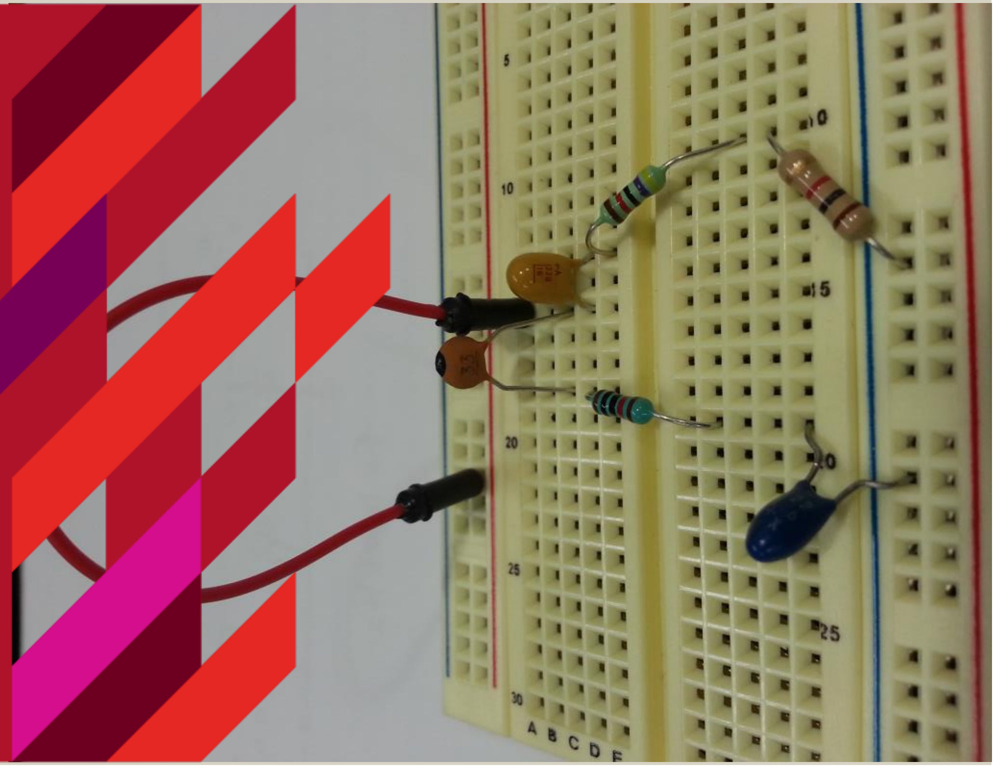
ELEC2070 Circuits and Devices

Week 3: Ideal Operational Amplifiers

Stuart Jackson

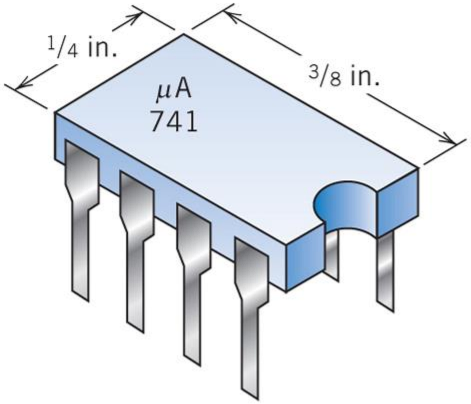


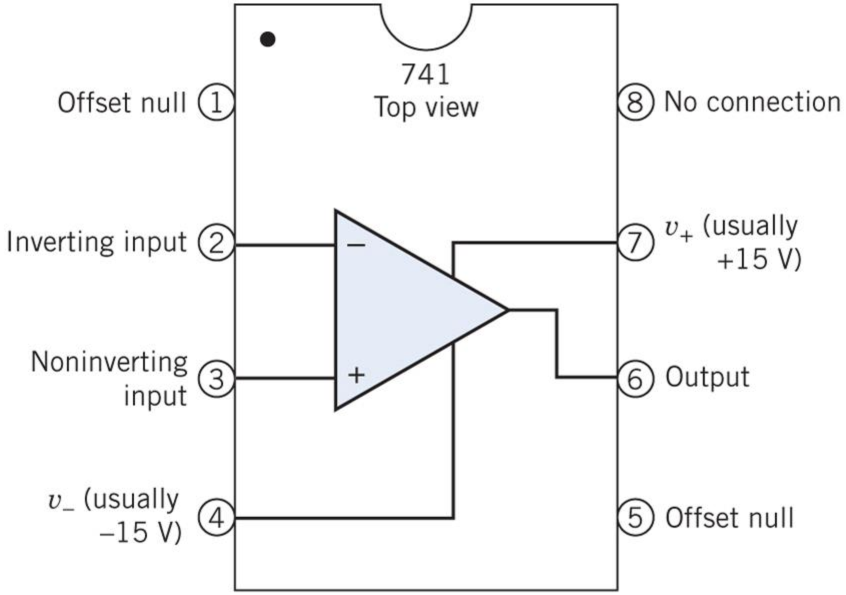
The “Big Ideas” in Chap. 6

- Operational amplifiers (or op amps) allow circuits to do “operations” (mathematical functions)
- In this lecture, we cover the basics of **ideal amplifiers**.
- Operational amplifiers are studied using Node Analysis
- Basic circuits for mathematical operations will be introduced

The operational amplifier

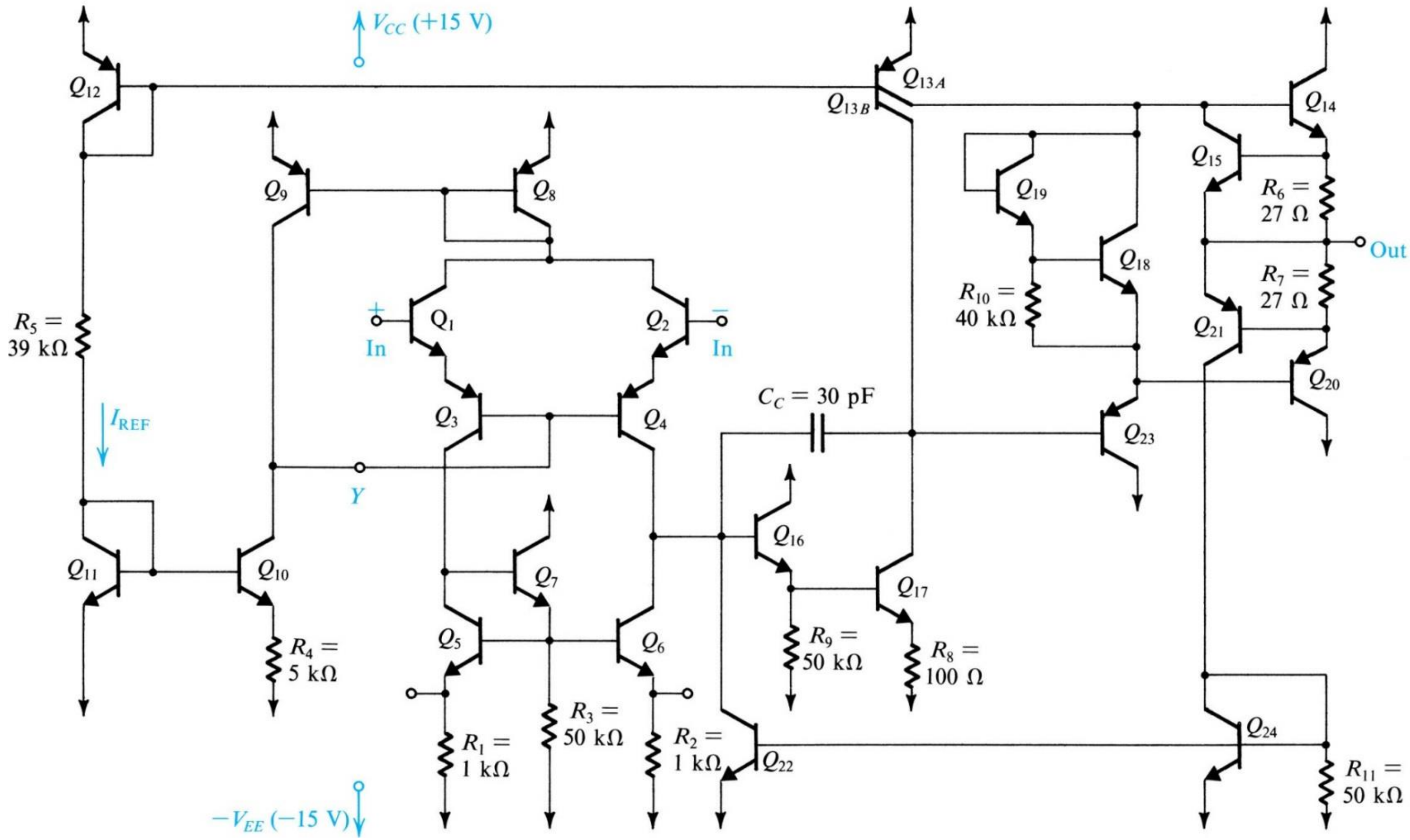
The most common op amp



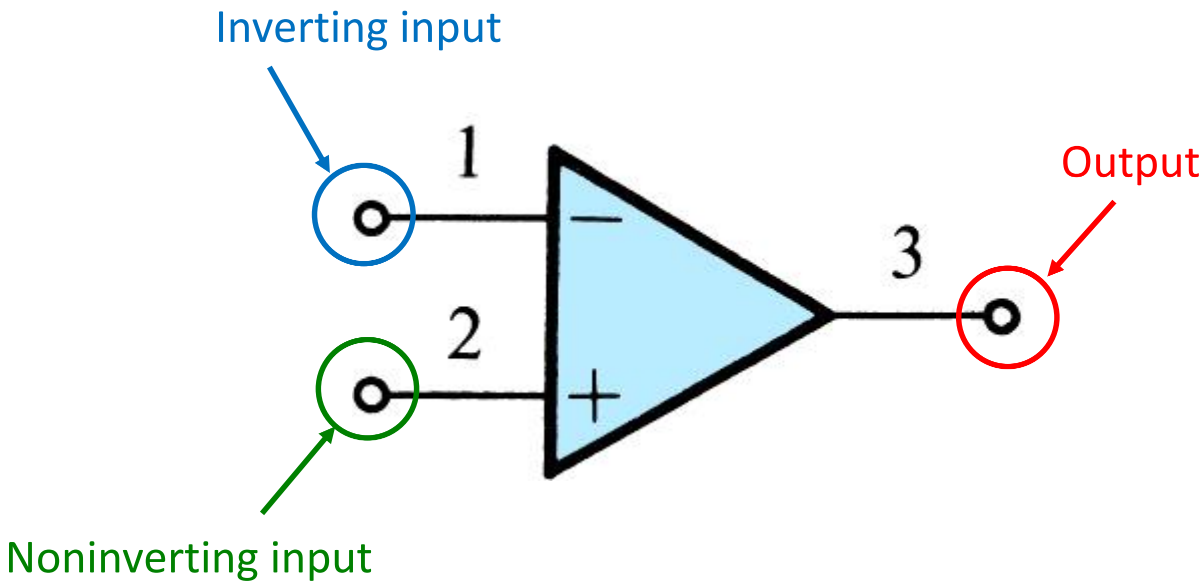


- Operational amplifiers are widely used in signal processing and control circuits.
- μA741 is the most common op amp.
- Op amps are **differential amplifiers**

