EC3301 Electron Devices and Circuits

Unit 1: Diodes Applications & Special diode types

Introduction

- **In this Lecture we will learn**

- ❑ application of the diode in the design of rectifier circuits, which convert ac voltages to dc as needed for powering electronic equipment.
- ❑ a number of other practical and important applications: limiting and clamping circuits.
- ❑ Special diode types: LED, Photo diode, Schottky diode, Varactor diode, Zener diode.

4.5. Rectifier Circuits

- One important application of diode is the **rectifier** –
  - Electrical device which converts alternating current (AC) to direct current (DC)
- One important application of rectifier is dc power supply.

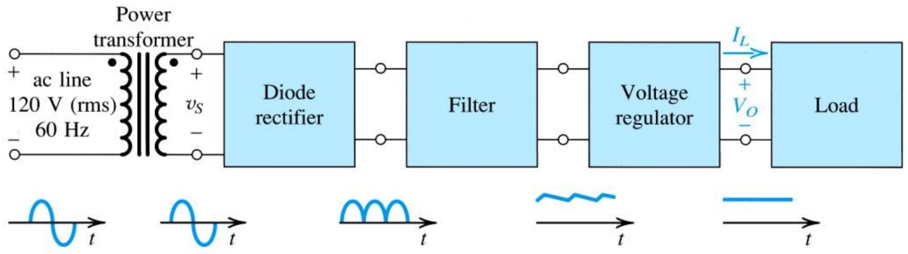


Figure 4.20: Block diagram of a dc power supply

step #1: Decrease RMS magnitude of AC wave via power transformer

step #2: convert full-wave AC signal to full-wave rectified signal (still time-varying and periodic)

step #3: employ low-pass filter to reduce wave amplitude by > 90%

step #4: employ voltage regulator to eliminate ripple

step #5: supply dc load

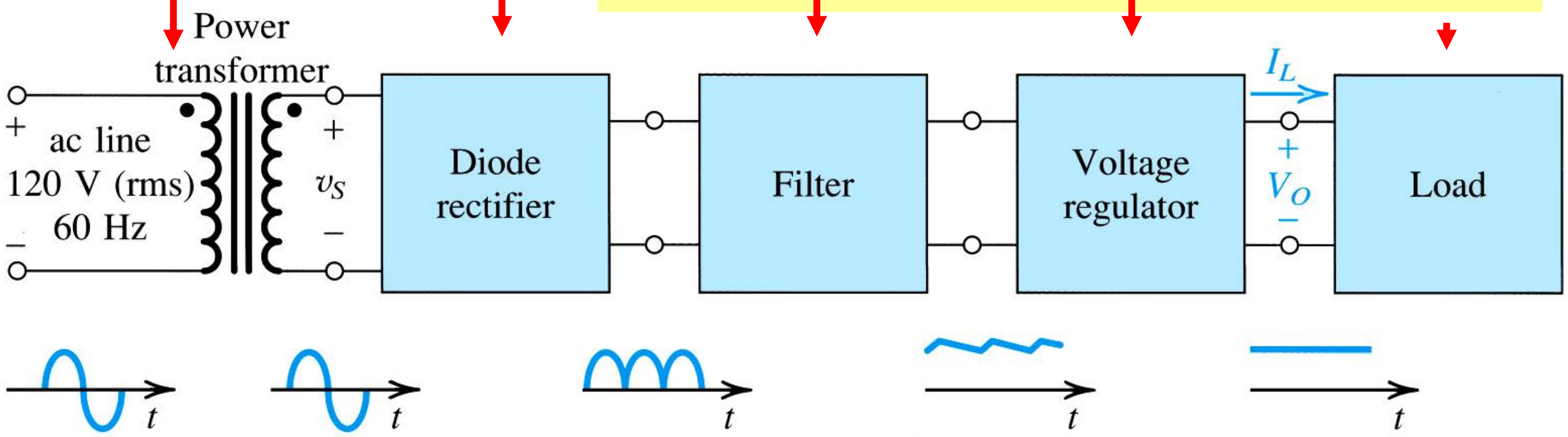


Figure 4.20: Block diagram of a dc power supply

4.5.1. The Half-Wave Rectifier

- **half-wave rectifier**
  - utilizes only alternate half-cycles of the input sinusoid
    - Constant voltage drop diode model is employed.

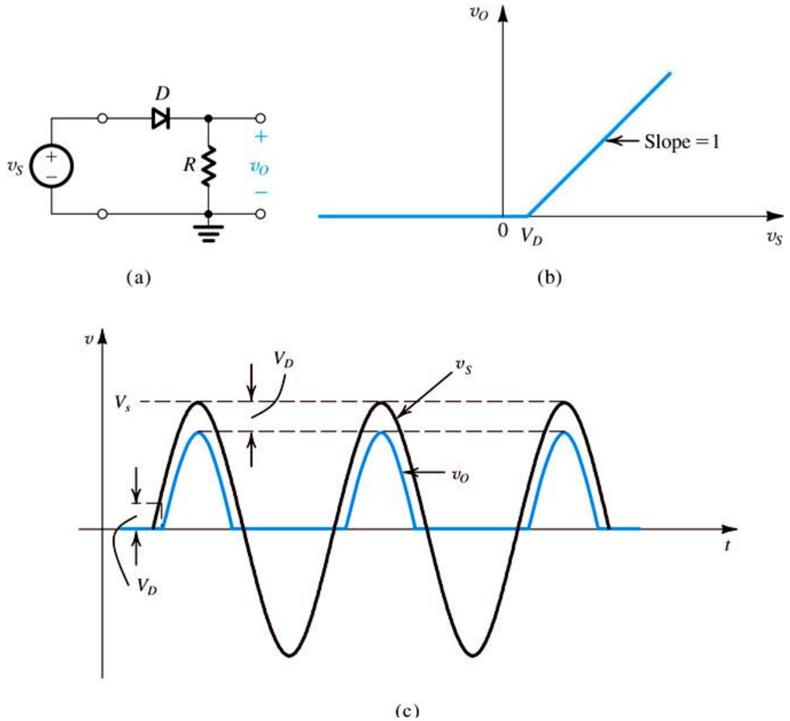


Figure 4.21: (a) Half-wave rectifier **(b)** Transfer characteristic of the rectifier circuit **(c)** Input and output waveforms

4.5.1. The Half-Wave Rectifier

In selecting diodes for rectifier design, two important parameters must be specified:

- **current-handling capability** – what is maximum forward current diode is expected to conduct?
- **peak inverse voltage (PIV)** – what is maximum reverse voltage it is expected to block w/o breakdown?

It is usually prudent to select a diode that has a reverse breakdown voltage at least 50% greater than the expected PIV.

4.5.2. The Full-Wave Rectifier

- **Q:** How does full-wave rectifier differ from half-wave?
  - **A:** It utilizes both halves of the input
    - One potential is shown to right.

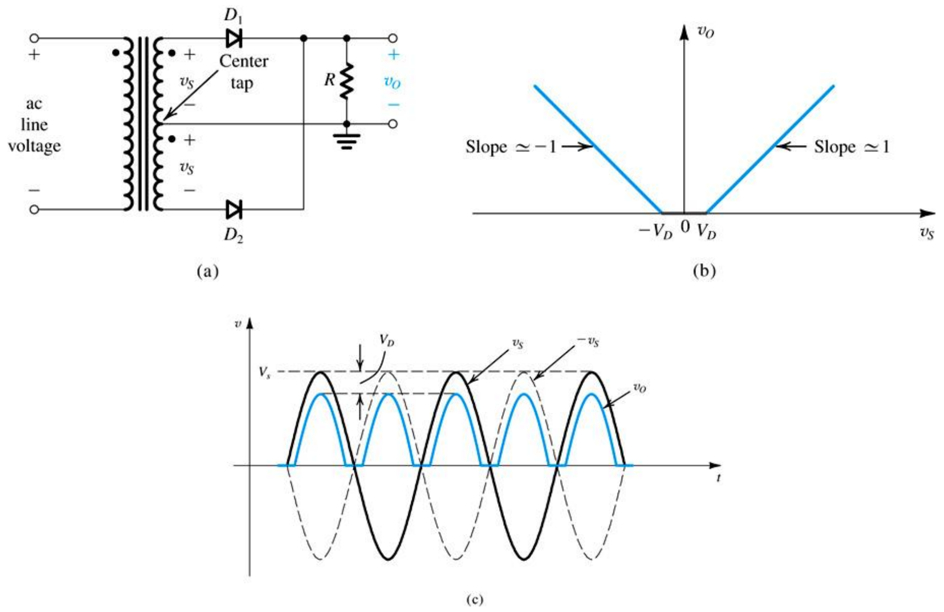


Figure 4.22: Full-wave rectifier utilizing a transformer with a center-tapped secondary winding.

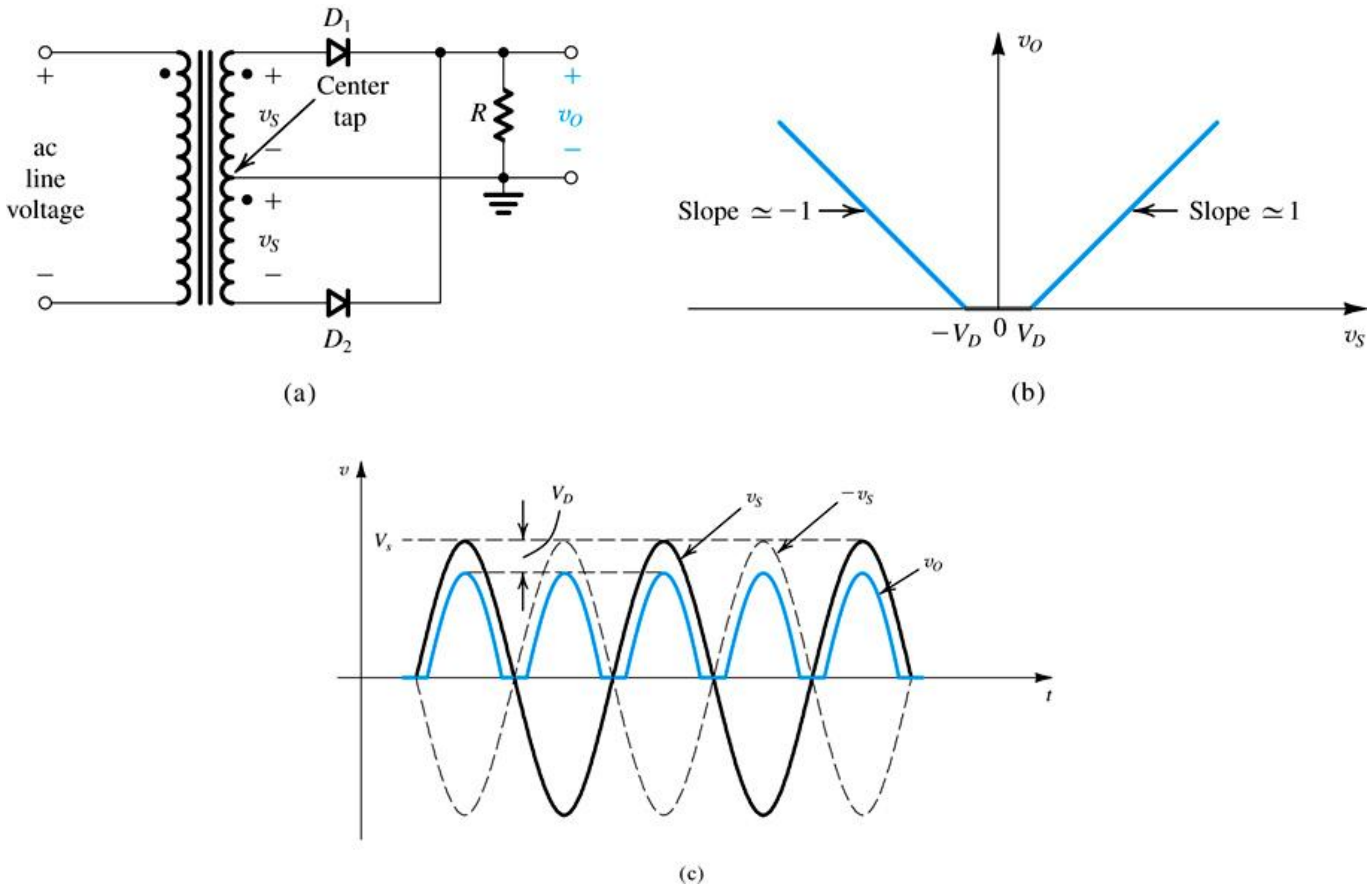
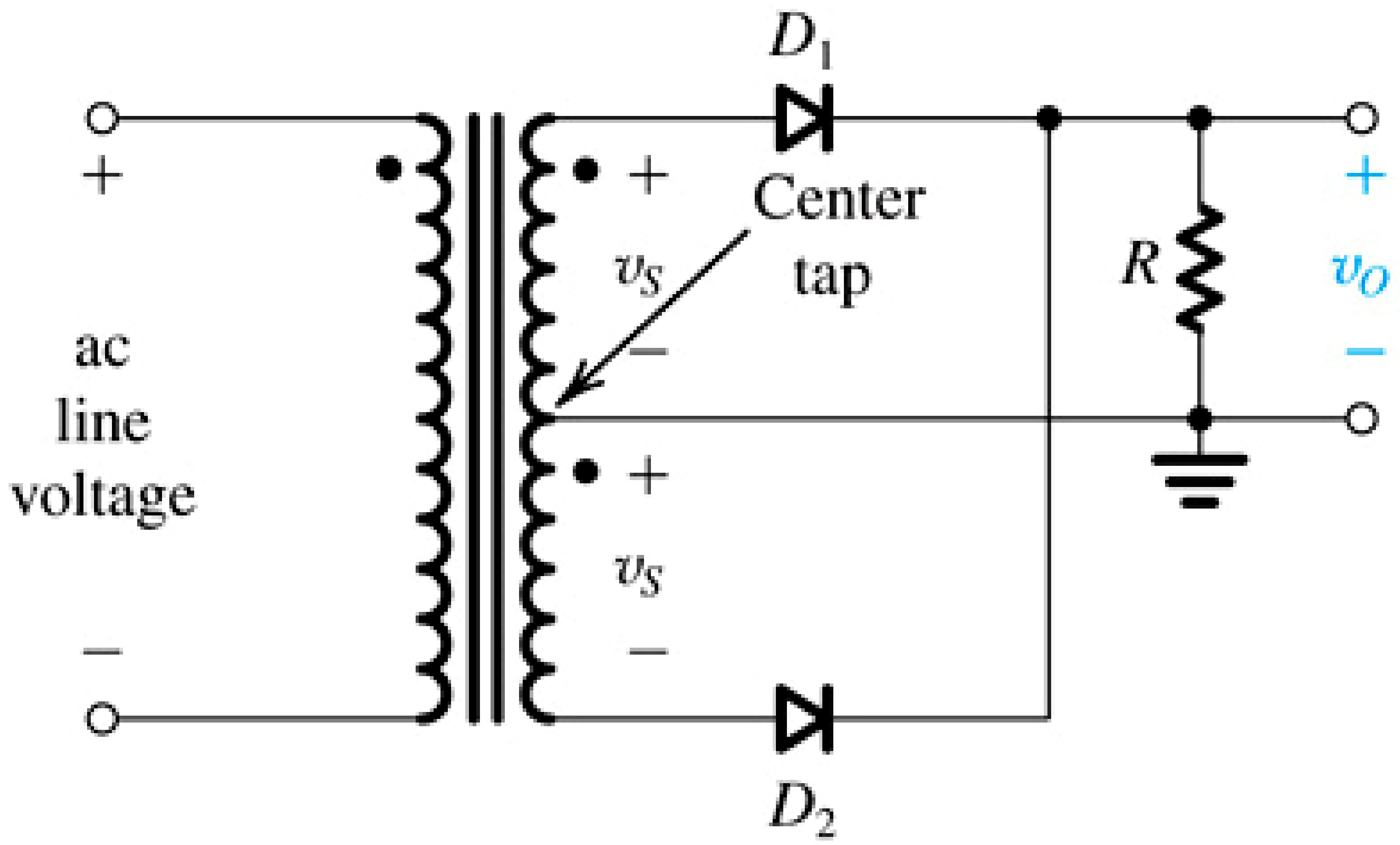
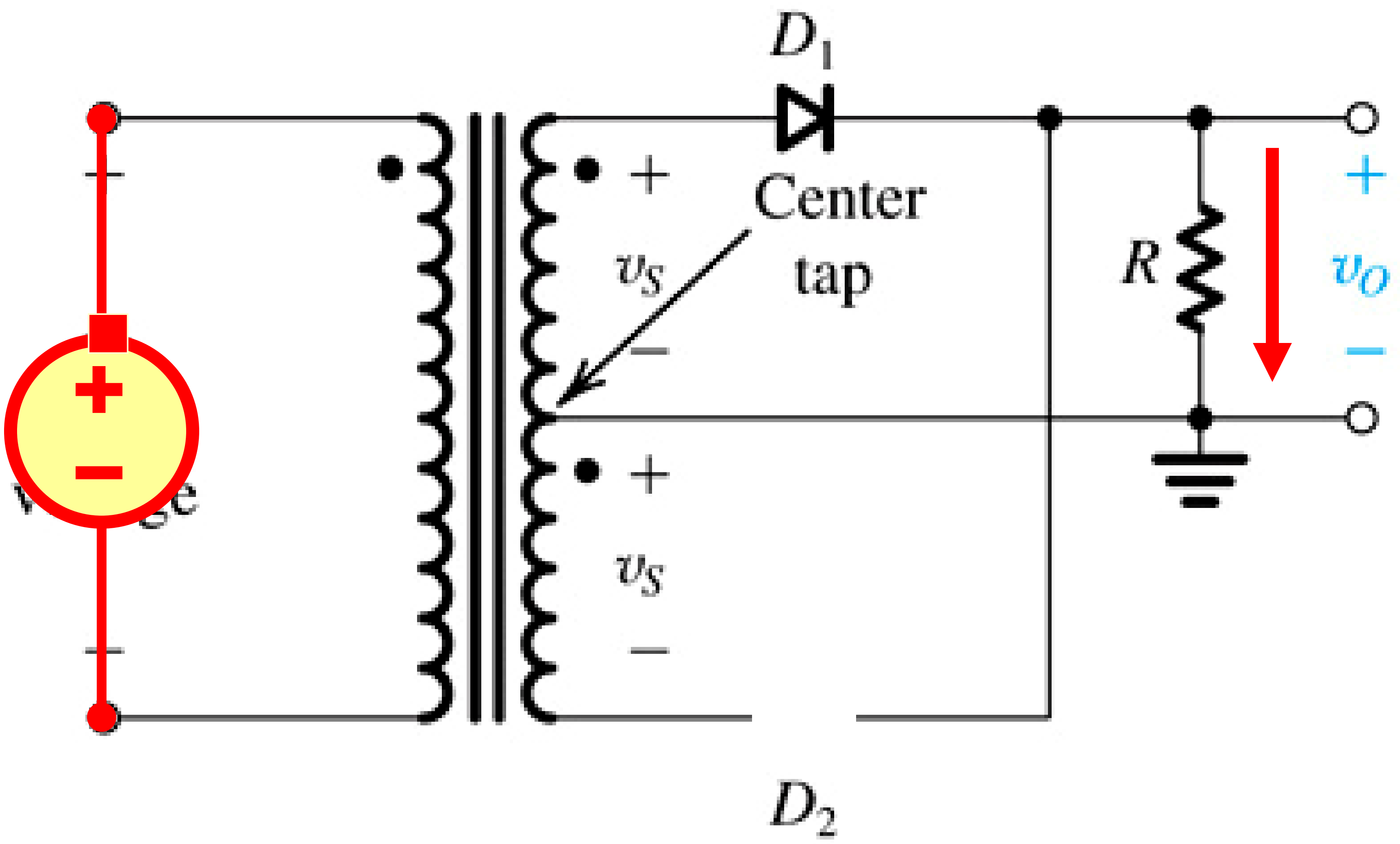


Figure 4.22: full-wave rectifier utilizing a transformer with a center-tapped secondary winding: **(a)** circuit; **(b)** transfer characteristic assuming a constant-voltage-drop model for the diodes; **(c)** input and output waveforms.

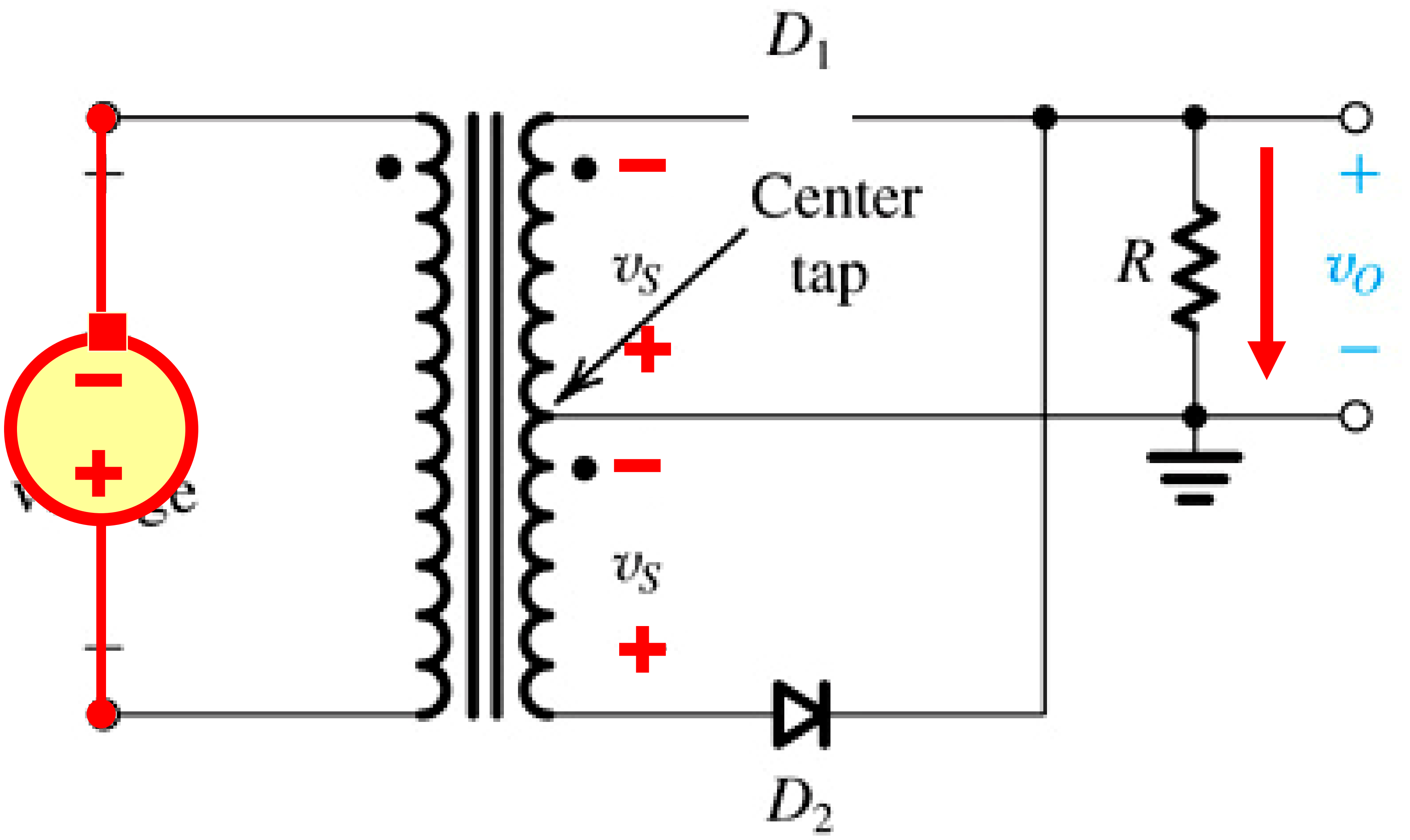


D_1
+
ac
line
voltage
−
+
v_S
−
Center
tap
+
v_S
−
D_2
R
+
v_O
−

When instantaneous source voltage is **positive**, D_1 conducts while D_2 blocks…



when instantaneous source voltage is **negative**, D_2 conducts while D_1 blocks

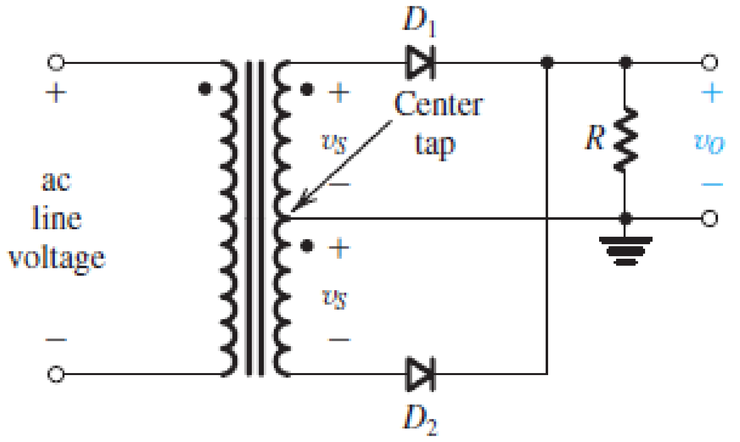


4.5.2. The Full-Wave Rectifier

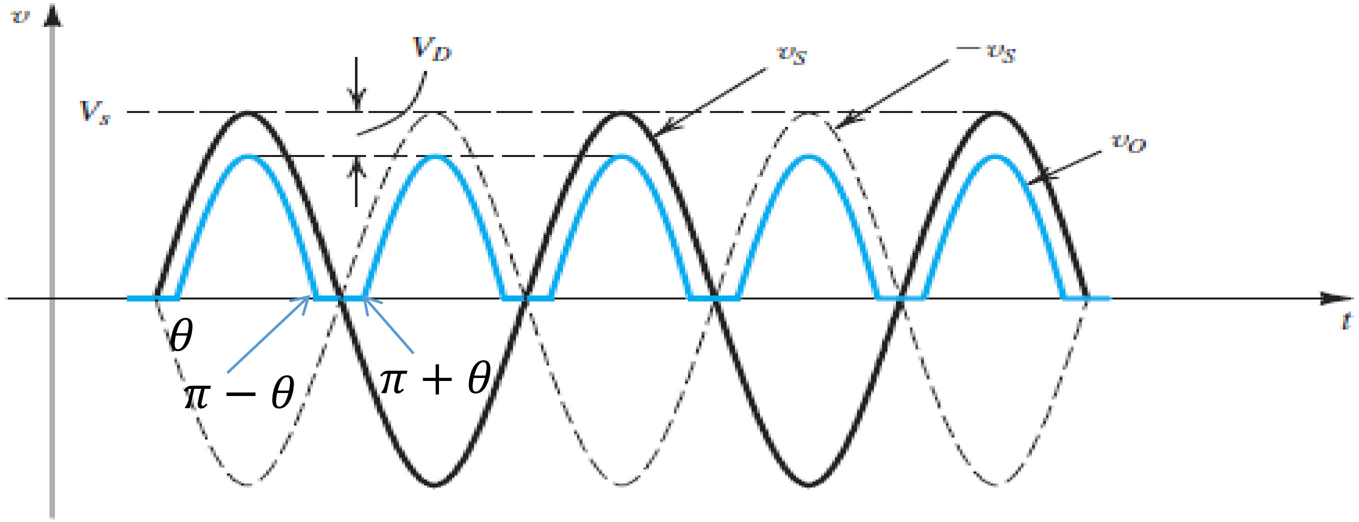
- **Q:** What are most important observation(s) from this operation?
  - **A:** The direction of current flowing across load never changes (both halves of AC wave are rectified). The full-wave rectifier produces a more "energetic" waveform than half-wave.
    - PIV for full-wave = $2V_S - V_D$

EXERCISE 4.20

For the full-wave rectifier circuit in Fig. 4.22(a), show the following: (a) The output is zero for an angle of $2\sin^{-1}(V_D/V_S)$ centered around the zero-crossing points of the sine-wave input. (b) The average value (dc component) of v_O is $V_o = \left(\frac{2}{\pi}\right)V_S - V_D$ (c) The peak current through each diode is $(V_S - V_D)/R$



EXERCIS



a. As shown in the diagram, the output is zero between $\pi - \theta$ to $\pi + \theta$ = 2θ

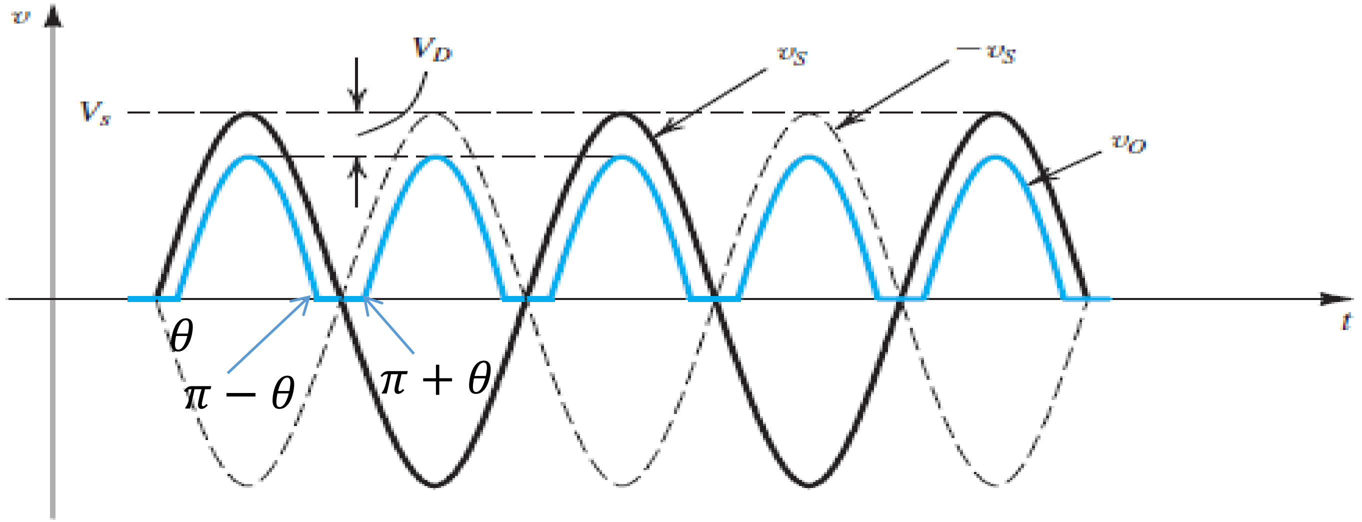
Here θ is the angle at which the input signal reaches V_D

$$\therefore V_S \sin\theta = V_D$$

$$\therefore \theta = \sin^{-1}\left(\frac{V_D}{V_S}\right)$$

The output is zero for an angle of $2\theta = 2\sin^{-1}\left(\frac{V_D}{V_S}\right)$

EXERCIS



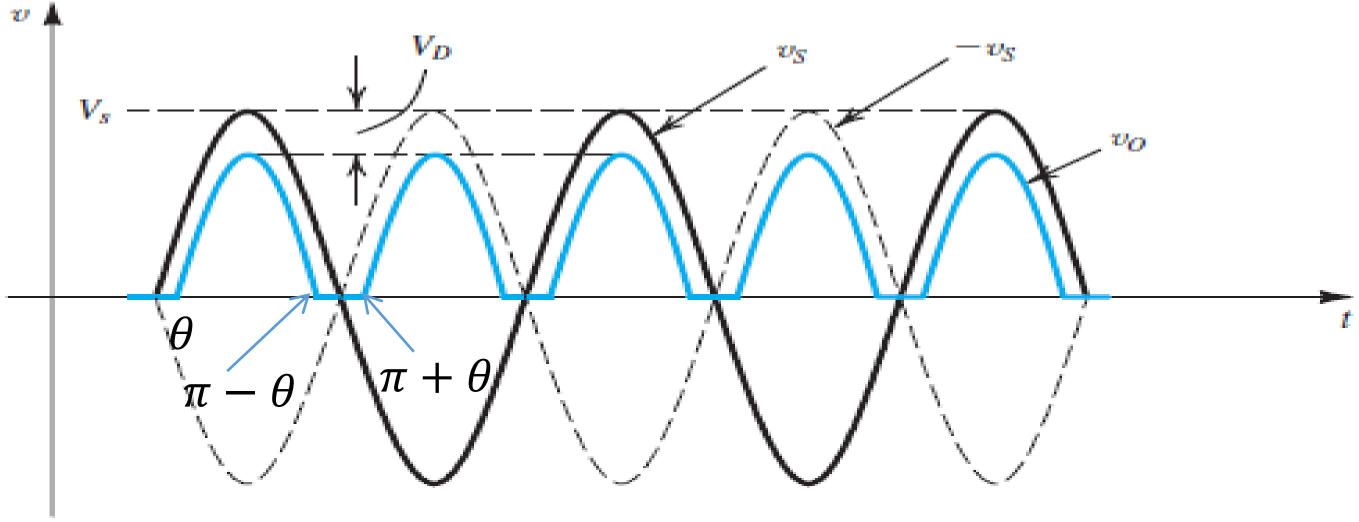
b. Average value of the output signal is given by

$$V_{\mathrm{o,avg}} = \frac{1}{2\pi}\left[2 \times \int_{\emptyset}^{\pi-\emptyset} (V_S \sin \emptyset - V_D) \mathrm{d}\emptyset\right]$$

$$= \frac{1}{\pi}\left[-V_S \cos \emptyset - V_D \emptyset\right]_{\emptyset=\theta}^{\pi-\theta}$$

$$= \frac{2V_S}{\pi} - V_D$$

EXERCISE 4.2[illegible]



C. The peak current occurs when $\phi = \frac{\pi}{2}$

$$\therefore \text{ peak current} = \frac{V_S \sin\frac{\pi}{2} - V_D}{R} = \frac{V_S - V_D}{R}$$

If $v_S = 12 \text{ Vrms} \quad \Rightarrow \quad then V_S = 12\sqrt{2}$

$$\therefore \text{ peak current} = \frac{12\sqrt{2} - 0.7}{100} = 163 \text{ mA}$$

4.5.3. The Bridge Rectifier

- An alternative implementation of the full-wave rectifier is **bridge rectifier.**
  - Shown to right.

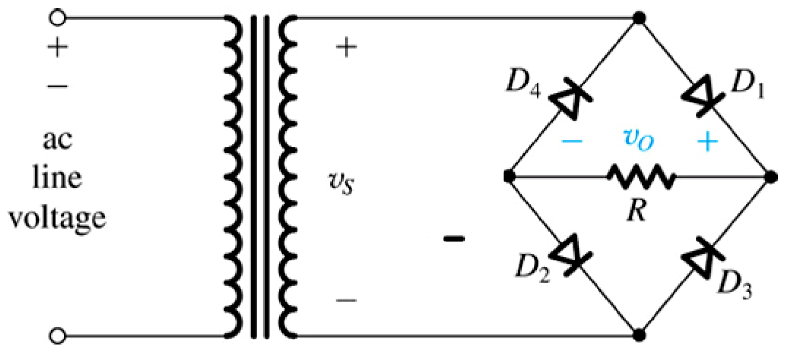


Figure 4.23: The bridge rectifier circuit.

when instantaneous source voltage is **positive**, D_1 and D_2 conduct while D_3 *and* D_4 block

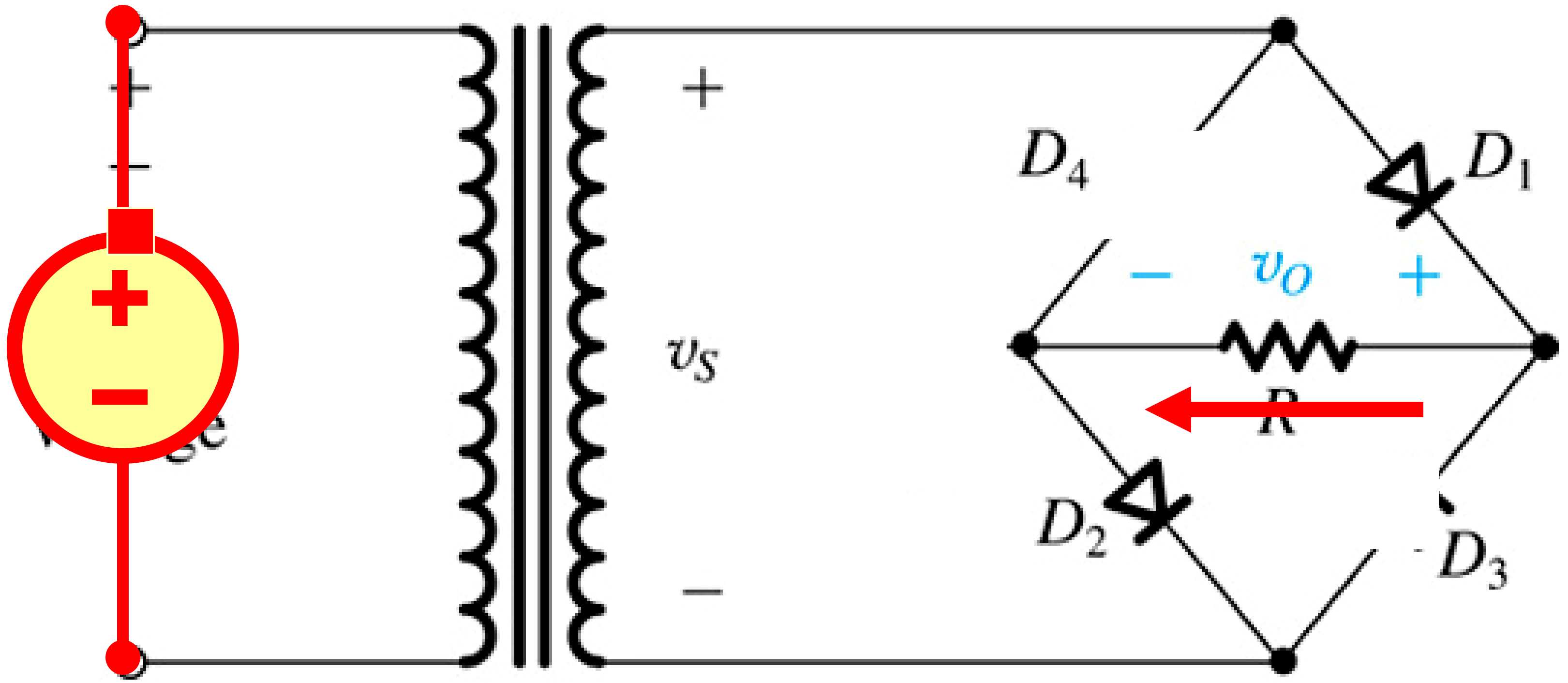


Figure 4.23: The bridge rectifier circuit.

when instantaneous source voltage is **positive**, D_1 and D_2 conduct while D_3 *and* D_4 block

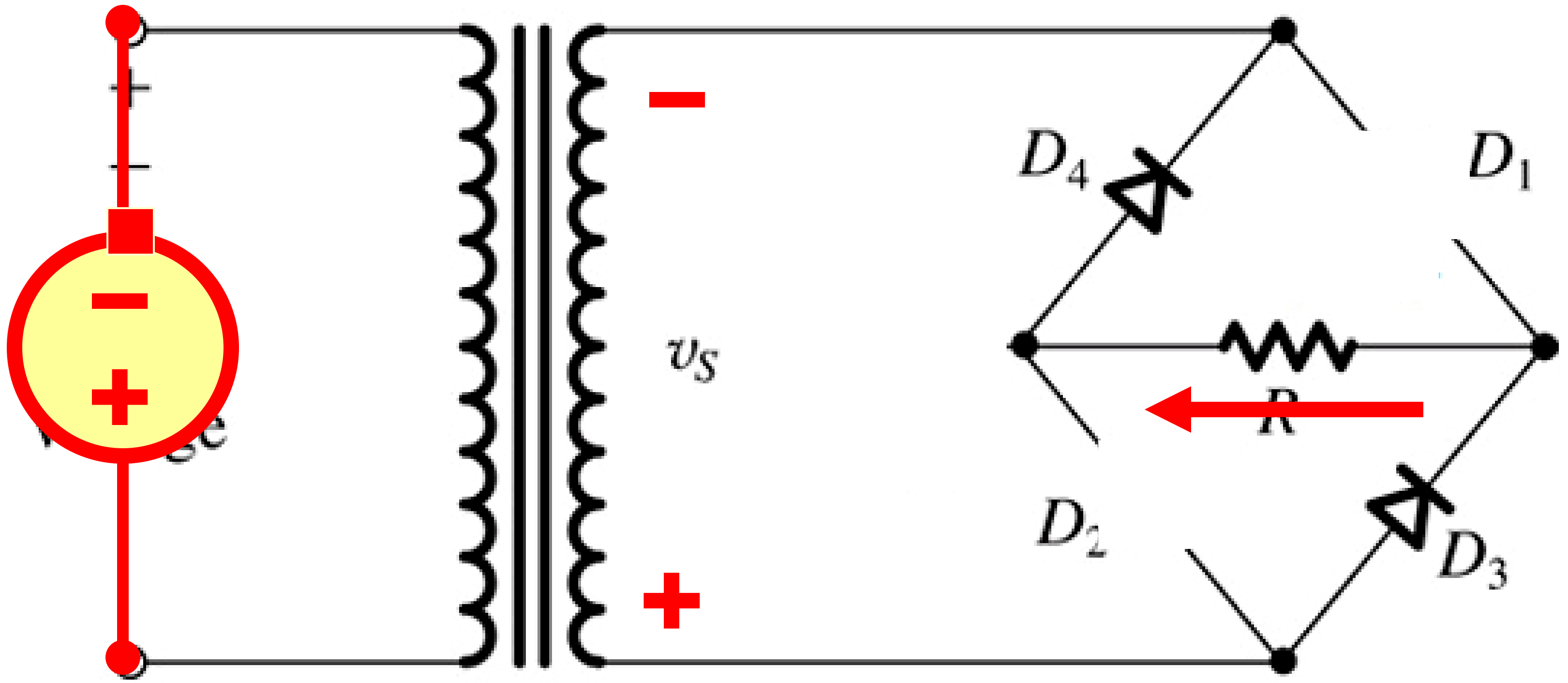


Figure 4.23: The bridge rectifier circuit.

4.5.3: The Bridge Rectifier (BR)

- **Q:** What is the main advantage of BR?
  - **A:** No need for center-tapped transformer.
- **Q:** What is main disadvantage?
  - **A:** Series connection of TWO diodes will reduce output voltage.
- PIV = $V_S - V_D$

4.5.4. The Rectifier with a Filter Capacitor

- Pulsating nature of rectifier output makes unreliable dc supply.
- As such, a **filter capacitor** is employed to remove ripple.

