Lecture 2

Intermediate circuit theory, nonlinear components

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Agenda

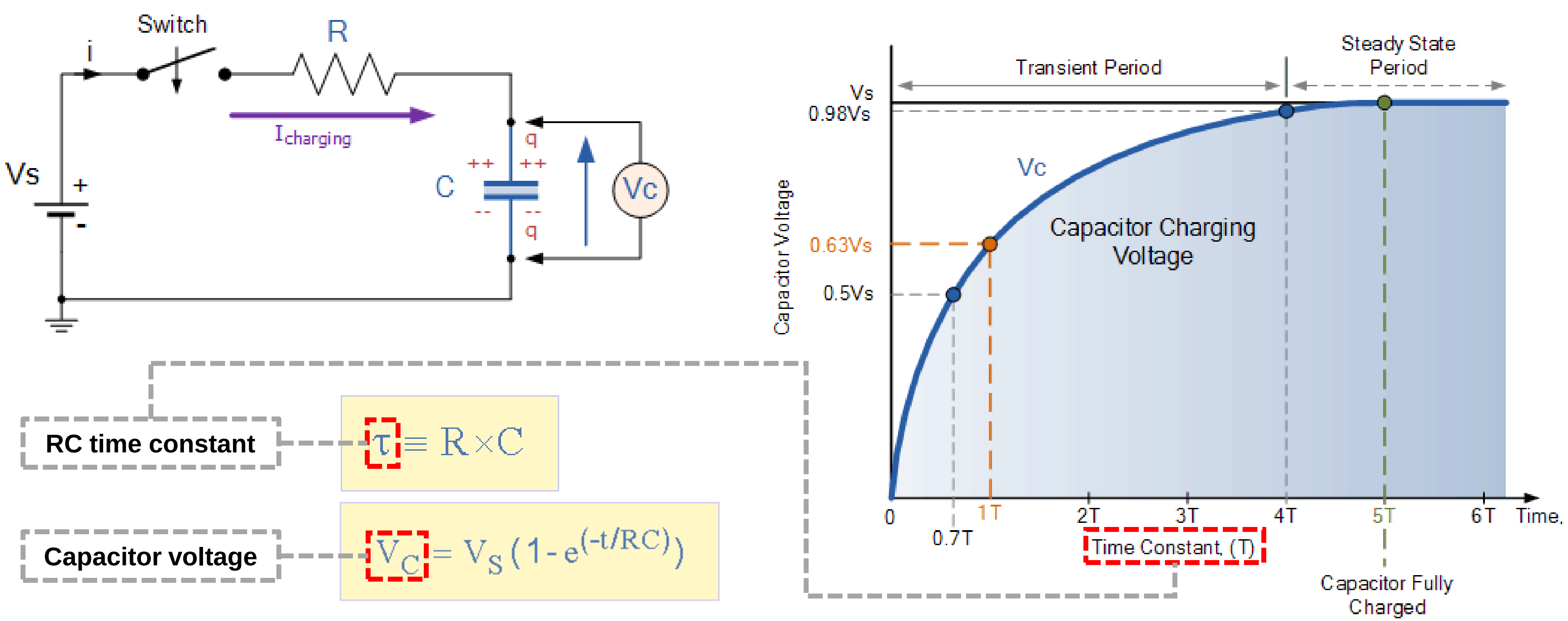
1. Lab 1 review: RC circuits
2. Nonlinear components: diodes, BJTs and MOSFETs
3. Operational amplifiers (op-amps)
4. Audio amplification
5. Lab 2 overview: components and specifications

Lab 1 review

Resistor-capacitor (RC) circuits

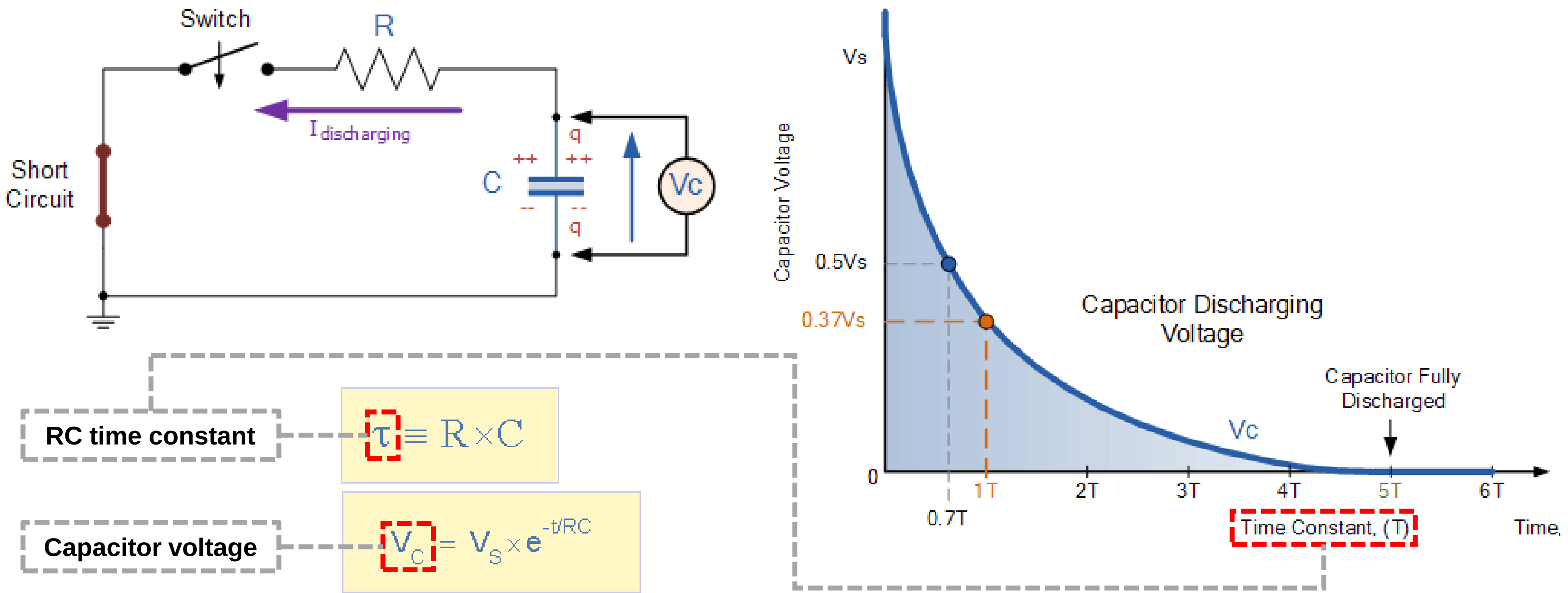
RC charging response

- Capacitor voltage V_c grows **exponentially** close to V_s
- Rate of exponential growth defined by resistor value (smaller resistor = faster charging)

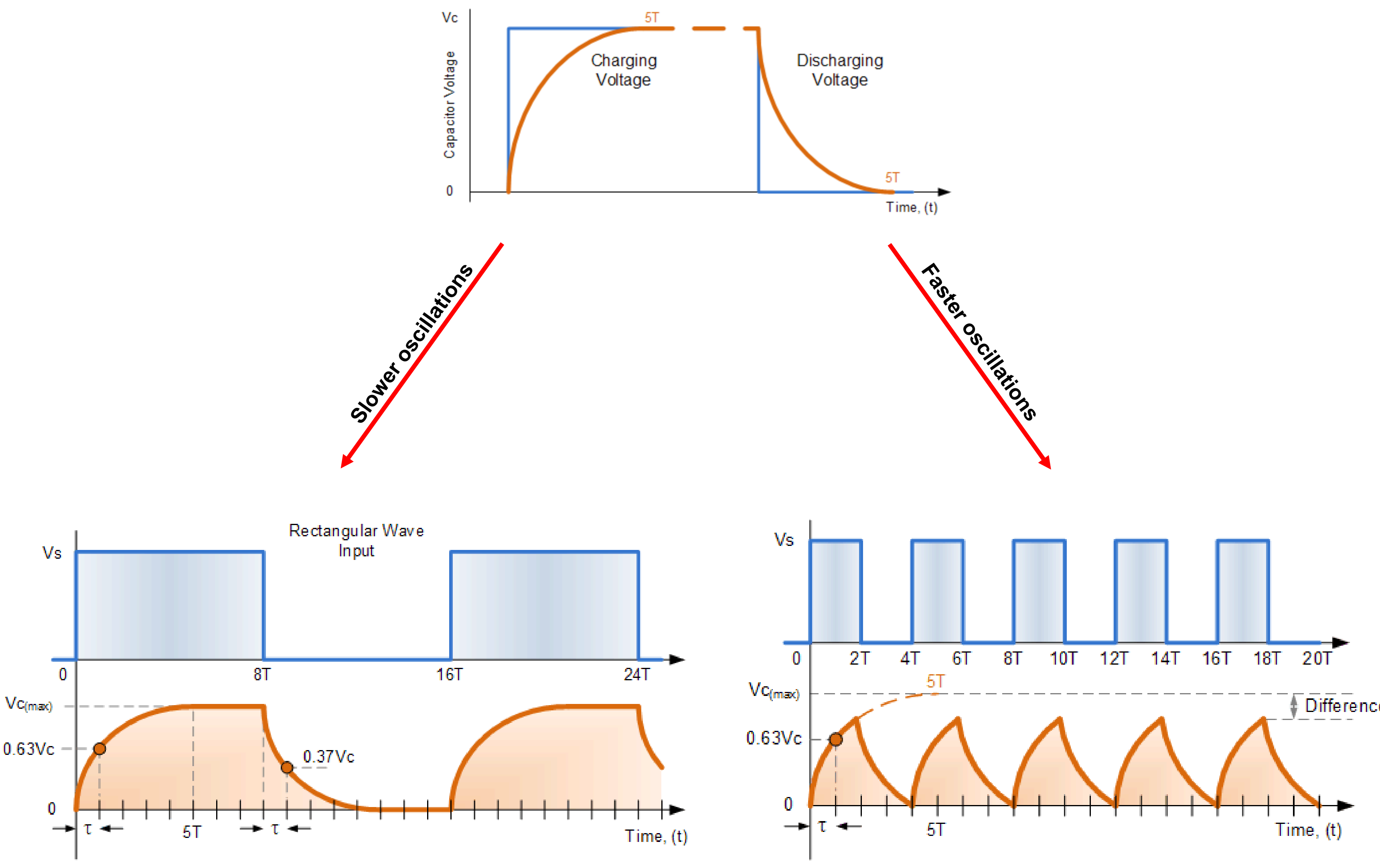


RC discharging response

- Capacitor voltage V_c decays **exponentially** to 0
- Rate of exponential decay defined by resistor value (smaller resistor = faster discharging)



