2018
Delaware Science Olympiad
Wonders of Electricity Workshop
(Basic of OpAmp and Digital Logic)

IEEE

DELAWARE BAY SECTION

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Agenda

- Review of basic circuit analysis theory
- OpAmp
- Digital Logic

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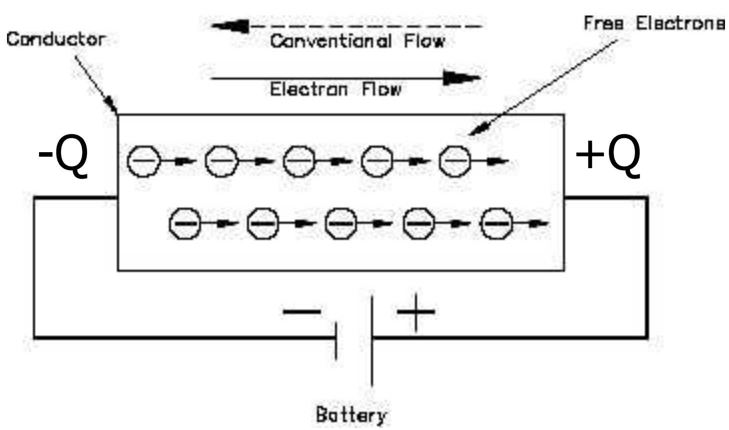
Electric Current

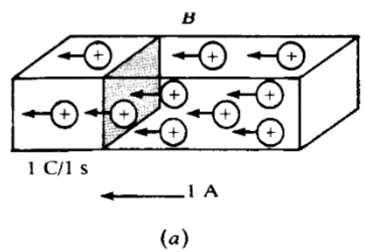
- The movement or the flow of electrical charge is called current
  - To produce a current, the charge must be moved by a potential difference.
- Current is represented by the letter symbol I
- The basic SI unit for measuring current is the Ampere (A) [Often abbreviated as Amp].
  - One Ampere (1A) of current is defined as the movement of one coulomb past any point of a conductor during one second of time

$$I = \frac{Q}{T}$$

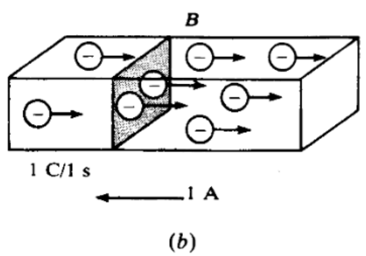
- In a conductor, the free electrons are charges that can be forced to move with relative ease by a potential difference.

Current flows in the same direction as positive ions but the opposite direction as free electrons.





Positive Ions



Negative Ions

Ohm's Law

- Ohm's law defines the relationship between current, voltage and resistance.
  - The current in a circuit is equal to the voltage applied to the circuit divided by the resistance of the circuit

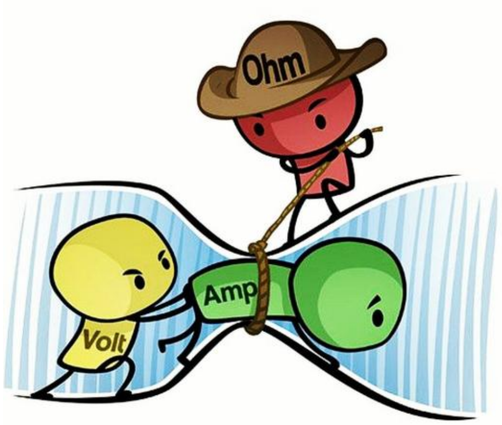
$$I = \frac{V}{R}$$

  - The resistance of a circuit is equal to the voltage applied to the circuit divide by the current in the circuit

$$R = \frac{V}{I}$$

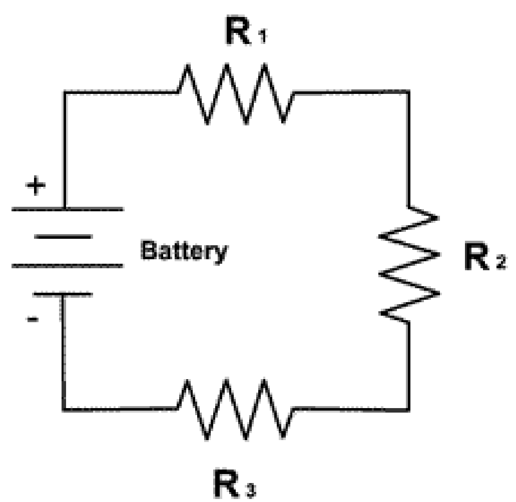
  - The applied voltage to a circuit is equal to the product of the current and resistance of the circuit