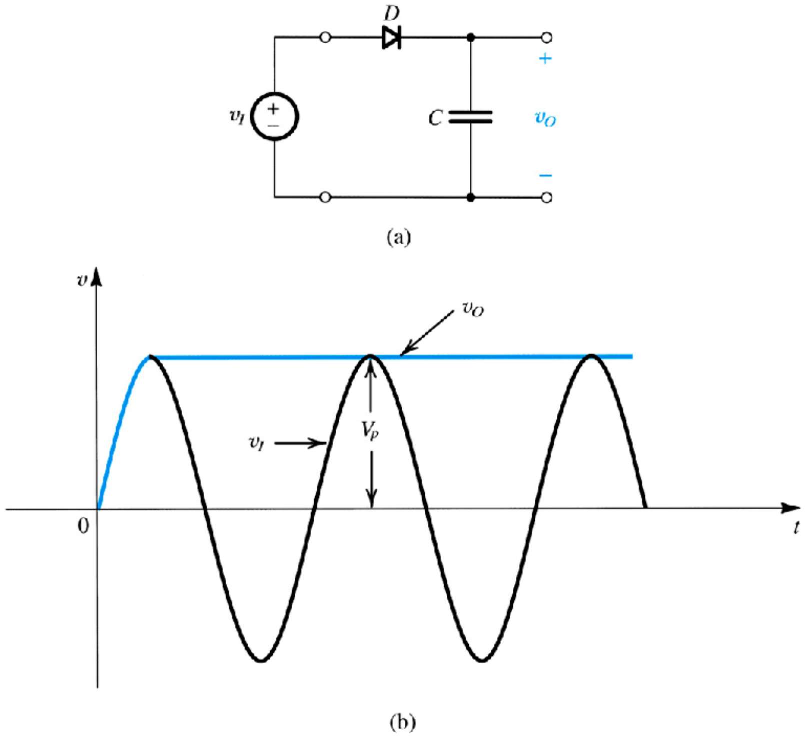


Figure 4.24: (a) A simple circuit used to illustrate the effect of a filter capacitor. **(b)** input and output waveforms assuming an ideal diode.

4.5.4. The Rectifier with a Filter Capacitor

- **step #1:** source voltage is positive, diode is forward biased, capacitor charges.
- **step #2:** source voltage is reverse, diode is reverse-biased (blocking), capacitor cannot discharge.
- **step #3:** source voltage is positive, diode is forward biased, capacitor charges (maintains voltage).

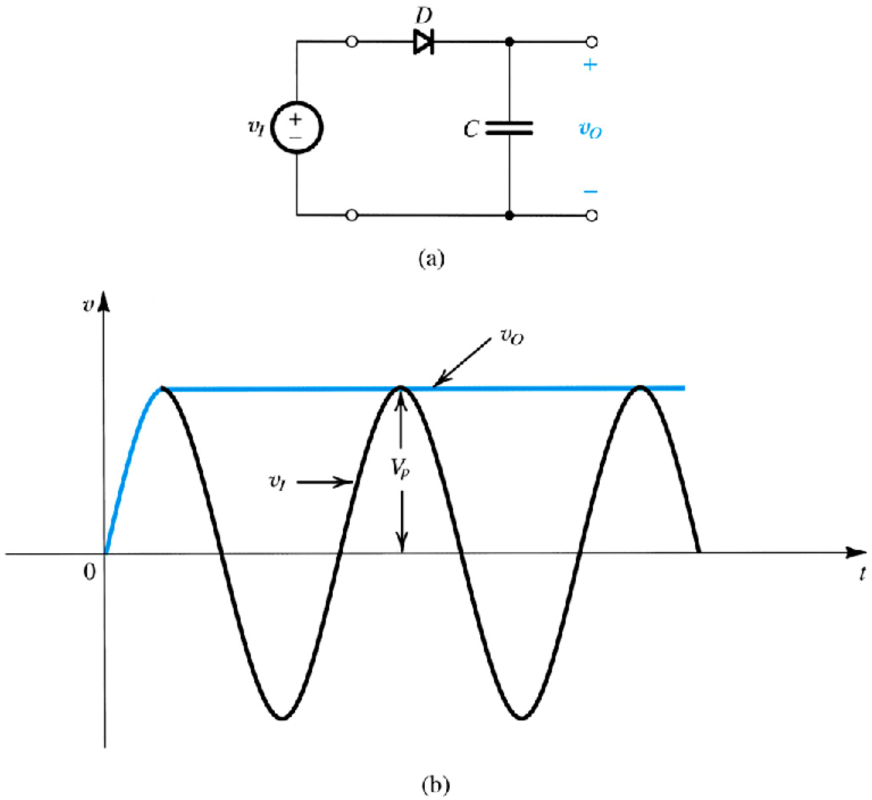


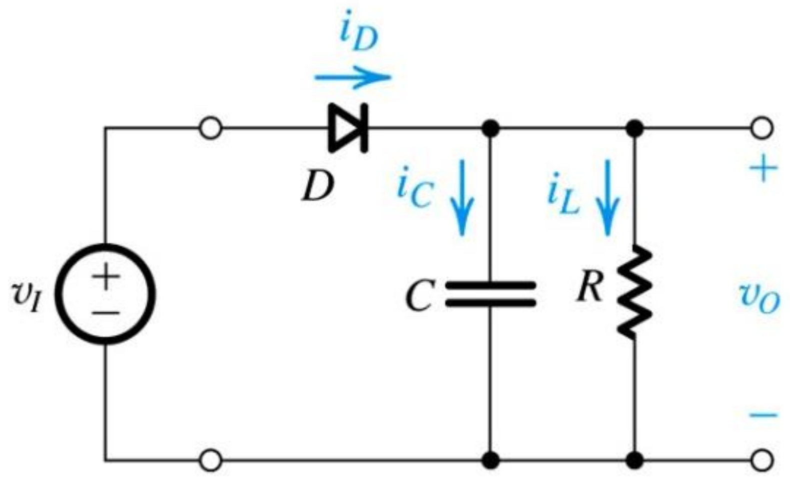
Figure 4.24 (a) A simple circuit used to illustrate the effect…

4.5.4. The Rectifier with a Filter Capacitor

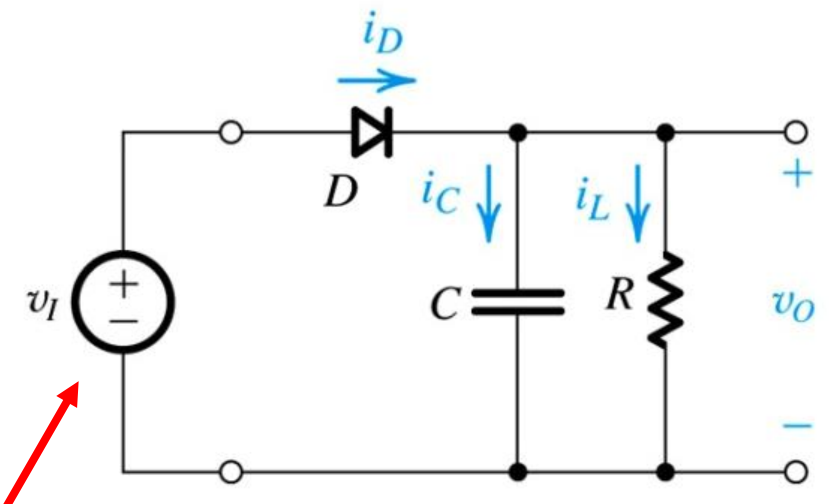
- **Q:** Why is this example unrealistic?
  - **A:** Because for any practical application, the converter would supply a load (which in turn provides a path for capacitor discharging).

4.5.4. The Rectifier with a Filter Capacitor

- **Q:** What happens when **load resistor** is placed in series with capacitor?
  - **A:** One must now consider the discharging of capacitor across load.



4.5.4. The Rectifier with a Filter Capacitor



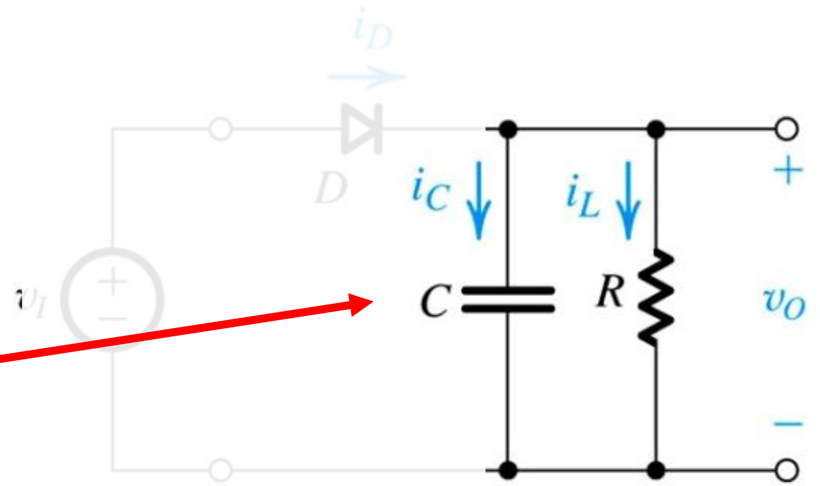
circuit state #1

output voltage for state #1

$$v_O(t) = v_I(t) - v_D$$

$$v_O(t) = V_{peak} e^{-\frac{t}{RC}}$$

output voltage for state #2



circuit state #2

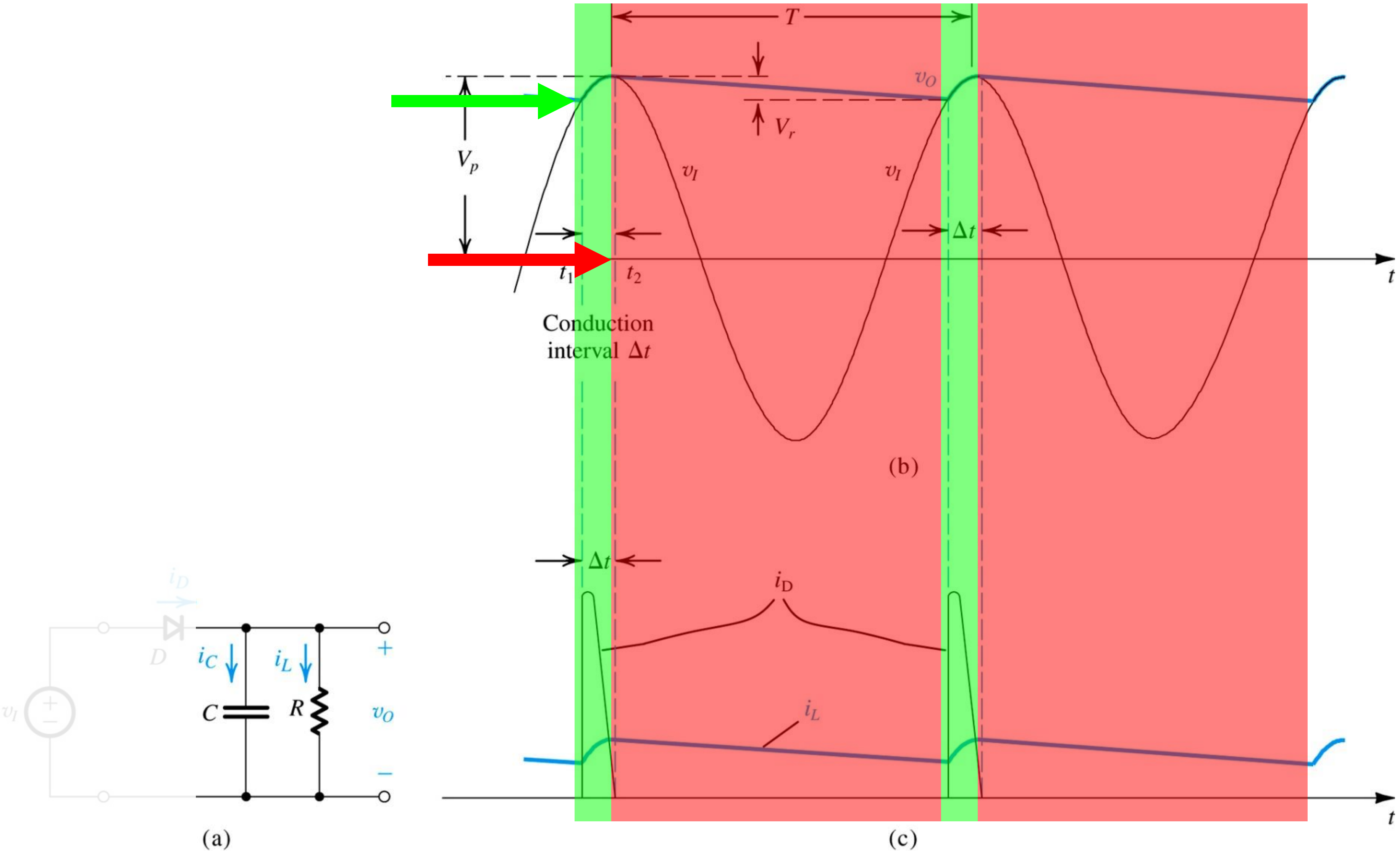


Figure 4.25: Voltage and Current Waveforms in the Peak Rectifier Circuit WITH *RC* >> *T*. The diode is assumed ideal.

A Couple of Observations

- The diode conducts for a brief interval (Δt) near the peak of the input sinusoid and supplies the capacitor with charge equal to that lost during the much longer discharge interval. The latter is approximately equal to T.
- Assuming an ideal diode, the diode conduction begins at time t_1 (at which the input v_I equals the exponentially decaying output v_O). Diode conduction stops at time t_2 shortly after the peak of v_I (the exact value of t_2 is determined by settling of I_D).

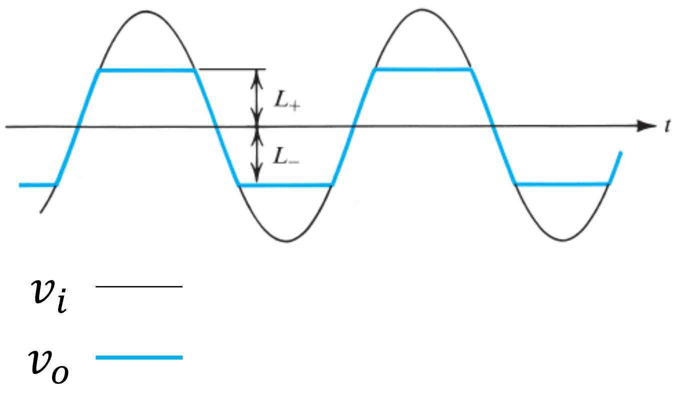
A Couple of Observations

- During the diode off-interval, the capacitor *C* discharges through *R* causing an exponential decay in the output voltage (v_O). At the end of the discharge interval, which lasts for almost the entire period *T*, voltage output is defined as follows – $v_O(T) = V_{peak} - V_r$.
- When the ripple voltage (V_r) is small, the output (v_O) is almost constant and equal to the peak of the input (v_I). the average output voltage may be defined as below…

$$\text{(eq4.27)}\ \mathbf{avg}(V_O) = V_{peak} - \frac{1}{2}V_r \approx V_{peak} \text{ if } V_r \text{ is small}$$

4.6: Limiting and Clamping Circuits

- **Q:** What is a **limiter circuit**?
  - **A:** One which limits voltage output.



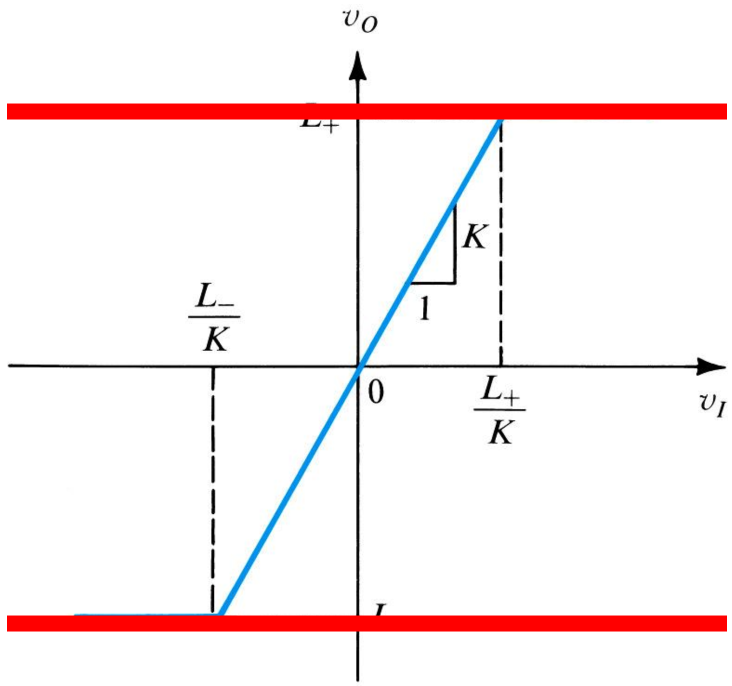


Figure 4.28: General transfer characteristic for a limiter circuit

4.6. Limiting and Clamping Circuits

- **passive limiter circuit**
  - has linear range
  - has nonlinear range
  - $K < 1$
  - examples include
    - single limiter operate in uni-polar manner
    - double limiter operate in bi-polar manner

$$v_O = \begin{cases} \overbrace{Kv_I}^{\text{over linear range}} \\ \underbrace{\text{constant value(s)}}_{\text{outside linear range}} \end{cases}$$

$$v_O = \begin{cases} L_- & v_I \leq \dfrac{L_-}{K} \\ Kv_I & \dfrac{L_-}{K} < v_I < \dfrac{L_+}{K} \\ L_+ & v_I \geq \dfrac{L_+}{K} \end{cases}$$

single limiters employ one diode

double limiters employ two diodes of opposite polarity

linear range may be controlled via string of diodes and dc sources

zener diodes may be used to implement soft limiting

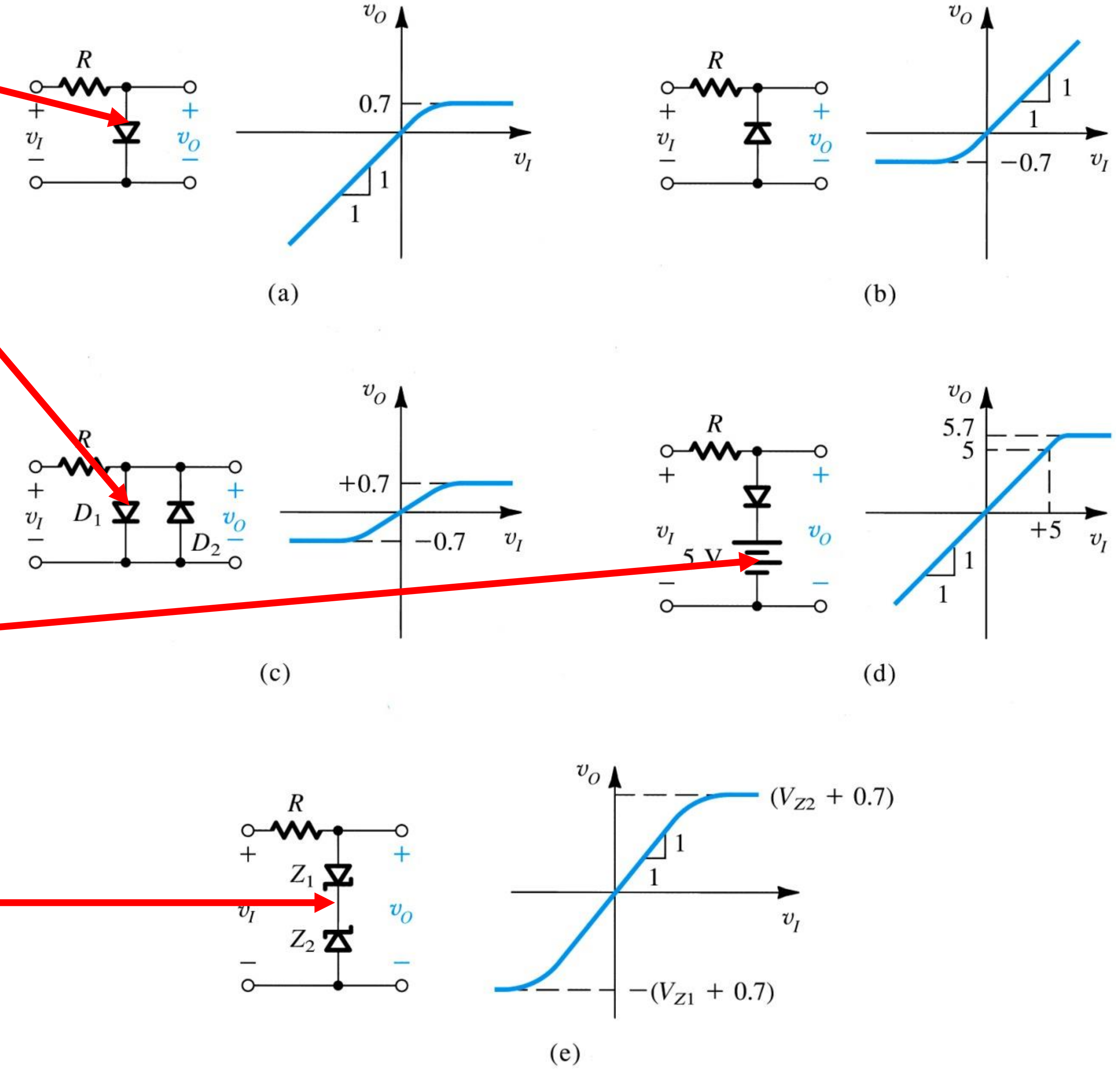


Figure 4.31: Variety of basic limiting circuits.

4.6.2. The Clamped Capacitor or DC Restorer

- **Q:** What is a **dc restorer**?
  - **A:** Circuit which removes the dc component of an AC wave.
- **Q:** Why is this ability important?
  - **A:** Average value of this output is effective way to measure duty cycle

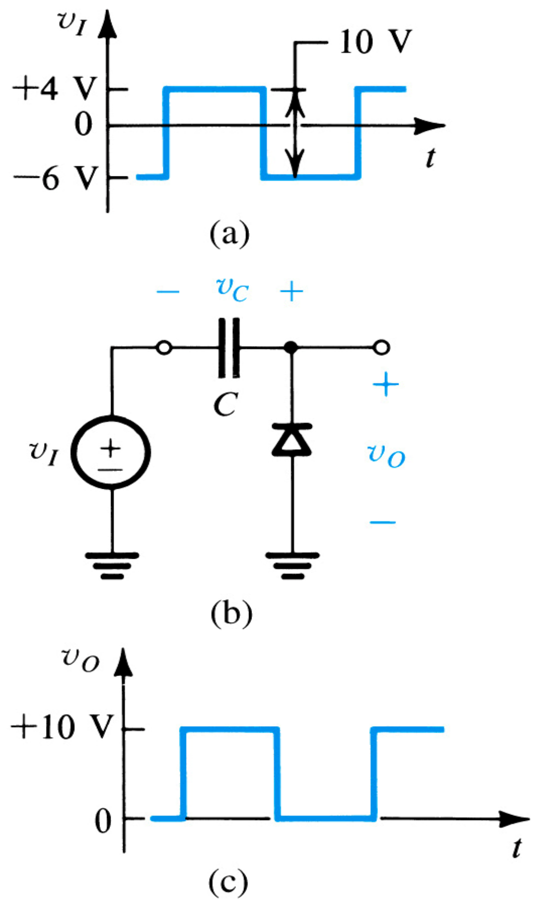


Figure 4.32: The clamped capacitor or dc restorer with a square-wave input and no load

4.6.3: The Voltage Doubler

- **Q:** What is a **voltage doubler**?
  - **A:** One which multiplies the amplitude of a wave or signal by two.

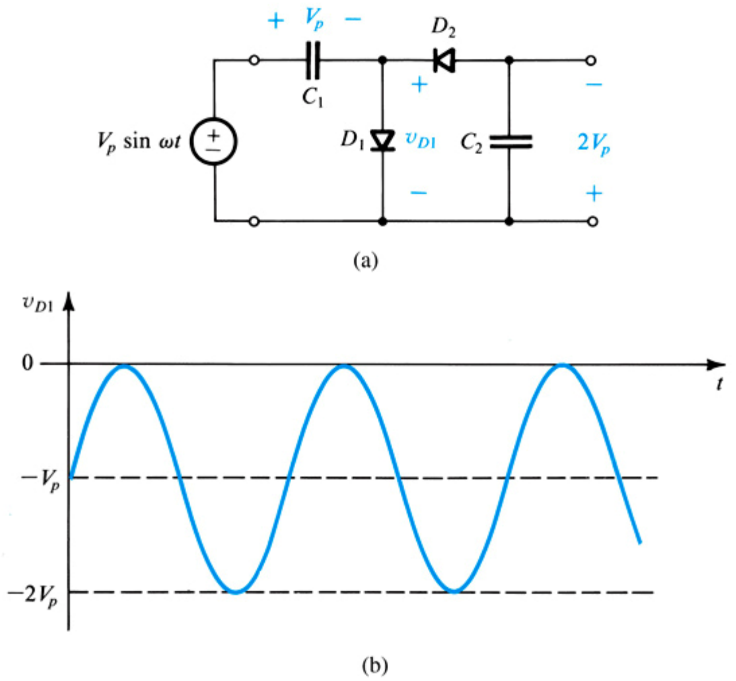
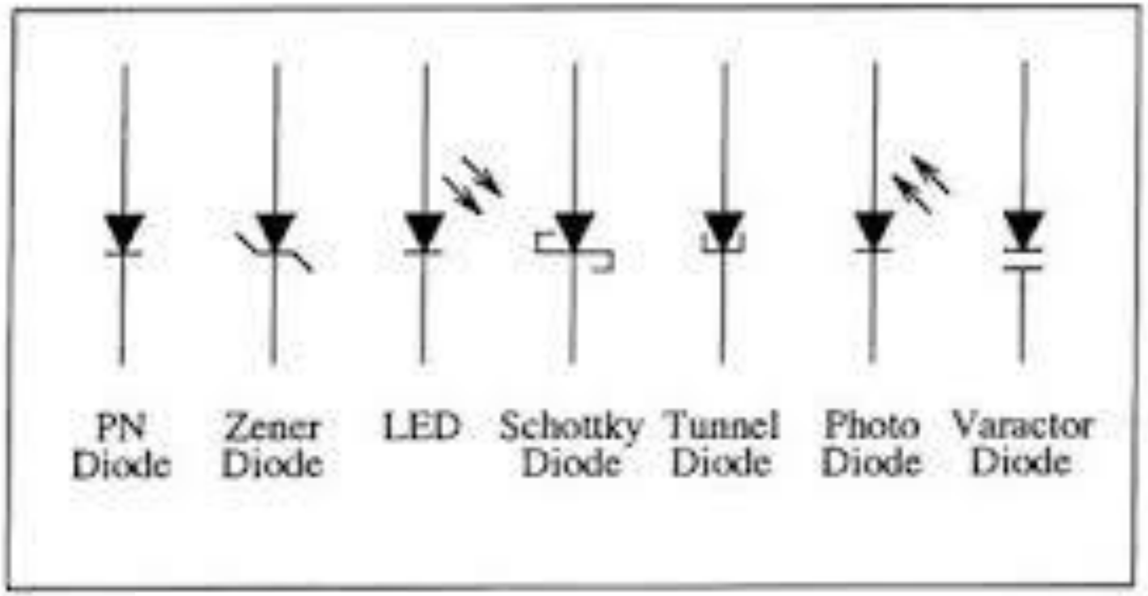


Figure 4.34: Voltage doubler: **(a)** circuit; **(b)** waveform of the voltage across D_1.

Special Diode Types

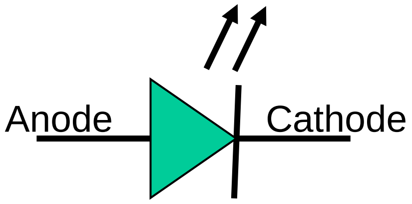


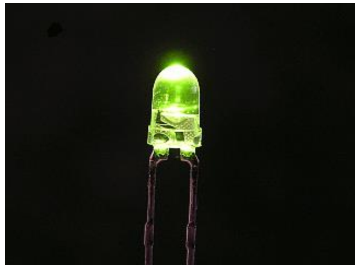
Optical Diodes

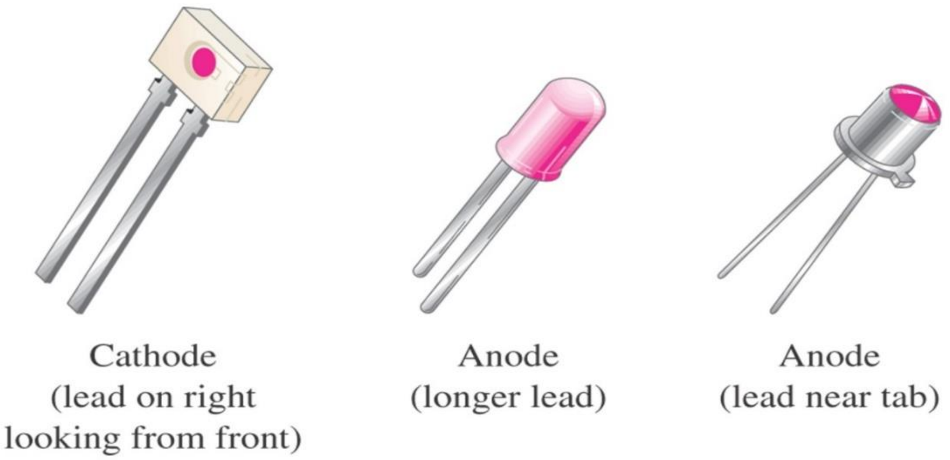
There are two popular types of optoelectronic devices:
light-emitting diode (LED) and *photodiode*.

The Light-Emitting Diode (LED)

LED is diode that emits light when biased in the forward direction of p-n junction.

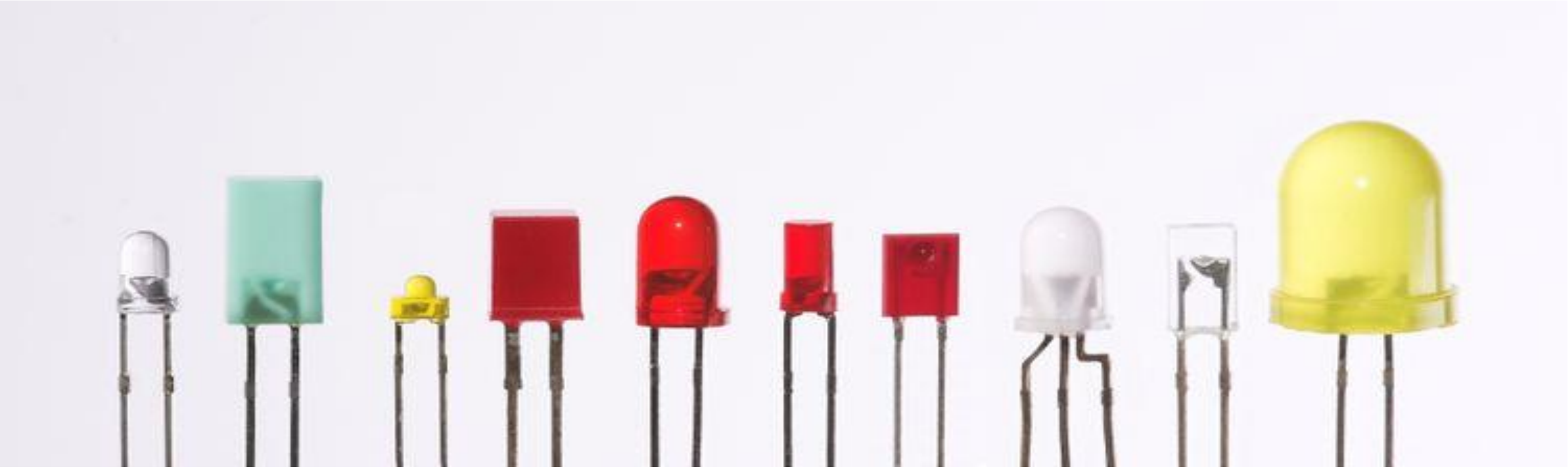






The schematic symbol and construction features.

The Light-Emitting Diode (LED)



LED that are produced in an array of shapes and sizes.

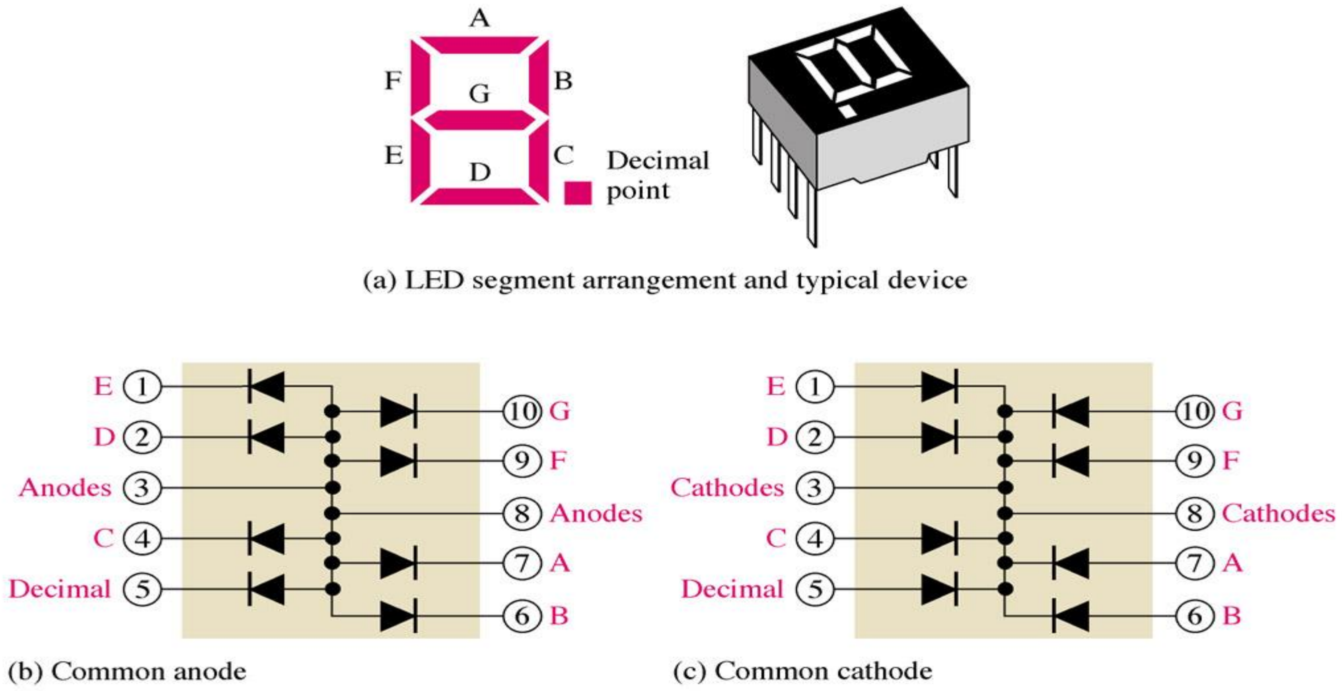
LED characteristics:

- characteristic curves are very similar to those for p-n junction diodes
- higher forward voltage (V_F)
- lower reverse breakdown voltage (V_{BR}).

The Light-Emitting Diode (LED)

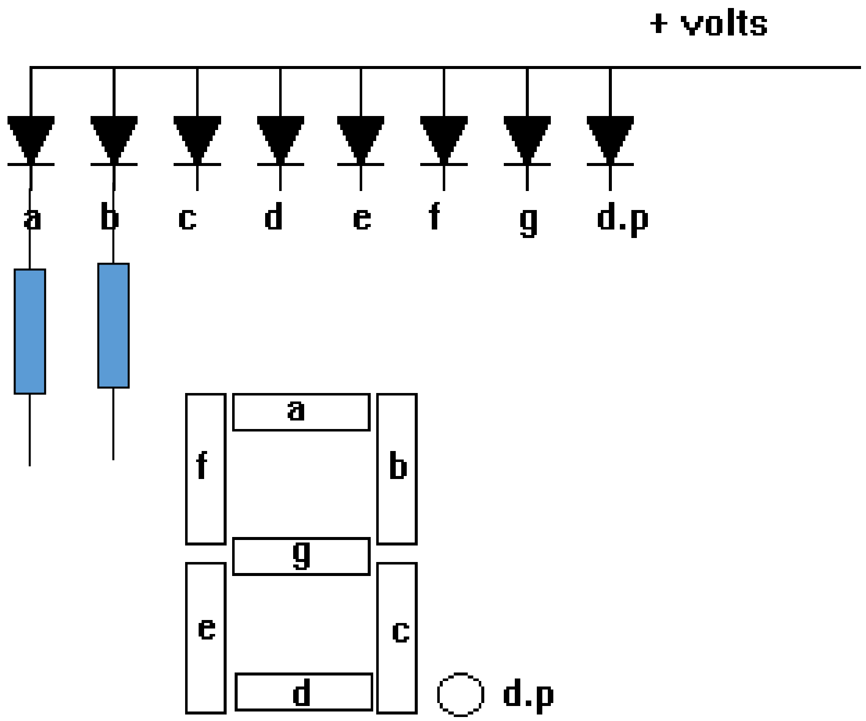
Application

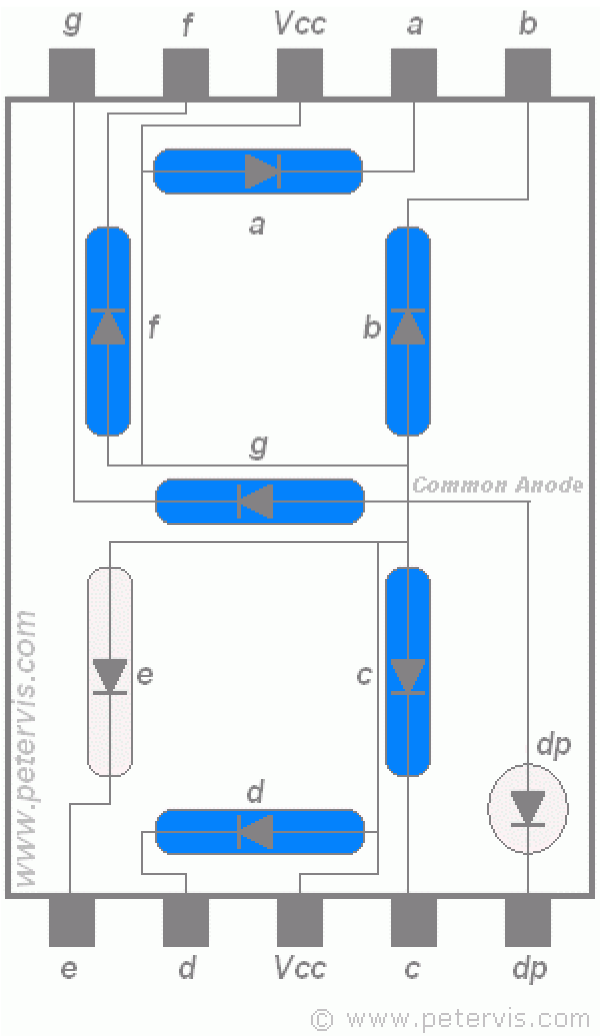
The seven segment display is an example of LEDs use for display of decimal digits.



The 7-segment LED display.

LED Displays



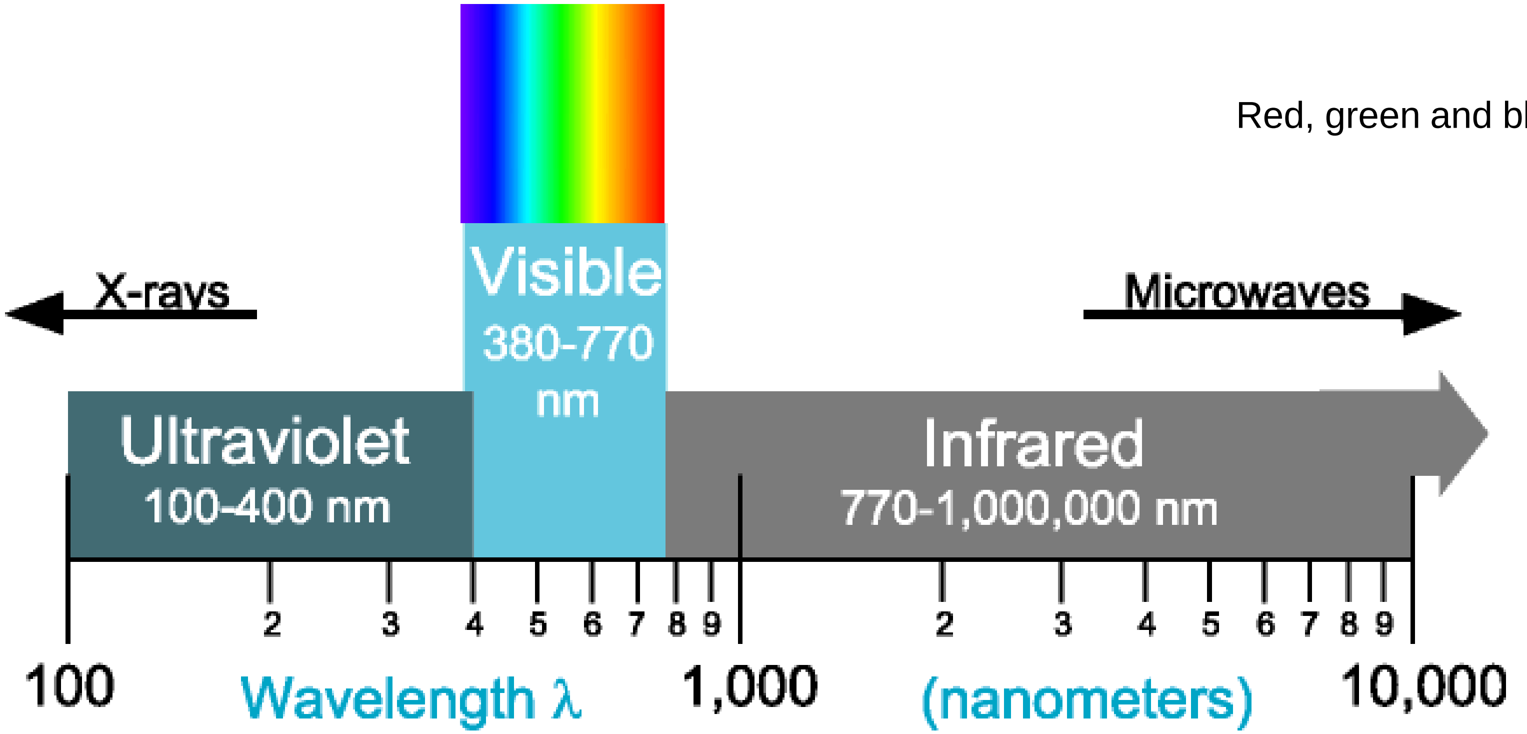


LED displays are packages of many LEDs arranged in a pattern, the most familiar pattern being the 7-segment displays for showing numbers (digits 0-9).

