Embedded Hardware Design and Development

Unit 1

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Overview of
Embedded Electronics
and
Embedded Computer Systems

Embedded System

- Embedded means something that is attached to another thing.
- can be thought of as a computer hardware system having software embedded in it.
- can be an independent system or it can be a part of a large system.
- is a microcontroller or microprocessor based system which is designed to perform a specific task.

Embedded System : Advantages

Low cost.

Small size.

High reliability.

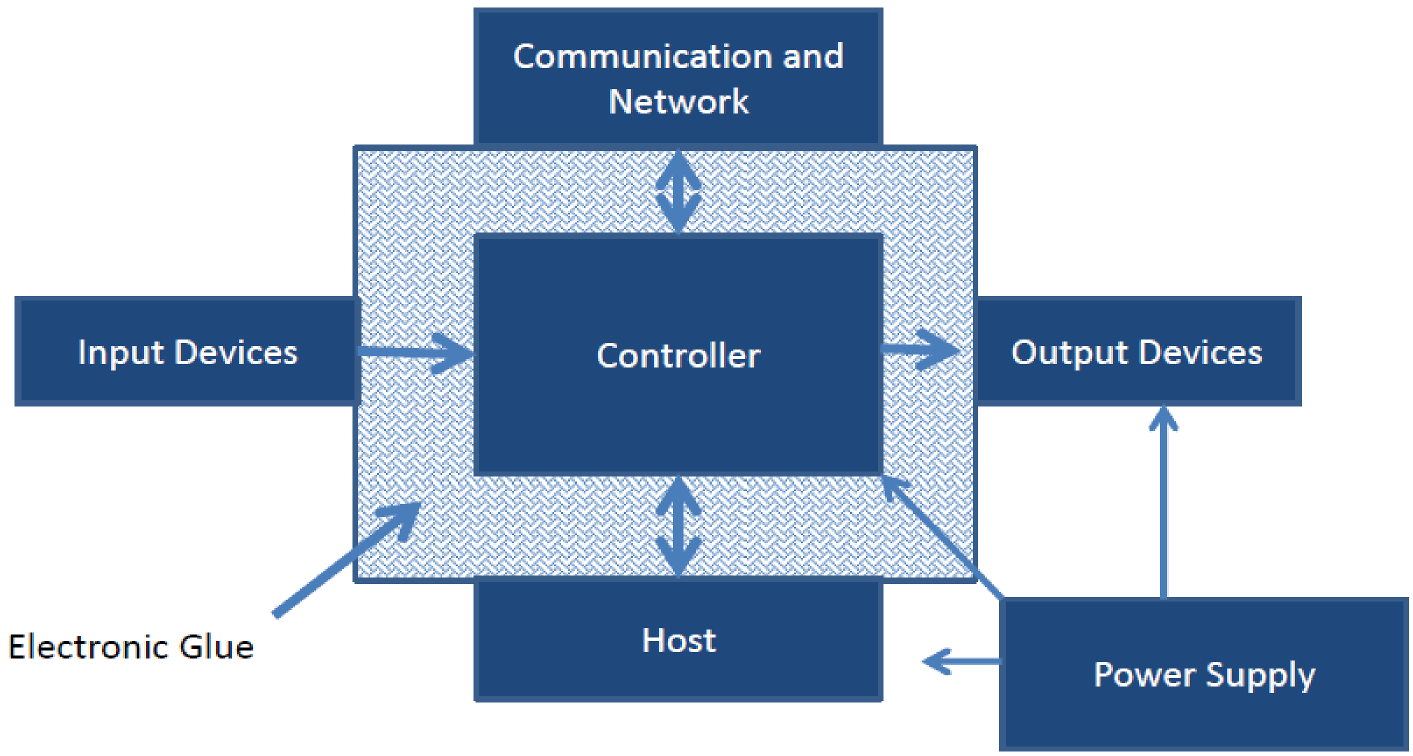
Fast operations.

Easy to manufacture.

Fewer interconnections.

Embedded System

Embedded System : 6-Box Model



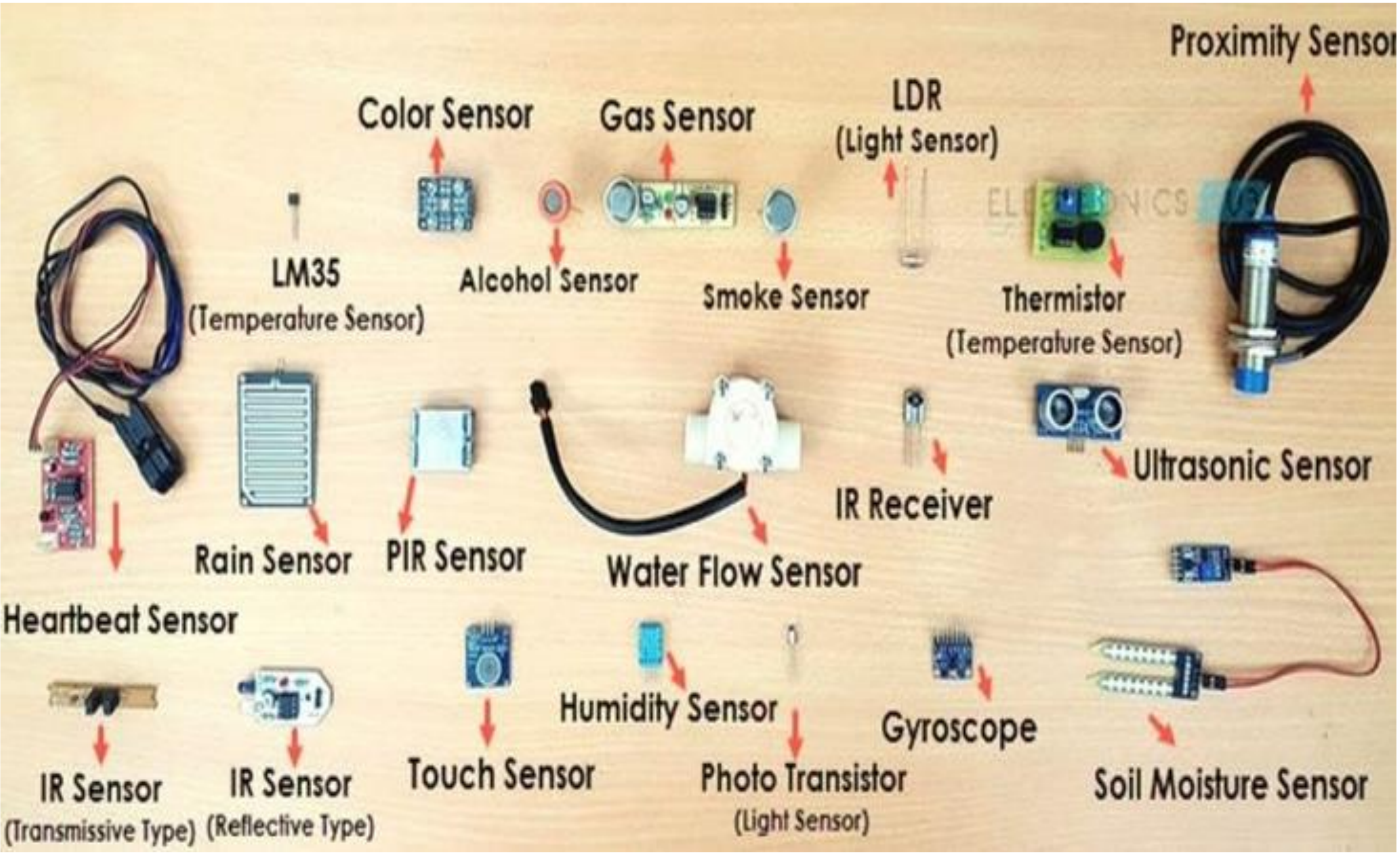
1. Input Devices

1. Input Devices

- Keyboards
  - Push button
  - Switches (DIP, Slide)
- Pointing device
  - mouse
  - touchpad
  - pointing stick
  - touchscreen
  - trackball

- Composite devices
  - Joystick controller
  - Gamepad (or joypad)
  - Paddle (game controller)
  - Jog dial/shuttle (or knob)
  - WiiRemote
- Graphic input devices
  - Webcam
  - Video Camera
- Audio input devices
  - Microphone

1. Input Devices

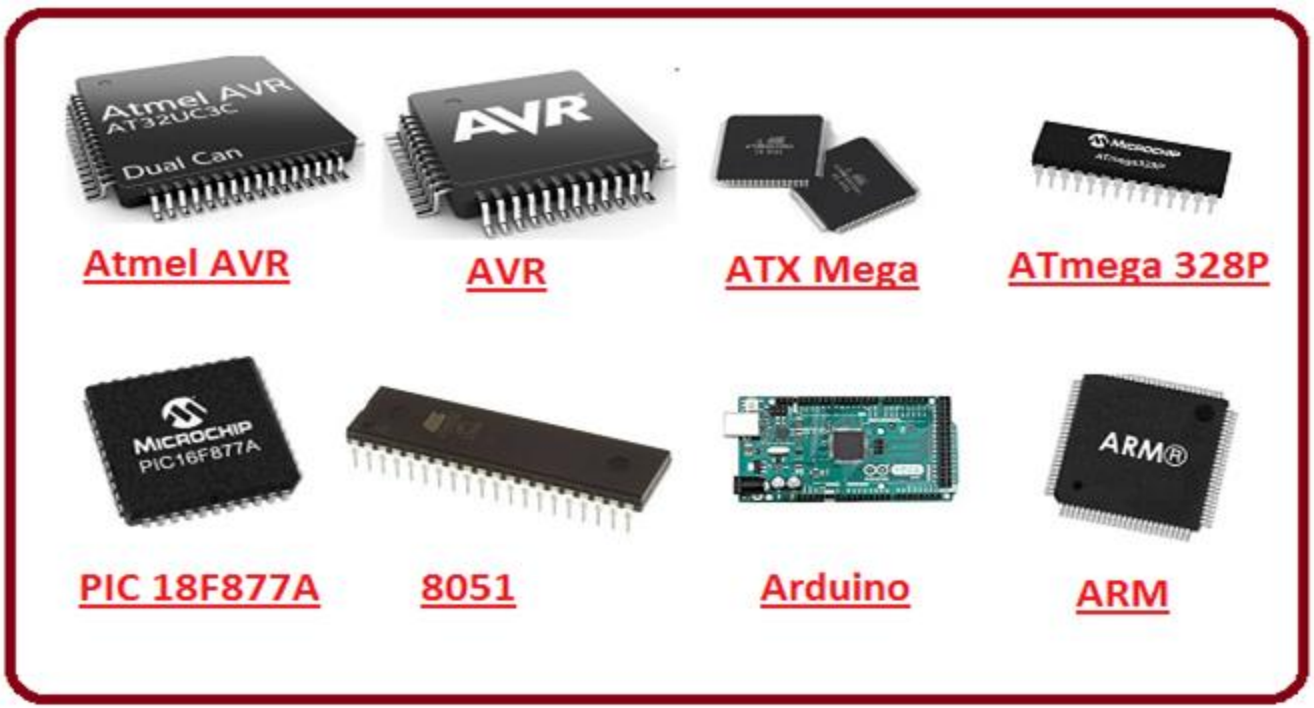


2. Output Devices

- Audio
  - Speakers
  - Headphones
  - Voice output communication aid (speech-generating device)
- Graphics
  - Screen (Monitor)
  - LCD, LED
- Printer
  - Punched tape
  - Braille embosser
  - Plotter
- Data through wired/wireless communication

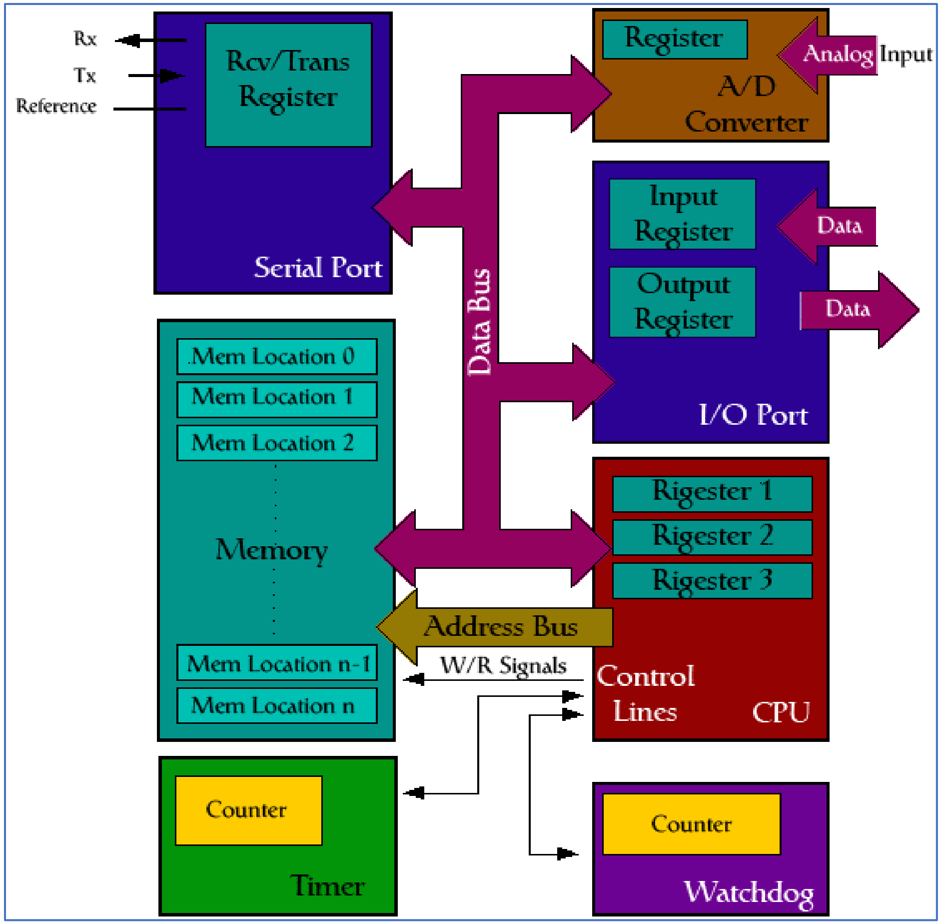
3. Controller

- The core of embedded system
- Controls the operations of peripherals by running a sequential set of operations
- Has variety of types

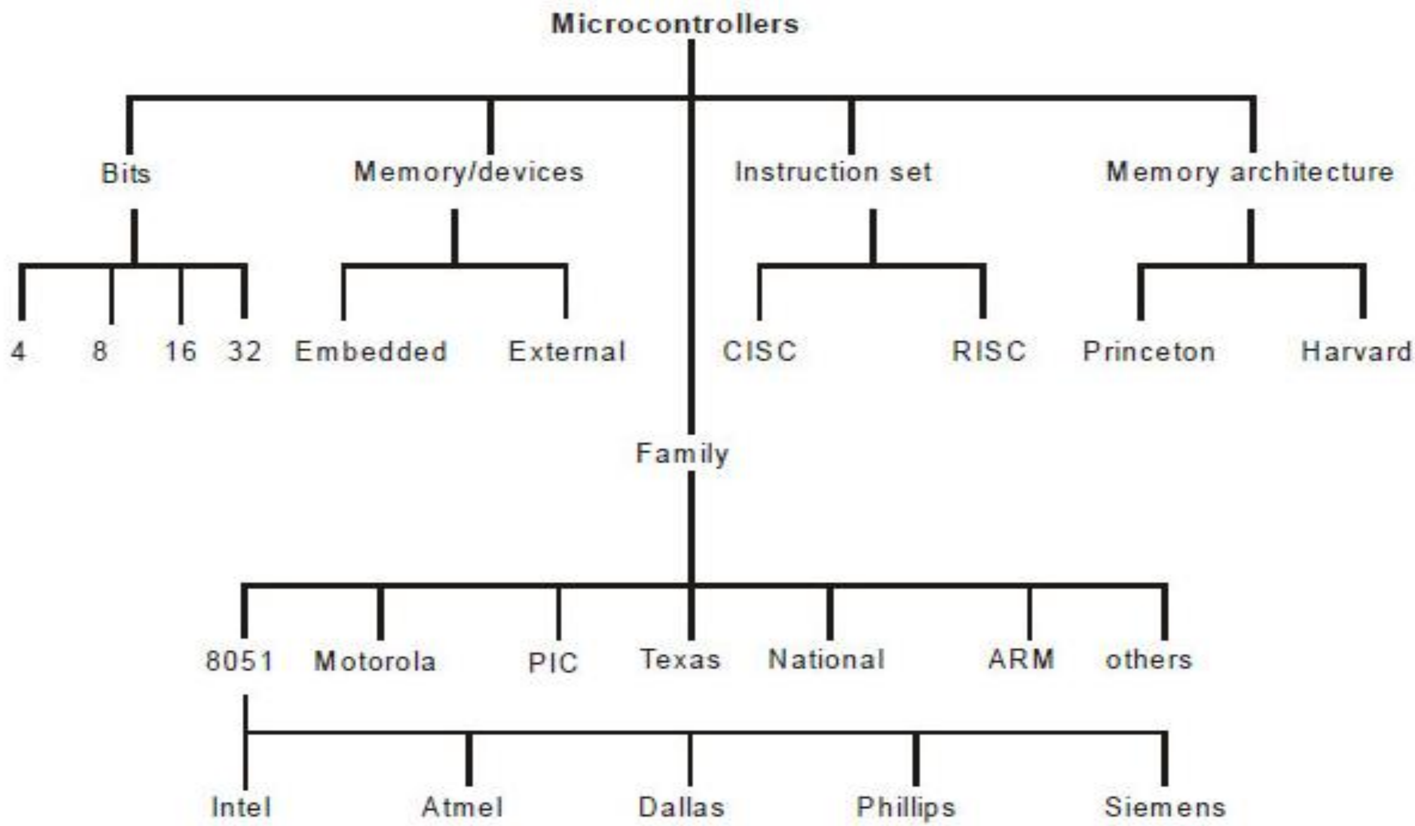


3. Controller : Building blocks

- CPU
- Memory
- Input/output ports
- Serial Ports
- Timers
- ADC
- DAC
- Special Functioning Blocks

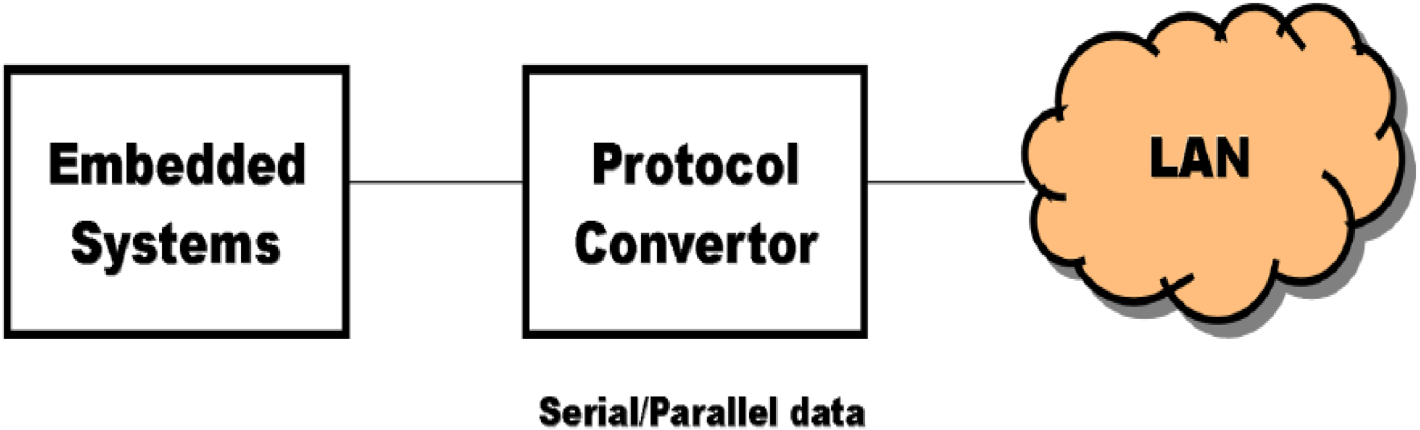


3. Controller



Types of microcontrollers

4. Communication and Network



4. Communication and Network

- **NoCs**– connecting processors inside MPSoCs (multiprocessor systems-on-chip)
- **SPI,I2C**– connecting discrete components inside boards
- **USB, FireWire**– connecting peripherals around a PC
- **Bluetooth, RFID**– connection of peripherals or sensors in small areas(BANs,PANs...)
- **SCSI, SCI-** High speed connection of servers in server farms (SANs)
- **CAN, field buses** connection of sensors, actuators and controlling equipment in a monitoring or control plant

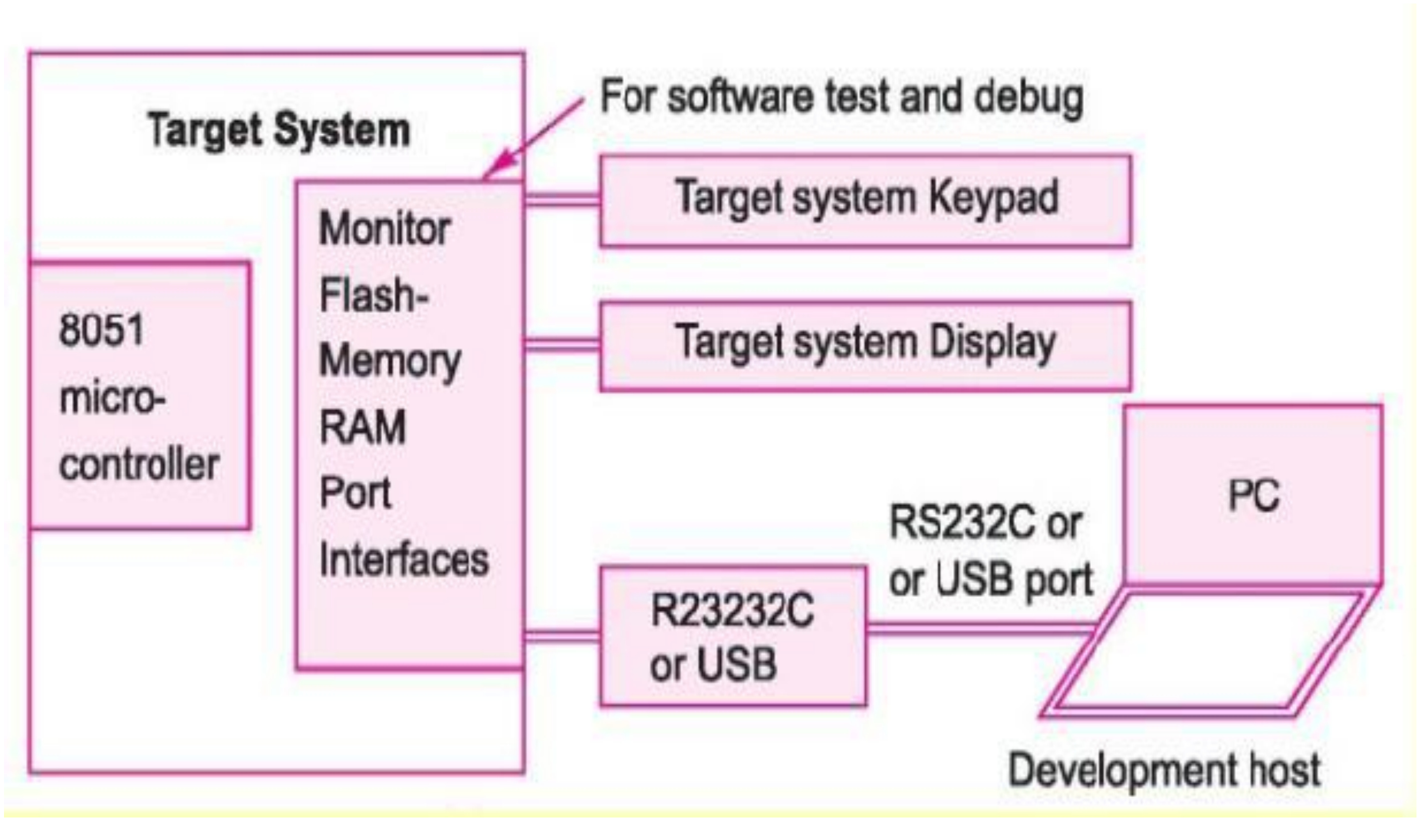
4. Communication and Network

- Zigbee, low power radios – connection of autonomous dispersed sensors(WSNs)
- Ethernet, WiFi – connection of PCs, and independent equipments in a local setup(LANs)
- 10G Ethernet – connection of large systems in large areas (MANs, WANs)
- Telecommunication networks – Global communications (MANs, WANs)

5. Host

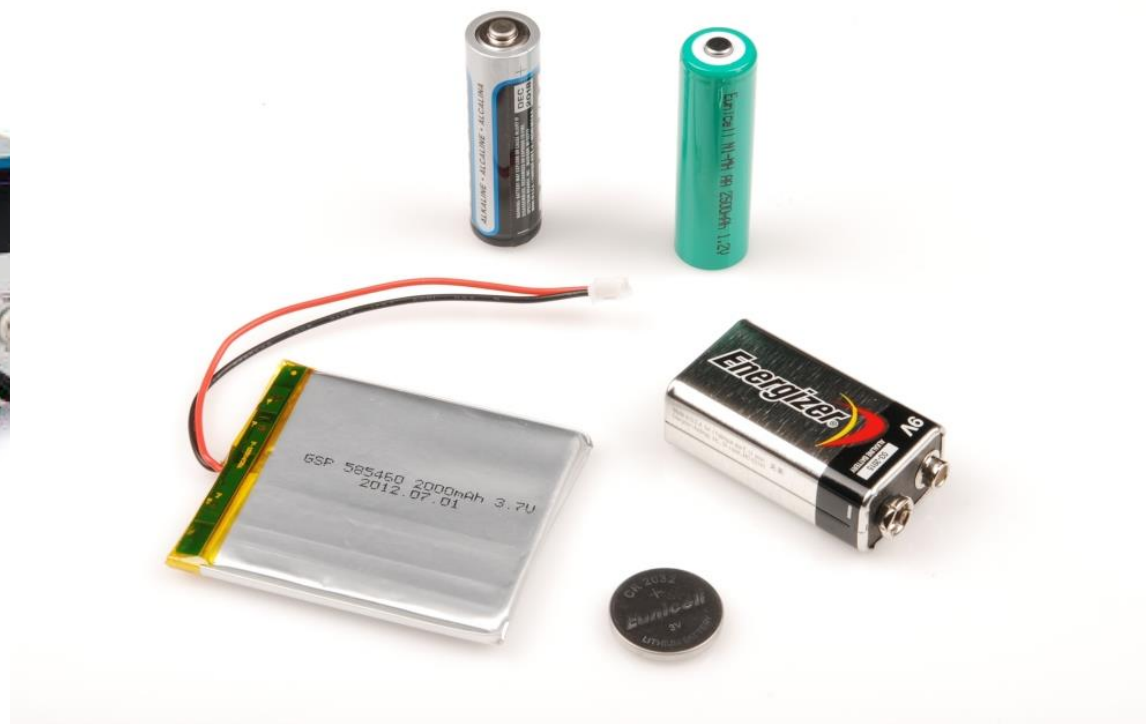
- Used During development process
- Does locating and burning the codes in the target board.
- Target board hardware and software later Copied to get the final embedded system
- Final system function exactly as the one tested and debugged and finalized during the development process

5. Host

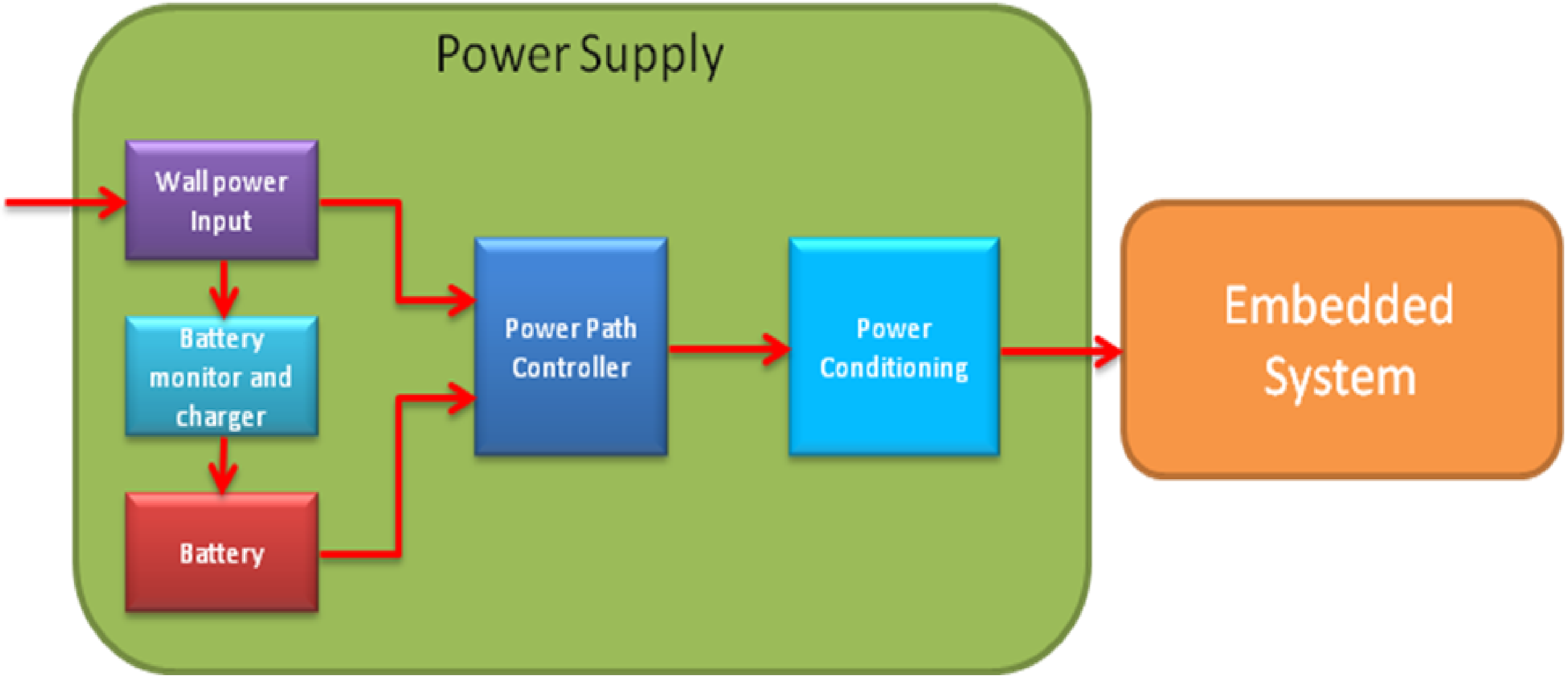


Target System
For software test and debug
Target system Keypad
Monitor
Flash-
Memory
RAM
Port
Interfaces
8051
micro-
controller
Target system Display
PC
RS232C or
or USB port
R23232C
or USB
Development host