RC transient response



RC Time constant tables

Charging

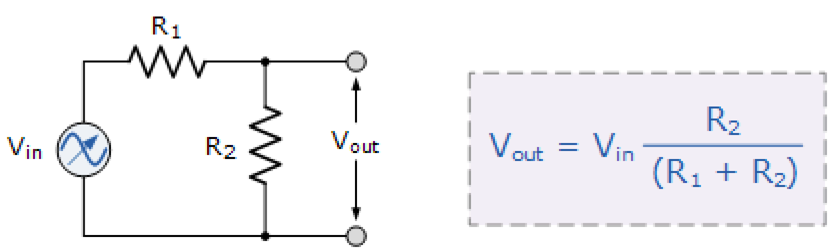
Time Constant	Percentage of applied voltage
0.5	39.3%
0.7	50.3%
1	63.2%
2	86.5%
3	95.0%
4	98.2%
5	99.3%

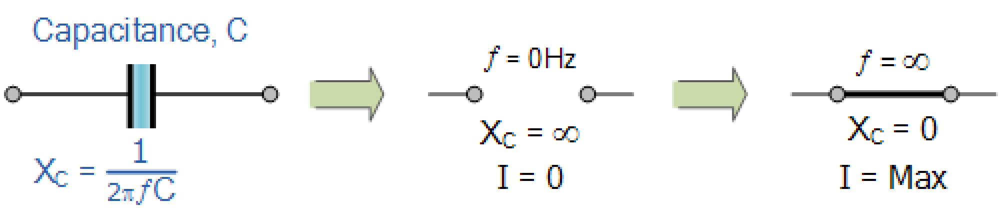
Discharging

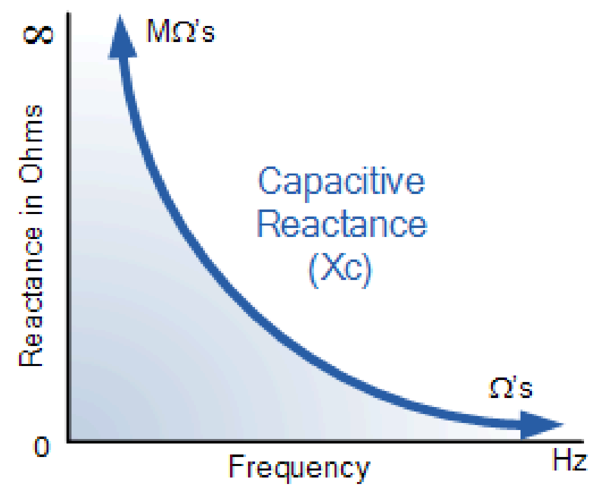
Time Constant	Percentage of applied voltage
0.5	60.7%
0.7	49.7%
1	36.8%
2	13.5%
3	5.0%
4	1.8%
5	0.7%

Filtering

- **Filter:** Circuit whose response depends on the frequency of the input
- **Reactance:** “Effective resistance” of a capacitor, varies inversely with frequency
- Can construct a voltage divider using a capacitor as a “resistor” to exploit this property

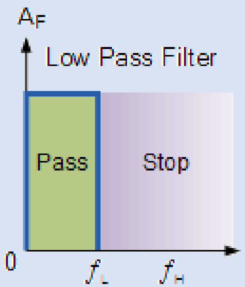


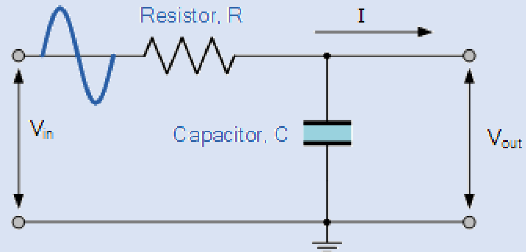




Types of filters

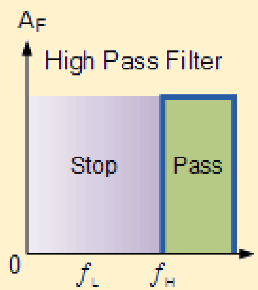
LPF

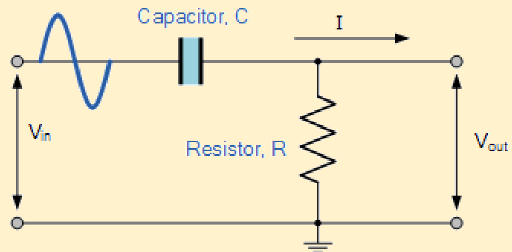




$$f_c = \frac{1}{2\pi RC} Hz$$

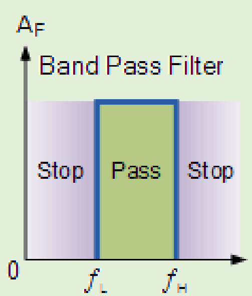
HPF

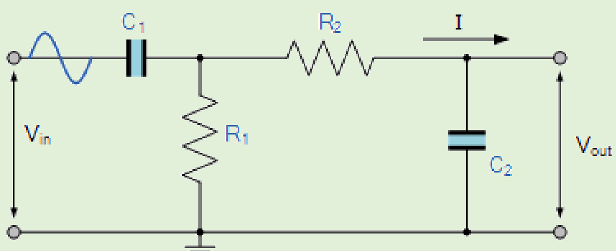




$$f_c = \frac{1}{2\pi RC} Hz$$

BPF





$$f_H = \frac{1}{2\pi R_1 C_1} Hz$$

$$f_L = \frac{1}{2\pi R_2 C_2} Hz$$

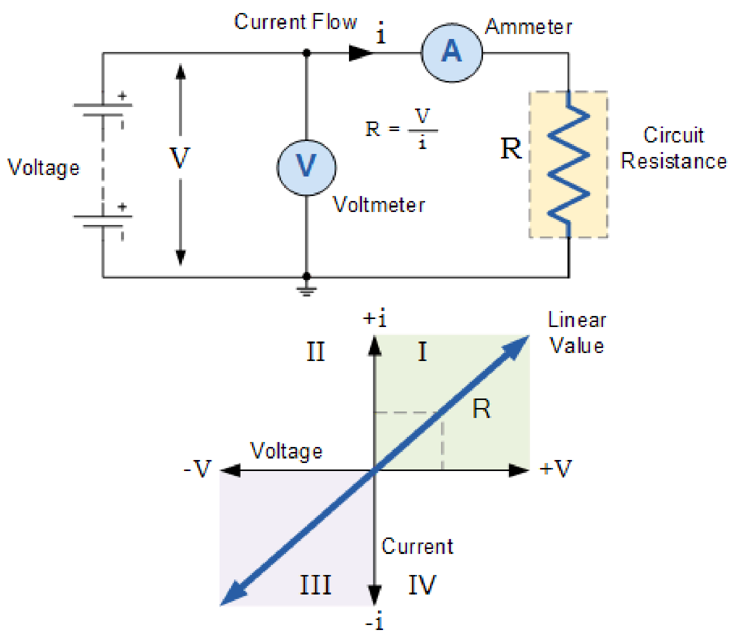
Nonlinear components

Diodes, BJTs and MOSFETs

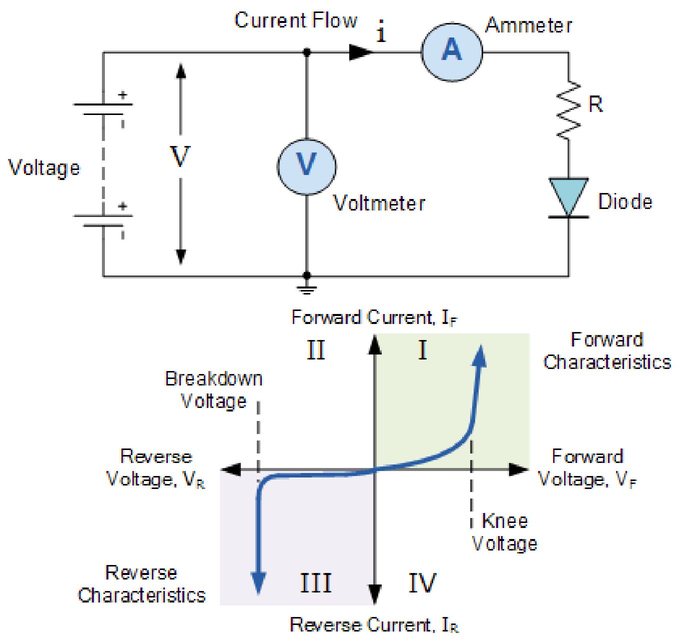
Linear vs. nonlinear components

- **I-V curve:** Relates current through a device to voltage across the device
- **Nonlinear components** have nonlinear I-V curves

I-V curve of linear component (resistor)



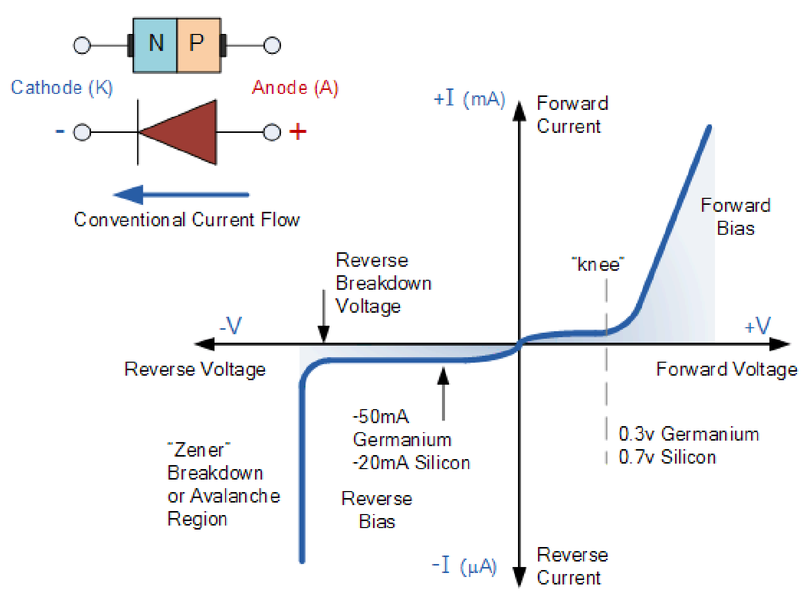
I-V curve of nonlinear component (diode)