The Light-Emitting Diode (LED)

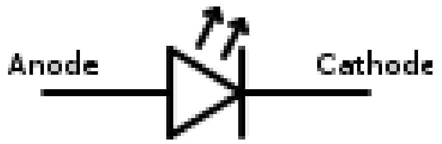
Light Spectrum

Red, green and blue LEDs

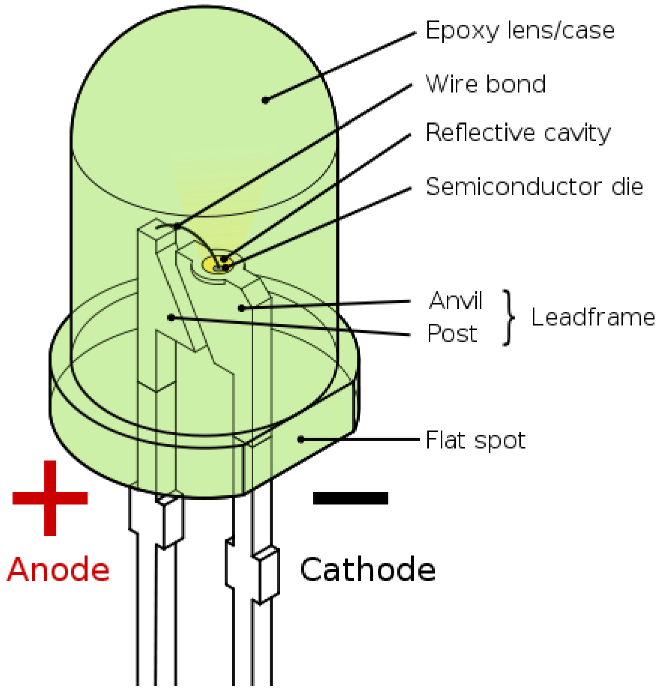


The optical portion of the electromagnetic spectrum

The Light-Emitting Diode (LED)



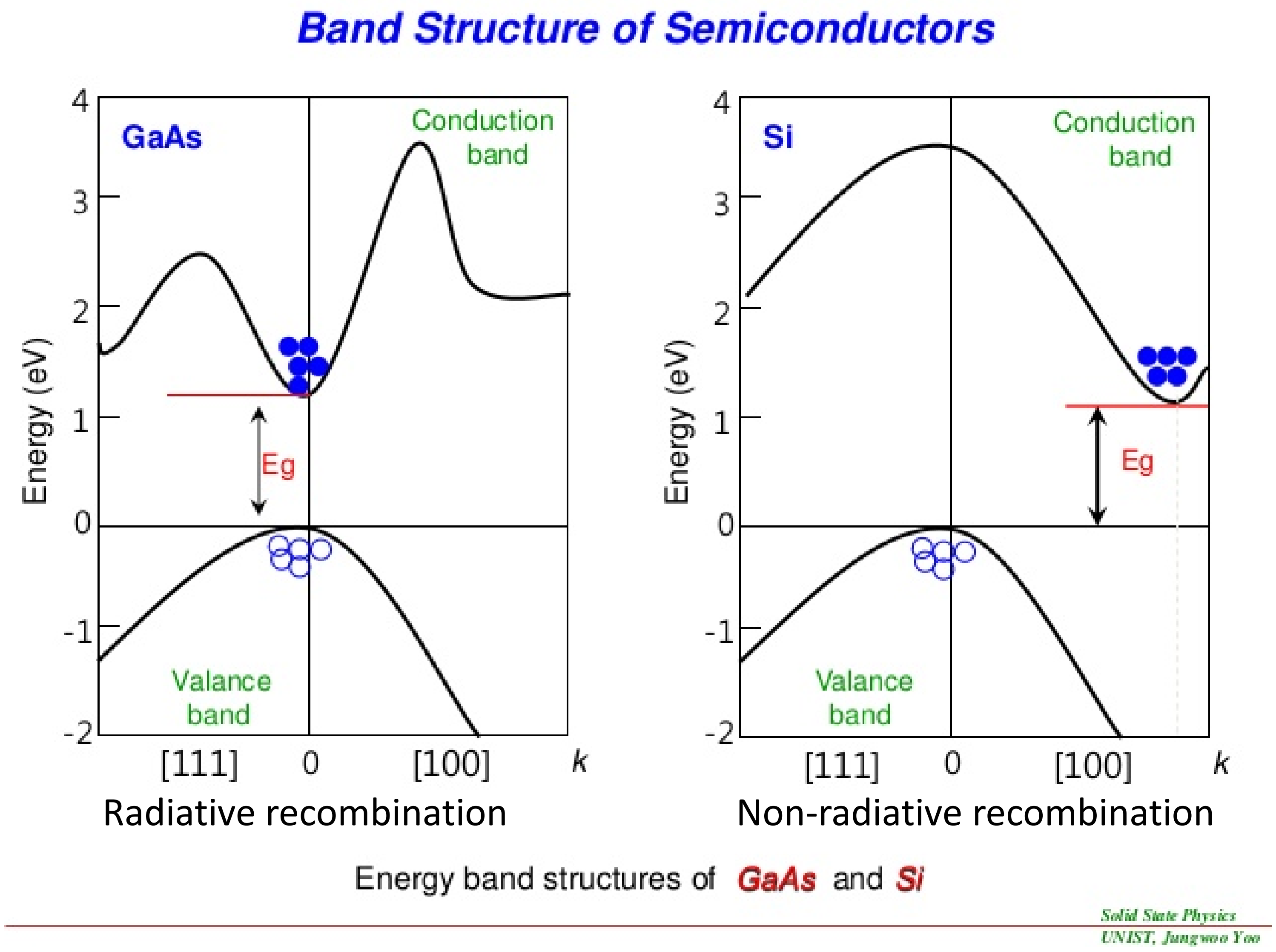
When a light-emitting diode is forward biased, electrons are able to recombine with holes within the device, releasing energy in the form of photons.



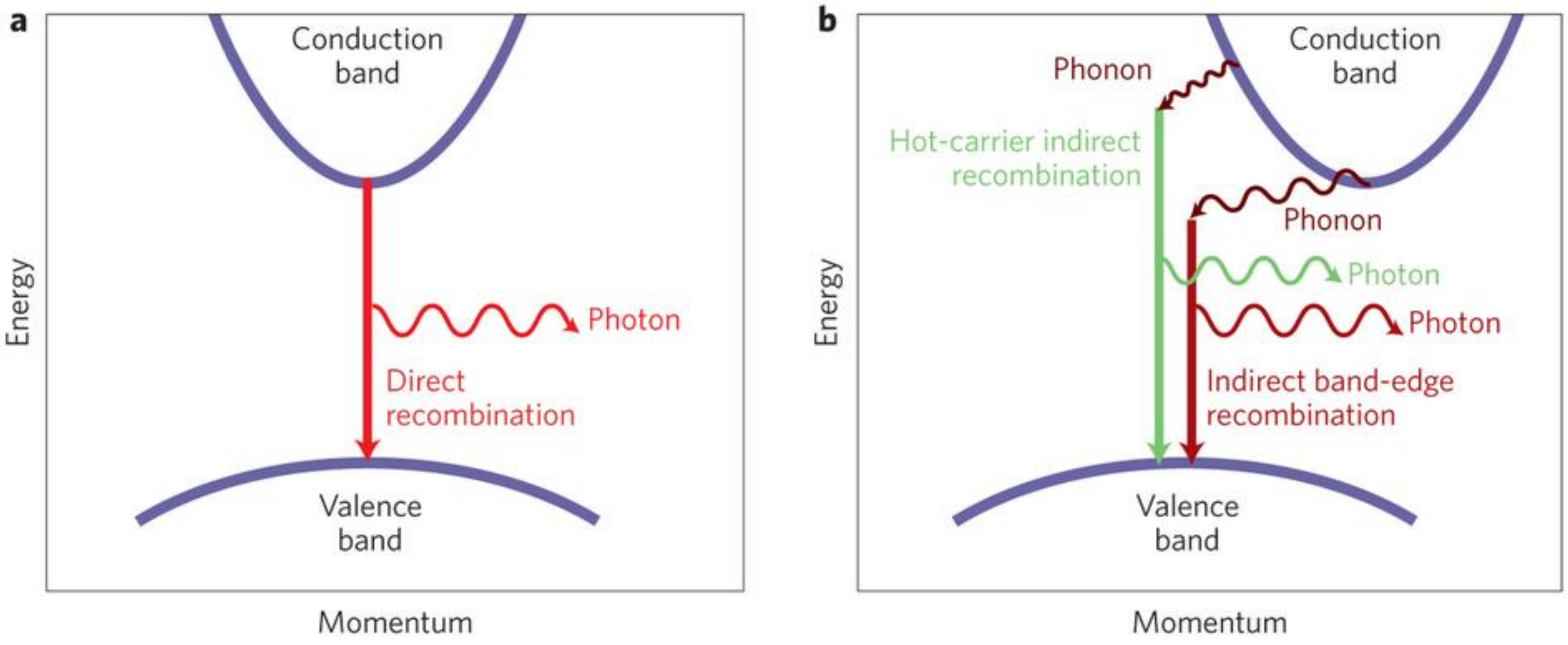
This effect is called electroluminescence and the color of the light (corresponding to the energy of the photon) is determined by the energy gap of the semiconductor.

Fabricating the *pn* junction using a semiconductor of the type known as direct-bandgap materials.

The Light-Emitting Diode (LED)



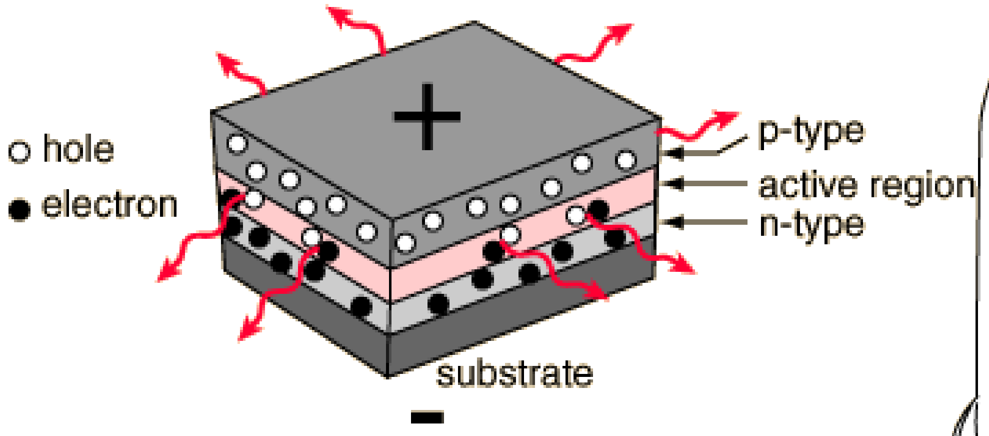
The Light-Emitting Diode (LED)

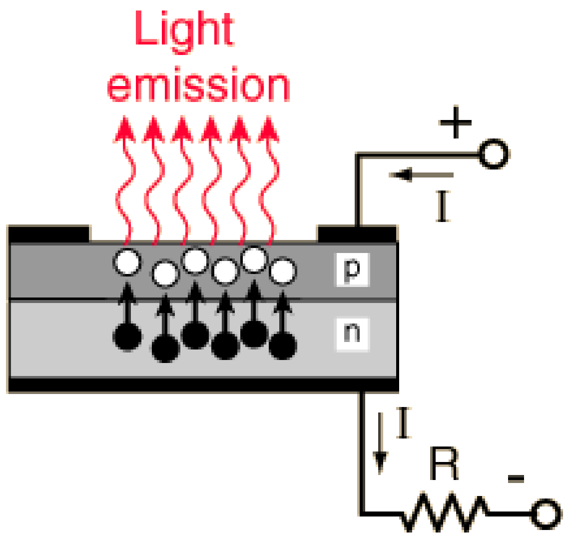


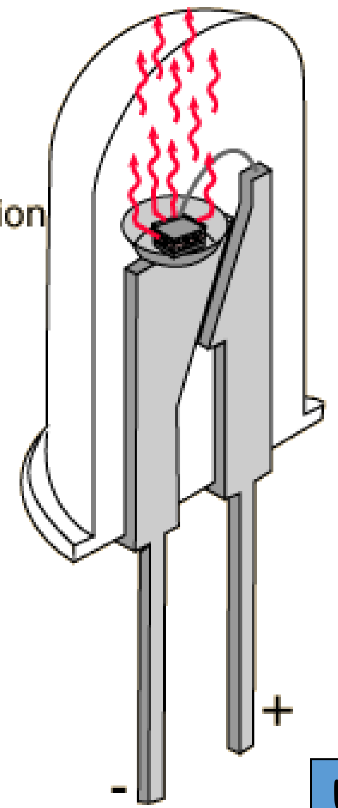
Radiative recombination

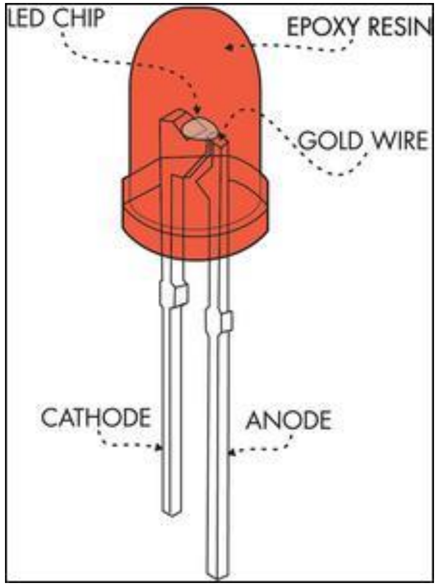
Non-radiative recombination

LED - Light Emitting Diodes







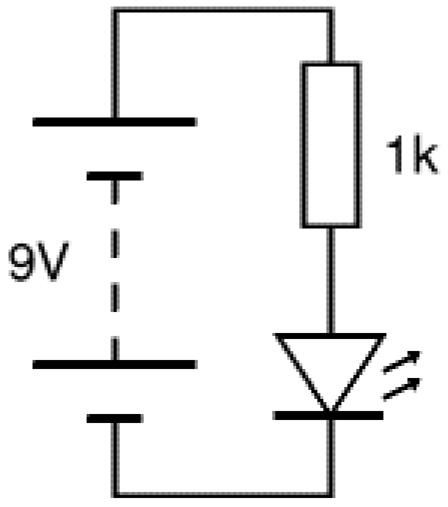


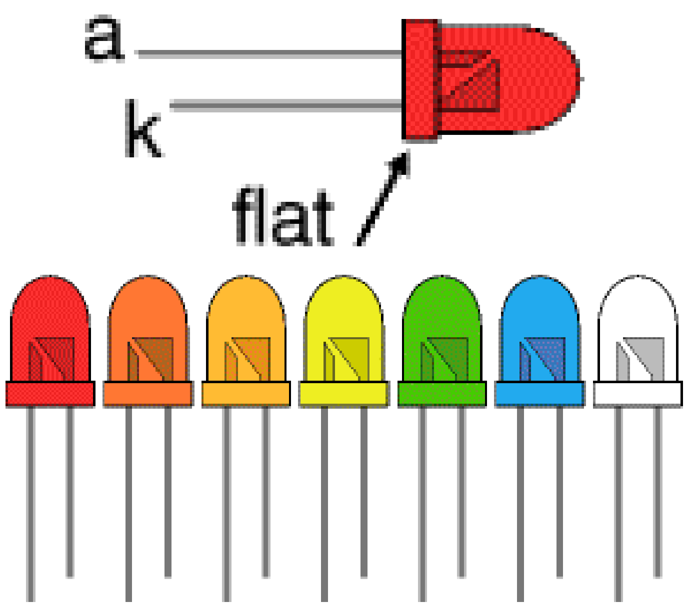
UV – AlGaN
Blue – GaN, InGaN
Red, green – GaP
Red, yellow – GaAsP
IR- GaAs

LED - Colors & voltage drop

	Color	Wavelength (nm)	Voltage (V)	Semiconductor Material
	Infrared	λ > 760	ΔV < 1.9	Gallium arsenide (GaAs) Aluminium gallium arsenide (AlGaAs)
	Red	610 < λ < 760	1.63 < ΔV < 2.03	Aluminium gallium arsenide (AlGaAs) Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
	Orange	590 < λ < 610	2.03 < ΔV < 2.10	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP)Gallium(III) phosphide (GaP)
	Yellow	570 < λ < 590	2.10 < ΔV < 2.18	Gallium arsenide phosphide (GaAsP) Aluminium gallium indium phosphide (AlGaInP) Gallium(III) phosphide (GaP)
	Green	500 < λ < 570	1.9 < ΔV < 4.0	Indium gallium nitride (InGaN) / Gallium(III) nitride (GaN) Gallium(III) phosphide (GaP)Aluminium gallium indium phosphide (AlGaInP) Aluminium gallium phosphide (AlGaP)
	Blue	450 < λ < 500	2.48 < ΔV < 3.7	Zinc selenide (ZnSe), Indium gallium nitride (InGaN), Silicon carbide (SiC) as substrate, Silicon (Si)
	Violet	400 < λ < 450	2.76 < ΔV < 4.0	Indium gallium nitride (InGaN)
	Purple	multiple types	2.48 < ΔV < 3.7	Dual blue/red LEDs,blue with red phosphor,or white with purple plastic
	Ultra-violet	λ < 400	3.1 < ΔV < 4.4	diamond (235 nm), Boron nitride (215 nm) , Aluminium nitride (AlN) (210 nm) Aluminium gallium nitride (AlGaN) (AlGaInN) — (to 210 nm)
	White	Broad spectrum	ΔV = 3.5	Blue/UV diode with yellow phosphor

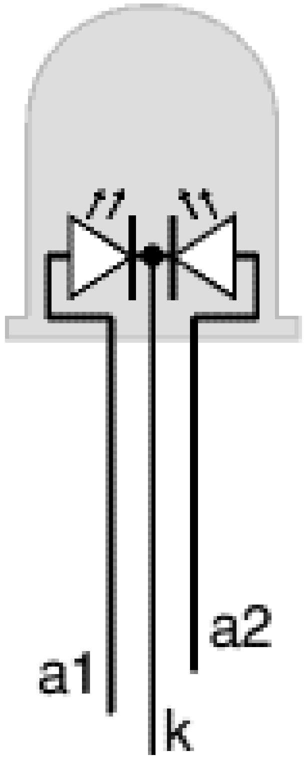
Testing an LED





Never connect an LED directly to a battery or a power supply!
It will be destroyed almost instantly because too much current will pass through and burn it out.
LEDs must have a resistor in series to limit the current to a safe value, for quick testing purposes a 1kΩ resistor is suitable for most LEDs if your supply voltage is 12V or less.
Remember to connect the LED the correct way!

Tri-color LEDs



The most popular type of tri-color LED has a red and a green LED combined in one package with three leads.

They are called tri-color because mixed red and green light appears to be yellow.

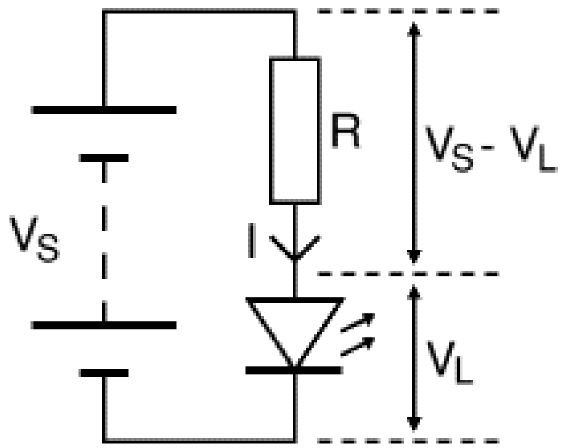
The diagram shows the organization of a tri-color LED. Note the different lengths of the three leads.

The central lead (k) is the common cathode for both LEDs, the outer leads (a1 and a2) are the anodes to the LEDs allowing each one to be lit separately, or both together to give the third color.

Calculating an LED resistor value

An LED must have a resistor connected in series to limit the current through the LED. The resistor value, R is given by:

$$R = (V_S - V_L) / I$$



V_S = supply voltage
V_L = LED voltage (usually 2V, but 4V for blue and white LEDs)
I = LED current (e.g. 20mA), this must be less than the maximum permitted
If the calculated value is not available, choose the nearest standard resistor value which is **greater,** to limit the current. Even greater resistor value will increase the battery life but this will make the LED less bright.

For example
If the supply voltage V_S = 9V, and you have a red LED (V_L = 2V), requiring a current I = 20mA = 0.020A,
R = (9V - 2V) / 0.02A = 350, so choose 390 (the nearest greater standard value).

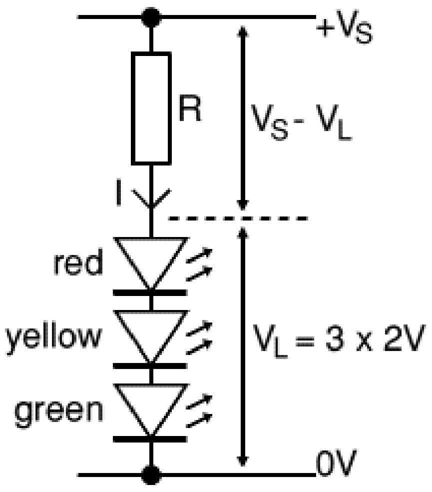
Connecting LEDs in series

If you wish to have several LEDs on at the same time, connect them in series.

This prolongs battery life by lighting several LEDs with the same current as just one LED.

The power supply must have sufficient voltage to provide about 2V for each LED (4V for blue and white) plus at least another 2V for the resistor.

To work out a value for the resistor you must add up all the LED voltages and use this for V_L.



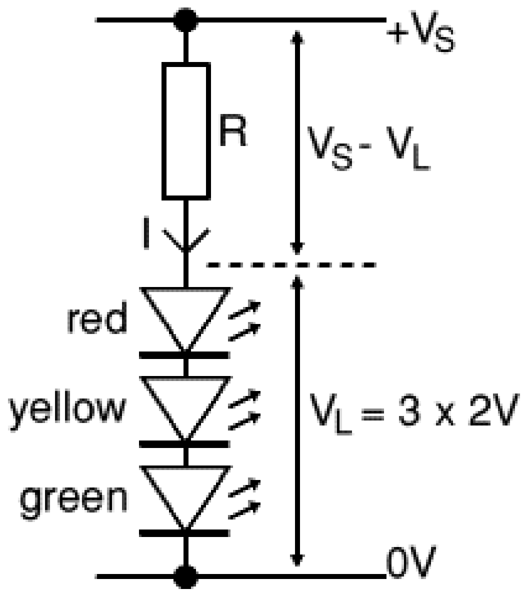
Connecting LEDs in series

Example

A red, a yellow and a green LED in series need a supply voltage of at least

3×2V + 2V = 8V,

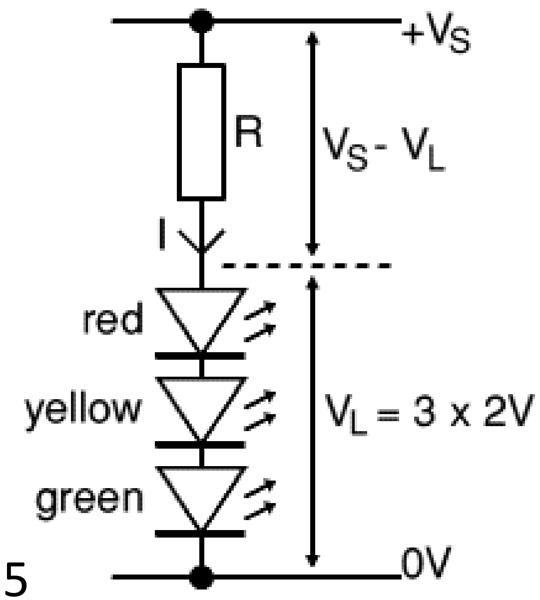
so choose a 9V battery. Adjust the resistor R to have current I=15 mA.



Connecting LEDs in series

Example

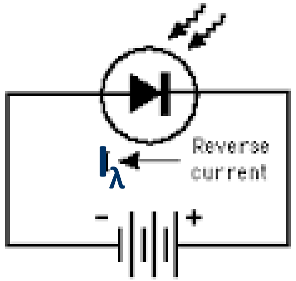
A red, a yellow and a green LED in series need a supply voltage of at least 3×2V + 2V = 8V, so choose a 9V battery. Adjust the resistor R to have current I=15 mA.

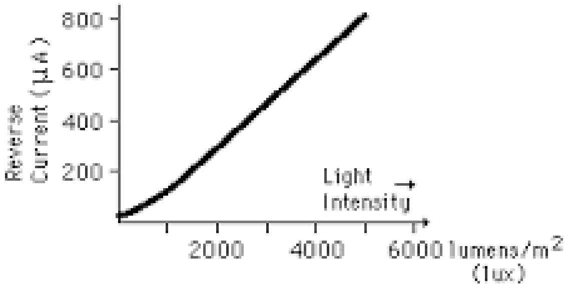


VL = 2V + 2V + 2V = 6V (the three LED voltages added up).
If the supply voltage VS is 9V and the current I must be 15mA = 0.015A,
Resistor R = (VS - VL) / I = (9 - 6) / 0.015 = 3 / 0.015 = 200,
so choose R = 220Ω (the nearest standard value which is greater).

The Photodiode

Photodiode is a p-n junction that can convert light energy into electrical energy.
It operates in *reverse bias voltage* (V_R), as shown in Figure, where **I_λ** is the reverse light current.
It has a small transparent window that allows light to strike the p-n junction.
The resistance of a photodiode is calculated by the formula as follows:

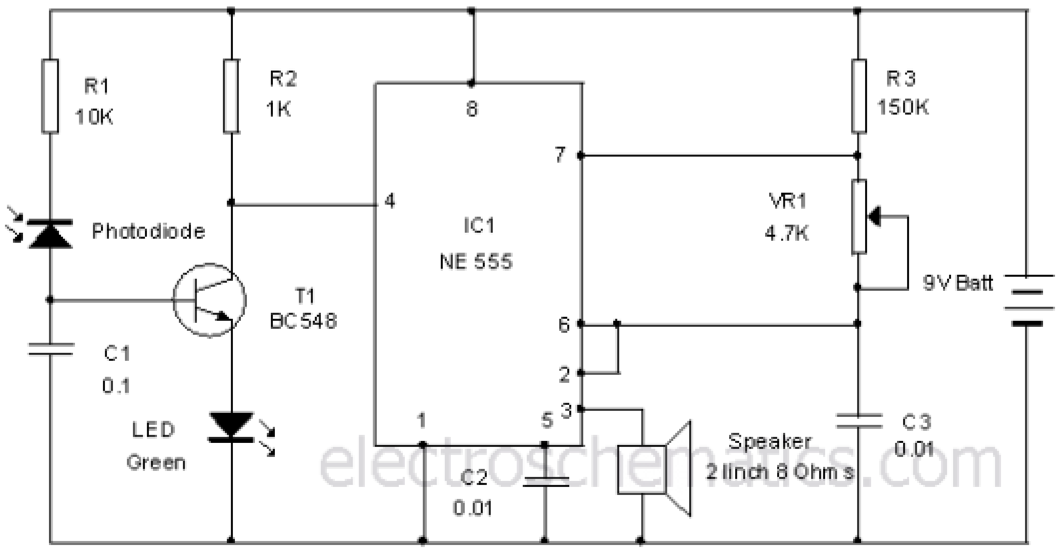




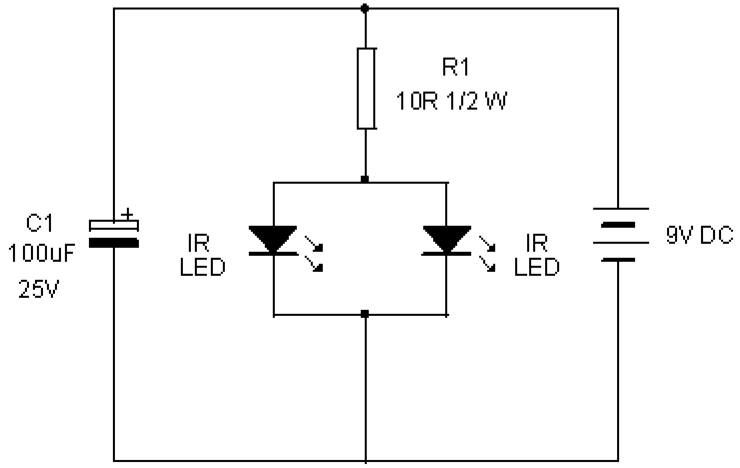
$$R_R = \frac{V_R}{I_\lambda}$$

Alarm System using Photodiode

Photodiode Alarm Circuit

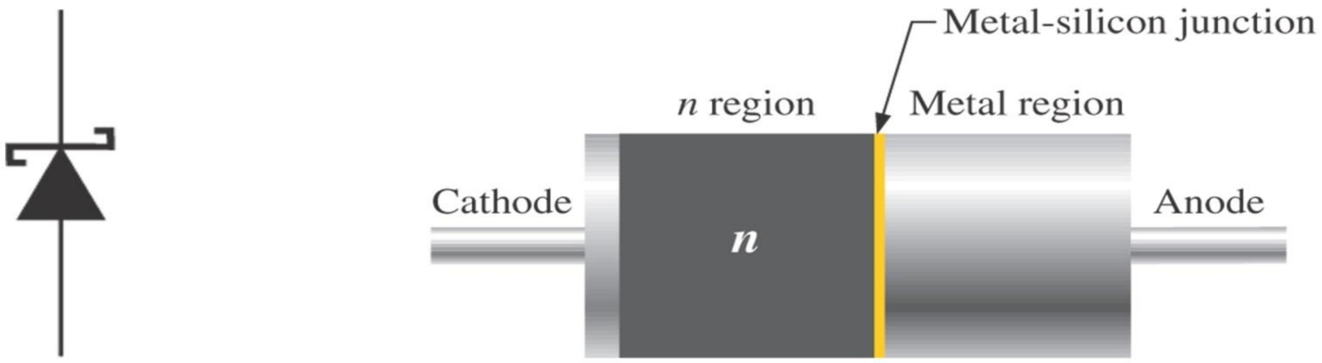


IR Transmitter Circuit



The Schottky Diode

- The Schottky diode's significant characteristic is its *fast switching speed*.
- This is useful for high frequencies and digital applications.
- It is not a typical diode in that it does not have a p-n junction.
- Instead, it consists of a doped semiconductor (usually n-type) and metal bound together.



Schottky diode (a) symbol and (b) basic internal construction

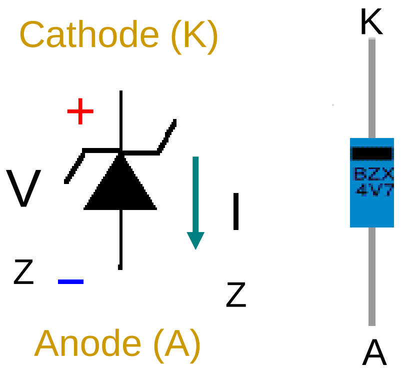
Zener Diode

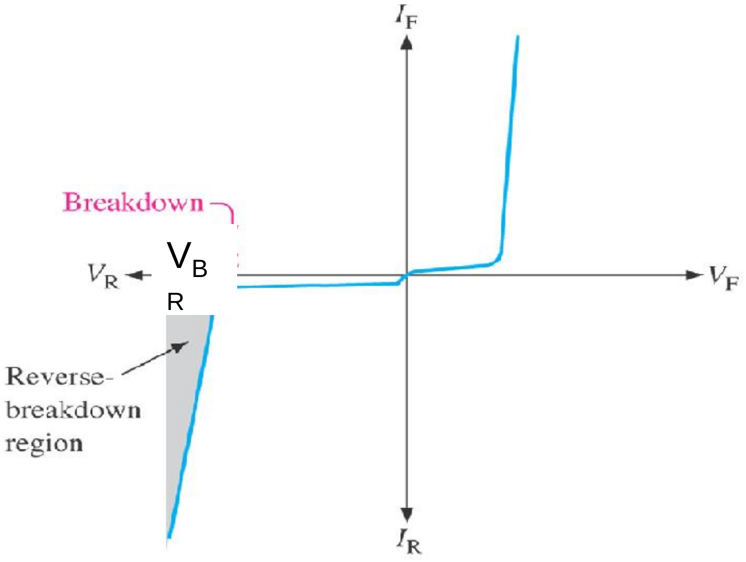
Zener diode is a p-n junction diode that is designed to operate in the *reverse breakdown region.*

Two things happen when the reverse breakdown voltage (V_{BR}) is reached:

- The diode current increases drastically.
- The reverse voltage (V_R) across the diode remains relatively constant.

In other words, the voltage across a zener diode operated in this region is *relatively constant* over a range of reverse current and *nearly equal to* its zener voltage (V_Z) rating.

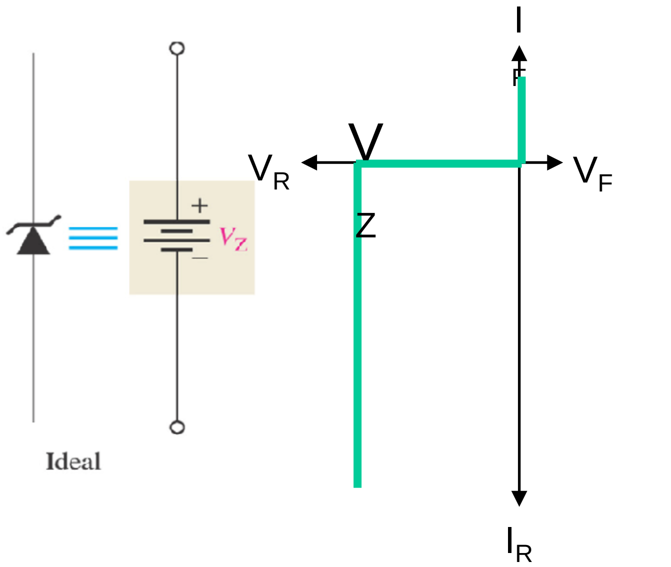




Zener diode voltage-curent (V-I) characteristic.

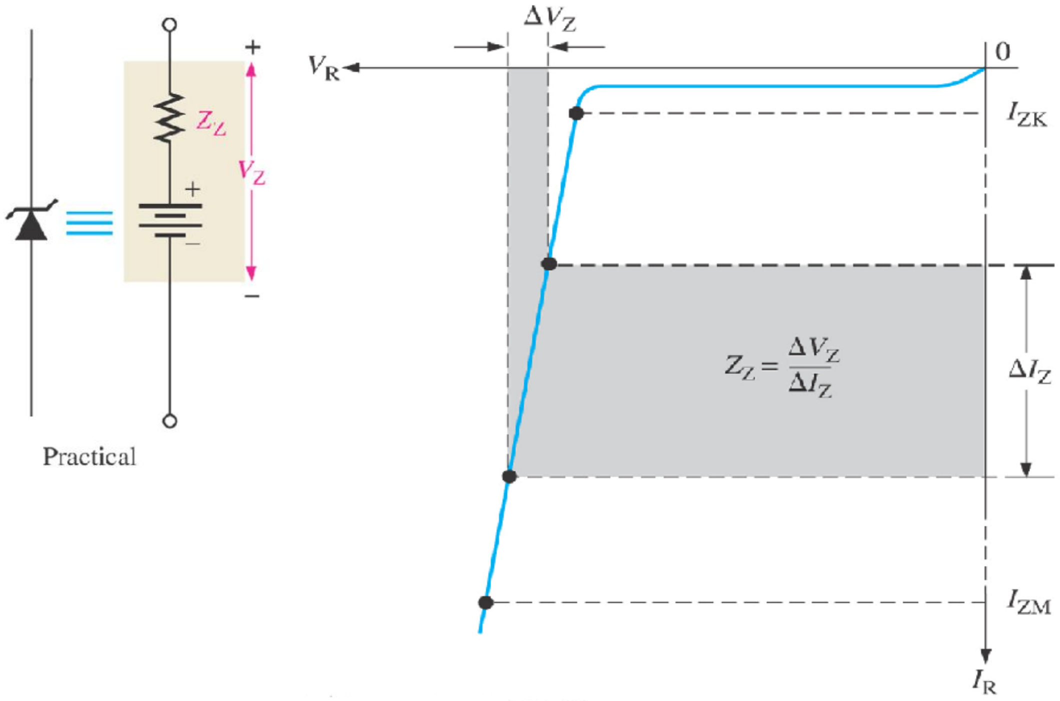
Zener Diode

Ideal-and-Practical Zener Equivalent Circuits



Ideal model and characteristic curve of a zener diode in reverse breakdown.

The constant voltage drop = the nominal zener voltage.



Practical model and characteristic curve of a zener diode, where the zener impedance (resistance), Z_Z is included.

A change in zener current (ΔI_Z) produces a small change in zener voltage (ΔV_Z).

Varactor (Varicap Diode)

Varactor is a type of p-n junction diode that operates in reverse bias. The capacitance of the junction is controlled by the amount of reverse bias.
Varactor diodes are also referred to as *varicaps* or *tuning diodes* and they are commonly used in communication systems.

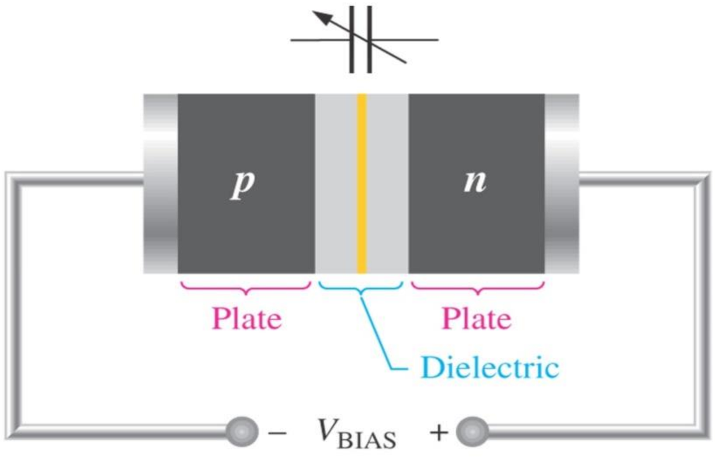
Varactor diode symbol

Basic Operation

The capacitance of a reverse-biased varactor junction is found as:

$$C = \frac{A\varepsilon}{d}$$

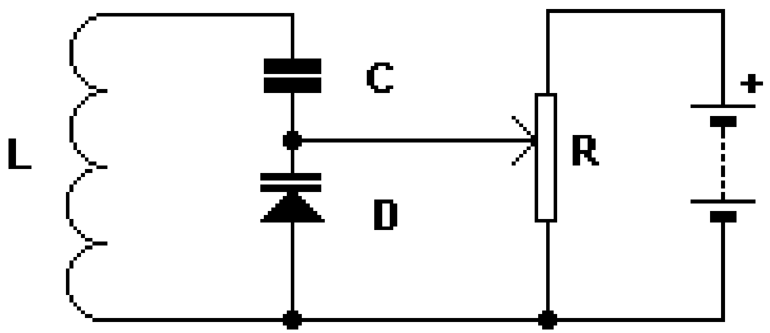
C = the total junction capacitance.
A = the plate area.
ε = the dielectric constant (permittivity).
d = the width of the depletion region (plate separation).



Reverse-biased varactor diode acts as a variable capacitor.

Varactor (Varicap Diode)

When the junction diode is reverse biased, the insulating barrier widens reducing diode capacitance.



The barrier forms the dielectric, of variable width, of a capacitor.

The N and P type cathode and anode are the two plates of the capacitor. In the diagram, the diode and coil form a resonant circuit.

The capacitance of the diode, and thereby the resonant frequency, is varied by means of the potentiometer controlling the reverse voltage across the varicap.

The capacitor prevents the coil shorting out the voltage across the potentiometer.

Summary (1)

- Rectifiers convert ac voltage into unipolar voltages. Half-wave rectifiers do this by passing the voltage in half of each cycle and blocking the opposite-polarity voltage in the other half of the cycle.
- The bridge-rectifier circuit is the preferred full-wave rectifier configuration.

Summary (2)

- The variation of the output waveform of the rectifier is reduced considerably by connecting a capacitor *C* across the output load resistance *R*. The resulting circuit is the peak rectifier. The output waveform then consists of a dc voltage almost equal to the peak of the input sine wave, V_p, on which is superimposed a ripple component of frequency $2f$ (in the full-wave case) and of peak-to-peak amplitude $V_r = V_p/2fRC$.

Summary (3)

- Combination of diodes, resistors, and possible reference voltage can be used to design voltage limiters that prevent one or both extremities of the output waveform from going beyond predetermined values – the limiting levels.
- Applying a time-varying waveform to a circuit consisting of a capacitor in series with a diode and taking the output across the diode provides a clamping function.
- By cascading a clamping circuit with a peak-rectifier circuit, a voltage doubler is realized.

Summary (4)

- Beyond a certain value of reverse voltage (that depends on the diode itself), breakdown occurs and current increases rapidly with a small corresponding increase in voltage.
- Diodes designed to operate in the breakdown region are called zener diodes. They are employed in the design of voltage regulators whose function is to provide a constant dc voltage that varies little with variations in power supply voltage and / or load current.

Unit 2 – Transistors

- Review of the physical principles of operation of semiconductor devices.
- Thermal management in power semiconductor devices.
- Power diodes.
- Power MOSFETs.
- ***The IGBT.***
- High-power, low-frequency semiconductor devices (thyristors).

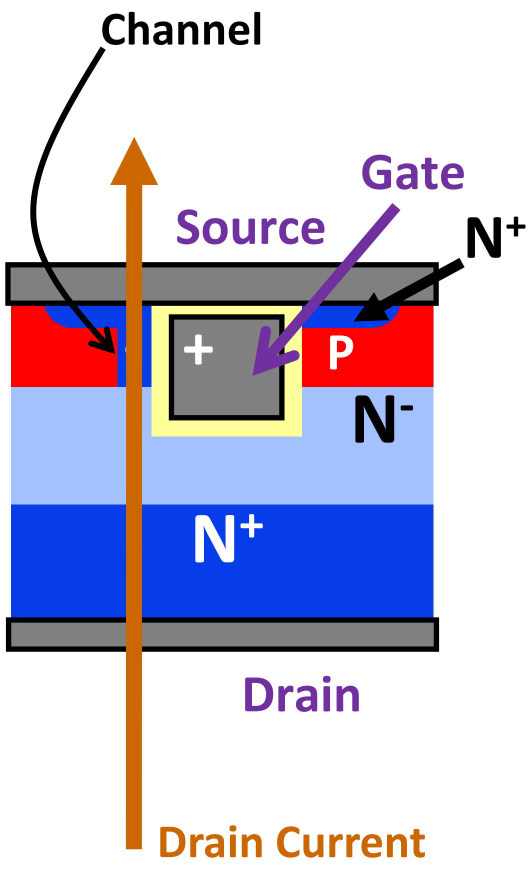
The Insulated Gate Bipolar Transistor (IGBT).

Outline

- The main topics to be addressed in this lesson are the following:
  - **Introduction.**
  - **Review of the basic structure and operation of bipolar junction transistors (BJTs).**
  - **Internal structures of IGBTs.**
  - **Static characteristics of the IGBTs.**
  - **Dynamic characteristics of the IGBTs.**
  - **Losses in the IGBTs.**

Introduction (I).

- Power MOSFETs are excellent power devices to be used in power converters up to a few kWs.
- They have good switching characteristics because they are unipolar devices.
- This means that the current is due to majority carriers exclusively and that it does not pass through any PN junction.
- Due to this, conductivity modulation does not take place.
- This fact limits the use of these devices for high power applications, because high-voltage devices exhibit high $R_{DS(ON)}$ values.
- The challenge is to have a device almost as fast as a MOSFET, as easy to control as a MOSFET, but with conductivity modulation.



Introduction (II).

• On the other hand, Bipolar Junction Transistors (BJTs) are devices in which the current passes through two PN junctions.

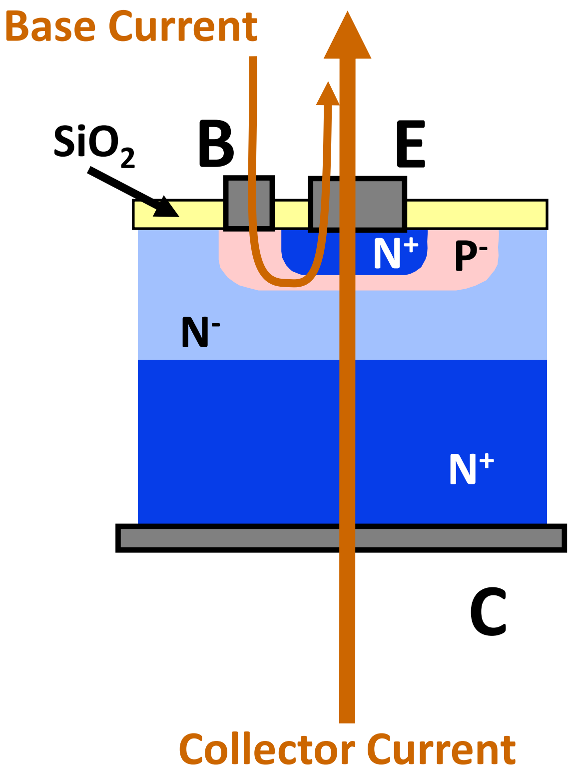
• Although the current is due to the emitter majority carriers, these carriers are minority carriers in the base. Therefore, the switching process strongly depends on the minority base carriers.