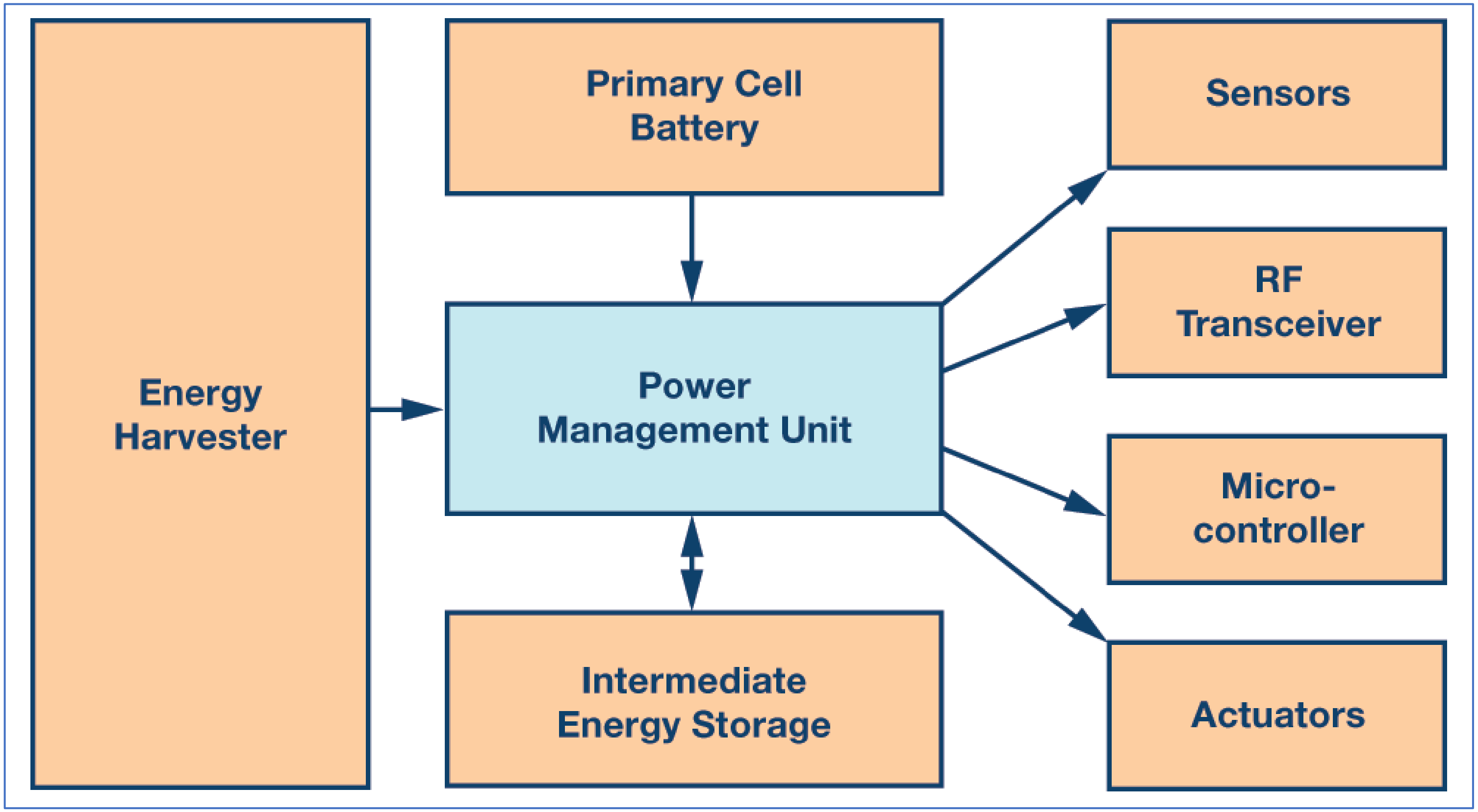
6. Power Supply



6. Power Supply



6. Power Supply



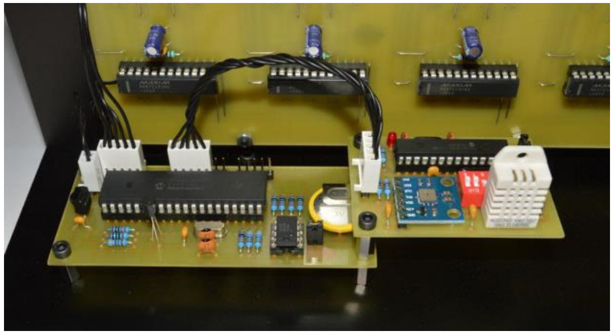
Electronic Glue

- Special circuitry that allows different types of circuits to work together
- Peripheral supporting circuits
- Interfaces
- Act as communication or conversion bridges


Relay Driver

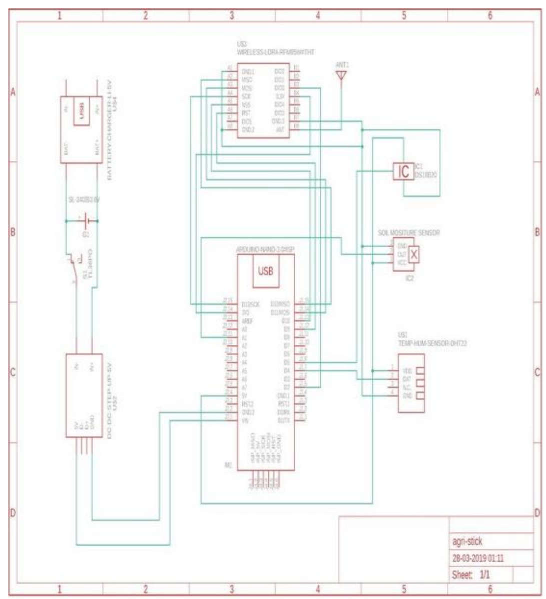

H Bridge motor driver

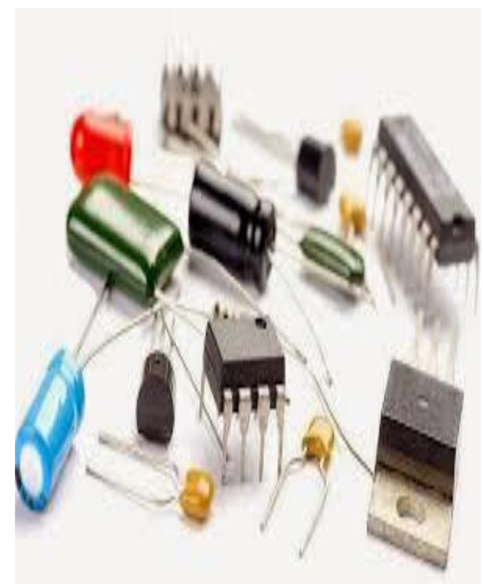

TTL to CMOS Converter



Hierarchical representation

System ← Circuit ← Devices





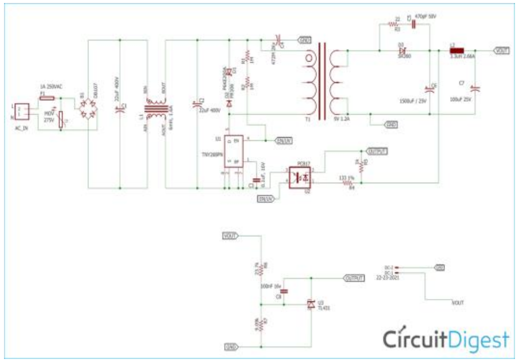
Agri-Stick” which is going to measure the four Agri parameters including **Soil Temperature, Soil Moisture, Atmospheric Temperature and Atmospheric Humidity**. (https://www.instructables.com/id/Agri-Stick/)

Hierarchical representation

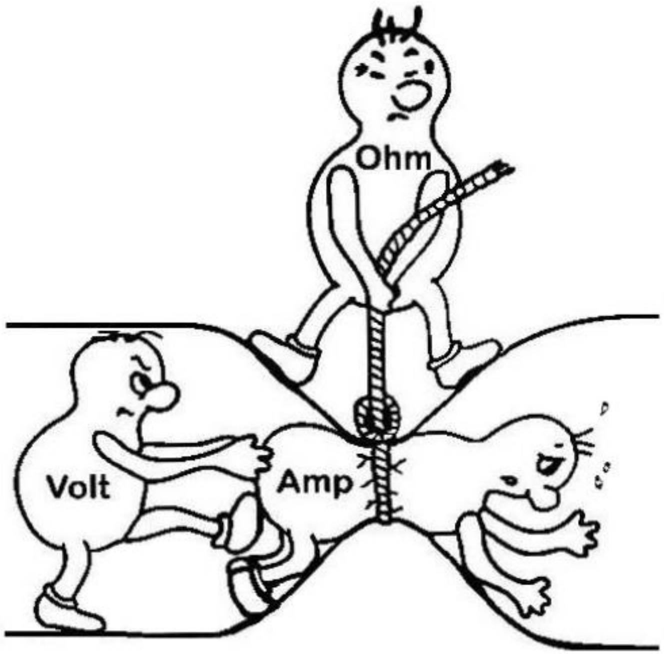
System implementation with electronic circuit

Circuit design with electronic devices

Electronic Devices

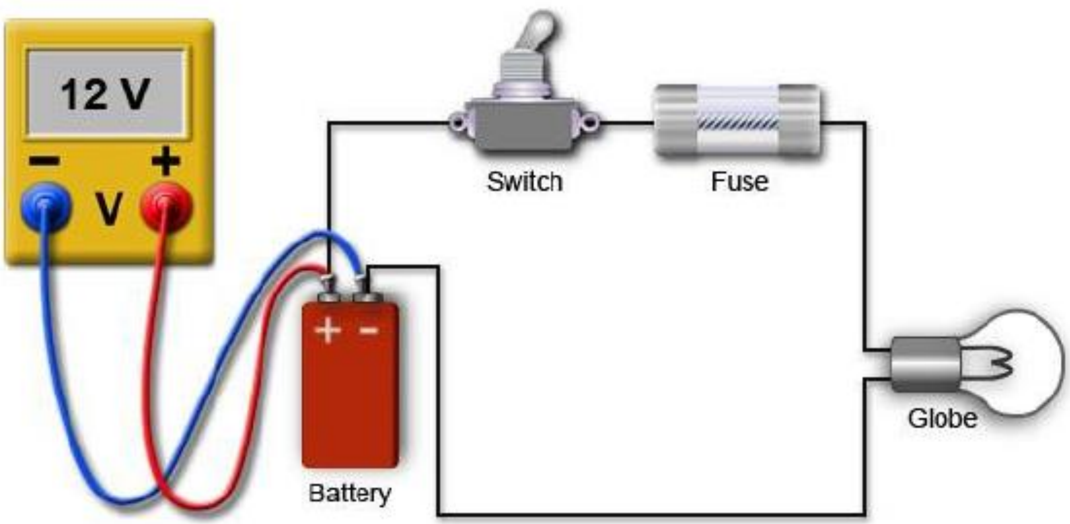


Important Parameters (Voltage, Current, Power)



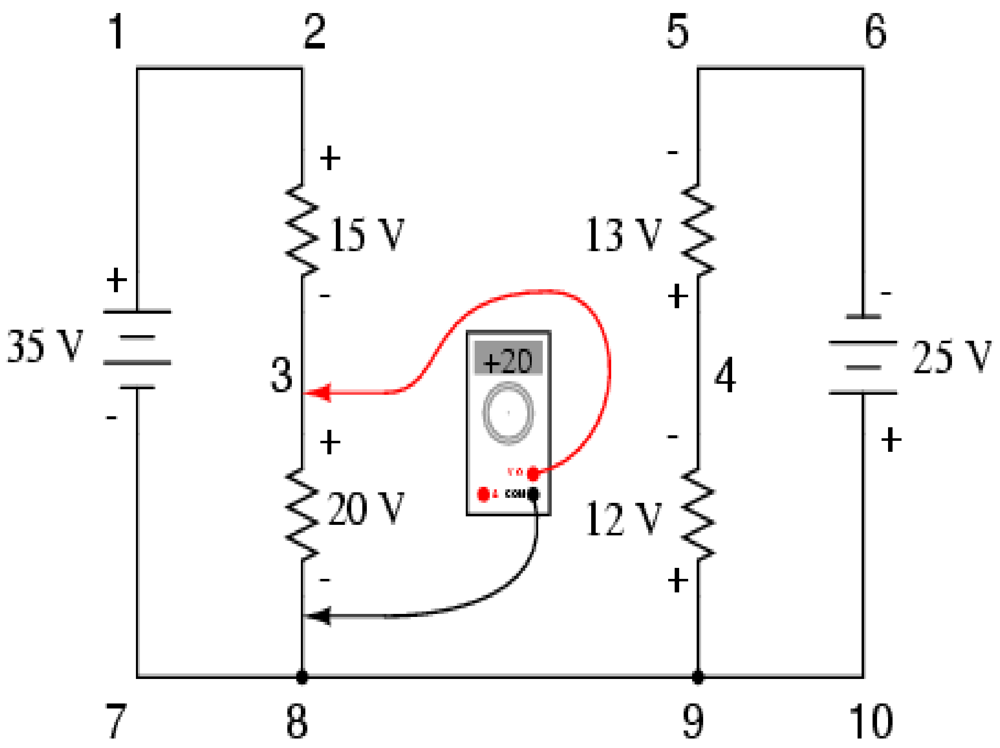
Voltage

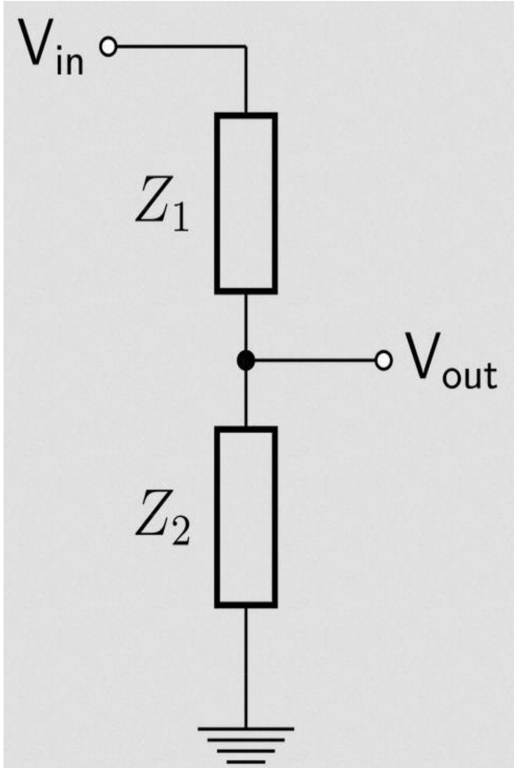
- Voltage, also called *electromotive force*, is a quantitative expression of the potential difference in charge between two points in an electrical field.



Voltage

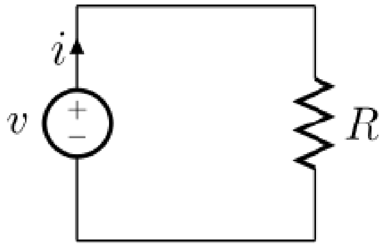
- The symbol for potential difference is E (for electromotive force)
- The practical unit of potential difference is the volt (V)

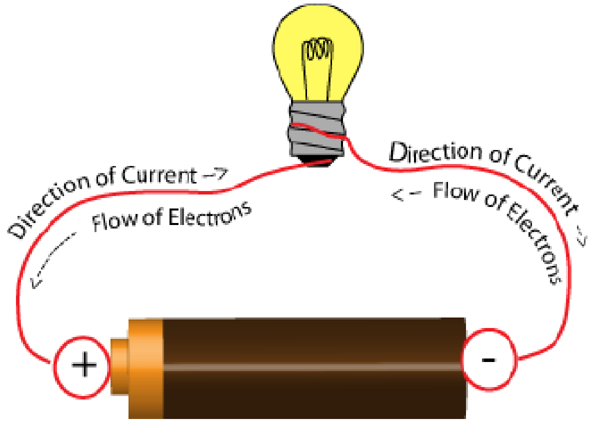




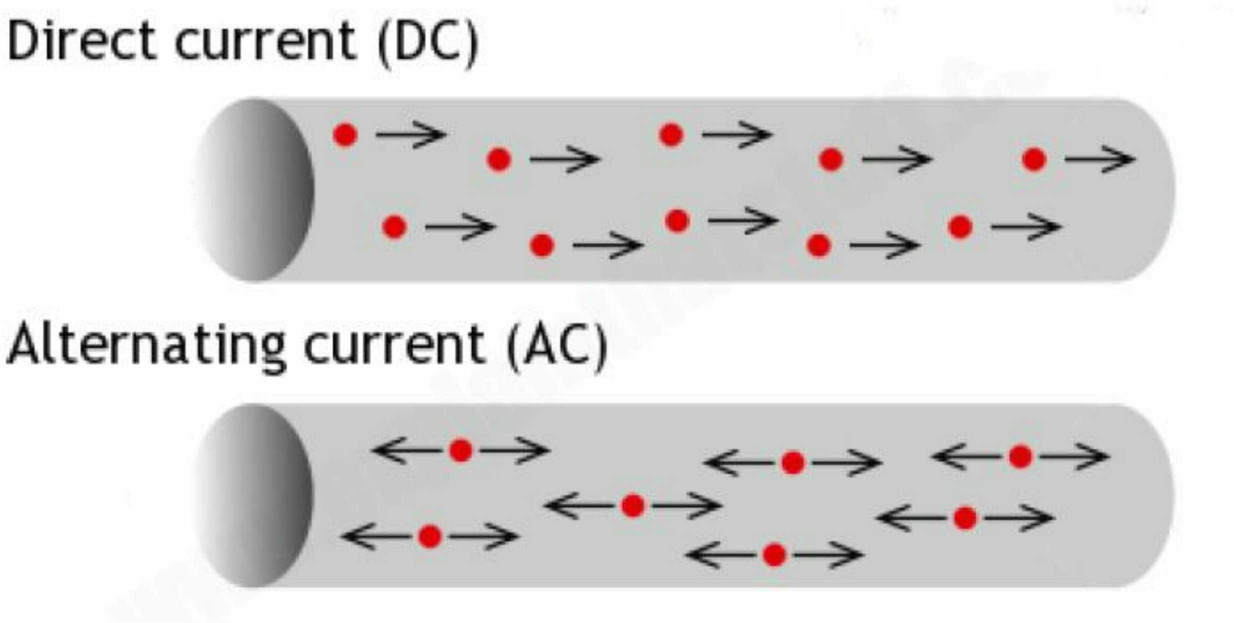
Current

- Electric current is defined as the rate at which charge flows through a surface (e.g. the cross section of a wire).
- The symbol for current is I (for intensity) and is measured in amperes.

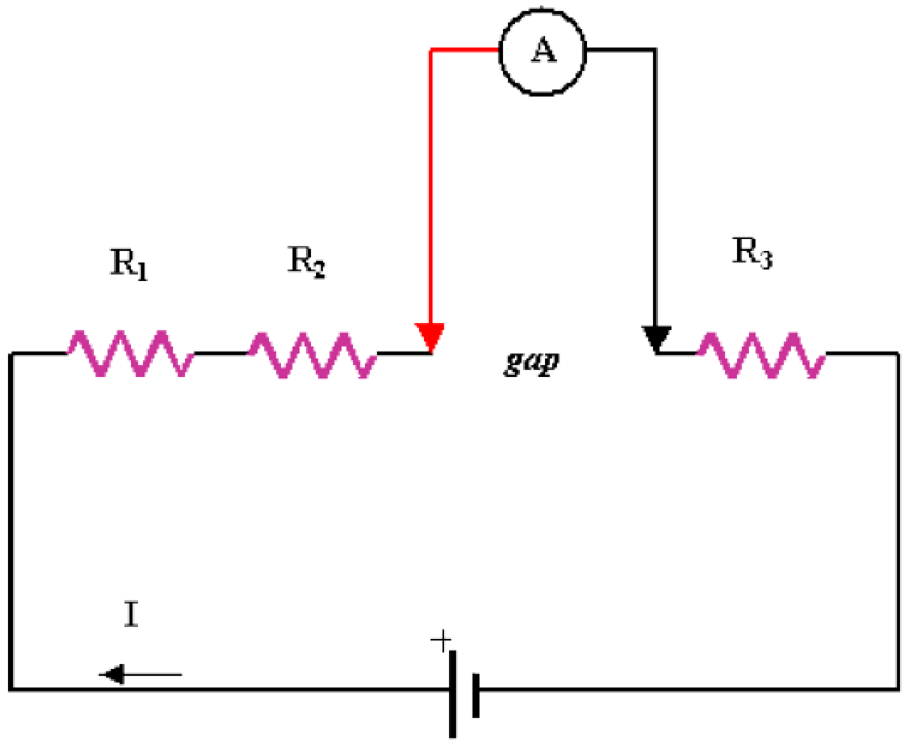




Current



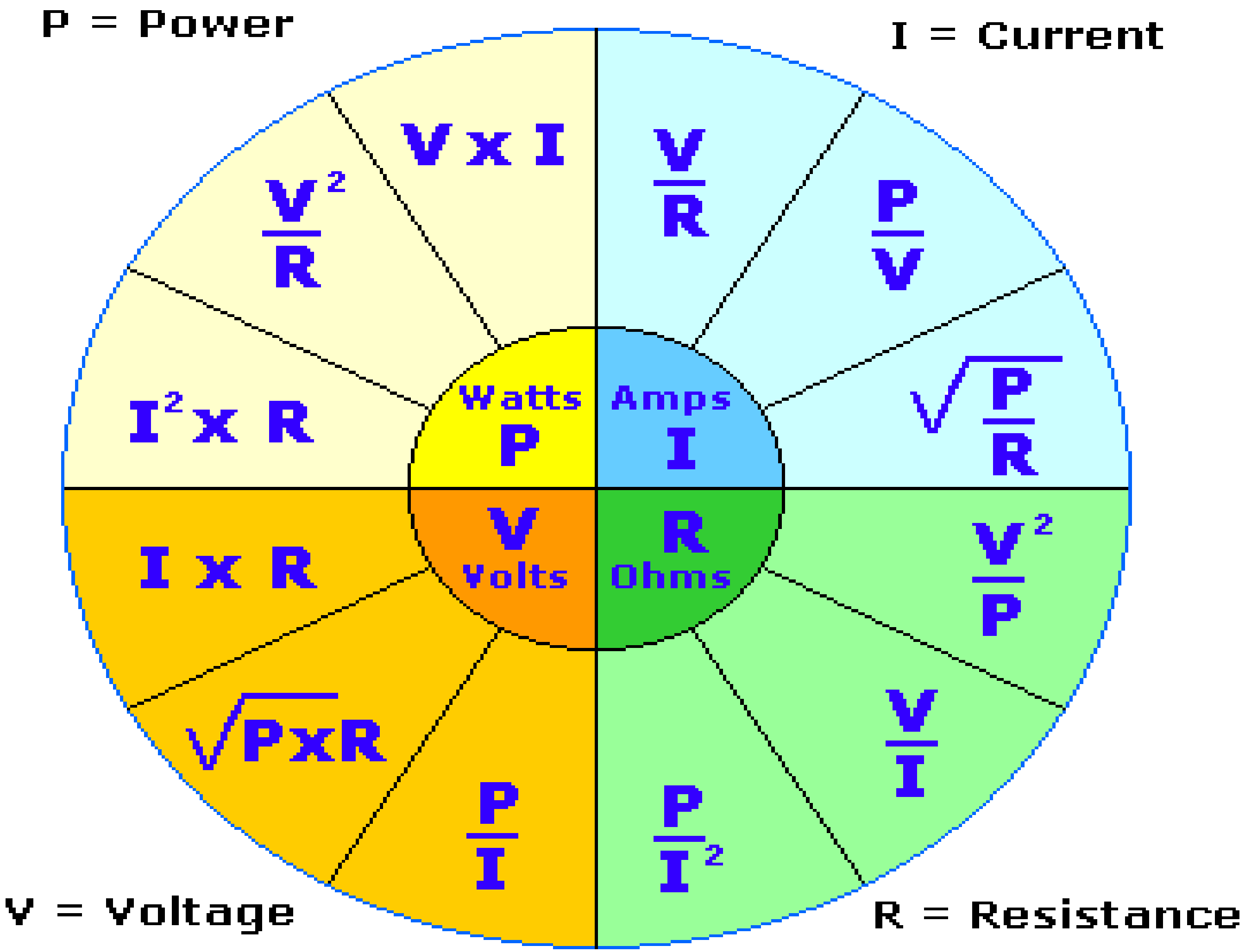
Current



Power

- Electric power is the rate, per unit time, at which electrical energy is transferred by an electric circuit.
- The unit of electrical power is the watt.

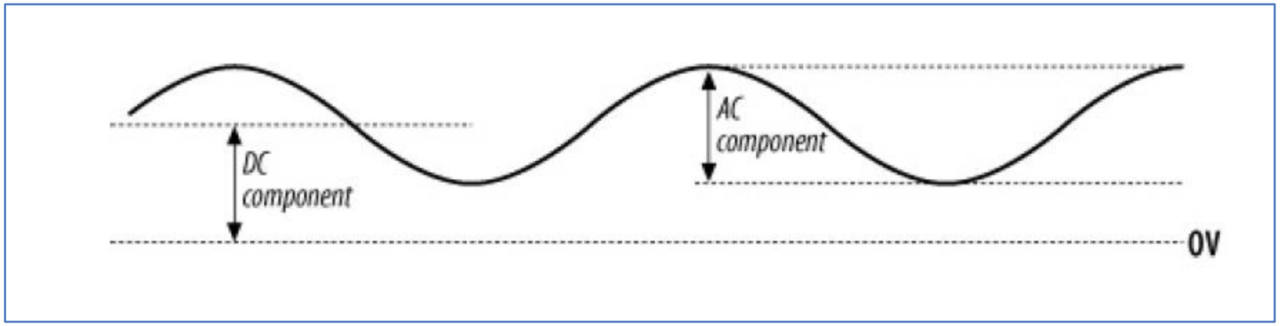
Voltage, Current, Power



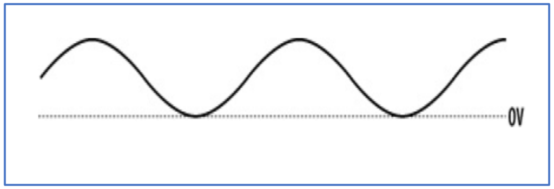
Electronics Fundamentals

Analog Signals

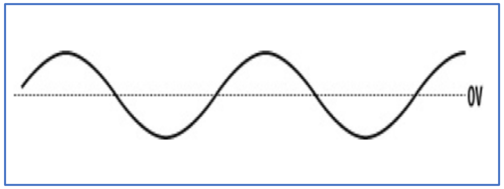
- A typical analog signal will have both an *AC component* and a *DC component*
- DC has a constant value
- AC has a value that changes sinusoidally



- Unipolar Signal



Bipolar Signal



Hardware Devices

Active Components:

- Those devices or components which require external source to their operation
- For Example: Diode, Transistors, SCR etc.
- Need specific conditions for operating
- Energy Donor

Passive Components:

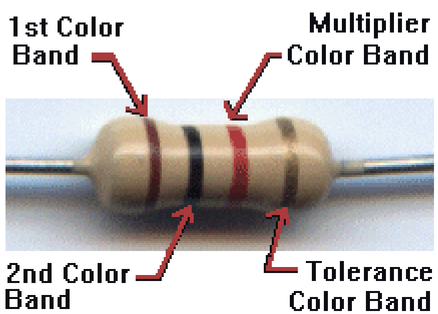
- Those devices or components which do not require external source to their operation
- For Example: Resistor, Capacitor, Inductor etc.
- Starts work automatically without using a specific voltage
- Energy Acceptor

A. Resistors:

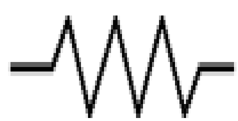
Resistors are passive elements that **oppose/restrict the flow of current.**

A voltage is developed across its terminal, proportional to the current through the resistor.

