5. Operational Amplifiers

- Operational Amplifiers
- Negative Feedback
- Ideal Op-Amp Model
- Op-Amp Circuits
- "Practical" Op-Amp Model

Today's Outline

5. Operational Amplifiers

- Operational Amplifiers
- Ideal Op-Amp Model
- Op-Amp Circuits

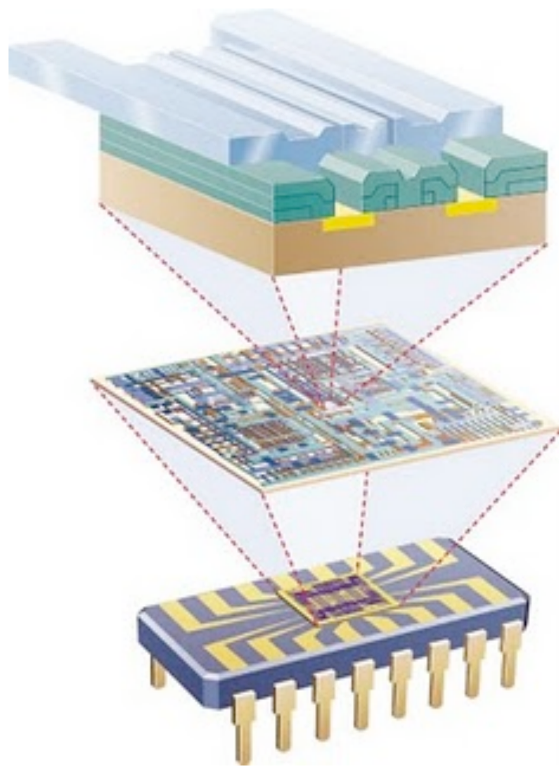
Operational Amplifier

The **operational amplifier** (also called an **op-amp** for short) is a very useful, general purpose amplifier circuit. It is composed of transistors, resistors, and capacitors. We will use an ***ideal model*** for the terminal characteristics of the op-amp and study some useful op-amp circuits.

transistors

circuit die

package

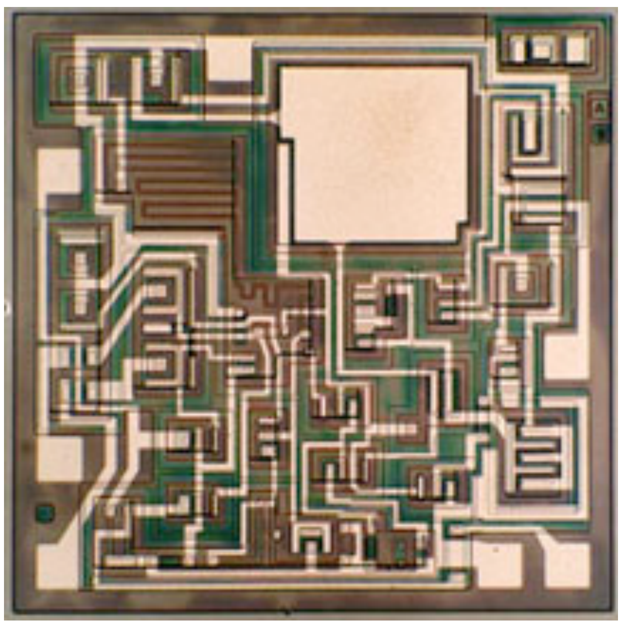


The op-amp is built in to many integrated circuits, and can also be found in discrete packages ready for use on a circuit board:

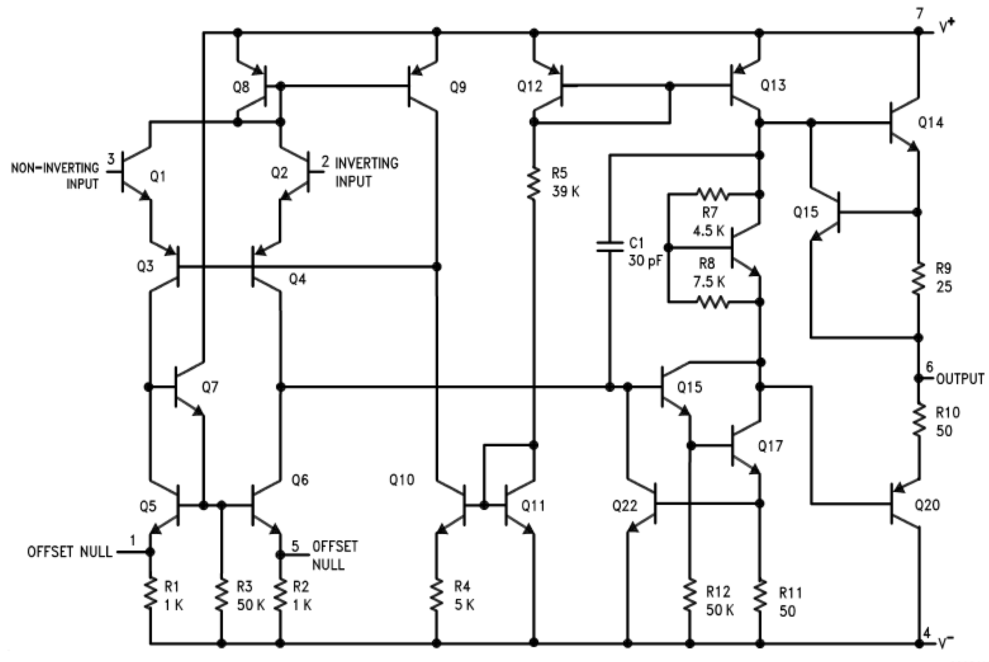
Operational Amplifier

The Fairchild µA741 is a classic op-amp design. Designed by David Fullagar, while under the supervision of Gordon Moore (PhD Chemistry, co-founder of Intel, introduced “Moore’s Law”).