• Due to this, BJTs (bipolar devices) are slower than MOSFETs (unipolar devices).

• Moreover, the control current (base current) is quite high (only 5 -20 times lower than the collector current) in power BJTs.

• However, as the collector current in BJTs passes through two PN junctions, they can be designed to have conductivity modulation.

• As a consequence, BJTs have superior characteristics in on-state than MOSFETs.



Introduction (III).

- **Summary of a comparison between BJTs and MOSFETs**

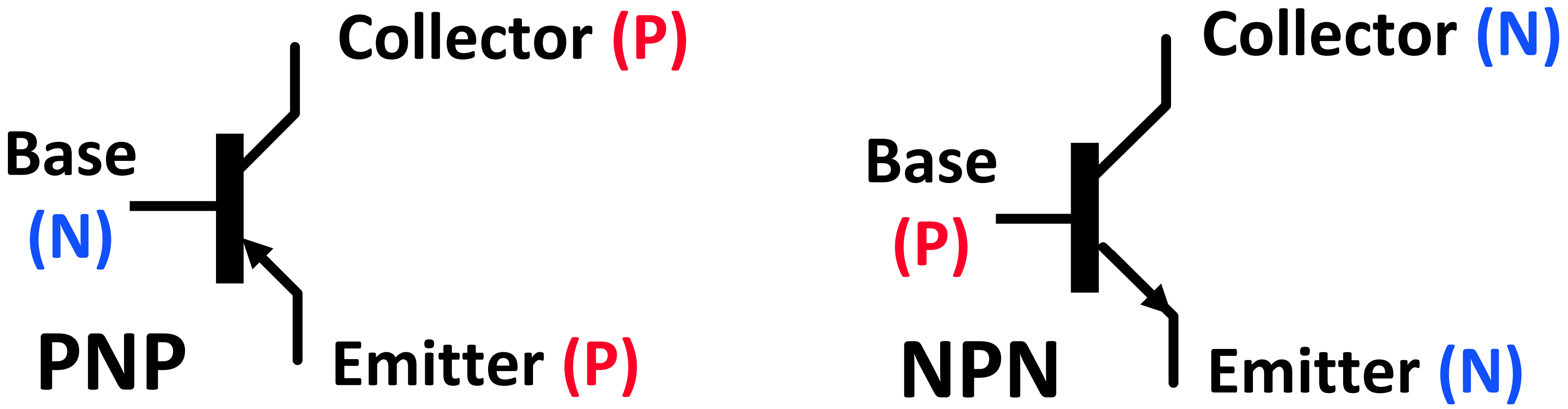
	Switching	Control	Conductivity modulation	Losses in on-state in high voltage devices
BJT	Slow	Difficult	Yes	Low
MOSFET	Fast	Easy	No	High

- **Could we have the advantages of both types of devices together in a different device?**
- **The answer is that we can design a different device with almost all the advantages of both BJTs and MOSFETs for medium and high voltage (from several hundreds of volts to several thousand of volts).**
- **This device is the IGBT (the Insulated Gate Bipolar Transistor).**
- **To understand its operation, we must review the structure and operation of the BJT.**

Review of the basics of BJTs (I).

PNP transistor: **Two P-type regions and a N-type region**

NPN transistor: **Two N-type regions and a P-type region**

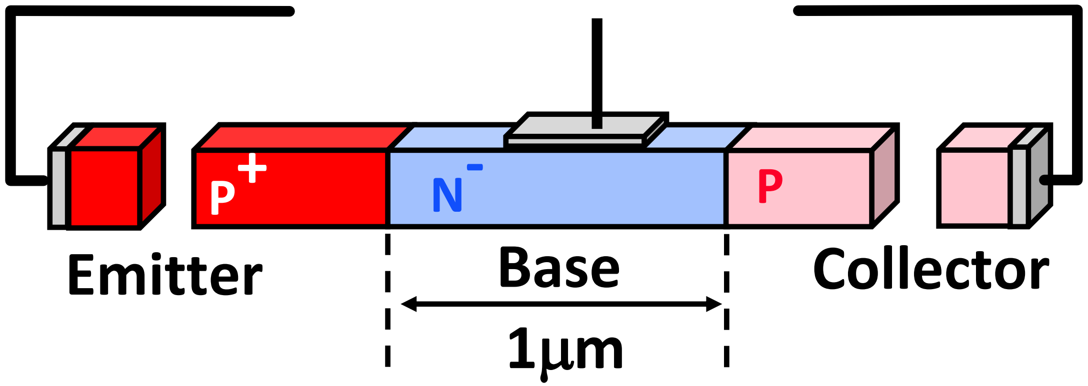


Conditions for such device to be a transistor:

- **The emitter region must be much more doped than the base region.**
- **The base region must be a narrow region (narrower than the diffusion length corresponding to the base minority carrier).**

Review of the basics of BJTs (II).

- **Example: a PNP-type silicon low-power transistor**
  (the actual geometry is quite different)



- **The emitter region must be much more doped than the base region.**

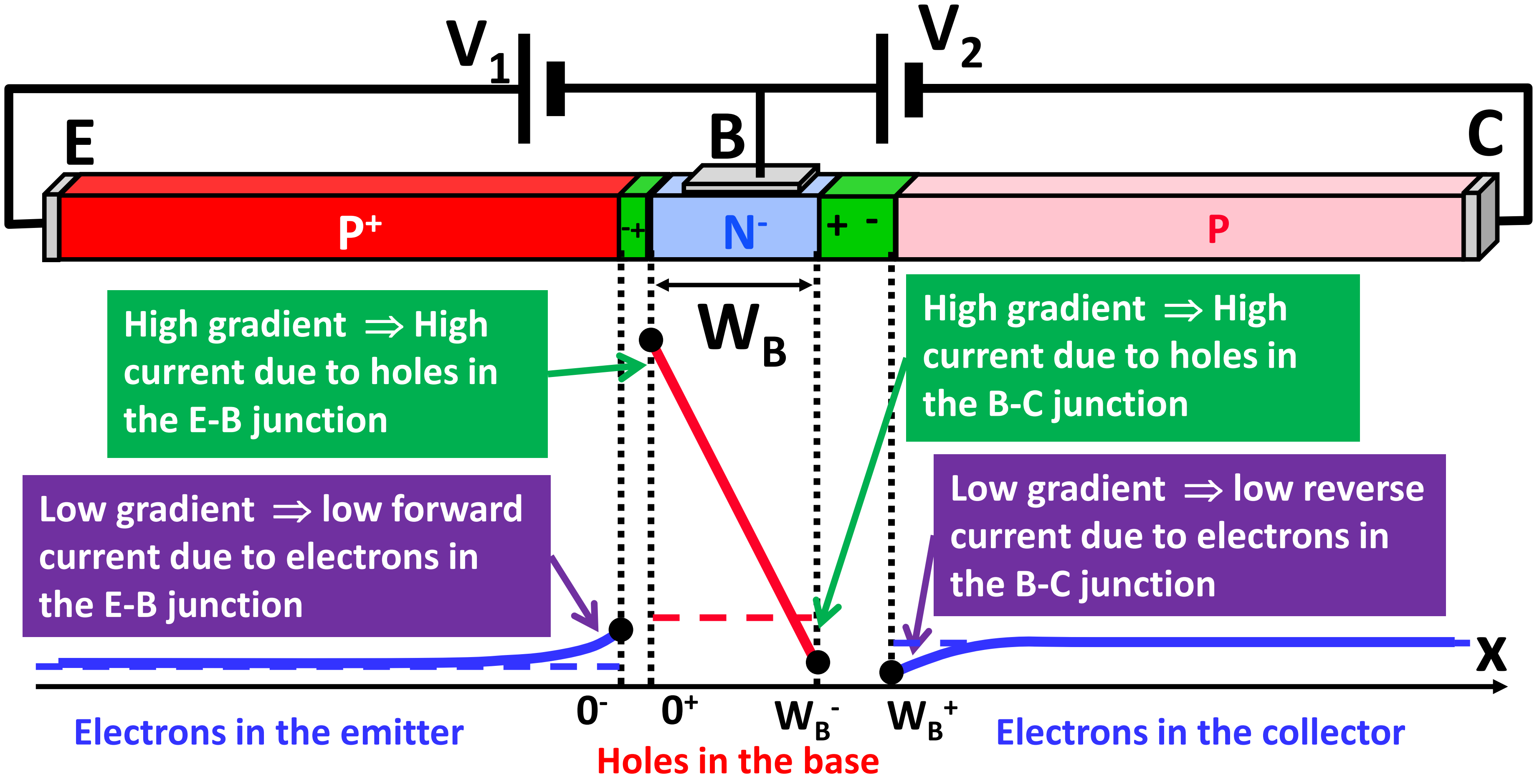
$N_{AE}=10^{15}$ atm/cm^3 **$N_{DB}=10^{13}$ atm/cm^3**

- **The base region must be narrower than the diffusion length corresponding to the holes in the base region.**

$$W_B = 1\ \mu m \ll L_p = 10\ \mu m$$

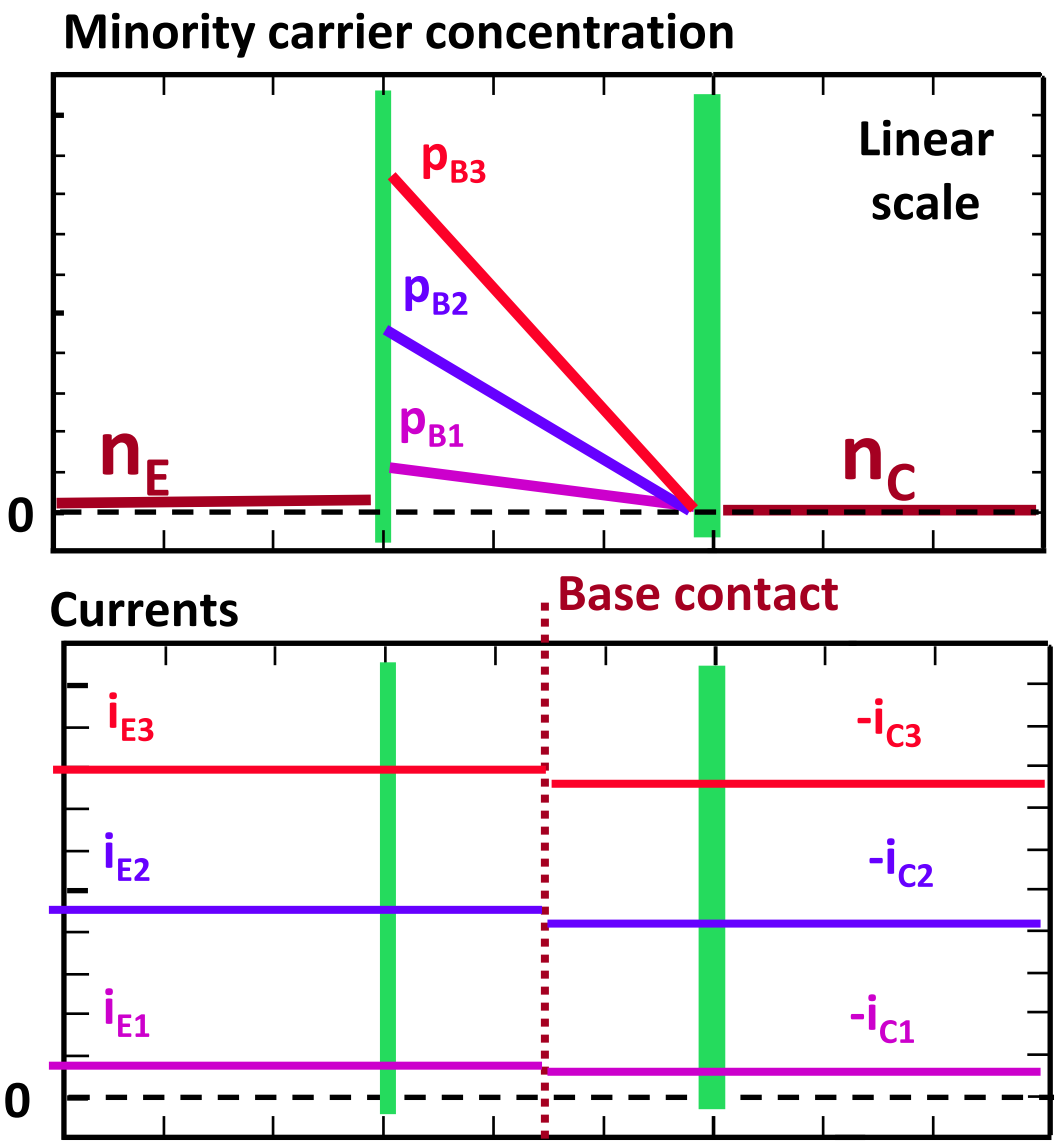
Review of the basics of BJTs (III).

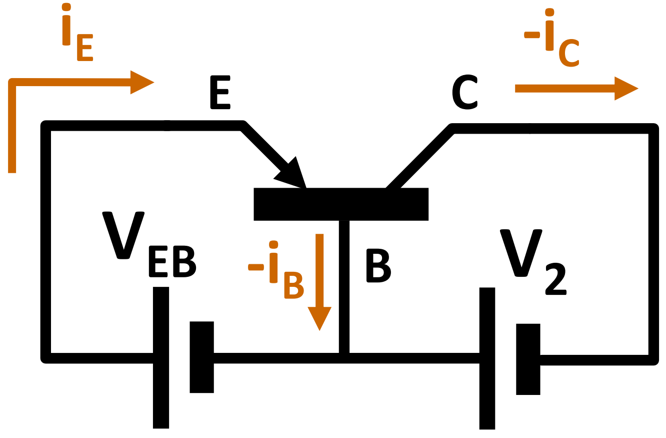
- **Operation in active region: E-B junction is forward biased and B-C junction is reverse biased.**
- **The concentration of minority carries when the junctions have been biased can be easily deduced form slide #80, Lesson 1.**



Review of the basics of BJTs (IV).

• **Currents passing through the transistor in active region.**





$V_{EB1} < V_{EB2} < V_{EB3}$

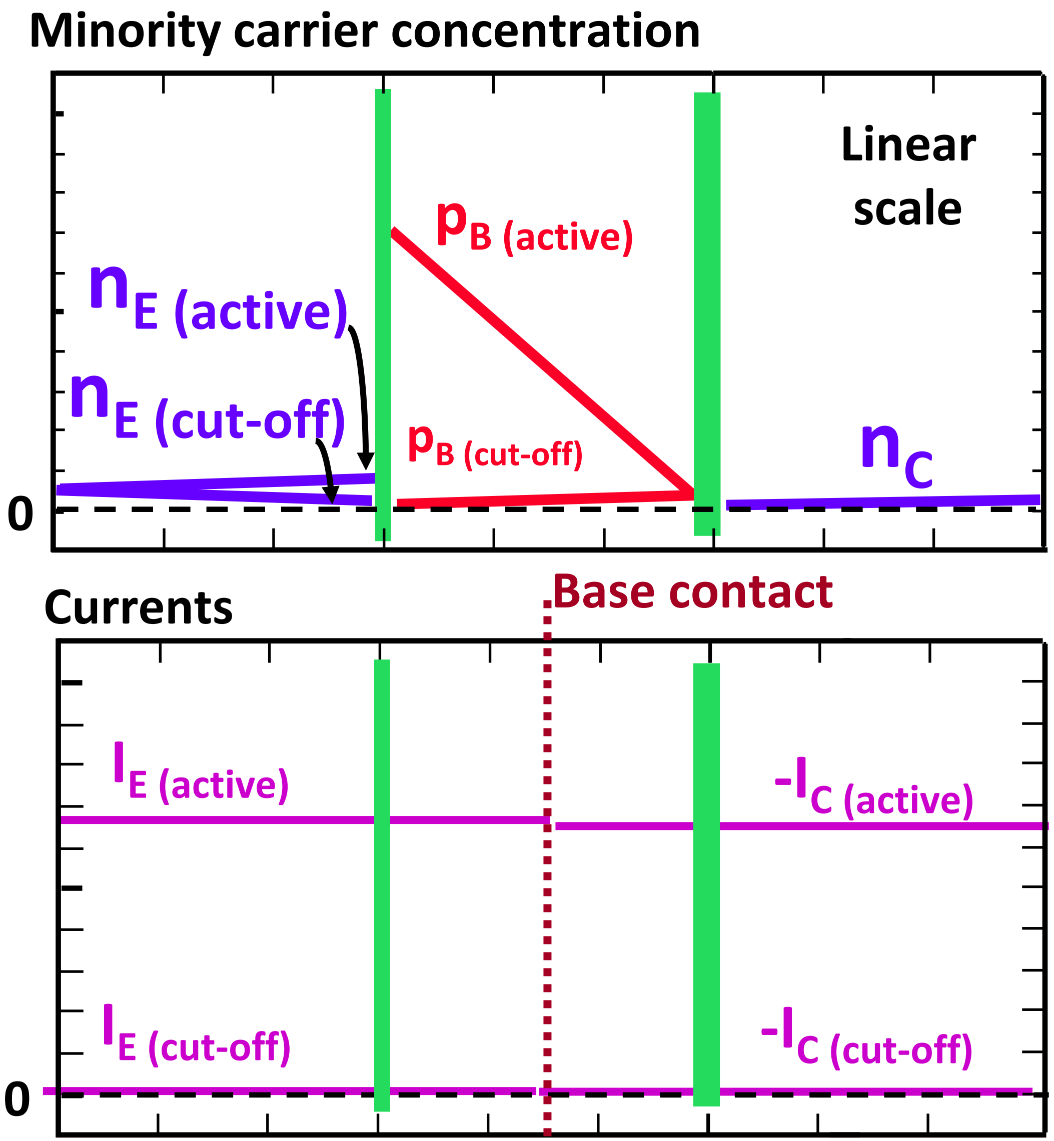
$i_E \approx I_S \cdot e^{v_{EB}/V_T}$

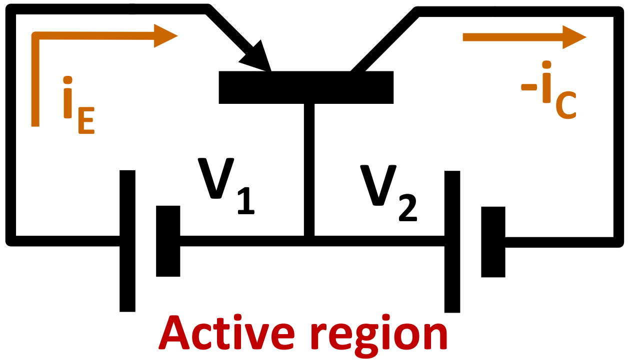
$-i_C \approx i_E \cdot \alpha$ ($\alpha \approx 0.98\text{-}0.995$)

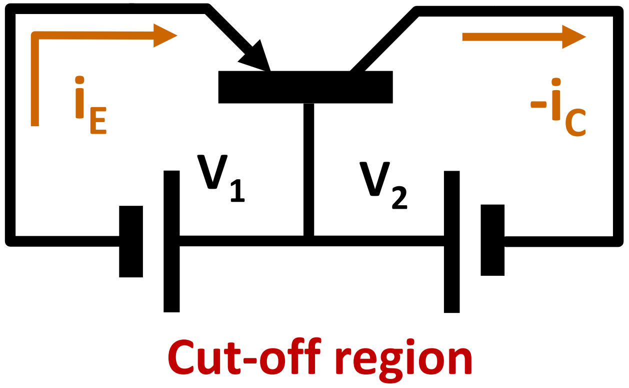
$i_C \approx \beta \cdot i_B$ ($\beta \approx 20\text{-}200$)

Review of the basics of BJTs (V).

- **Operation in cut-off region: E-B and B-C junctions are reverse biased.**

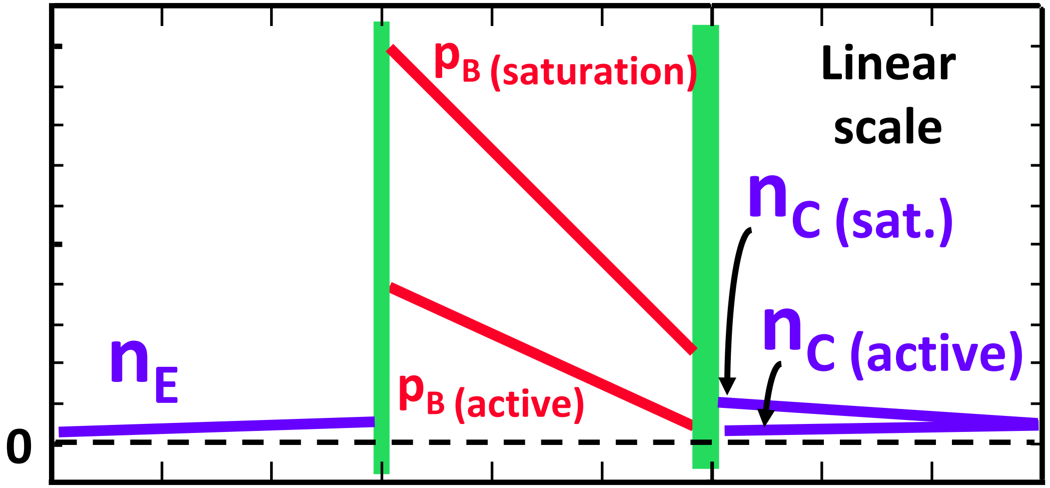




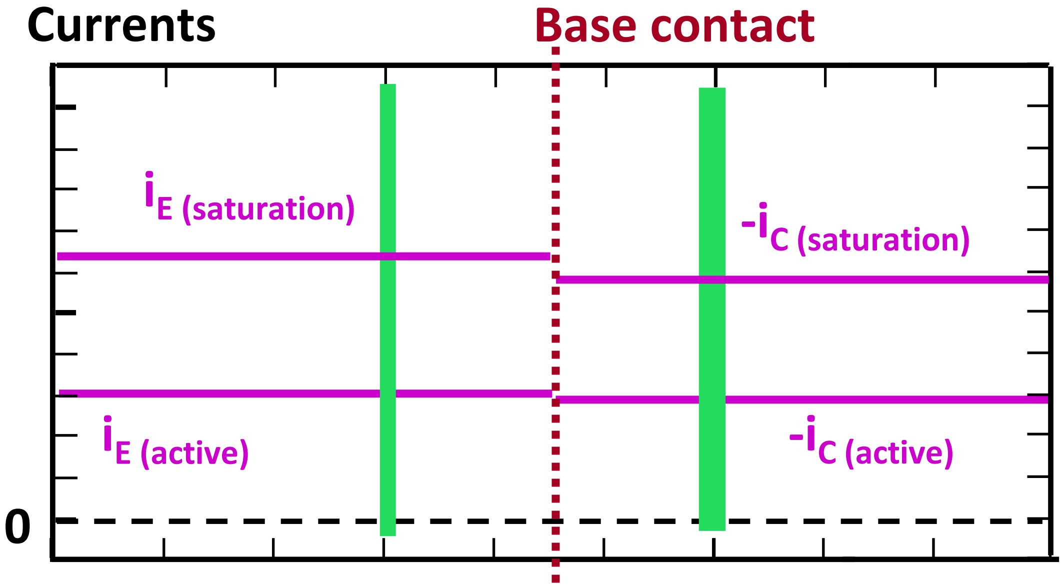


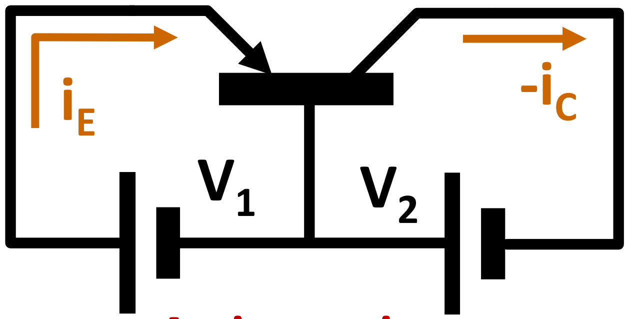
- **Operation in saturation region: E-B and B-C junctions forward biased.**

Minority carrier concentration

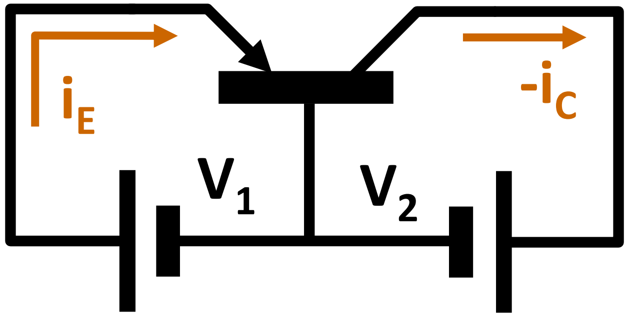


Currents





Active region

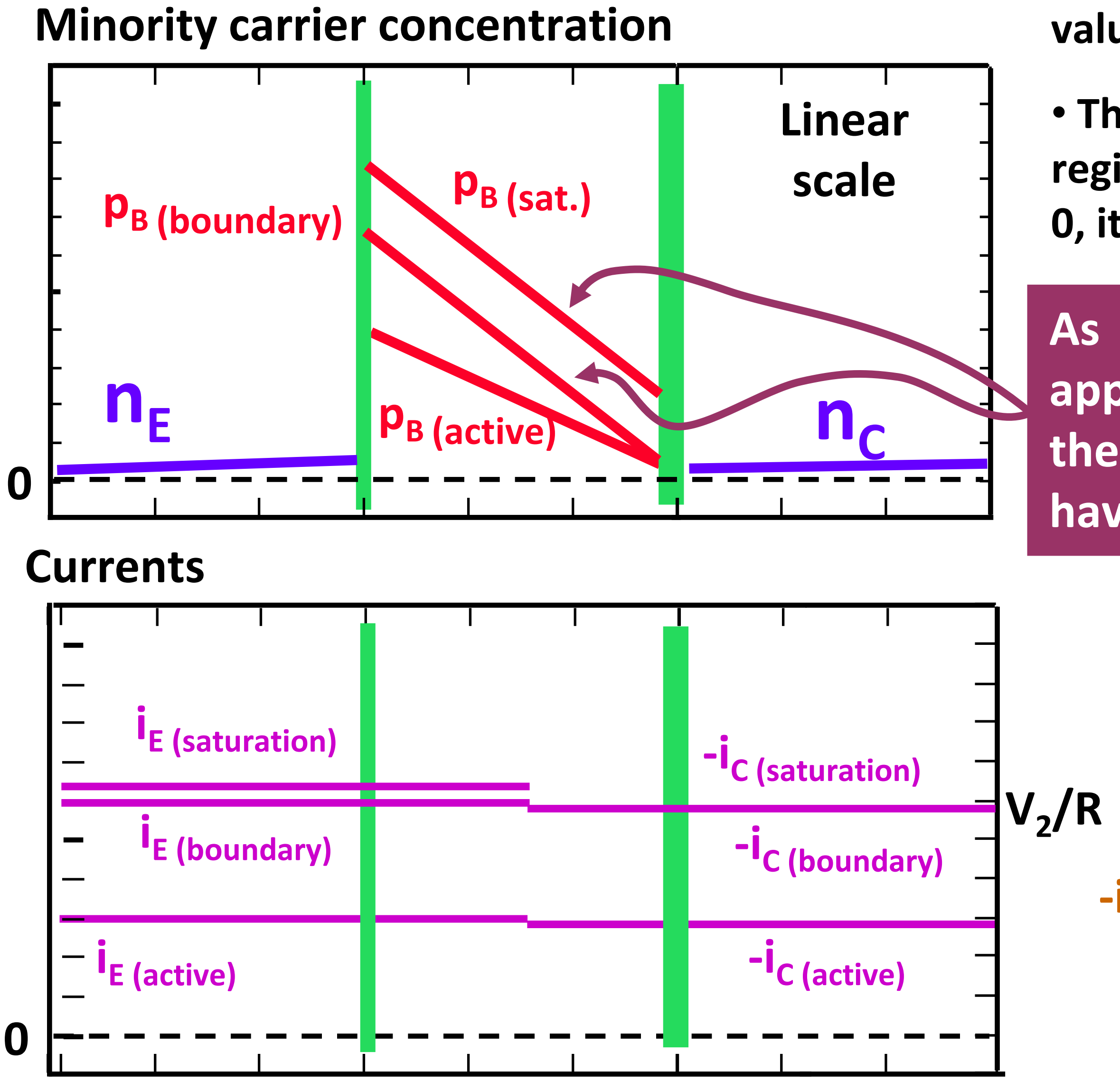


Saturation region

- **However, the operation in saturation usually takes place in other type of circuits.**

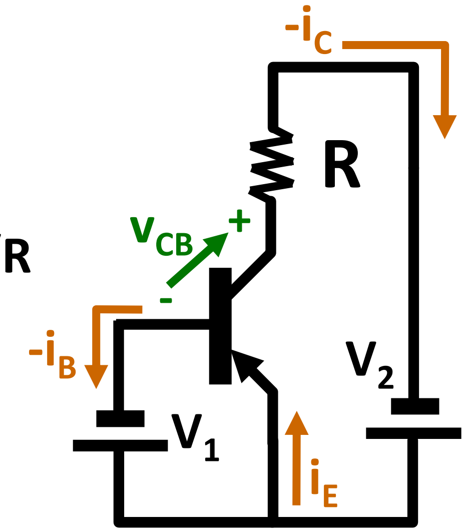
Review of the basics of BJTs (VII).

- **Usual circuit to study the saturation region.**



- **We are going to increase the value of V_1.**
- **The transistor will be in active region while $v_{CB} < 0$. When $v_{CB} > 0$, it is in saturation.**

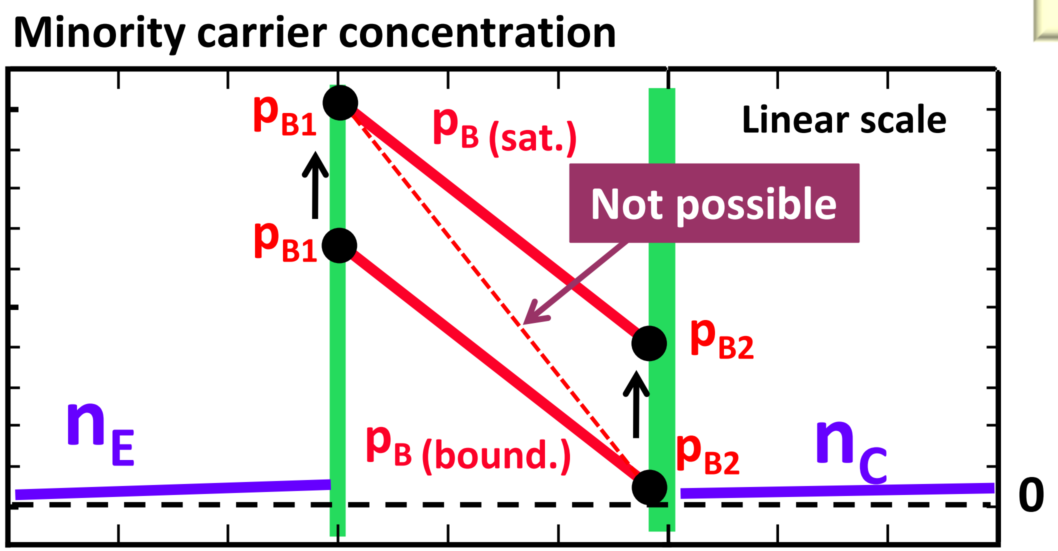
As the collector current is approximately constant, these concentration profiles have the same slope.

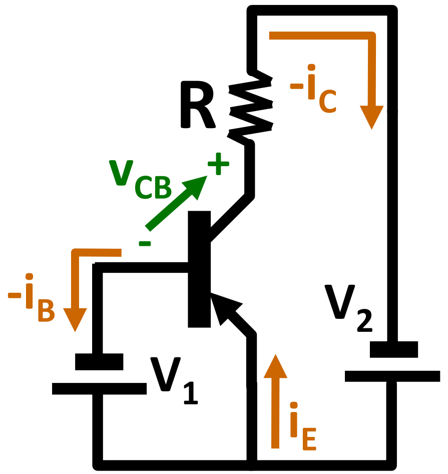


Review of the basics of BJTs (VIII). Very important!!!

- We can increase the height of point p_{B1} as much as we want, because we can increase V_1 indefinitely.
- However, the collector current (≈ emitter current) is limited to the maximum possible value of V_2/R (otherwise, the transistor would behave as a power generator, which means that energy is generated from nothing).
- As the current passing through the transistor (from emitter to collector) is limited, then the slope of p_B is also limited.
- As a consequence, p_{B2} must also increase to maintain the current constant, which implies that the base-collector junction becomes forward bias.

The transistor becomes saturated.

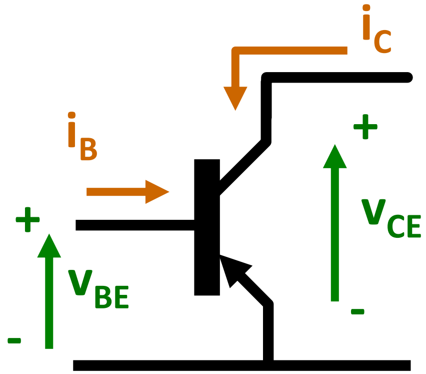




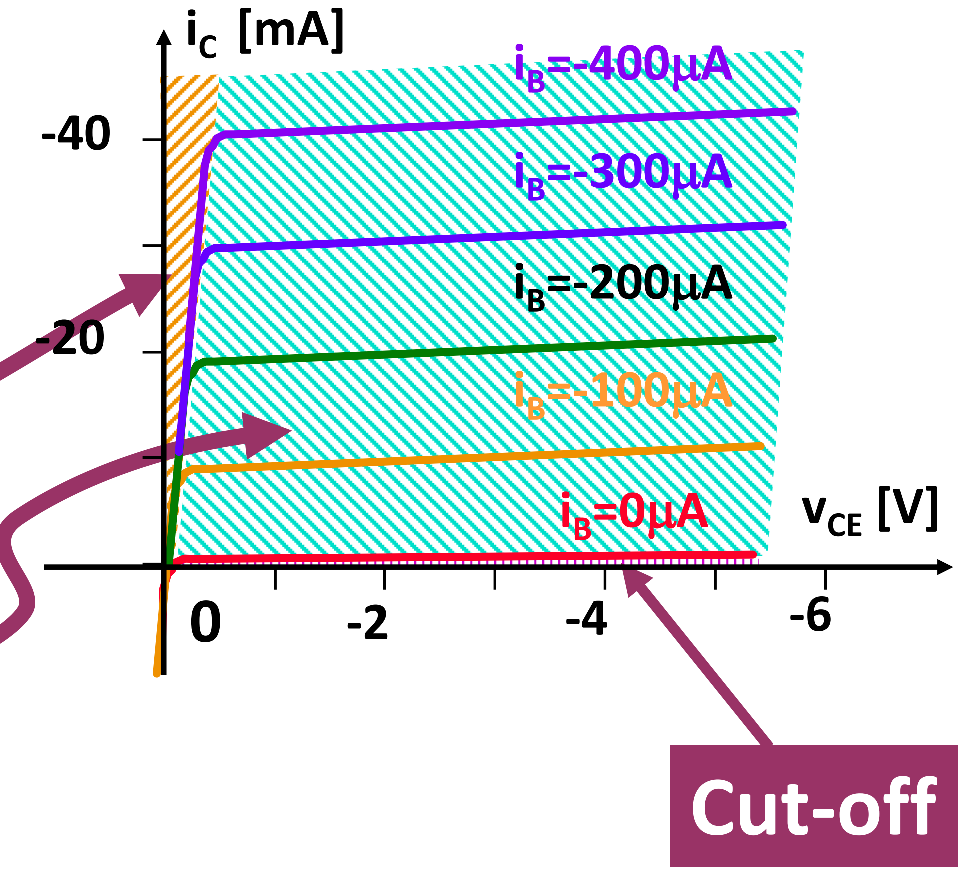
Review of the basics of BJTs (IX).

- **Output characteristic curves.**

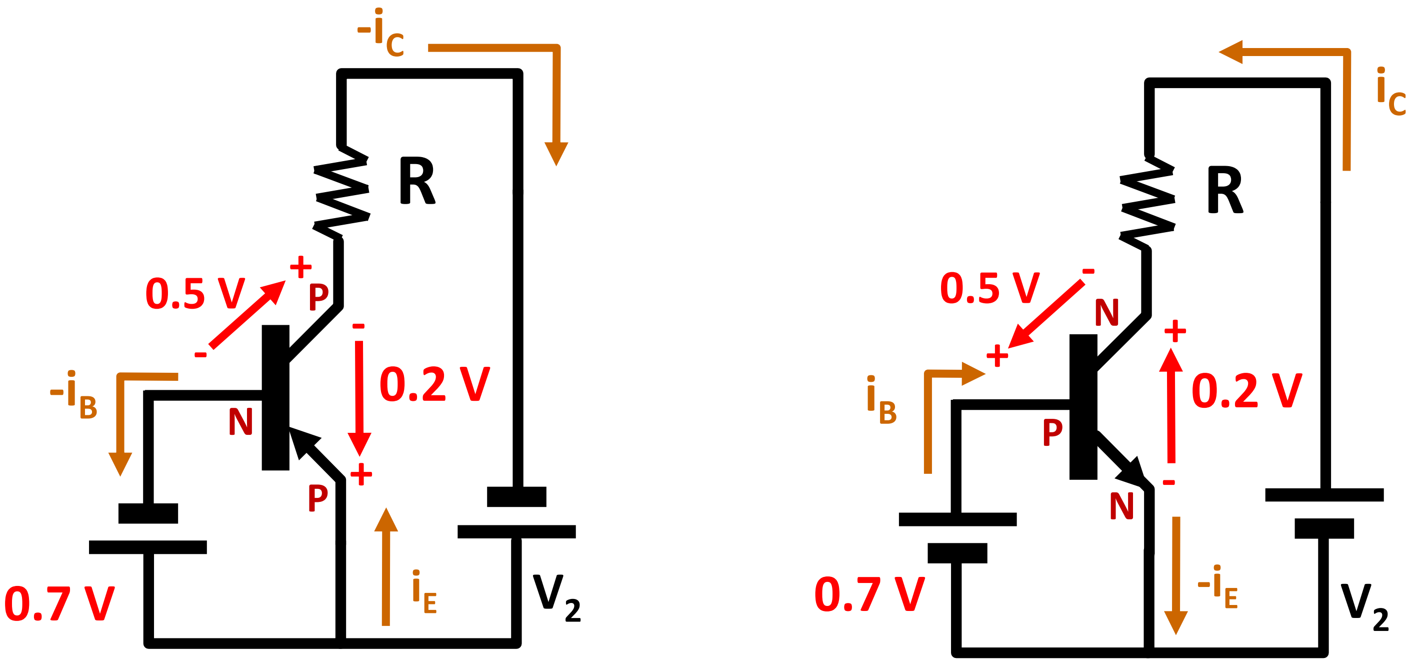
Voltage and current references



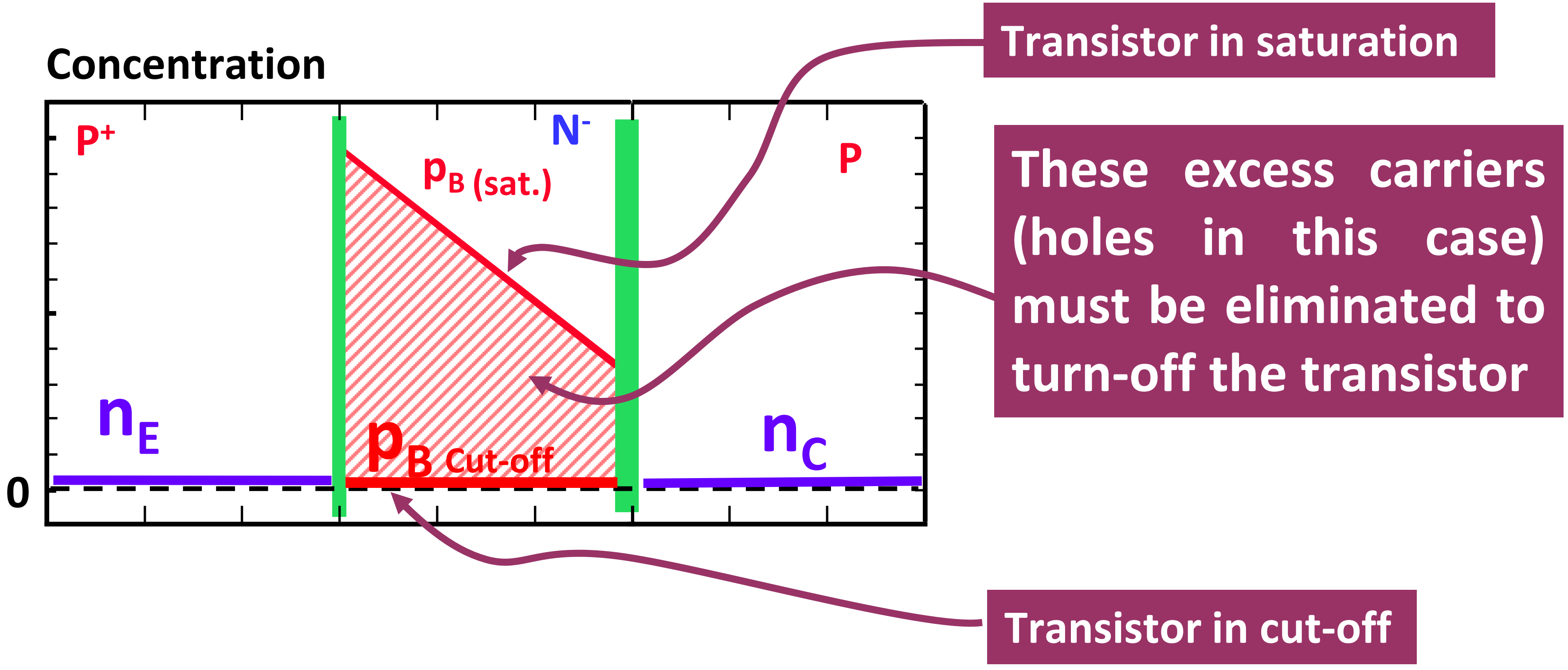
Output curves



- **The on-state of bipolar transistors is quite good, because the voltage drop between collector and emitter is quite low.**
- **However, the turn-off is quite slow (next slide).**

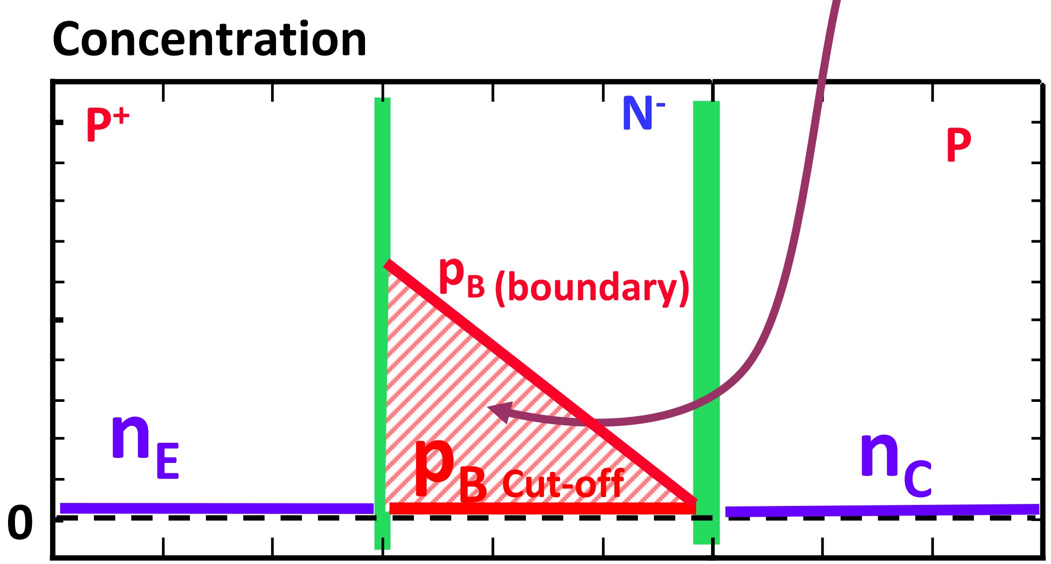


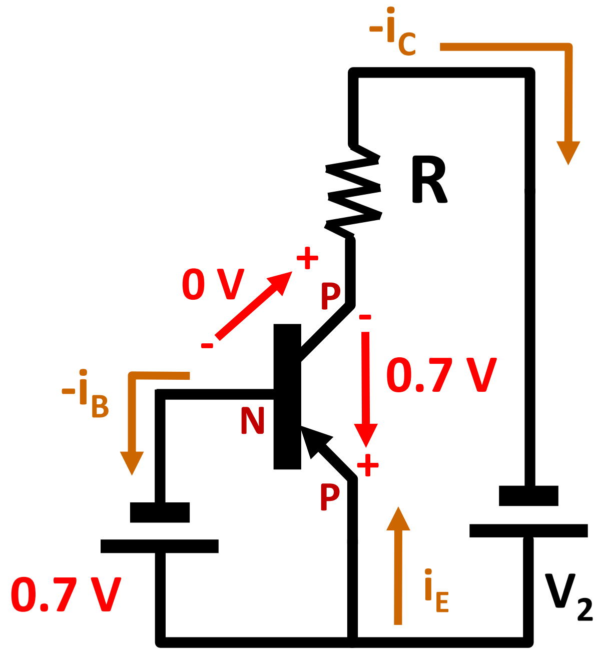
• **The longest time in the switching process of a bipolar transistor is the one corresponding to eliminating the excess of minority carriers in the base region when the transistor turns-off.**



- **A good trade-off between switching speed and voltage drop in on-state can be reached using anti-saturation circuitry (circuits to maintain the transistor just in the boundary between active region and saturation).**

Excess carriers to be eliminated when the transistor turns-off (lower than in saturation).