The µA741 Circuit

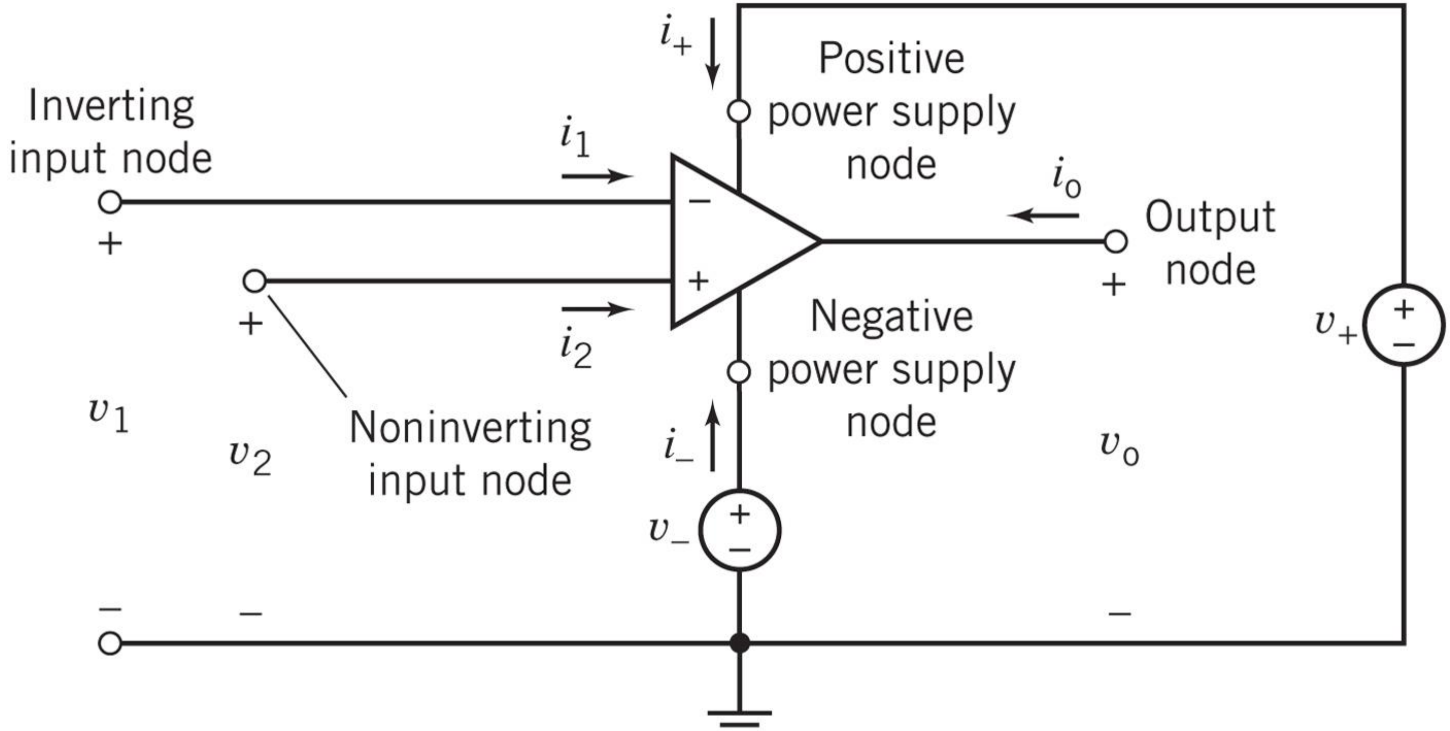


The op amp - definitions



In some circuit diagrams, the top terminal is the non-inverting input – be careful!

Op amp schematic



- The DC power supplies “bias” the op amp
- These are usually **not** included in the schematic
- The power supplies add energy (power) to a circuit

Use Node Analysis for op amps

1. Since we generally omit op amp power supplies - using KCL could create some problems
2. At the ground node: we have 2 currents involving the power supplies
   - cannot use KCL at ground node if power supplies are omitted!
3. At the op amp: applying KCL means

$$i_1 + i_2 + i_0 + i_+ + i_- = 0$$

Hence KCL won't work if power supplies omitted

USE Node Analysis instead for op amps

The ideal operational amplifier

Keeping the op amp in the "linear regime"

Data for μA741:

We need:

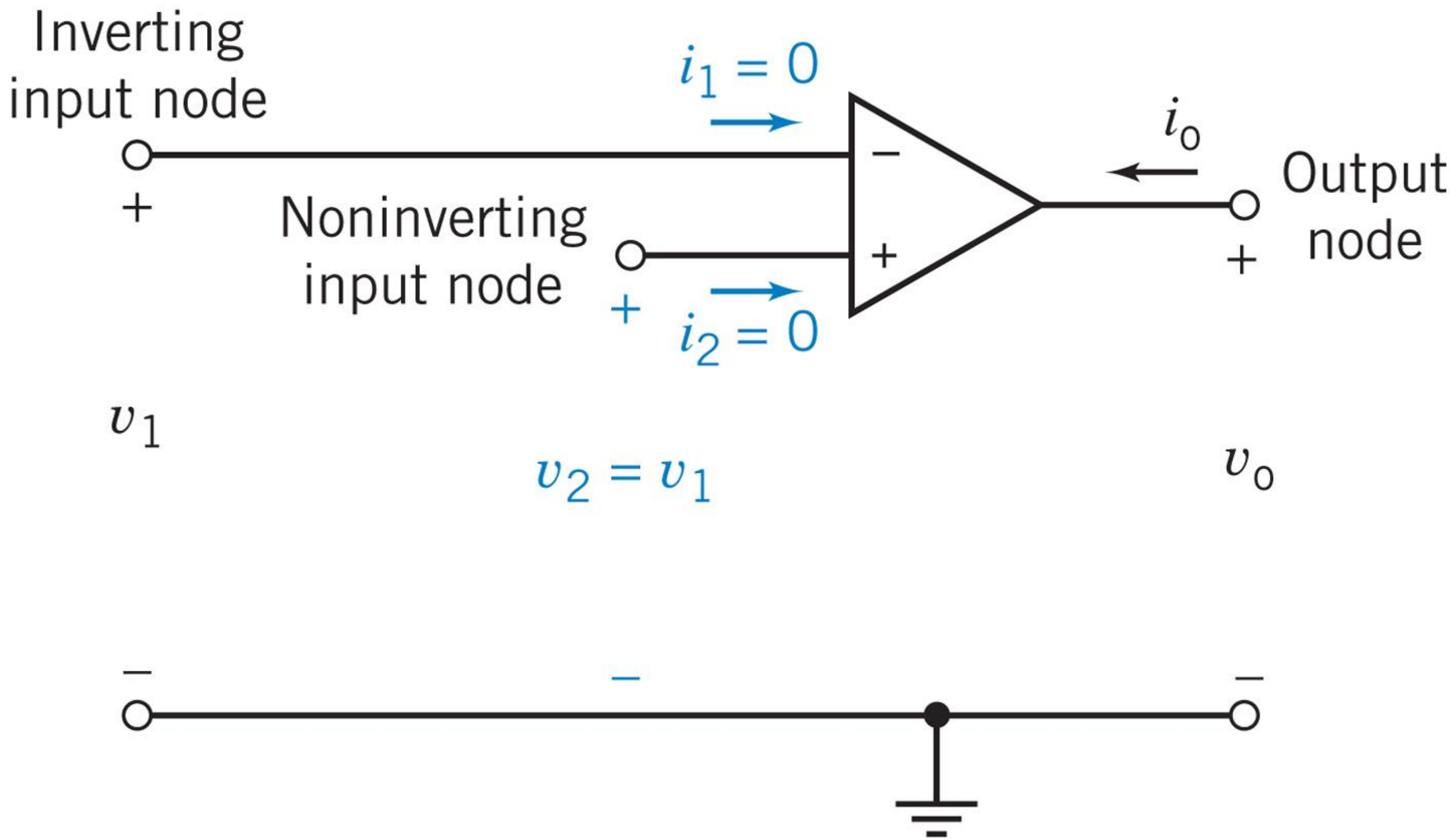
The output voltage: $$|v_o| \leq v_{sat}$$ 14 V

The output current: $$|i_o| \leq i_{sat}$$ 2 mA

The change in the output voltage $$\left|\frac{dv_o(t)}{dt}\right| \leq SR$$ The "slew rate" 500,000 V/s

We can use "ideal operational amplifier" conditions for all our calculations if we stay within these limits

The ideal operational amplifier



Operating conditions for an ideal op amp

VARIABLE	IDEAL CONDITION
Inverting node input current	$i_1 = 0$
Noninverting node input current	$i_2 = 0$
Voltage difference between inverting node voltage v_1 and noninverting node voltage v_2	$v_2 - v_1 = 0$

These conditions make Node Analysis of circuits with op amps easy!

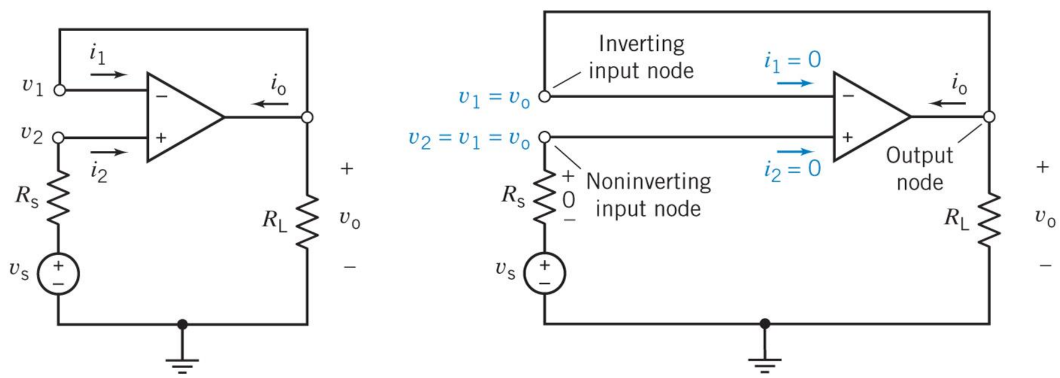
Remember: the ideal operational amplifier is a **model** for a linear operational amplifier

Input and output

As opposed to the circuits that we have studied so far, an op amp circuit always has an *output* that depends on some type of *input*. Therefore, we will analyze op amp circuits with the goal of obtaining an expression for the output in terms of the input quantities. *We will find that it is usually a good idea to begin the analysis of an op amp circuit at the input, and proceed from there.*

Example 6.3.1

Consider the circuit (a):



(a) (b)

How does the output voltage change with input voltage?