You will learn how to design your own op-amp in a future course (ECSE 334)!



photograph of die



schematic

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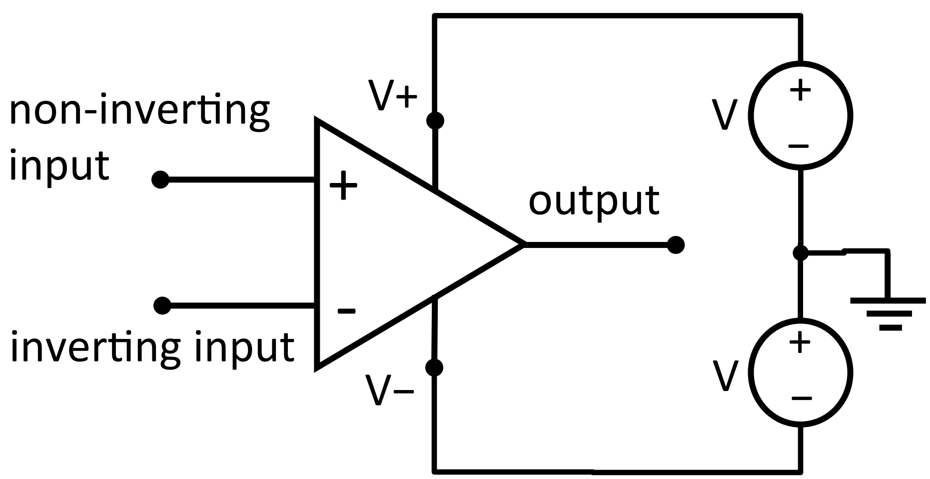
Operational Amplifier

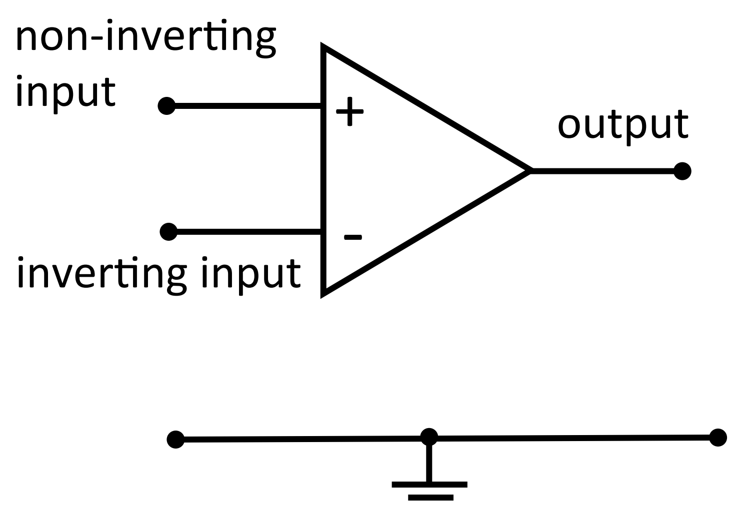
Op-Amp Circuit Element:

– a 6-terminal circuit when power supply terminals are included

– the op-amp can often be modeled as a 4-terminal device

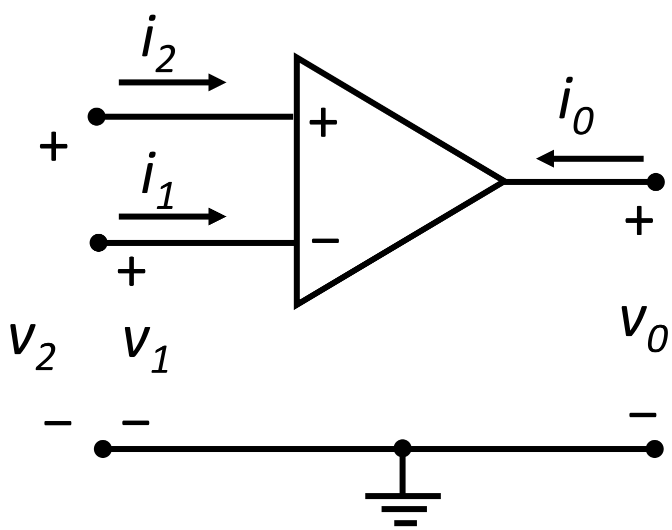
– the "reference terminal" is physically connected to the op-amp power supply and is drawn without connection to the rest of the circuit symbol

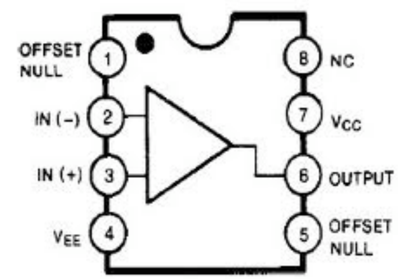




Operational Amplifier

Op-Amp Circuit Variables: By convention, voltage variables are defined with respect to the ***reference terminal***. Although drawn as a physically separate entity in a diagram, the reference is physically connected to the op-amp through the power supply.



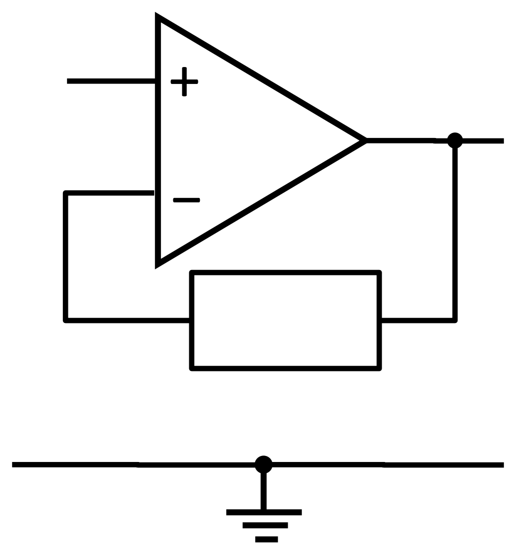


Negative Feedback

Negative Feedback Loop: The connection of the output terminal back to the inverting input terminal, through a circuit element.