$$V = I \text{ x } R$$

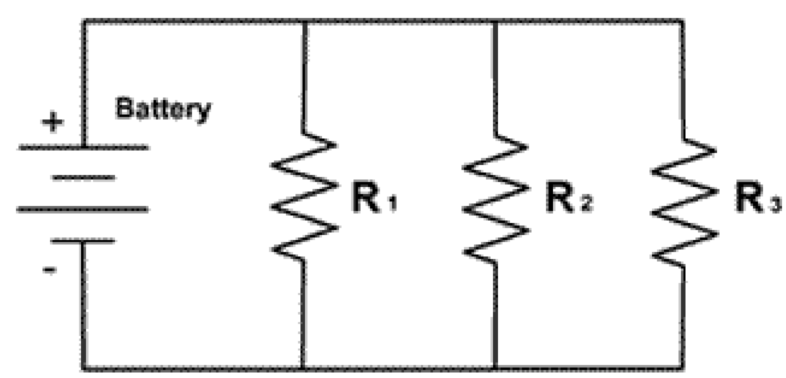


Simple Circuits

- Components of an electrical circuit or electronic circuit can be connected in many different ways. The two simplest of these are called **series** and **parallel** and occur very frequently.
- Components connected in series are connected along a single path, so the same current flows through all of the components.
- Components connected in parallel are connected so the same voltage is applied to each component.



Serial Circuit



Parallel Circuit

Analyze a circuit using Ohm's Law (Serial Circuit)

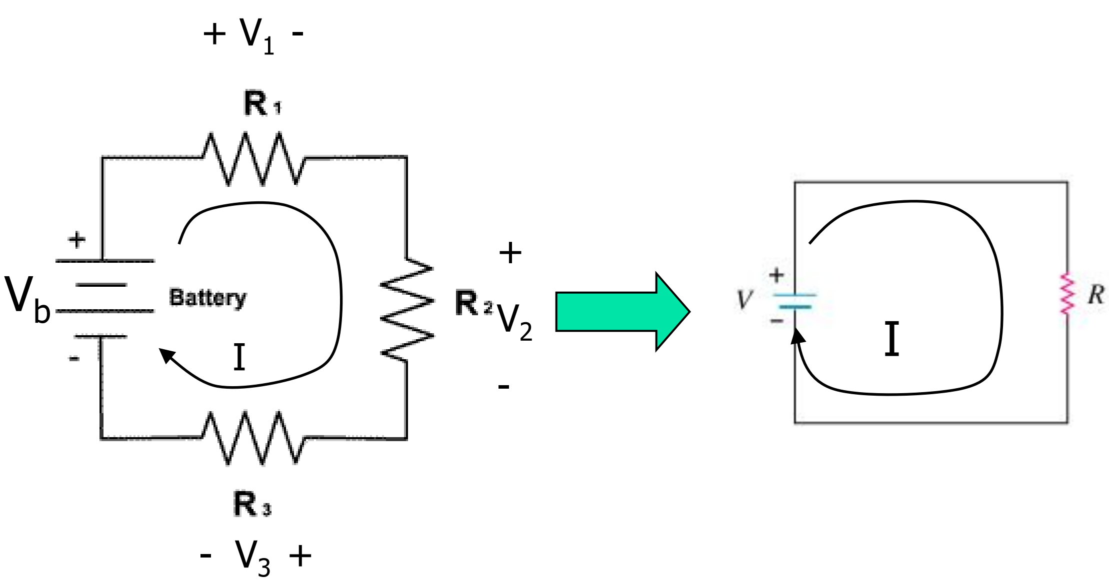
- 3 Resistors (R1,R2 and R3) are connected in serial along with the Battery. So, this circuit is a serial circuit
- Serial circuit has only one path for the electric current to flow. So, the same amount of current flows through R1, R2 and R3
- Using Ohm's Law,
  - V1 = R1 * I
  - V2 = R2 * I
  - V3 = R3 * I
- The direction of the voltages of each resistors follows the current flowing through the resistors
- The battery voltage is
  - Vb = V1 + V2 + V3

    = R1 * I + R2 * I + R3 * I

    = (R1 + R2 + R3) * I
- The equivalent circuit at the right:

  R = Vb/I

  = (R1+R2+R3)



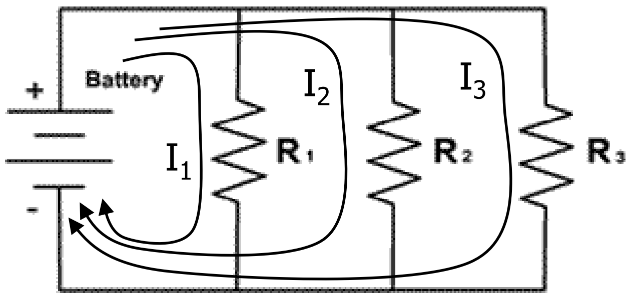
Analyze a circuit using Ohm's Law (Parallel Circuit)

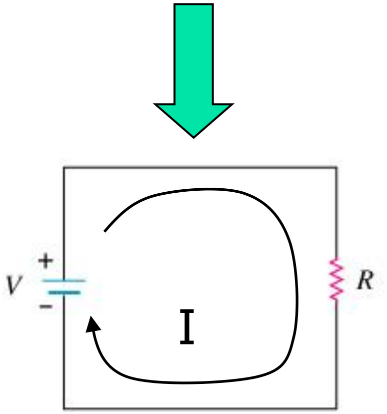
- 3 Resistors (R1,R2 and R3) are connected in parallel. So this circuit is a parallel circuit
- A parallel circuit has multiple path for electrical current to flow. However, all resistors are connected to the same battery. So, the voltages across each resistors are the same
- Using Ohm's Law,
  - I1 = Vb/R1
  - I2 = Vb/R2
  - I3 = Vb/R3
- The direction of the current of each resistors follows the voltage across the resistors
- Since the battery supplies all currents for each resistor. The total current out of the battery I is
  - I = I1 + I2 + I3

    = Vb/R1 + Vb/R2 + Vb/R3
- The equivalent circuit at the right:

  R = Vb/I

  = 1/ (1/R1 + 1/R2 + 1/R3)





Power & Energy

- The **power** consumed by an electrical component is equal to the product of the voltage drop across the component and the current flowing through the component. The unit of power is the watt (w).