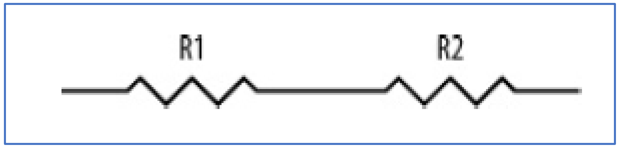
$$V = IR$$



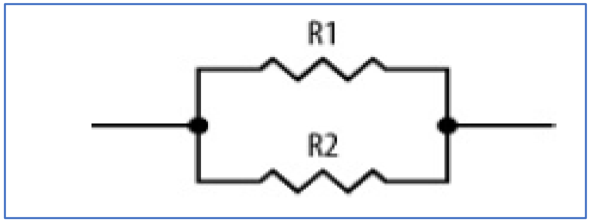
Units: Ohms (Ω)



A. Resistors: Connections

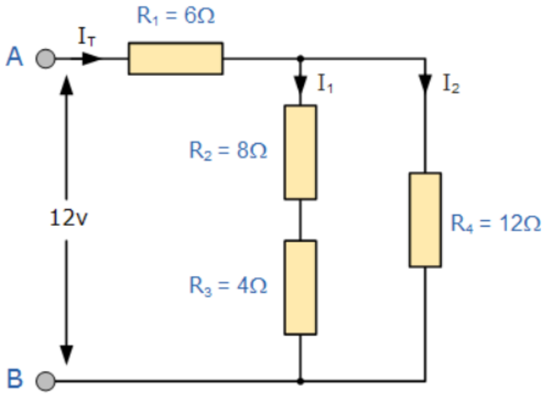


$$R_{TOTAL} = R1 + R2$$



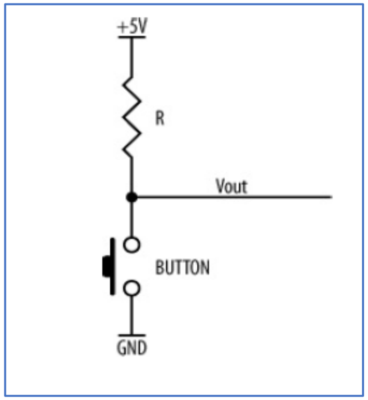
$$R_{TOTAL} = 1 / (1/R1 + 1/R2)$$

Calculate the total current (I_T) , I1, I2 taken from the 12v supply

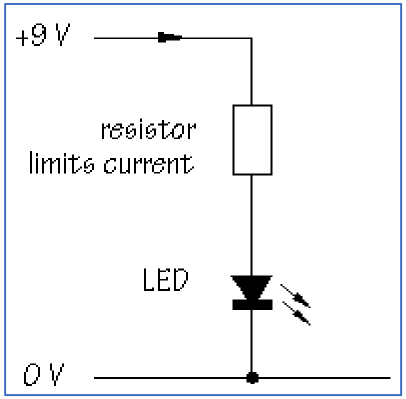


A. Resistors: Applications

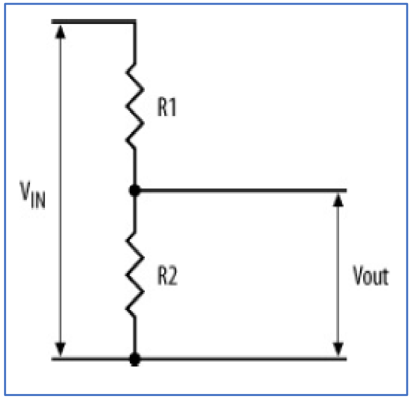
Pull Up/ Pull Down
Simple circuit can be used to switch an input between two logic level thresholds



Current Limiting Resistor



Voltage Divider



$$V_{OUT} = V_{IN} * R2 / (R1 + R2)$$

A. Resistors: Specifications

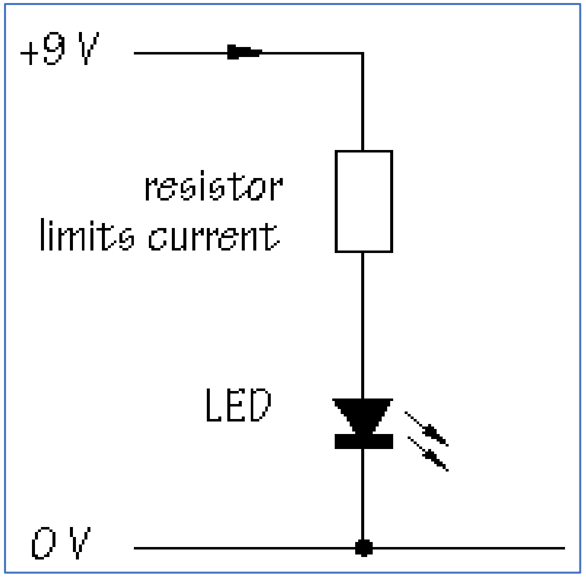
Factors which must be considered while selecting a resistor for a particular application normally include,

a) The required value of resistance expressed in Ω , K Ω or M Ω.

b) The desire accuracy or tolerance.

c) The power rating which must be equal to or greater than maximum expected power dissipation.

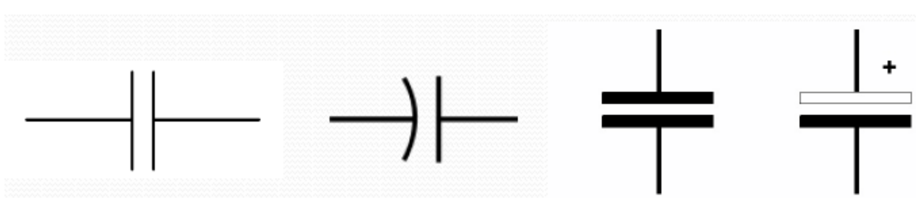
d) Noise performance should be low.



B. Capacitors

- Behave like a tiny rechargeable battery.
  (**store energy and release it later.)**
- are made of two parallel conductors separated by a dielectric.
- Types of capacitors are ceramic, mica, polyster, paper, air
- are used for **filtering, tuning, separating signals , etc.**

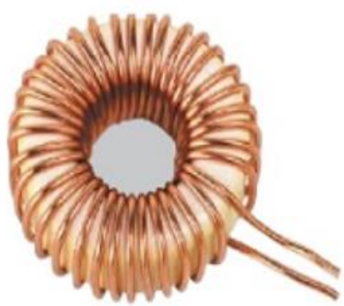
- The ability of a capacitor to store charge is called "**Capacitance**"
- ***C = Q/V*** *(amount of charge stored/applied voltage)*
- The unit of capacitance is the **Farad (F).**
  Commonly used capacitances are much smaller than 1 F
  micro-Farads (**μF**), nano-Farads (**nF)**, pico-Farads (**pF**).



C. Inductor

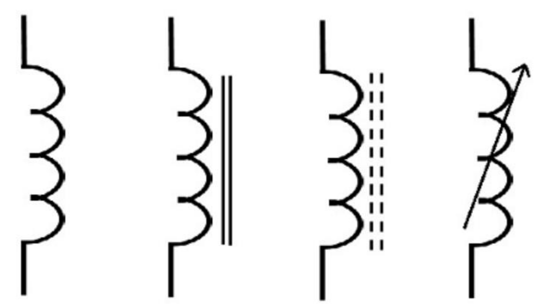
- Inductor is a passive two-terminal component that temporarily stores energy in the form of a magnetic field.
- It is usually called as a **coil**.
- Measured in units of **Henry (H)**
- Used in,
    - tuning & filter circuits, in radio receivers as a built in antenna coil
    - in transformer & coupled circuits to transfer energy from one circuit to another.
    - used to minimize the alternating current, while permitting flow of direct current.

Core



Core wounded with wire

Inductors having different types of core



Air Core Inductor

Iron Core Inductor

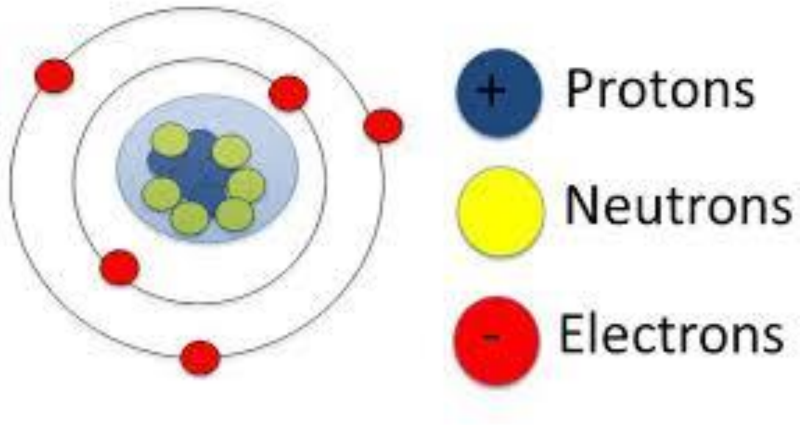
Ferrite Core Inductor

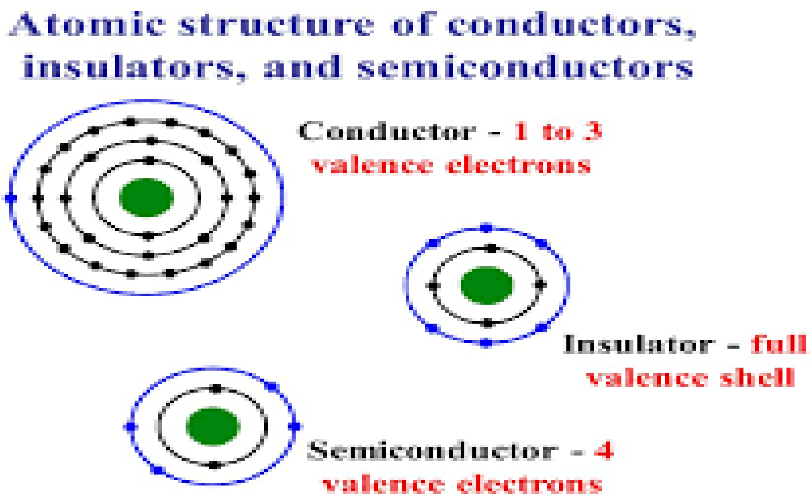
Variable Core Inductor

Active Devices

Materials classifications:

- Conductors
- Insulators
- Semi-Conductors





Materials classifications:

- ***Insulators***
- An **insulator** is a material that does not conduct electrical current under normal conditions.
- Most good insulators are **compounds** rather than single-element materials and have very high resistivities.
- Valence electrons are **tightly bound** to the atoms; therefore, there are very few free electrons in an insulator.
- Examples of insulators are **rubber, plastics, glass, mica**, and **quartz**.

Materials classifications:

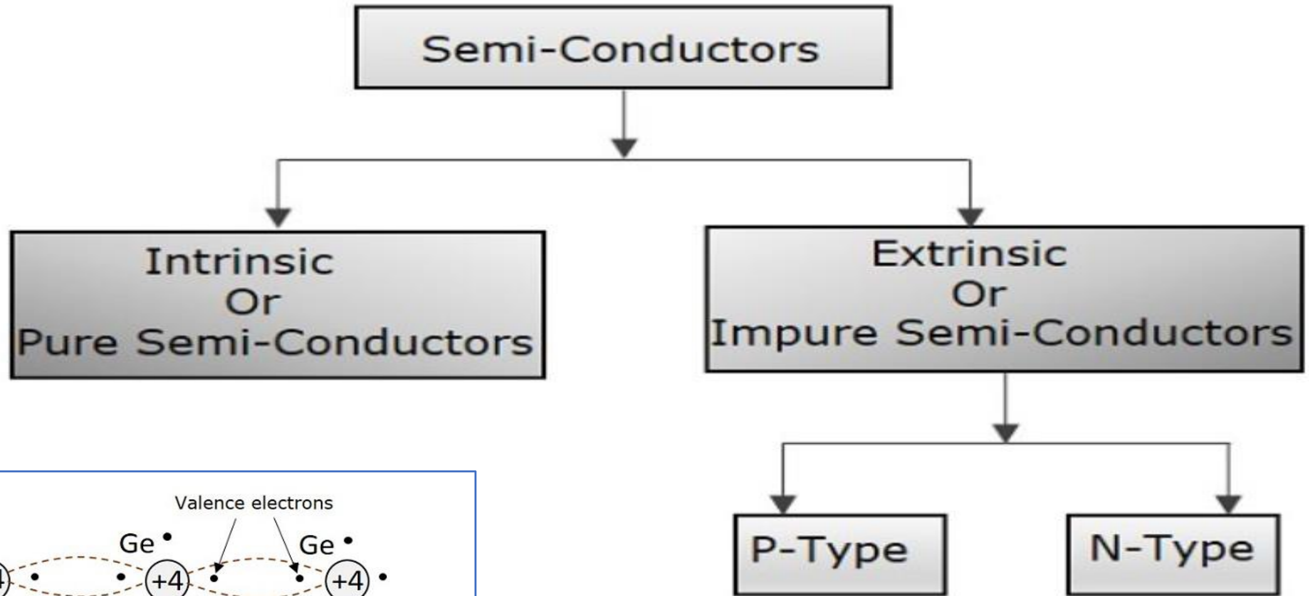
Conductors

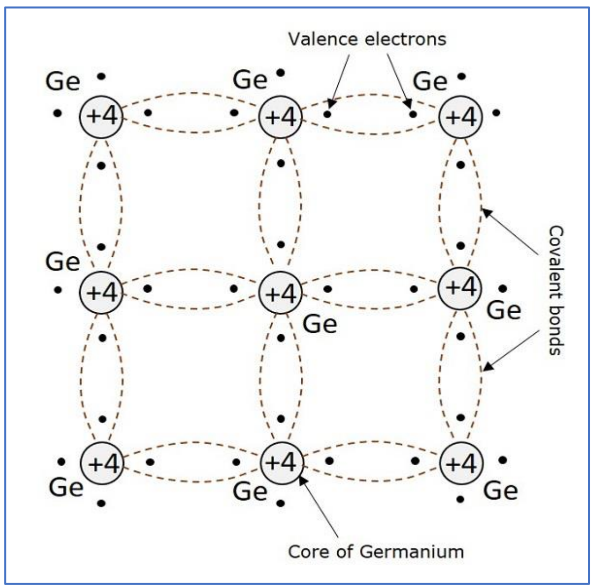
- A **conductor** is a material that easily conducts electrical current.
- Most metals are good conductors.
- The best conductors are **single-element materials**, such as **copper (Cu), silver (Ag), gold (Au), and aluminum (Al)**
- Characterized by atoms with only one valence electron very loosely bound to the atom.
- These loosely bound valence electrons become free electrons.

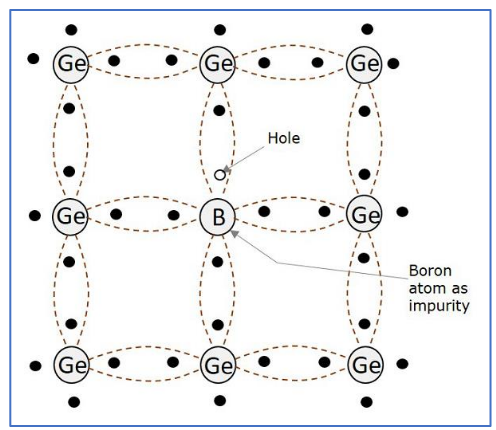
Materials classifications:

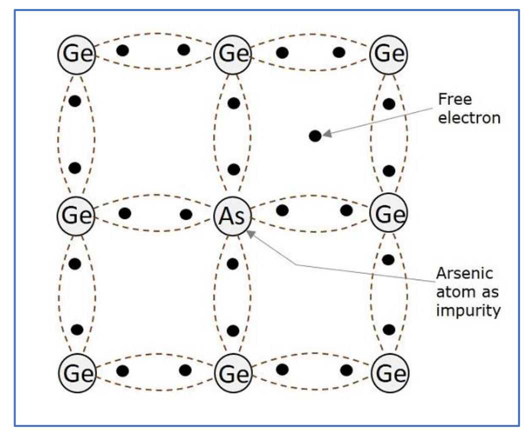
- ***Semiconductors***
- A **semiconductor** is a material that is between conductors and insulators in its ability to conduct electrical current.
- A semiconductor in its pure (intrinsic) state is neither a good conductor nor a good insulator.
- Single-element semiconductors - **silicon (Si), germanium (Ge)**
- Compound semiconductors - **gallium arsenide, indium phosphide, gallium nitride, silicon carbide, and silicon germanium**
- The single-element semiconductors are characterized by atoms with four valence electrons.
- Silicon is the most commonly used semiconductor.

Semiconductors





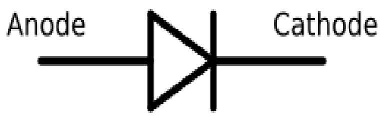




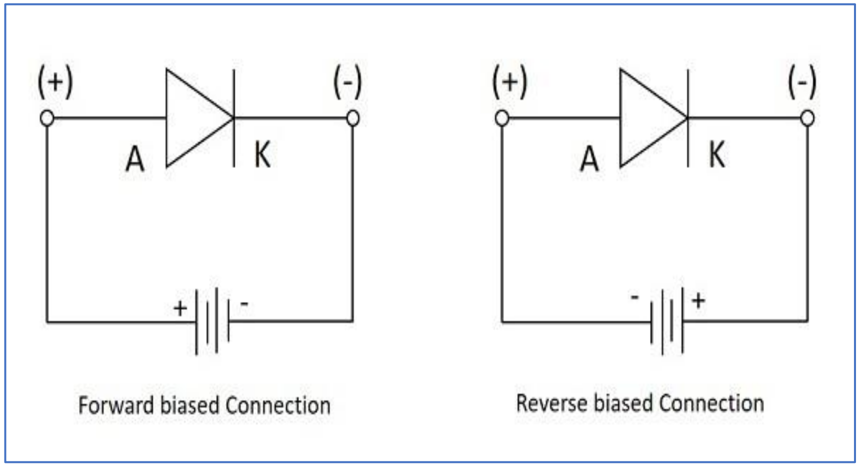
Trivalent Impurities:
Gallium, Indium, Aluminum, Boron

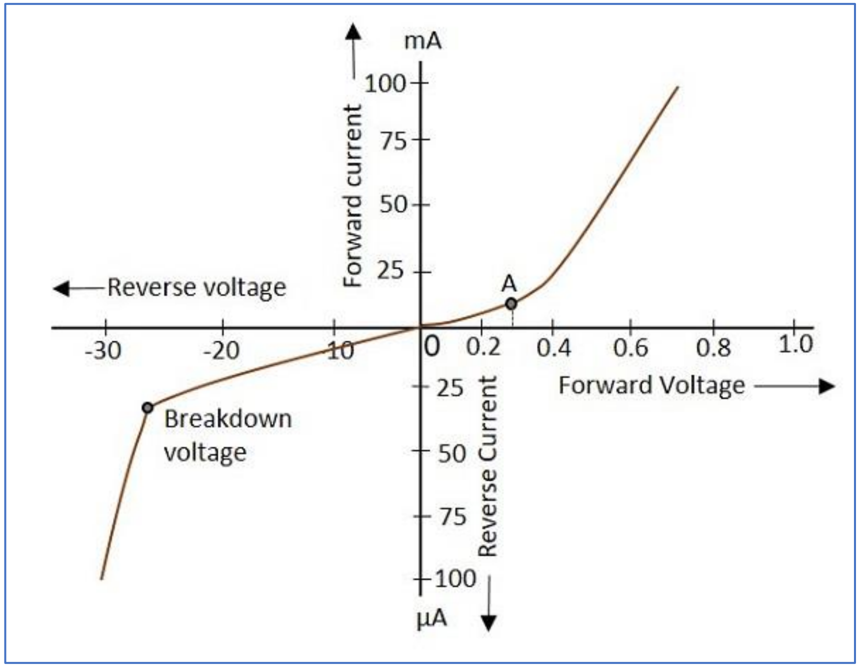
Pentavalent Impurities:
Bismuth, Antimony, Arsenic, Phosphorus

Diode



Diodes are semiconductor devices that **allow current in only one direction**





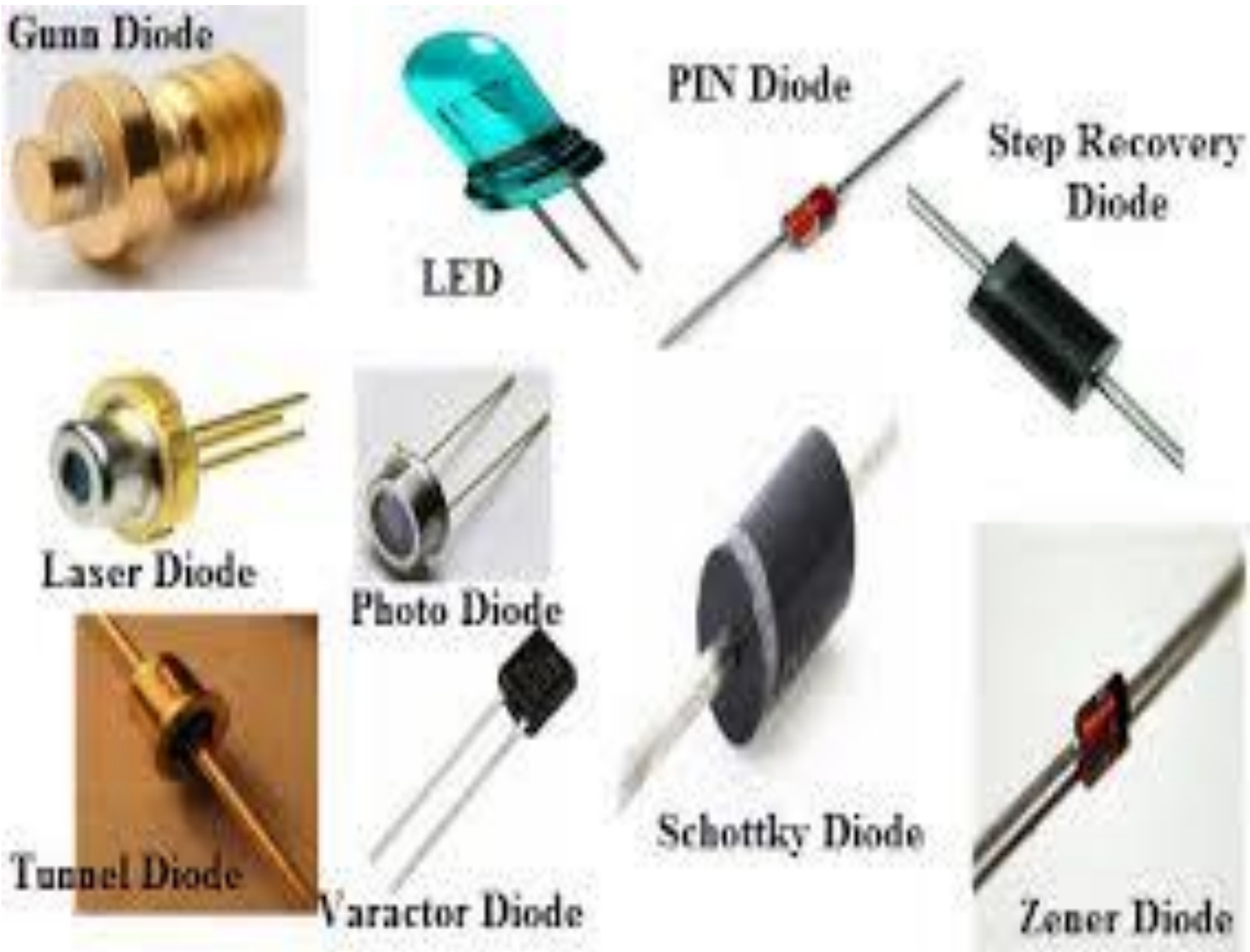
Diode Datasheets

ELECTRICAL CHARACTERISTICS (T_{amb} = 25 °C, unless otherwise specified)						
PARAMETER	**TEST CONDITION**	**SYMBOL**	**MIN.**	**TYP.**	**MAX.**	**UNIT**
Forward voltage	I_F = 10 mA	V_F			1000	mV
Reverse current	V_R = 20 V	I_R			25	nA
	V_R = 20 V, T_j = 150 °C	I_R			50	µA
	V_R = 75 V	I_R			5	µA
Breakdown voltage	I_R = 100 µA, t_p/T = 0.01, t_p = 0.3 ms	$V_{(BR)}$	100			V
Diode capacitance	V_R = 0 V, f = 1 MHz, V_{HF} = 50 mV	C_D			4	pF
Rectification effiency	V_{HF} = 2 V, f = 100 MHz	η_r	45			%
Reverse recovery time	$I_F = I_R$ = 10 mA, i_R = 1 mA	t_{rr}			8	ns
	I_F = 10 mA, V_R = 6 V, i_R = 0.1 x I_R, R_L = 100 Ω	t_{rr}			4	ns

ABSOLUTE MAXIMUM RATINGS (T_{amb} = 25 °C, unless otherwise specified)				
PARAMETER	**TEST CONDITION**	**SYMBOL**	**VALUE**	**UNIT**
Repetitive peak reverse voltage		V_{RRM}	100	V
Reverse voltage		V_R	75	V
Peak forward surge current	t_p = 1 µs	I_{FSM}	2	A
Repetitive peak forward current		I_{FRM}	500	mA
Forward continuous current		I_F	300	mA
Average forward current	V_R = 0	$I_{F(AV)}$	150	mA
Power dissipation	l = 4 mm, T_L = 45 °C	P_{tot}	440	mW
	l = 4 mm, $T_L \leq$ 25 °C	P_{tot}	500	mW

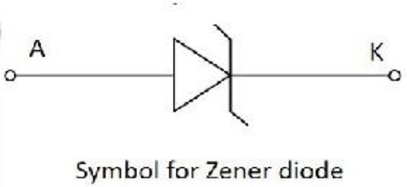
1N4148 diode

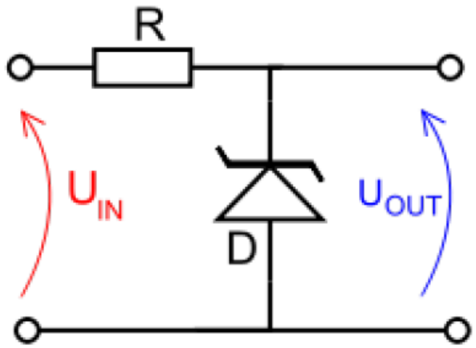
Special Purpose Diode

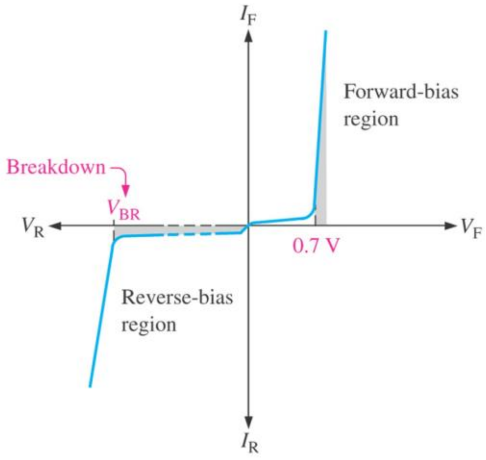


Special Purpose Diode

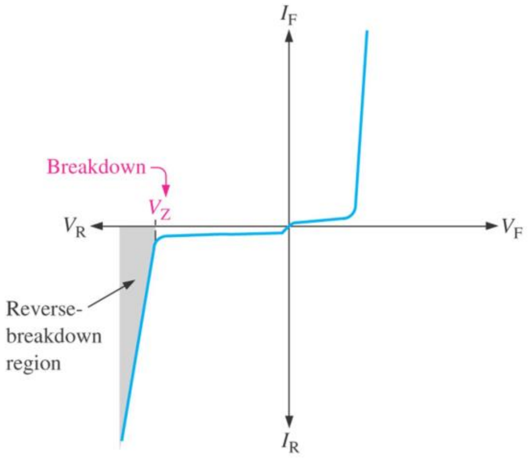
- A **Zener diode** is a type of diode
- The basic function is to maintain a specific voltage across its terminals within given limits of line or load change.
- Typically it is used for
  - A stable reference voltage
  - Voltage limiter
  - Basic (shunt) regulator
  - For protection against voltage peaks.







(a) The normal operating regions for a rectifier diode are shown as shaded areas.



(b) The normal operating region for a zener diode is shaded.

Special Purpose Diode

Schottky Diode

Special Features

- Low forward voltage drop
- Fast switching action

Applications

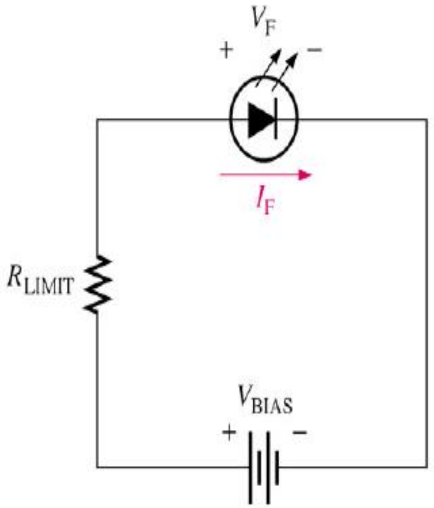
- Switching Power Supply
- Voltage clamping
- Discharge protection

Special Purpose Diode

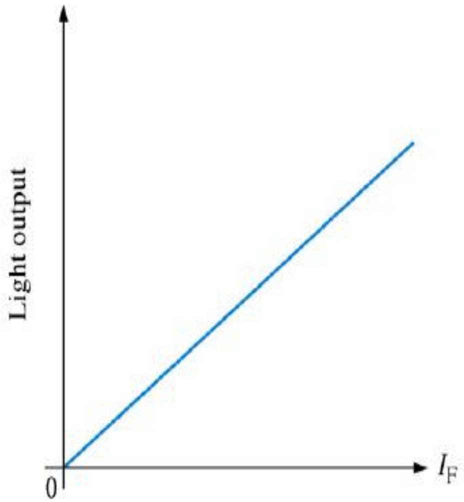
Type	Maximum Breakdown Voltage	Maximum Current Rating	Forward Voltage Drop	Switching Speed	Applications
High Voltage Rectifier Diodes	30kV	~500mA	~10V	~100nS	HV circuits
General Purpose diodes	~5kV	~10kA	0.7 - 2.5 V	~25µS	50 Hz Rectifiers
Fast Recovery	~3kV	~2kA	0.7 - 1.5 V	<5uS	SMPS. Inverters, Resonant ckts.
Schottky Diodes	~100V	~300A	0.2 - 0.9 V	~30nS	LV HF Rectification
Power Zener Diodes	Operates in break down ~300 V	~75 W	-	-	References, Voltage Clamps

Special Purpose Diode

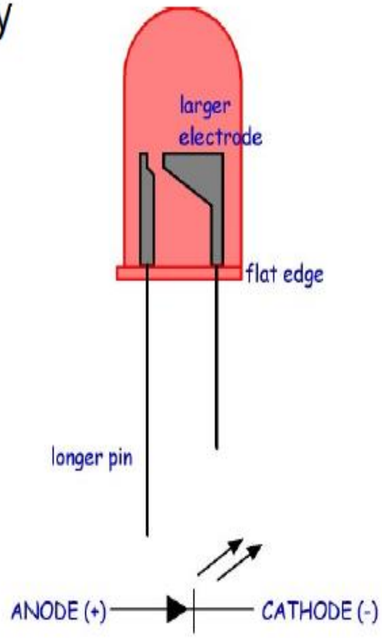
The **light-emitting diode** (LED) emits photons as visible light. Its purpose is for indication and other intelligible displays. Various impurities are added during the doping process to vary the color output.