– circuit output is stable, in contrast to positive feedback (*we will return to this point in later lectures*)

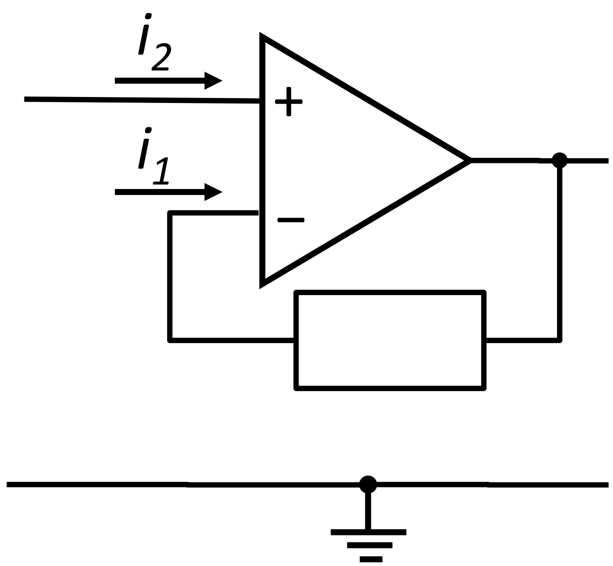
– the amplifier becomes ***programmable*** by using different circuit elements in the negative feedback loop, allowing one to perform different operations on circuit signals



Open Input Approximation

Open input approximation: The currents at the op-amp input terminals are identically zero:

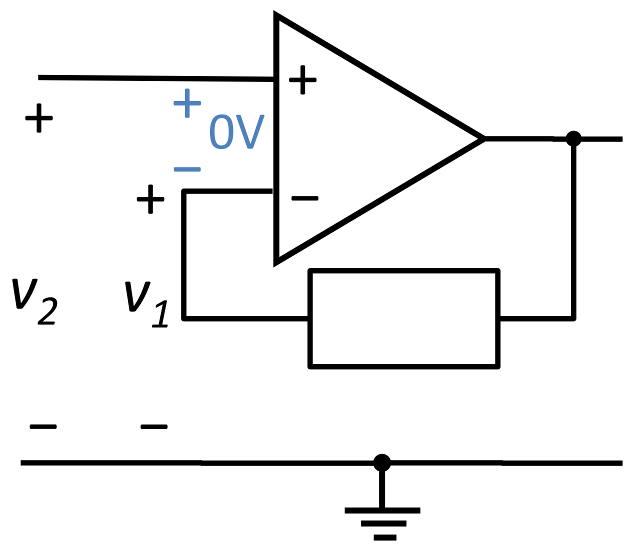
$$i_2 = i_1 = 0$$



Virtual Short Approximation

Virtual short approximation: The input voltage difference for an op-amp in a negative feedback loop is identically zero:

$$v_2 = v_1$$



It is the negative feedback loop that enables the op-amp to reach this condition.

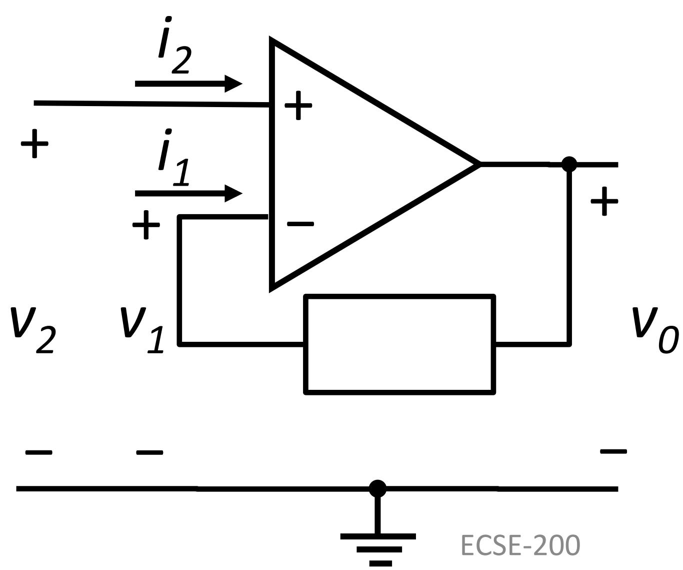
Ideal Op-Amp Model

Ideal Op-Amp Model: *Idealized* terminal equations for an op-amp,

$v_2 = v_1$ (virtual short approximation)

$i_2 = i_1 = 0$ (open input approximation)

The circuit solution that is found using these terminal equations is useful only for stable circuits, meaning those with ***negative feedback***



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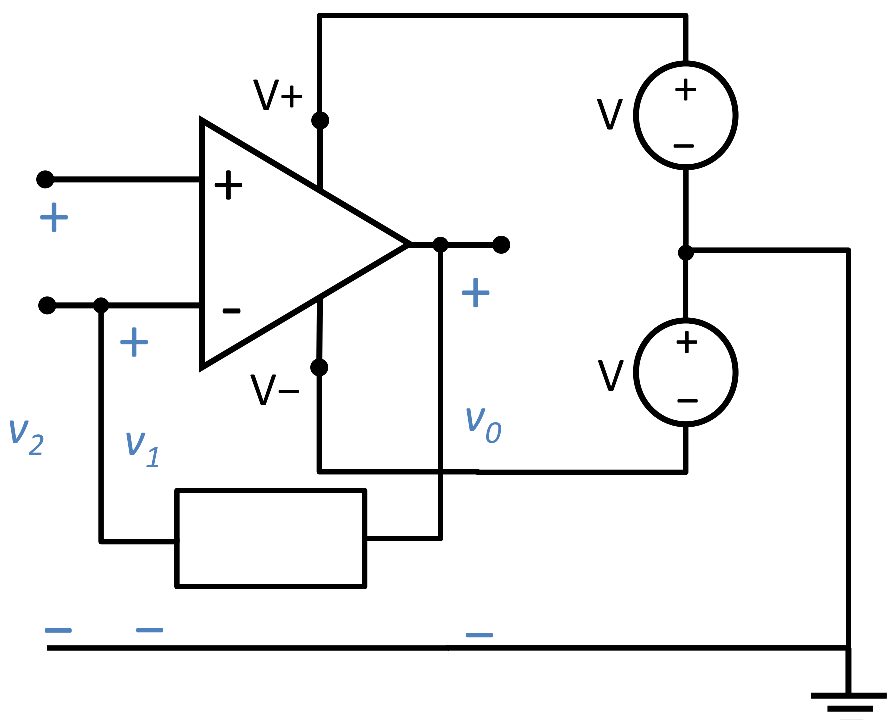
output voltage limit