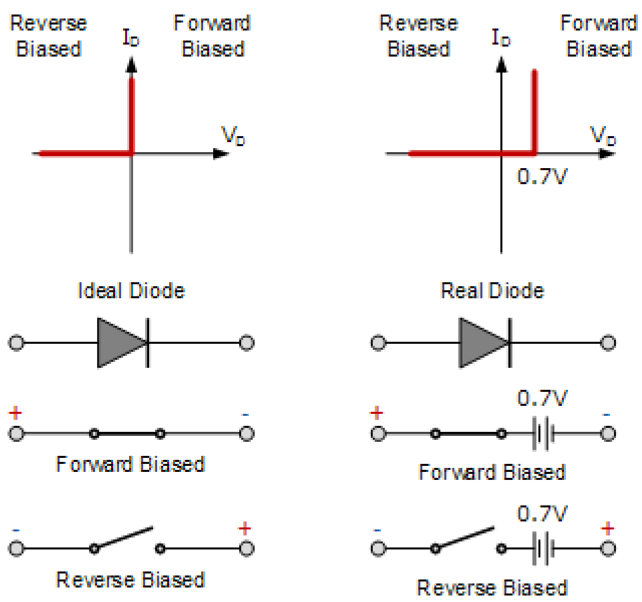
Diodes

- **Diode:** only allows current to flow one way
- Can be modeled by a **switch** in series with a voltage source
- Important to ensure proper **polarity** when prototyping

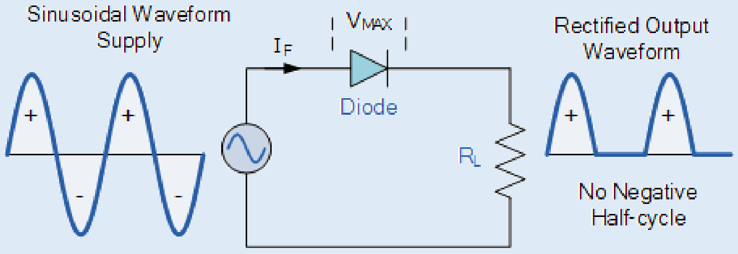
Diode symbol and I-V characteristic



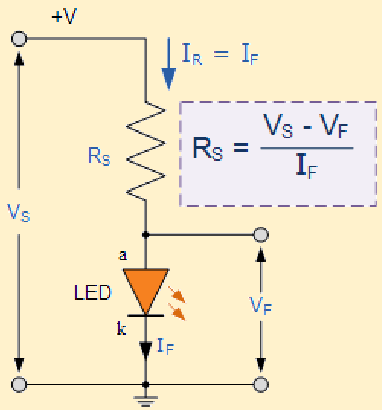
Ideal vs. real diode characteristics



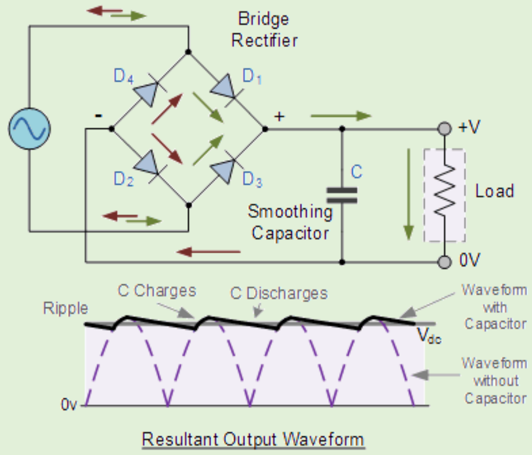
Example diode circuits



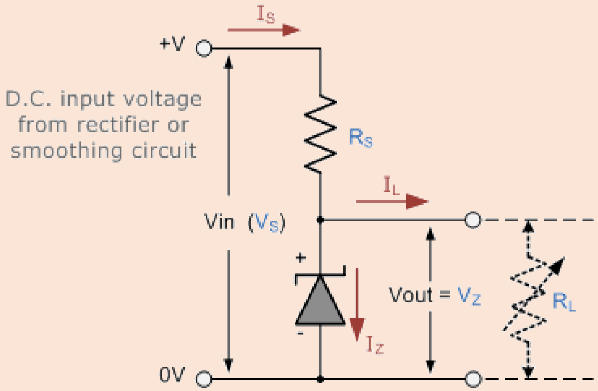
Half-wave rectifier



Light-emitting diode (LED) with current-limiting resistor

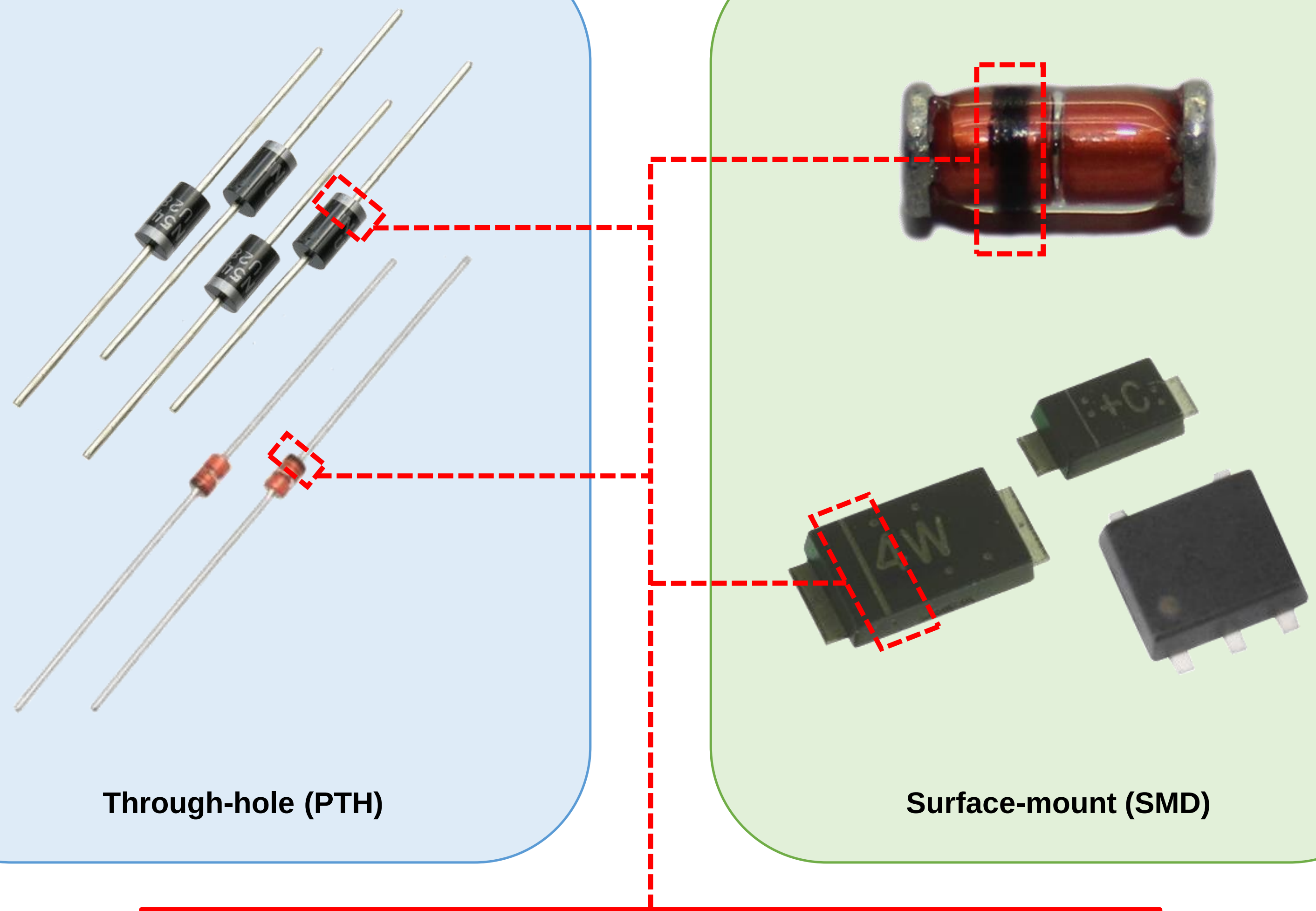


Full-wave rectifier with smoothing capacitor



Zener diode voltage reference

Diodes



Through-hole (PTH)

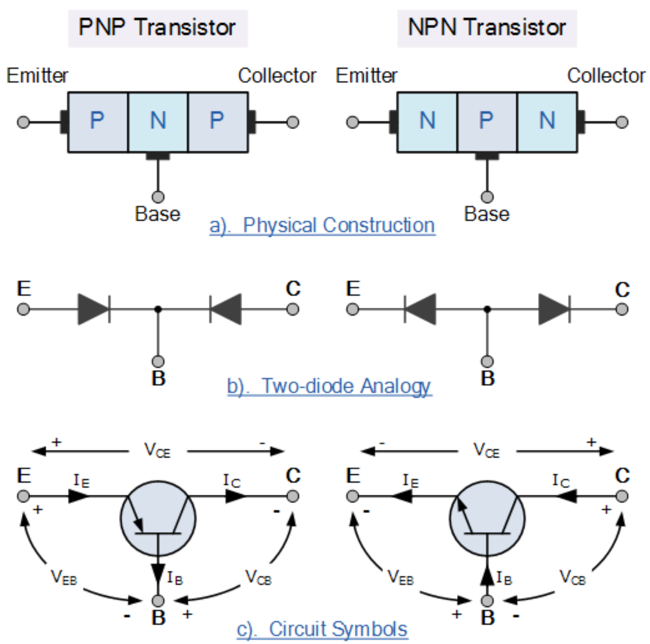
Surface-mount (SMD)

Pay attention to polarity: the striped side is always the cathode (K)

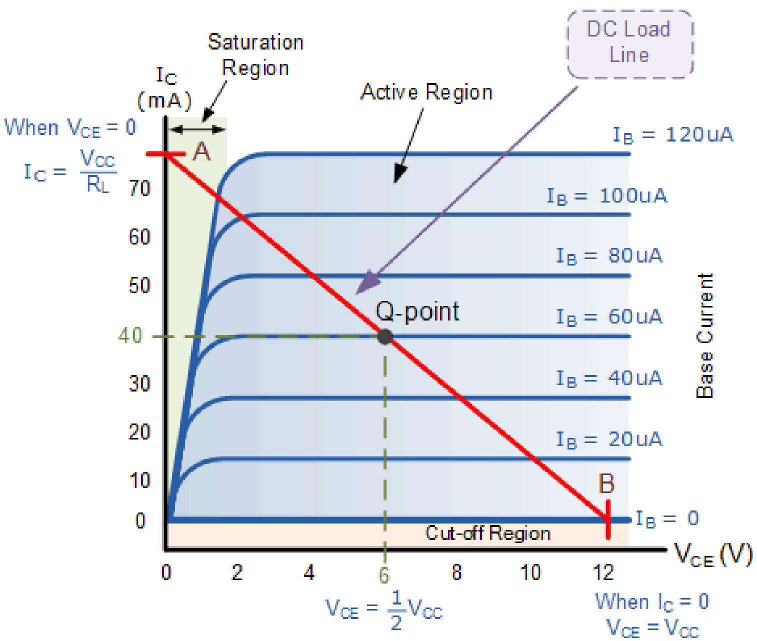
BJTs

- **BJT (bipolar junction transistor):** Current-driven amplifier
- Two types: NPN and PNP
- **Base** controls current from **emitter** to **collector**