Figure (b) shows what we know from an ideal op amp. Note that $v_1 = v_0$ since they are connected via a short.

We can now express the voltage across R_s as:

$v_s – v_2 = v_s – v_1 = v_s – v_0$ therefore:

$v_s = v_0$ (because no current is flowing through R_S, since $i_2 = 0$)

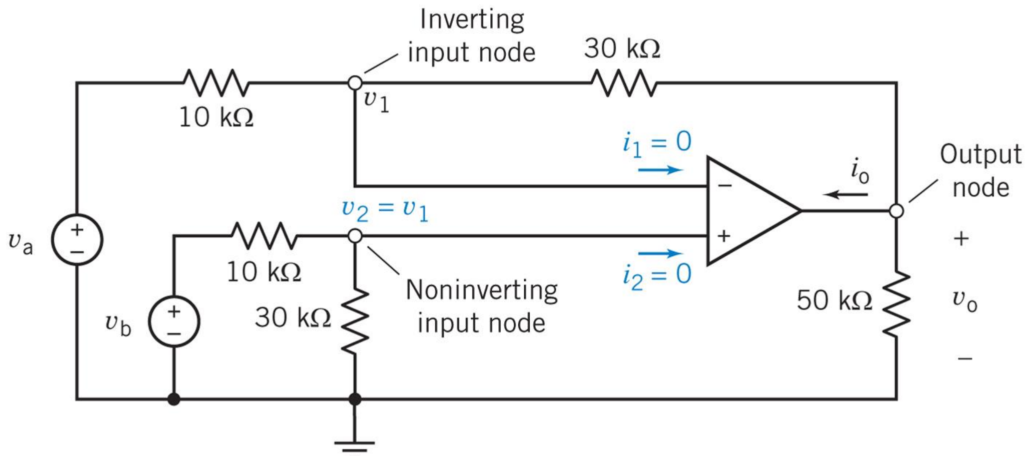
Node Analysis of circuits

For ideal op amps we can always say:

1. $v_1 = v_2$ hence we can eliminate v_1 or v_2 from the node equations
2. Inputs currents are always zero. This helps for node analysis of inputs
3. The output current is not zero and is always involved in a KCL equation at the output node.

Example 6.4.1

Consider the following difference amplifier:



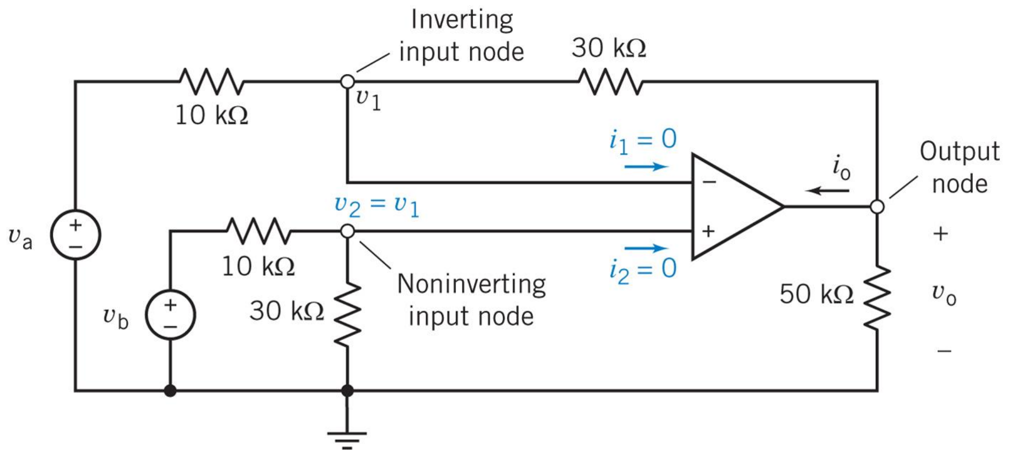
Find v_0 in terms of the two input voltages.

At the noninverting input node (and since $v_2 = v_1$) :

$$\frac{v_1}{30{,}000} + \frac{v_1 - v_b}{10{,}000} + i_2 = 0$$

Since i_2=0 we get $v_1 = \frac{3}{4} v_b$

Example 6.4.1



At the inverting input node:

$$\frac{v_1 - v_a}{10{,}000} + \frac{v_1 - v_0}{30{,}000} + i_1 = 0,$$

Of course i_1=0 so

$$v_0 = 4v_1 - 3v_a$$

and since $v_1 = \frac{3}{4} v_b$ we get

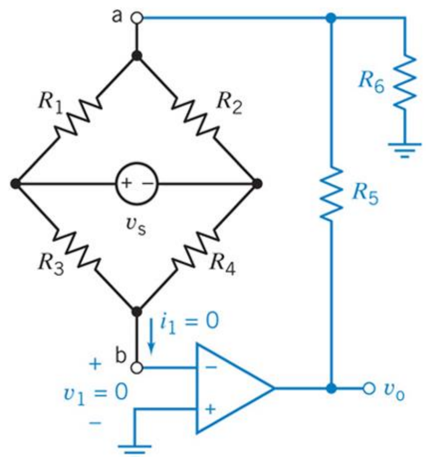
$$v_0 = 3(v_b - v_a)$$

Example 6.4.2

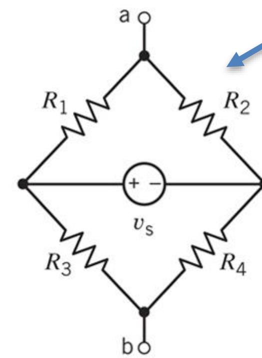
Consider a bridge amplifier:

The resistors R_5 and R_6 are used to amplify the output of the bridge.

Determine the output voltage versus the input voltage.



(a)

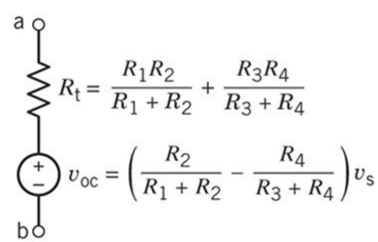


(b)

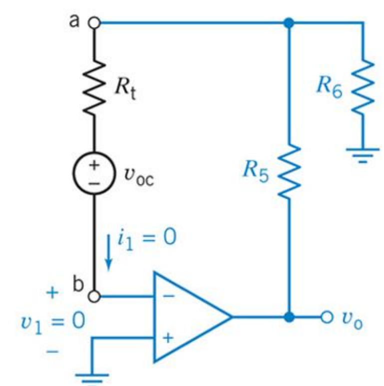
This is the bridge

Solution:

Find Thevenin circuit for the bridge circuit.



(c)



(d)

Hint: Find v_{oc} using mesh analysis.
Find R_{th} by switching off v_s

Example 6.4.2

Now we have a simple circuit which we can apply Node Analysis

Now $v_b = v_1 = 0$

And $v_a = v_1 + v_{oc} + i_1 R_t$
but $i_1 = 0$
Hence $v_a = v_{oc}$

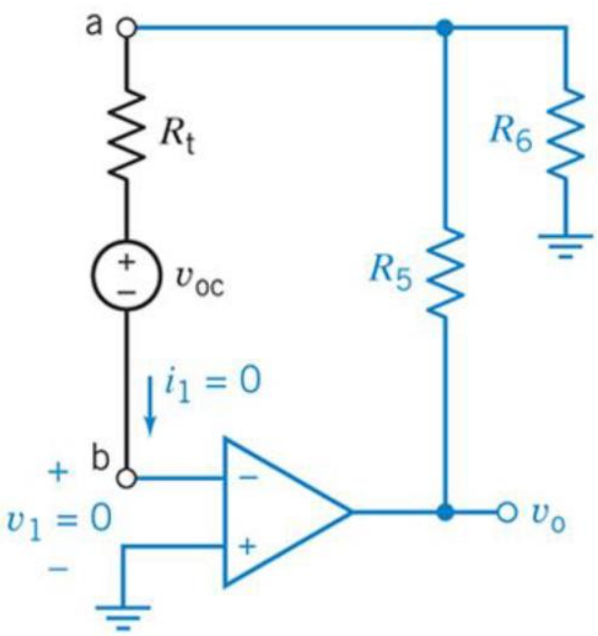
Node equation at node a:

$i_1 + (v_a - v_0)/R_5 + v_a/R_6 = 0$

Substituting from above: $(v_{oc} - v_0)/R_5 + v_{oc}/R_6 = 0$

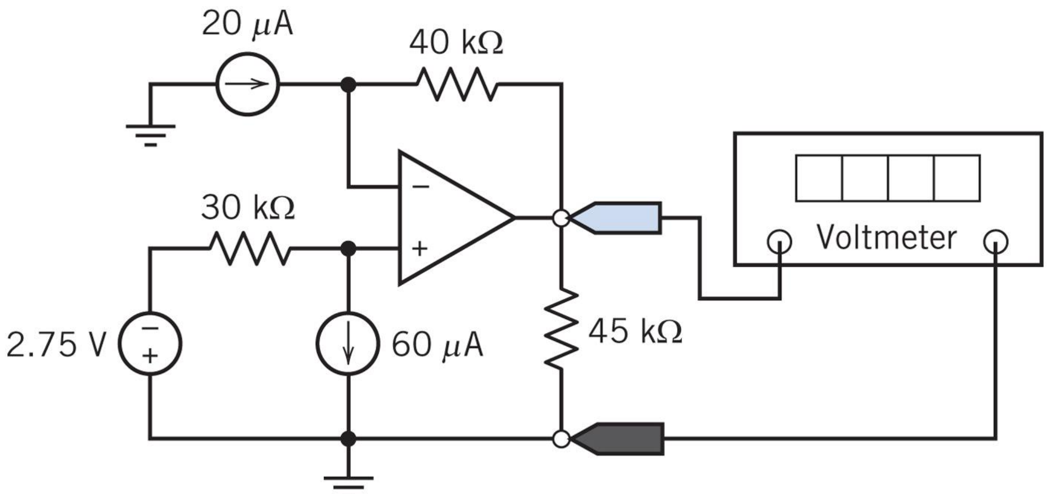
Hence $v_0 = v_{oc}(1+R_5/R_6)$

You can now substitute the expression for v_{oc} to find v_0 in terms of v_s



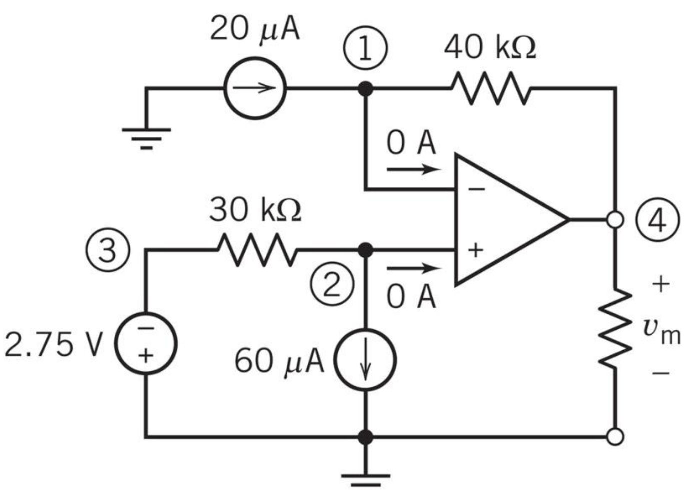
Example 6.4.3

We need to determine the voltage measured by the voltmeter for this circuit



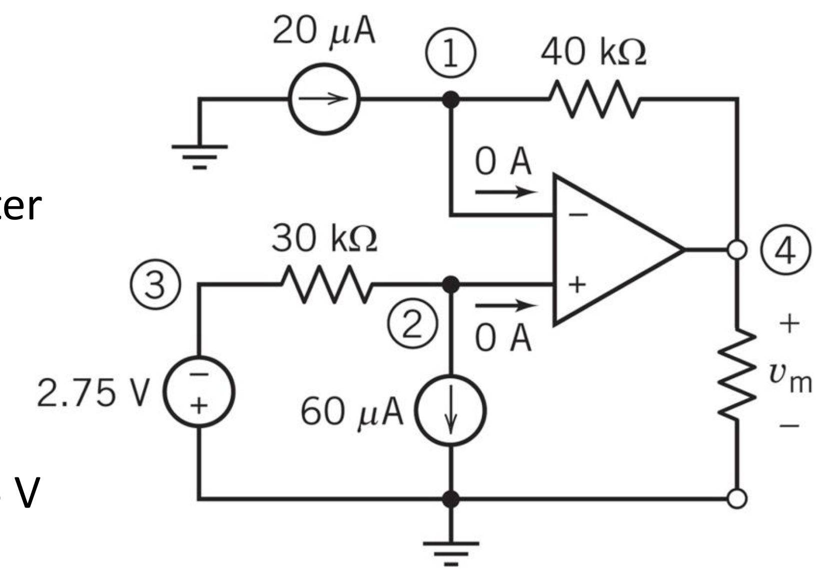
This is easy since we are dealing with an ideal op amp

The circuit we are dealing with looks like:



Example 6.4.3

In this circuit we have labelled 4 nodes with the voltages: v_1, v_2, v_3, v_4



Of course v_m is the output measured by the voltmeter and $v_m = v_4$

We can also see that $v_3 = -2.75$ V

KCL at node 2: $(v_3 – v_2)/30{,}000=60\text{x}10^{-6}$ or $v_2 = -4.55$ V

Since the 2 input voltages are equal, $v_1 = -4.55$V

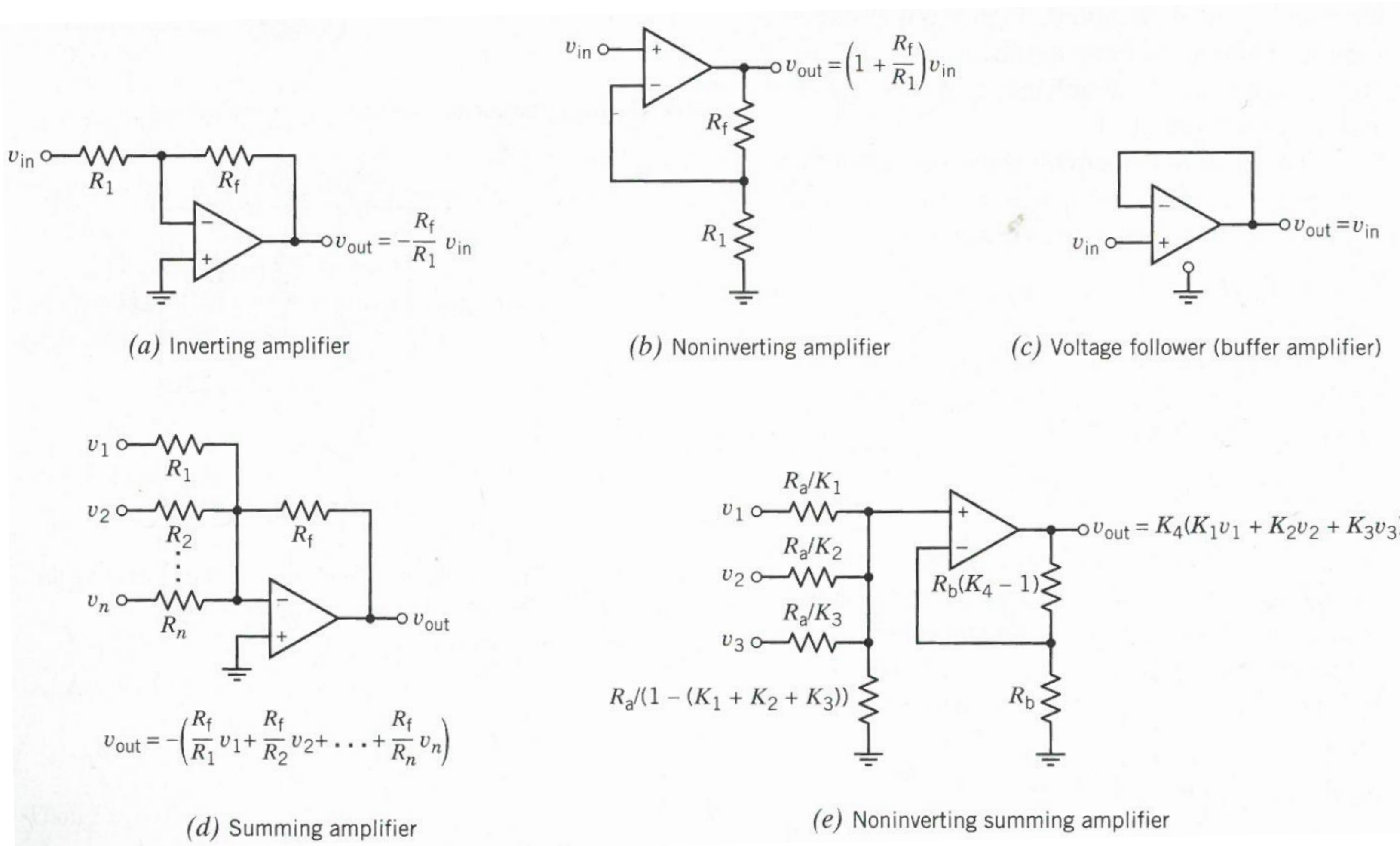
Doing KCL at node 1: $20\text{x}10^{-6} = (v_1 - v_4)/40{,}000$

Or $v_4 = -5.35$ V (since $v_1 = -4.55$V)

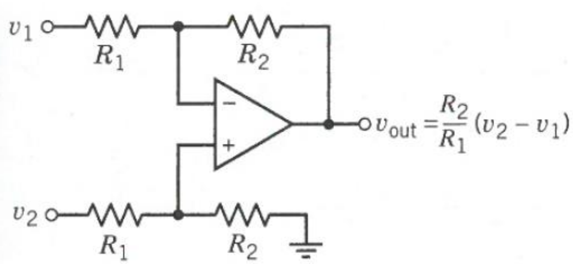
This is what the voltmeter will read.

Designing circuits using op amps

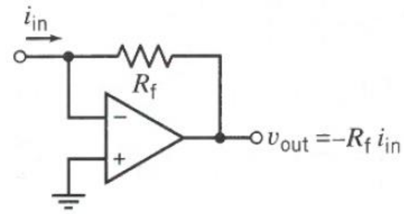
Functional op amp circuits



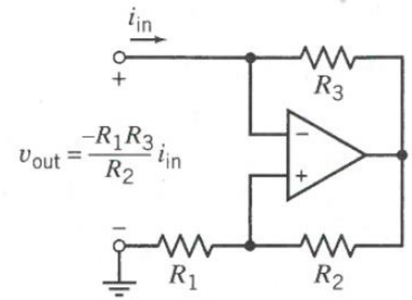
Functional op amp circuits



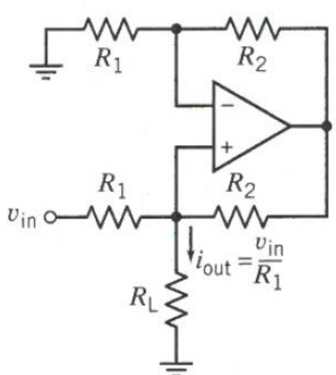
(f) Difference amplifier



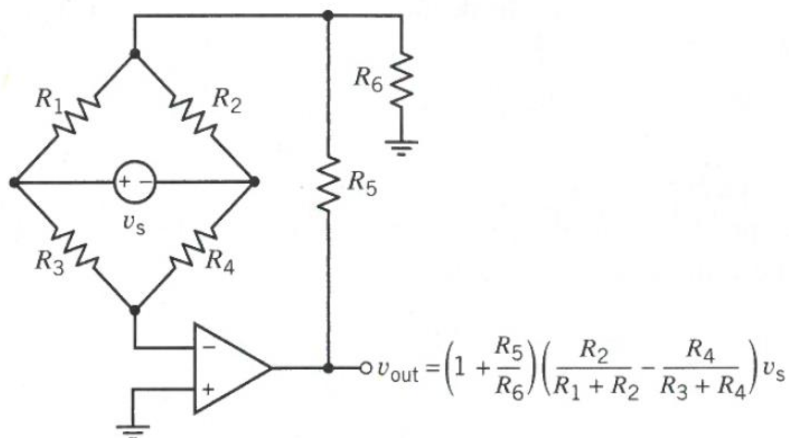
(g) Current-to-voltage converter



(h) Negative resistance convertor



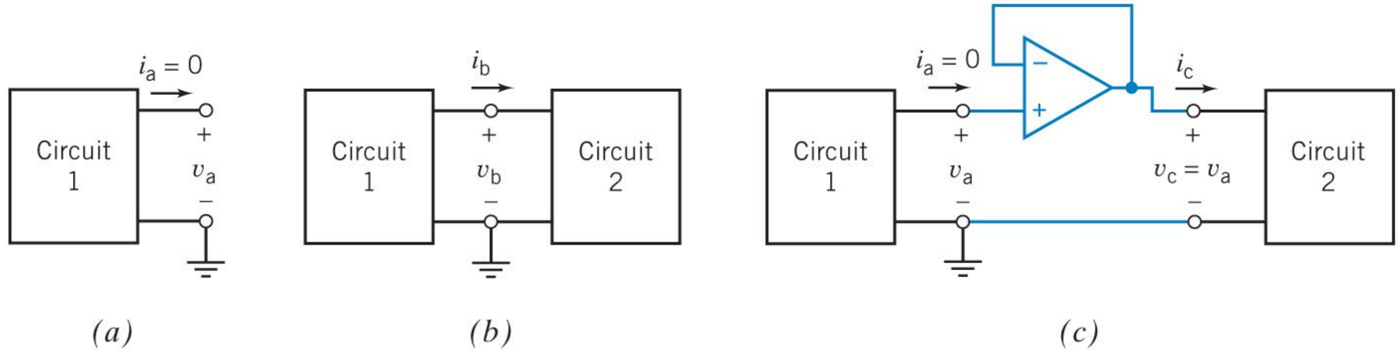
(i) Voltage-controlled current source (VCCS)