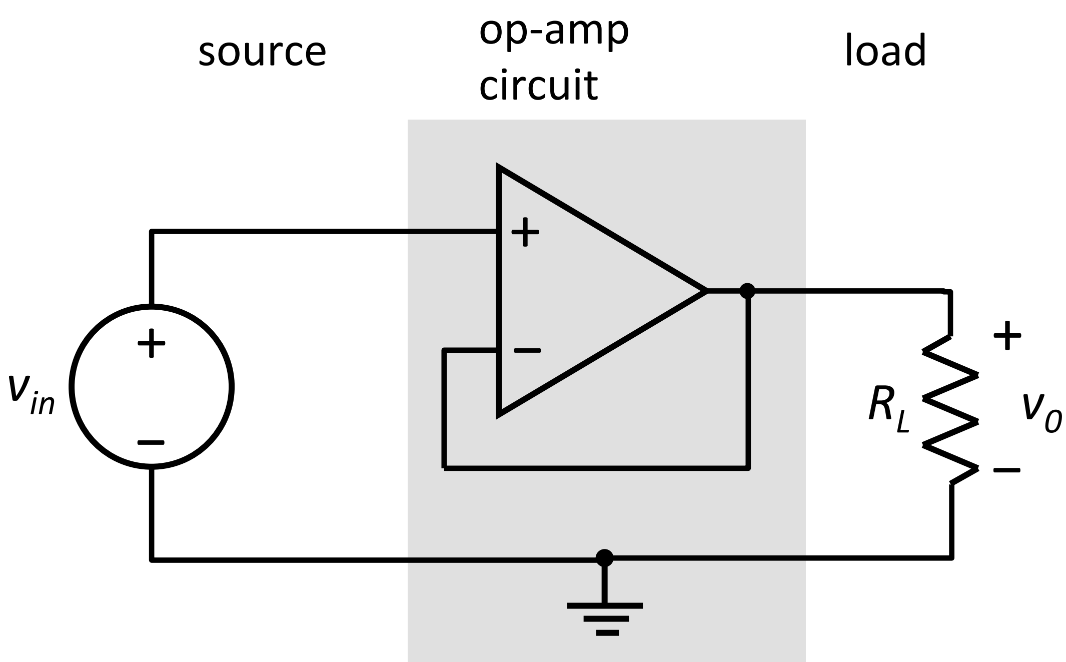
Output voltage cannot exceed power supply voltages: $-V < v_0 < +V$

When $v_0 = \pm V$, the op-amp output is said to "***saturate***", and the ***ideal op-amp approximation no longer applies***. Saturation is undesired op-amp behaviour.



Example 1

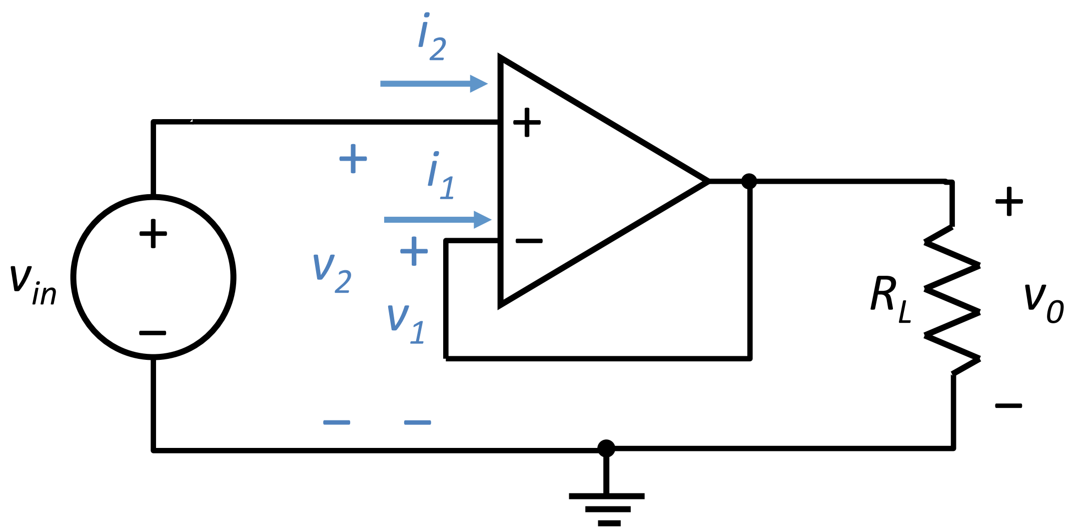
Find the ratio v_0 / v_{in}, which we call the voltage gain. Assume ideal op-amp behaviour. Calculate the power delivered by the independent voltage source, and the power absorbed by the load resistor.



Example 1

Use ideal op-amp equations.

Ideal op-amp: $v_2 = v_1$
$i_2 = i_1 = 0$



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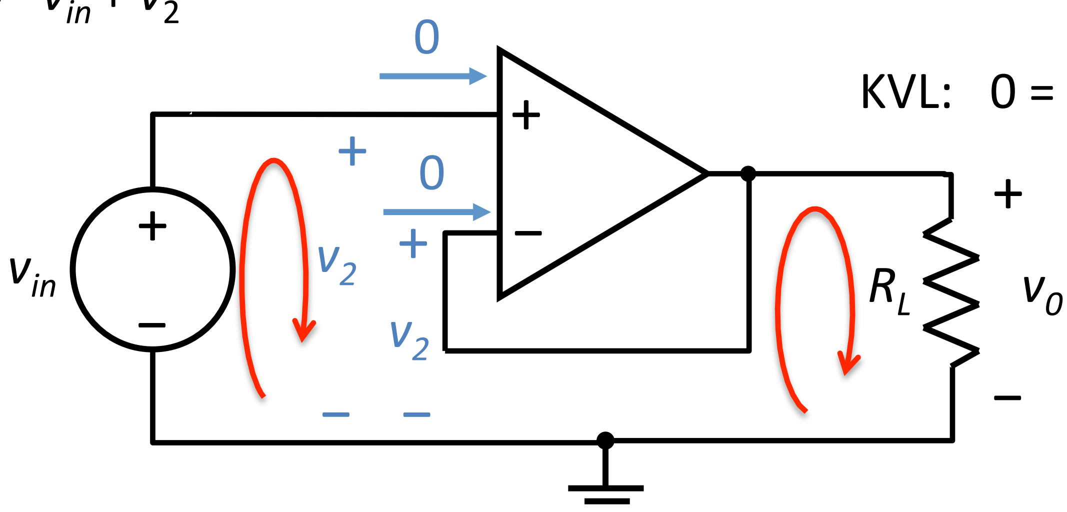
Example 1

Apply KVL.