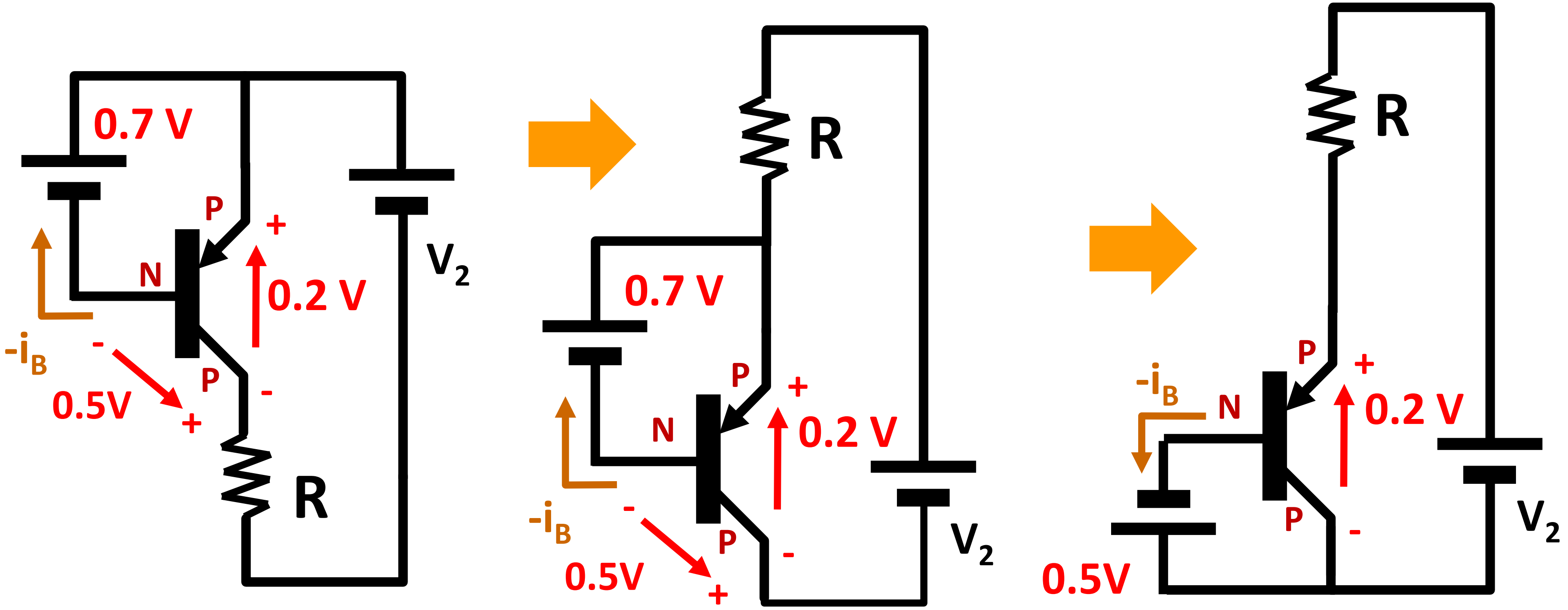




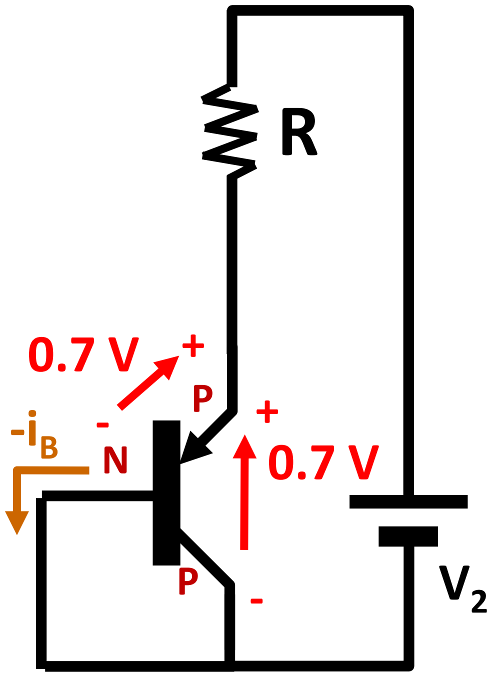
Voltages just in the boundary between active region and saturation

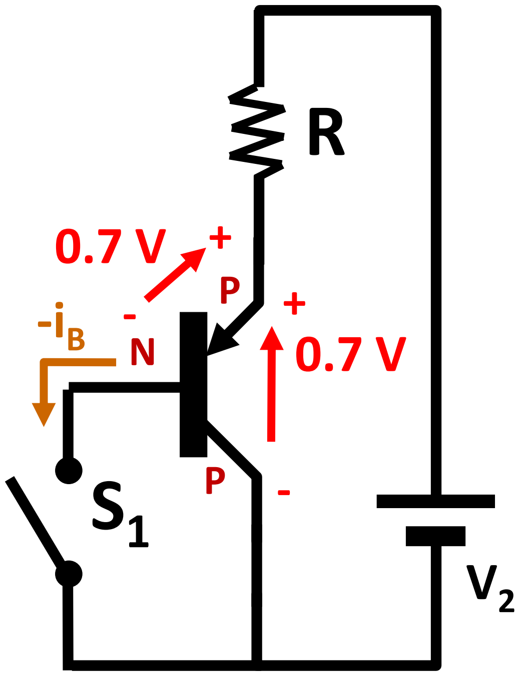
- **Hard-saturation circuits**

(the voltage across the transistor terminals is the same).



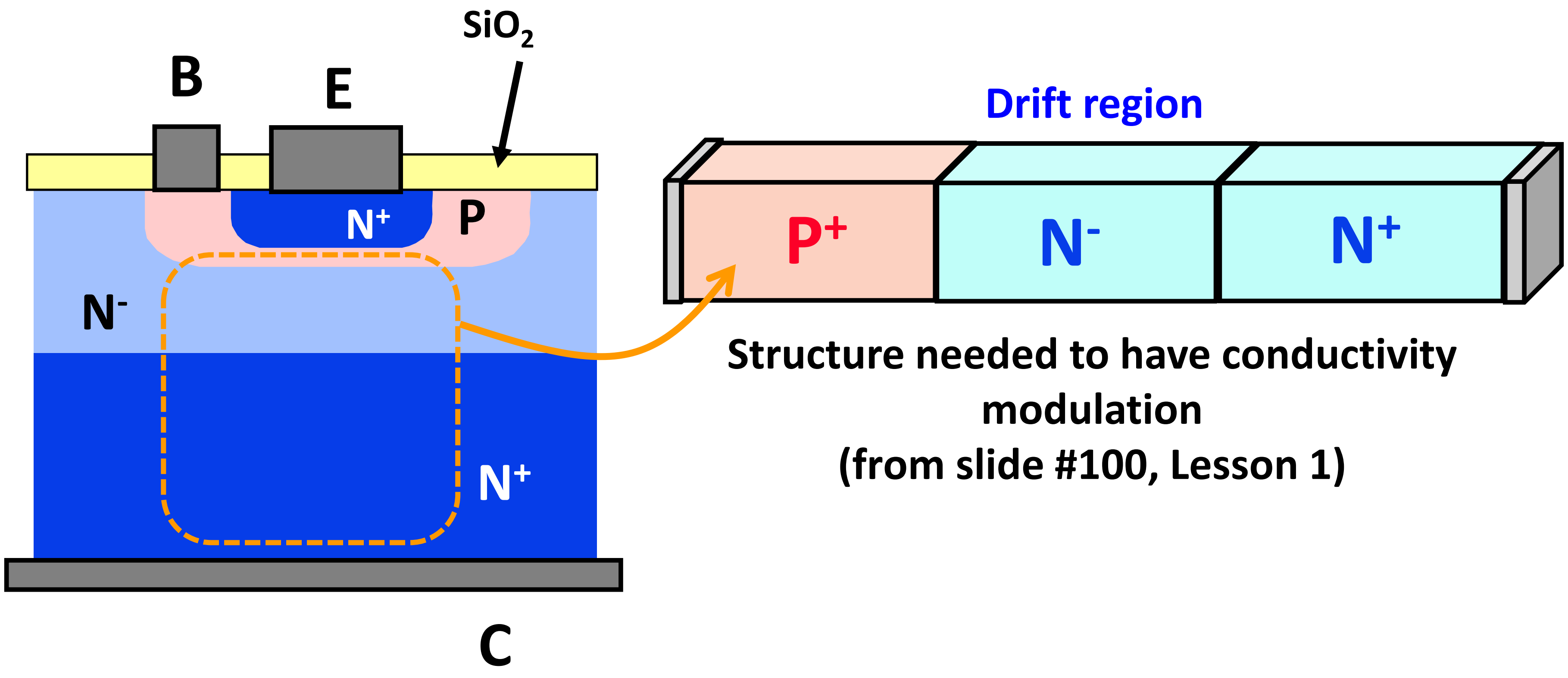
- **Soft-saturation circuit (anti-saturation circuit).**





- **In soft-saturation (boundary), when S_1 closed.**
- **In cut-off, when S_1 open.**

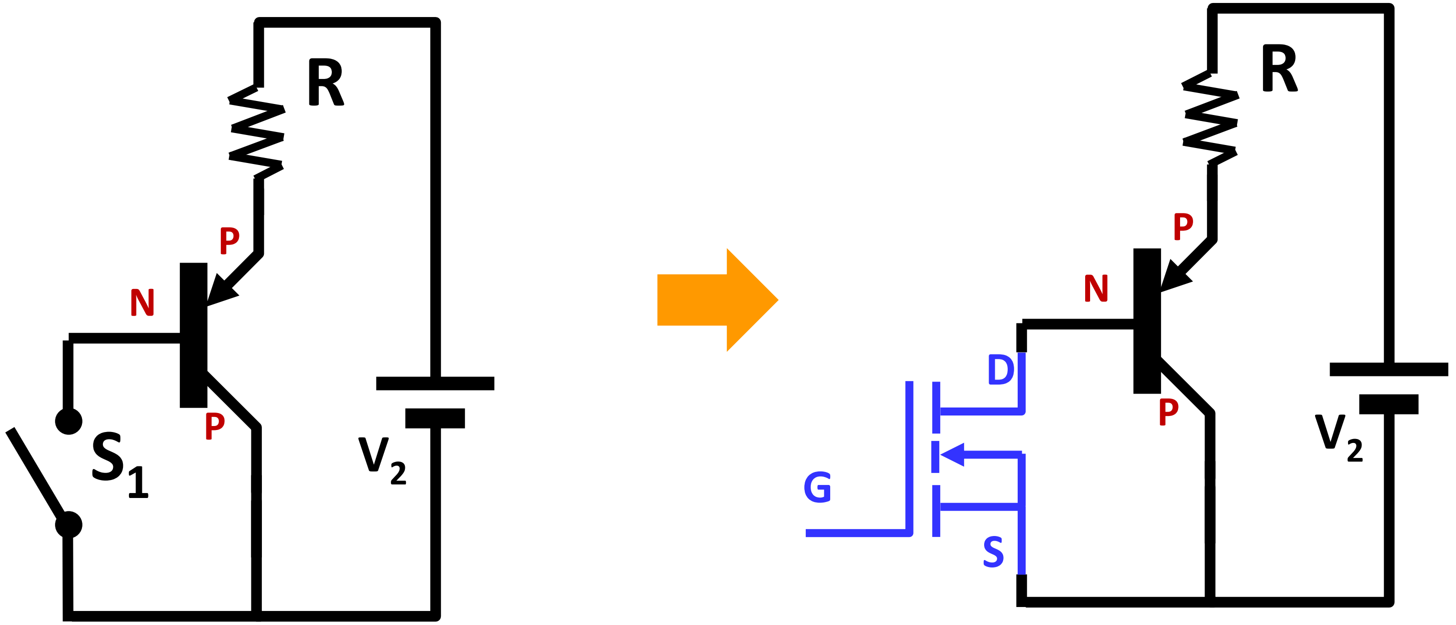
- **As a bipolar transistor is a "bipolar device", conductivity modulation can take place if the transistor is properly designed.**



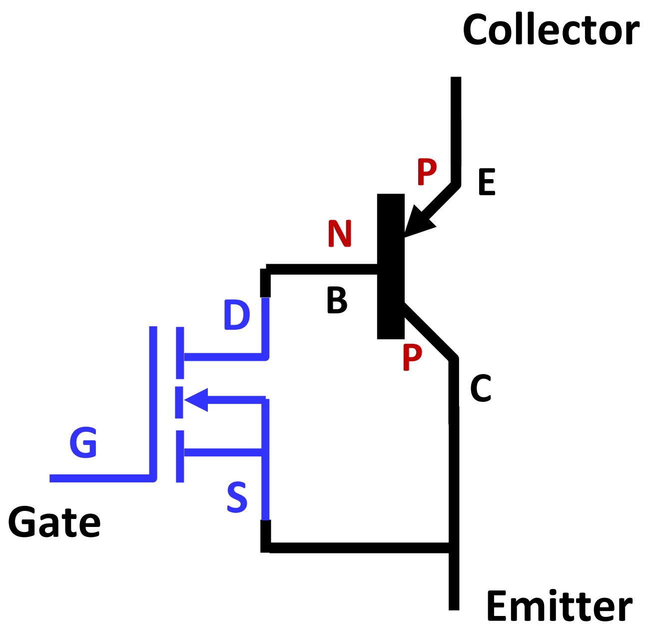
Structure needed to have conductivity modulation (from slide #100, Lesson 1)

Principle of operation and structure of the IGBT (I).

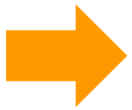
- **The IGBT (the Insulated Gate Bipolar Transistor) is based on a structure that allows:**
  - **Conductivity modulation (good behaviour for high voltage devices when they are in on-state).**
  - **Anti-saturation (not so slow switching process as in the case of complete saturation).**
  - **And control from an insulated gate (as in the case of a MOSFET).**

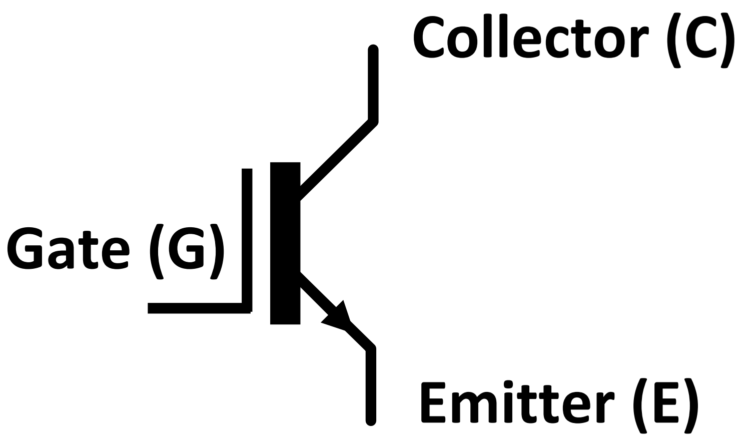


Principle of operation and structure of the IGBT (II).

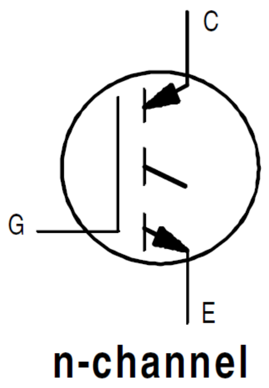


Simplified equivalent circuit for an IGBT.



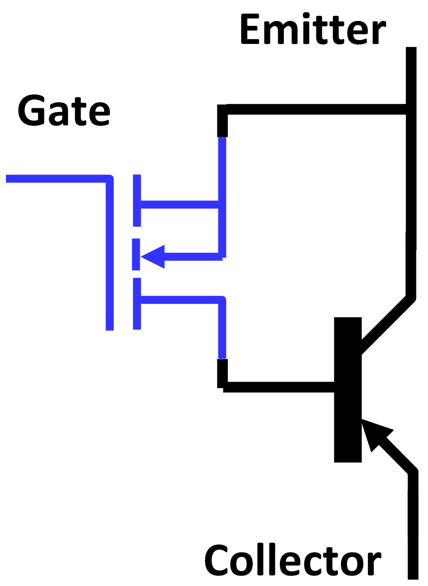


Schematic symbol for a N-channel IGBT.

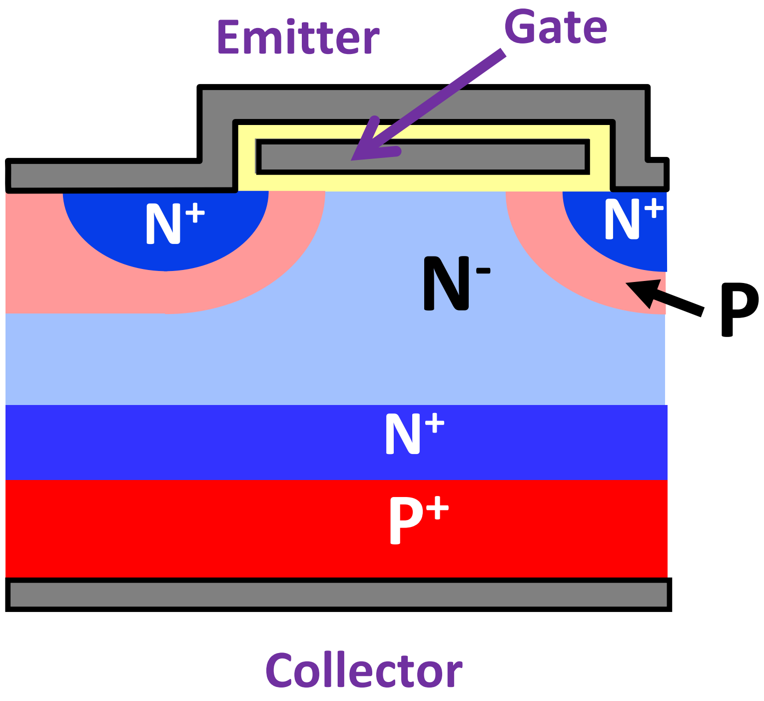


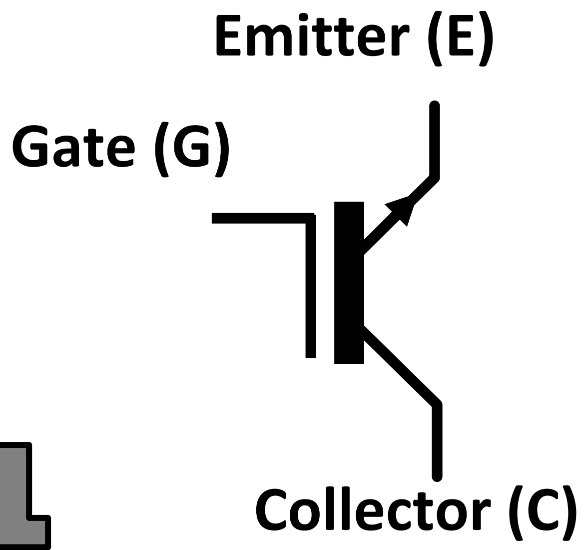
Another schematic symbol also used.

Principle of operation and structure of the IGBT (III).



- Internal structure (I).





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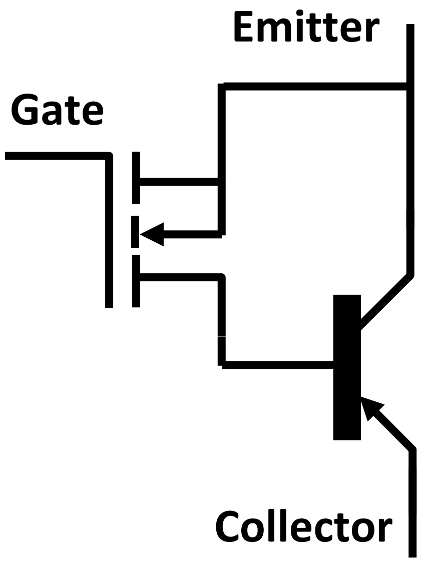
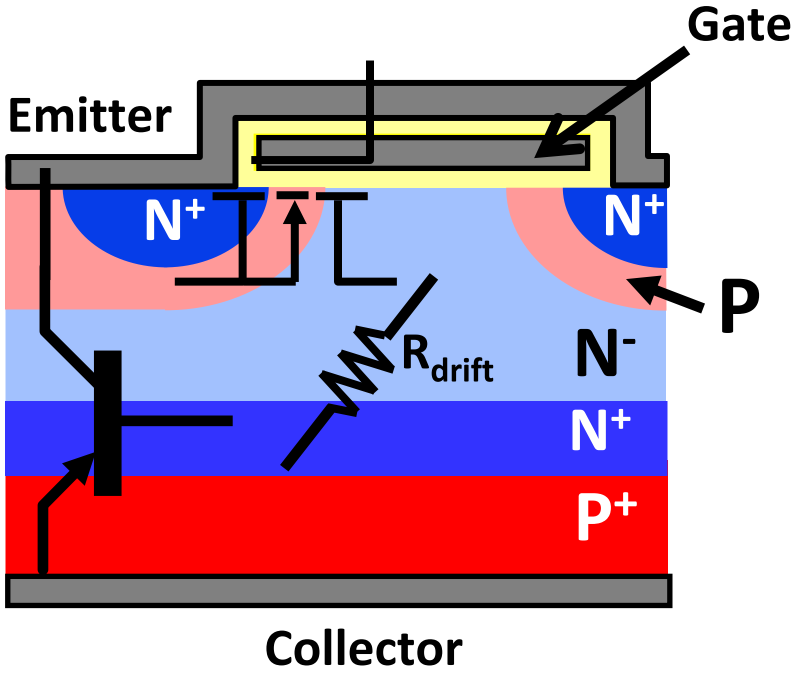
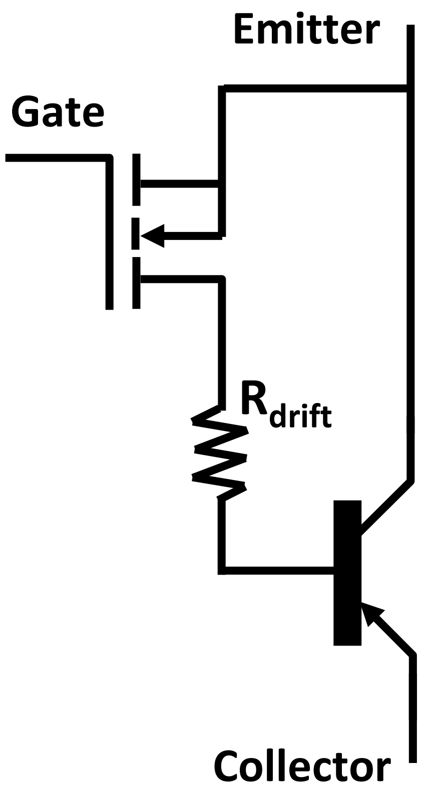
Principle of operation and structure of the IGBT (IV).

- **Internal structure (II).**



Simplest model for an IGBT.





Model taking into account the drift region resistance.

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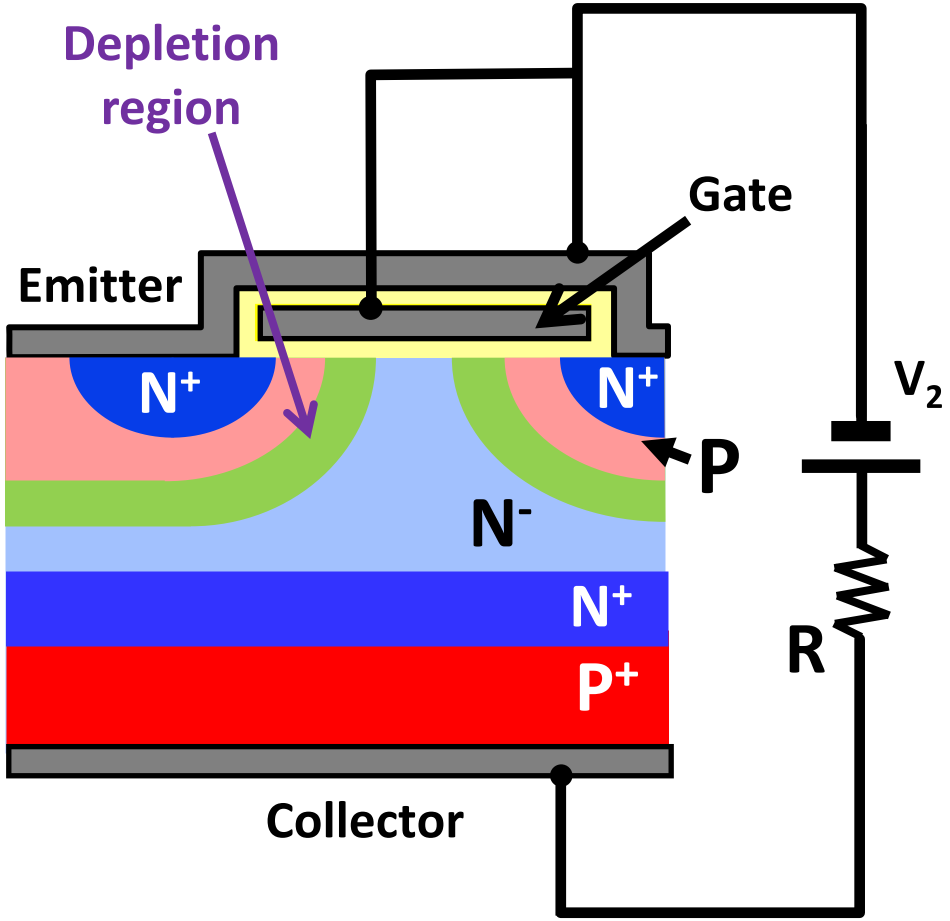
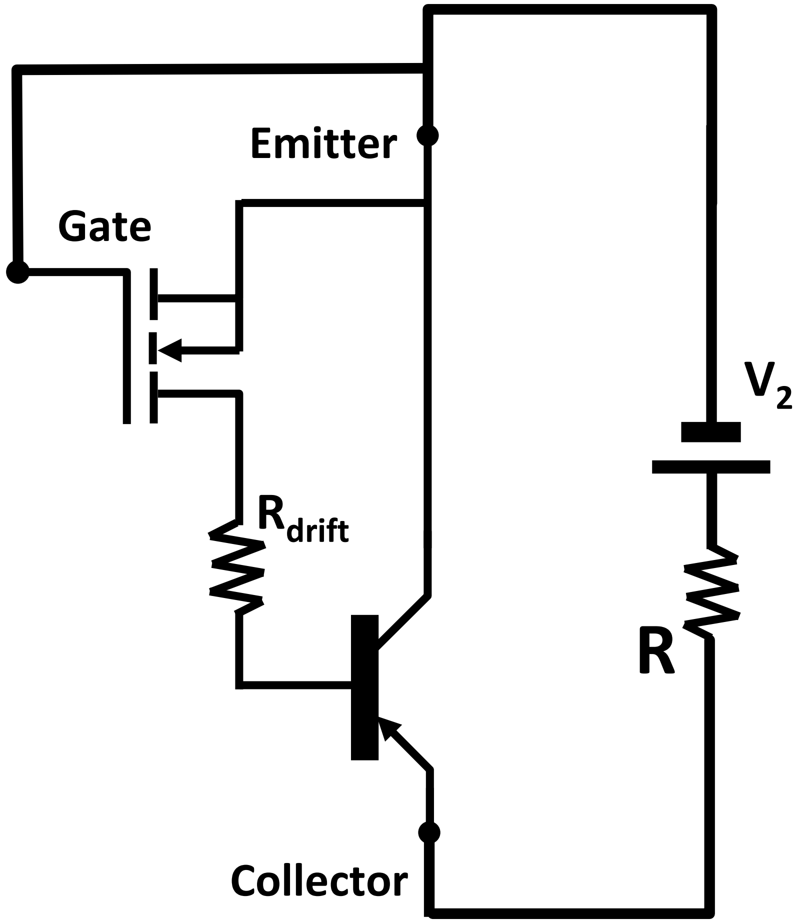
Principle of operation and structure of the IGBT (V).

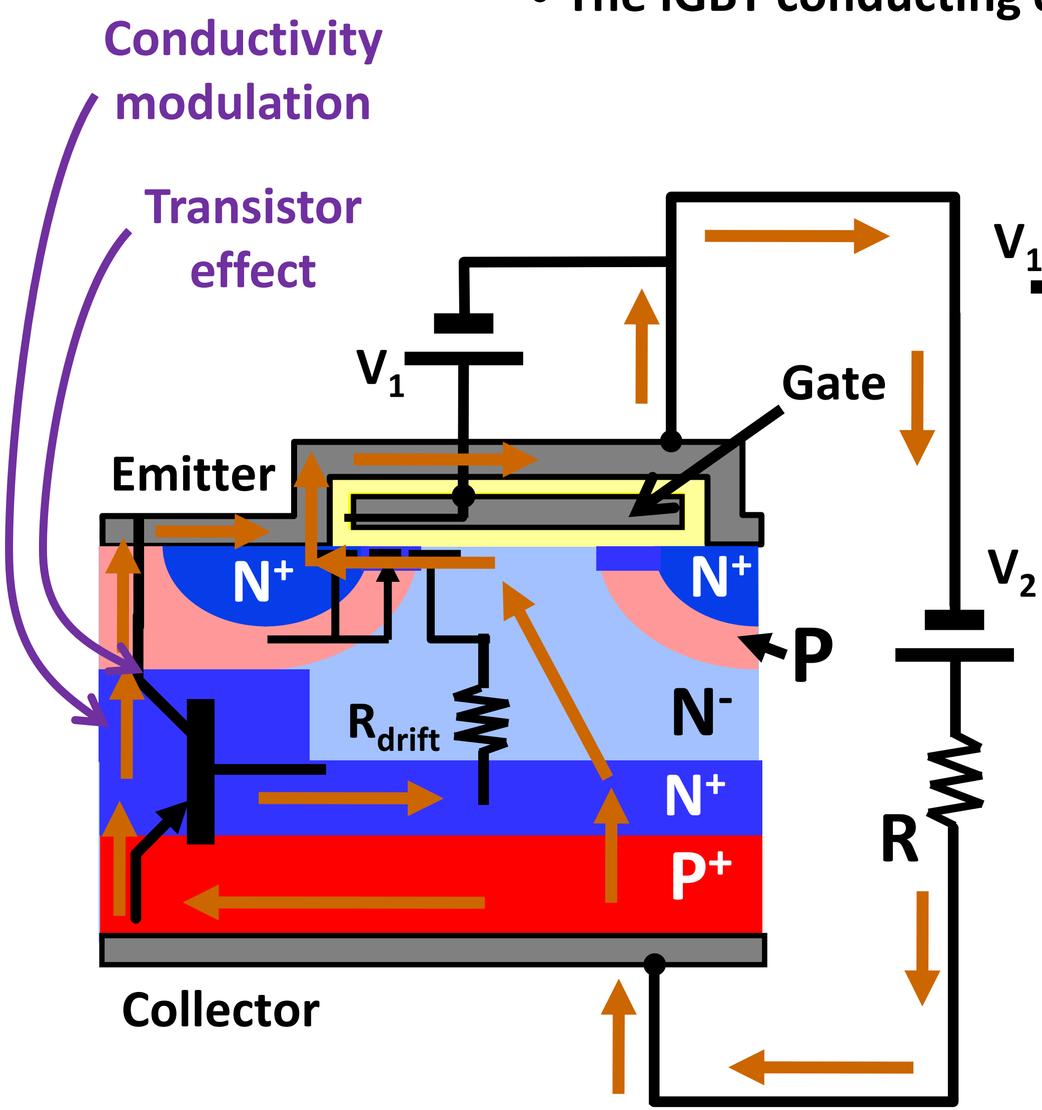
- **The IGBT blocking (withstanding) voltage.**

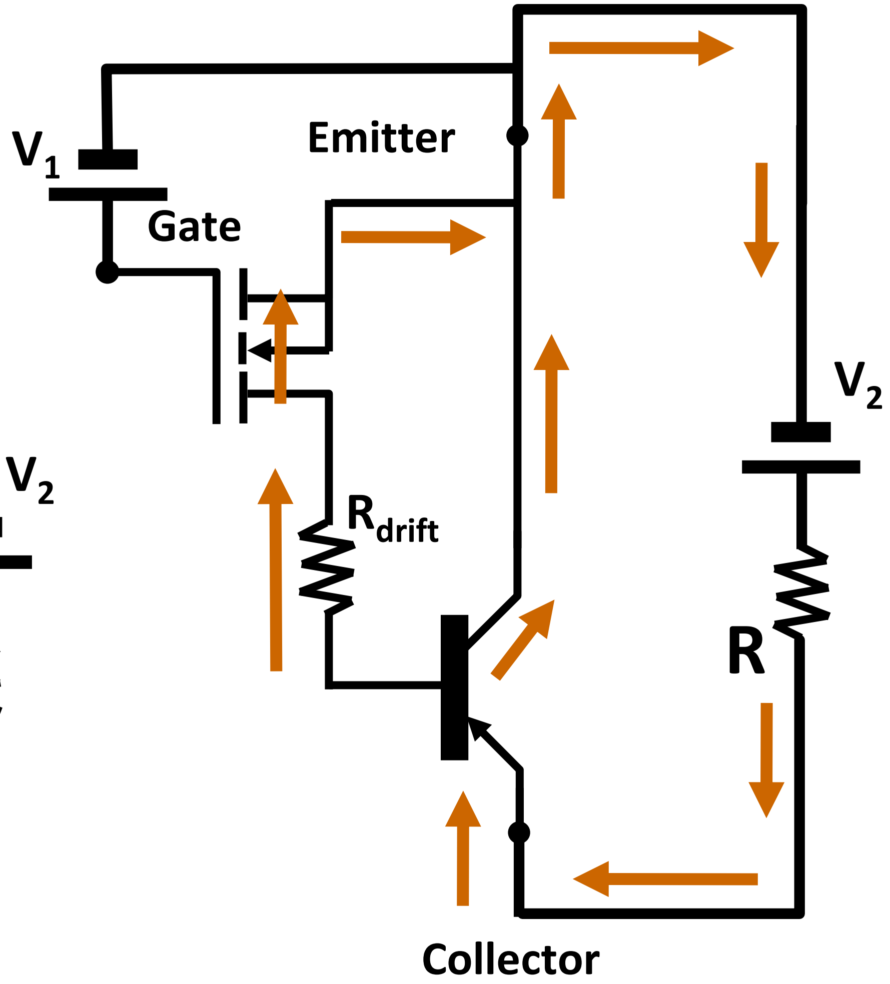




Principle of operation and structure of the IGBT (VI).

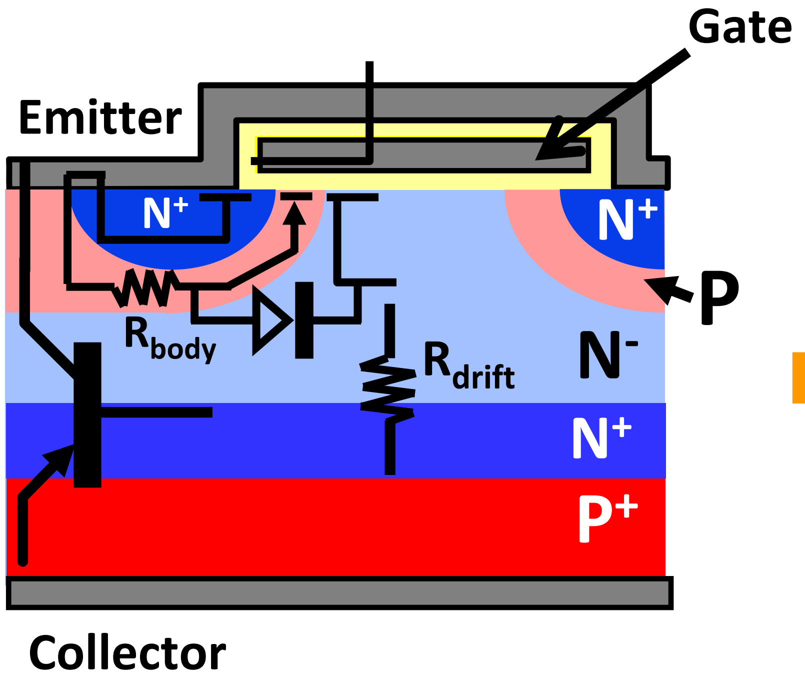
- **The IGBT conducting current (a first approach).**



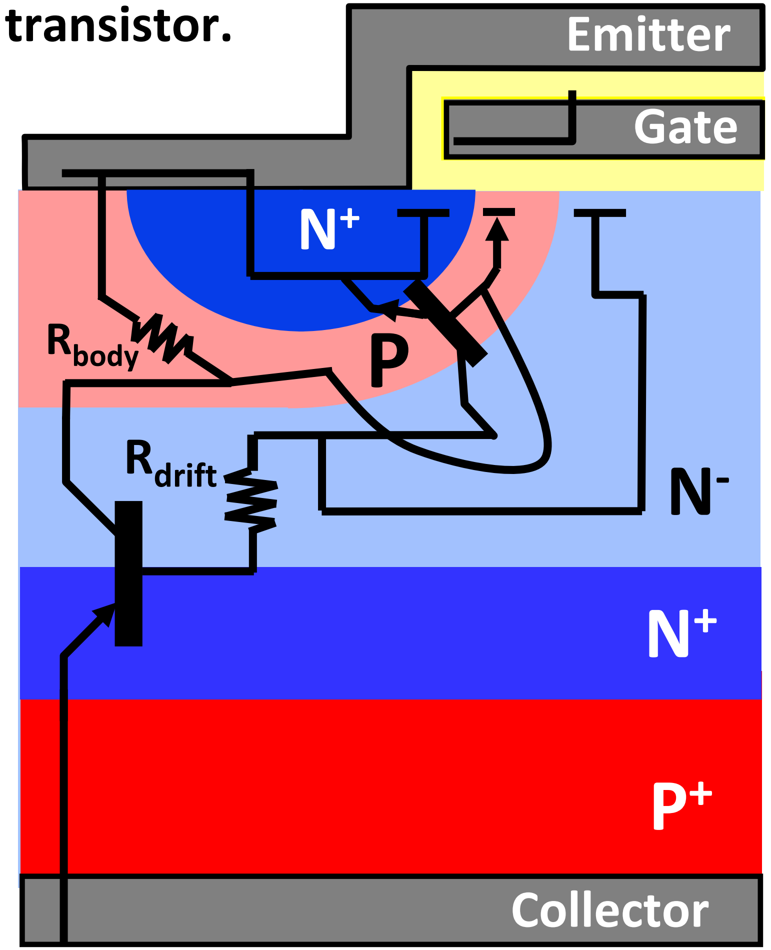


Principle of operation and structure of the IGBT (VII).

- **A more accurate model.**
- **However, there is another parasitic transistor.**

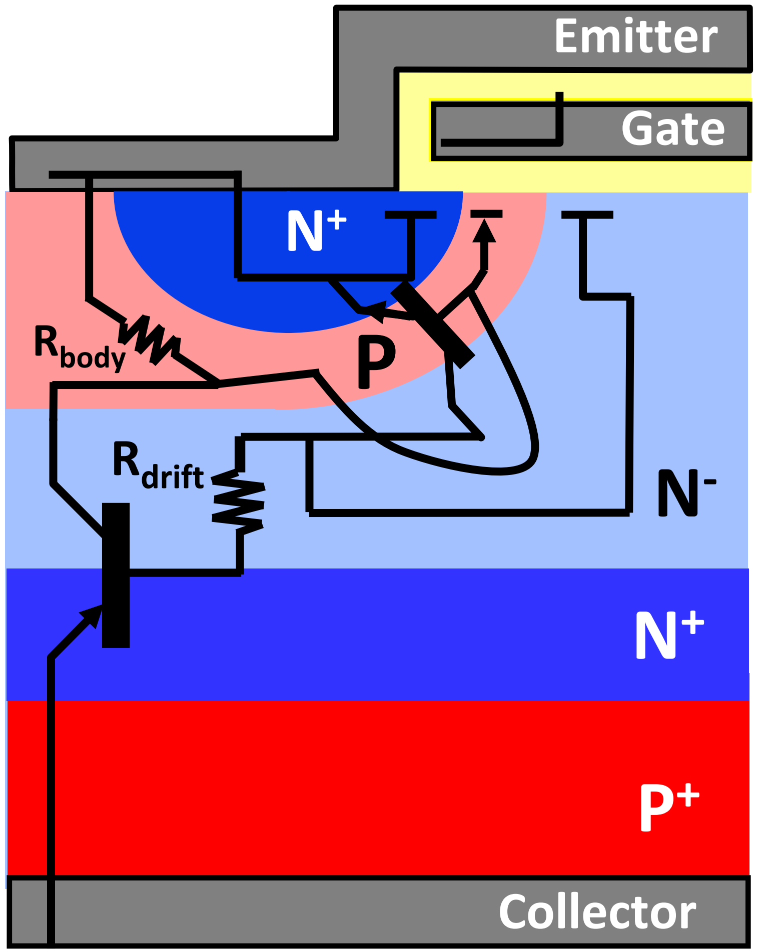


Model taking into account the MOSFET-body resistance.