  Power(w) = Voltage(v) x Current(amps)

- Using Ohm's Law, power can be computed as $P = I^2 \times R$ or V^2 / R

- The **energy** consumed by an electrical component is equal to the product of the power and the amount of time that the component is energized. The units of power are watt seconds, watt hours, kilowatt hours, etc.

- Household electrical consumption is metered by kilowatt hours (kwh) used and is billed at around 10 -20 cents per kwh.

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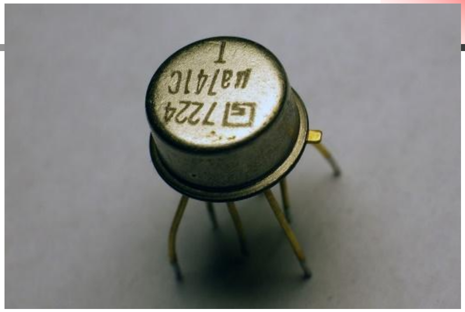
Agenda

- Review of basic circuit analysis theory
- OpAmp
- Digital Logic

What is Operational Amplifier (Op-amp)



An amplifier that is:

- ✓ DC-coupled, Differential Input
- ✓ High-gain electronic voltage amplifier
- ✓ (Usually) Single-ended output

An op-amp produces an output potential (relative to circuit ground) that is typically hundreds of thousands of times larger than the potential difference between its input terminals.

Operational amplifiers had their origins in analog computers, where they were used to perform mathematical operations in many linear, non-linear, and frequency-dependent circuits.

Op-amps are among the most widely used electronics devices.

History

- Developmental Background of OpAmp:

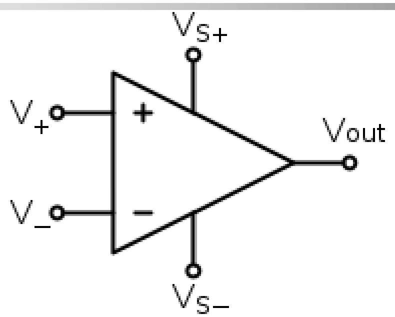
1. Fleming Diode, patented by J.A Fleming in 1904
2. Audion, or Triode, patented by Lee De Forest in 1906. This was the first active device capable of signal amplification.
3. The invention of the feedback amplifier principle at Bell Telephone Laboratories, patented by Harold S. Black in 1928.

   This principle is so important that it is ranked one of the most notable developments of 20th century for great value to engineering. It took US Patent Office 9 long years to review and final issue his patent.

- After World War II, the vacuum tube OpAmps were improved and refined. But they were fundamentally large, bulky and power hunger. So, after a decade or more, those vacuum tube OpAmps began to be replaced by miniaturized solid state OpAmp in 1950s and 1960s

- A final major history of OpAmp began with development of the first integrated circuit OpAmp in the mid 1960.

Standard Pin Configuration



V+: non-inverting input

When a voltage is applied directly to the non-inverting input, the amplifier output becomes "positive" in value.

V-: inverting input

When a voltage is applied directly to the non-inverting input, the amplifier output becomes "negatve" in value.

The pair of V+ and V- sometime is called differential inputs collectively.

Vout: output

VS+: positive power supply

A DC voltage is needed to provide power for the Op-amp to function. This voltage needs to be higher (or more positive) than VS-

VS-: negative power supply

A DC voltage is needed to provide power for the Op-amp to function. This voltage needs to be lower (more negative) than VS+

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Ideal Op-amps

An ideal op-amp is usually considered to have the following characteristics

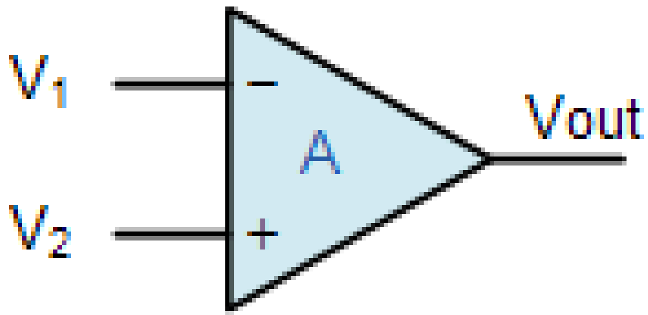
- Infinite open-loop gain $G = v_{out} / v_{in}$
- Infinite input impedance R_{in}, and so zero input current
- Zero input offset voltage
- Infinite output voltage range
- Infinite bandwidth with zero phase shift and infinite slew rate
- Zero output impedance R_{out}
- Zero noise
- Infinite common-mode rejection ratio (CMRR)
- Infinite power supply rejection ratio.