KVL: $0 = -v_{in} + v_2$



KVL: $0 = -v_2 + v_0$

Combining the above: $v_{in} = v_2 = v_0$

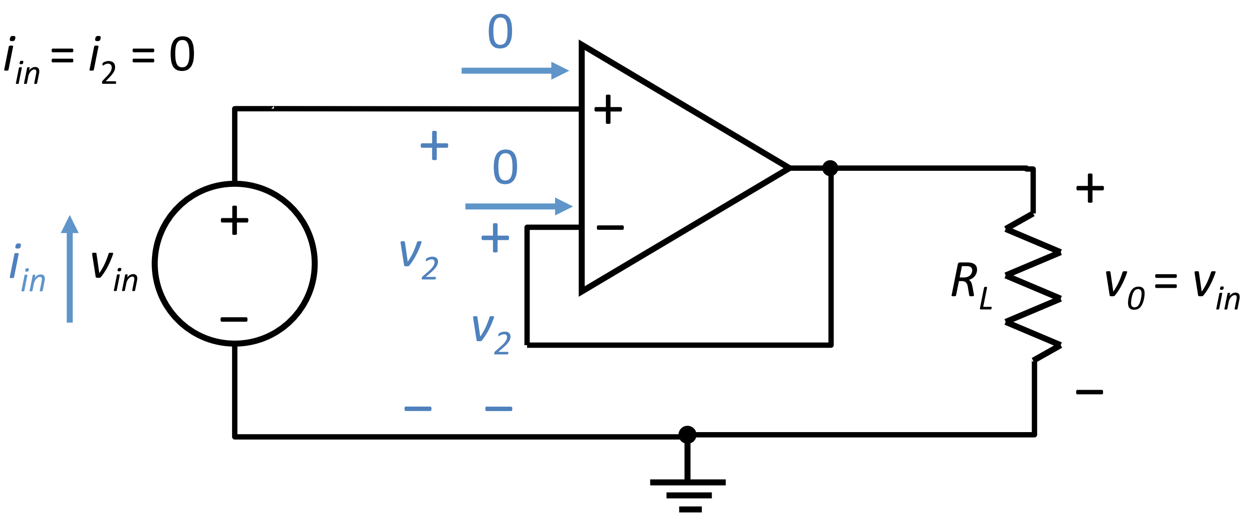
$$\boxed{\frac{v_0}{v_{in}} = 1}$$

This op-amp circuit is configured as a ***voltage follower***, sometimes also called a ***buffer***.

Example 1

Calculate power delivered by source and absorbed by load resistor.

KCL: $i_{in} = i_2 = 0$



Power delivered by independent source:

$P_{\text{in}} = v_{in}\, i_{in}$ *note* i_{in} *reference direction!*

$= v_{in}\, 0$

$= 0$ W

Power absorbed by load resistor:

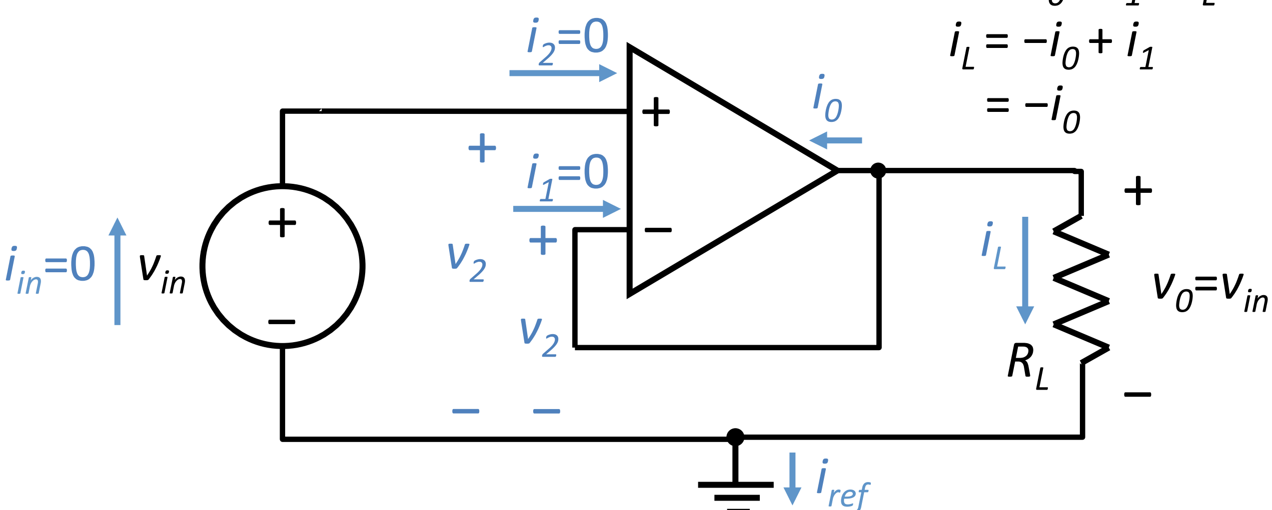
$P_{\text{abs}} = (\, v_0\,)^2 /\, R_L$

$= (\, v_{in}\,)^2 /\, R_l$

The ideal voltage follower draws no power from the source, and delivers power to the load. This is very useful if the source (eg. a computer port) is not capable of delivering sufficient power to the load (eg. a peripheral at the end of a long cable).

Example 1

Question: How is the current flowing on the load side?



KCL: $0 = i_0 + i_1 + i_L$

$i_L = -i_0 + i_1$

$= -i_0$

Ohm's Law:

$v_0 = i_L R_L$

$i_L = v_0 / R_L$

$= v_{in} / R_L$

KCL: $0 = -i_L + i_{ref} + i_{in}$

$i_{ref} = i_L - i_{in}$

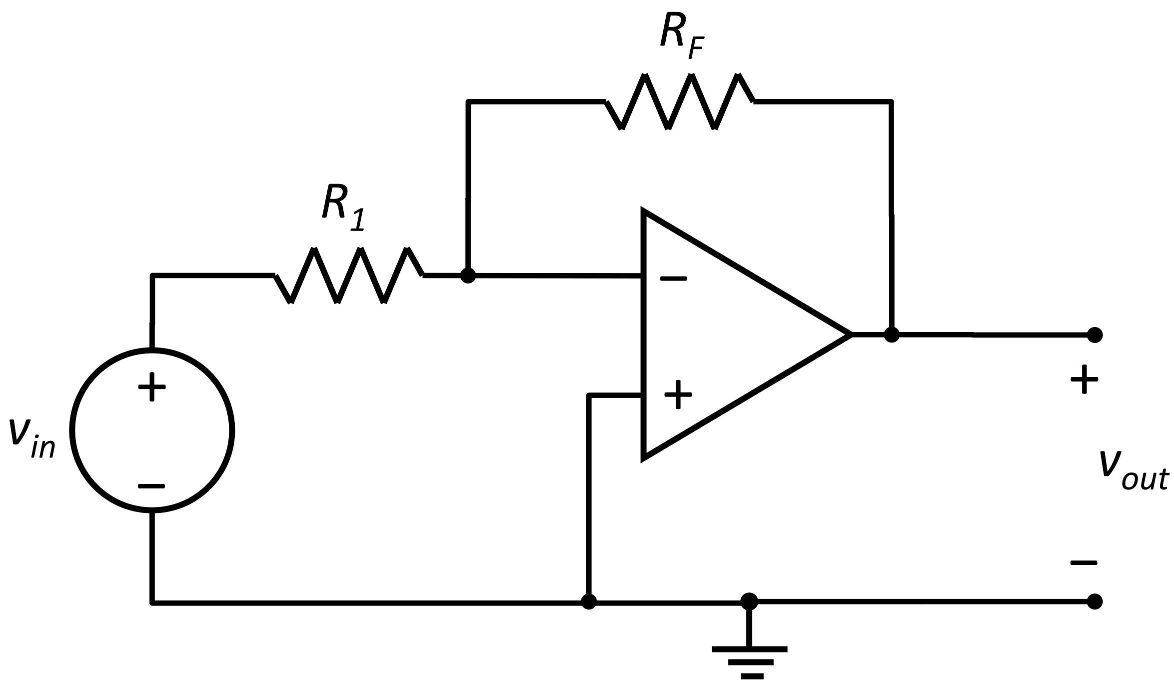
$= i_L$

$= -i_0$

It is the op-amp output and reference terminal together that supply current through the load. Note that no net charge is accumulated within the op-amp (or its power supplies, not illustrated).

Example 2

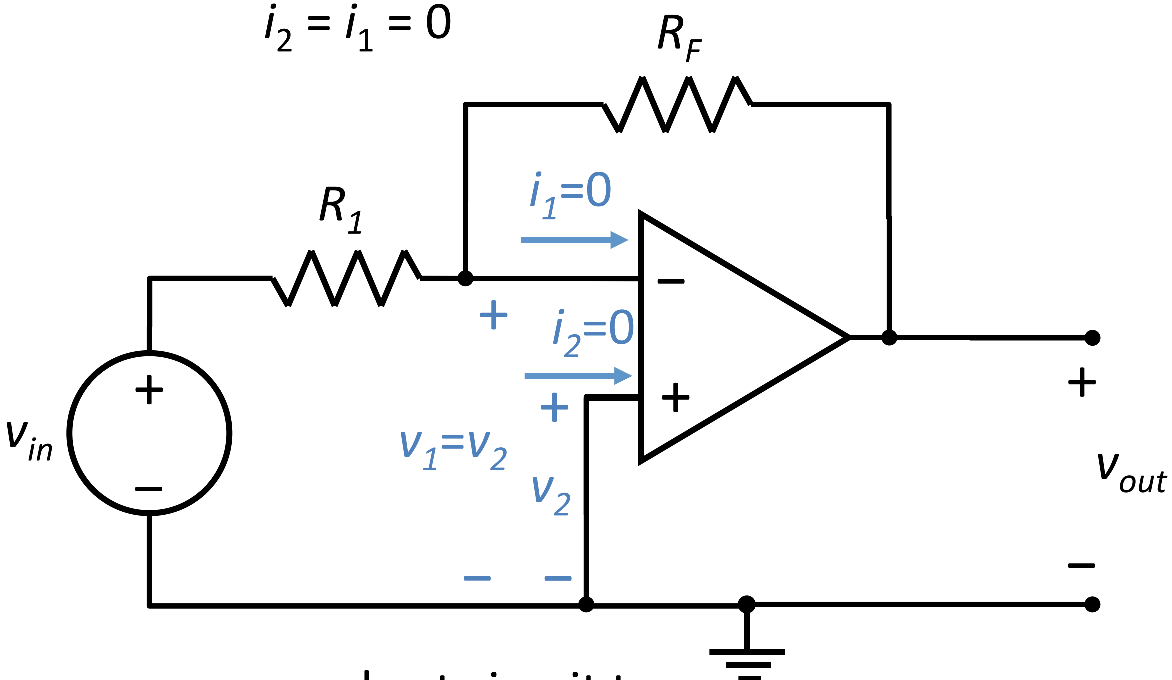
Assuming ideal op-amp behaviour, find the voltage gain v_{out}/v_{in}.