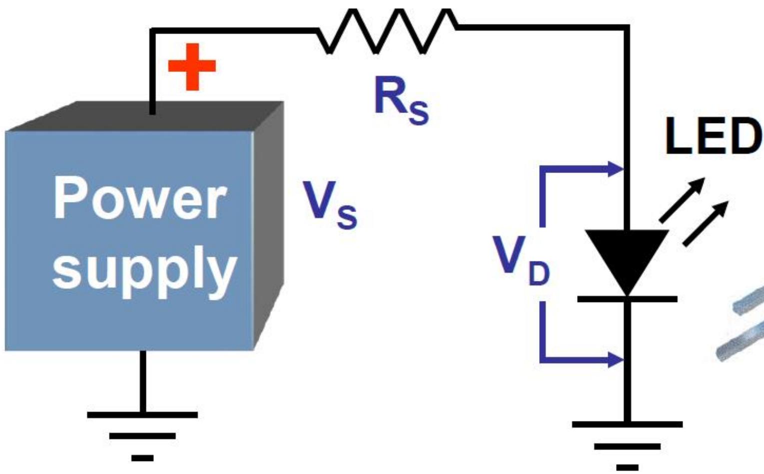
(a) Forward-biased operation

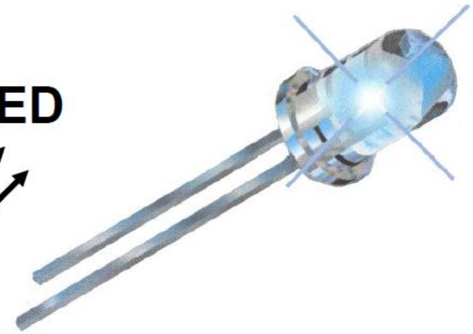


(b) General light output versus forward current



Special Purpose Diode

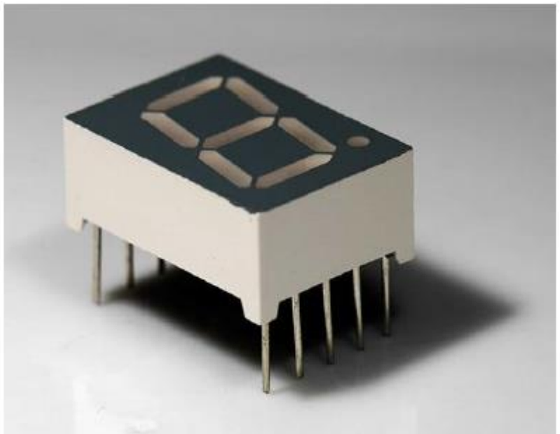


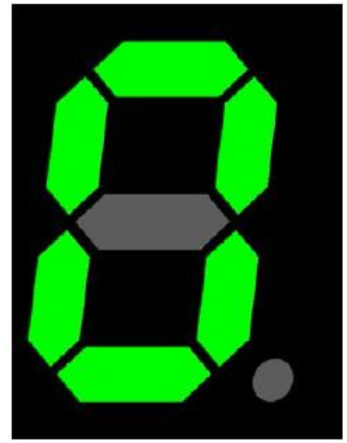


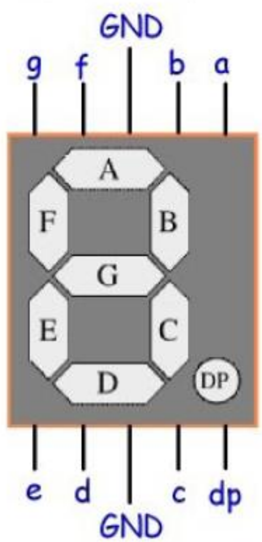
$$I_S = \frac{V_S - V_D}{R_S}$$

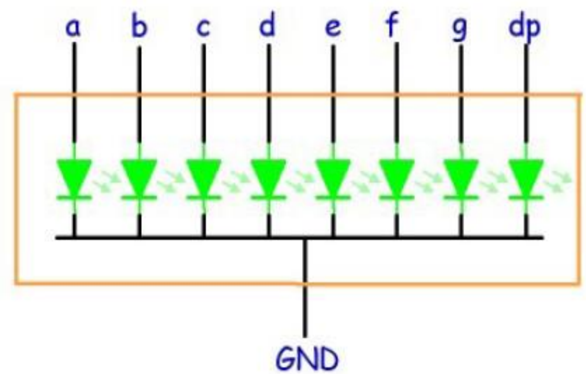
The typical voltage drop for most LEDs is from 1.5 to 2.5 V.

Special Purpose Diode



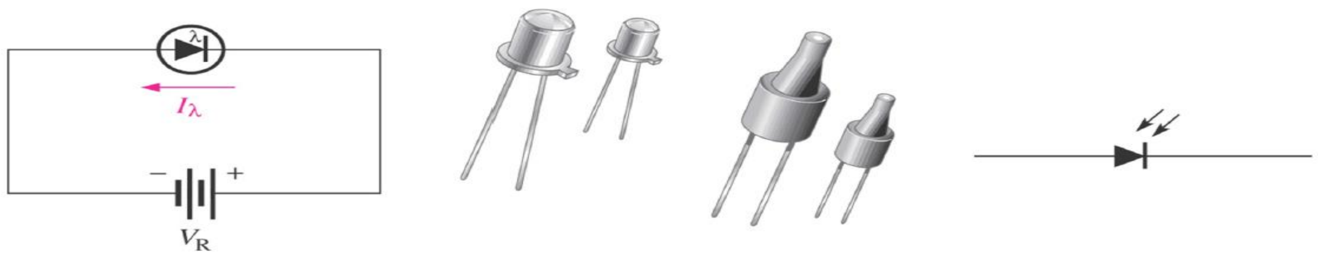




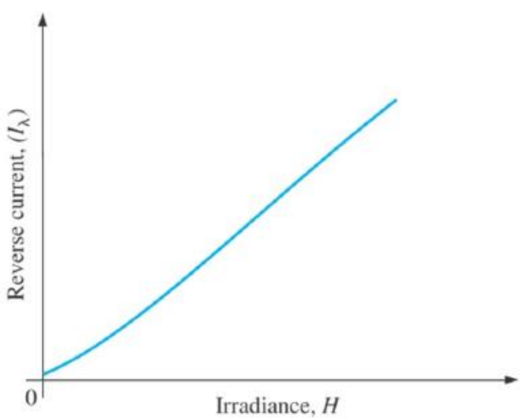


Special Purpose Diode

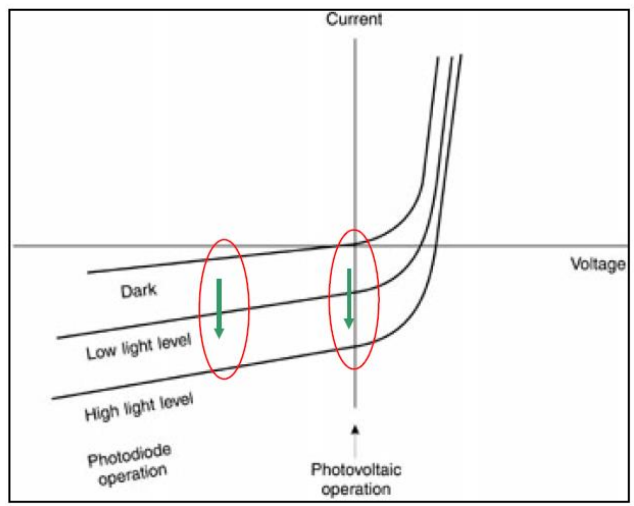
The **photodiode** is used to vary current by the amount of light that strikes it. It is placed in the circuit in reverse bias. As with most diodes when in reverse bias, no current flows, but when light strikes the exposed junction through a tiny window, reverse current increases proportional to light intensity.



(a) Reverse-bias operation (b) Typical devices (c) Alternate symbol



(a) General graph of reverse current versus irradiance



Checkpoint

A diode has forward resistance of the order of ……………

1.kΩ

2.Ω

3.MΩ

4.none of the above

Answer : ??

The reverse current in a diode is of the order of ……………….

1.kA

2.mA

3.μA

4.A

Answer : ??

Checkpoint

A diode has forward resistance of the order of ……………

1.kΩ
2.Ω
3.MΩ
4.none of the above

Answer : 2

The reverse current in a diode is of the order of ………………..

1.kA
2.mA
3.μA
4.A

Answer : 3

Checkpoint

When a diode is used as a rectifier, the most important consideration is ………..
1.forward characteristic
2.doping level
3.reverse characteristic
4.PIV rating
Answer :?

In the breakdown region, a zener diode behaves like a …………… source.
1.constant voltage
2.constant current
3.constant resistance
4.none of the above
Answer :?

Checkpoint

When a diode is used as a rectifier, the most important consideration is ………..

1.forward characteristic
2.doping level
3.reverse characteristic
4.PIV rating

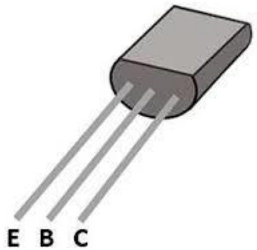
Answer :4

In the breakdown region, a zener diode behaves like a …………… source.

1.constant voltage
2.constant current
3.constant resistance
4.none of the above

Answer :1

Transistors

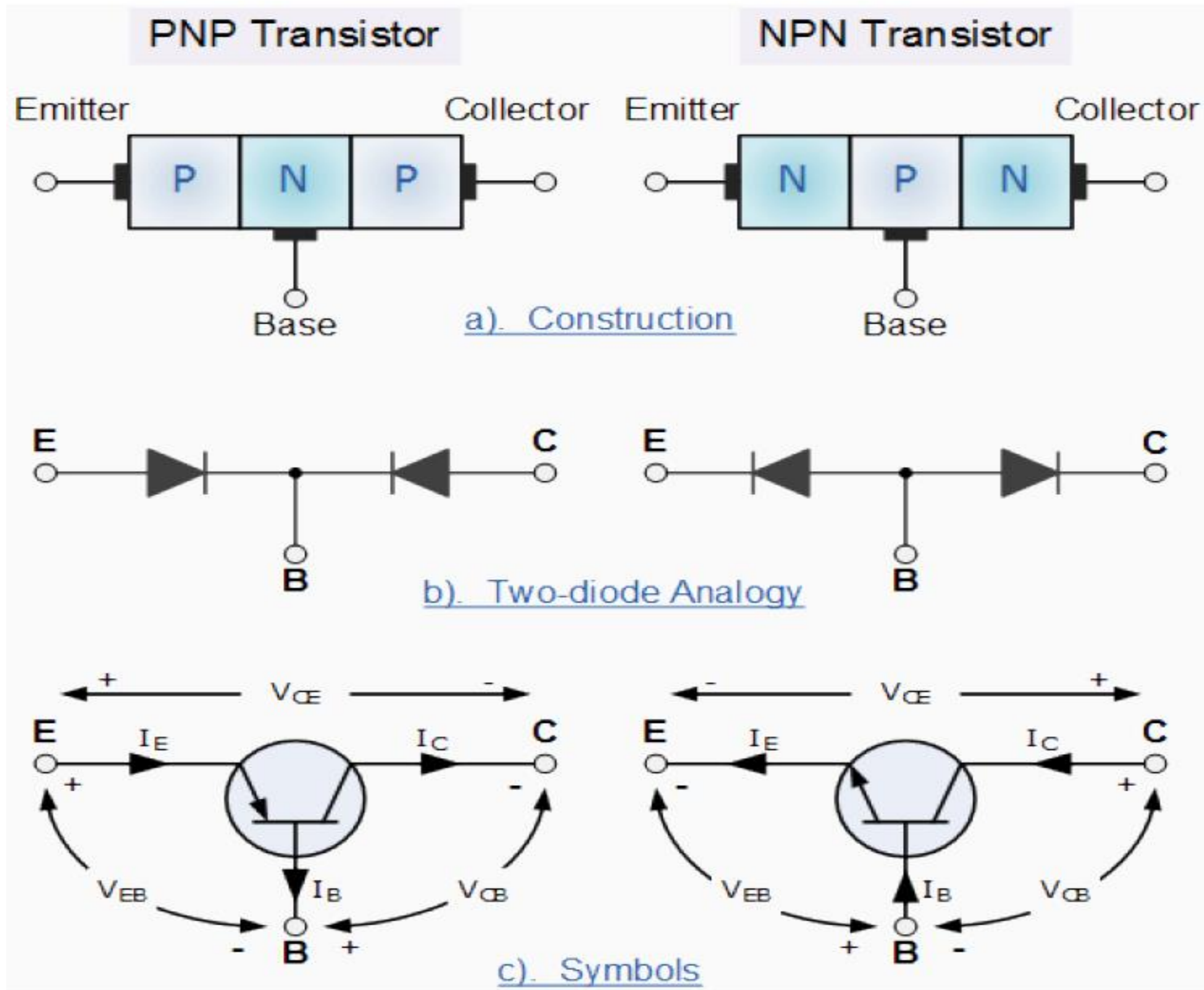


Transistor --
Transfer resistor

Two types –
NPN and PNP

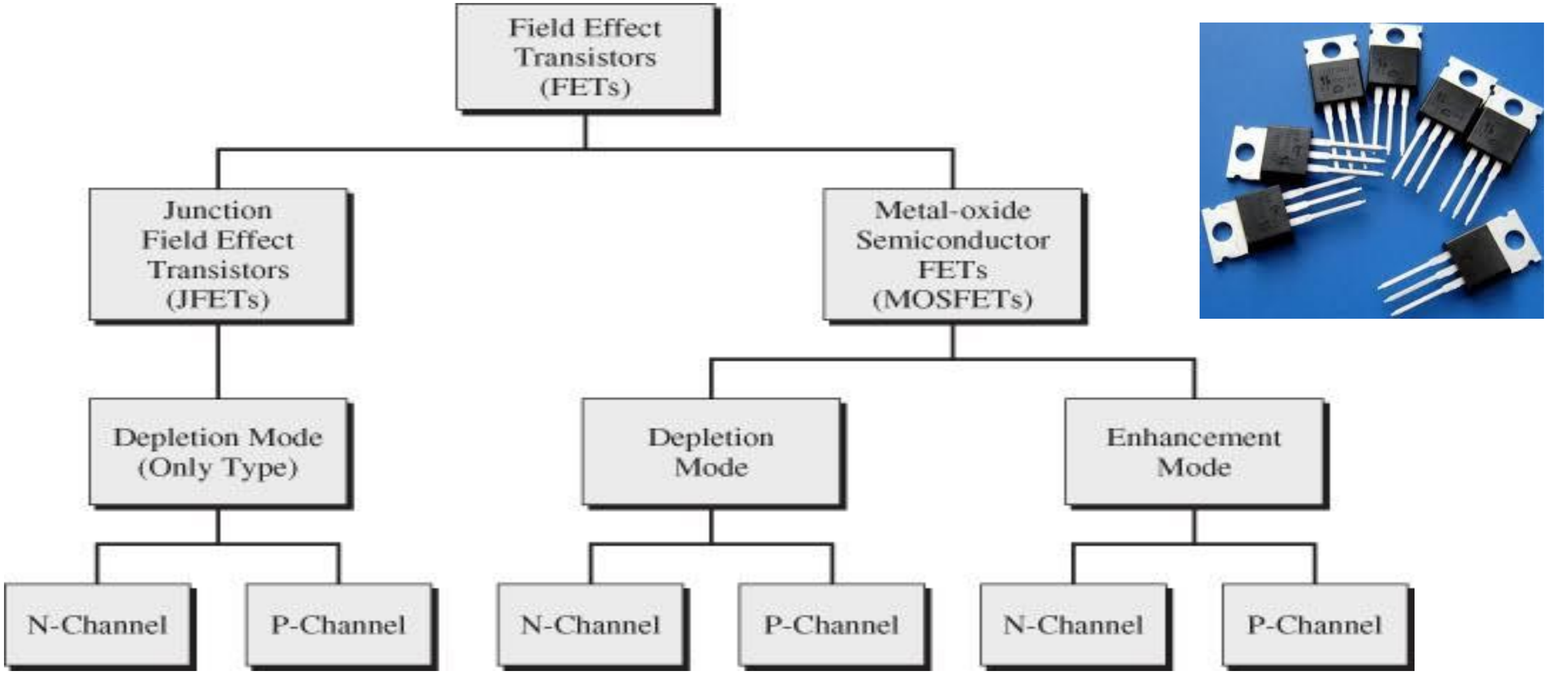
Three terminals --
Emitter (E),
Base (B),
Collector (C)

It is current-
controlled device



Field Effect Transistors (FET)

- An electronic device which uses an electric field to control the flow of current.
- FETs are devices with three terminals: *source*, *gate*, and *drain*.
- FETs control the flow of current by the application of a voltage to the gate, which in turn alters the conductivity between the drain and source.

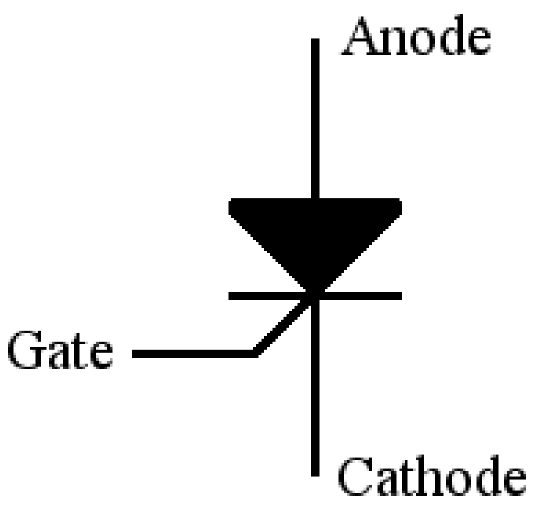


BJT Vs. FET

BJT	FET
High voltage gain	Low voltage gain
Low current gain	High current gain
Low input impedance	Very high input impedance
Low output impedance	High output impedance
Medium Noise Generation	Low Noise generation
Medium switching time	Fast switching time
Robust	Easily damaged
Requires zero input to turn it "OFF"	Some need an input to turn it "OFF"
It is a Current controlled device.	It is a Voltage controlled device.
Cheap	More expensive than BJT.
Easy to bias	Difficult to bias

Silicon Controlled Rectifier

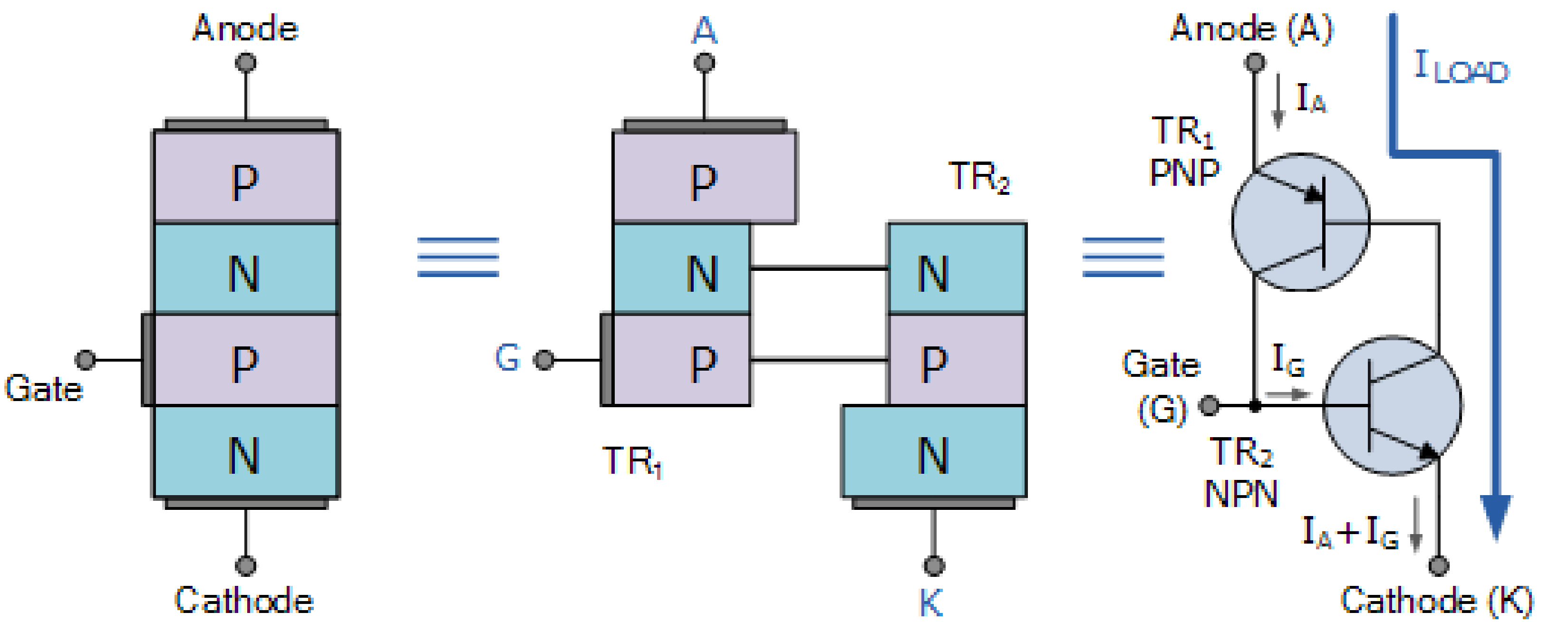
- An SCR can be seen as a conventional rectifier controlled by a gate signal
- It is a 4-layered, 3 junctions & 3-terminal device
- When the gate to cathode voltage exceeds a certain threshold, the device turns 'on' and conducts current
- The name "silicon controlled rectifier" is a trade name for the type of **thyristor** commercialized at General Electric in 1957.



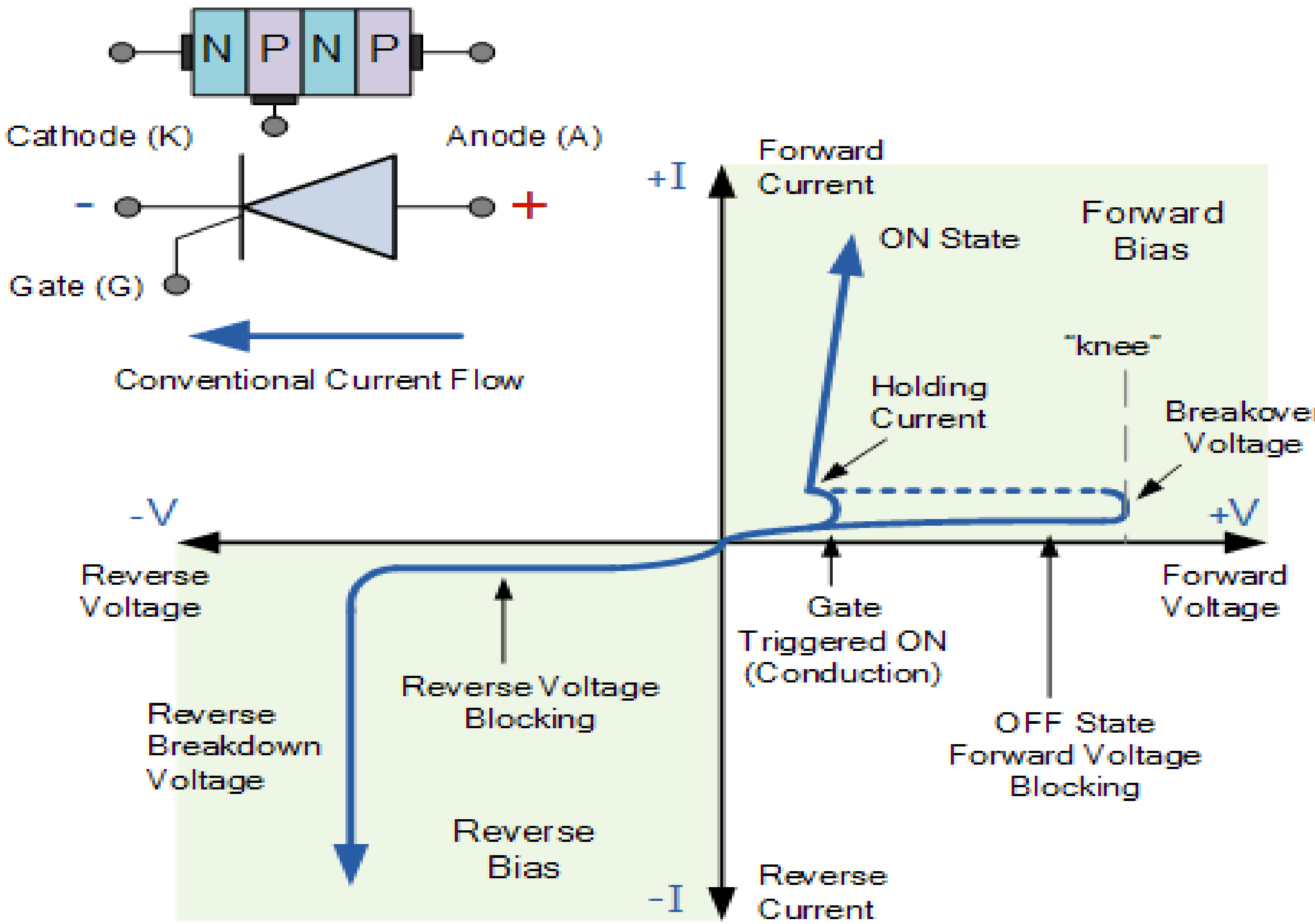
Back

Silicon Controlled Rectifier

- The operation of a SCR can be understood in terms of a pair of tightly coupled **B**ipolar **J**unction **T**ransistors
- SCR has three states:
  - Reverse blocking mode, forward blocking mode, and forward conducting mode



V-I characteristics of SCR



Specifications of SCR

Gate Trigger Current

Gate Trigger Current is the minimum gate current needed to switch the SCR ON. Just like a BJT, an SCR needs sufficient current applied to its gate terminal in order to turn on.

Gate Trigger Voltage

Gate Trigger Voltage is the minimum gate voltage required to trigger the gate terminal, which then turns on the SCR.

Holding Current

Holding Current is the minimum current through the anode-to-cathode terminal required to maintain the SCR's on state.

While the gate trigger current is the current needed to switch the SCR to the on state, the holding current is the current required to maintain this on state.

On-state Voltage

On State-Voltage is the anode-to-cathode voltage present when the SCR is on.

Peak Gate Power Dissipation

The Peak Gate Power Dissipation is the maximum power that may be dissipated between the gate and the cathode region in a silicon-controlled rectifier (SCR).

Applications of SCR

- Controlled rectifiers
- DC to DC converters or choppers
- DC to AC converters or inverters
- As a static switch
- Battery chargers
- Speed control of motors
- Lamp dimmers

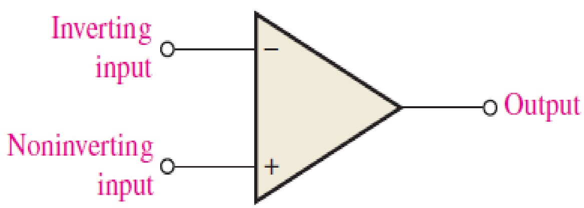
Overview of hardware circuits as building blocks

Analog blocks

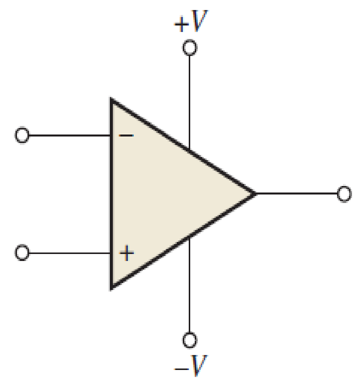
The Operational Amplifier

- Usually Called OpAmps
- An amplifier is a device that accepts a varying input signal and produces a similar output signal with a larger amplitude.
- Usually connected so part of the output is fedback to the input.(Feedback Loop)
- Most OpAmps behave like voltage amplifiers. They take an input voltage and output a scaled version.
- They are the basic components used to build analog circuits.
- The name “operational amplifier” comes from the fact that they were originally used to perform mathematical operations such as integration and differentiation.
- Integrated circuit fabrication techniques have made high-performance operational amplifiers very inexpensive in comparison to older discrete devices.

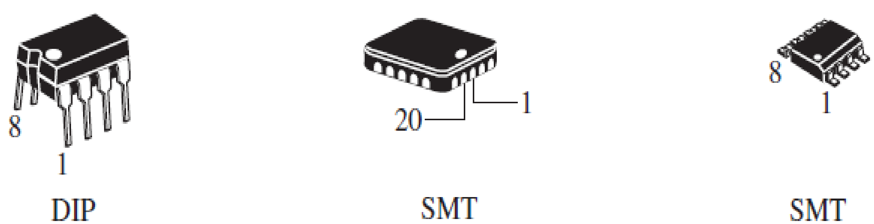
The Operational Amplifier



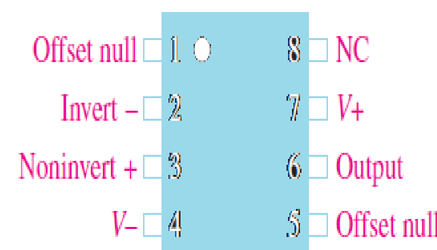
(a) Symbol



(b) Symbol with dc supply connections

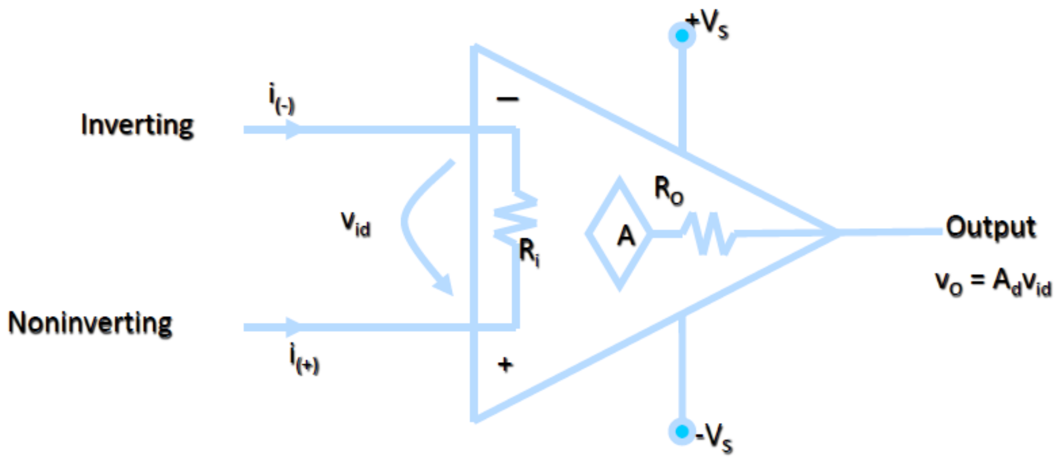


(c) Typical packages. Pin 1 is indicated by a notch or dot on dual in-line (DIP) and surface-mount technology (SMT) packages, as shown.