These ideals can be summarized by the two "golden rules":

- **In a closed loop** the output attempts to do whatever is necessary to make the voltage difference between the inputs zero.
- The inputs draw no current.

Open Loop Amplifier

Vout = A (V2-V1)

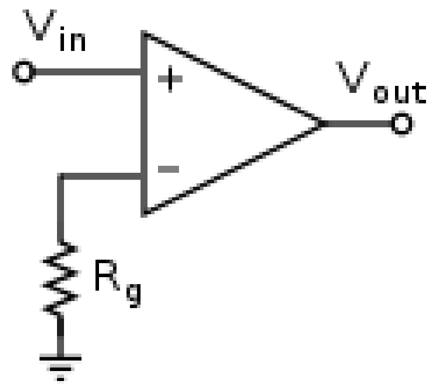


A is the open loop gain of the amplifier.
It is called open loop because of the absence of a feedback loop from the output to the input

A is typically very large. For integrated circuit Op-amp, 100,000 or more

Comparator

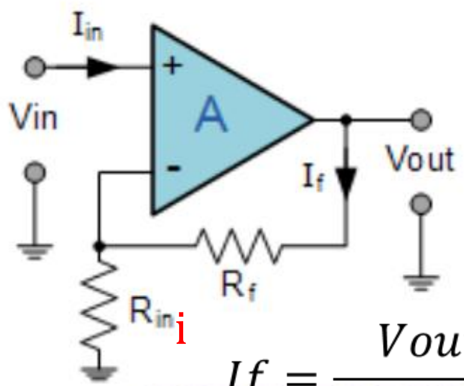
Vout = High (if Vin > 0V, or Ground)
Vout = Low (if Vin =< 0V or Ground)



An Op-amp without negative feedback is a comparator.

Non-inverting Amplifier

$$\text{Vout} = \text{Vin}\ x\ (1 + \frac{Rf}{Rin})$$



$$If = \frac{Vout}{Rf + Rin}$$

Characteristics:

1. Gain is always greater than 1
2. Input impedance is high

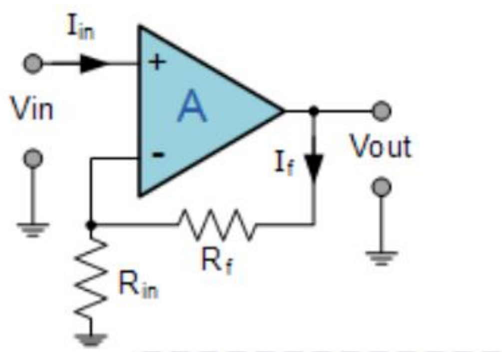
At an ideal op-amp, the voltage difference of non-inverting and inverting input of the op-amp is zero.

$$\text{Vin} - ixRin = 0$$

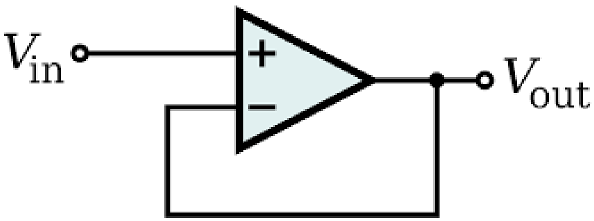
$$Vin = \frac{Vout}{Rf + Rin}\ x\ Rin$$

$$Vout = Vin\ x\ \left(\frac{Rf + Rin}{Rin}\right) = Vin\ x\ (1 + \frac{Rf}{Rin})$$

Voltage Follower

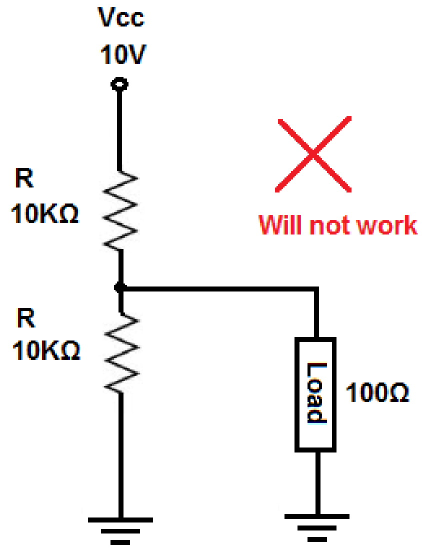


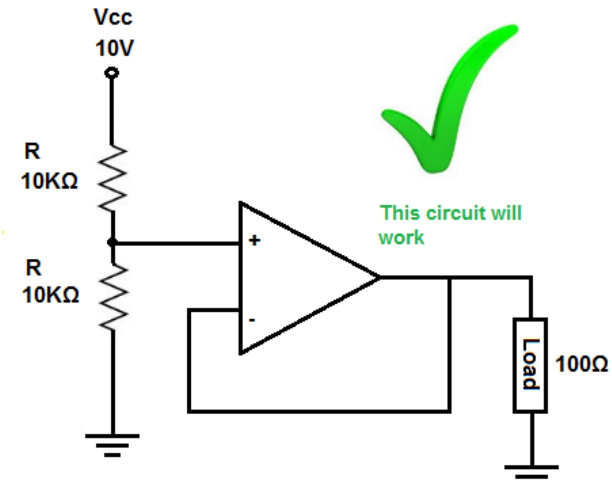
Make Rin to ∞
Make Rf = 0 ohm



This is a voltage follower with Gain = 1
It is also call a buffer.