Example 2

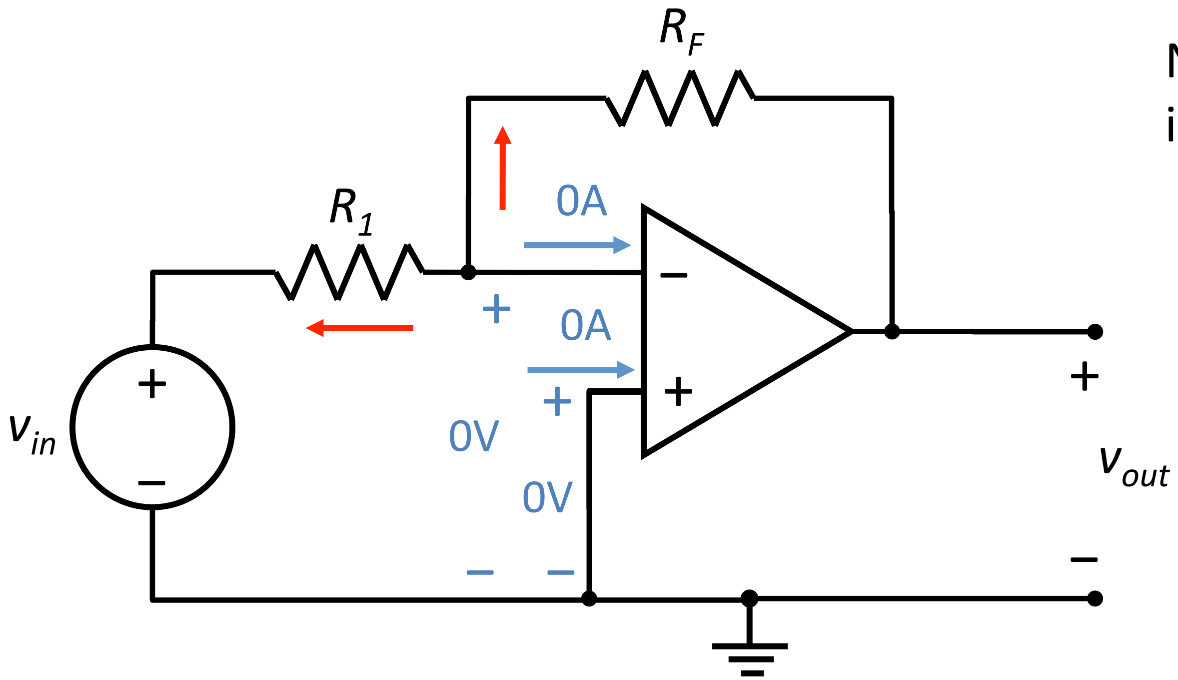
Ideal op-amp: $v_2 = v_1$

$i_2 = i_1 = 0$



short circuit to reference: $v_2 = 0$

Example 2



Node voltage equation at inverting input:

$$0 = \frac{0 - v_{in}}{R_1} + \frac{0 - v_{out}}{R_F}$$

$$\boxed{\frac{v_{out}}{v_{in}} = -\frac{R_F}{R_1}}$$

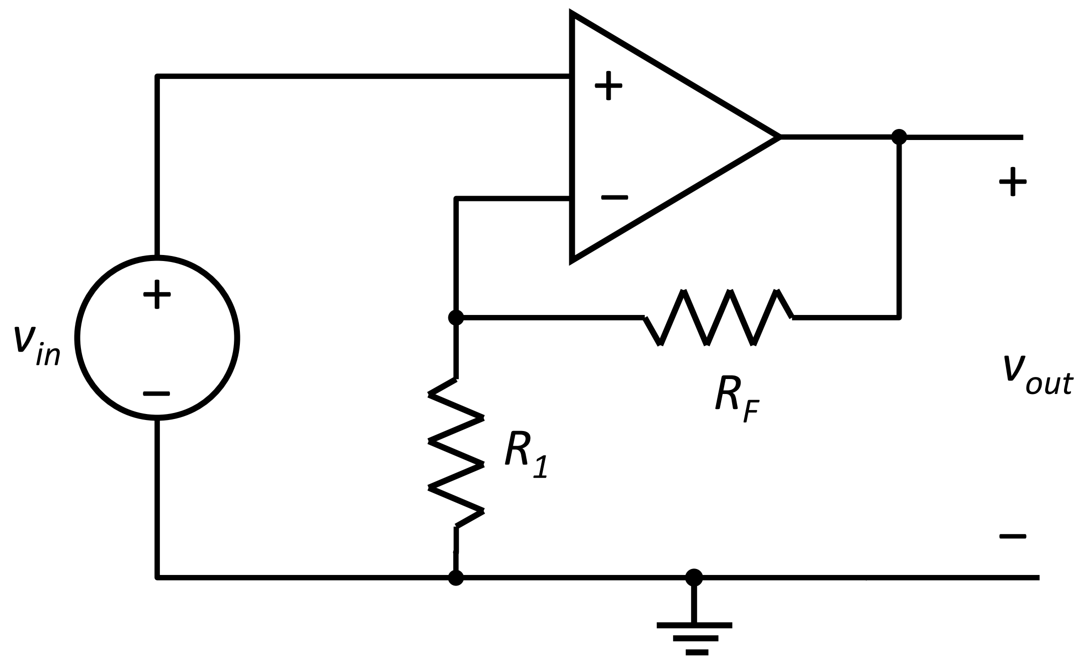
This op-amp circuit is configured as an ***inverting amplifier***. The voltage gain is:

- negative, hence the sign of the v_{out} is inverted from that of v_{in}
- programmed by the ratio of R_F to R_1

This circuit forces the current flowing in R_1, which is determined by the input voltage, through the feedback resistor R_F.

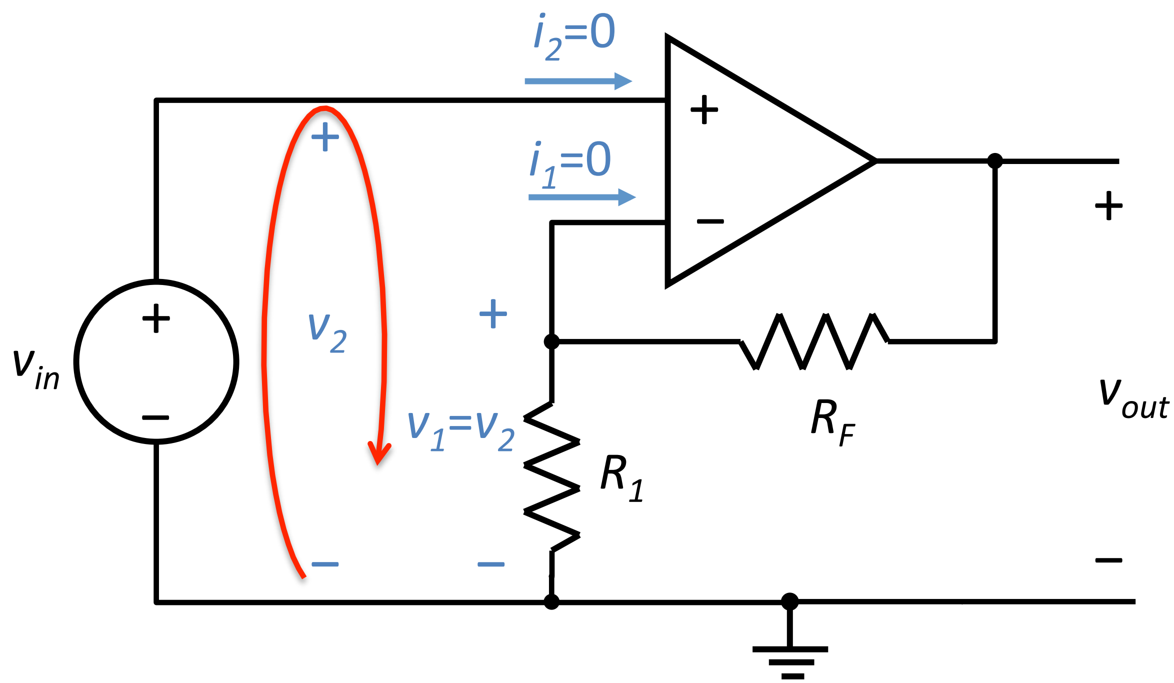
Example 3

Assuming ideal op-amp behaviour, find the voltage gain v_{out}/v_{in}.