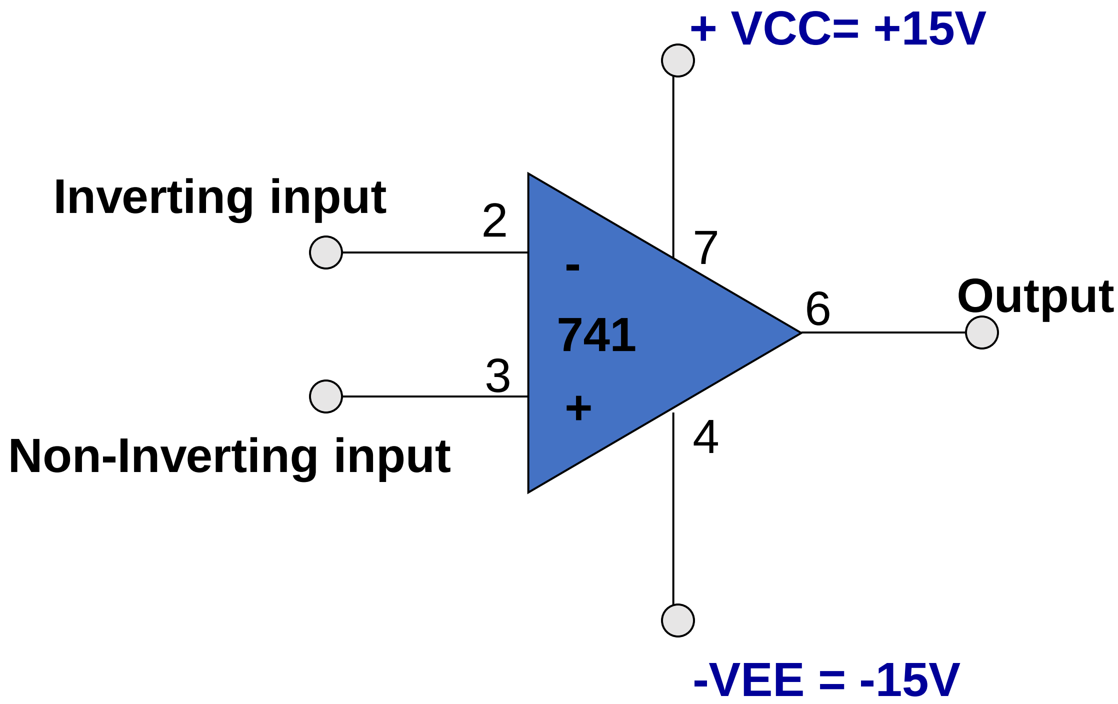
Typical Pin Diagram

The Operational Amplifier

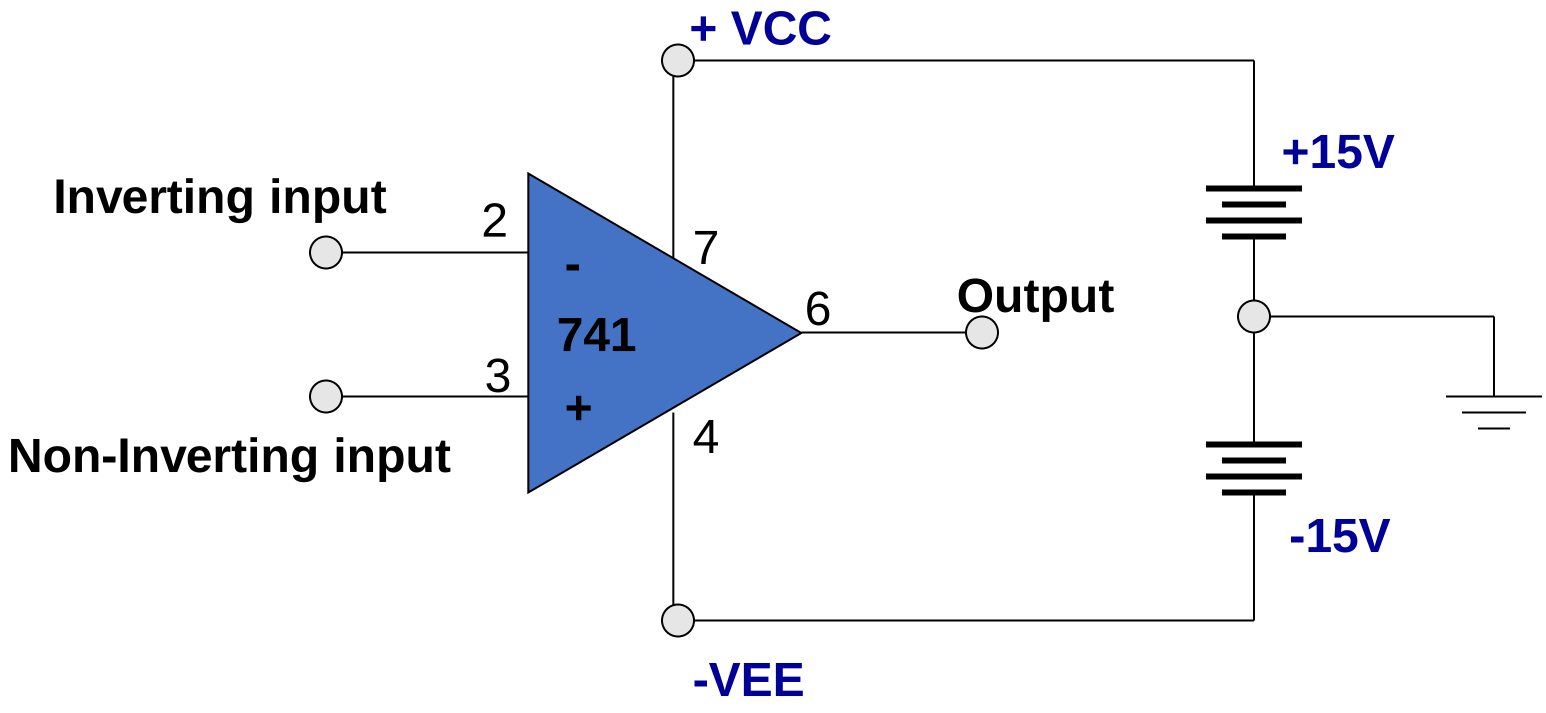


- i(+), i(-): Currents into the amplifier on the inverting and noninverting lines respectively
- vid: The input voltage from inverting to non-inverting inputs
- +VS, -VS: DC source voltages, usually +15V and –15V
- Ri: The input resistance, ideally infinity
- A : The gain of the amplifier. Ideally very high, in the $1x10^{10}$ range.
- RO: The output resistance, ideally zero
- vO: The output voltage; vO= AOL*vid where AOL is the open-loop voltage gain

DC power supply for an OP-AMP

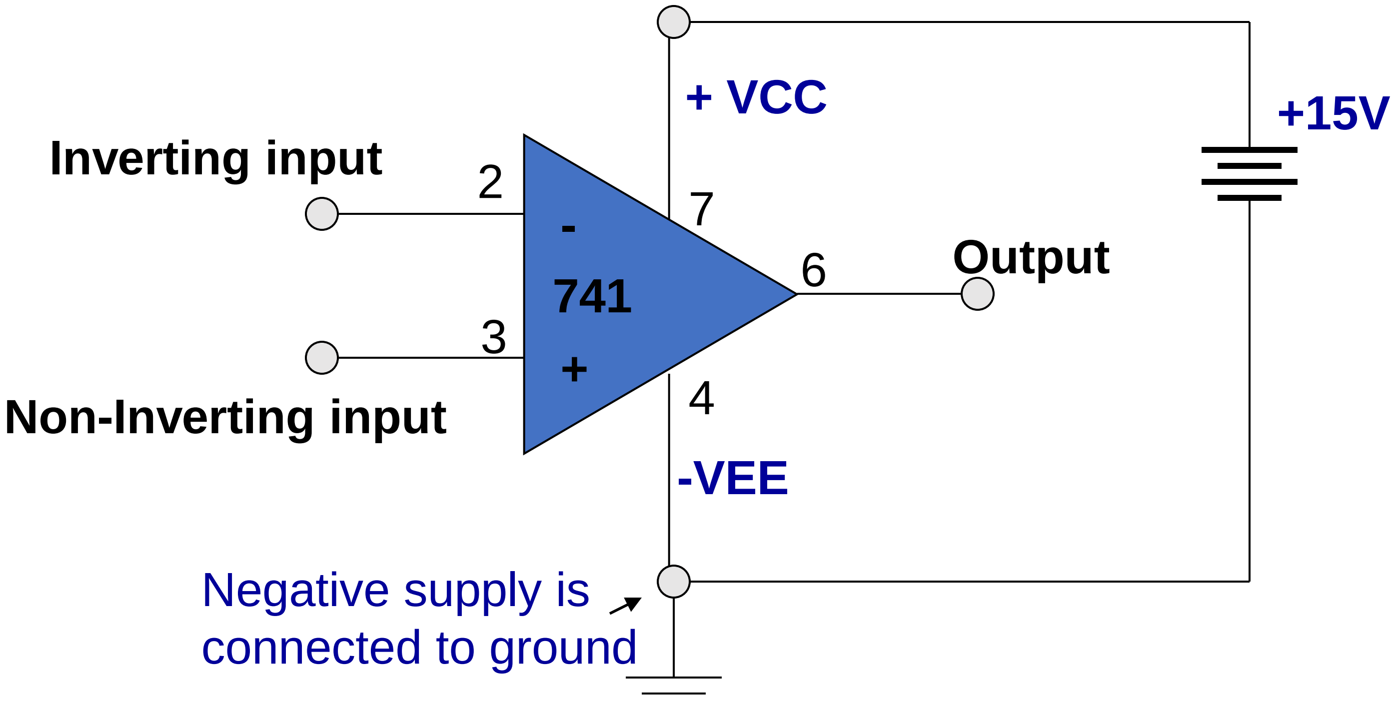


DC power supply for an OP-AMP



Dual polarity supply

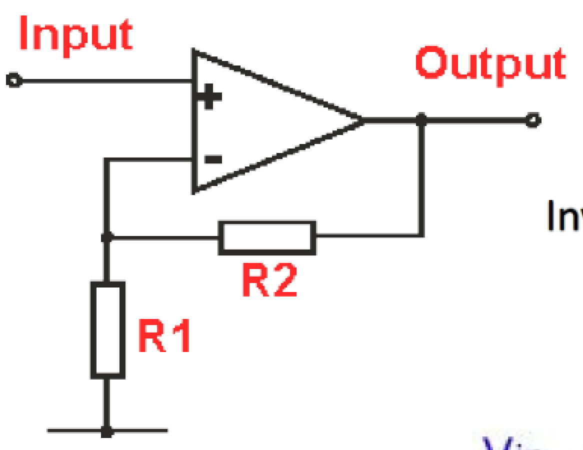
DC power supply for an OP-AMP



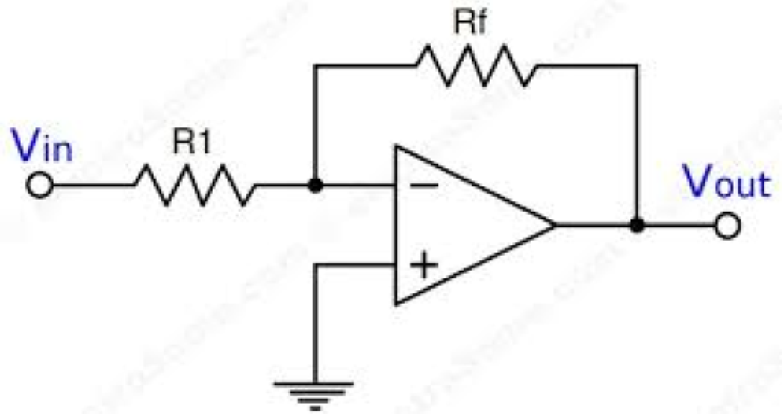
Single polarity supply

The Operational Amplifier

Non-inverting Configuration



Inverting Configuration



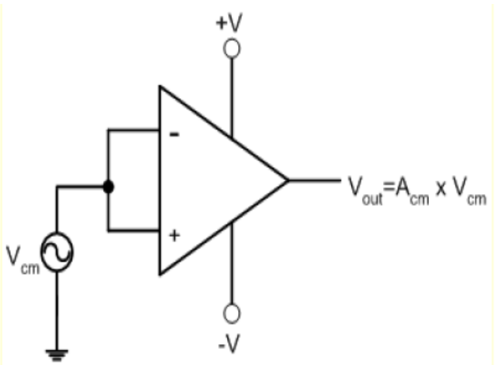
OP-AMP PARAMETERS

Common-Mode Rejection

- Common Mode signal is when both inputs have the same voltage “common voltage”, phase and frequency.
- Common-mode rejection is used for removal of unwanted noise signals
- Output should be zero in this case, both signals canceling each other

Common-Mode Rejection Ratio

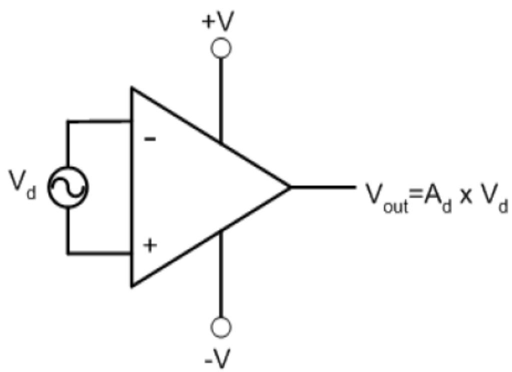
CMRR is the measure for how well it rejects an unwanted signal.



It is the ratio of open loop to common mode gain (*Acm*). The open loop gain is a datasheet value.

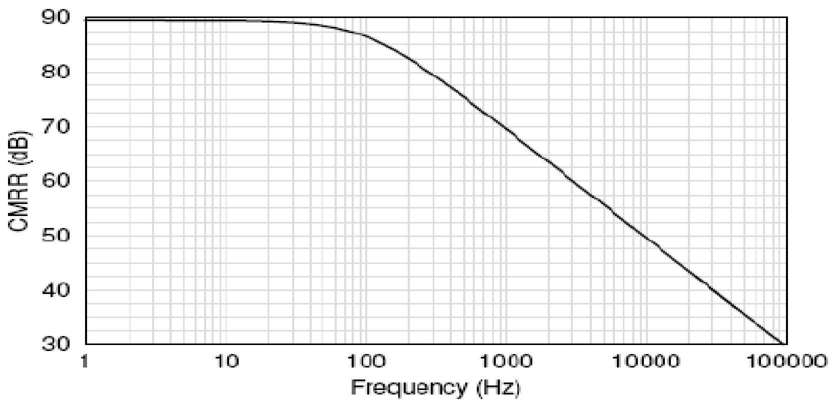
$$CMRR = 20\log\left(\frac{A_N}{A_{cm}}\right)$$

A_N: Open-loop gain / Noise gain
A_{cm}: Common mode gain



Common-Mode Rejection Ratio

- Ability of an op-amp to reject common mode signals (noise) while amplifying desired signal (differential signal).
- The higher value of CMRR is the better.
- Means that the Aol is high and Acm is low.
- Usually expressed in dB
- Decreases with frequency



Power Supply Rejection Ratio

One of the reasons op amps are so useful, is that they can be operated from a wide variety of power supply voltages.

The 741 op amp can be operated from bipolar supplies ranging from ±5V to ±18V with out too many changes to the parameters of the op amp.

The power supply rejection ratio (SVRR) refers to the slight change in output voltage that occurs when the power supply of the op amp changes during operation.

$$SVRR = 20 \log (\Delta V_s / \Delta V_o)$$

The SVRR value is given for a specified op amp. For the 741 op amp, SVRR = 96 dB over the range ±5V to ±18V.

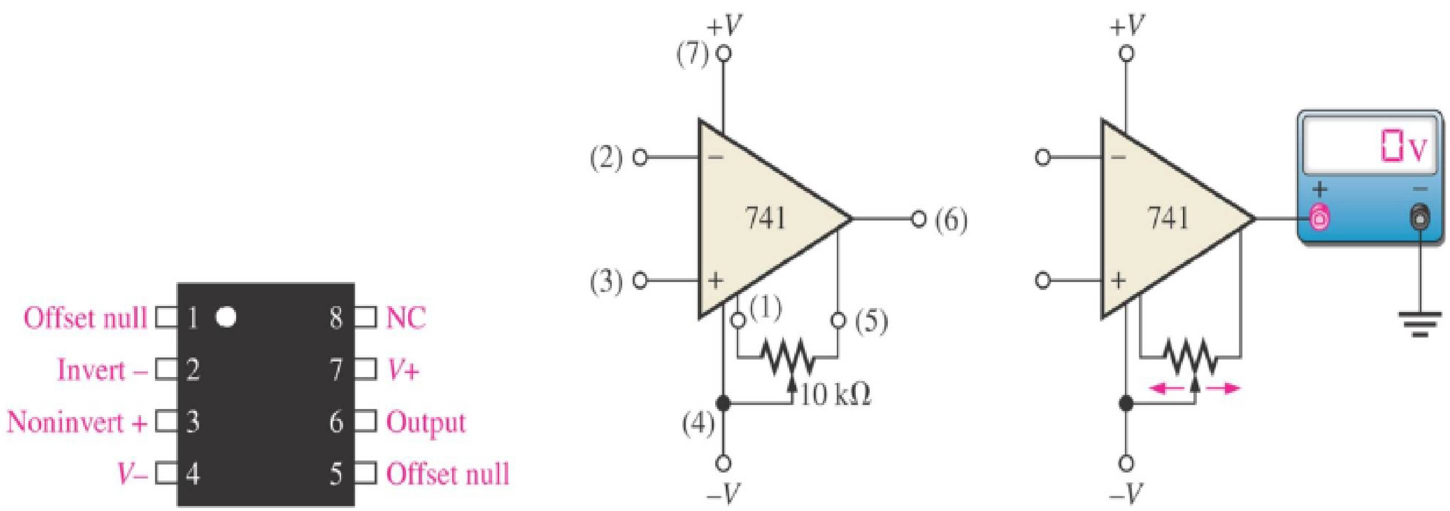
Input Offset Voltage

- Ideally, output of an op-amp is zero if the input is zero volts.
- Realistically, a small dc voltage will appear at the output when no input voltage is applied.
- Thus, differential dc voltage is needed to force the output to zero volts. Typical value; 2mV or less. Ideal case; 0V
- This is called *Input Offset Voltage*
  - *Specified on an op-amp data sheet*

V_{OS}

Input Offset Voltage Compensation

- With no input, the potentiometer is adjust until the output voltage read is zero volt.



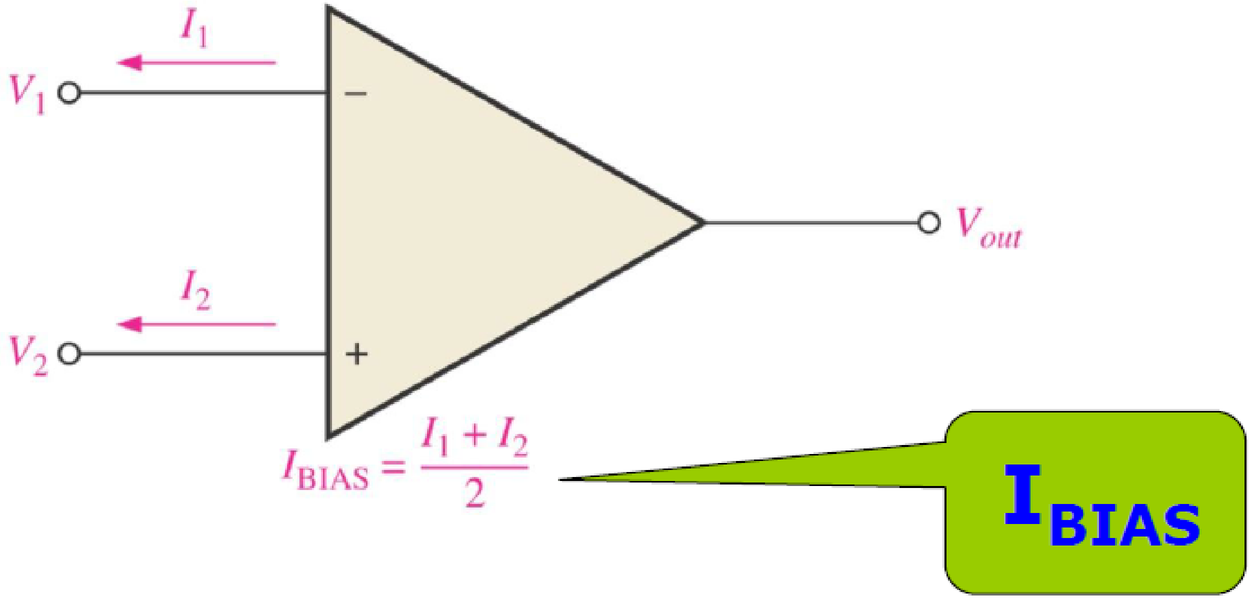
(a) 8-pin DIP or SMT package (b) External potentiometer (c) Adjust for zero output

Input Bias Current

- Ideally, should be zero. Practically is required (dc current) by the inputs op-amp to operate the first stage.
  - Positive input bias current:
    - Small current seen on the non-inverting input of an amplifier
  - Negative input bias:
    - Small current seen on the inverting input of an amplifier

Input Bias Current

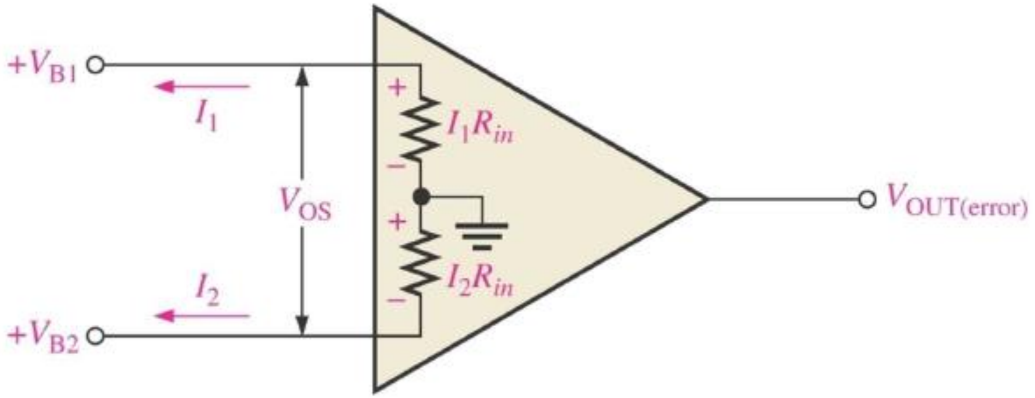
- Input Bias Current:
  - Average of currents on inputs of an amplifier



Input Offset Current

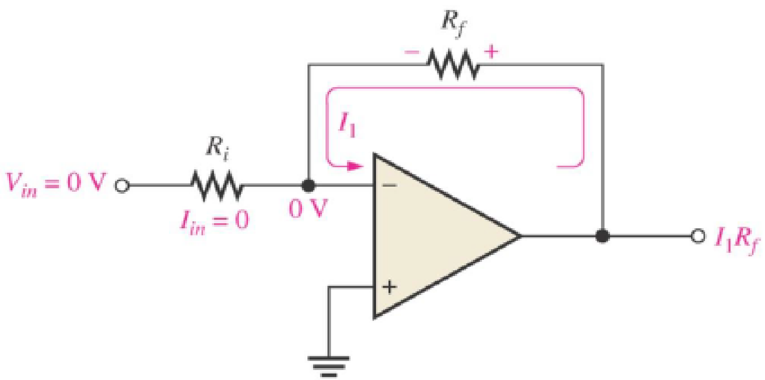
- Ideally input offset currents should be equal to obtain zero output voltage
- Realistically, to set output to zero, one input would require more current than the other.
- *Input Offset Current* : Difference between the two input currents to achieve zero output. Expressed as an absolute value.

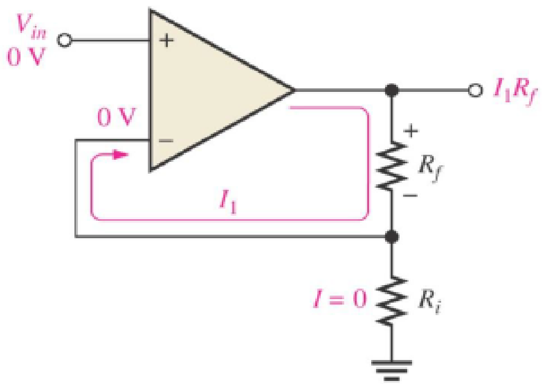
Input Offset Current



$$I_{os} = \left| I_1 - I_2 \right|$$

Bias Current Compensation



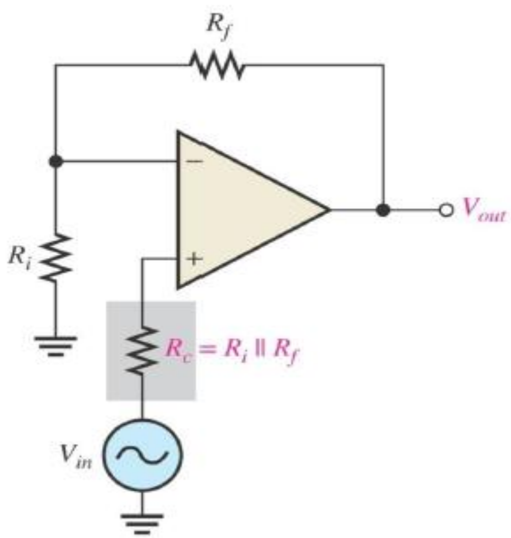


Small input bias current, I_1 flows from the output terminal through R_f will create voltage drop across R_f. So the output voltage (error) is I_1R_f.

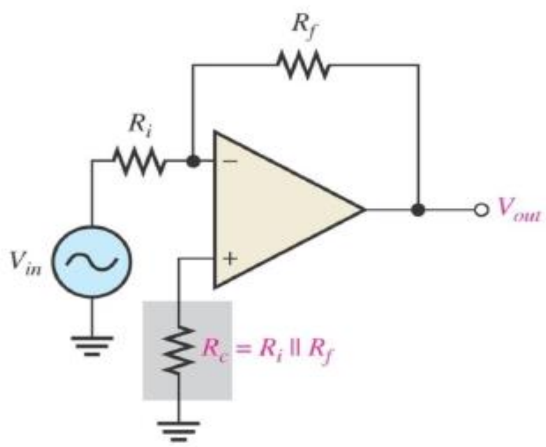
The input bias current, I_1 flows from the output terminal through R_f will create voltage drop across R_f. So the output voltage (error) is I_1R_f.

Bias Current Compensation

- How to avoid ?
  - Add R_c to compensate the effect of bias current
  - The value of compensating resistor, R_c is equal to the combination (parallel) of R_i and R_f



(a) Noninverting amplifier



(b) Inverting amplifier

Gain-Bandwidth Product

In most operational amplifiers, the open-loop gain begins dropping off at very low frequencies.

Therefore, to make the op amp useful at higher frequencies, gain is traded for bandwidth.

The Gain-Bandwidth Product (GBW) is given by:

$GBW = A_N BW$

Cascaded Amplifiers -Bandwidth

Quite often, one amplifier does not increase the signal enough and amplifiers are cascaded so the output of one amplifier is the input to the next.

The amplifiers are matched so:

$BW_S = BW_1 = BW_2 = GBW / A_N$

where, BW_S is the bandwidth of all the cascaded amplifiers and A_N is the noise gain.