(j) Bridge amplifier

Let's look at some examples

Voltage follower

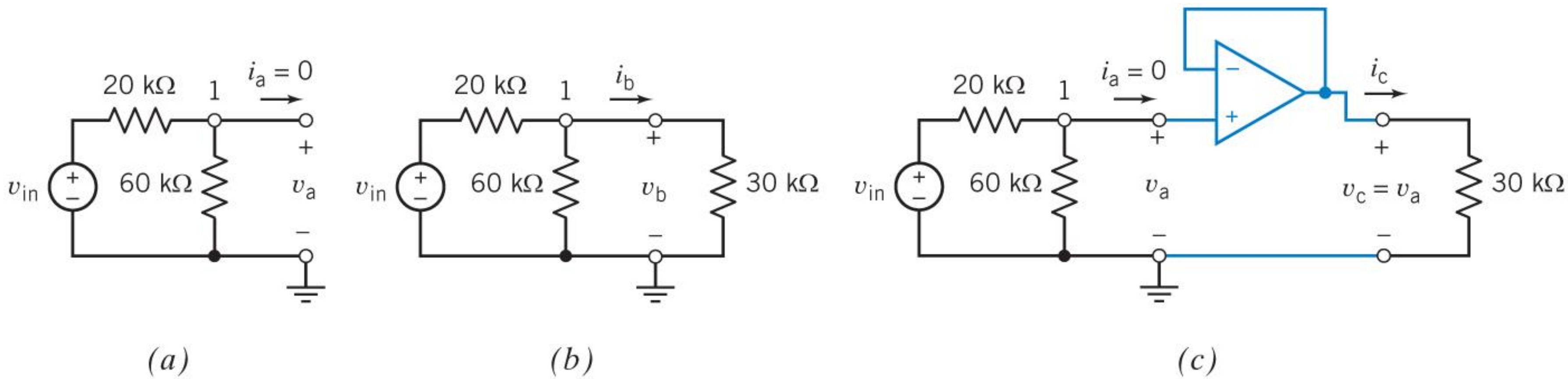


One of the problems when circuit 1 is connected to circuit 2 is **loading**.

Or we have $v_a \neq v_b$ (circuit 2 **loads** circuit 1 and i_b is the **load current**)

Therefore we need a design a solution: use a **voltage follower** – copies the voltage

Example 6.5.1



In this circuit (a) we can apply KCL at node 1:

$(v_a - v_{in})/20{,}000 + v_a / 60{,}000 + i_a = 0$

Or $v_a = 0.75\ v_{in}$

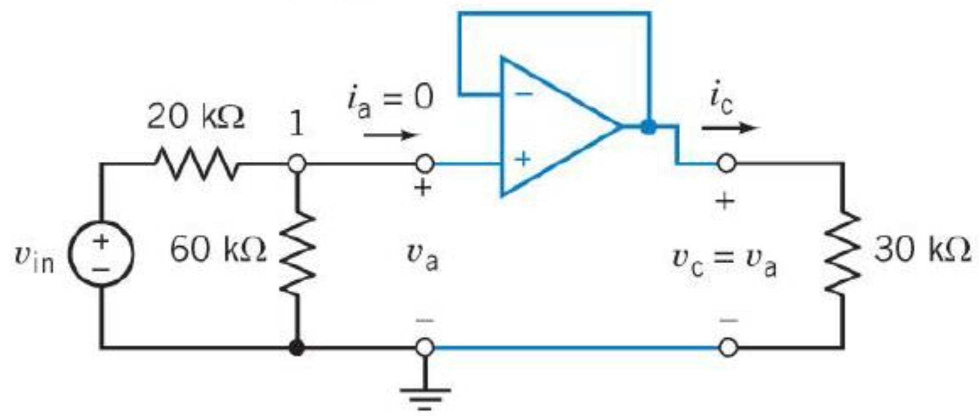
If we connect 30k resistor, i.e., circuit (b) we now have:

$(v_b - v_{in})/20{,}000 + v_b / 60{,}000 + v_b /30{,}000 = 0$ or $v_b = 0.5\ v_{in}$

- the loading comes from the new current in the resistor

Example 6.5.1

Now we can add a voltage follower:



At node 1:

$(v_a - v_{in})/20{,}000 + v_a/60{,}000 = 0$

Hence $v_a = 0.75\ v_{in}$ but $v_c = v_a$

Hence $v_c = 0.75\ v_{in}$

The voltage follower provides the current for the 30k resistor not the independent power supply v_{in} therefore keeping the voltage the SAME.

Power supplied to op amps

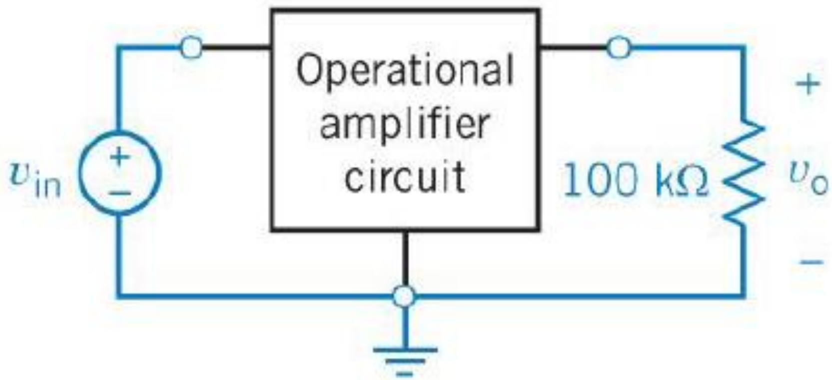
Q: If no current flows into or out of either input terminal of an op amp, why does current flow from the output?

A: In ELEC2070 (and for many other applications) we are treating op amps as an independent element (like a resistor) but in reality they are supplied with an independent power source!

Scaling a voltage

Want a circuit to create the following:

$v_o = K\, v_{in}$



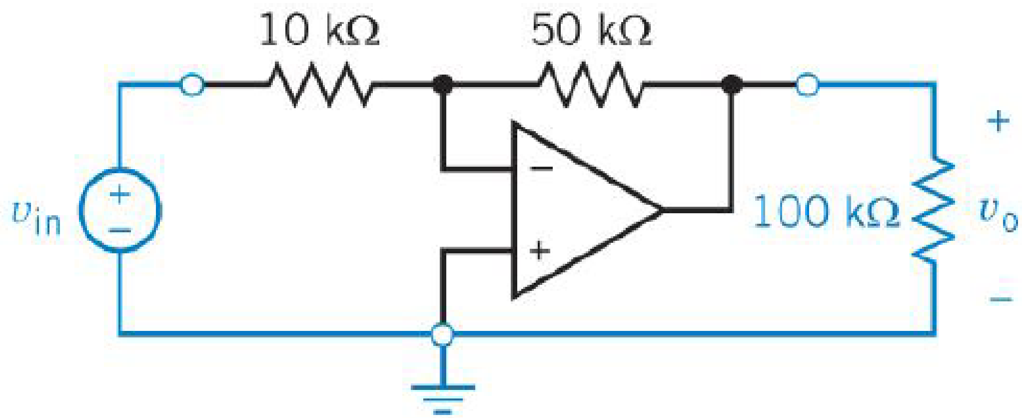
We want an amplifier circuit and K is called the **gain**. The gain can essentially be any number.

In general: Choose resistors in real op amp circuits between 5 kΩ and 500 kΩ (this is because the currents in IC's must be small)

Amplifiers

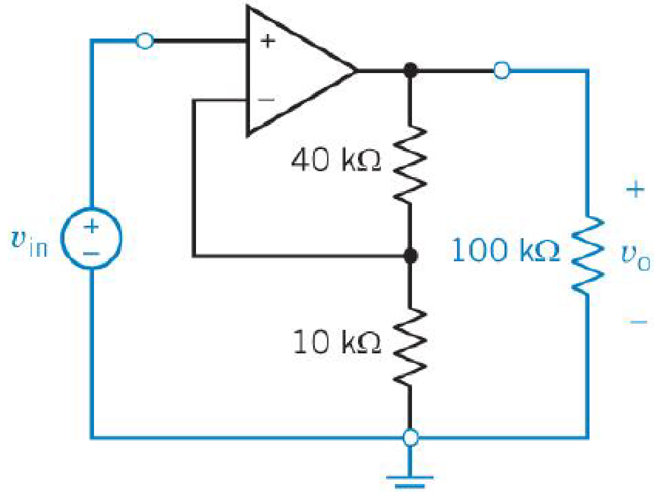
Inverting amplifier, where the gain is – R_f / R_1