Example 3

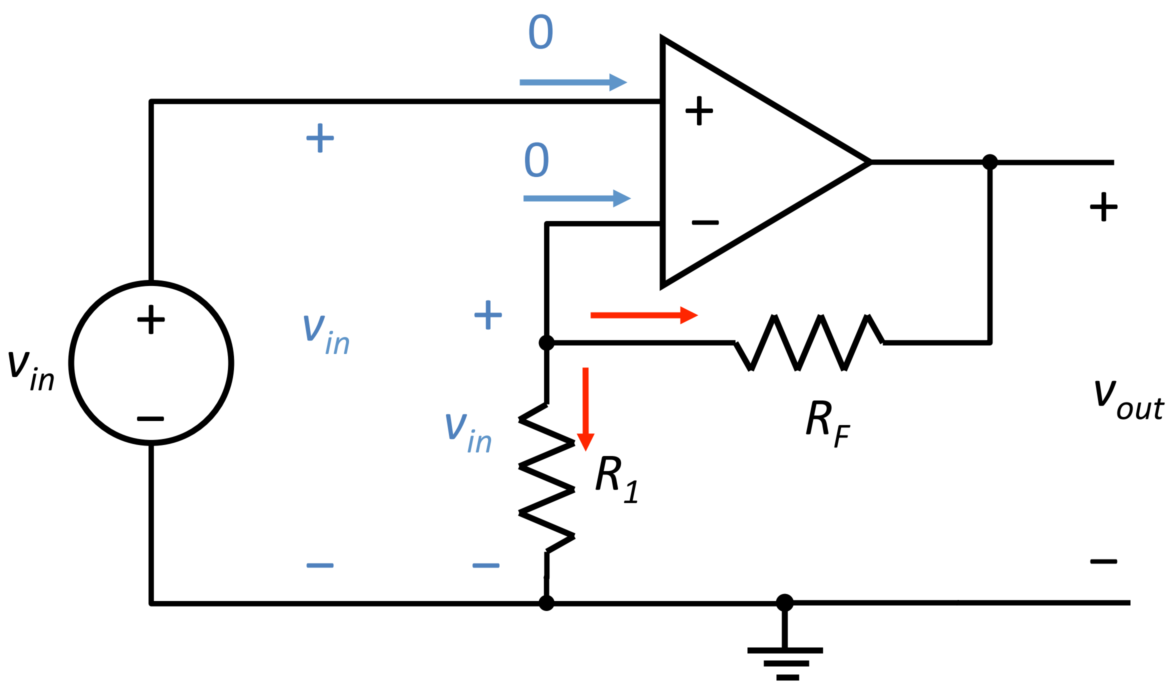
Ideal op-amp: $v_2 = v_1$
$i_2 = i_1 = 0$



KVL: $0 = -v_{in} + v_2$

$v_2 = v_{in}$

Example 3



Node voltage equation at inverting input:

$$0 = \frac{v_{in}}{R_1} + \frac{v_{in} - v_{out}}{R_F}$$

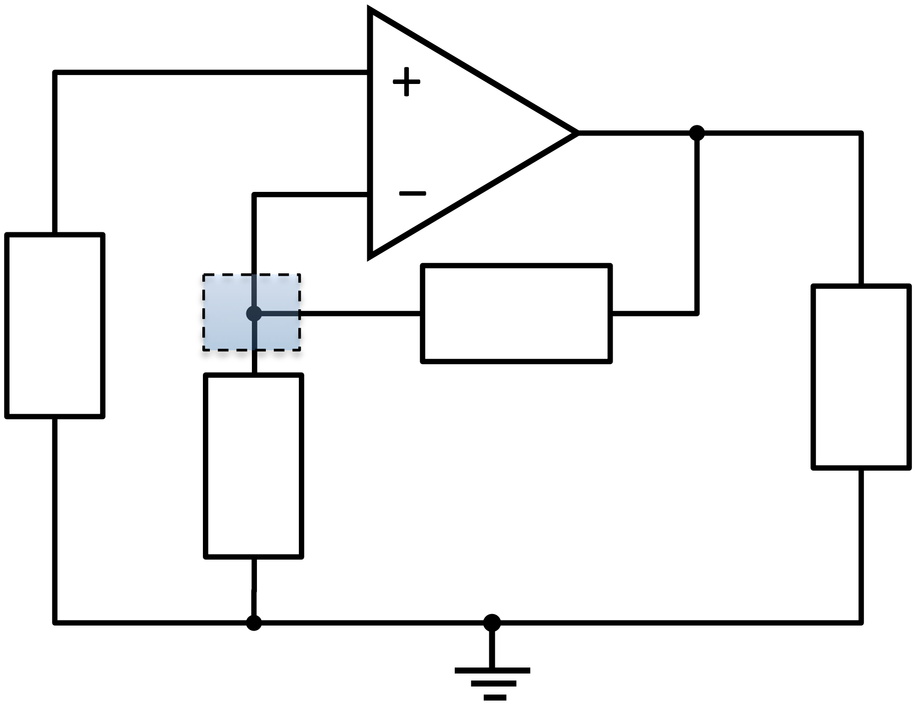
$$0 = v_{in}\left(\frac{1}{R_1} + \frac{1}{R_F}\right) - v_{out}\left(\frac{1}{R_F}\right)$$

$$\boxed{\frac{v_{out}}{v_{in}} = 1 + \frac{R_F}{R_1}}$$

This op-amp circuit is configured as a ***non-inverting amplifier***. The voltage gain is:

- positive, hence the sign of the v_{out} is the same as that of v_{in}
- programmed by the ratio of R_F to R_1

a note on analysis



Ideal op-amp circuits in negative feedback can ***often*** be analyzed by:

- determining what is the non-inverting input voltage
- analyzing current flow at the inverting input terminal

a diversion

the Art of Electronics,
P. Horowitz, W. Hill
1989

Fantastic cook book (reference book with recipes) for a myriad of useful circuits, including op-amp circuits, digital circuits, and transistor circuits.

Includes useful rules of thumb for practical circuit designs.