier saturation.

Op-Amp Example



Op-Amp Example