K = -5



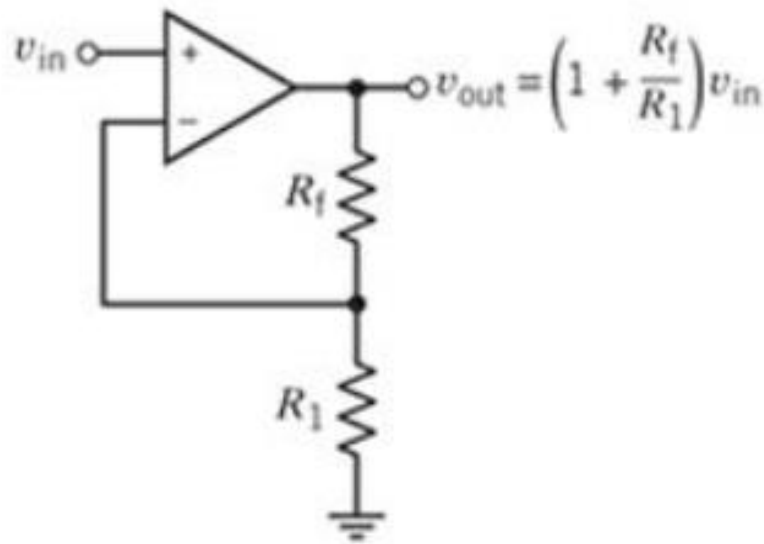
Noninverting amplifier, where the gain is (1+ R_f/R_1)

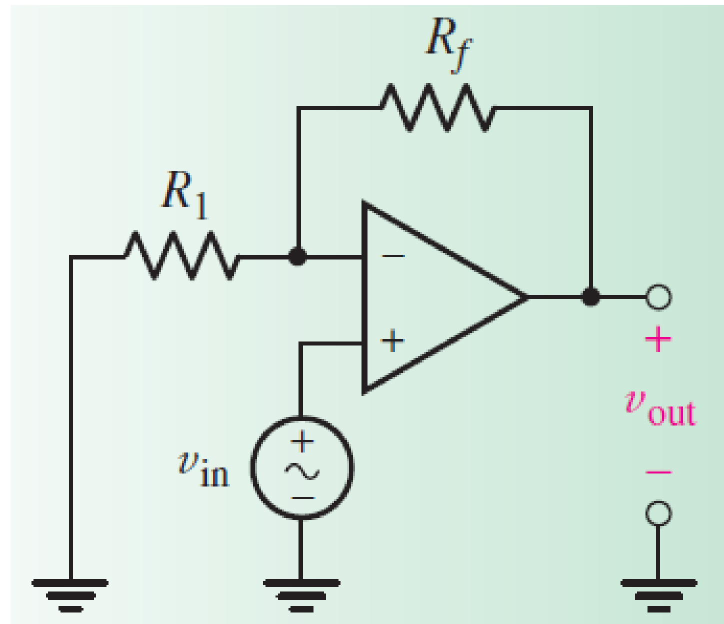
K = 5



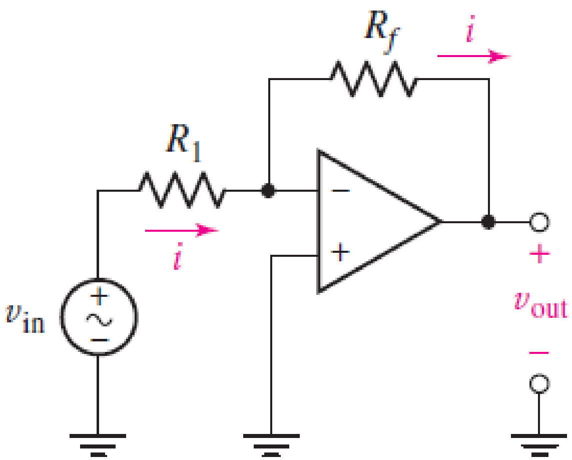
Top terminal (from each textbook)

For example, a noninverting amplifier.





Virtual ground

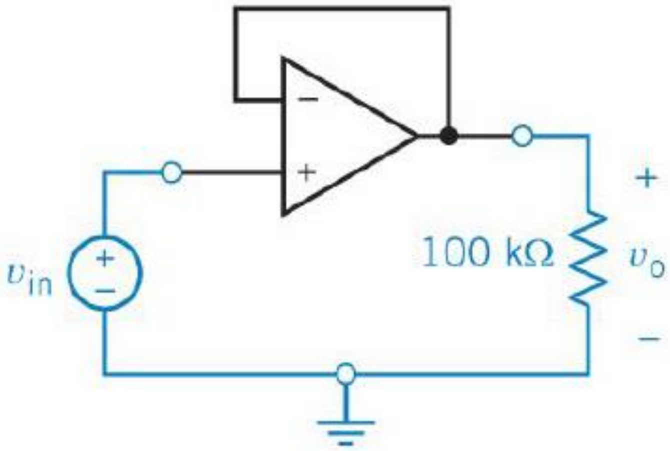


The fact that the inverting input terminal finds itself at zero volts in this type of circuit configuration leads to what is often referred to as a "virtual ground." This does not mean that the pin is actually grounded, which is sometimes a source of confusion for students. The op amp makes whatever internal adjustments are necessary to prevent a voltage difference between the input terminals. The input terminals are not shorted together.

Amplifiers

Voltage follower (buffer amplifier)
(same as R_f = 0, or R_1 = 0 in noninverting amp)

K = 1

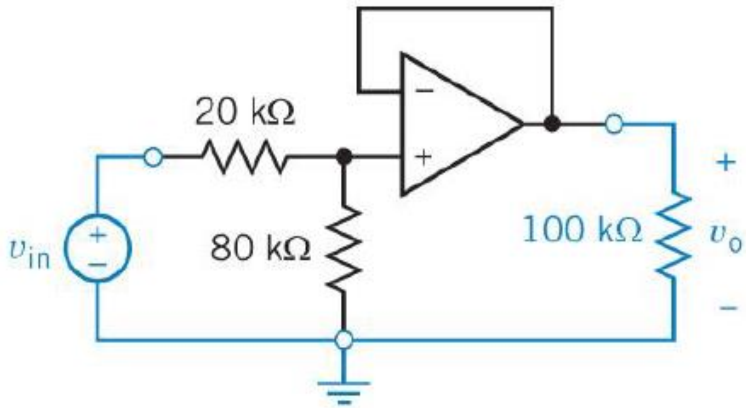


For gains 0<K<1 no amplifier exists but we can use:

Voltage divider + Follower

Here, K = 0.8

This arrangement could be called an attenuator



Using the noninverting summing amplifier

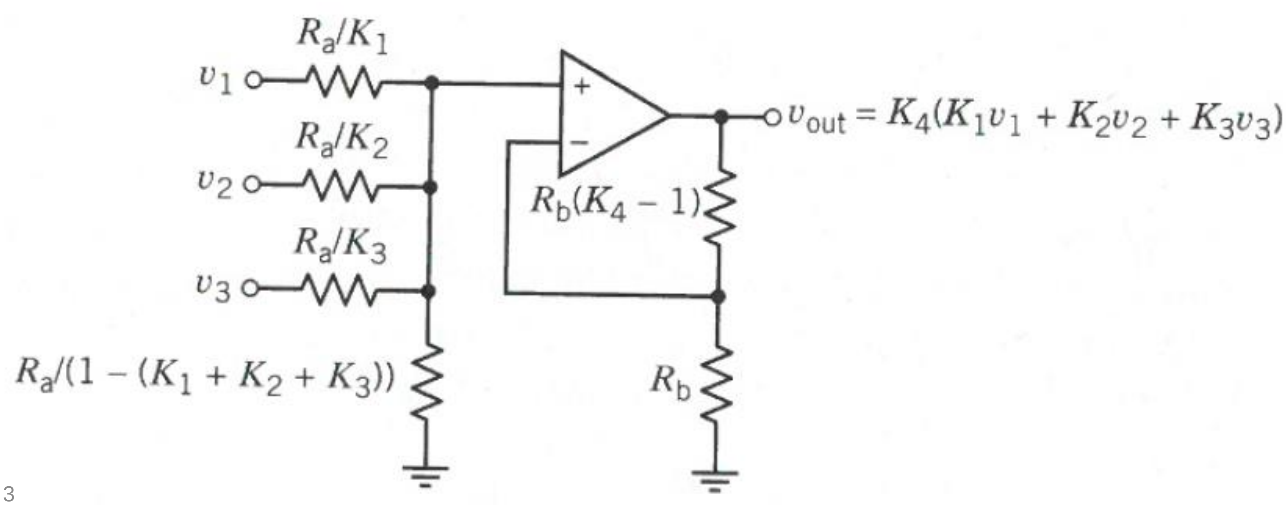
Want to achieve the following summation of voltages:

$v_0 = 2v_1 + 3v_2 + 4v_3$

Want inputs between -1 V and 1 V

Consider an op amp that has i_{sat} = 2 mA and v_{sat} = 15 V

Solution: The noninverting summing amplifier



Example 6.5.3

Want to achieve the following: $v_0 = 2v_1 + 3v_2 + 4v_3$
Need to choose the values for K_i (i=1,2,3) and R_a and R_b
We must have $K_1 + K_2 + K_3 < 1$ (so that the LH bottom resistor is not negative or infinite)

Choose $K_1 = 0.2$, $K_2 = 0.3$ $K_3 = 0.4$ (this keeps $K_1 + K_2 + K_3 < 1$)

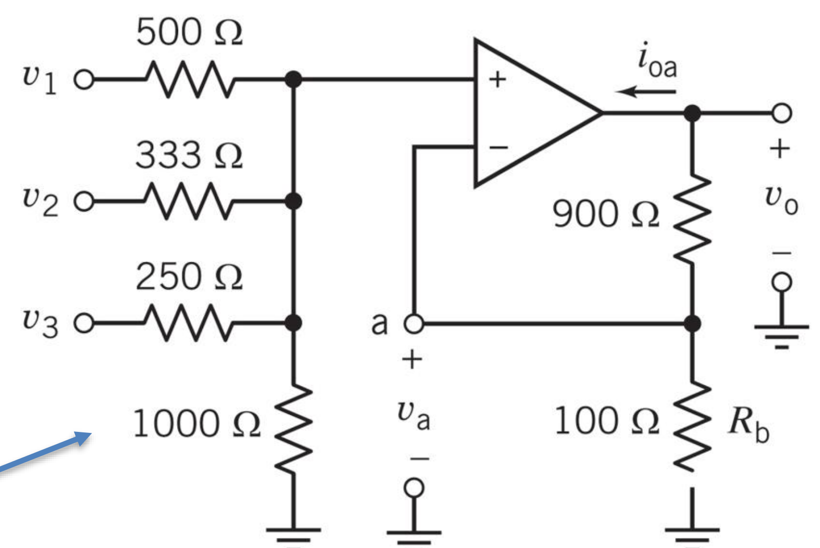
To keep $v_0 = 2v_1 + 3v_2 + 4v_3$, the output is $v_0 = K_4 (K_1 v_1 + K_2 v_2 + K_3 v_3)$ so we choose $K_4 = 10$

We now have what we :

$v_0 = 10(0.2v_1 + 0.3v_2 + 0.4v_3)$

Which means we now have K_1, K_2 and K_3

Since we have some flexibility in the values of R_a and R_b we choose $R_a = R_b = 100\ \Omega$, now we have