The Total Bandwidth of the Cascaded Amplifiers is:

$BW_T = BW_s(2^{1/n} – 1)^{1/2}$

where n is the number of amplifiers that are being cascaded

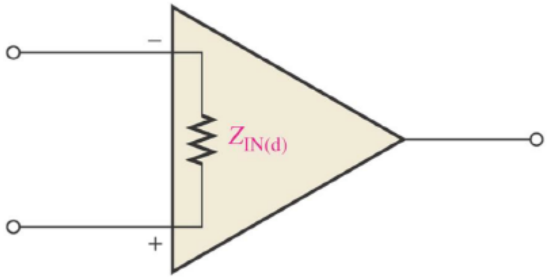
Input Impedance

- Two basic ways of specifying input impedance, i.e. *differential input impedance* and *common-mode input impedance*
- Differential input impedance: total resistance between the inverting and non-inverting inputs
- Common-mode input impedance: resistance between each input and ground

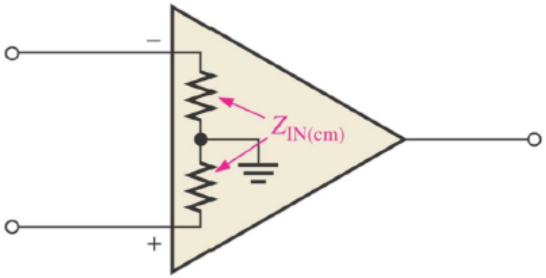
$Z_{IN(cm)}$

$Z_{IN(d)}$

Input Impedance



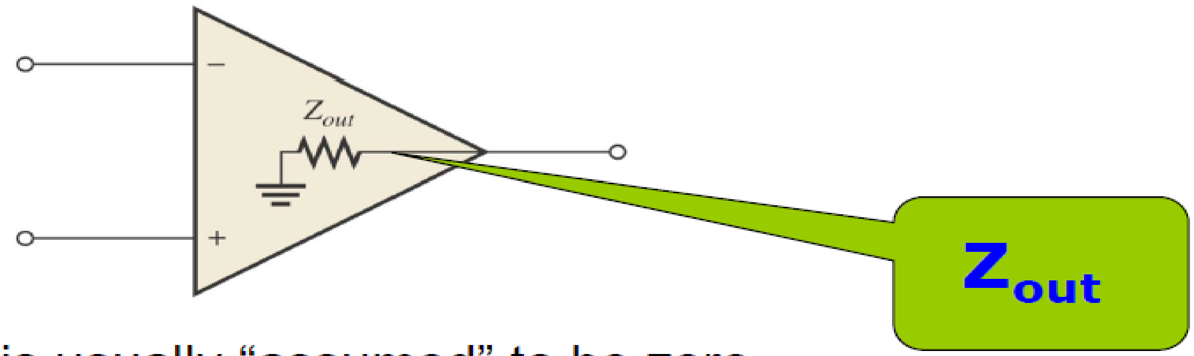
(a) Differential input impedance



(b) Common-mode input impedance

Output Impedance

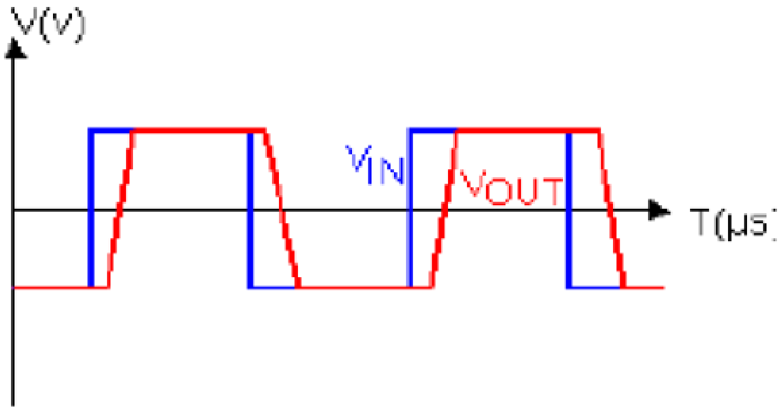
- Ideally should be zero
- *Output Impedance* is the total resistance viewed from the output terminal of the op-amp.



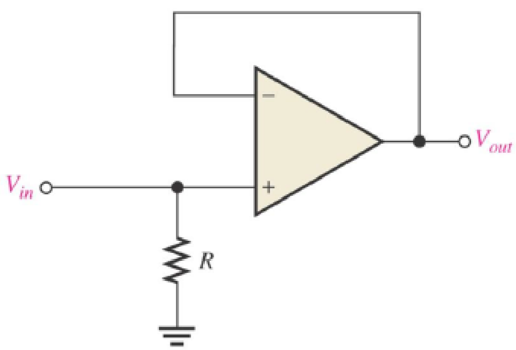
- It is usually "assumed" to be zero
  - This way op-amp behaves as a voltage source
  - Op-amp capable of driving a wide range of loads

Slew Rate

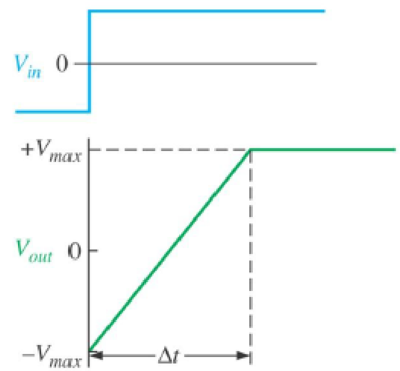
- ***Maximum*** rate of change of the output voltage per unit time
- Basically says how fast the output can "follow" the input signal



Slew Rate



(a) Test circuit



(b) Step input voltage and the resulting output voltage

Formula to measure Slew Rate : $$SR = \frac{\Delta V_{out}}{\Delta t} Volt / \mu s$$

$$where, \Delta V_{out} = +V_{max} - (-V_{max})$$

Slew Rate

- Maximum freq allowable to avoid distortion on the output is depends on BW and SR.

  Lets the output, $v_o = K\sin(2\pi f t)$ and the

  Slew Rate is, $SR = 2\pi f K$

  Therefore the max freq allowable, f_{max} :

  $$f \le \frac{SR}{2\pi K} Hz$$

Slew Rate

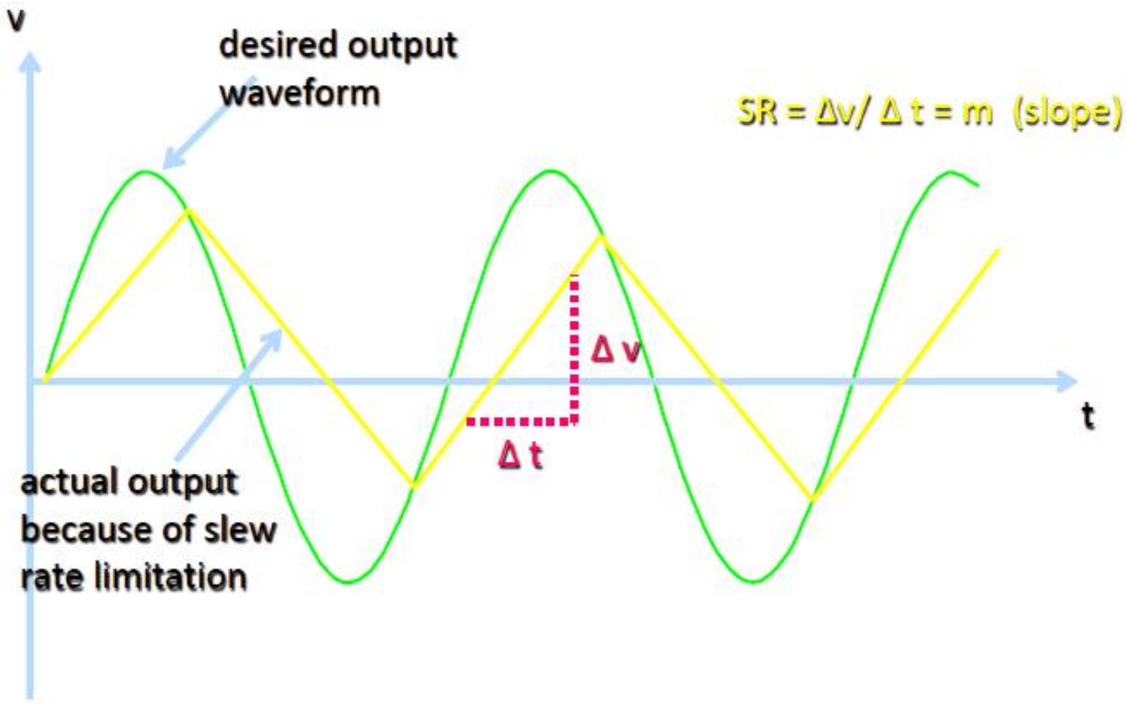
A limitation of the maximum possible rate of change of the output of an operational amplifier.

$SR = 2\pi f V_{o(max)}$

$SR = \Delta v_o / \Delta t_{max}$

Slew Rate is independent of the closed-loop gain of the op amp.

Slew Rate



The picture above shows exactly what happens when the slew rate limitations are not met and the output of the operational amplifier is distorted.

Power Bandwidth

The maximum frequency at which a sinusoidal output signal can be produced without causing distortion in the signal.

The power bandwidth, BW_p is determined using the desired output signal amplitude and the slew rate specifications of the op amp.

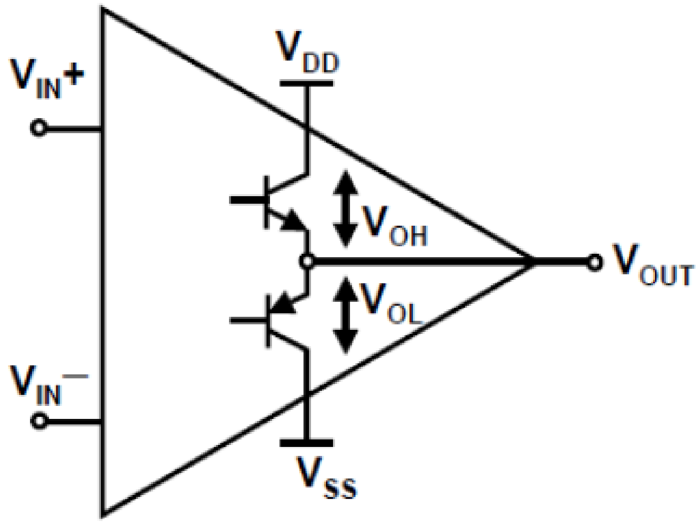
$BW_p = \quad SR / 2\pi V_{o(max)}$

$SR = 2\pi f V_{o(max)}$ where SR is the slew rate

Rail to Rail

- Rail means supply voltage (VDD and VSS)
- Rail-to-Rail output of amplifier
- In reality, Output can not reach the rails
- The difference from the rail is called Headroom

Rail to Rail



<u>Headroom</u>

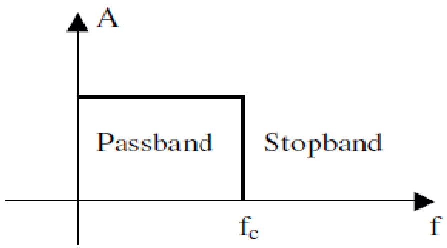
- When $V_{OUT} \rightarrow V_{DD}$:
  $V_{DD} - V_{OUT} = V_{OH}$
- When $V_{OUT} \rightarrow V_{SS}$:
  $V_{OUT} - V_{SS} = V_{OL}$

Open-Loop Op Amp Characteristics

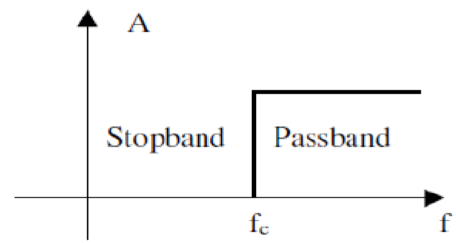
Device	LM741C	LF351	OP-07	LH0003	AD549K
Technology	BJT	BiFET	BJT	Hybrid BJT	BiFET
$A_{OL(typ)}$	200 k	100 k	400 k	40 k	100 k
R_{in}	2 MΩ	10^{12} Ω	8 MΩ	100 kΩ	10^{13} Ω || 1 pF
R_o	50 Ω	30 Ω	60 Ω	50 Ω	~100 Ω
SR	0.5 V/μs	13 V/μs	0.3 V/μs	70 V/μs	3 V/μs
CMRR	90 dB	100 dB	110 dB	90 dB	90 dB

Filters

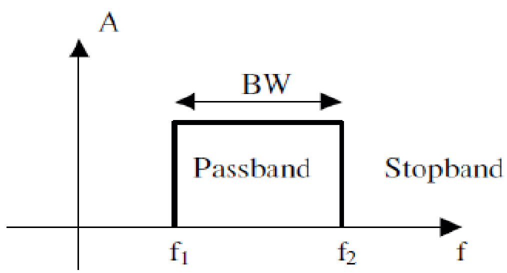
- To filter / cancel out unwanted characteristics of a signal



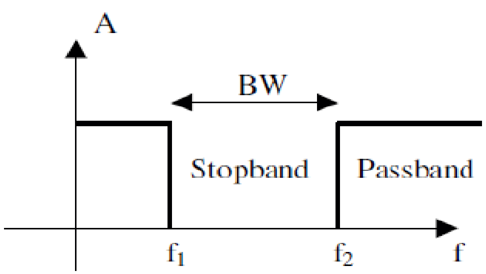
LOW-PASS FILTER RESPONSE



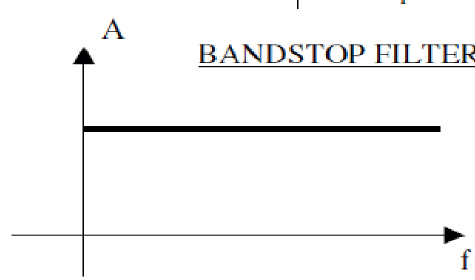
HIGH-PASS FILTER RESPONSE



BANDPASS FILTER RESPONSE



BANDSTOP FILTER RESPONSE

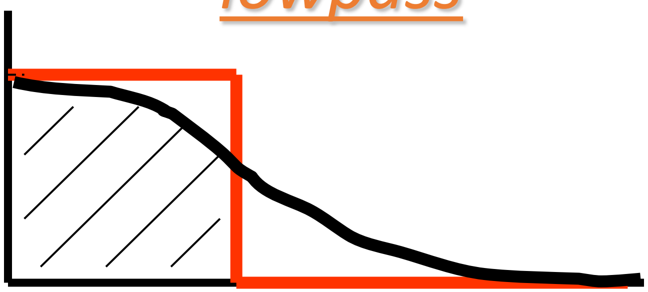


ALLPASS FILTER RESPONSE

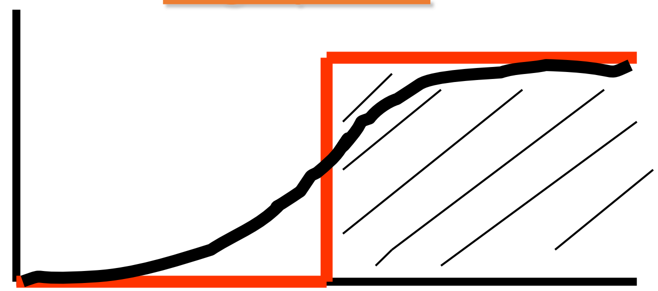
Filters

- Realistic Filters

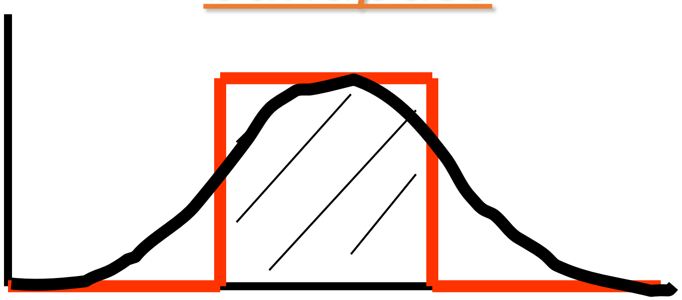
lowpass



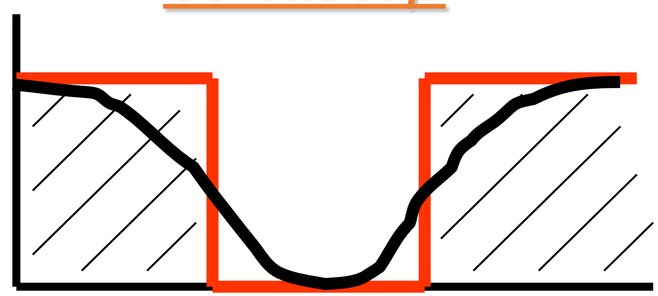
highpass



bandpass



bandstop



Filters

- Filters may be classified as either digital or analog.

- ***Digital filters*** are implemented using a digital computer

  or special purpose digital hardware.

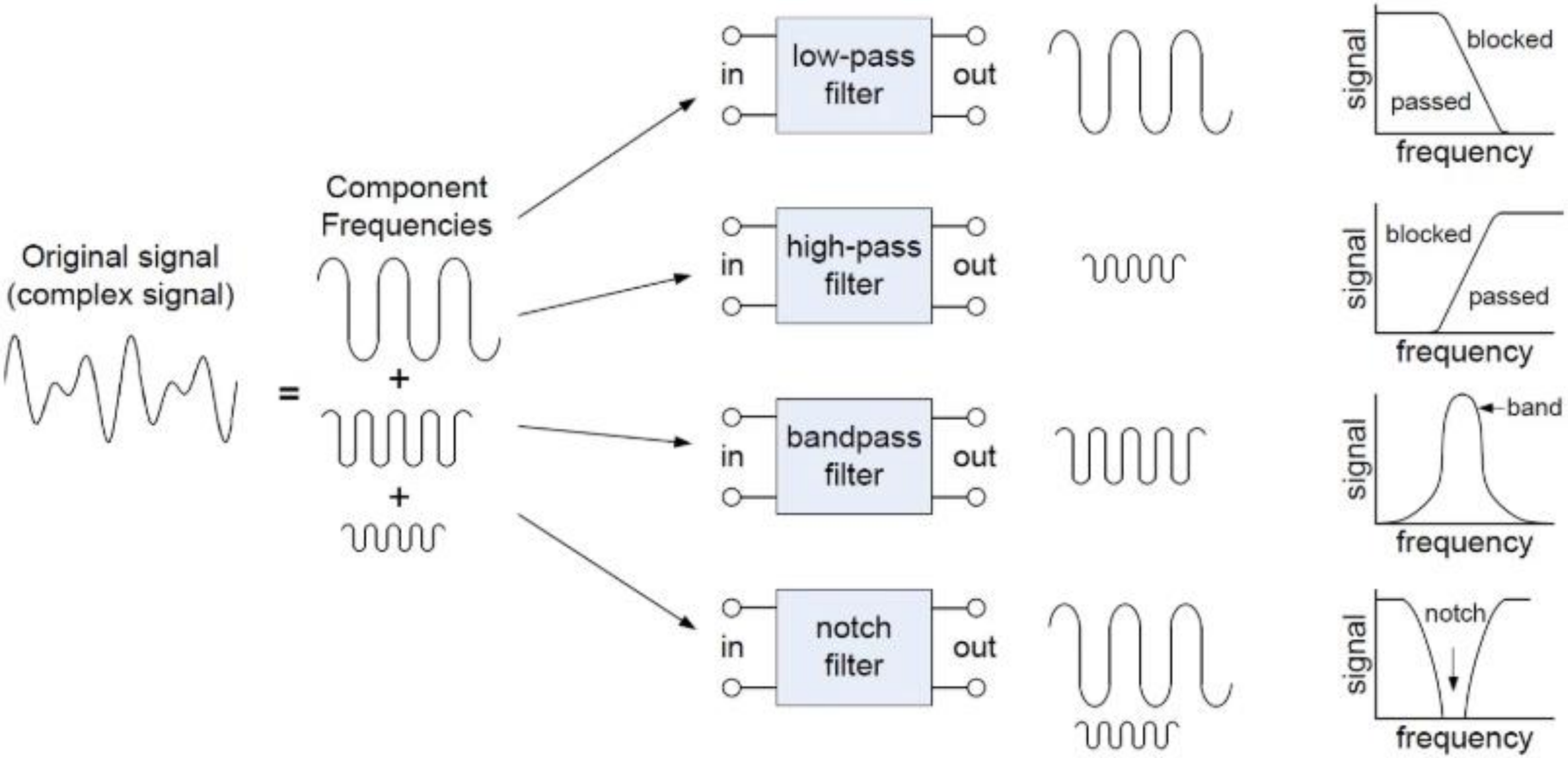
- ***Analog filters*** may be classified as either passive or active and are usually implemented with R, L, and C components and operational amplifiers.

Filters

- An ***active filter*** is one that, along with R, L, and C components, also contains an energy source, such as that derived from an operational amplifier.

- A ***passive filter*** is one that contains only R, L, and C components.
  - It is not necessary that all three be present.
  - L is often omitted (on purpose) from assive filter design because of the size and cost of inductors – and they also carry along an R that must be included in the design.

Filters



Original signal
(complex signal)
=
Component
Frequencies
+
+
in
low-pass
filter
out
in
high-pass
filter
out
in
bandpass
filter
out
in
notch
filter
out
signal
blocked
passed
frequency
signal
blocked
passed
frequency
signal
band
frequency
signal
notch
frequency

Current and voltage references

- Current and voltage references are the electronic implementations of independent, ideal sources.
- They provide currents or voltages that are independent on load impedance, temperature variations and supply voltage.
- A part of the supply current or voltage values, references are often characterized by two parameters:
  - sensitivity
  - temperature coefficient

Current and voltage references

- The **sensitivity** is defined as the relative variation of the reference current or voltage *Xref* with any circuit parameter *y*.
- Typical quantities influencing *Xref* are for example
  - resistances
  - transistor parameters
  - supply voltage.

$$S_{Xref}^{y} = \frac{\partial X_{ref}}{\partial y} \cdot \frac{y}{X_{ref}}$$

Current and voltage references

- The **temperature coefficient** is defined as the sensitivity of *Xref* to temperature variations, normalized to one degree.
- The temperature coefficient can be specified in *V*(*A*)/°C

$$\boxed{TC = \frac{\partial X_{ref}}{\partial T} \cdot \frac{1}{X_{ref}}}$$

Voltage references

The voltage divider reference

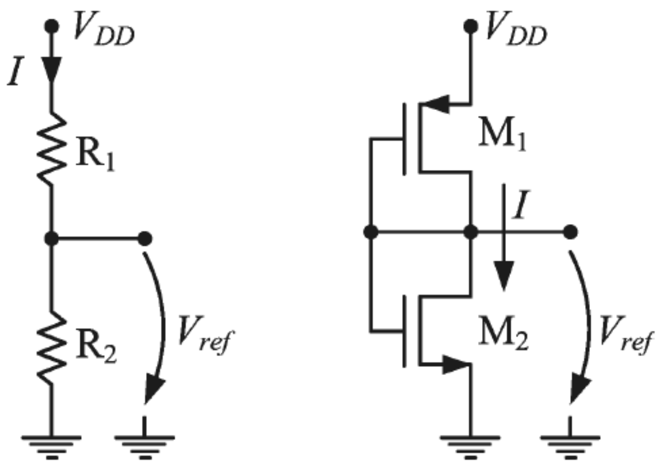
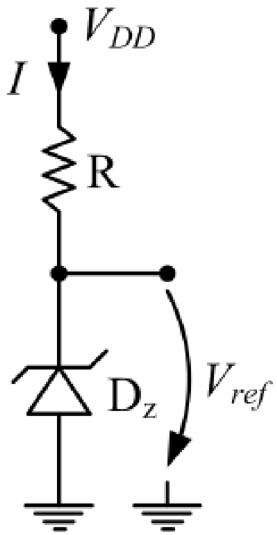


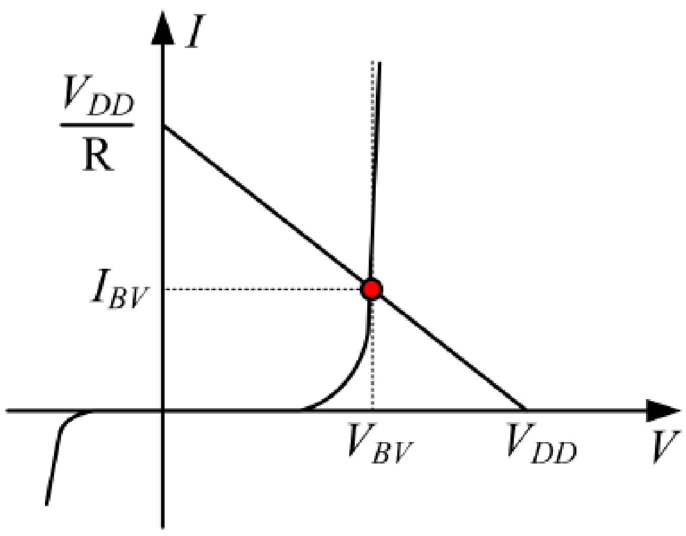
Figure 1. A resistive and a MOS divider as voltage references

$$V_{ref} = \frac{R_2}{R_1 + R_2} \cdot V_{DD}$$

Voltage references

The Zener diode voltage reference





Current references

Self biased current mirror reference

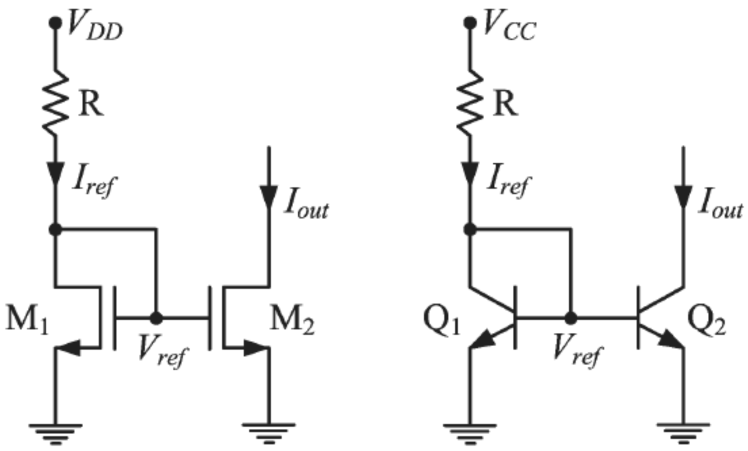


Figure 5. Self biased current mirror references

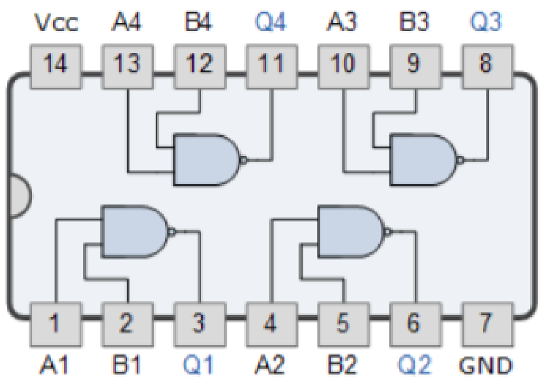
$$I_{out} = I_{ref} = \frac{V_{DD/CC} - V_{ref}}{R}$$

$$\begin{cases} I_{out-MOS} = I_{D2} = \beta\left(V_{ref} - V_{Th}\right)^2 \\ I_{out-BJT} = I_{C2} = I_S e^{\frac{V_{ref}}{V_T}} \end{cases}$$

Digital building blocks

- Logic Families (TTL, CMOS, ECL, RTL etc.),
- characteristics (delay, threshold voltages, noise margins, fan in/out etc.).
- Pull-up & Pull Down configurations,
- Active High & Active Low levels,
- Open Collector/Drain configurations.

Common ICs



7400 Quad 2-input Logic NAND Gate

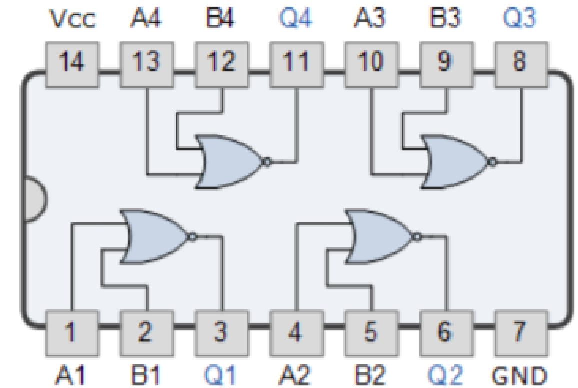
Also:

74LS00 Quad 2-input

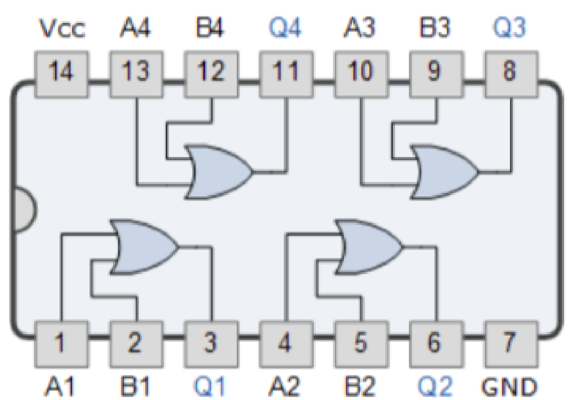
74LS10 Triple 3-input

74LS20 Dual 4-input

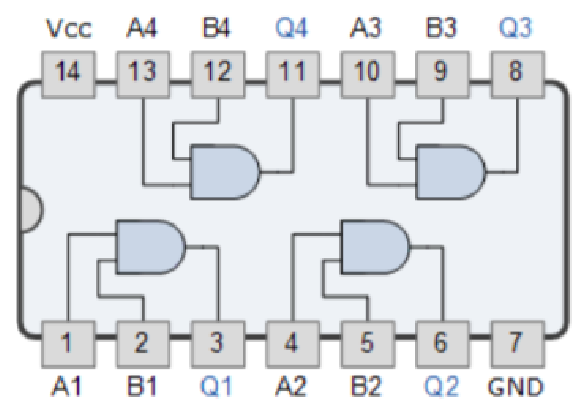
74LS30 Single 8-input



7402 Quad 2-input NOR Gate



7432 Quad 2-input Logic OR Gate



7408 Quad 2-input AND Gate

Some parameters

- Voltage Parameters:
  - V_{IH}(min): high-level input voltage, the minimum voltage level required for a logic 1 at an *input*.
  - V_{IL}(max): low-level input voltage
  - V_{OH}(min): high-level output voltage
  - V_{OL}(max): low-level output voltage

Current Parameters

- I_{IH}(min): high-level input current, the current that flows into an input when a specified high-level voltage is applied to that input.
- I_{IL}(max): low-level input current
- I_{OH}(min): high-level output current
- I_{OL}(max): low-level output current

Figure : Some parameters

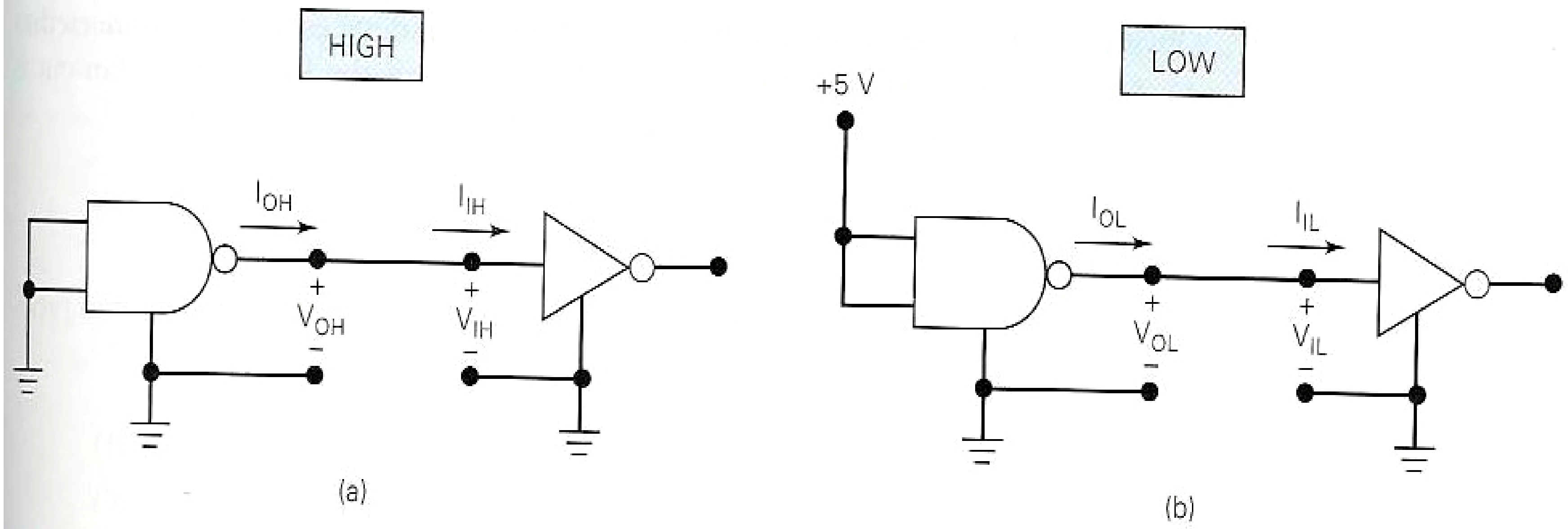


FIGURE 8-1 Currents and voltages in the two logic states.