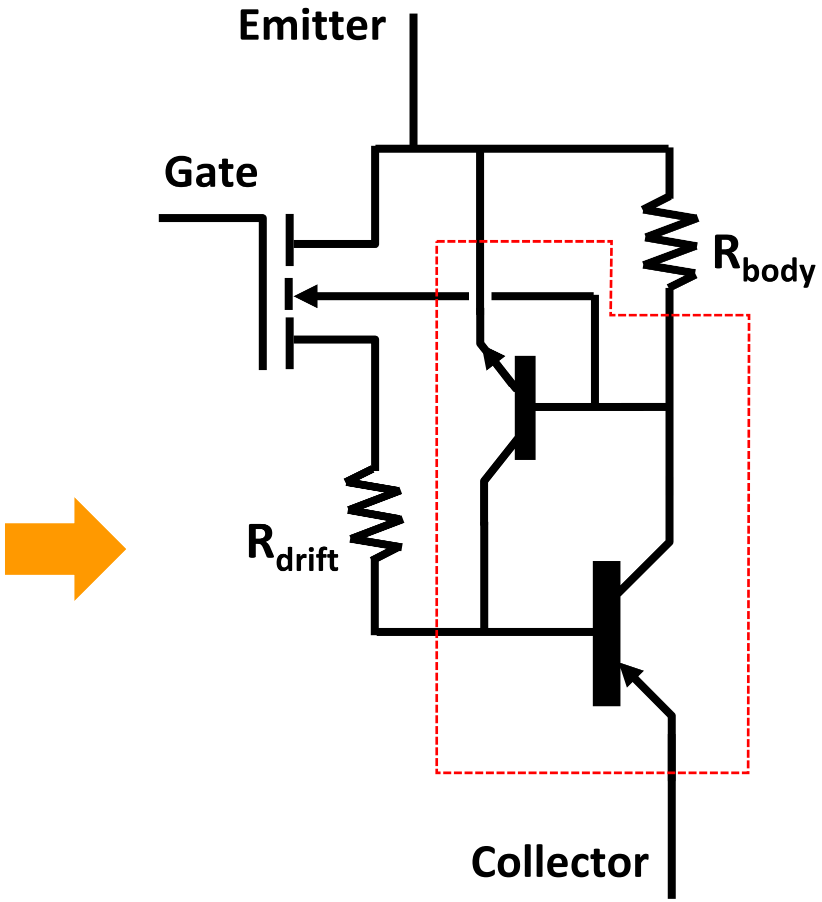


Model taking into account the parasitic NPN transistor.

Principle of operation and structure of the IGBT (VIII).



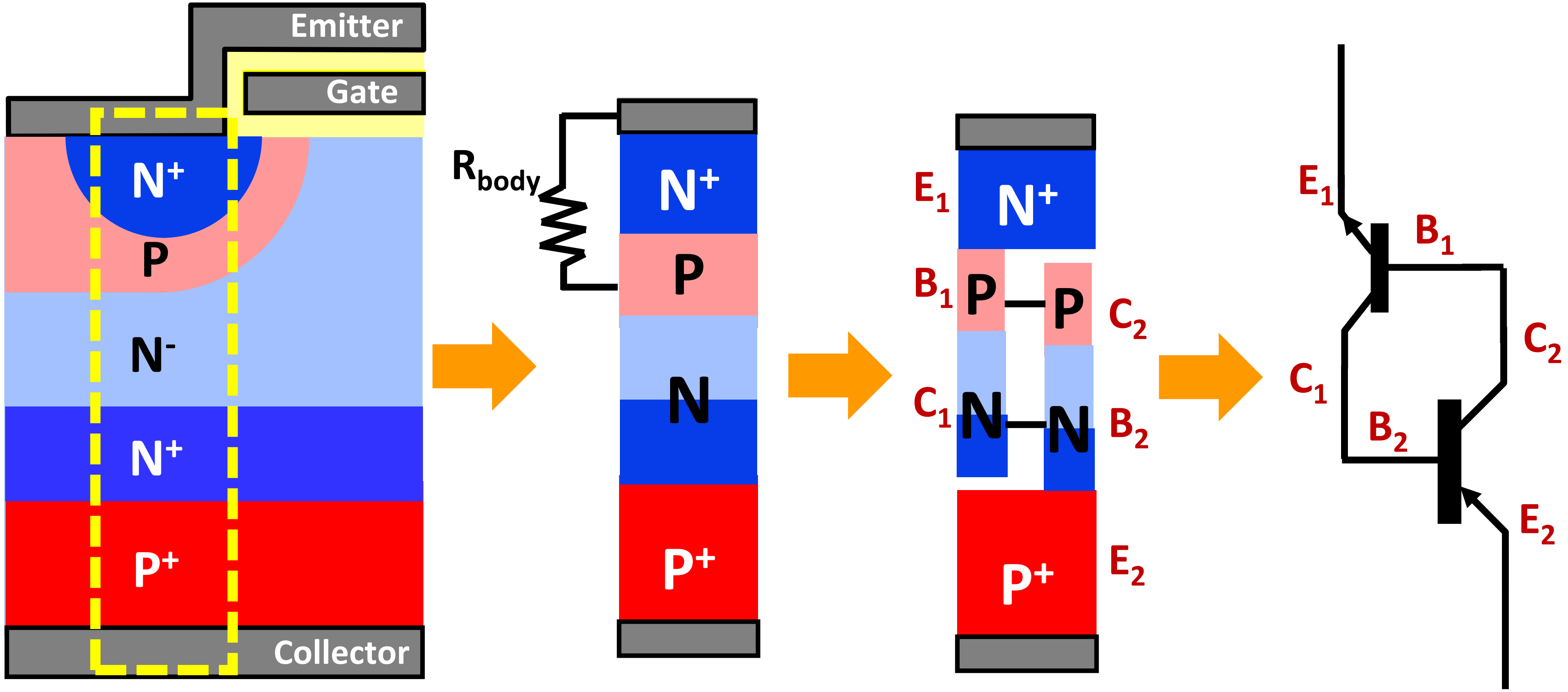
Model taking into account the parasitic NPN transistor.



- The final result is that there is a ***parasitic thyristor***.

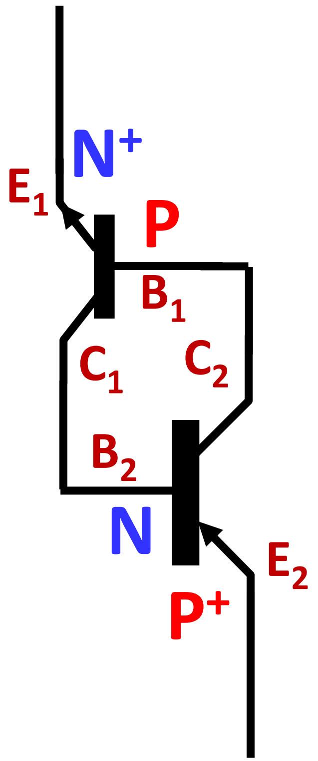
Principle of operation and structure of the IGBT (IX).

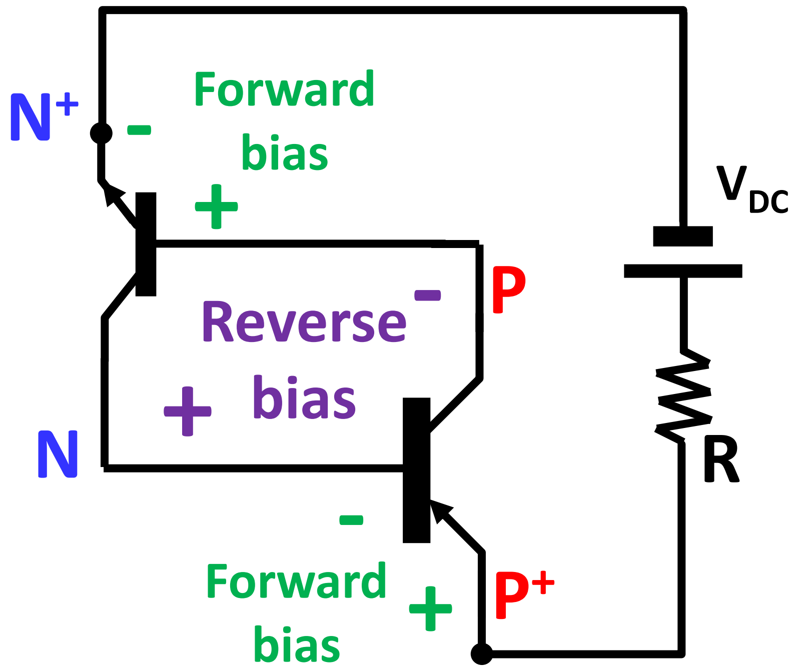
- **The basics of the thyristor: the PNPN structure (I).**



Principle of operation and structure of the IGBT (X).

• The basics of the thyristor: the PNPN structure (II).





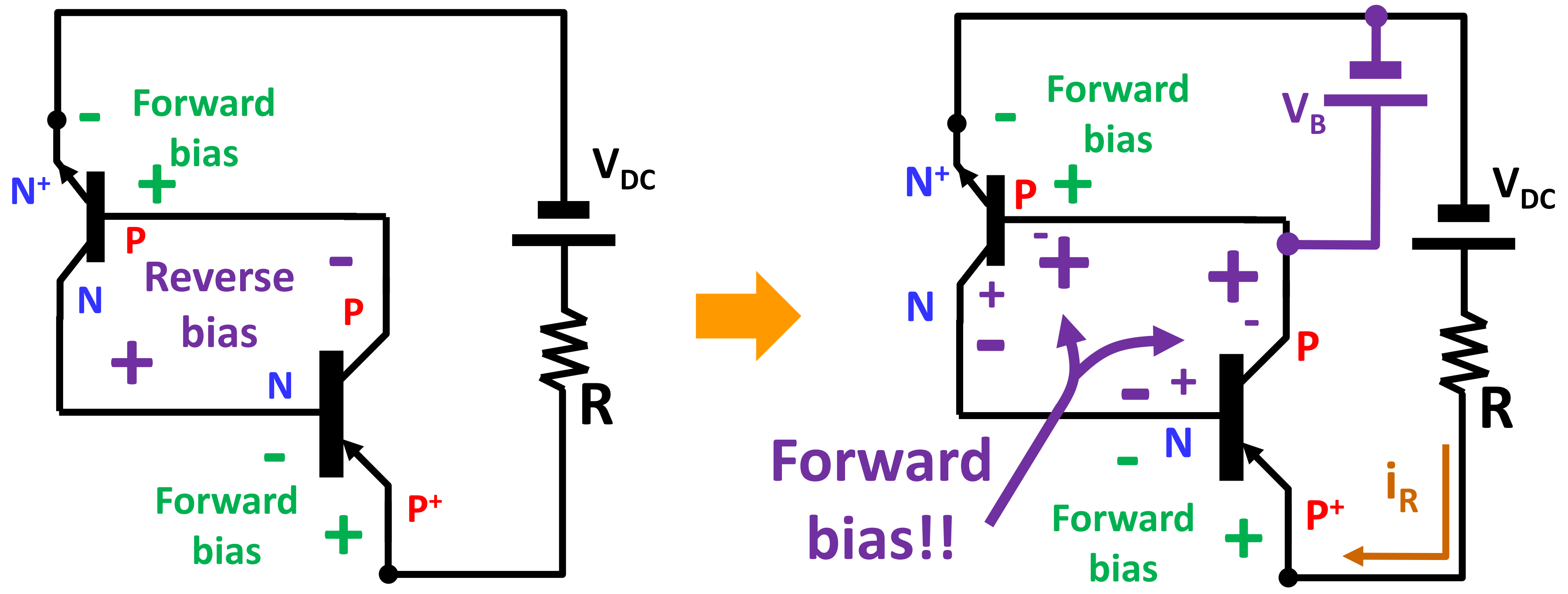
• There are two junctions forward biased and one is reverse biased.

• As a consequence, the PNPN device can block (withstand) voltage without conducting current.

• However, it will be able to conduct current as well, as it is going to be shown in the next slide.

Principle of operation and structure of the IGBT (XI).

• The basics of the thyristor: the PNPN structure (III).



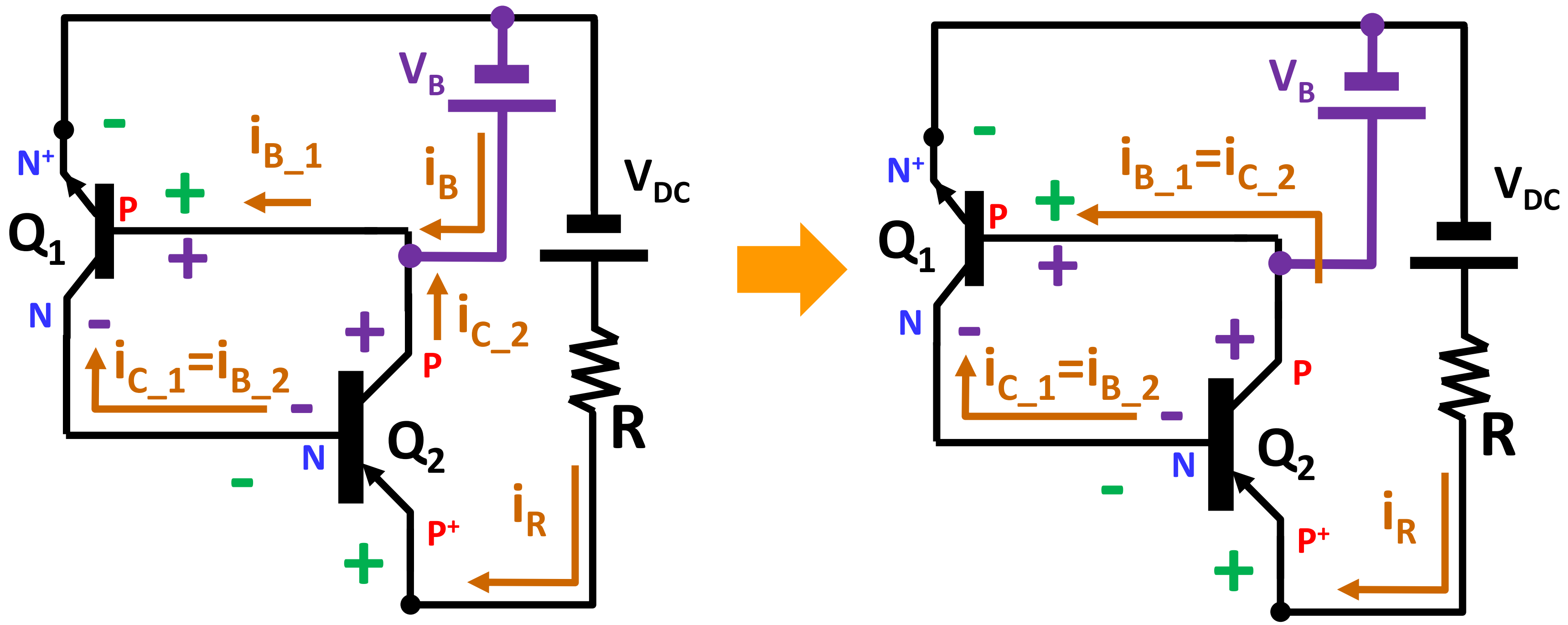
• If V_B is high enough (0.6-0.7 V in a silicon device), then the NPN transistor becomes saturated.

• As a consequence, the base-collector junctions corresponding to both the NPN and the PNP transistor become forward biased. Both transistors are saturated.

• Therefore, all the junctions are forward biased right now and the voltage across the device is quite low (e.g., 0.9-1.2 V). The current passing through R can be quite high (approximately V_{DC}/R).

Principle of operation and structure of the IGBT (XII).

• **The basics of the thyristor: the PNPN structure (IV).**



• **Initially, the current needed for transistor Q_1 to start conducting (active region) comes from the voltage source V_B.**

• **When i_{C_1} increases, i_{C_2} strongly increases because $i_{C\_2} = \beta_2 \cdot i_{B\_2} = \beta_2 \cdot i_{C\_1}$. Therefore, current i_{B_1} will be mainly due to i_{C_2}.**

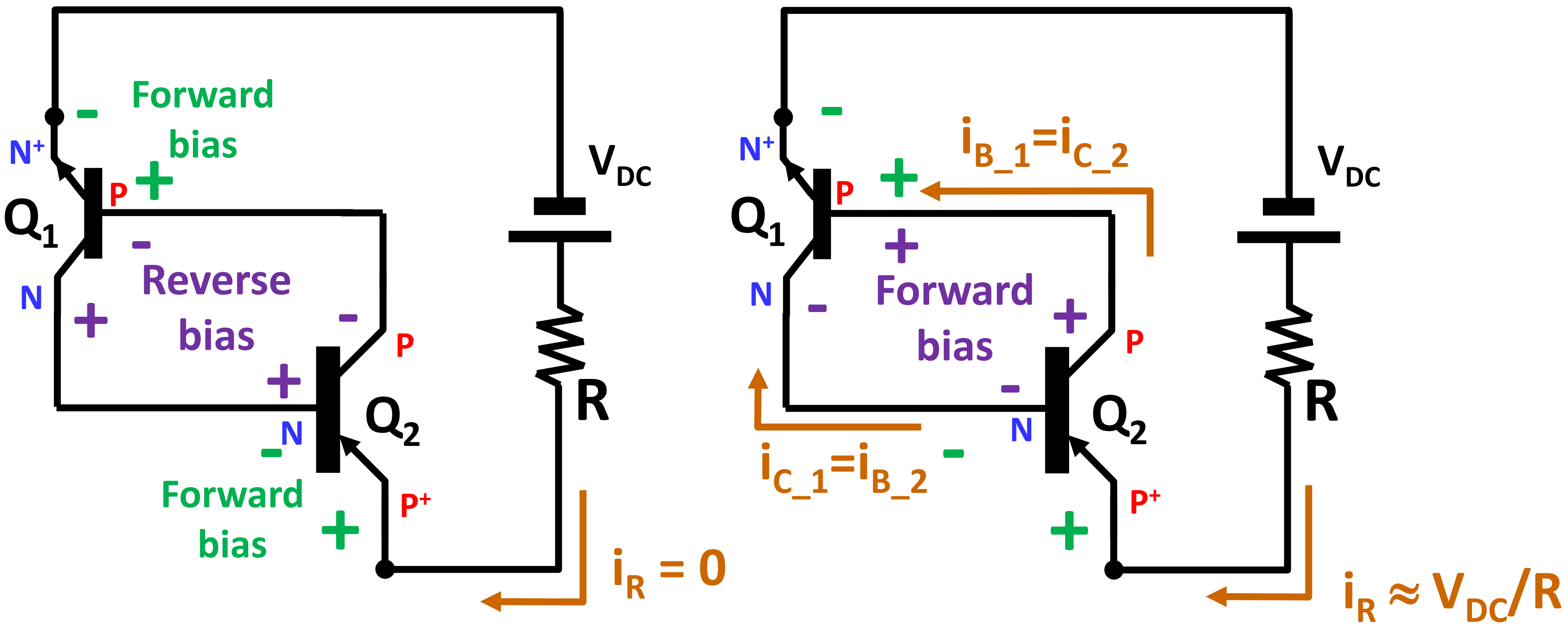
• **As i_{C_2} is the main current needed to maintain both transistors saturated, the situation does not change if we remove V_B.**

Principle of operation and structure of the IGBT (XIII).

- **The basics of the thyristor: the PNPN structure (V).**

- **A PNPN structure has two different stable states (so, it works as a flip-flop):**

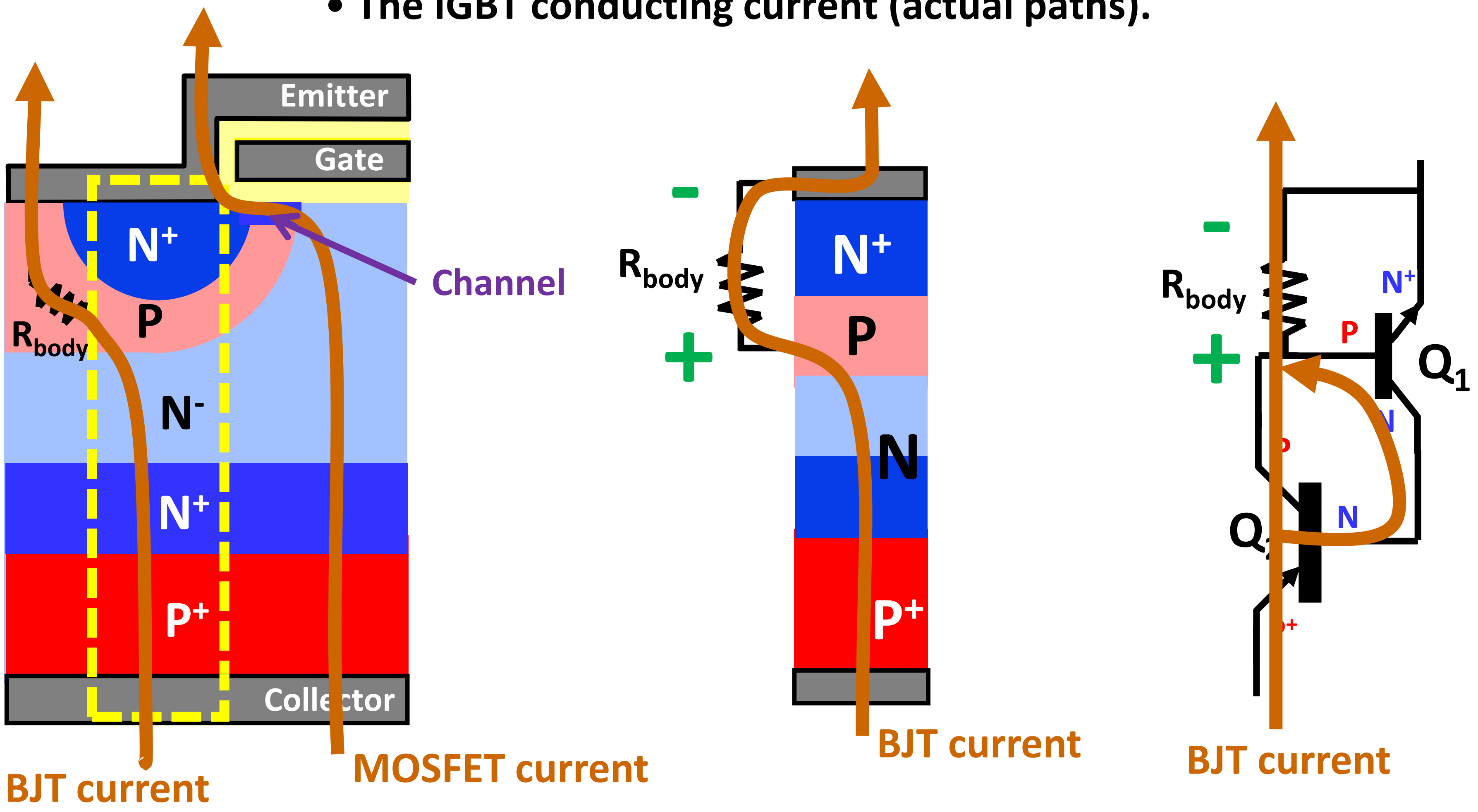
➤ ***As a open-circuit (I_R = 0).*** ➤ ***As a short-circuit ($I_R \approx V_{DC}/R$).***



- **The device state at a specific moment depends on whether Q_1 emitter-base junction has been forward biased previously.**
- **The only way to turn-off the device is by decreasing I_R up to zero.**

Principle of operation and structure of the IGBT (XIV).

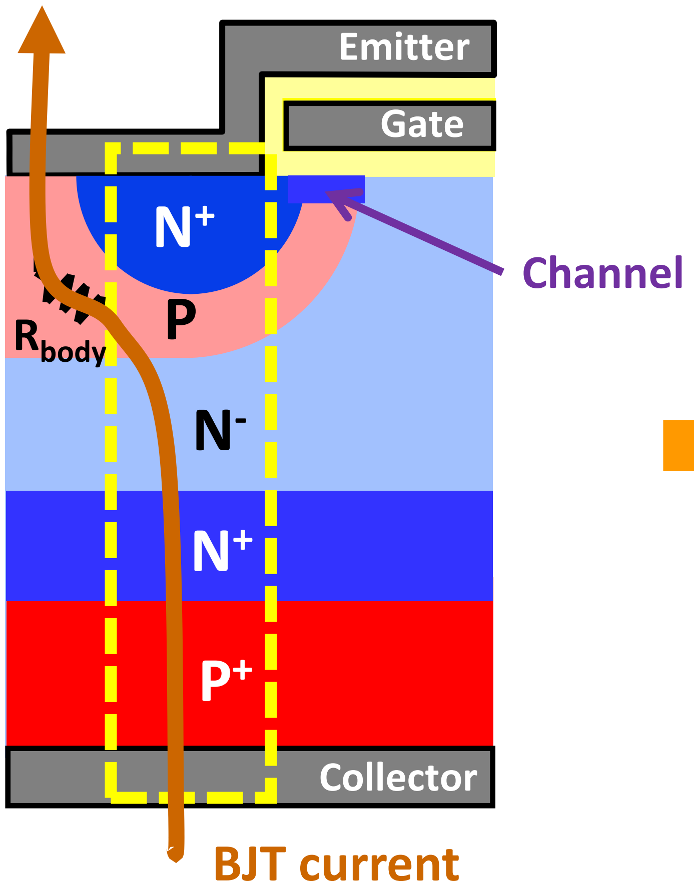
- **The IGBT conducting current (actual paths).**

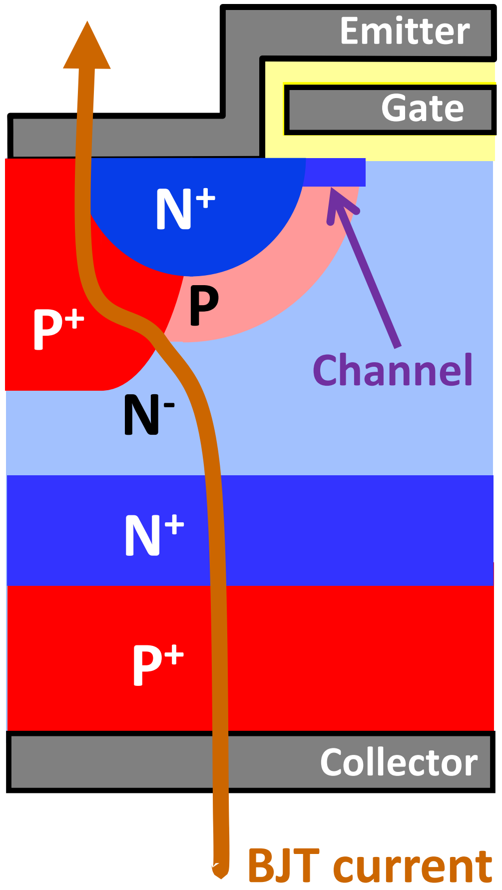


- **The voltage across R_{body} must not be high enough to turn-on the PNPN structure, which is called *latch-up*.**
- **Else, the total device cannot be turned-off by the gate voltage any more.**

Principle of operation and structure of the IGBT (XV).

- To avoid the IGBT latch-up, R_{body} must be as low as possible.

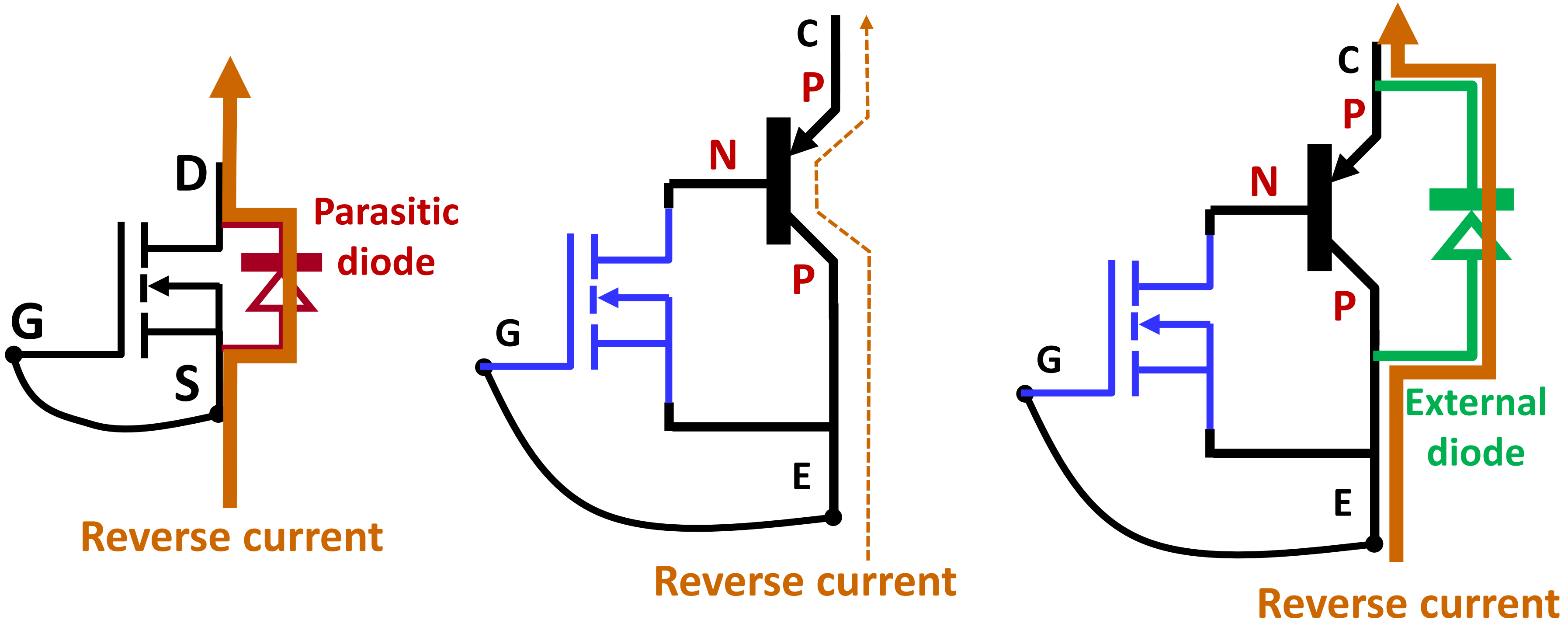




- The new P^+ region decreases R_{body}, thus increasing the value of the current needed to reach the voltage drop on R_{body} corresponding to latch-up.

Principle of operation and structure of the IGBT (XVI).

- **The IGBT cannot conduct reverse current when v_{GE} = 0 (it is not as the MOSFET).**



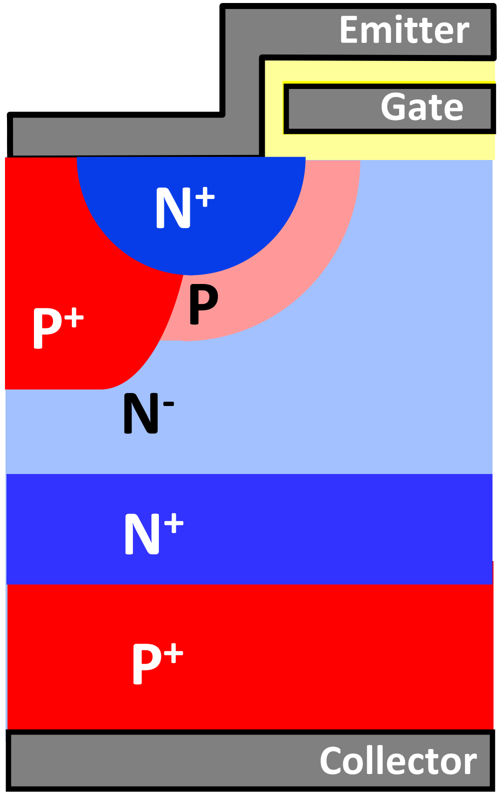
- **This means that it is able to block reverse voltage.**

- **Symmetrical IGBTs are especially designed for blocking reverse voltage. However, they have worse forward voltage drop than asymmetrical (standard) IGBTs.**

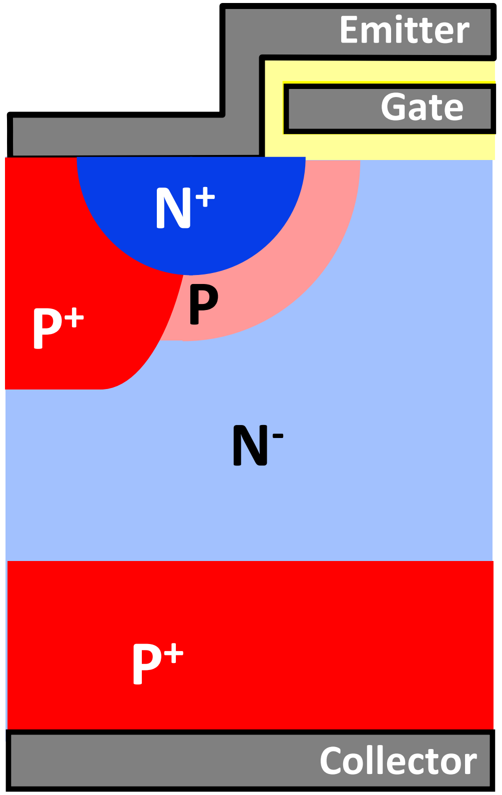
- **To conduct reverse current when v_{GE} = 0, an external diode must be added.**

Principle of operation and structure of the IGBT (XVII).

- **Asymmetrical versus symmetrical IGBT structures.**

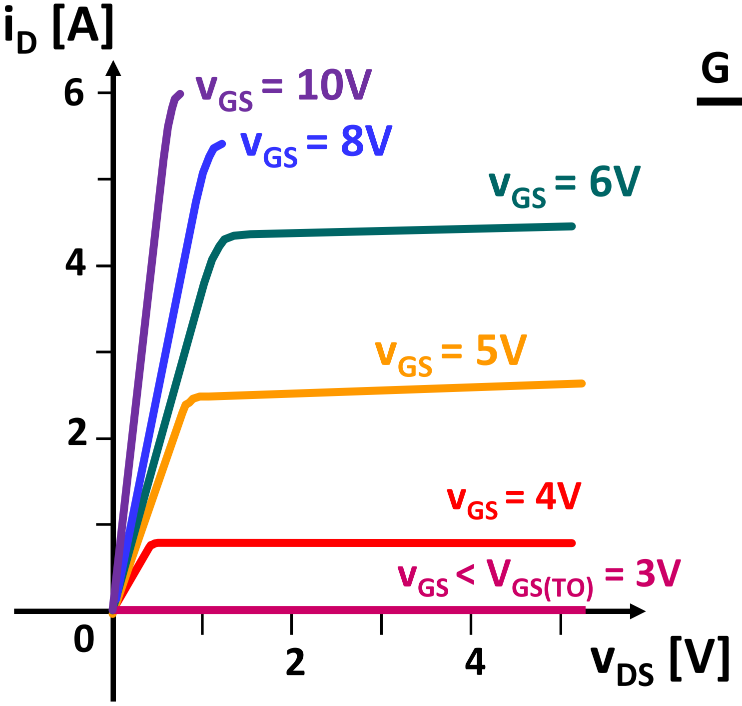


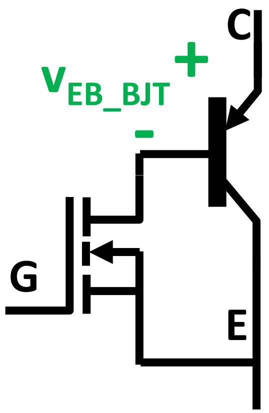
- **Asymmetrical IGBT**
(also called punch-through IGBT).

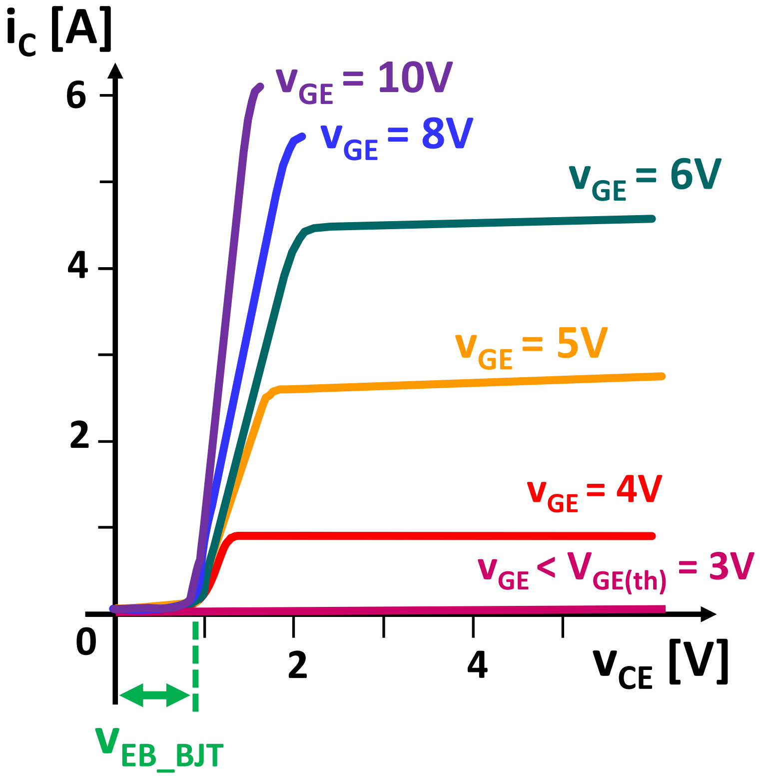


- **Symmetrical IGBT**
(non-punch-through IGBT).

Static output characteristic curves of a IGBT.





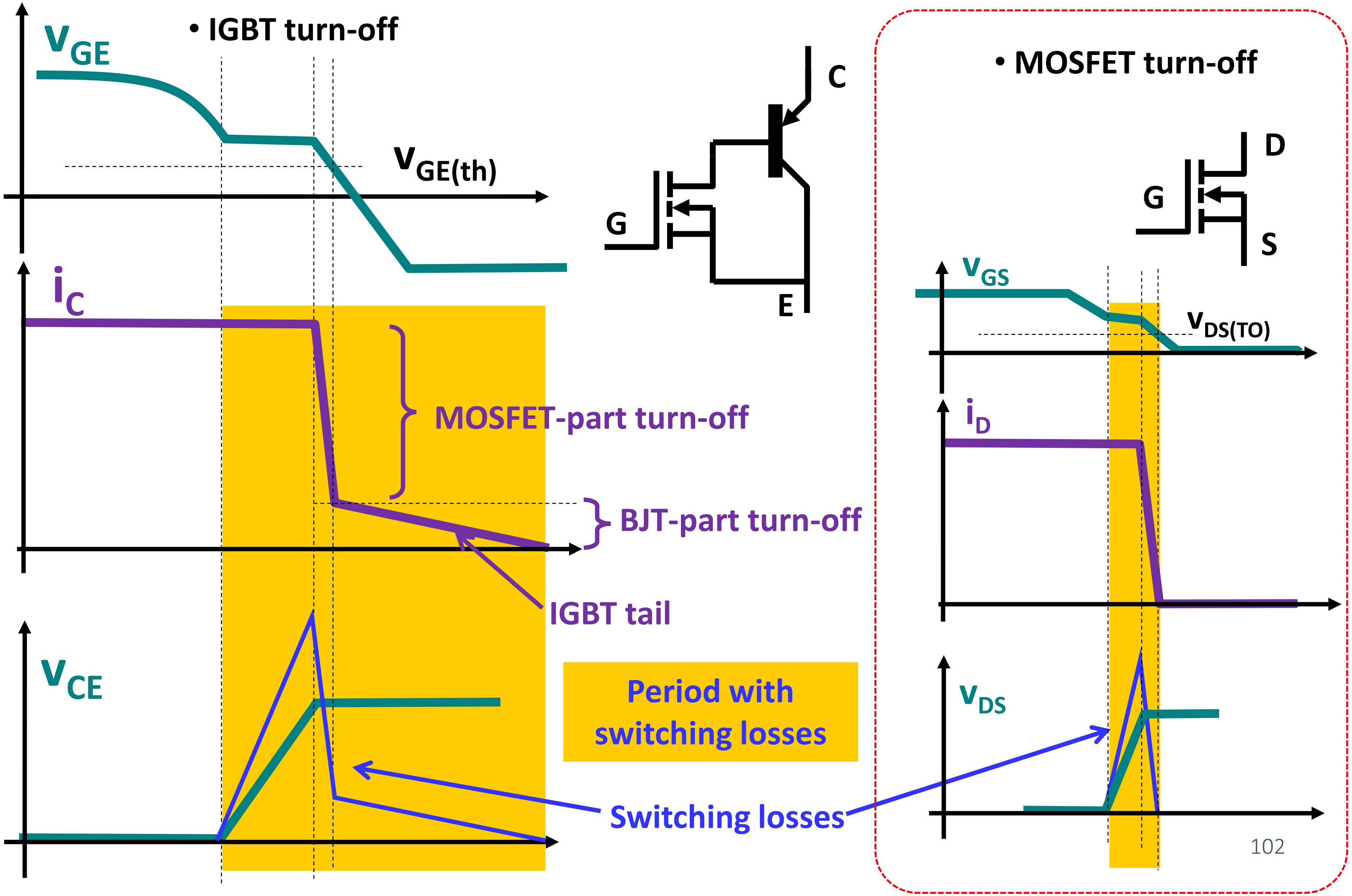


- **Static output characteristic curve of a MOSFET.**
- **It is also the one corresponding to the MOSFET part of a IGBT.**

- **Static output characteristic curve of a IGBT.**
- **It can be easily obtained from the MOSFET characteristic curve by adding the voltage drop v_{EB_BJT} corresponding to the emitter-to-base junction of the BJT part of the IGBT.**

Dynamic characteristics of the IGBTs (II).