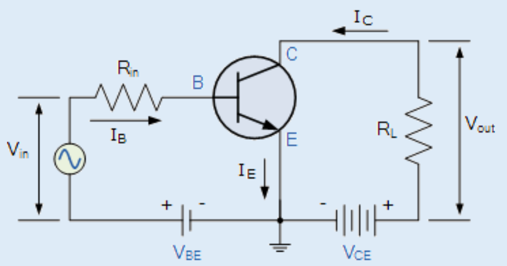
NPN and PNP BJTs



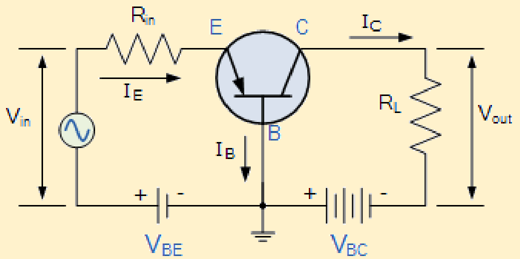
NPN I-V characteristics



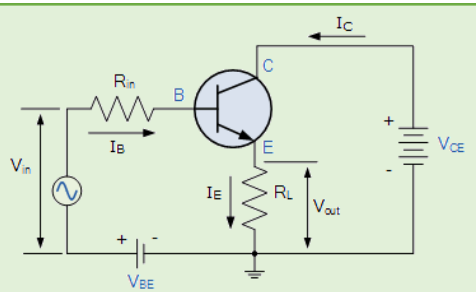
BJT amplifier circuits



Common-emitter amplifier



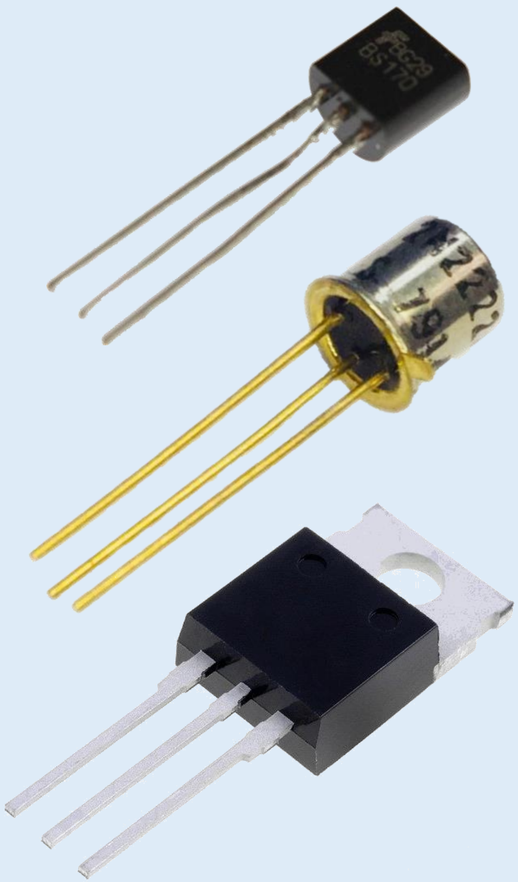
Common-base amplifier



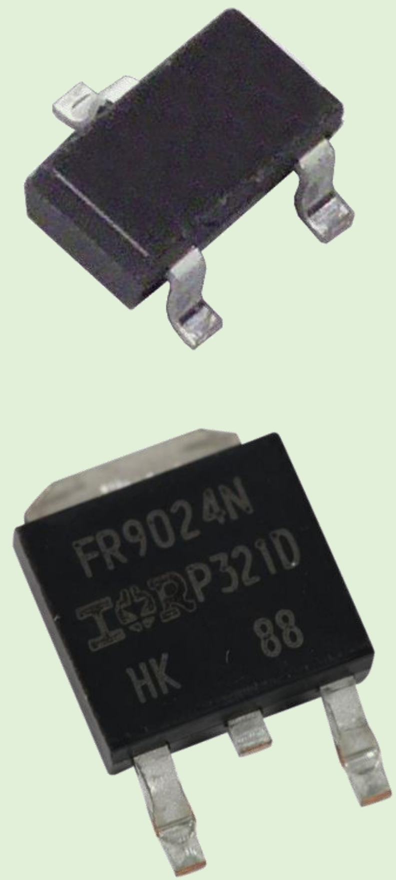
Common-collector amplifier

Characteristic	Common Base	Common Emitter	Common Collector
Input Impedance	Low	Medium	High
Output Impedance	Very High	High	Low
Phase Shift	0º	180º	0º
Voltage Gain	High	Medium	Low
Current Gain	Low	Medium	High
Power Gain	Low	Very High	Medium

BJTs



Through-hole (PTH)

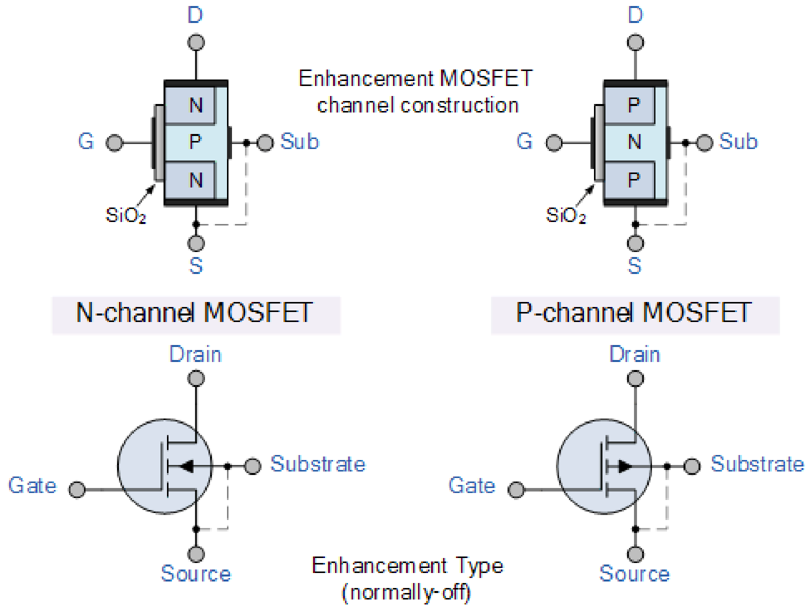


Surface-mount (SMD)

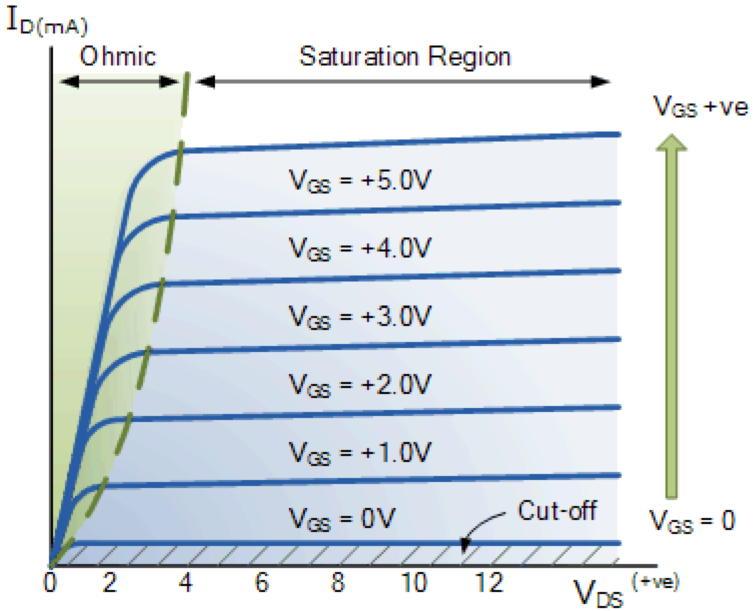
MOSFETs

- **MOSFET:** Metal-oxide-semiconductor field effect transistor
- Typically used as a **voltage-controlled** switch
- **Gate** controls current from **drain** to **source**

N-channel and P-channel MOSFETs

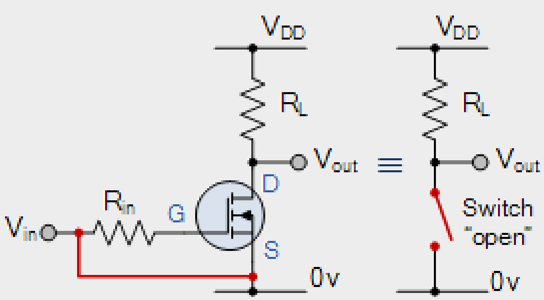


N-channel I-V characteristics

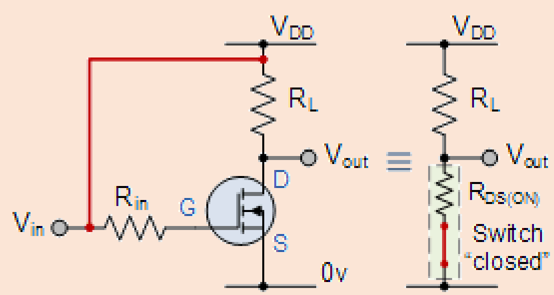


MOSFET as a switch

- Drain-source junction conducts when **gate voltage** (V_{GS}) exceeds the **threshold voltage** (V_T)
- N-channel MOSFETS are **low-side** switches
- P-channel MOSFETS are **high-side** switches

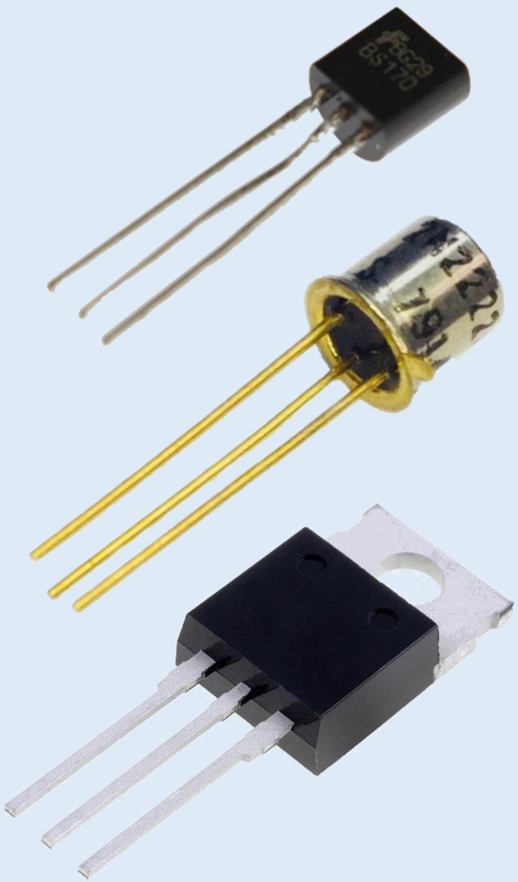


V_{GS} = 0: Switch "open"