Some Definitions

- **Fan in**
- Fan in is the number of inputs connected to the gate without any degradation in the voltage level.
- **Fan-out**
- Fan out specifies the number of standard loads that the output of the gate can drive without impairment of its normal operation

Some Definitions

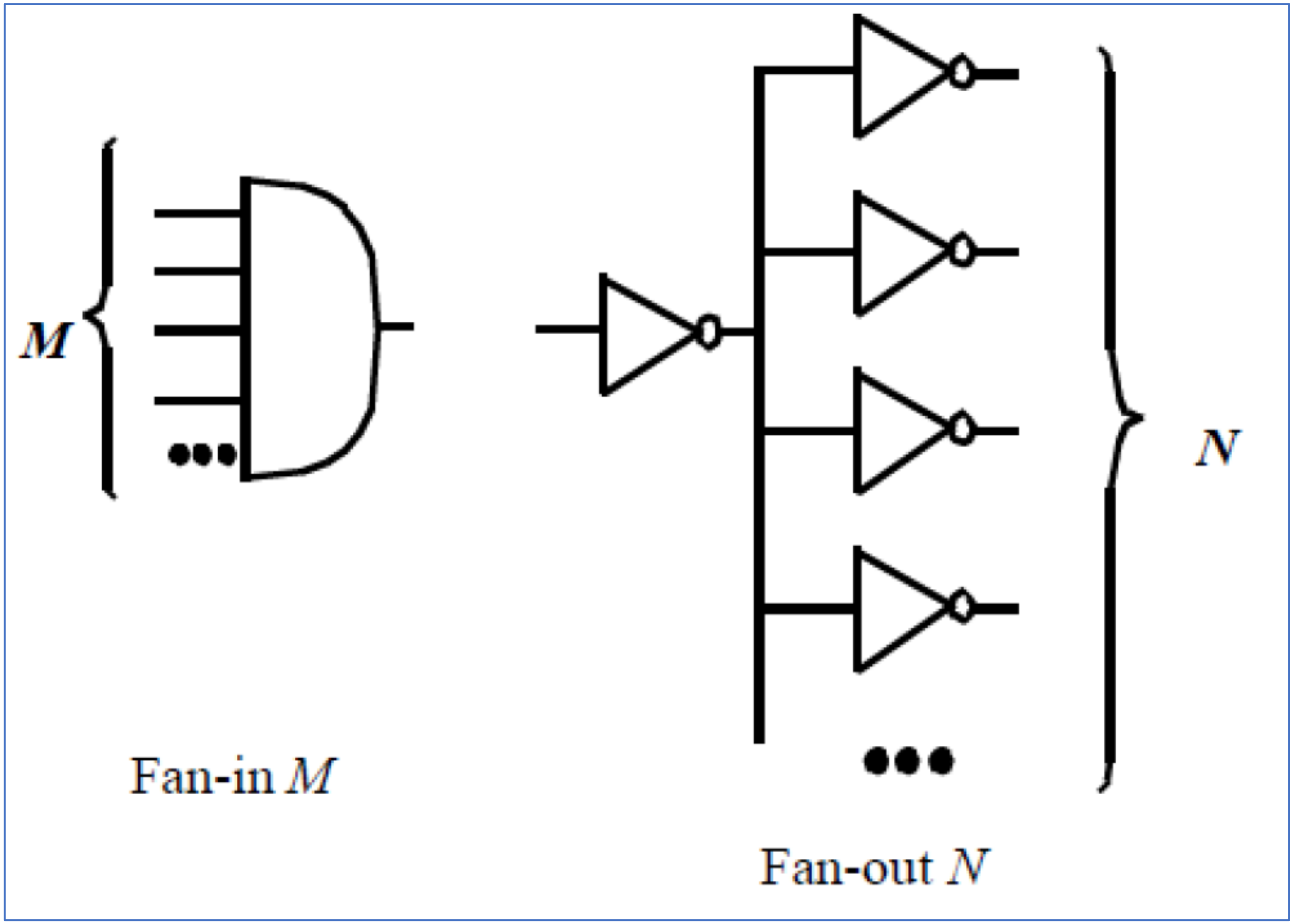
Fan-Out

- The maximum number of standard logic inputs that an output can drive reliably.
- Also known as the *loading factor*.
- Related to the current parameters (both in high and low states.)

Fan in

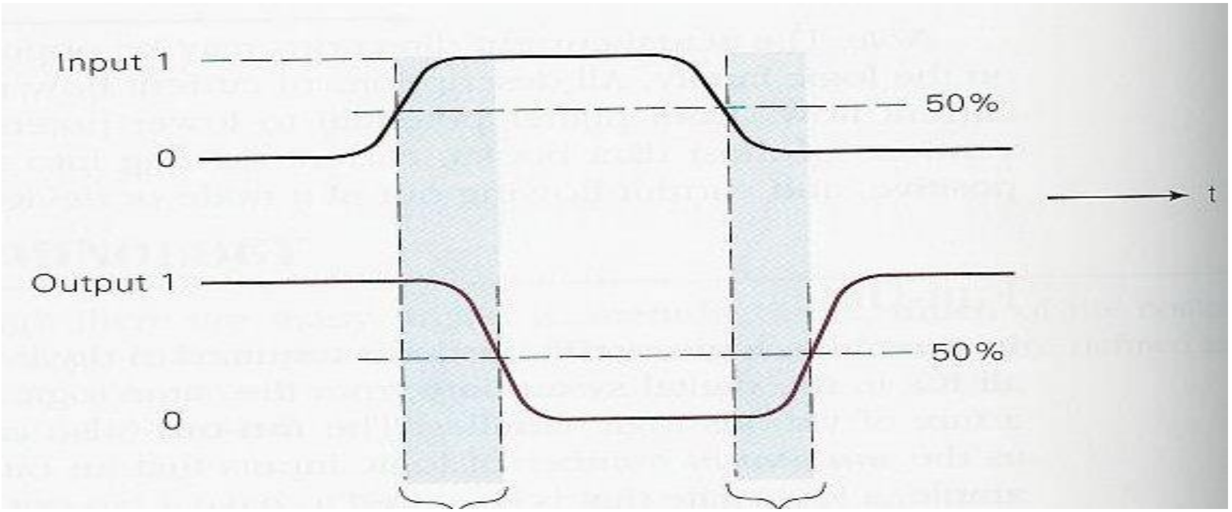
- Fan in is the number of inputs connected to the gate without any degradation in the voltage level.

Some Definitions



Propagation Delays

- t_{pLH}: delay time in going from logical 0 to logical 1 state (LOW to HIGH)
- t_{pHL}: delay time in going from logical 1 to logical 0 state (HIGH to LOW)
- Measured at 50% points.

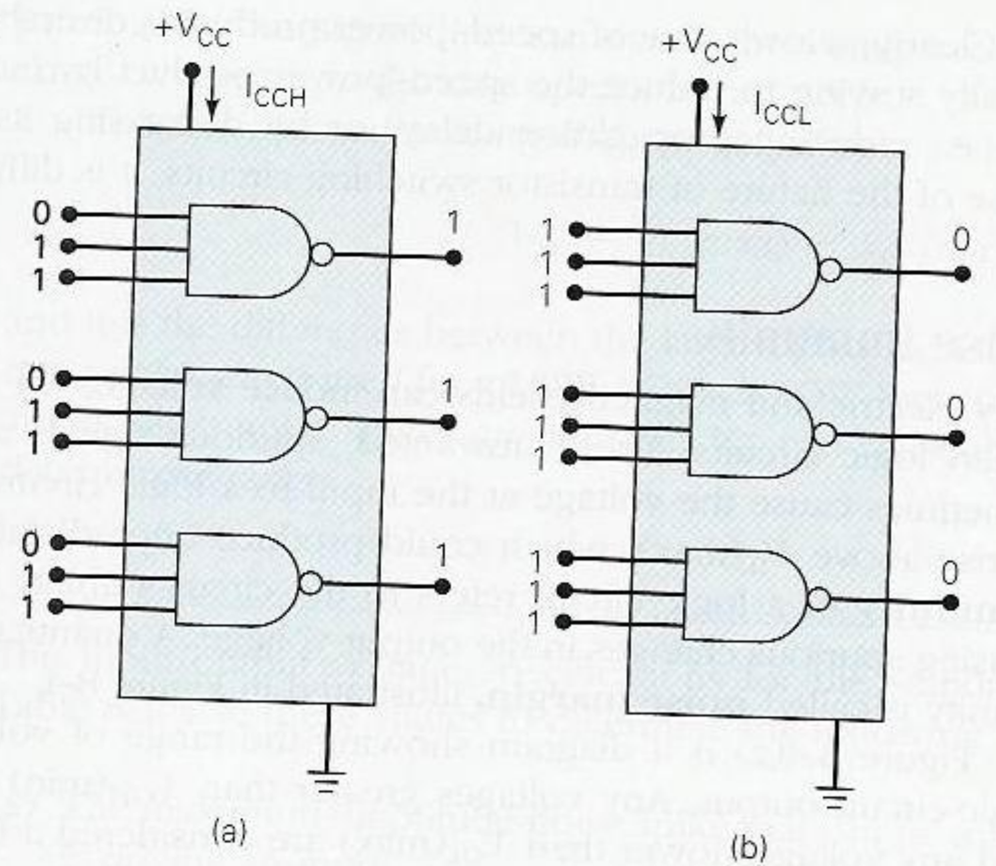


Power Requirements

- Every IC needs a certain amount of electrical power to operate.
- V_{cc} (TTL)
- V_{DD}(MOS)
- Power dissipation determined by I_{cc} and V_{cc}.
- Average $I_{cc}(avg) = (I_{CCH} + I_{CCL})/2$
- $P_D(avg) = I_{cc}(avg) \times V_{cc}$

Power Requirements

FIGURE 8-3 I_{CCH} and I_{CCL}.



Speed-Power Product

- Desirable properties:
  - Short propagation delays (high speed)
  - Low power dissipation
- Speed-power product measures the combined effect.

Noise Immunity

- What happens if noise causes the input voltage to drop below V_{IH}(min) or rise above V_{IL}(max)?
- The noise immunity of a logic circuit refers to the circuit's ability to tolerate noise without causing spurious changes in the output voltage.
- $V_{NH}=V_{OH}(min)-V_{IH}(min)$
- $V_{NL}=V_{IL}(max)-V_{OL}(max)$

Figure : Noise Margin

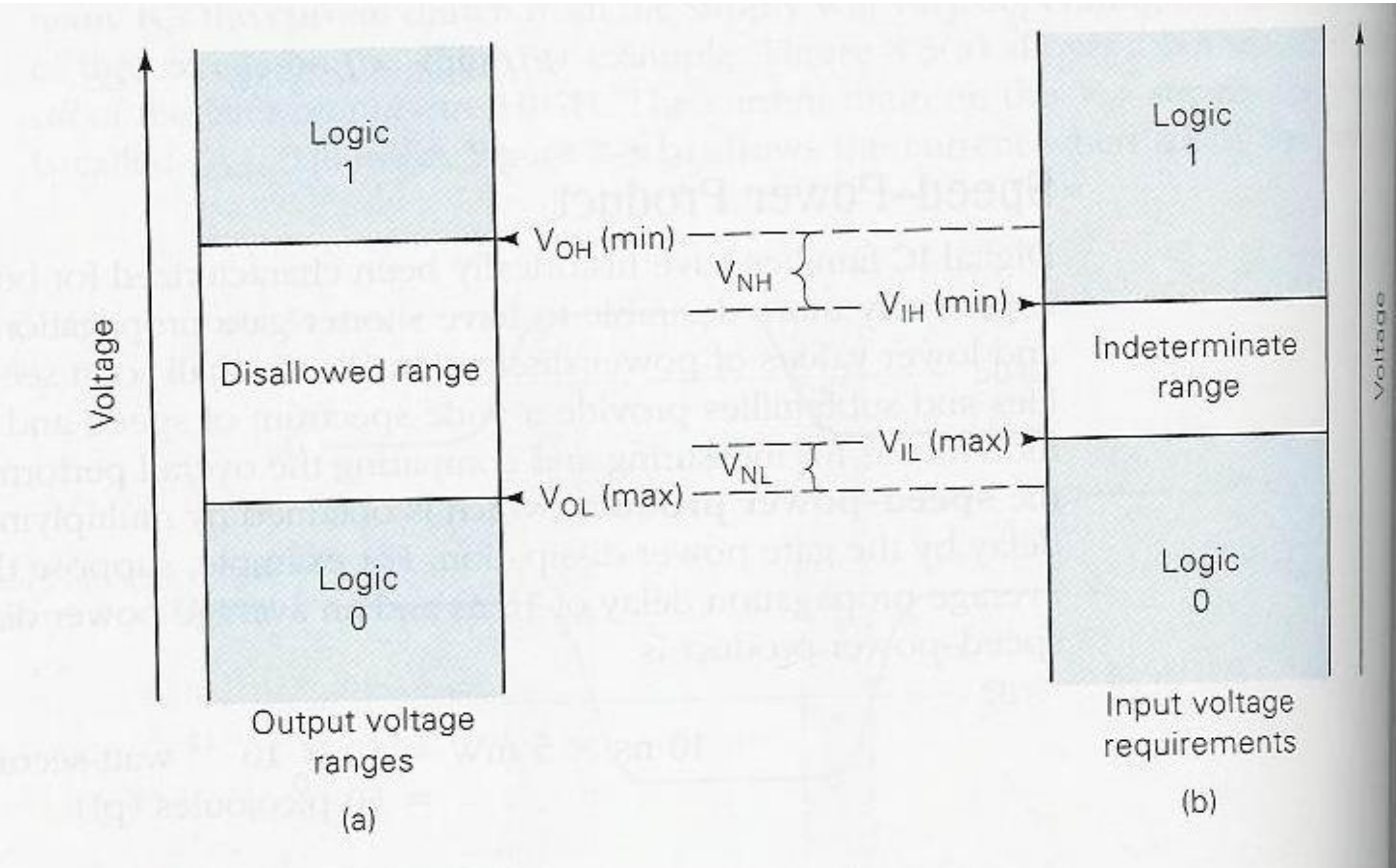


FIGURE 8-4 dc noise margins.

Invalid Voltage Levels

- For proper operation the input voltage levels to a logic must be kept outside the indeterminate range.
- Lower than V_{IL}(max) and higher than V_{IH}(min).

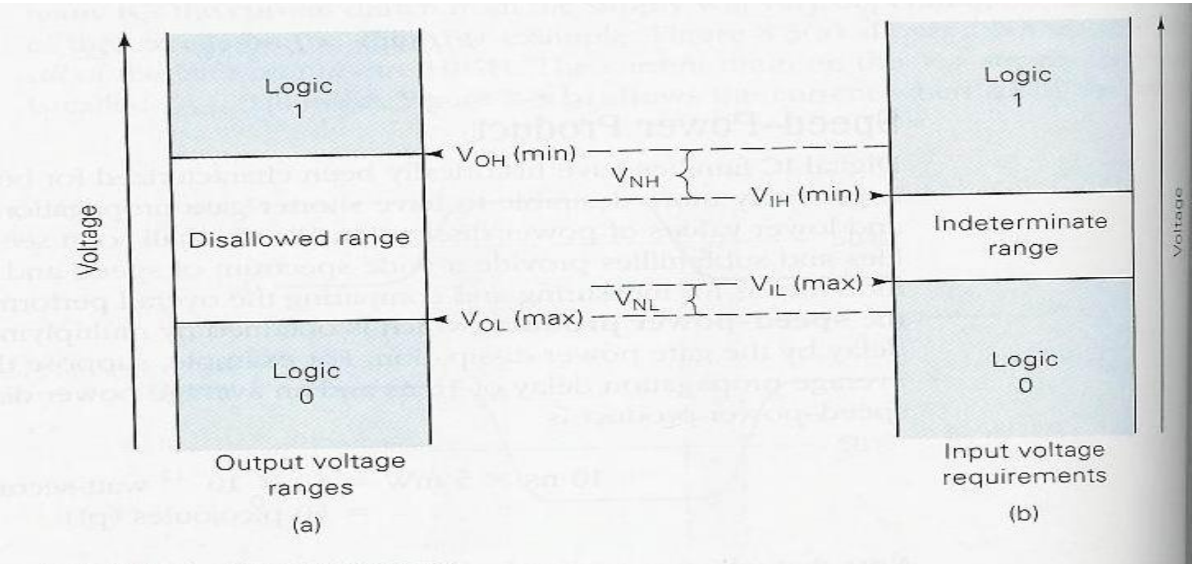
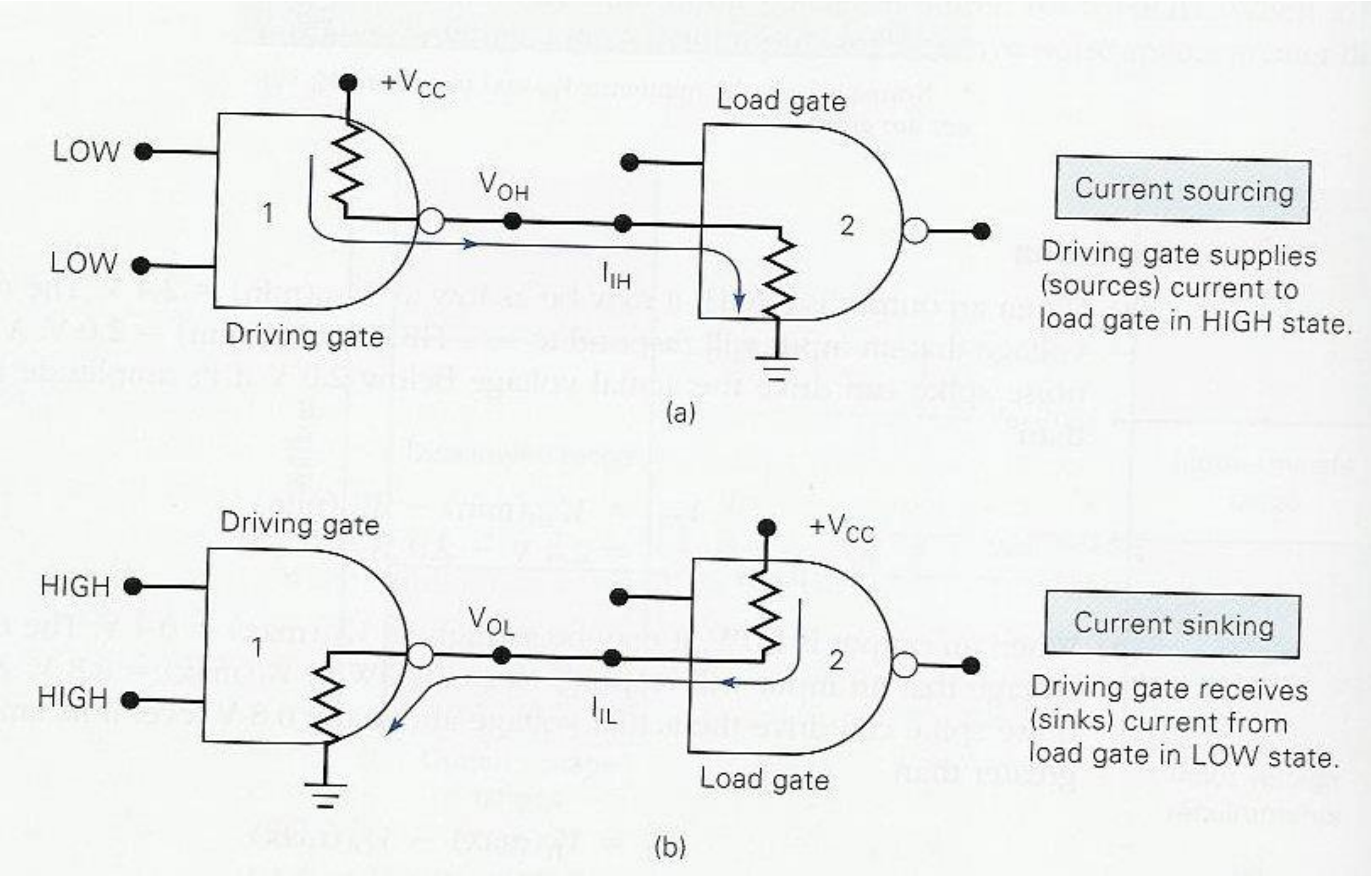


FIGURE 8-4 dc noise margins.

Current-Sourcing and Sinking



Digital Logic Families

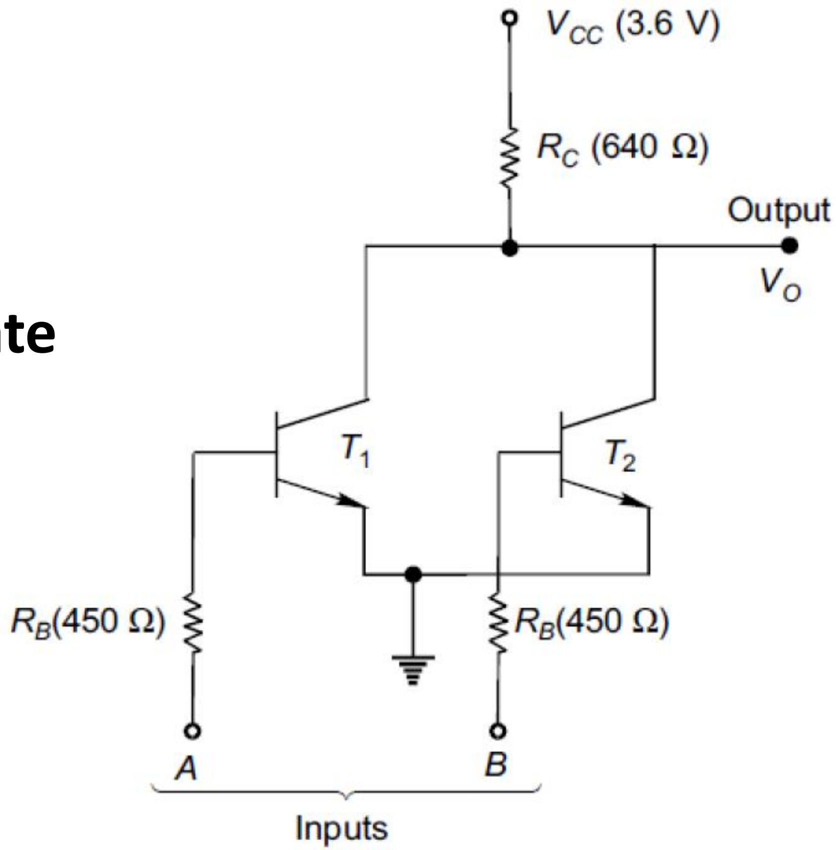
- Register-Transistor Logic (RTL)
- Transistor-Transistor Logic (TTL)
- Emitter-Coupled Logic (ECL)
- Complementary Metal Oxide Semiconductor (CMOS)

Resistor-Transistor Logic (RTL)

- The most popular form of logic in common use before the development of ICs
- Consist of resistors and transistors
- Earliest logic family to be integrated
- Although being obsolete now, because of its simplicity and for historical reasons, it is proper to devote some attention to it and introduce some of the important concepts, useful for all types of gates, through this.

Resistor-Transistor Logic (RTL)

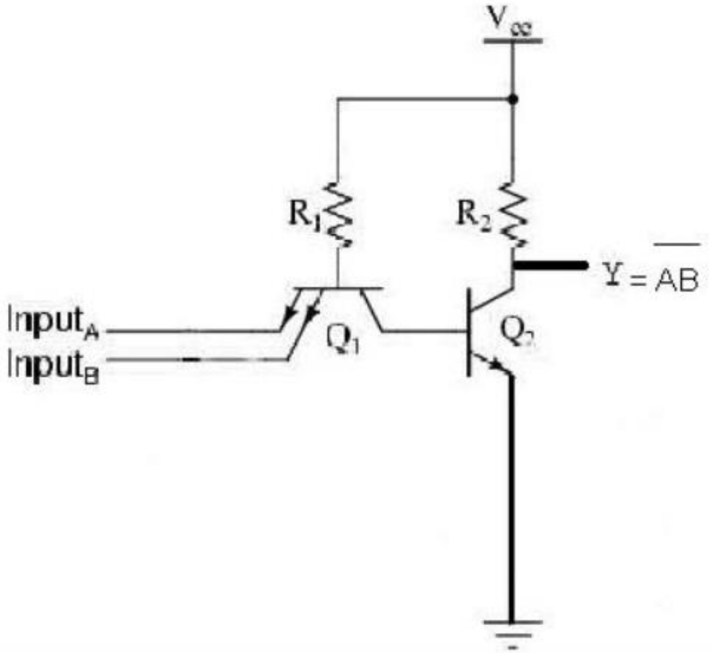
RTL NOR Gate



The TTL Logic Family

- **Transistor-transistor logic.**
- based on bipolar transistors
- one of the most widely used families for small- and medium-scale devices – rarely used for VLSI
- typically operated from 5V supply
- typical noise immunity about 1 – 1.6 V
- many forms, some optimised for speed, power, etc.
- high speed versions comparable to CMOS (≈ 1.5 ns)
- low-power versions down to about 1 mW/gate

TTL NAND Gate

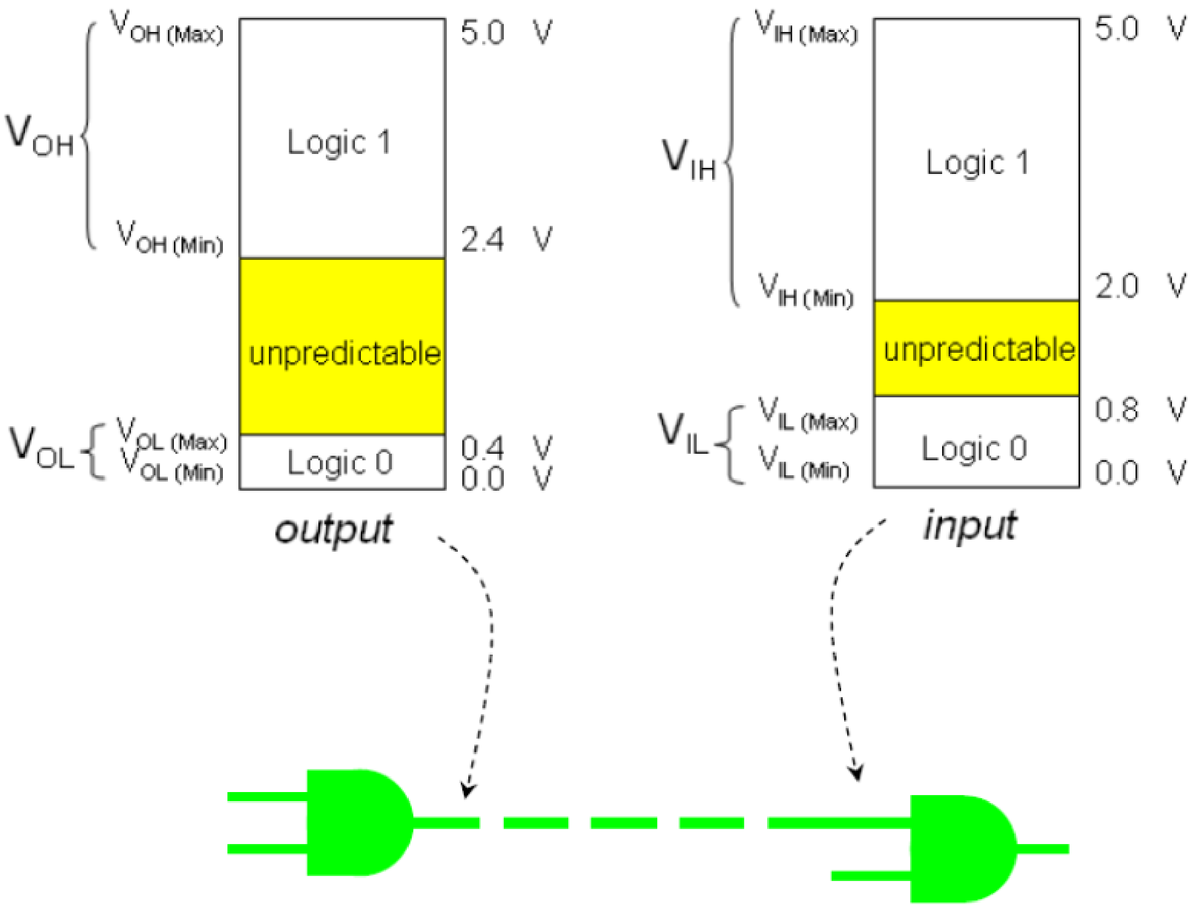


A	B	Y
0	0	1
0	1	1
1	0	1
1	1	0

TTL NAND Gate

- Input terminals: emitter of Q1
- Output terminals: collector of Q2
- When any input = logic '0' Q1 emitter junction is forward biased.
  - Also its collector junction is FB,
  - So Q1 goes in saturation.
  - Base of Q2 is at Low voltage
  - This causes base-emitter junction of Q2 to be RB, so Q2 goes in cut-off
  - Hence output is 5V or logic '1'
- When all inputs = logic '1' Q1 emitter junction is RB.
  - so Q1 goes in cut-off.
  - Its collector voltage increases
  - This forward biases Q2,
  - so Q2 goes in saturation
  - Hence output is 0V