- **Comparing IGBT and MOSFET Turn-off.**



Unit 3 Amplifiers

Frequency Response of BJT Amplifiers

The Decibel (dB)

- A logarithmic measurement of the ratio of power or voltage
- Power gain is expressed in dB by the formula:

$$A_P = 10 \log a_P$$

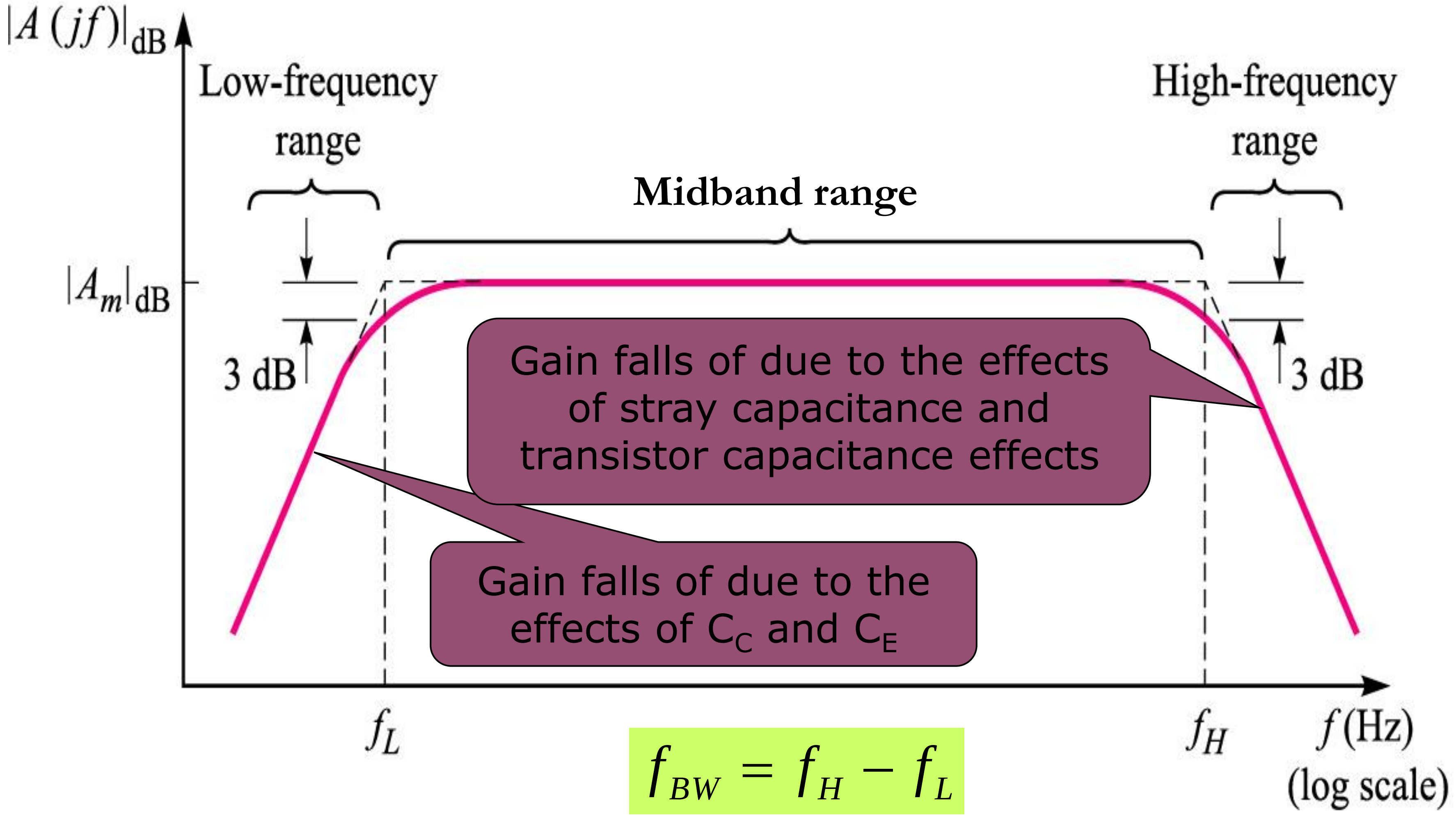
where a_p is the actual power gain, Pout/Pin

Voltage gain is expressed by:

$$A_{V(dB)} = 20 \log a_v$$

- If a_v is greater than 1, the dB is +ve, and if a_v is less than 1, the dB gain is –ve value & usually called *attenuation*

Amplifier gain vs frequency



$$f_{BW} = f_H - f_L$$

Definition

- Frequency response of an amplifier is the graph of its *gain versus the frequency*.
- *Cutoff frequencies* : the frequencies at which the voltage gain equals 0.707 of its maximum value.
- *Midband* : the band of frequencies between $10f_L$ and $0.1f_H$ where the voltage gain is maximum. The region where coupling & bypass capacitors act as short circuits and the stray capacitance and transistor capacitance effects act as open circuits.
- *Bandwidth* : the band between upper and lower cutoff frequencies
- Outside the midband, the voltage gain can be determined by these equations:

$$A = \frac{A_{mid}}{\sqrt{1+\left(f_1 / f\right)^2}}$$

Below midband

$$A = \frac{A_{mid}}{\sqrt{1+\left(f / f_2\right)^2}}$$

Above midband

Lower & Upper Critical frequency

- Critical frequency / the cutoff frequency
- The frequency at which output power drops by 3 dB. [in real number, 0.5 of it's midrange value.
- An output voltage drop of 3dB represents about a 0.707 drop from the midrange value in real number.
- Power is often measured in units of dBm. This is decibels with reference to 1mW of power. [0 dBm = 1mW], where;

$$10\log\left(\frac{1\text{mW}}{1\text{mW}}\right) = 0\text{dBm}.$$

Gain & frequencies

- *Gain-bandwidth product* : constant value of the product of the voltage gain and the bandwidth.
- *Unity-gain frequency* : the frequency at which the amplifier's gain is 1

$$f_T = A_{mid} BW$$

LOW FREQUENCY

- At low frequency range, the gain falloff due to coupling capacitors and bypass capacitors.
- As signal frequency $\Downarrow$, the reactance of the coupling capacitor, $X_C \Uparrow$ - no longer behave as short circuits.

Short-circuit time-constant method (SCTC)

- To determine the lower-cutoff frequency having *n* coupling and bypass capacitors:

$$\omega_L \cong \sum_{i=1}^{n} \frac{1}{R_{iS} C_i}$$

R_{iS} = resistance at the terminals of the *i*th capacitor C_i with all the other capacitors replaced by short circuits.

Common-emitter Amplifier

Given :

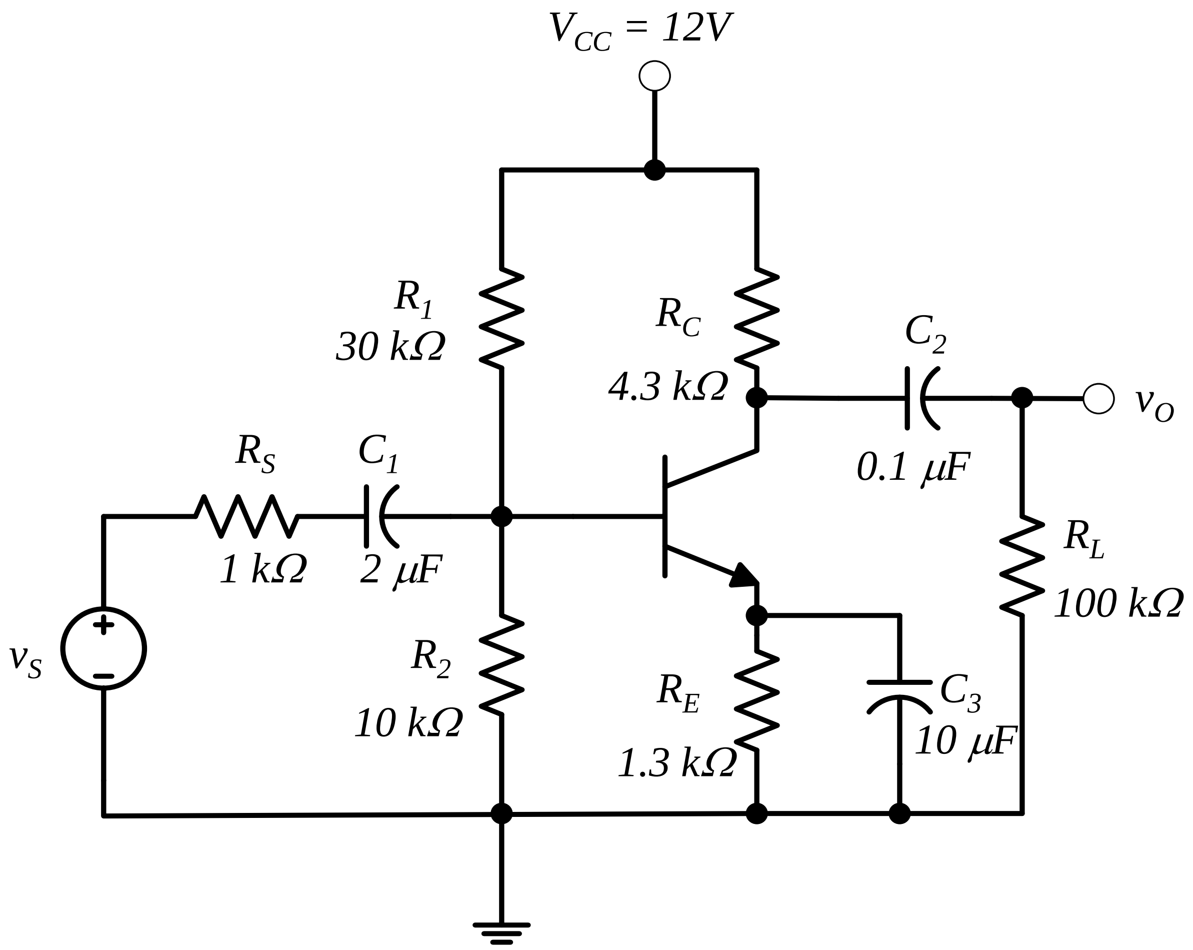
Q-point values : 1.73 mA, 2.32 V

β = 100, V_A = 75 V

Therefore,

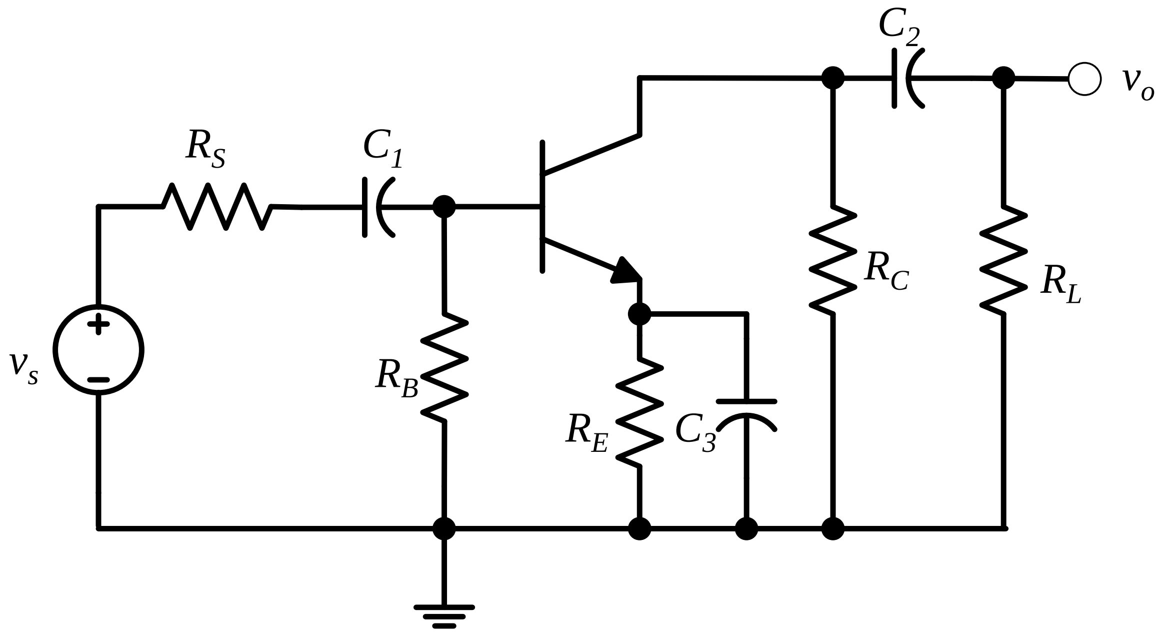
r_π = 1.45 kΩ,

r_o =44.7 kΩ



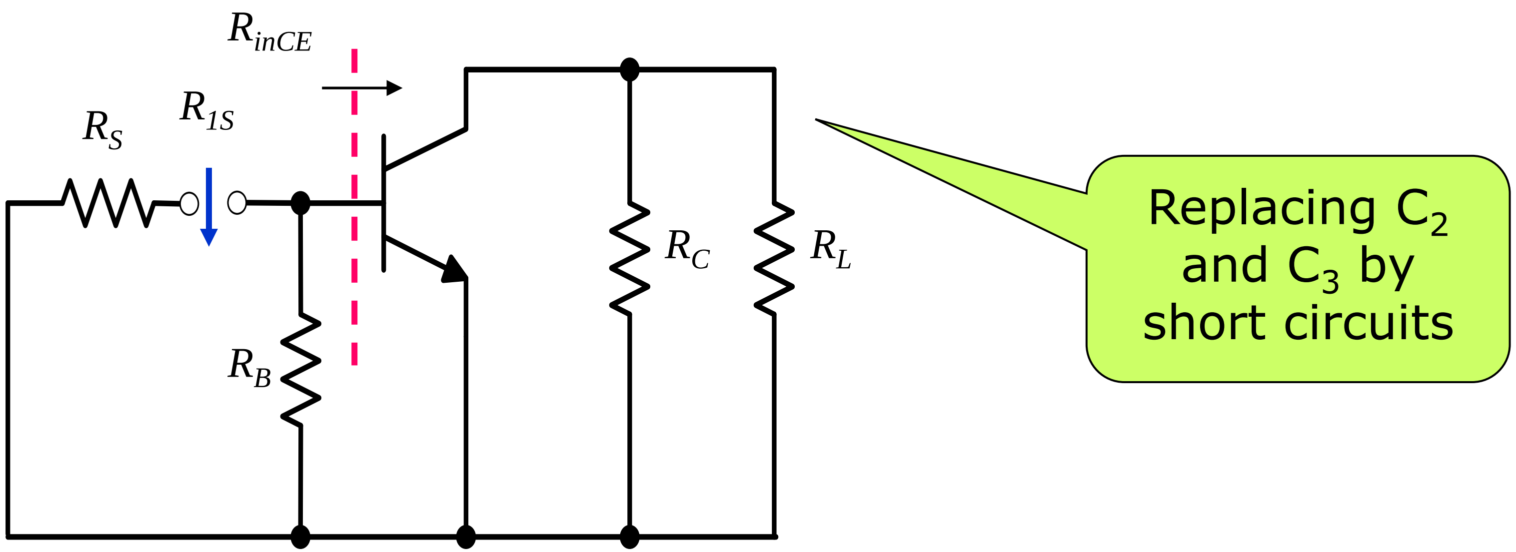
Common-emitter Amplifier

- Low-frequency ac equivalent circuit



In the above circuit, there are 3 capacitors (coupling plus bypass capacitors). Hence we need to find 3 resistances at the terminals of the 3 capacitors in order to find the lower cut-off frequency of the amplifier circuit.

Circuit for finding R_{1S}

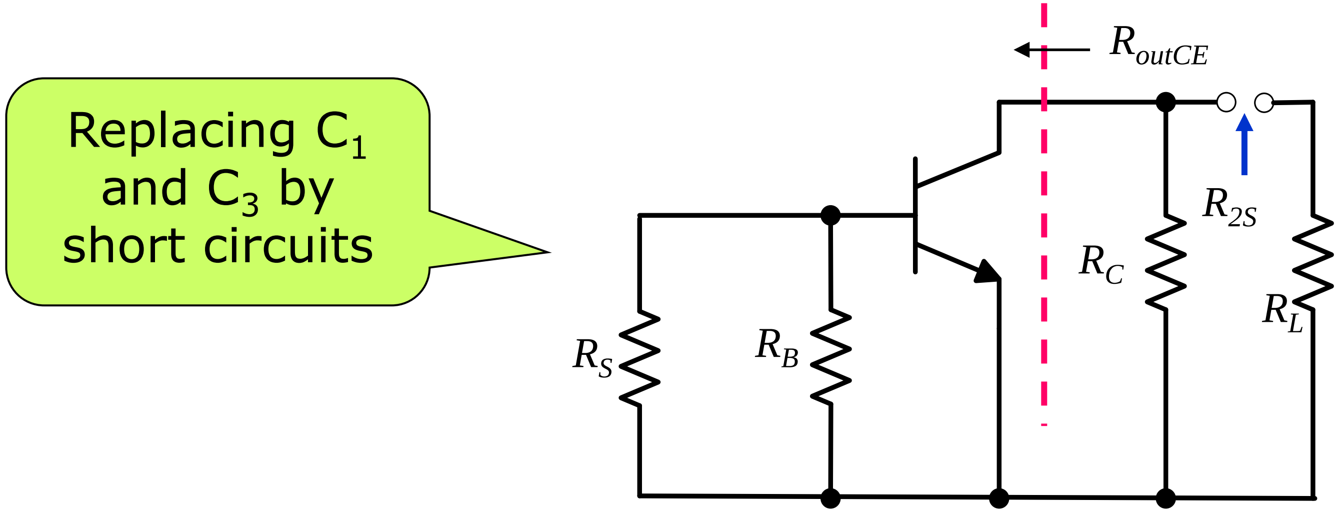


$$R_{1S} = R_S + (R_B \| R_{inCE}) = R_S + (R_B \| r_\pi) = 1000 + (7500 \| 1450) = 2220\ \Omega$$

$$\text{where} \quad R_B = R_1 \| R_2 = 7500\ \Omega$$

$$\frac{1}{R_{1S}C_1} = \frac{1}{(2.22\,k\Omega)(2.00\,\mu F)} = 225\, rad/s$$

Circuit for finding R_{2S}

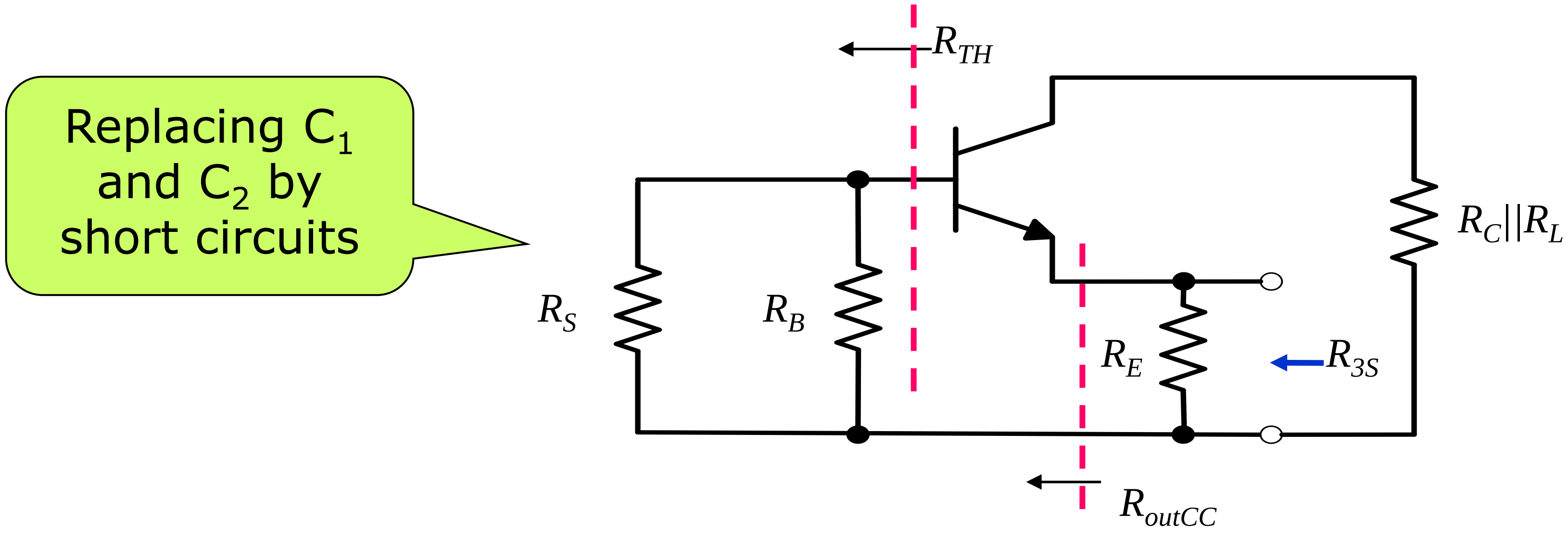


$$R_{2S} = R_L + \left(R_C \| R_{outCE}\right) = R_L + \left(R_C \| r_o\right) = 100\,k + \left(4.3k \| 44.7k\right) = 104\,k\Omega$$

where $r_0 = 44.7k\Omega$

$$\frac{1}{R_{2S}C_2} = \frac{1}{(104\,k\Omega)(0.100\,\mu F)} = 96.1\,rad/s$$

Circuit for finding R_{3S}



$$R_{3S} = R_E \| R_{outCC} = R_E \left\| \frac{r_\pi + R_{TH}}{\beta + 1} = 1300 \right\| \frac{1450 + 882}{101} = 22.7\,\Omega$$

$$R_{TH} = R_S \| R_B = 882\,\Omega$$

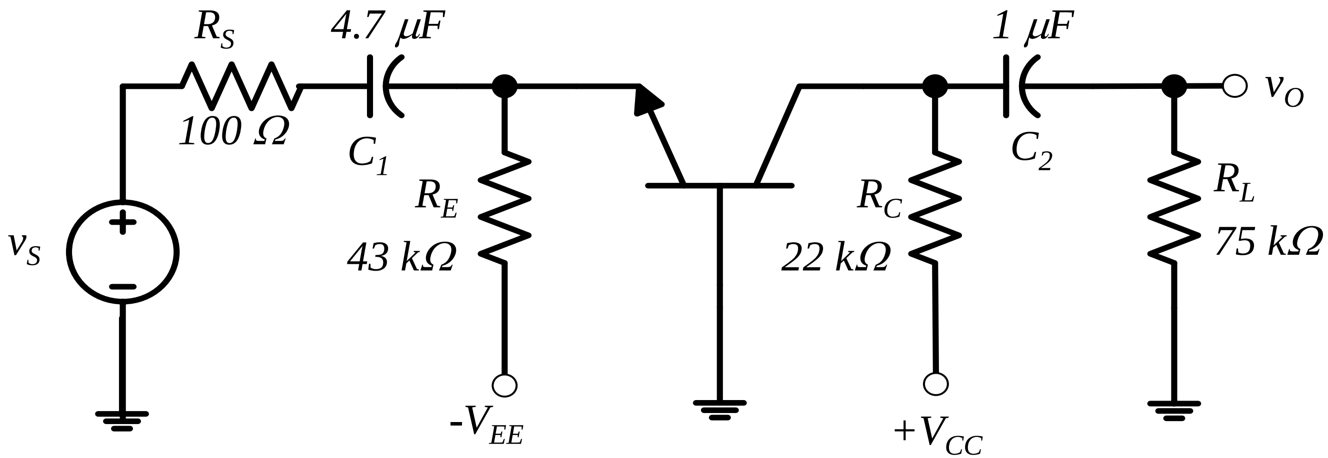
$$\frac{1}{R_{3S} C_3} = \frac{1}{(22.7\Omega)(10\mu F)} = 4410\, rad/s$$

Estimation of ω_L

$$\omega_L \cong \sum_{i=1}^{3} \frac{1}{R_{iS} C_i} = 225 + 96.1 + 4410 = 4730\, rad/s$$

$$f_L = \frac{\omega_L}{2\pi} = 753\, Hz$$

Common-base Amplifier



Given :

Q-point values : 0.1 mA, 5 V

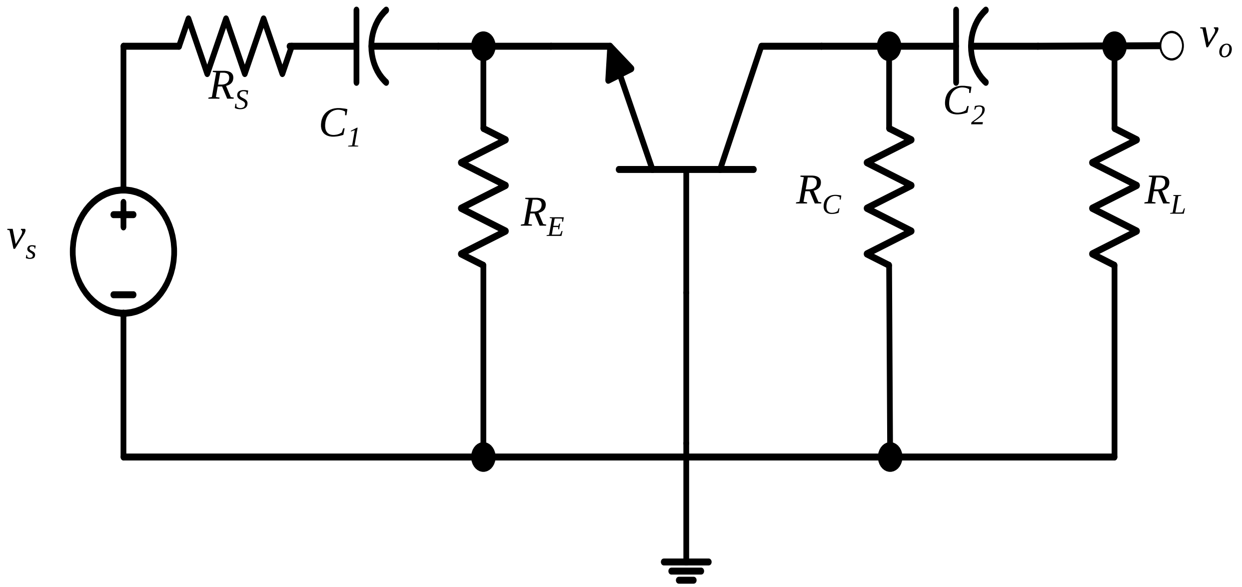
β = 100, V_A = 70 V

Therefore,

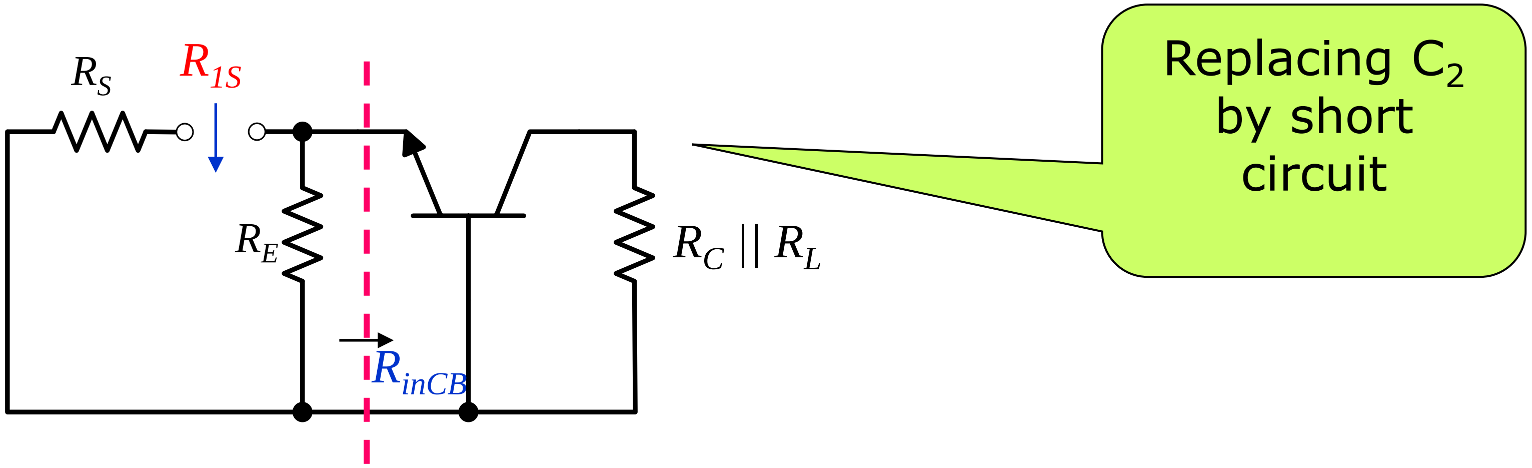
g_m = 3.85 mS, r_o = 700 kΩ

r_π = 26 Ω

Common-base Amplifier
- Low-frequency ac equivalent circuit



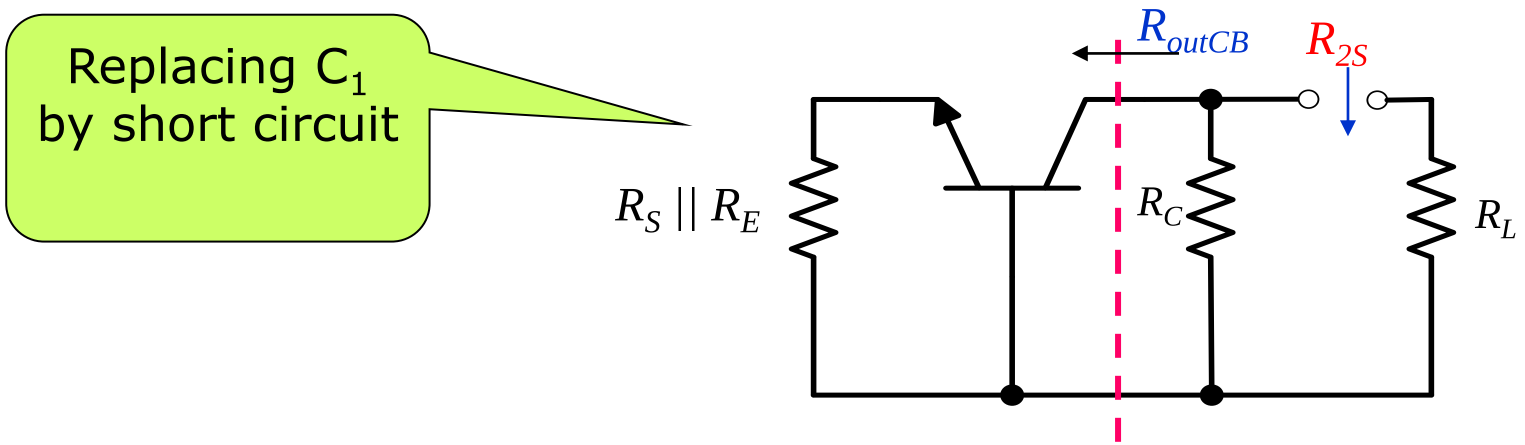
Circuit for finding R_{1S}



$$R_{1S} = R_S + \left(R_E \| R_{inCB}\right) \cong R_S + \left(R_E \left\| \frac{r_\pi}{1+\beta}\right.\right) = 100 + \left(4300 \| 0.26\right) \cong 100\,\Omega$$

$$\frac{1}{R_{1S}C_1} = \frac{1}{(100\,\Omega)(4.7\,\mu F)} = 2.13\times10^{-3}\ rad/s$$

Circuit for finding R_{2S}



$$R_{2S} = R_L + \left(R_C \| R_{outCB}\right) \cong R_L + R_C = 75\,k + 22\,k = 97\,k\Omega$$

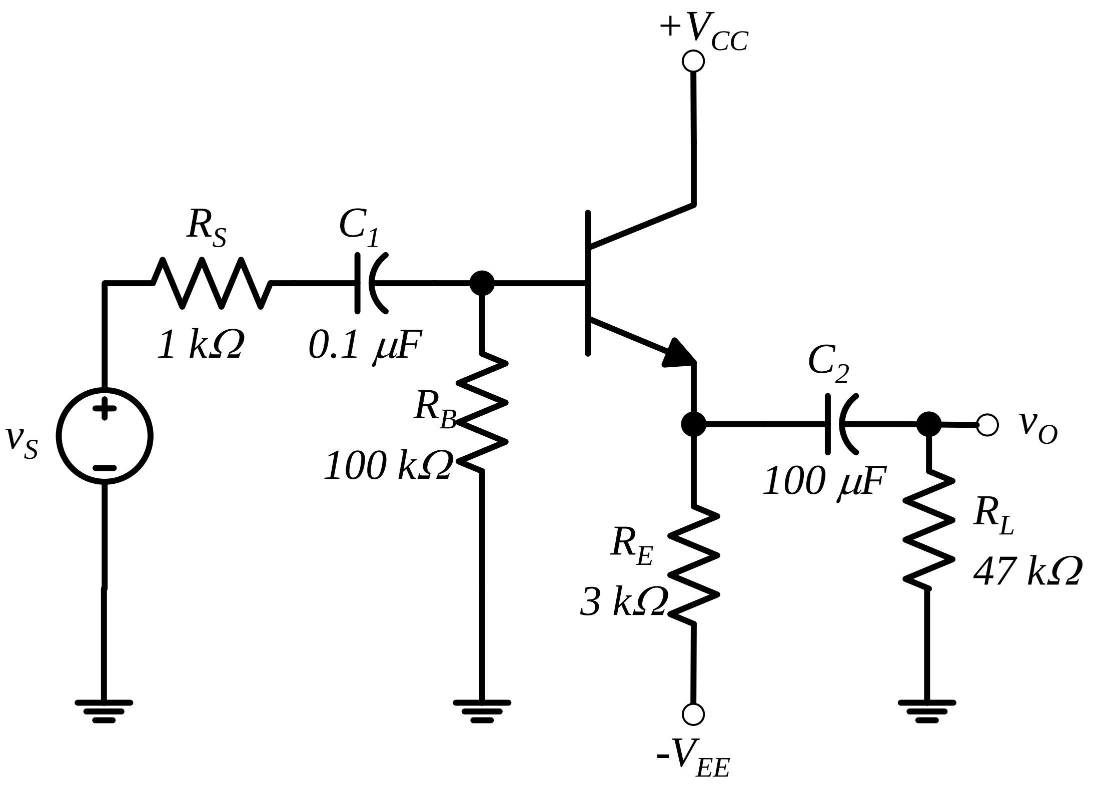
$$\frac{1}{R_{2S}C_2} = \frac{1}{(97\,k\Omega)(1\mu F)} = 10.309\,rad/s$$

Estimation of ω_L

$$\omega_L \cong \sum_{i=1}^{2} \frac{1}{R_{iS} C_i} = 2.13 \times 10^{-3} + 10.309 \cong 10.309\, rad/s$$

$$f_L = \frac{\omega_L}{2\pi} = 1.64\, Hz$$

Common-collector Amplifier



Given :

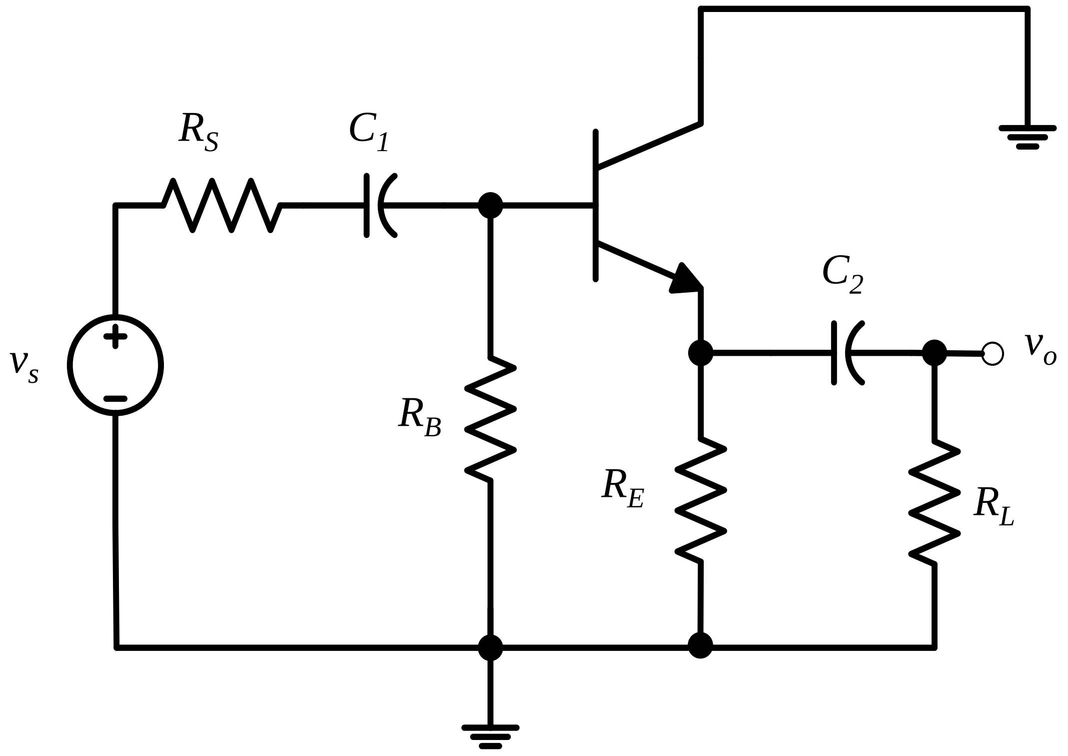
Q-point values : 1 mA, 5 V

β = 100, V_A = 70 V

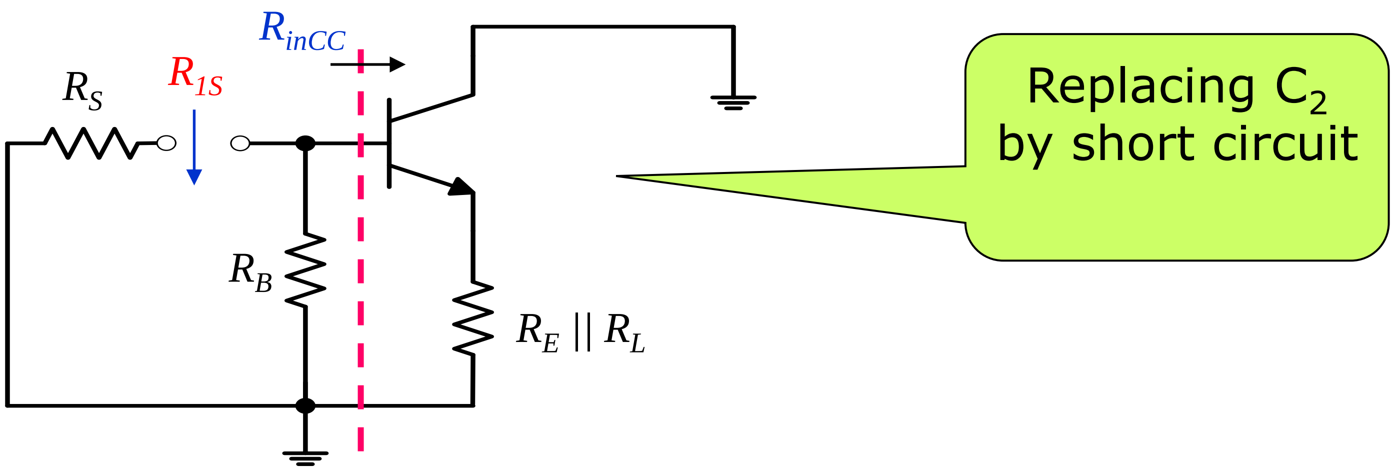
Therefore,

r_π = 2.6 kΩ, r_o =70 kΩ

Common-collector Amplifier
- Low-frequency ac equivalent circuit



Circuit for finding R_{1S}



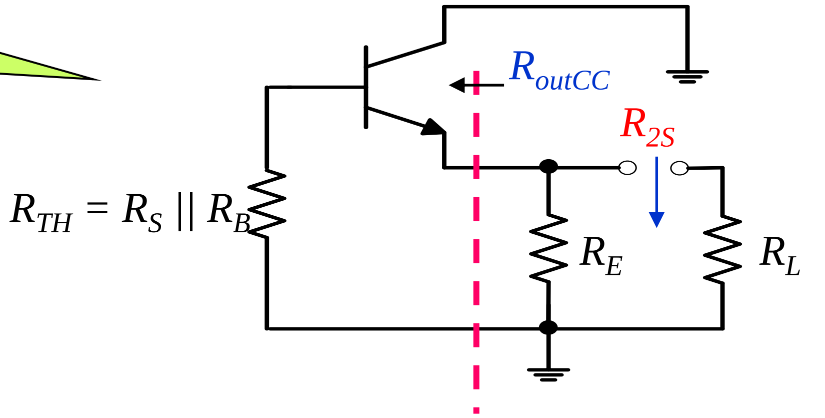
$$R_{1S} = R_S + \left(R_B \| R_{inCC}\right) = R_S + \left(R_B \| \left[r_\pi + (\beta+1)\left(r_o \| \ R_E \| R_L\right)\right]\right)$$

$$= 74.43\, k\Omega$$

$$\frac{1}{R_{1S}C_1} = \frac{1}{(74.43\,k\Omega)(0.1\mu F)} = 136.18\, rad/s$$

Circuit for finding R_{2S}

Replacing C_1
by short circuit



$$R_{2S} = R_L + \left(R_E \| R_{outCC}\right) = R_L + \left(R_E \left\| \frac{R_{TH} + r_\pi}{\beta + 1} \right\| r_o \right)$$

$$= 47.038\, k\Omega$$

$$\frac{1}{R_{2S} C_2} = \frac{1}{(47.038\, k\Omega)(100\, \mu F)} = 0.213\, rad/s$$

Estimation of ω_L

$$\omega_L \cong \sum_{i=1}^{2} \frac{1}{R_{iS} C_i} = 136.18 + 0.213 = 136.393\, rad/s$$

$$f_L = \frac{\omega_L}{2\pi} = 21.7\, Hz$$

Example

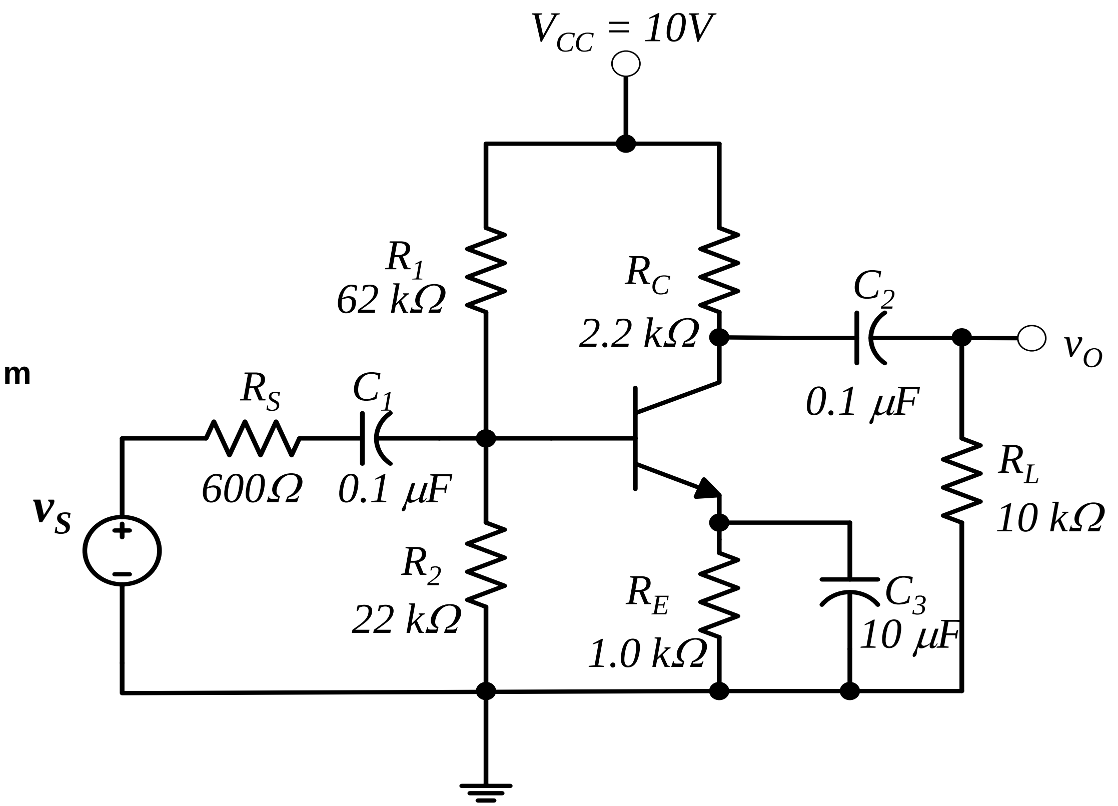
Given :

Q-point values : 1.6 mA, 4.86 V

β = 100, V_A = 70 V

Therefore,

r_π = 1.62 kΩ, r_o = 43.75 kΩ, g_m = 61.54 mS



Determine the total low-frequency response of the amplifier.