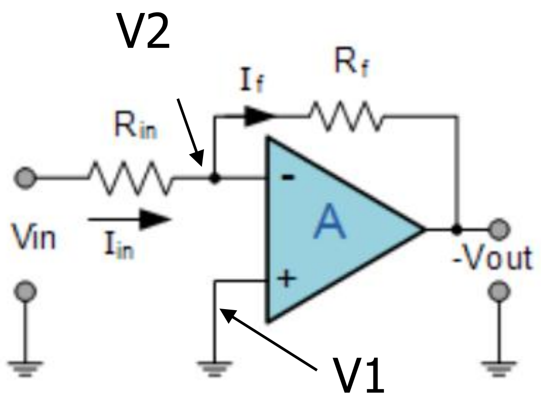
It provides isolation between input and output. The signal is regenerated to provide driver to next circuit.





Inverting Amplifier

$$\text{Vout} = \text{-Vin}\ x\ (\frac{Rf}{Rg})$$



Characteristics:

1. Gain is always negative.
2. Input impedance can be small

At an ideal op-amp, the voltage difference of non-inverting and inverting input of the op-amp is zero. Thus V2 = V1=0

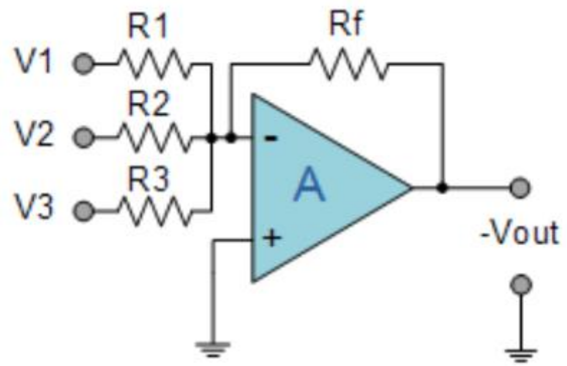
$$Iin = \frac{Vin - V2}{Rin} = \frac{Vin}{Rin}$$

$$If = \frac{V2 - Vout}{Rf} = -\frac{Vout}{Rf}$$

$$Iin = \frac{Vin}{Rin} = If = -\frac{Vout}{Rf}$$

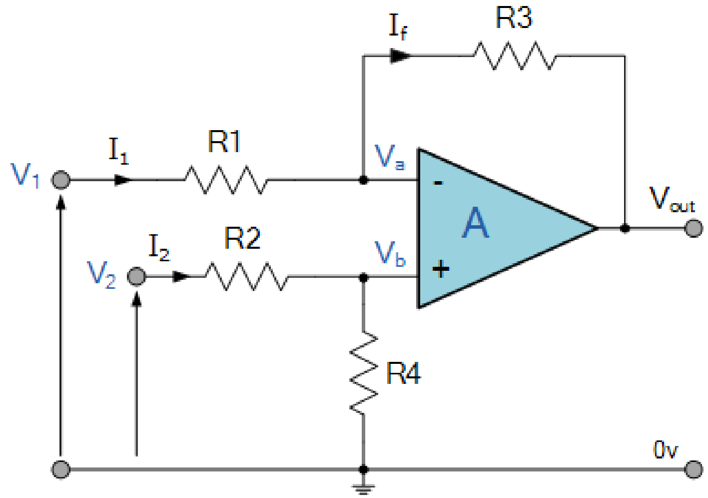
$$Vout = -\text{Vin}\ x\ (\frac{Rf}{Rg})$$

OpAmp Adder (Summing OpAmp)



$$Vout = -(\frac{Rf}{R1}V1 + \frac{Rf}{R1}V2 + \frac{Rf}{R1}V3)$$

OpAmp Subtractor (Differential OpAmp)



When R1=R2 and R3=R4

$$\text{Vout} = \frac{R3}{R1}(V2 - V1)$$

Transimpedance Amplifier

So far, we know the Gain of an Opamp is very high. The input of an ideal Opamp draw not current. So, if we put some input current into the inverting input, the gain is so high that all of the input current must go through the feedback resistor. So, the output will be Vout = - (Iin x R) See the figure

Now, we have a current to voltage converter. It is often referred to as a Transimpedance Amplifter (TIA) where the "gain" or transimpedance is equal to the feedback resistor.