TTL Voltage Levels



TTL Types

- **Standard TTL**
  - typical gate propagation delay of 10ns
  - and a power dissipation of 10 mW per gate,
  - for a power–delay product (PDP) or switching energy of about 100 pJ
- **Low-power TTL (L)**
  - Slow switching speed (33ns)
  - reduction in power consumption (1 mW)
  - (now essentially replaced by CMOS logic)

TTL Types

- **High-speed TTL (H)**
  - faster switching than standard TTL (6ns)
  - but significantly higher power dissipation (22 mW)

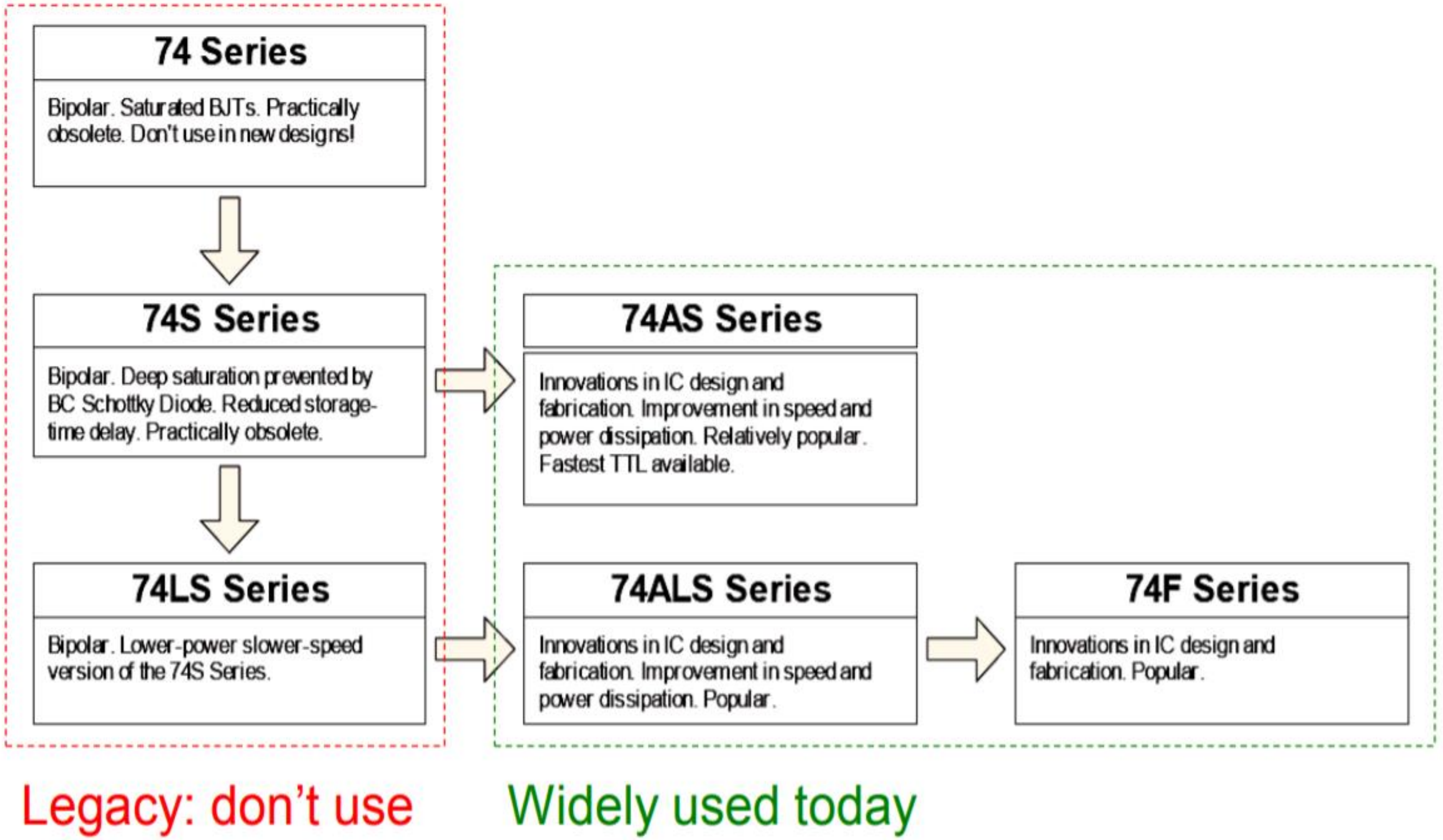
TTL Types

- **Schottky TTL (S)**
  - used Schottky diode clamps at gate inputs to prevent charge storage and improve switching time.
  - A Schottky diode has a very low forward-voltage drop of 0.15–0.45V approx (silicon diode has a voltage drop of 0.6–1.7V). This lower voltage drop can provide higher switching speed.
  - Faster speed of (3ns)
  - but had higher power dissipation (19 mW)

TTL Types

- **Low-power Schottky TTL (LS)**
  - used the higher resistance values of low-power TTL and the Schottky diodes to
  - provide a good combination of speed (9.5ns)
  - and reduced power consumption (2 mW), and PDP of about 20 pJ.

TTL Types


74 Series
Bipolar. Saturated BJTs. Practically obsolete. Don't use in new designs!
74S Series
Bipolar. Deep saturation prevented by BC Schottky Diode. Reduced storage-time delay. Practically obsolete.
74LS Series
Bipolar. Lower-power slower-speed version of the 74S Series.
74AS Series
Innovations in IC design and fabrication. Improvement in speed and power dissipation. Relatively popular. Fastest TTL available.
74ALS Series
Innovations in IC design and fabrication. Improvement in speed and power dissipation. Popular.
74F Series
Innovations in IC design and fabrication. Popular.
Legacy: don't use
Widely used today

Comparison of TTL Series

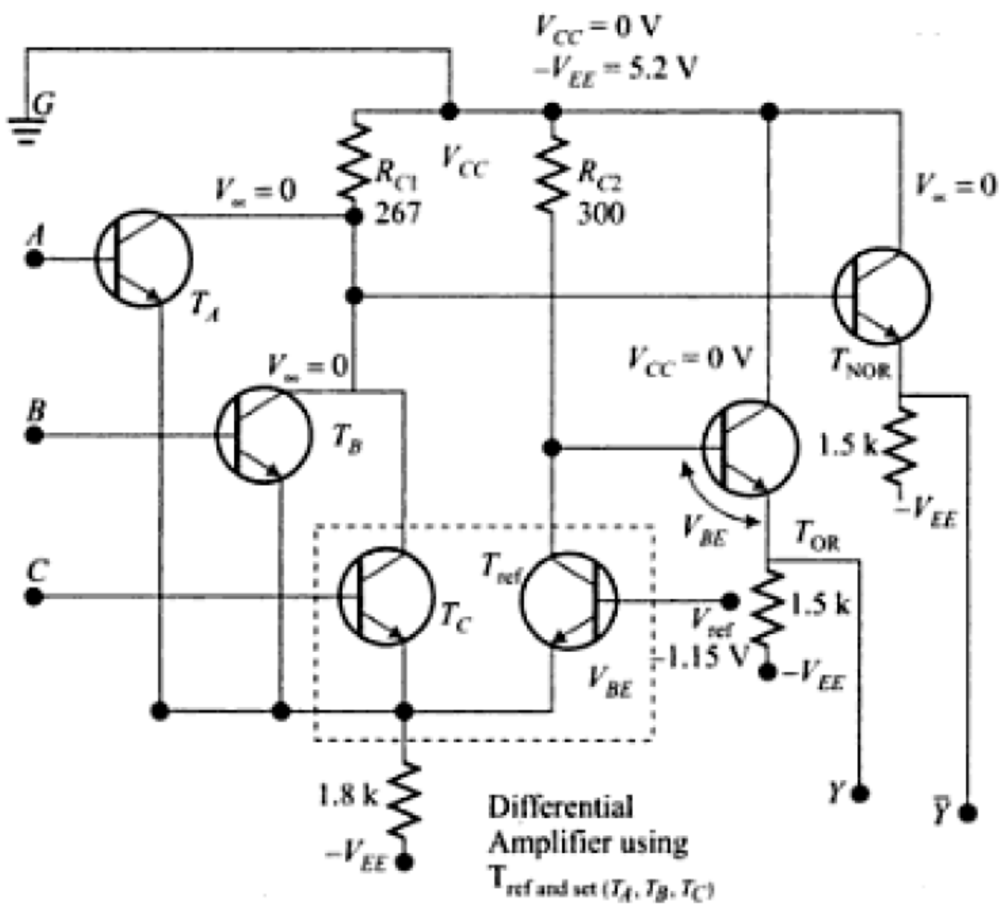
TABLE 8-6 Typical TTL series characteristics.

	74	74S	74LS	74AS	74ALS	74F
Performance ratings						
Propagation delay (ns)	9	3	9.5	1.7	4	3
Power dissipation (mW)	10	20	2	8	1.2	6
Speed–power product (pJ)	90	60	19	13.6	4.8	18
Max. clock rate (MHz)	35	125	45	200	70	100
Fan-out (same series)	10	20	20	40	20	33
Voltage parameters						
V_{OH}(min)	2.4	2.7	2.7	2.5	2.5	2.5
V_{OL}(max)	0.4	0.5	0.5	0.5	0.5	0.5
V_{IH}(min)	2.0	2.0	2.0	2.0	2.0	2.0
V_{IL}(max)	0.8	0.8	0.8	0.8	0.8	0.8

Emitter-coupled logic (ECL)

- based on bipolar transistors, but removes problems of storage time by preventing the transistors from saturating
- very fast operation - propagation delays of 1ns or less
- high power consumption, perhaps 60 mW/gate
- low noise immunity of about 0.2-0.25 V
- used in some high speed specialist applications, but now largely replaced by high speed CMOS

Emitter-coupled logic (ECL)



Emitter-coupled logic (ECL)

- Input
  - Input is at base of transistor
  - The emitter of Tref and input transistors couples together. [Hence the name ECL]
  - ECL basic gate is OR/NOR gate
  - If any input is not connected, the transistor Ti base-emitter will be at cutoff. Therefore, it will be taken as low logic level

Emitter-coupled logic (ECL)

- Output
  - The outputs (T_{OR} and T_{NOR}) are taken from the emitters of each transistor
  - Collector of T_{OR} and T_{NOR} connects to GND in the CC amplifier mode (also called emitter-follower mode).
  - The emitter gives the output, which also connects to -VEE through a resistance R (~1.5kΩ)

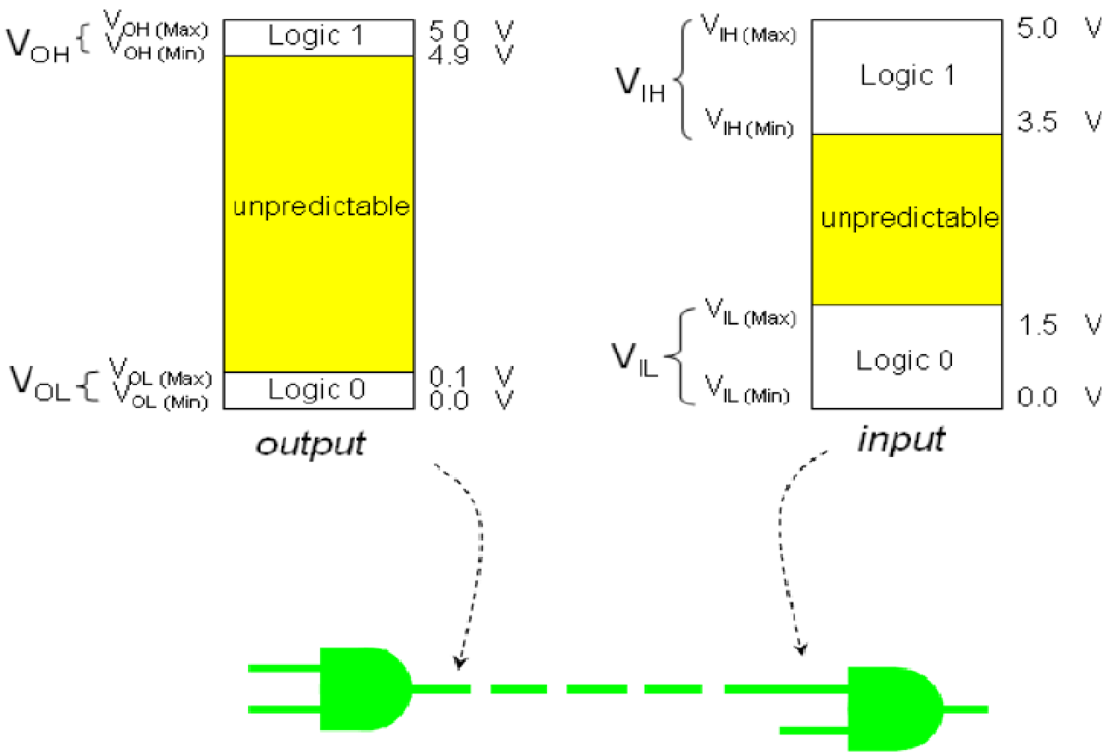
Emitter-coupled logic (ECL)

- Faster speed (2 ns propagation delay)
- of operation than TTL (10 ns), 74S TTL(3 ns)
- More power dissipation (50 mW/gate) than TTL (10 mW), 74S (19mW)
- Noise Margin at ‘1’or ‘0’output and input = 0.4V (– 1.7V and – 1.4V)

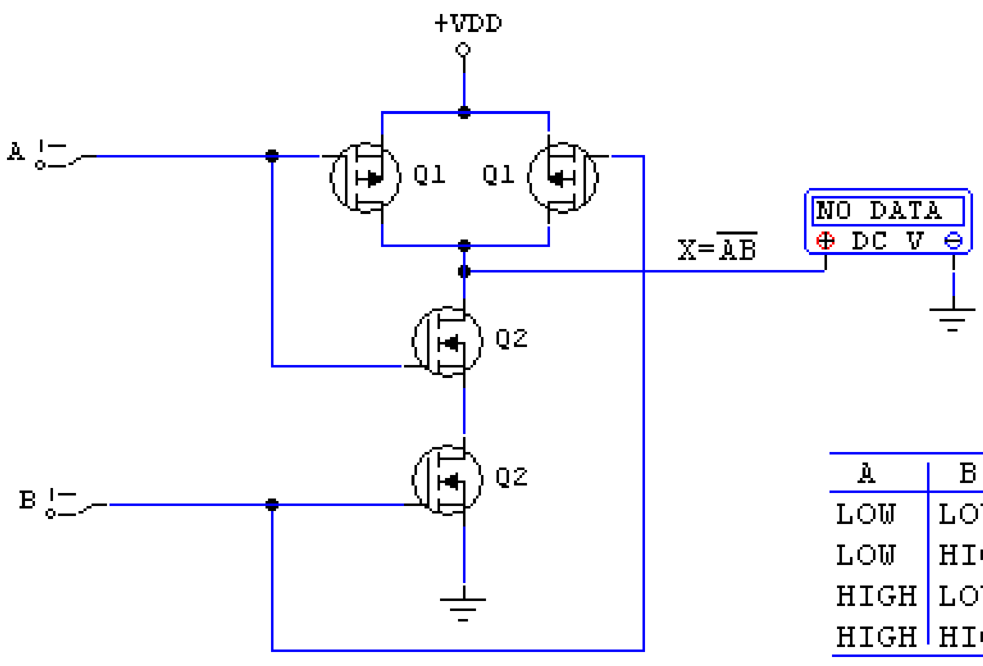
Complementary metal oxide semiconductor (CMOS)

- most widely used family for large-scale devices
- combines high speed with low power consumption
- usually operates from a single supply of 5 – 15 V
- excellent noise immunity of about 30% of supply voltage
- High fan-out : can be connected to a large number of gates (about 50)
- CMOS gates have equal no.of PMOS and NMOS
- CMOS inverter has a very high input resistance

CMOS Logic Levels



Complementary metal oxide semiconductor (CMOS)



A	B	X
LOW	LOW	HIGH
LOW	HIGH	HIGH
HIGH	LOW	HIGH
HIGH	HIGH	HIGH

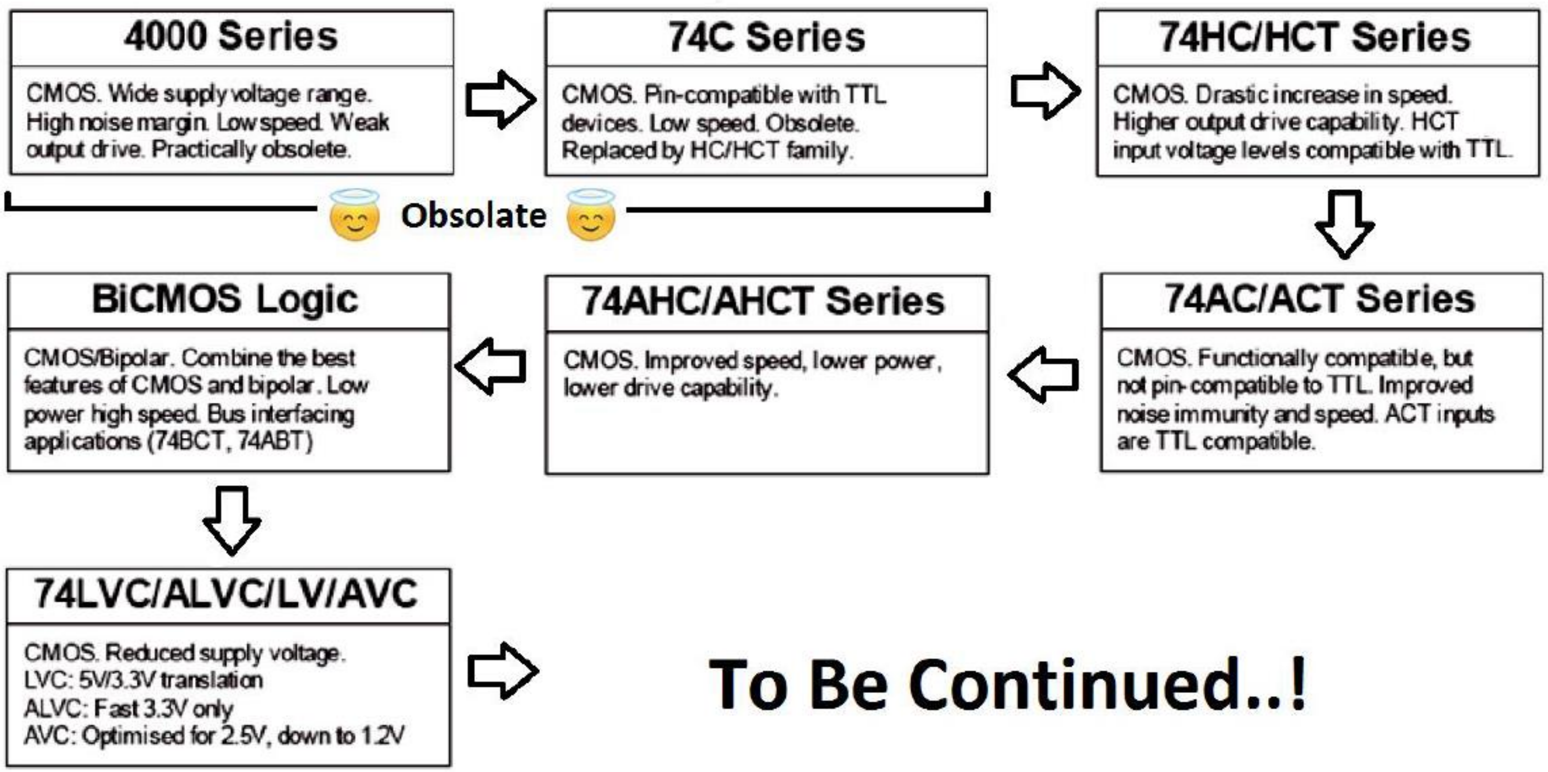
CMOS NAND gate.

CMOS Evolution

- Reduction of dynamic losses through successively decreasing supply voltages:

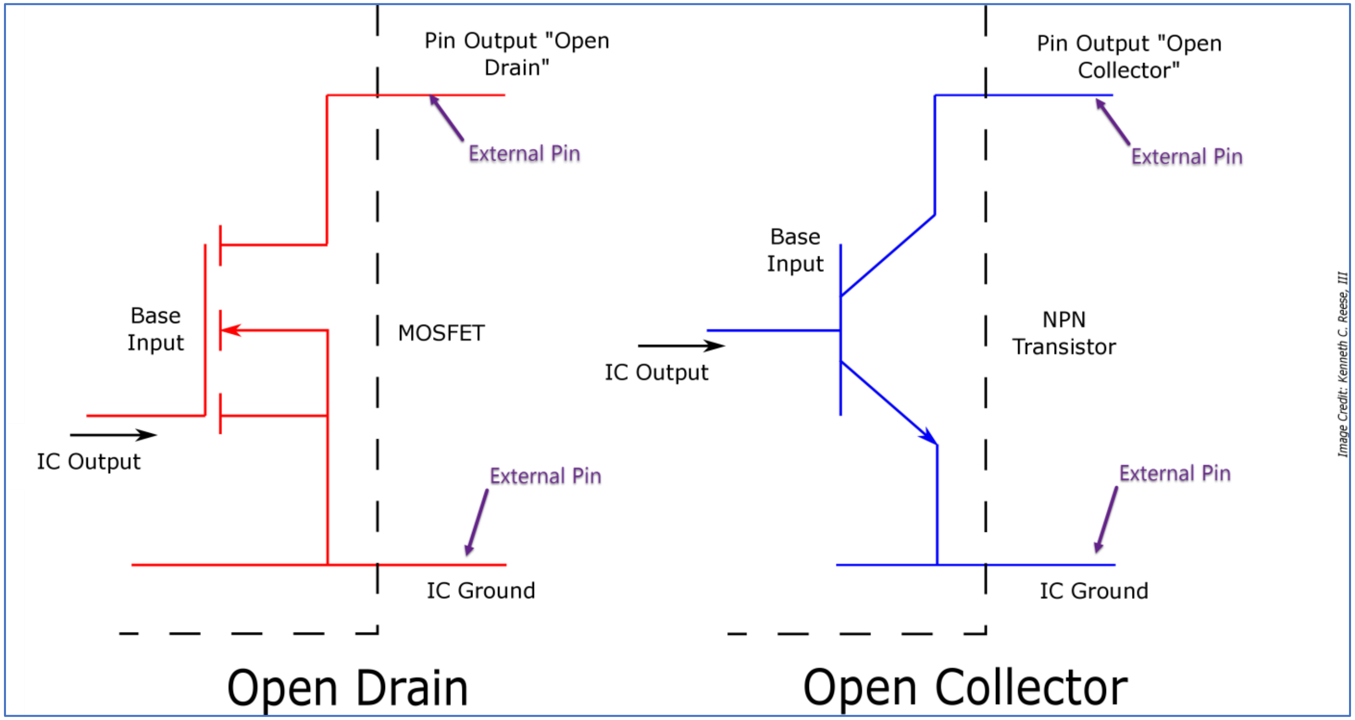
  12V →5V →3.3V →2.5V →1.8
- Power reduction is one of the keys to progressive growth of integration

CMOS Evolution



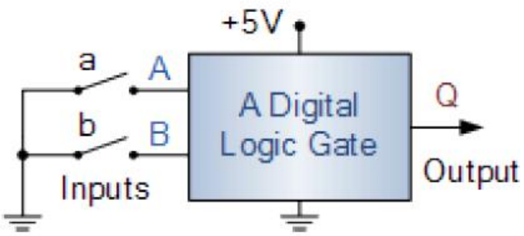
Open Collector/Drain Configuration

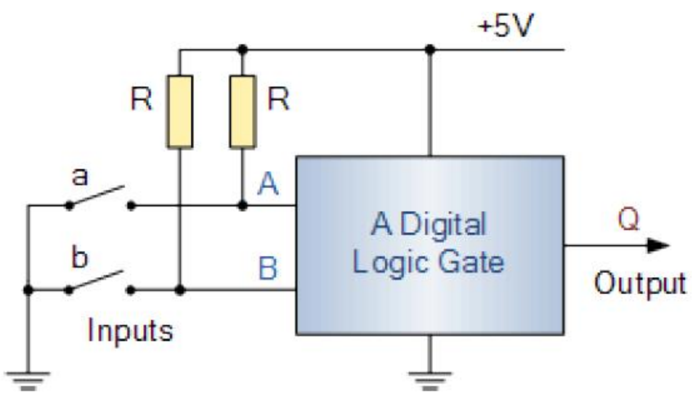
- An **open collector/open drain** is a common type of output found on many integrated circuits (IC).
- It behaves like a switch that is either connected to ground or disconnected.
- It is employed into output port of controllers to reduce the output circuitry.

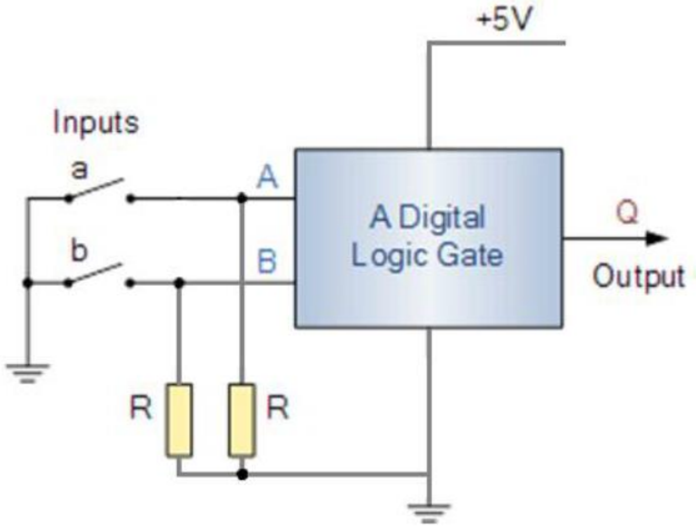


Pull Up / Pull Down Configuration

Pull-up and Pull-down resistors are used to correctly bias the inputs of digital gates to stop them from floating about randomly when there is no input condition



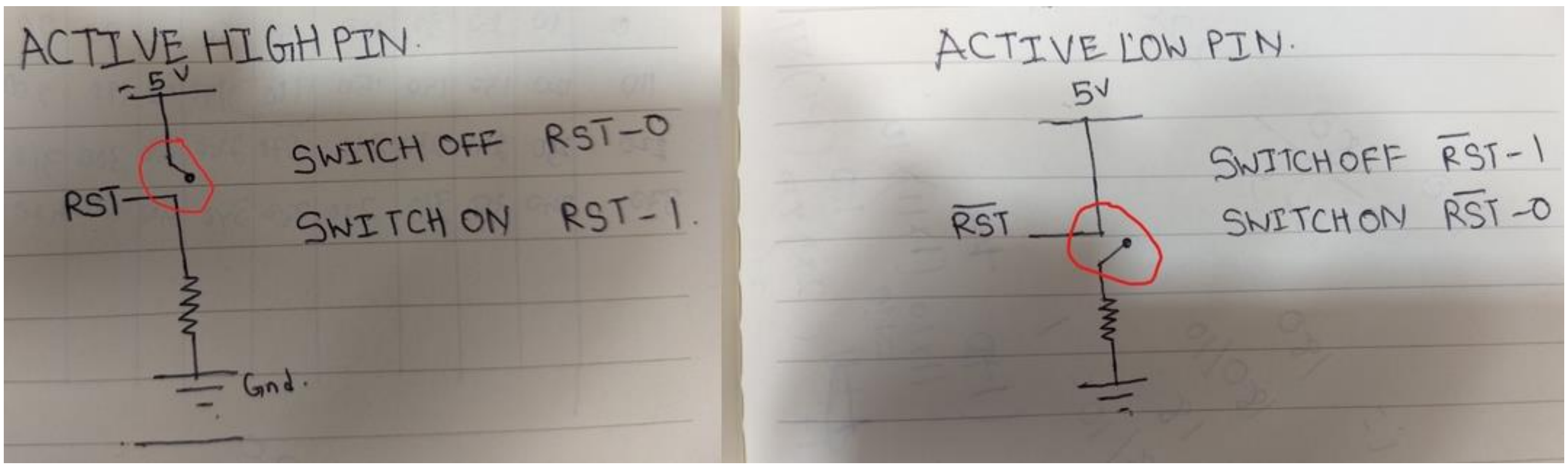




Active High & Active Low levels

- The pins in microcontroller or in datasheet of any IC pins particularly are labelled as **Active High** pin or **Active Low** pin
- If it's an **active**-**low** pin, you must “pull” that pin **LOW** by connecting it to ground.
- For an **active high** pin, you connect it to **HIGH** voltage (usually 3.3V/5V).

Active High & Active Low levels



Thank You !!!