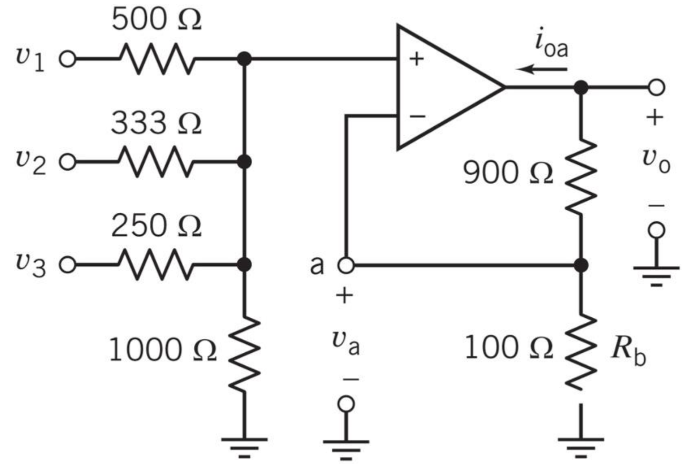


Checking the circuit

Node equations

Noninverting terminal:

$(v_a - v_1)/500 + (v_a - v_2)/333 + (v_a - v_3)/250 + v_a/1000 = 0$



Inverting terminal:

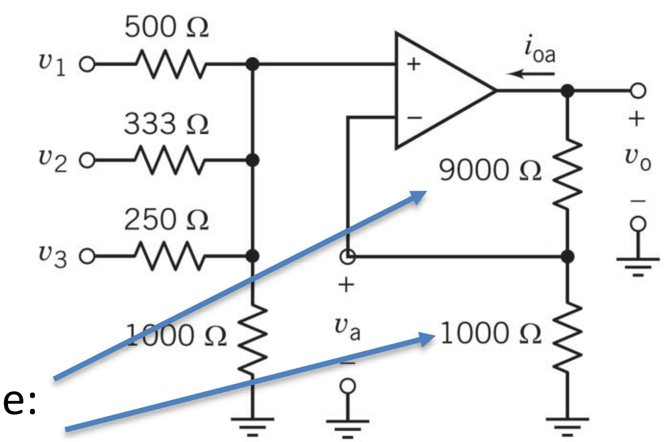
$(v_a - v_0)/900 + v_a/100 = 0$. Solving gives: $v_a = v_0/10$.

Putting this into top equation: $v_0 = 2v_1 + 3v_2 + 4v_3$

Let's check to see if it is operating in "ideal" conditions

Max. value: $|v_0| = 2|v_1| + 3|v_2| + 4|v_3|$ since $|v_1| < 1$ V then

$|v_0| < 9$ V , which is $< v_{sat}$ but $i_0 = |9V/1000| = 9$ mA $> i_{sat}$ so use:



Solving linear algebraic equations

Algebraic equations

Assume we want to solve this $$z = 4x - 5y + 2$$

This could be solved using an op amp circuit to give: $$v_z = 4v_x - 5v_y + 2$$

A **signal** is a voltage or current used to represent something.

Here v_x , v_y , v_z , are signals representing x, y, z

$$v_z = 4v_x - 5v_y + 2$$

output inputs

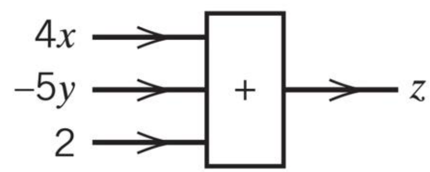
Block diagrams

Our equation can be re-written as: $$z = 4x + (-5)y + 2$$

This can be visualised as:

(a)

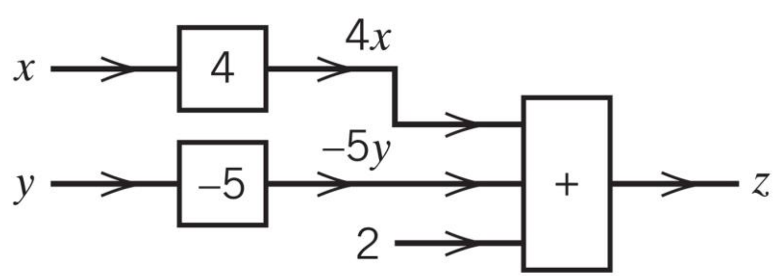
Multiplication block



(b)

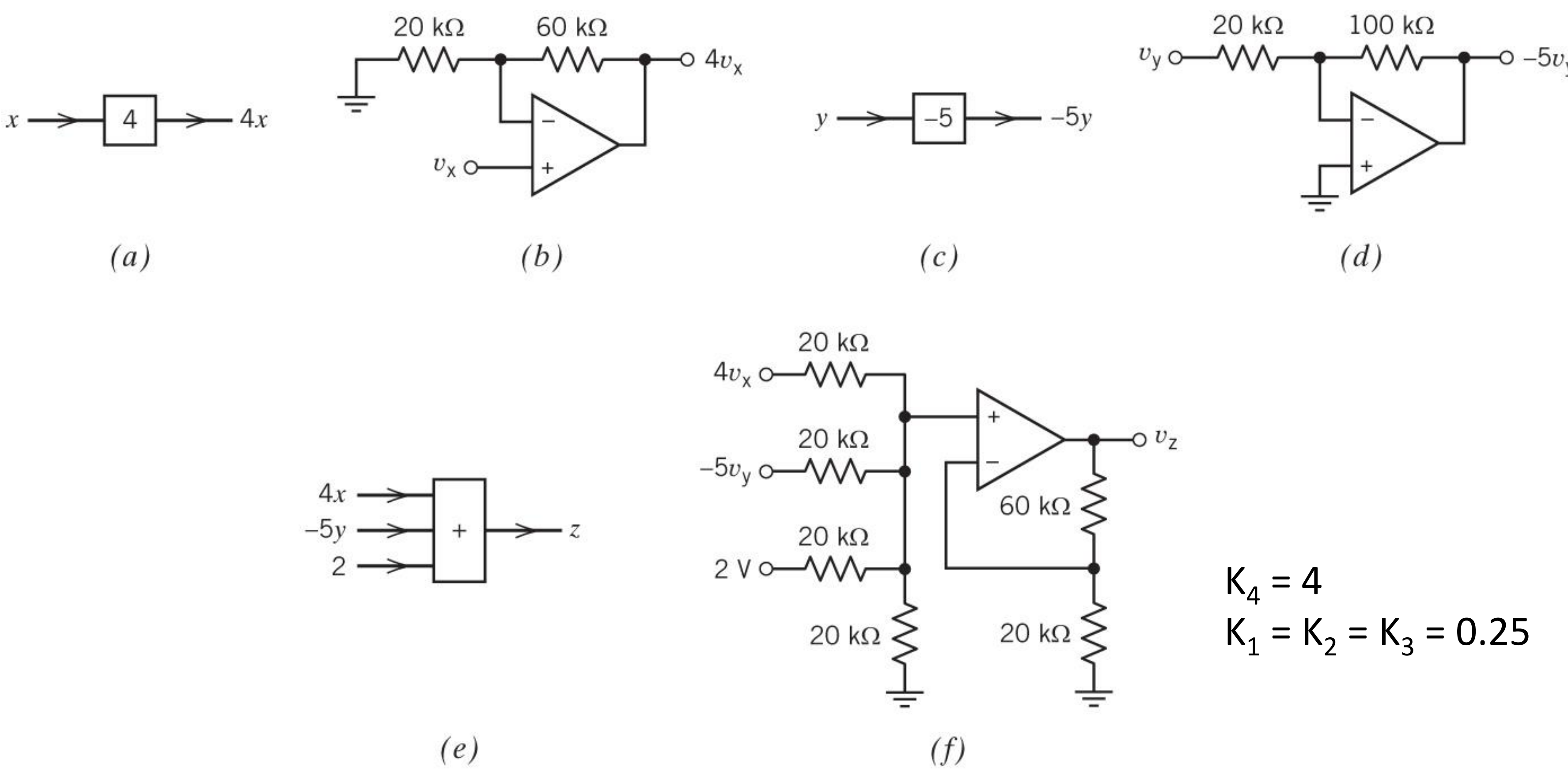
Addition block

Block diagram for our equation:



Designing the circuit

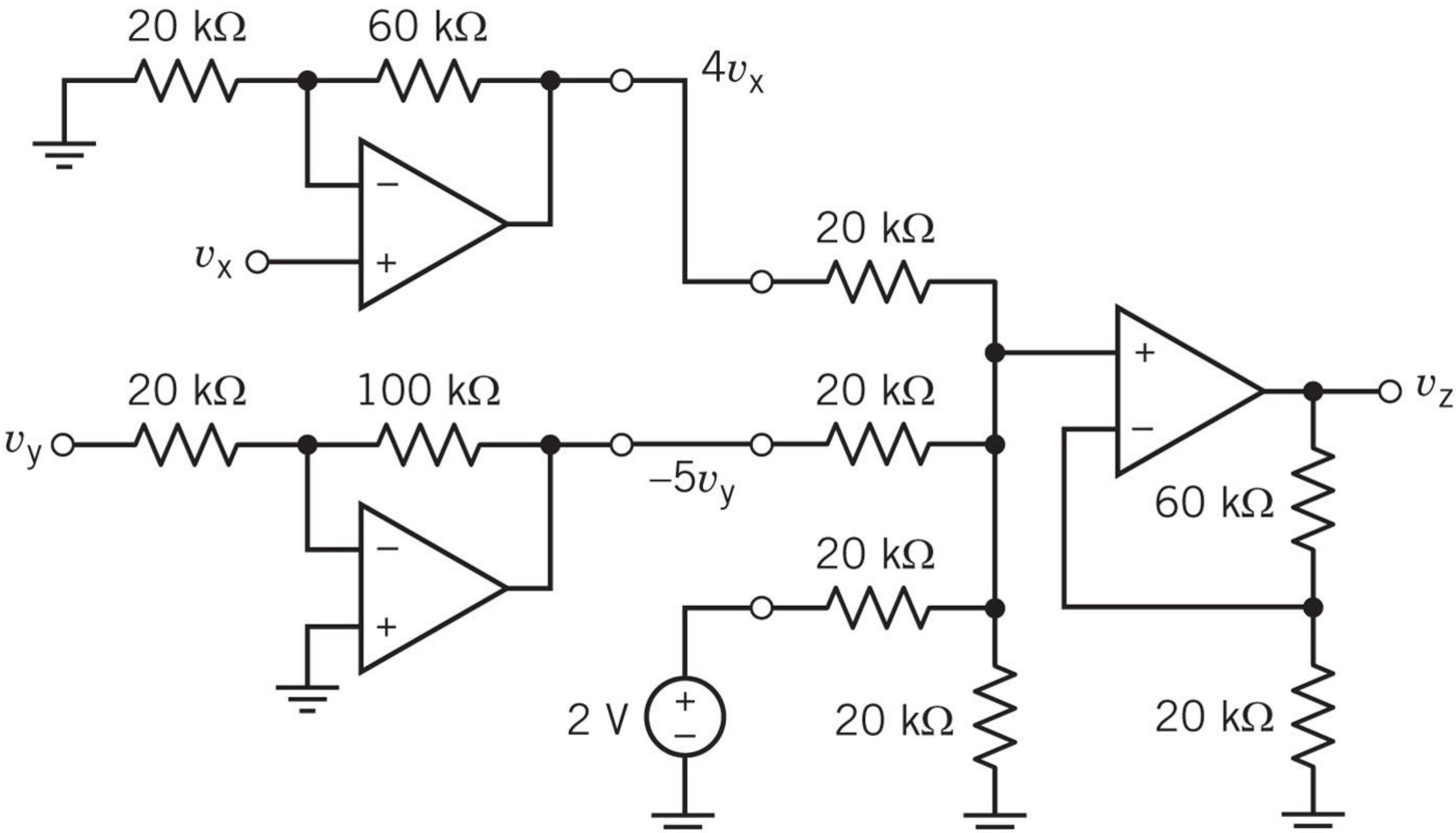
Op amp amplifiers are an obvious choice



$K_4 = 4$

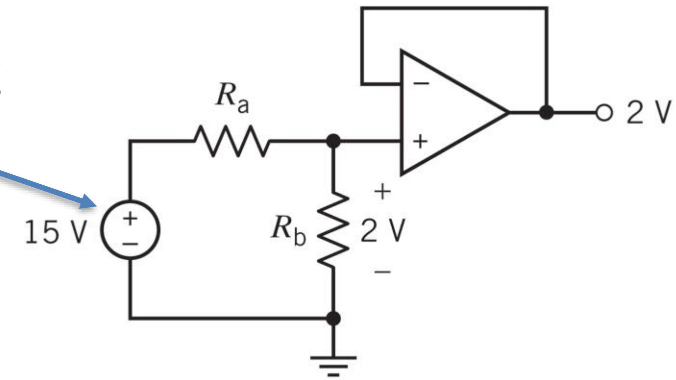
$K_1 = K_2 = K_3 = 0.25$

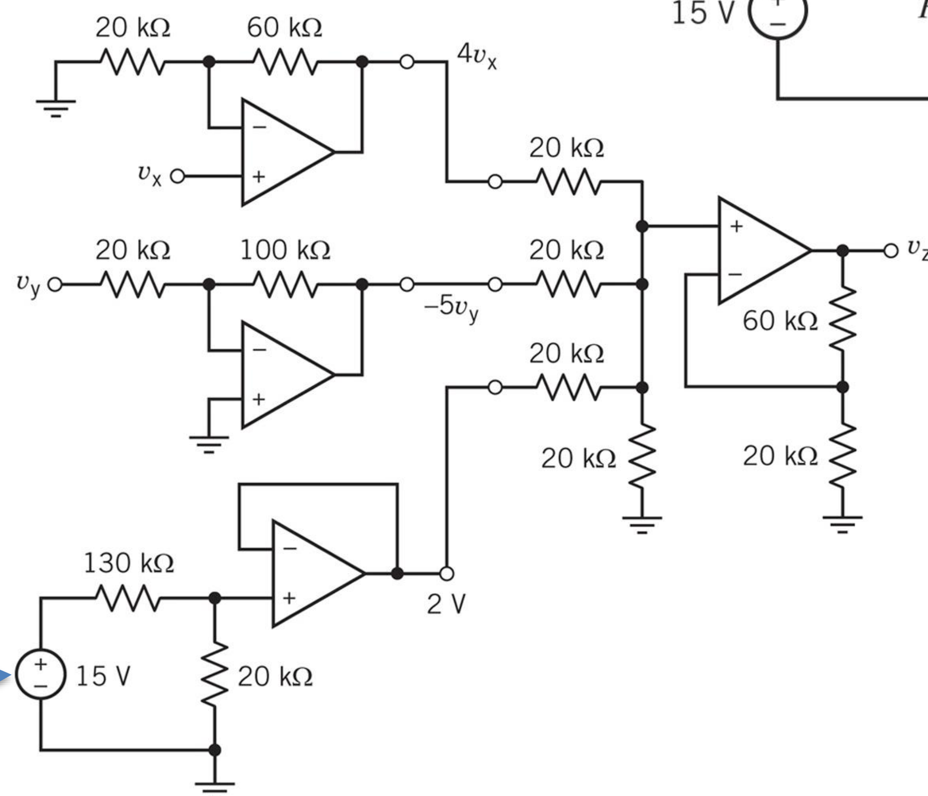
Overall circuit



How can we improve this?

Take the 2 V input from the bias sources to the op amp!





Which produces:

bias source to the op amp

Remember to check i_z and v_z to make sure they are below saturation levels for the op amp

Characteristics of practical operational amplifiers

Real op amps

We know that ideal op amps have: $i_1 = 0, \quad i_2 = 0, \quad \text{and} \quad v_1 - v_2 = 0$

Real op amps have:

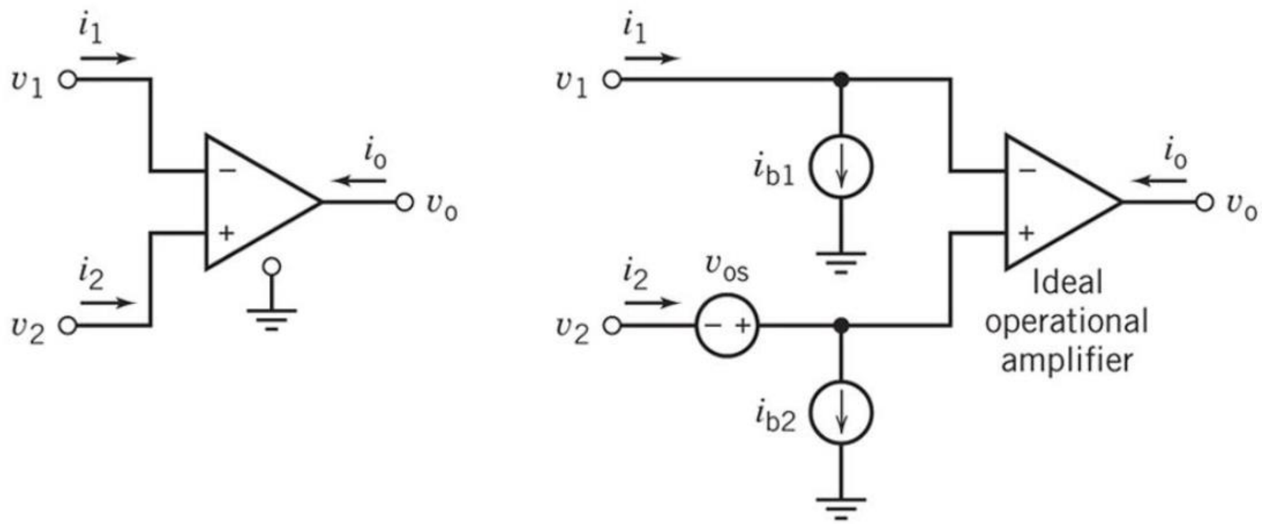
- Nonzero bias currents
- Nonzero input offset voltage
- Finite input resistance
- Nonzero output resistance
- Finite voltage gain

For small signals, the actual currents and voltages in real op amps become very important

Models for realistic op amps

The **offset model** accounts for:

- Nonzero bias currents
- Nonzero input offset voltage



Actual op amps

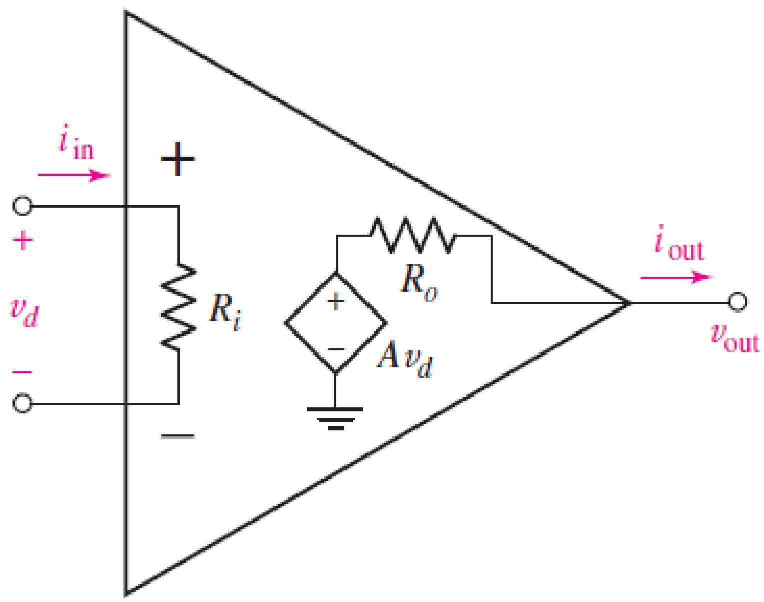
TABLE 6.3 Typical Parameter Values for Several Types of Op Amps

Part Number	μA741	LM324	LF411	AD549K	OPA690
Description	General purpose	Low-power quad	Low-offset, low-drift JFET input	Ultralow input bias current	Wideband video frequency op amp
Open loop gain A	2×10^5 V/V	10^5 V/V	2×10^5 V/V	10^6 V/V	2800 V/V
Input resistance	2 MΩ	*	1 TΩ	10 TΩ	190 kΩ
Output resistance	75 Ω	*	$\sim$1 Ω	$\sim$15 Ω	*
Input bias current	80 nA	45 nA	50 pA	75 fA	3 μA
Input offset voltage	1.0 mV	2.0 mV	0.8 mV	0.150 mV	$\pm$1.0 mV
CMRR	90 dB	85 dB	100 dB	100 dB	65 dB
Slew rate	0.5 V/μs	*	15 V/μs	3 V/μs	1800 V/μs
PSpice Model	✓	✓	✓		

* Not provided by manufacturer.

✓ Indicates that a PSpice model is included in Orcad Capture CIS Lite Edition 16.3.

Open loop gain



Note the actual **open-loop voltage gain** is very large compared to what we encountered in our previous examples.

There is a distinction between this parameter and the closed-loop voltage gain that characterises a particular op amp circuit. The “loop” refers to an external path between the output pin and the inverting input pin; it can be a wire, a resistor etc. depending on the application.