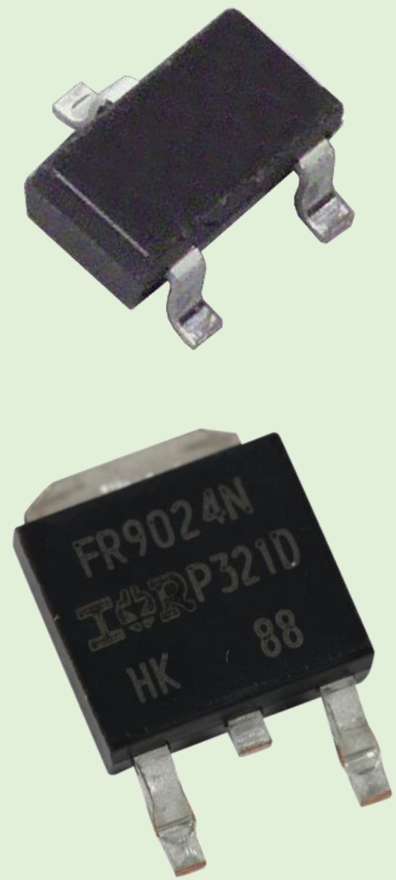


V_{GS} = V_{DD}: Switch "closed"

MOSFETs



Through-hole (PTH)



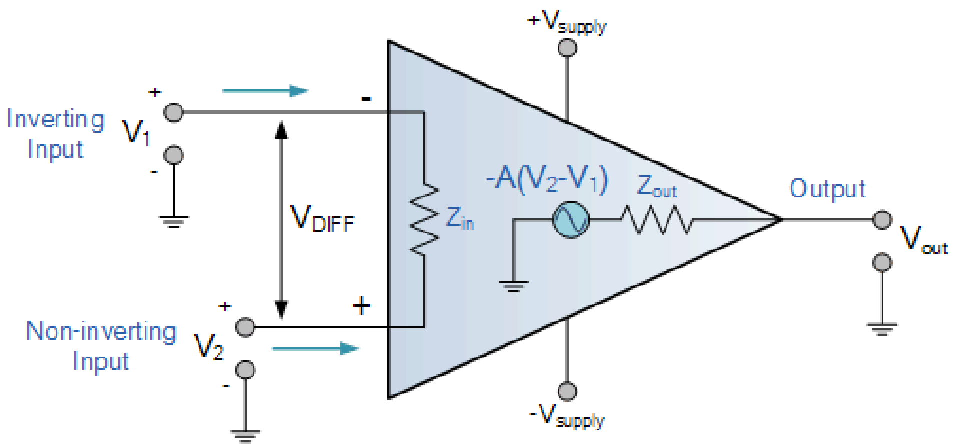
Surface-mount (SMD)

Operational amplifiers (op-amps)

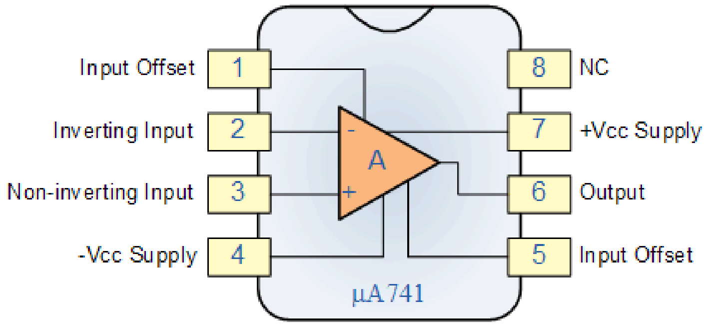
Operational amplifiers

- **Operational amplifier (op-amp):** Amplifies the difference between two voltages
- "Operational": can be used for arithmetic operations (addition, subtraction, multiplication by a constant)
- Many common circuits can be enhanced with op-amps

Op-amp equivalent circuit



uA741 / LM741 pinout diagram



Ideal op-amp properties

Two "golden rules"[1] of op-amps:

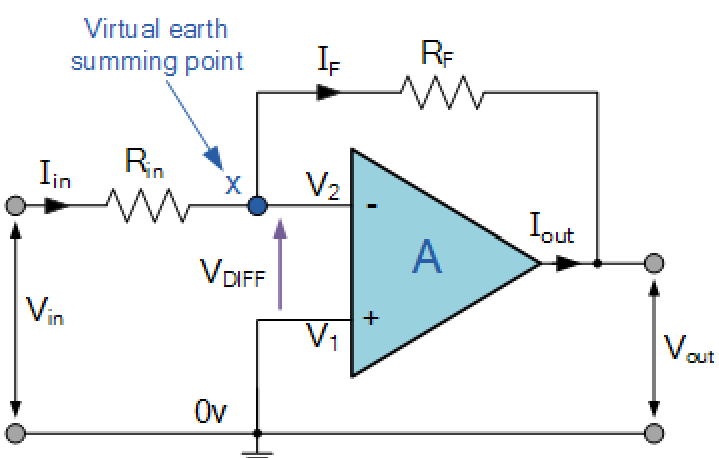
1. In a **closed loop** the output attempts to do whatever is necessary to make the voltage difference between the inputs zero.
2. The inputs draw no current.

[1] Horowitz, Paul; Hill, Winfield (1989). *The Art of Electronics.*

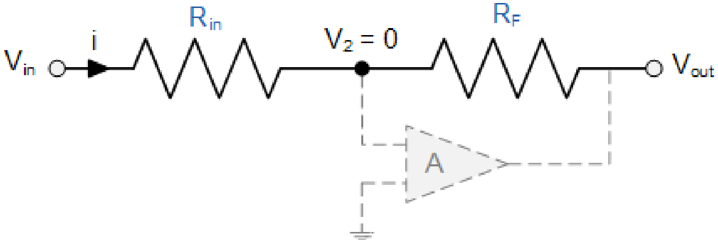
Inverting amplifier

- **Inverting amplifier:** Multiplies input by a negative constant (A_V)
- To solve for voltage gain, assume the output forces the difference ($V_1 – V_2$) to 0

Inverting amplifier circuit



“Virtual ground” analysis

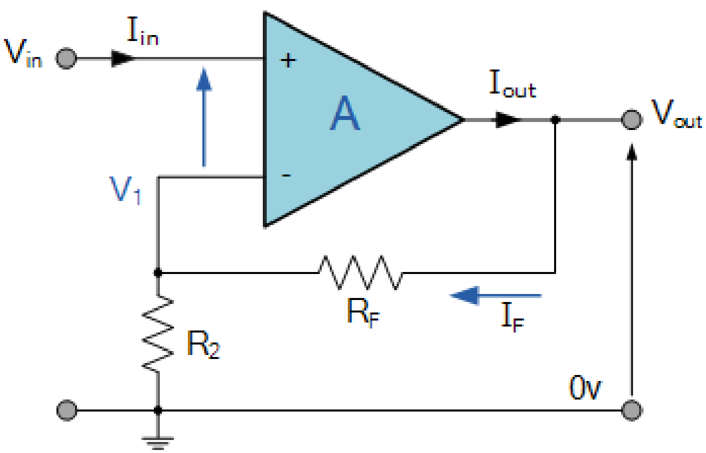


$$\text{Gain (Av)} = \frac{V_{out}}{V_{in}} = -\frac{R_f}{R_{in}}$$

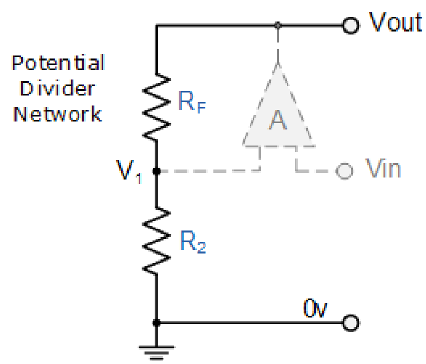
Non-inverting amplifier

- **Non-inverting amplifier:** Multiplies input by a positive constant (A_V)
- Voltage gain can be derived from “golden rules” and resistor divider formula

Non-inverting amplifier circuit



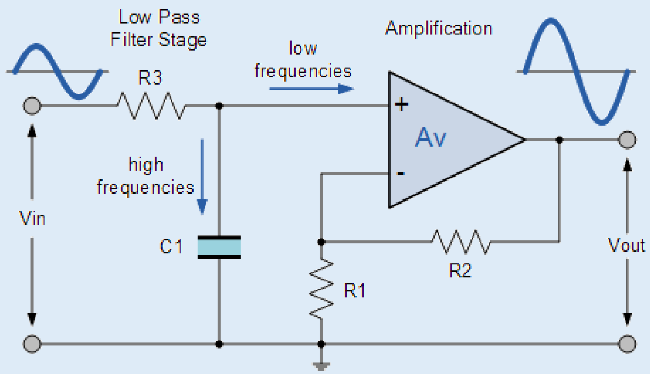
Voltage gain derivation



$$A_{(v)} = 1 + \frac{R_F}{R_2}$$

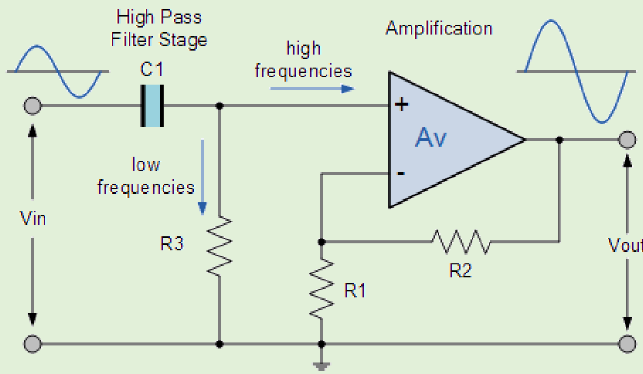
Op-amp LPF and HPF

- Same function as passive LPF and HPF
- Adds **amplification**, which is useful for small or high-impedance inputs



$$\text{DC gain} = \left(1 + \frac{R_2}{R_1}\right) \qquad fc = \frac{1}{2\pi RC} Hz$$