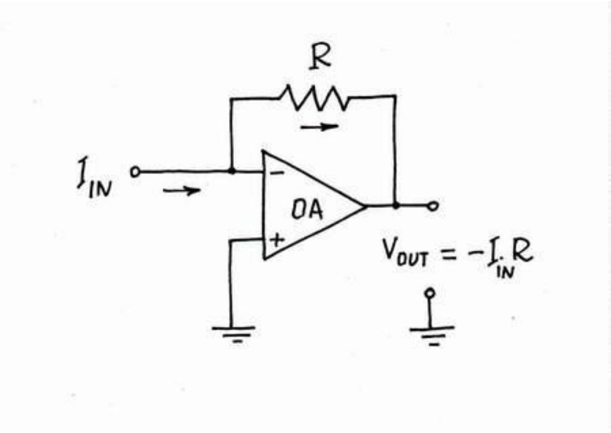


Photo Receiver

An important application when you need an Opam to amplify the signal from a sensor, such as photodiode.

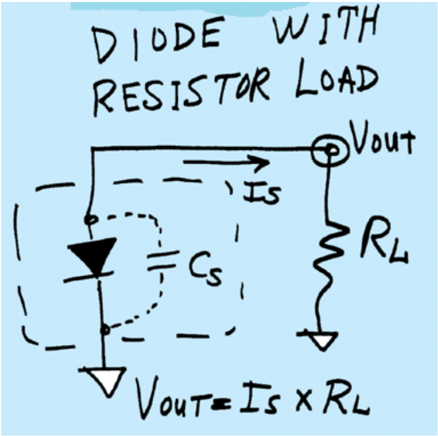
Photodiode puts out current but often have a lot of capacitance. If we just let the photo diode dump its current out into a resistor, there are two problems:

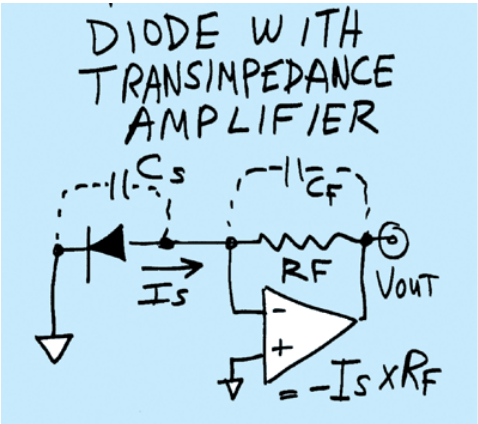
1. In order to get high gain, the resistor value needs to be higher. However, response speed will be slow and time-constant will be large

   t = RL x Cs

2. But if we choose a smaller sensing resistor to get a smaller t, the gain will be low. We may not distinguish the signal from noise.

To avoid this terrible compromise, it is a good idea to feed to the photodiode's output current directly into the inverting input of an Opamp. Here, the response is not RL x Cs but faster. And, gain can be larger because now we can use a larger RF.



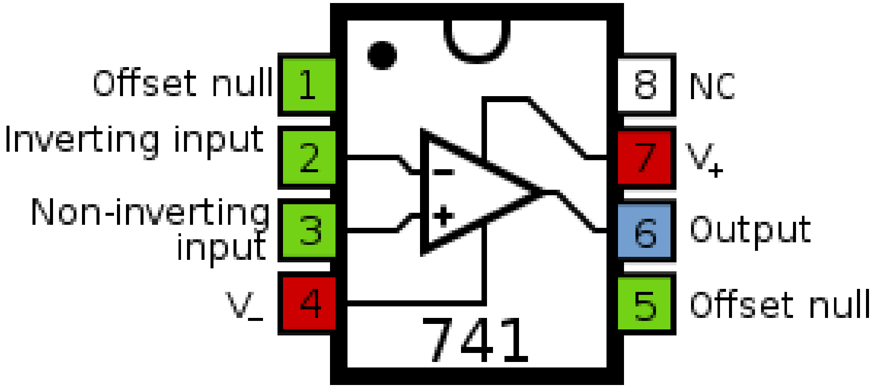


LM741

- LM741, initially designed by National Semiconductor in 1960s, is general-purpose operational amplifier intended for a wide range of analog applications. The high gain and wide range of operating voltage provide superior performance in integrator, summing amplifier, and general feedback applications.
- LM741 can operate with a single or dual power supply voltage.
- Here is some of its specification

Parameter	Min	Nom	Max	Unit
Supply Voltage	+/-10	+/-15	+/-22	V
Operating Tempeature	-55		125	C
Input Offset Voltage		1	5	mV
Input Bias Current		20	200	nA
Large Signal Voltage Gain		50	200	V/mV
Transient Response (Rise Time)		0.3		Us
Supply Current		1.7	2.8	mA