Active LPF with amplification

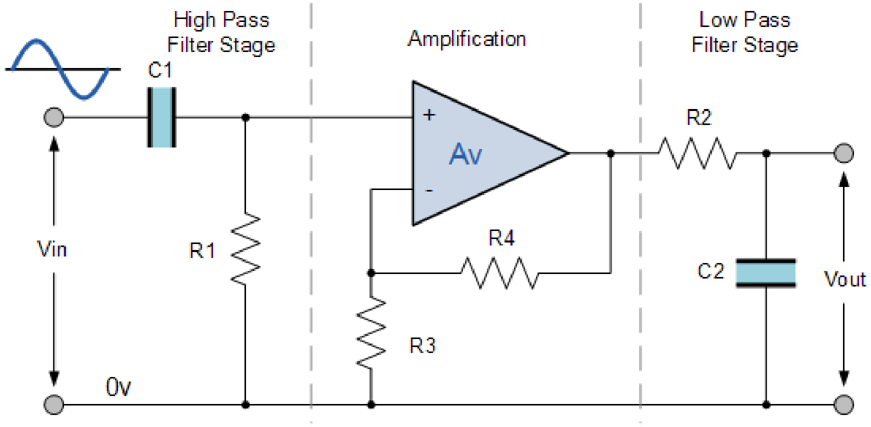


$$\text{DC gain} = \left(1 + \frac{R_2}{R_1}\right) \qquad fc = \frac{1}{2\pi RC} Hz$$

Active HPF with amplification

Op-amp BPF

- Same function as passive BPF
- Adds **amplification**, which is useful for small or high-impedance inputs
- Adds **isolation** between HPF and LPF stage



$$f_H = \frac{1}{2\pi R_1 C_1} Hz$$

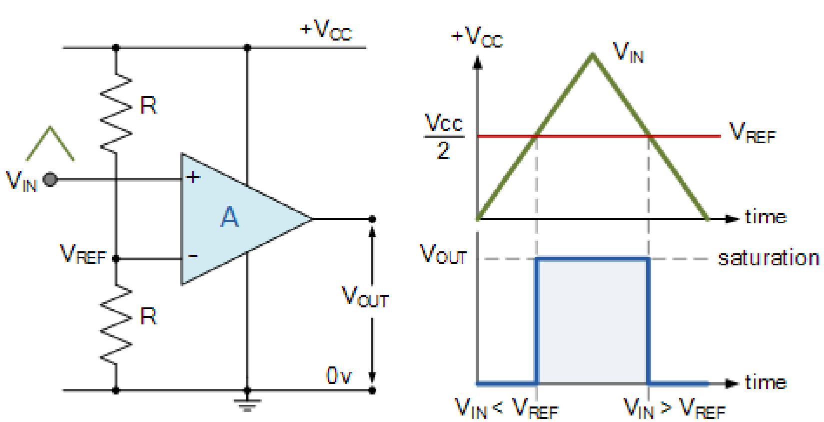
$$f_L = \frac{1}{2\pi R_2 C_2} Hz$$

$$A_V = 1 + \frac{R_4}{R_3}$$

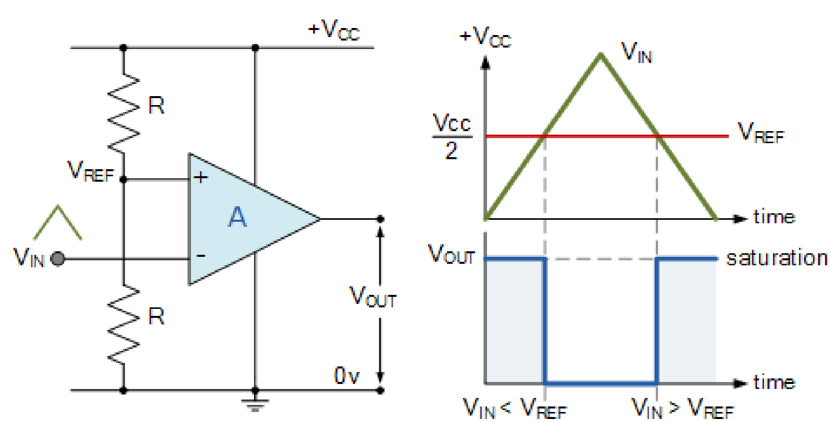
Comparator

- **Comparator:** Compares input voltage (V_{IN}) with reference voltage (V_{REF})
- Exploits “infinite” gain to produce **binary output**
- Most op-amps cannot operate **rail-to-rail**

Non-inverting comparator circuit

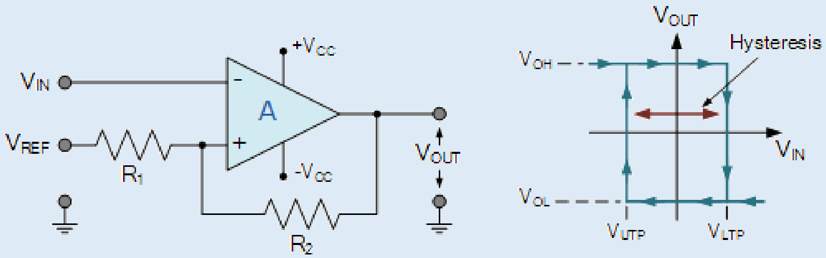


Inverting comparator circuit

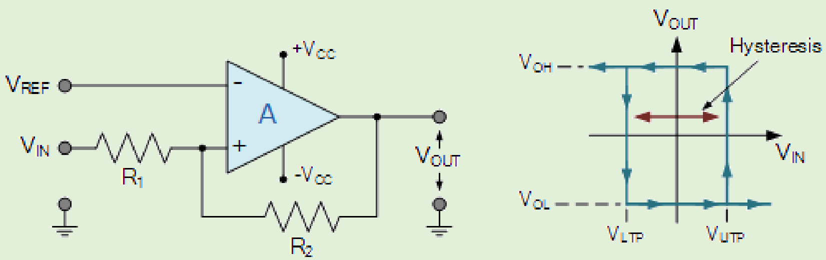


Comparator with hysteresis

- **Hysteresis:** Removes noise from comparator output
- Creates upper and lower "trip points" (V_{UTP} and V_{LTP})
- Amount of hysteresis determined by R_1 and R_2



Inverting comparator with hysteresis



Non-inverting comparator with hysteresis

$$\beta = \frac{R_1}{R_1 + R_2}$$

$$V_{HYSTERESIS} = V_{UTP} - V_{LTP}$$

$$V_{HYSTERESIS} = +\beta Vcc - (-\beta Vcc)$$

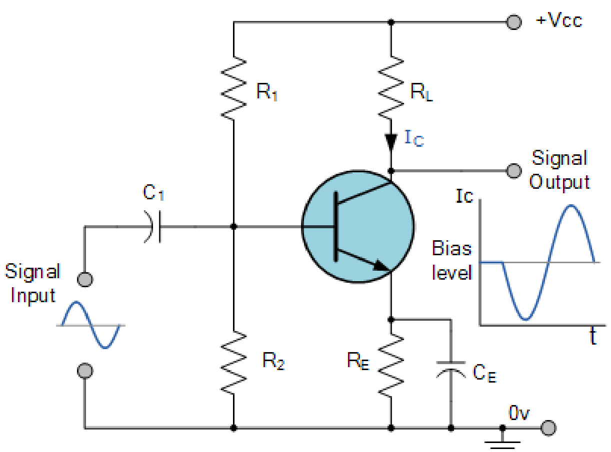
$$\therefore V_{HYSTERESIS} = 2\beta Vcc$$

Audio amplification

Class A amplifier

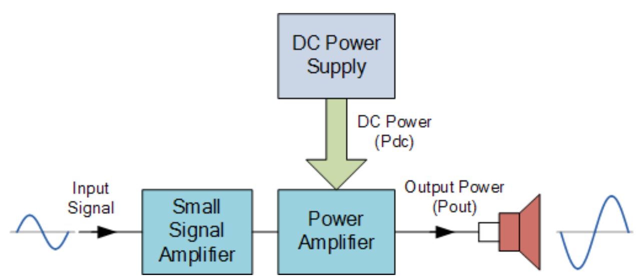
- **Class A amplifier:** Uses BJT to "pull down" output
- Value of **load resistor** (R_L) determines voltage gain
- Commonly used on input stage for **high voltage gain**
- Not ideal as a power amplifier due to **low efficiency**

Class A amplifier circuit



Class A amplifier voltage gain and efficiency

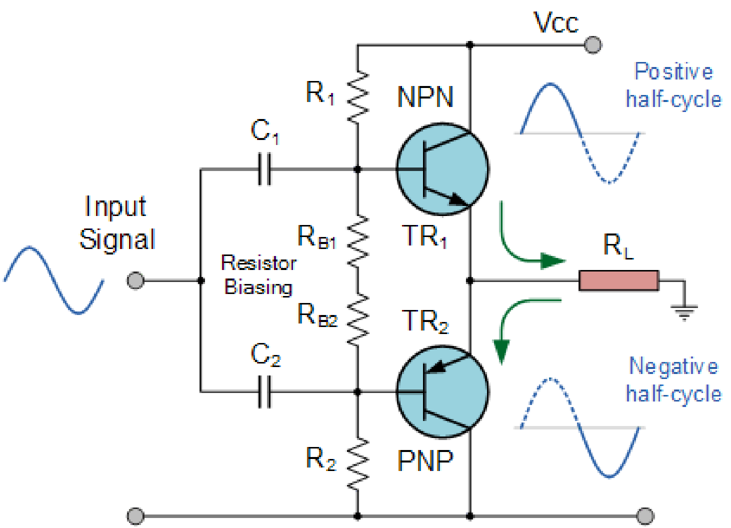
$$\text{Voltage Gain} = \frac{V_{out}}{V_{in}} = \frac{\Delta V_L}{\Delta V_B} = -\frac{R_L}{R_E}$$



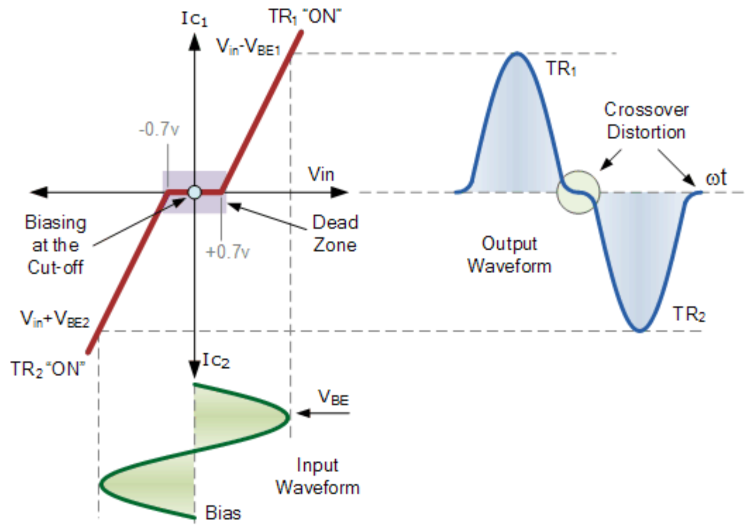
Class B amplifier

- **Class B amplifier:** Much more efficient than Class A
- Uses **"push-pull"** output: only one BJT on at a time
- Introduces **crossover distortion** in the output signal

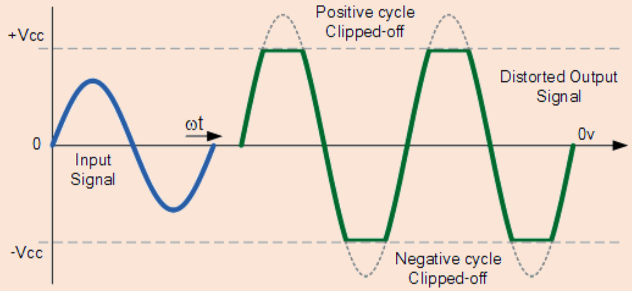
Class B amplifier circuit



Crossover distortion in Class B amplifier

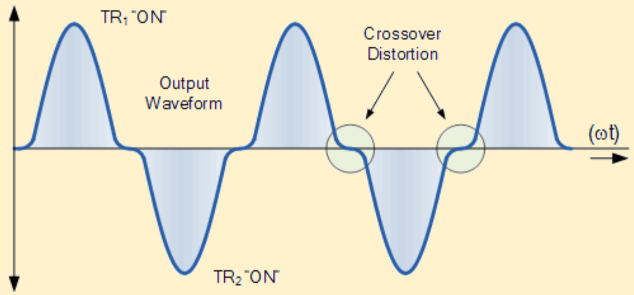


Distortion



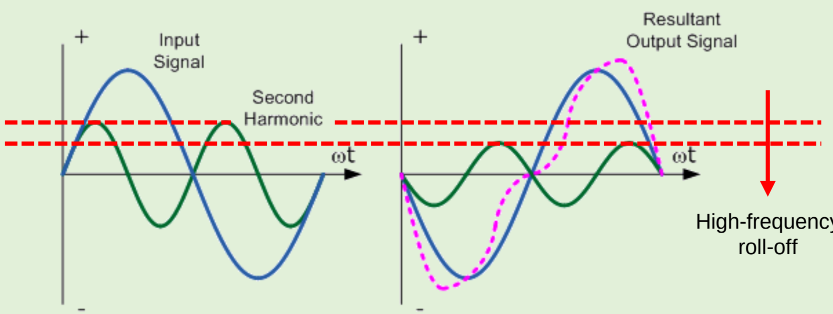
Amplitude distortion

- Caused when signal "clips" above or below the power supply rails
- Detrimental to signal quality
- Eliminate by increasing power supply voltage or decreasing input



Crossover distortion

- Caused when output signal crosses through 0 volts
- Can have significant effects when input is small
- Eliminate by biasing output stage slightly on at all times (Class AB)



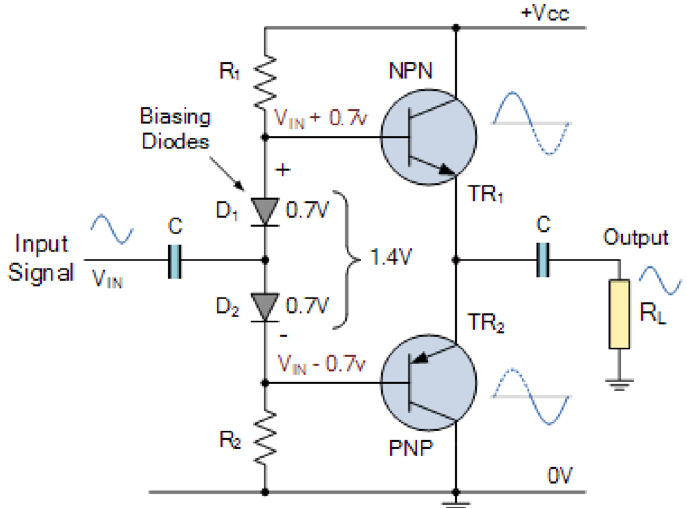
Frequency distortion

- Caused when amplifier frequency response is nonlinear
- Minimal effects on signal quality
- Eliminate by using transistors with lower input/output capacitance

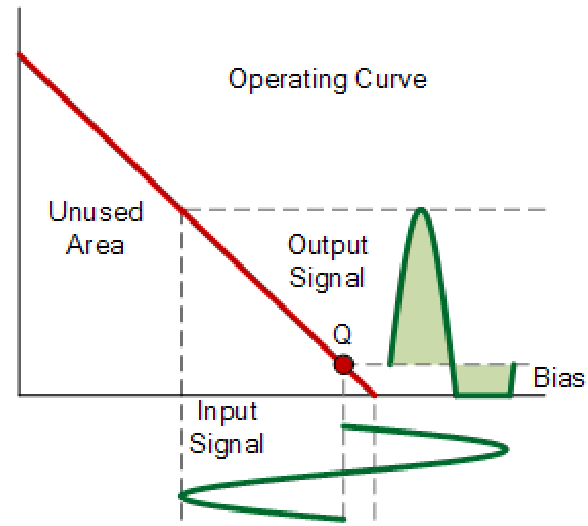
Class AB amplifier

- Same principle as Class B, but with added **bias voltage**
- **Biasing diodes** keep both output transistors on slightly after the input crosses 0 volts
- Result: minimal **crossover distortion**, less efficient

Class B amplifier circuit



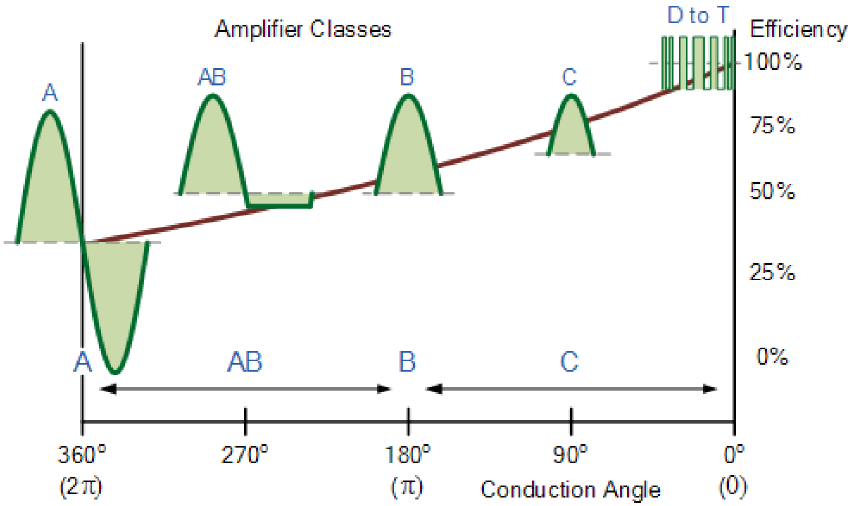
Class B amplifier biasing



Summary of amplifier classes

- **Class A:** High quality, low efficiency
- **Class B:** Low quality, high efficiency
- **Class AB:** High quality, average efficiency

Conduction angle and efficiency comparison



Summary of characteristics

Characteristic	Class A	Class B	Class AB
Signal quality	High	Low	High
Efficiency	Low	High	Medium
Conduction angle	360º	180º	180º – 360º
Output impedance	High	Medium	Low

Lab 2 overview

Components and specifications

Exercise 1: Op-amps

- **Goal:** Build and test basic op-amp circuits
- **New parts:** LM741 op-amp

- **Power pins are hidden** on schematic by convention but must be connected
- Be extremely careful not to switch **positive and negative power supplies**

LM741

Supply voltage: Most op-amps rated for dual-supply operation

Short circuit duration: Very tolerant of breadboard accidents

Input offset voltage: Should be low for high-precision applications

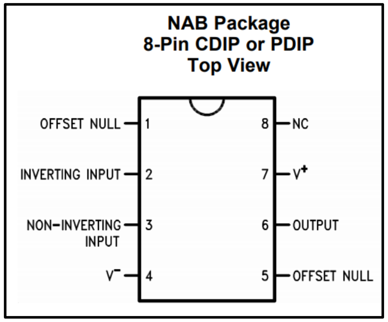
Input bias current: Higher for bipolar devices (LM741), lower for JFET devices (LF356)

Slew rate: Important if used in high-frequency circuits

6.1 Absolute Maximum Ratings

over operating free-air temperature range (unless otherwise noted)[1][2][3]

		MIN	MAX	UNIT
Supply voltage	LM741, LM741A		±22	V
	LM741C		±18	
Power dissipation [4]			500	mW
Differential input voltage			±30	V
Input voltage [5]			±15	V
Output short circuit duration		Continuous		
Operating temperature	LM741, LM741A	–50	125	°C
	LM741C	0	70	
Junction temperature	LM741, LM741A		150	°C
	LM741C		100	
Soldering information	PDIP package (10 seconds)		260	°C
	CDIP or TO-99 package (10 seconds)		300	°C
Storage temperature, T_{stg}		–65	150	°C



6.5 Electrical Characteristics, LM741 [1]

PARAMETER	TEST CONDITIONS		MIN	TYP	MAX	UNIT
Input offset voltage	$R_S \le 10$ kΩ	T_A = 25°C		1	5	mV
		$T_{AMIN} \le T_A \le T_{AMAX}$			6	mV
Input offset voltage adjustment range	T_A = 25°C, V_S = ±20 V			±15		mV
Input offset current	T_A = 25°C			20	200	nA
	$T_{AMIN} \le T_A \le T_{AMAX}$			85	500	
Input bias current	T_A = 25°C			80	500	nA
	$T_{AMIN} \le T_A \le T_{AMAX}$				1.5	μA
Input resistance	T_A = 25°C, V_S = ±20 V		0.3	2		MΩ
Input voltage range	$T_{AMIN} \le T_A \le T_{AMAX}$		±12	±13		V
Large signal voltage gain	V_S = ±15 V, V_O = ±10 V, $R_L \ge 2$ kΩ	T_A = 25°C	50	200		V/mV
		$T_{AMIN} \le T_A \le T_{AMAX}$	25			
Output voltage swing	V_S = ±15 V	$R_L \ge 10$ kΩ	±12	±14		V
		$R_L \ge 2$ kΩ	±10	±13		
Output short circuit current	T_A = 25°C			25		mA
Common-mode rejection ratio	$R_S \le 10$ Ω, V_{CM} = ±12 V, $T_{AMIN} \le T_A \le T_{AMAX}$		80	95		dB
Supply voltage rejection ratio	V_S = ±20 V to V_S = ±5 V, $R_S \le 10$ Ω, $T_{AMIN} \le T_A \le T_{AMAX}$		86	96		dB
Transient response — Rise time	T_A = 25°C, unity gain			0.3		μs
Transient response — Overshoot				5%		
Slew rate	T_A = 25°C, unity gain			0.5		V/μs
Supply current	T_A = 25°C			1.7	2.8	mA
Power consumption	V_S = ±15 V	T_A = 25°C		50	85	mW
		$T_A = T_{AMIN}$		60	100	
		$T_A = T_{AMAX}$		45	75	