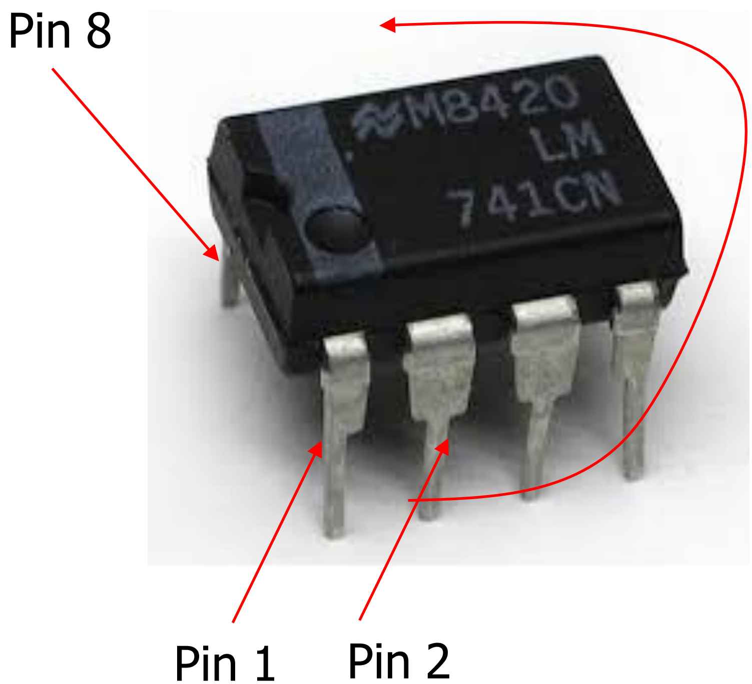
LM741 -- Continued



NC – No Electrical Connection

Pin 1 and 5 can be used to adjust offset voltage from few mV to zero. For most application that precision is not critical, simple leave them unconnected

The pin number increments at counter clockwise way



Experiement (1) –

Non-Inverting Amplifier

Experiement (2) –
Inverting Amplifier

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Digital Logic – Concept

- Rather than referring to voltage levels of signals, we should consider signals that are logically 1 or 0 (or asserted or de-asserted)

Logic operation: NOT, AND, OR, XOR

Truth tables

NOT

A	$\overline{A}$
0	1
1	0

AND

A	B	A and B
0	0	0
0	1	0
1	0	0
1	1	1

OR

A	B	A or B
0	0	0
0	1	1
1	0	1
1	1	1

XOR

A	B	A xor B
0	0	0
0	1	1
1	0	1
1	1	0

Gates

Output is 1 iff:

- NOT: Input is 0
- AND: Both inputs are 1s
- OR: At least one input is 1
- XOR: Inputs are not equal

- Gates are simplest digital logic circuits, and they implement basic logic operations (functions)
- Gates are designed using transistors
- Gates are used to build more complex circuits that implement more complex logic functions.

Digital Logic – Basic Laws of Boolean Algebra

- Operation AND: *
- Operation OR: +
- Inverse of A: $\overline{A}$
- Identity Laws: A + 0 = A, A * 1 = A
- Inverse laws: A+$\overline{A}$ = 1, A *$\overline{A}$ = 0
- Zero and one laws A + 1 = 1, A * 0 = 0
- Commutative laws: A+B = B + A, A * B = B * A
- Associative laws:
  - A+(B+C) = (A+B) + C; A*(B*C) = (A*B)*C
- Distributive laws:
  - A * (B+C) = (A*B) + (A *C); A + (B * C) = (A+B) * (A +C)
- DeMorgan's laws:

$$\overline{(A+B)} = \overline{A} * \overline{B}$$

$$\overline{(A*B)} = \overline{A} + \overline{B}$$

Digital Logic – Minimization using Boolean Laws

- Consider one of logic equations:

$$y1 = \overline{x_1} * \overline{x_2} * \overline{x_3} + \overline{x_1} * \overline{x_2} * x_3 + \overline{x_1} * x_2 * x_3 + x_1 * x_2 * x_3$$

$$= \overline{x_1} * \overline{x2} * (\overline{x_3} + x_3) + x_2 * x_3 * (\overline{x_1} + x_1)$$

$$= \overline{x_1} * \overline{x_2} + x_2 * x_3$$

- But if we start grouping in some other way, we may not end up with the minimal equation.

Digital Logic Example
(Three-way Light Switch)

- Supposed a room has three doors and a switch by each door controls a single light in the room.
  - Let x, y, and z denote the state of the switches
  - Assume the light is off if all switches are open
  - Closing any switch turns the light on. Closing another switch will have to turn the light off.
  - Light is on if any one switch is closed and off if two (or no) switches are closed.
  - Light is on if all three switches are closed

Digital Logic Example - Continued
(Three-way Light Switch)

- We can write down a truth table

X	Y	Z	F	
0	0	0	0	m_0
0	0	1	1	m_1
0	1	0	1	m_2
0	1	1	0	m_3
1	0	0	1	m_4
1	0	1	0	m_5
1	1	0	0	m_6
1	1	1	1	m_7

We write down those will give us output value of 1:

$F(x,y,z) = m_1 + m_2 + m_4 + m_7$

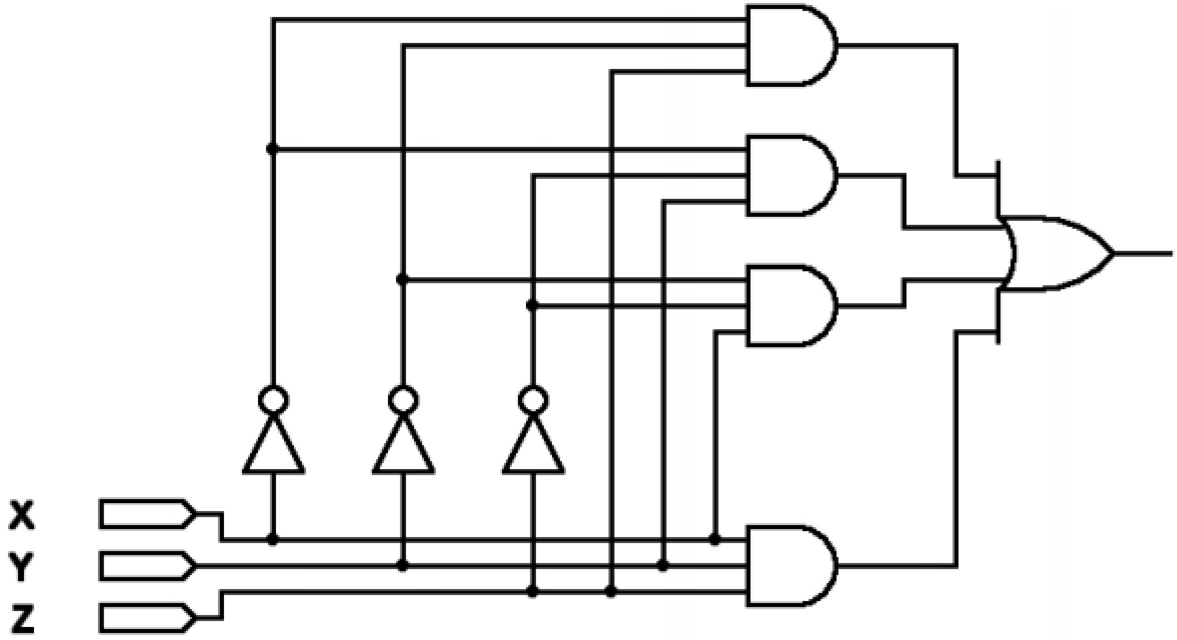
$F(x,y,z) = \bar{X}\bar{Y}Z + \bar{X}Y\bar{Z} + X\bar{Y}\bar{Z} + XYZ$

We are 3 input variables and 2 states for each input variable. Therefore the truth table has 8 entries.

Digital Logic Example - Continued
(Three-way Light Switch)

- Digital logic circuit diagram for the three-way light switch

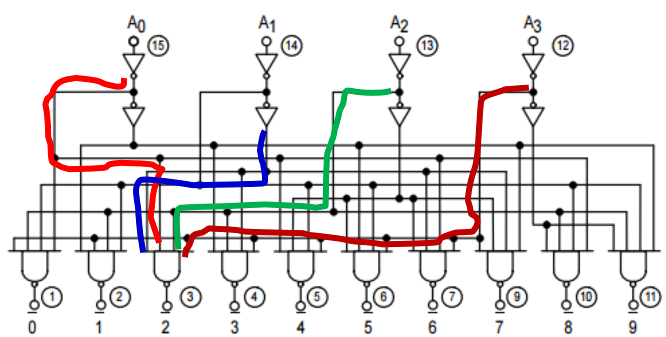
This is the simplest sum-of-products form.



Digital Logic Integrated Circuit

- BCD – Binary Coded Decimal. Decimal numbers are represented by a fixed number of bits, usually 4 or 8.
- 74LS42 – A BCD decoder
  - The LS42 decoder accepts four active HIGH BCD inputs and
  - provides ten mutually exclusive active LOW outputs, as shown by logic symbol or diagram.
  - The active LOW outputs facilitate addressing other ciruit units with LOW input enables

LOGIC DIAGRAM



V_{CC} = PIN 16
GND = PIN 8
○ = PIN NUMBERS

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Decimal digit	BCD			
	8	4	2	1
0	0	0	0	0
1	0	0	0	1
2	0	0	1	0
3	0	0	1	1
4	0	1	0	0
5	0	1	0	1
6	0	1	1	0
7	0	1	1	1
8	1	0	0	0
9	1	0	0	1

TRUTH TABLE

A_0	A_1	A_2	A_3	0	1	2	3	4	5	6	7	8	9
L	L	L	L	L	H	H	H	H	H	H	H	H	H
H	L	L	L	H	L	H	H	H	H	H	H	H	H
L	H	L	L	H	H	L	H	H	H	H	H	H	H
H	H	L	L	H	H	H	L	H	H	H	H	H	H
L	L	H	L	H	H	H	H	L	H	H	H	H	H
H	L	H	L	H	H	H	H	H	L	H	H	H	H
L	H	H	L	H	H	H	H	H	H	L	H	H	H
H	H	H	L	H	H	H	H	H	H	H	L	H	H
L	L	L	H	H	H	H	H	H	H	H	H	L	H
H	L	L	H	H	H	H	H	H	H	H	H	H	L
L	H	L	H	H	H	H	H	H	H	H	H	H	H
H	H	L	H	H	H	H	H	H	H	H	H	H	H
L	L	H	H	H	H	H	H	H	H	H	H	H	H
H	L	H	H	H	H	H	H	H	H	H	H	H	H
L	H	H	H	H	H	H	H	H	H	H	H	H	H
H	H	H	H	H	H	H	H	H	H	H	H	H	H

H = HIGH Voltage Level
L = LOW Voltage Level