Offset adjustment: Offset can be “nulled” with a potentiometer connected from pin 1 to pin 5

Voltage gain: Nearly infinite (200 V / mV = 200,000 V / V)

Output swing: Most op-amps will not operate “rail-to-rail”

Source: http://www.ti.com/lit/ds/symlink/lm741.pdf

Exercise 2: LED driver

- **Goal:** use BJT and function generator to drive an LED
- **New parts:** 2N3904 BJT (NPN)

- Very important to check **orientation** of transistors

2N3904

"Absolute maximum" ratings: Values outside these ranges will cause permanent damage to the device

Maximum voltages: Limited by power supply (V_{CEO}, V_{CBO}) or input range (V_{EBO})

Maximum current: Limited by load impedance

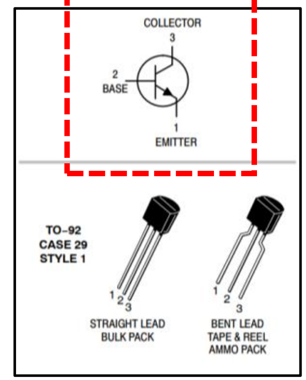
Gain-bandwidth product: Defines maximum gain in an amplifier

Small-signal gain: Ratio of collector current to base current

Pin diagram: Pinning for 2N3904 is like "ABC" (actually EBC)

MAXIMUM RATINGS

Rating	Symbol	Value	Unit
Collector – Emitter Voltage	V_{CEO}	40	Vdc
Collector – Base Voltage	V_{CBO}	60	Vdc
Emitter – Base Voltage	V_{EBO}	6.0	Vdc
Collector Current – Continuous	I_C	200	mAdc
Total Device Dissipation @ T_A = 25°C Derate above 25°C	P_D	625 5.0	mW mW/°C
Total Device Dissipation @ T_C = 25°C Derate above 25°C	P_D	1.5 12	W mW/°C
Operating and Storage Junction Temperature Range	T_J, T_{stg}	–55 to +150	°C



SMALL–SIGNAL CHARACTERISTICS

Characteristic		Symbol	Min	Max	Unit
Current – Gain – Bandwidth Product (I_C = 10 mAdc, V_{CE} = 20 Vdc, f = 100 MHz)	2N3903 2N3904	f_T	250 300	– –	MHz
Output Capacitance (V_{CB} = 5.0 Vdc, I_E = 0, f = 1.0 MHz)		C_{obo}	–	4.0	pF
Input Capacitance (V_{EB} = 0.5 Vdc, I_C = 0, f = 1.0 MHz)		C_{ibo}	–	8.0	pF
Input Impedance (I_C = 1.0 mAdc, V_{CE} = 10 Vdc, f = 1.0 kHz)	2N3903 2N3904	h_{ie}	1.0 1.0	8.0 10	k Ω
Voltage Feedback Ratio (I_C = 1.0 mAdc, V_{CE} = 10 Vdc, f = 1.0 kHz)	2N3903 2N3904	h_{re}	0.1 0.5	5.0 8.0	$X\ 10^{-4}$
Small–Signal Current Gain (I_C = 1.0 mAdc, V_{CE} = 10 Vdc, f = 1.0 kHz)	2N3903 2N3904	h_{fe}	50 100	200 400	–
Output Admittance (I_C = 1.0 mAdc, V_{CE} = 10 Vdc, f = 1.0 kHz)		h_{oe}	1.0	40	μmhos
Noise Figure (I_C = 100 μAdc, V_{CE} = 5.0 Vdc, R_S = 1.0 k Ω, f = 1.0 kHz)	2N3903 2N3904	NF	– –	6.0 5.0	dB

Source: *https://www.onsemi.com/pub/Collateral/2N3903-D.PDF*

Exercise 3: Audio amplifier

- **Goal:** Build a high-quality, high-efficiency audio amplifier
- **New parts:** TIP41, TIP42 complementary power BJTs

- Don't force large pins into breadboard, look at the holes and **make sure the pins line up**
- Make sure **output capacitor** is oriented correctly

TIP41, TIP42

Collector-emitter voltage: Capable of switching high voltages

Packaging: Collector electrically connected to case

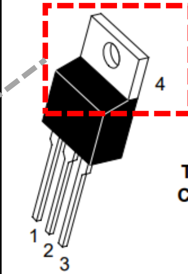
Collector current: Capable of driving high-current loads

Power dissipation: Capable of dissipating much more power than small-signal devices (2N3904)

DC current gain: Much lower current gain than small-signal devices

MAXIMUM RATINGS

Rating		Symbol	Value	Unit
Collector−Emitter Voltage	TIP41, TIP42 TIP41A, TIP42A TIP41B, TIP42B TIP41C, TIP42C	V_{CEO}	40 60 80 100	Vdc
Collector−Base Voltage	TIP41, TIP42 TIP41A, TIP42A TIP41B, TIP42B TIP41C, TIP42C	V_{CB}	40 60 80 100	Vdc
Emitter−Base Voltage		V_{EB}	5.0	Vdc
Collector Current−	Continuous Peak	I_C	6.0 10	Adc
Base Current		I_B	2.0	Adc
Total Power Dissipation @ T_C = 25°C Derate above 25°C		P_D	65 0.52	W W/°C
Total Power Dissipation @ T_A = 25°C Derate above 25°C		P_D	2.0 0.016	W W/°C
Unclamped Inductive Load Energy (Note 1)		E	62.5	mJ
Operating and Storage Junction, Temperature Range		T_J, T_{stg}	−65 to +150	°C



TO−220AB
CASE 221A
STYLE 1

STYLE 1:
PIN 1. BASE
2. COLLECTOR
3. EMITTER
4. COLLECTOR

ELECTRICAL CHARACTERISTICS (T_C = 25°C unless otherwise noted)

Characteristic		Symbol	Min	Max	Unit
OFF CHARACTERISTICS					
Collector−Emitter Sustaining Voltage (Note 2) (I_C = 30 mAdc, I_B = 0)	TIP41, TIP42 TIP41A, TIP42A TIP41B, TIP42B TIP41C, TIP42C	$V_{CEO(sus)}$	40 60 80 100	− − − −	Vdc
Collector Cutoff Current (V_{CE} = 30 Vdc, I_B = 0) (V_{CE} = 60 Vdc, I_B = 0)	 TIP41, TIP41A, TIP42, TIP42A TIP41B, TIP41C, TIP42B, TIP42C	I_{CEO}	 − −	 0.7 0.7	mAdc
Collector Cutoff Current (V_{CE} = 40 Vdc, V_{EB} = 0) (V_{CE} = 60 Vdc, V_{EB} = 0) (V_{CE} = 80 Vdc, V_{EB} = 0) (V_{CE} = 100 Vdc, V_{EB} = 0)	 TIP41, TIP42 TIP41A, TIP42A TIP41B, TIP42B TIP41C, TIP42C	I_{CES}	 − − − −	 400 400 400 400	μAdc
Emitter Cutoff Current (V_{BE} = 5.0 Vdc, I_C = 0)		I_{EBO}	−	1.0	mAdc
ON CHARACTERISTICS (Note 2)					
DC Current Gain (I_C = 0.3 Adc, V_{CE} = 4.0 Vdc) (I_C = 3.0 Adc, V_{CE} = 4.0 Vdc)		h_{FE}	30 15	− 75	−
Collector−Emitter Saturation Voltage (I_C = 6.0 Adc, I_B = 600 mAdc)		$V_{CE(sat)}$	−	1.5	Vdc
Base−Emitter On Voltage (I_C = 6.0 Adc, V_{CE} = 4.0 Vdc)		$V_{BE(on)}$	−	2.0	Vdc

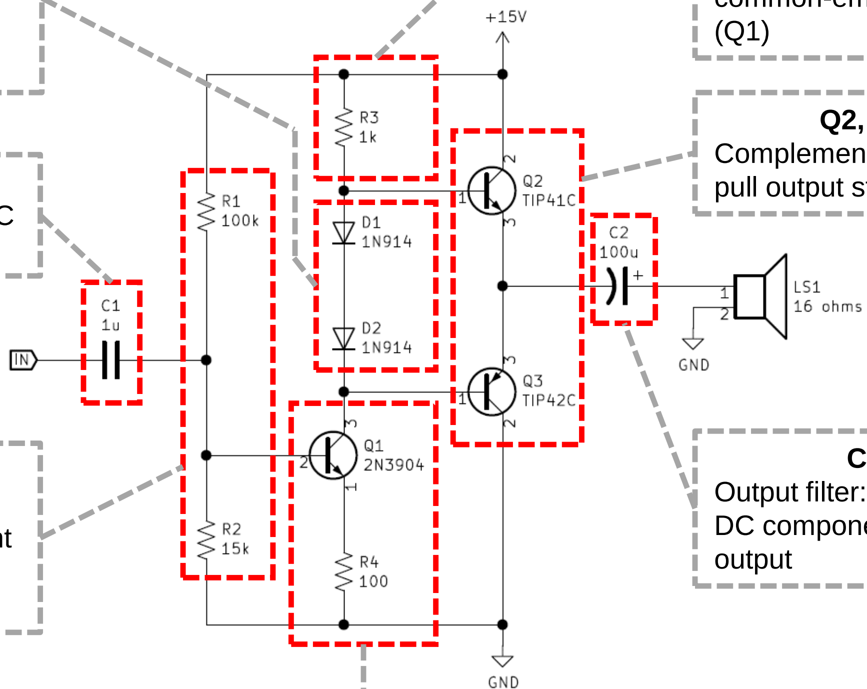
Source: http://www.farnell.com/datasheets/40034.pdf

Audio amplifier analysis

D1, D2
Output biasing diodes: Biases Q2 and Q3 slightly on to eliminate crossover distortion

C1
Input filter: removes DC component from input

R1, R2
Q1 biasing network: sets the operating point for common-emitter (Class A) stage



R3
Sets voltage gain of common-emitter stage (Q1)

Q2, Q3
Complementary push-pull output stage

C2
Output filter: removes DC component from output

Q1
Common-emitter amplification stage: Provides current gain for driving output power transistors (Q2 and Q3)

Further reading

- Filter design tool: http://sim.okawa-denshi.jp/en/Fkeisan.htm
- Advanced BJT theory (from 6.012 course notes): https://ocw.mit.edu/courses/electrical-engineering-and-computer-science/6-012-microelectronic-devices-and-circuits-spring-2009/lecture-notes/MIT6_012S09_lec17.pdf
- Overview of amplifier classes: https://www.maximintegrated.com/en/design/technical-documents/tutorials/5/5590.html