Low frequency due to C_1 and C_2 C_3

Low frequency due to C_1

$$R_{1S} = R_S + \left(R_B \| r_\pi\right) = 600 + \left(16.24k \| 1.62k\right) = 2.07\,k\Omega$$

$$R_B = R_1 \| R_2 = 16.24\,k\Omega$$

$$f_{C_1} = \frac{1}{2\pi R_{1S} C_1} = \frac{1}{2\pi(2.07\,k\Omega)(0.1\mu F)} = 768.86\,Hz \cong 769Hz$$

Low frequency due to C_2

$$R_{2S} = R_L + \left(R_C \| r_o\right) = 10\,k + \left(2.2k \| 43.75k\right) = 12.09\,k\Omega$$

$$f_{C_2} = \frac{1}{2\pi R_{2S} C_2} = \frac{1}{2\pi(12.09\,k\Omega)(0.1\mu F)} = 131.64\,Hz \cong 132Hz$$

Low frequency due to C_3

Low frequency due to C_3

$$R_{3S} = R_E \left\| \frac{r_\pi + R_{TH}}{\beta + 1} = 1k \right\| \frac{1.62k + 0.58k}{101} = 21.32\,\Omega$$

$$R_{TH} = R_S \| R_B = 0.58\,k\Omega$$

$$f_{C_3} = \frac{1}{2\pi R_{3S} C_3} = \frac{1}{2\pi(21.32\Omega)(10\mu F)} = 746.5\,Hz \cong 747\,Hz$$

Unit -4 Classification Of Amplifiers

1. According to frequency capabilities.

Amplifiers are classified as audio amplifiers , radio frequency amplifiers

- **AF Amplifier** are used to amplify the signals lying in the audio range (i.e. 20 Hz to 20 kHz)
- **RF amplifiers** are used to amplify signals having very high frequency.

2. According to coupling methods.

- R-C coupled amplifiers,
- Transformer coupled amplifiers
- Direct Coupled

Classification Of Amplifiers

3. According to use.

a. Voltage amplifiers

- Amplify the input voltage, if possible with minimal current at the output.
- The power gain of the voltage amplifier is low.
- The main application is to strengthen the signal to make it less affected by noise and attenuation.
- Ideal voltage amp. have infinite input impedance & zero output impedance.

a. Power amplifiers

- Amplify the input power, if possible with minimal change in the output voltage
- Power amp. are used in devices which require a large power across the loads.
- In multi stage amplifiers, power amplification is made in the final stages
  - ✓ Audio amplifiers and RF amplifiers use it to deliver sufficient power the load.
  - ✓ Servo motor controllers use power it to drive the motors.

Classification Of Amplifiers

	Voltage amplifiers	Power amplifiers
current gain	low	high
Voltage gain	high	low
Heat dissipation	low	high
cooling mechanism	not required	required
Transistor Size	Small	Large to dissipate heat
Base Width	small	Wide to handle higher current
Beta	Usually high >100	Low usually < 20

Amplifier Classes (Mode of operation)

- In small-signal amplifiers, the main factors are usually amplification linearity and magnitude of gain.
- Large-signal or power amplifiers, on the other hand, primarily provide sufficient power to an output load to drive a speaker or other power device, typically a few watts to tens of watts.
- The main features of a large-signal amplifier are the circuit's power efficiency, the maximum amount of power that the circuit is capable of handling, and the impedance matching to the output device.
- Amplifier classes represent the amount the output signal varies over one cycle of operation for a full cycle of input signal.

Power Amplifier Classes:

1. **Class A**: The output signal varies for a full 360° of the input signal.
   - Bias at the half of the supply

2. **Class B**: provides an output signal varying over one-half the input signal cycle, or for 180° of signal.
   - Bias at the zero level

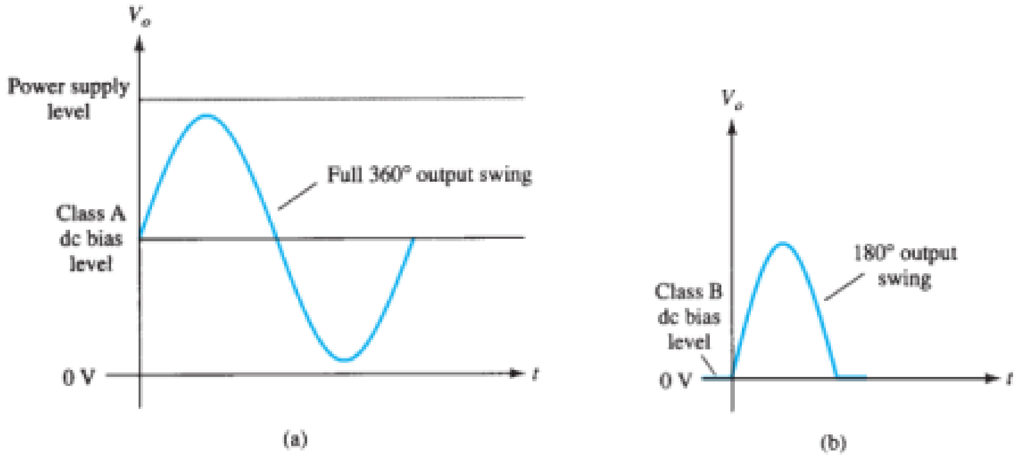


FIG. 12.1
Amplifier operating classes.

Amplifier Efficiency

Power Amplifier Classes …

3. **Class AB**: An amplifier may be biased at a dc level above the zero-base-current level of class B and above one-half the supply voltage level of class A.

4. **Class C:** The output of a class C amplifier is biased for operation at less than 180° of the cycle and will operate only with a tuned (resonant) circuit, which provides a full cycle of operation for the tuned or resonant frequency.

5. **Class D:** This operating class is a form of amplifier operation using pulse (digital) signals, which are on for a short interval and off for a longer interval.

- The **power efficiency** of an amplifier, defined as the ratio of power output to power input, improves (gets higher) going from class A to class D.

TABLE 12.1

Comparison of Amplifier Classes

			Class		
	A	AB	B	C[a]	D
Operating cycle	360°	180° to 360°	180°	Less than 180°	Pulse operation
Power efficiency	25% to 50%	Between 25% (50%) and 78.5%	78.5%		Typically over 90%

[a]Class C is usually not used for delivering large amounts of power, and thus the efficiency is not given here.

SERIES-FED CLASS A AMPLIFIER

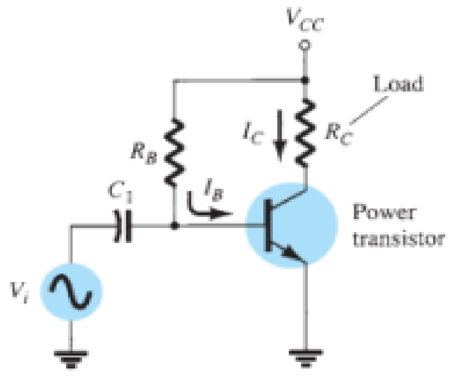


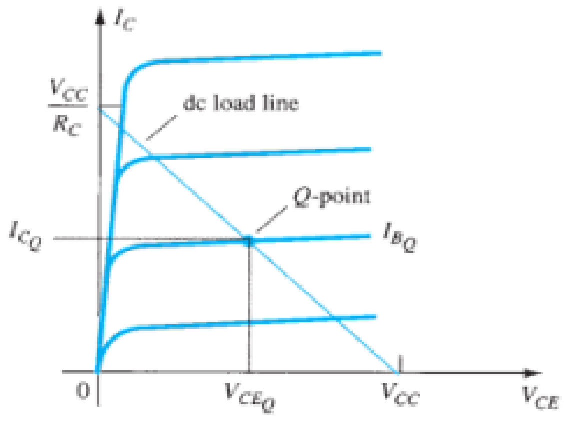
FIG. 12.2
Series-fed class A large-signal amplifier.

- DC Bias Operation

$$I_B = \frac{V_{CC} - 0.7\text{ V}}{R_B}$$

$$I_C = \beta I_B$$

$$V_{CE} = V_{CC} - I_C R_C$$



- AC Operation

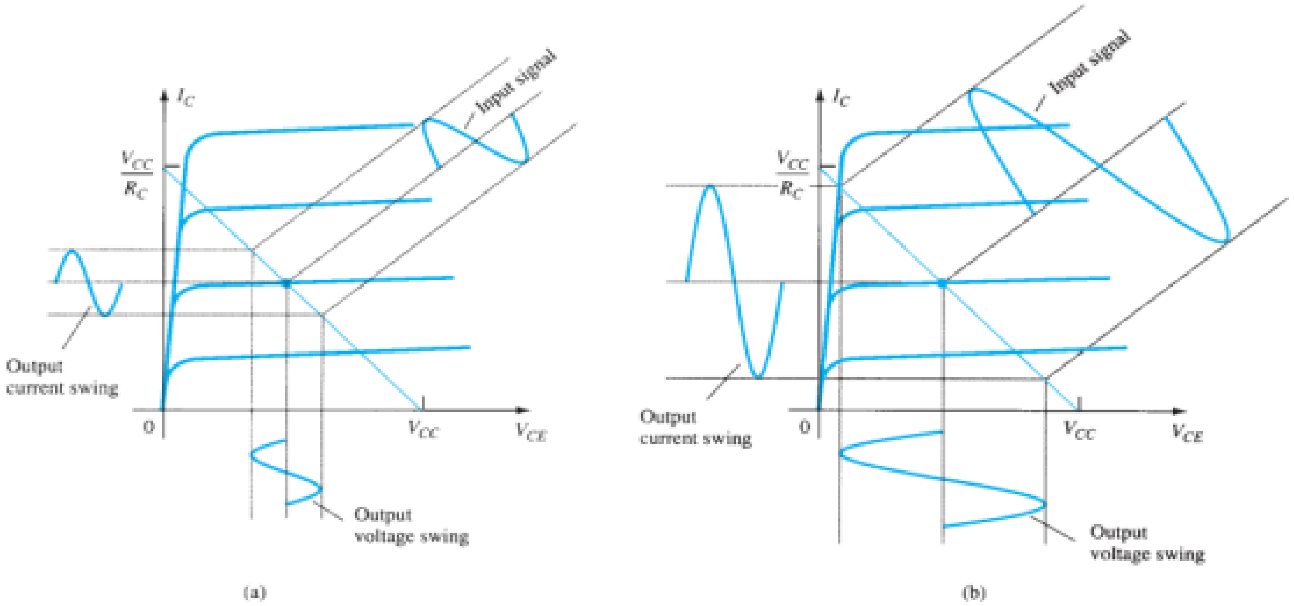


FIG. 12.4
Amplifier input and output signal variation.

Power Considerations

- The power drawn from the supply is $P_i(\text{dc}) = V_{CC}I_{C_Q}$

- Output Power

$$P_o(\text{ac}) = V_{CE}(\text{rms})I_C(\text{rms})$$

$$P_o(\text{ac}) = I_C^2(\text{rms})R_C$$

$$P_o(\text{ac}) = \frac{V_C^2(\text{rms})}{R_C}$$

- Efficiency

$$\%\ \eta = \frac{P_o(\text{ac})}{P_i(\text{dc})} \times 100\%$$

- Maximum Efficiency

$$\text{maximum } V_{CE}(\text{p-p}) = V_{CC}$$

$$\text{maximum } I_C(\text{p-p}) = \frac{V_{CC}}{R_C}$$

$$\text{maximum } P_o(\text{ac}) = \frac{V_{CC}(V_{CC}/R_C)}{8} = \frac{V_{CC}^2}{8R_C}$$

$$\text{maximum } P_i(\text{dc}) = V_{CC}(\text{maximum } I_C) = V_{CC}\frac{V_{CC}/R_C}{2} = \frac{V_{CC}^2}{2R_C}$$

The maximum power input can be calculated using the dc bias current set to one-half the

$$\text{maximum } \%\ \eta = \frac{\text{maximum } P_o(\text{ac})}{\text{maximum } P_i(\text{dc})} \times 100\% = \frac{V_{CC}^2/8R_C}{V_{CC}^2/2R_C} \times 100\% = 25\%$$

N.B.:

$$V_{\text{RMS}} = \frac{V_{\text{P}}}{\sqrt{2}}$$

The Class B and Class AB Push-Pull Amplifiers

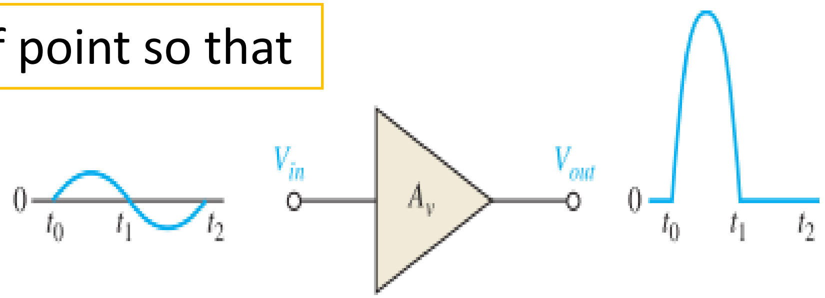
- Class B amplifier: When an amplifier is biased at cutoff so that it operates in the linear region for 180º of the input cycle and is in cutoff for 180º
- Class AB amplifiers: are biased to conduct for slightly more than 180o
- Both are more efficient than a class A amplifier;

- A disadvantage of class B or class AB is that it is more difficult to implement the circuit in order to get a linear reproduction of the input waveform.
- The term **push-pull** refers to a common type of class B or class AB amplifier circuit in which two transistors are used on alternating half-cycles to reproduce the input waveform at the output.

Class B Operation

➢ The class B amplifier is biased at the cutoff point so that

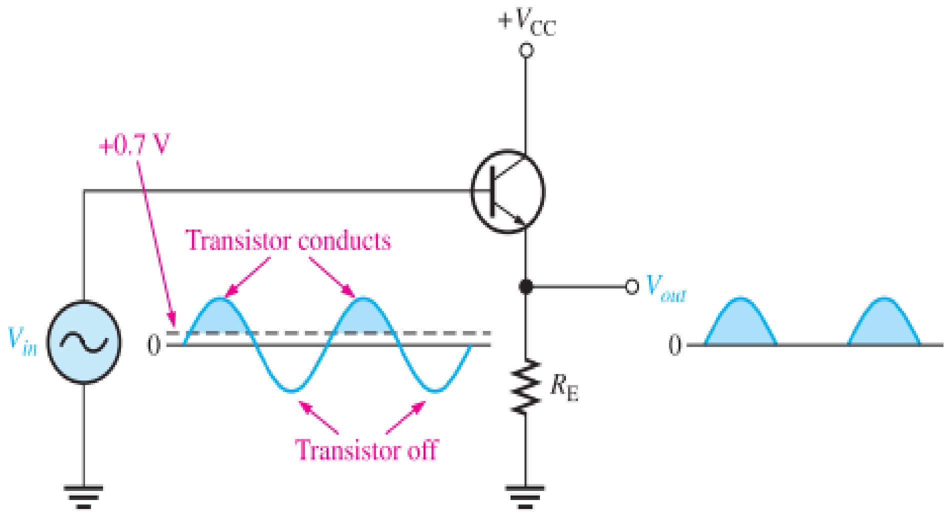
$$I_{CQ} = 0 \text{ and } V_{CEQ} = V_{CE(cutoff)}.$$



➢ It is brought out of cutoff and operates in its linear region when the input signal drives the transistor into conduction.

➢ The Circuit only conducts for the positive half of the cycle.

➢ Can not amplify the entire cycle



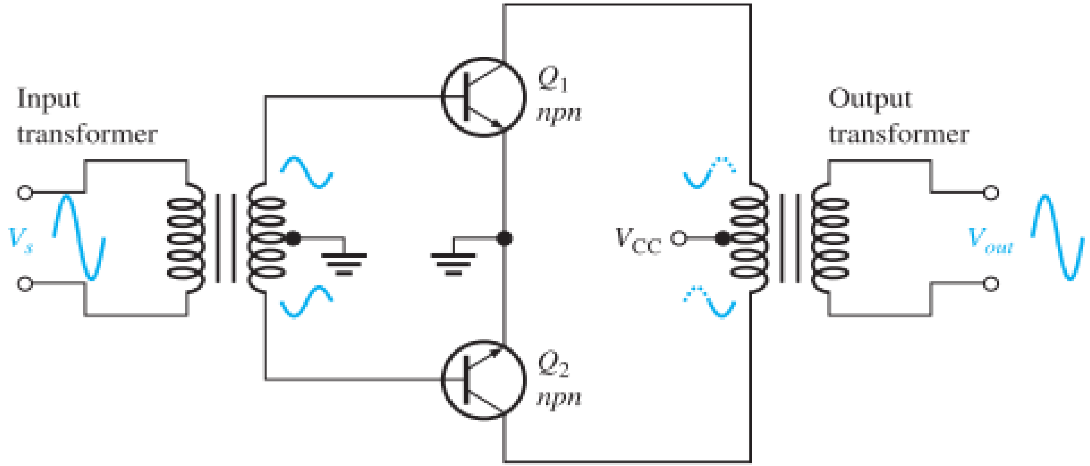
emitter-follower circuit

Class B Push-Pull Operation

- To amplify the entire cycle, it is necessary to add a second class B amplifier that operates on the negative half of the cycle.
- The combination of two class B amplifiers working together is called push-pull operation
- There are **two common approaches** for using push-pull amplifiers to reproduce the entire waveform.

1. Transformer Coupling

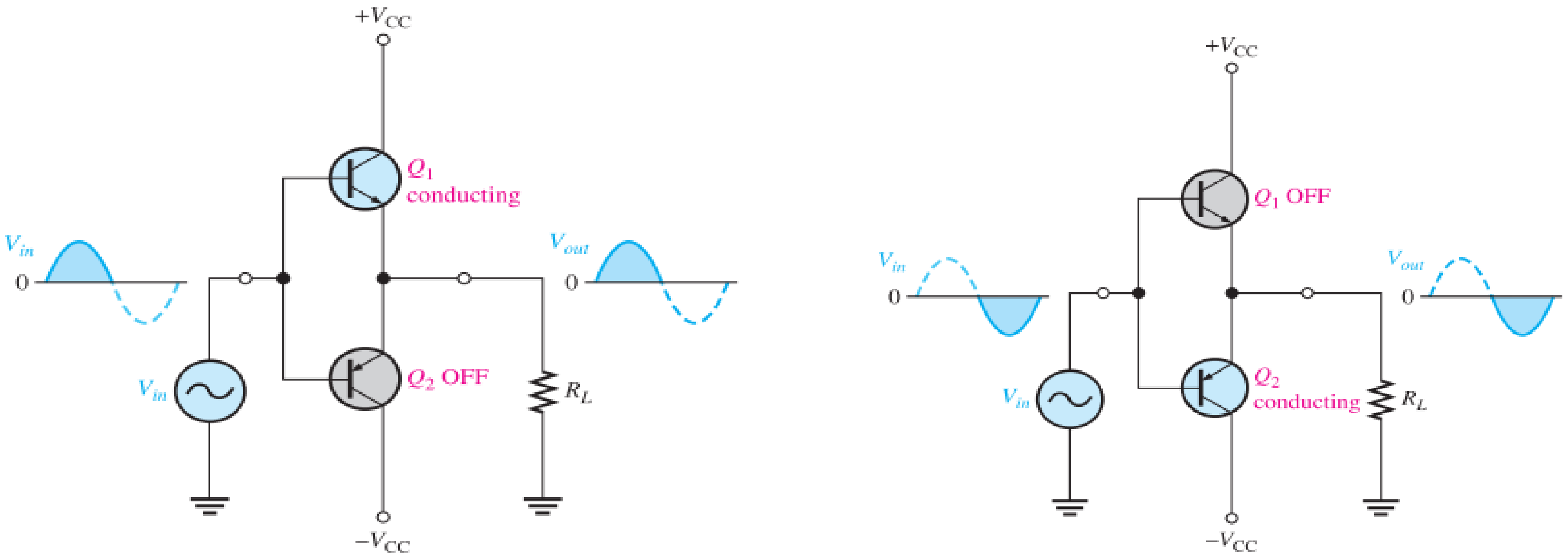
- ✓ The input transformer thus converts the input signal to two out-of-phase signals for the two npn transistors.



- ✓ The output transformer combines the signals by permitting current in both directions, even though one transistor is always cut off.

2. Complementary Symmetry Transistors

- ✓ The figure shows one of the most popular types of push-pull class B amplifiers using two emitter-followers and both positive and negative power supplies.
- ✓ This is a complementary amplifier because one emitter-follower uses an npn transistor and the other a pnp, which conduct on opposite alternations of the input cycle.

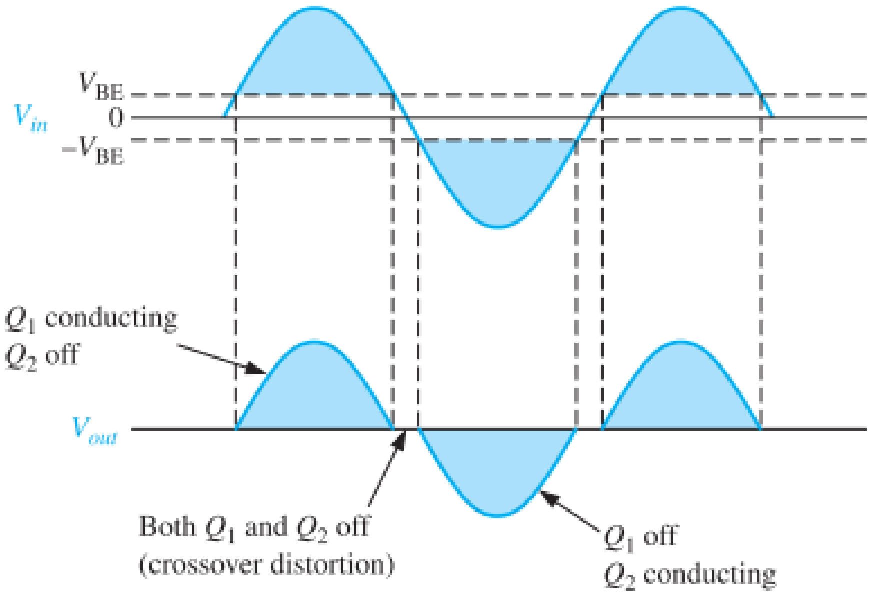


(a) During a positive half-cycle

(b) During a negative half-cycle

Crossover Distortion

- ✓ When the dc base voltage is zero, both transistors are off and the input signal voltage must exceed V_{BE} before a transistor conducts.
- ✓ Because of this, there is a time interval between the positive and negative alternations of the input when neither transistor is conducting, as shown in Figure.
- ✓ The resulting distortion in the output waveform is called **crossover distortion**.



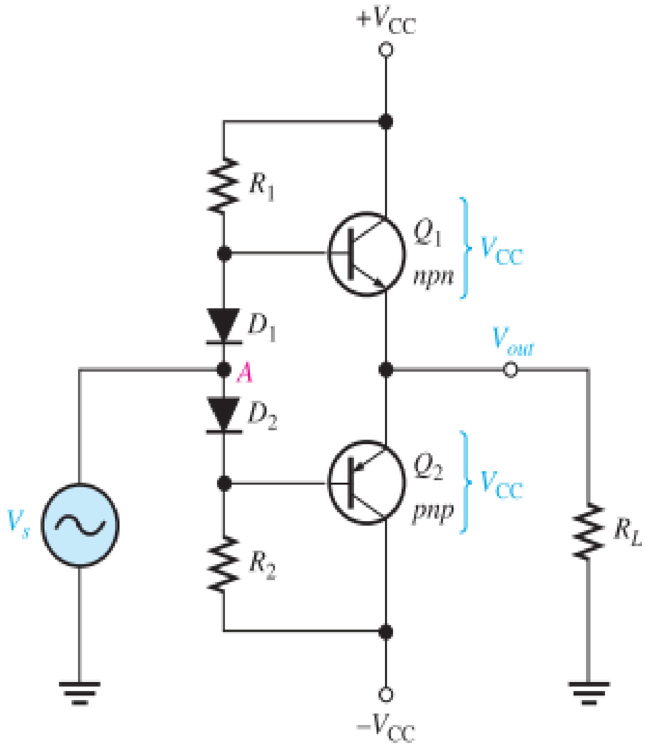
Biasing the Push-Pull Amplifier for Class AB Operation

- ✓ To overcome crossover distortion, the biasing is adjusted to just overcome the VBE of the transistors
- ✓ In class AB operation, the push-pull stages are biased into slight conduction, even when no input signal is present.
- ✓ This can be done with a voltage-divider and diode arrangement, as shown

- ➢ Using equal values of R1 and R2 the positive and negative supply voltages forces the voltage at point A to equal 0 V and eliminates the need for an input coupling capacitor.

- ➢ When the diode characteristics of D1 and D2 are closely matched to the characteristics of the transistor BE junctions, the current in the diodes and the current in the transistors are the same; **((current mirror.))**

The diode current will be the same as ICQ



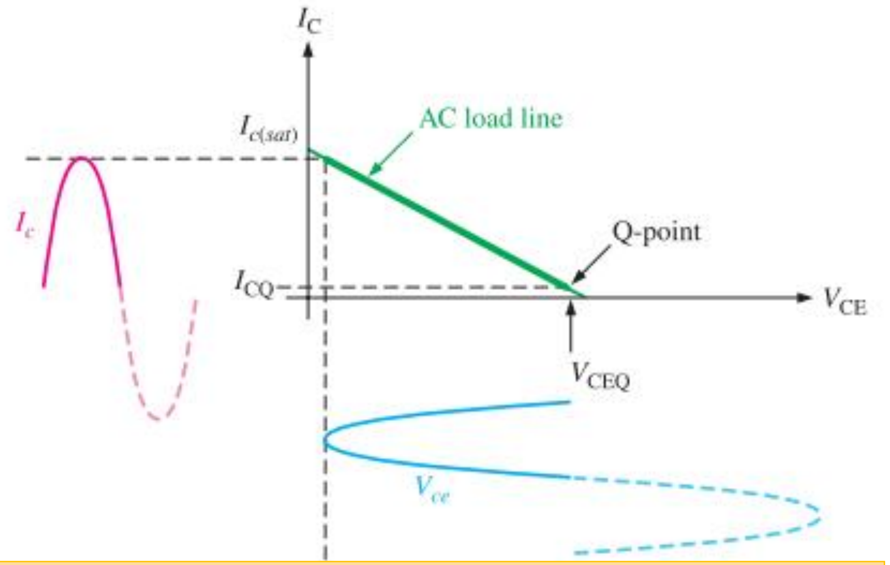
$$I_{CQ} = \frac{V_{CC} - 0.7\text{ V}}{R_1}$$

Biasing the Push-Pull Amplifier for Class AB Operation

✓ AC Operation

- The Q-point is slightly above cutoff. (In a true class B amplifier, the Q-point is at cutoff.)
- The ac cutoff voltage is at Vcc
- The ac saturation current is:

$$I_{c(sat)} = \frac{V_{CC}}{R_L}$$



✓ In class A , the Q-point is near the middle and there is significant current in the transistors even with no signal.

✓ In class B , when there is no signal, the transistors have only a very small current and therefore dissipate very little power.

✓ Thus, the efficiency of a class B amplifier can be much higher than a class A amplifier.

The ideal maximum peak output voltage is

$$V_{out(peak)} \cong V_{CEQ} \cong V_{CC}$$

The ideal maximum peak current is

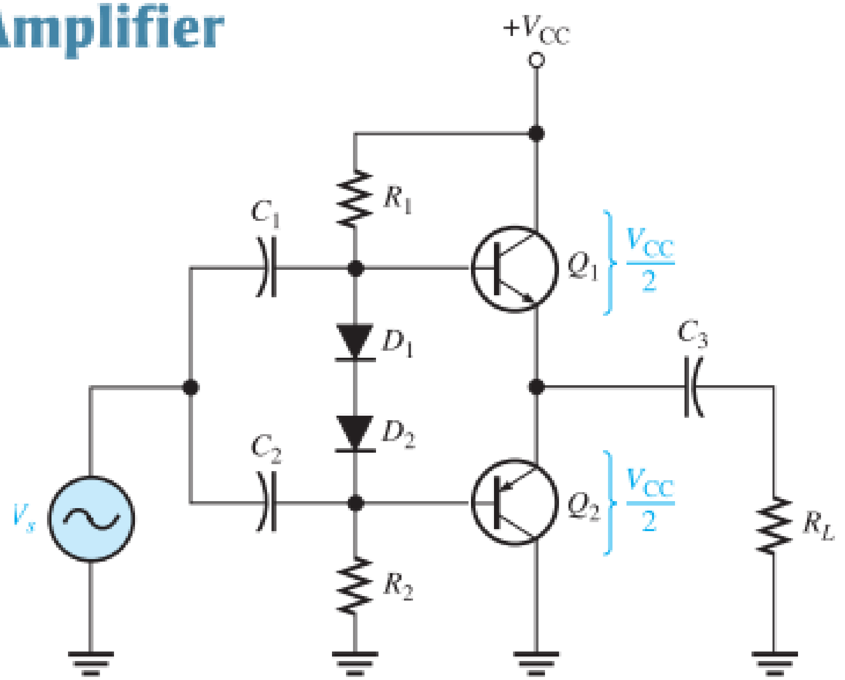
$$I_{out(peak)} \cong I_{c(sat)} \cong \frac{V_{CC}}{R_L}$$

Single-Supply Push-Pull Amplifier

- The circuit operation is the same as that described previously, except the bias is set to force the output emitter voltage to be

$$V_{out(peak)} \cong V_{CEQ} = \frac{V_{CC}}{2}$$

$$I_{out(peak)} \cong I_{c(sat)} = \frac{V_{CEQ}}{R_L}$$



Maximum Output Power

$$P_{out} = I_{out(rms)}V_{out(rms)}$$

$$I_{out(rms)} = 0.707I_{out(peak)} = 0.707I_{c(sat)}$$

$$V_{out(rms)} = 0.707V_{out(peak)} = 0.707V_{CEQ}$$

$$P_{out} = 0.5I_{c(sat)}V_{CEQ}$$

Substituting $V_{CC}/2$ for V_{CEQ}, the maximum average output power is

$$\mathbf{P_{out} = 0.25I_{c(sat)}V_{CC}}$$

DC Input Power

The dc input power comes from the V_{CC} supply and is

$$P_{DC} = I_{CC}V_{CC}$$

Since each transistor draws current for a half-cycle, the current is a half-wave signal with an average value of

$$I_{CC} = \frac{I_{c(sat)}}{\pi}$$

$$P_{DC} = \frac{I_{c(sat)}V_{CC}}{\pi}$$

Efficiency

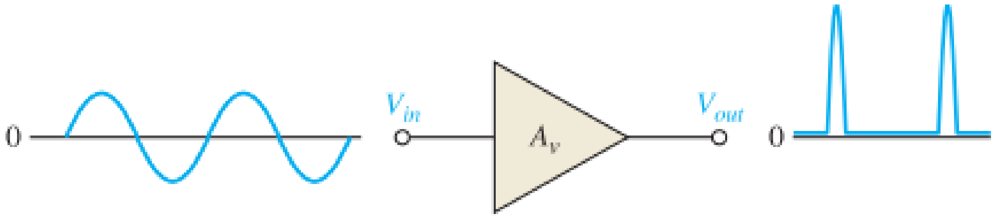
$$\eta = \frac{P_{out}}{P_{DC}}$$

$$\eta_{max} = \frac{P_{out}}{P_{DC}} = \frac{0.25I_{c(sat)}V_{CC}}{I_{c(sat)}V_{CC}/\pi} = 0.25\pi$$

$$\mathbf{\eta_{max} = 0.79}$$

Class C amplifiers

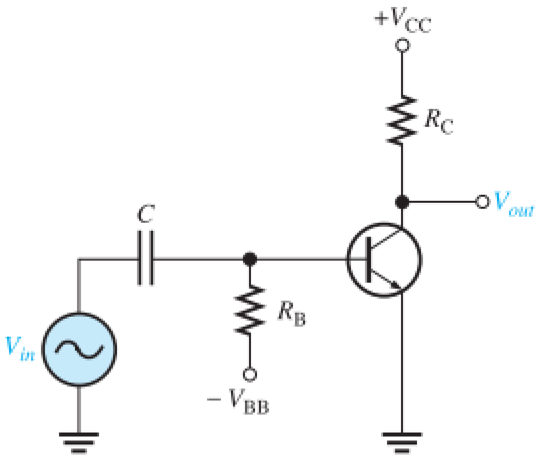
- Class C amplifiers are biased so that conduction occurs for much less than 180o
- Class C amplifiers are more efficient than either class A , B, or AB



- The output amplitude is a nonlinear function of the input, so class C amplifiers are not used for linear amplification.
- They are generally used in radio frequency (RF) applications, including resonance circuits

Basic Class C Operation

- A class C amplifier is normally operated with a resonant circuit load, so the resistive load is used only for the purpose of illustrating the concept.
- The ac source voltage has a peak value that exceeds the barrier potential of the base-emitter junction for a short time near the positive peak of each cycle,

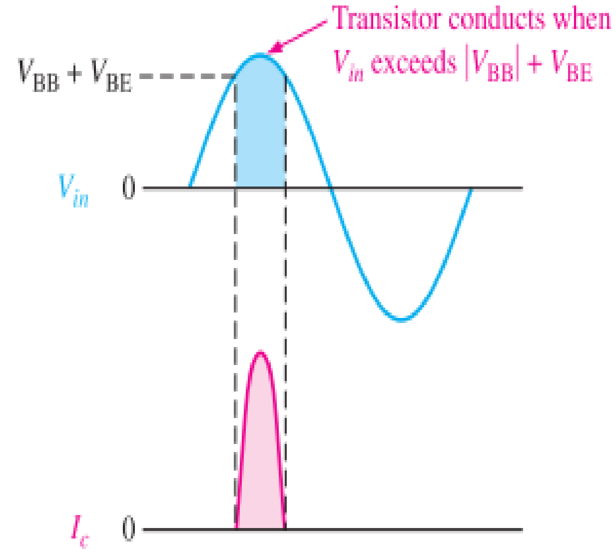


(a) Basic class C amplifier circuit

Class C amplifiers

Basic Class C Operation

- During this short interval, the transistor is turned on.
- The power dissipation of the transistor in a class C amplifier is low because it is on for only a small percentage of the input cycle



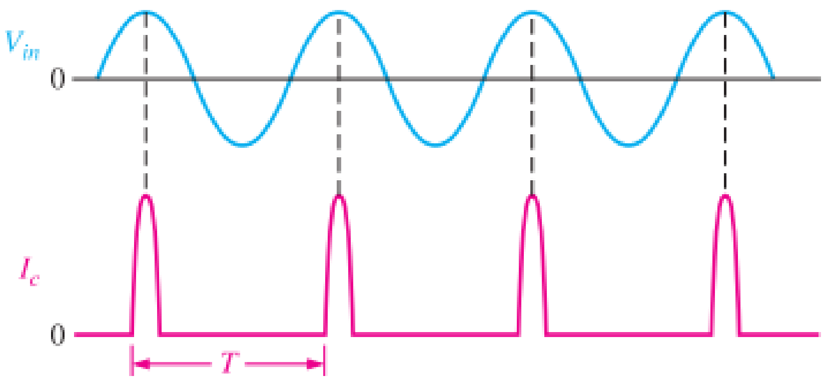
(b) Input voltage and output current waveforms

- The power dissipation during the on time is

$$P_{D(on)} = I_{c(sat)}V_{ce(sat)}$$

- The power dissipation averaged over the entire cycle is

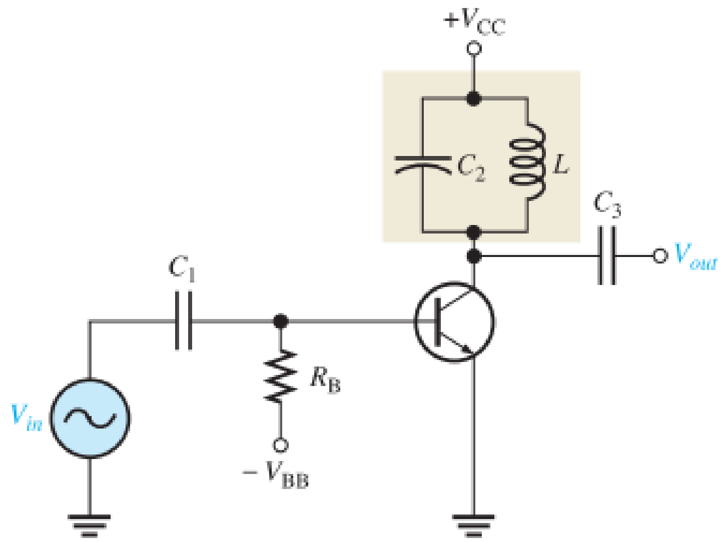
$$P_{D(avg)} = \left(\frac{t_{on}}{T}\right)P_{D(on)} = \left(\frac{t_{on}}{T}\right)I_{c(sat)}V_{ce(sat)}$$



Tuned Class C Operation

- Because the collector voltage (output) is not a replica of the input, the resistively loaded class C amplifier alone is of no value in linear applications.
- It is therefore necessary to use a class C amplifier with a parallel resonant circuit (tank), as shown

- The short pulse of collector current on each cycle of the input initiates and sustains the oscillation of the tank circuit so that an output sinusoidal voltage is produced

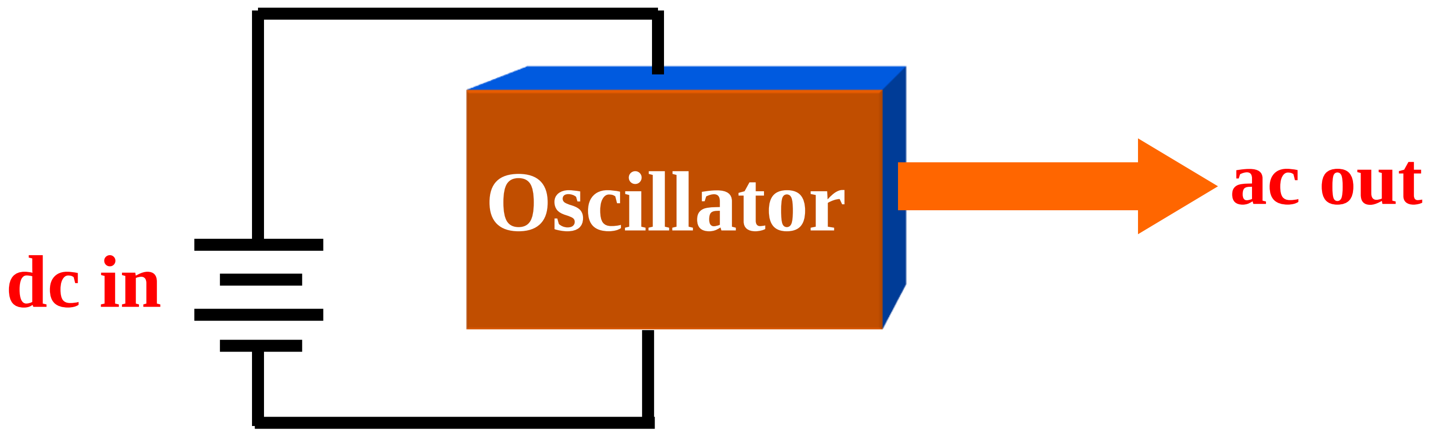


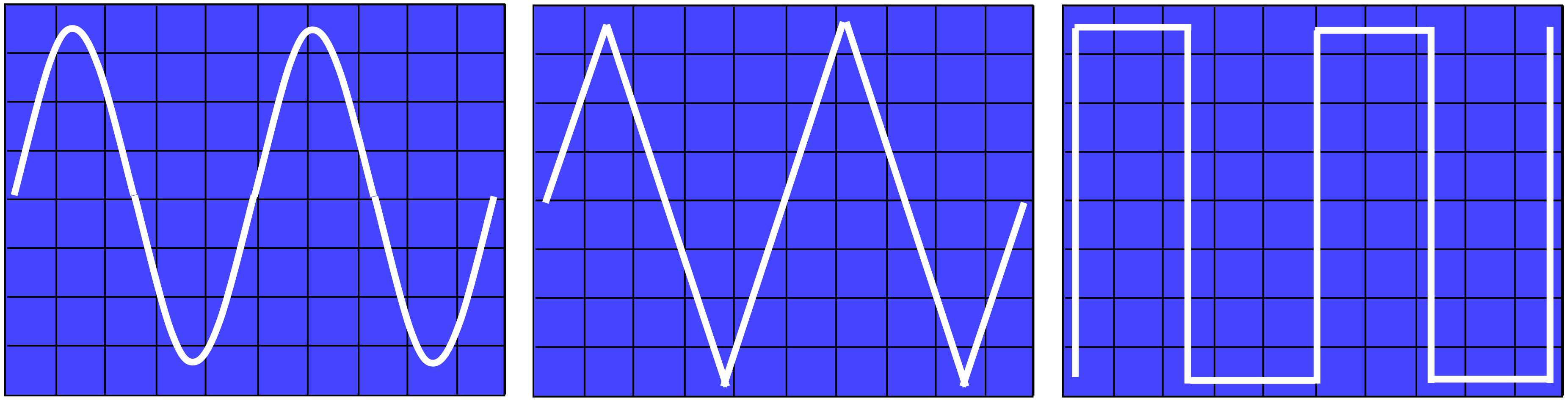
(a) Basic circuit

Unit- 5 Oscillators

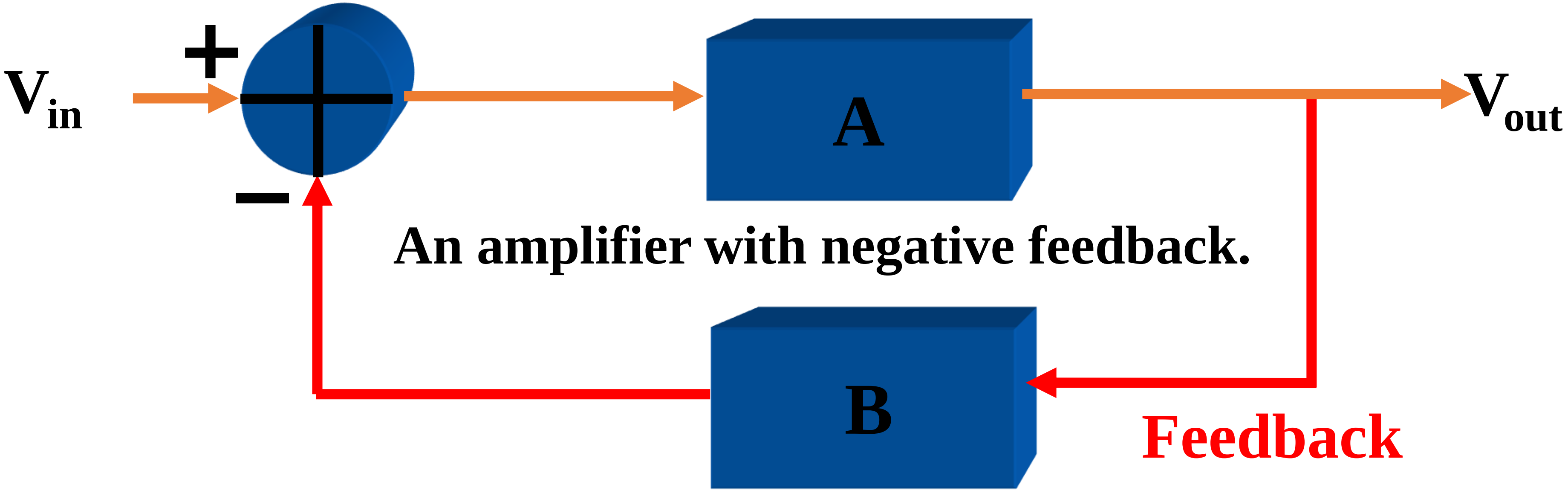
- Oscillator Characteristics
- RC Circuits
- LC Circuits
- Crystal Circuits
- Relaxation Oscillators
- Undesired Oscillations
- Troubleshooting
- Direct Digital Synthesis

Oscillators convert dc to ac.

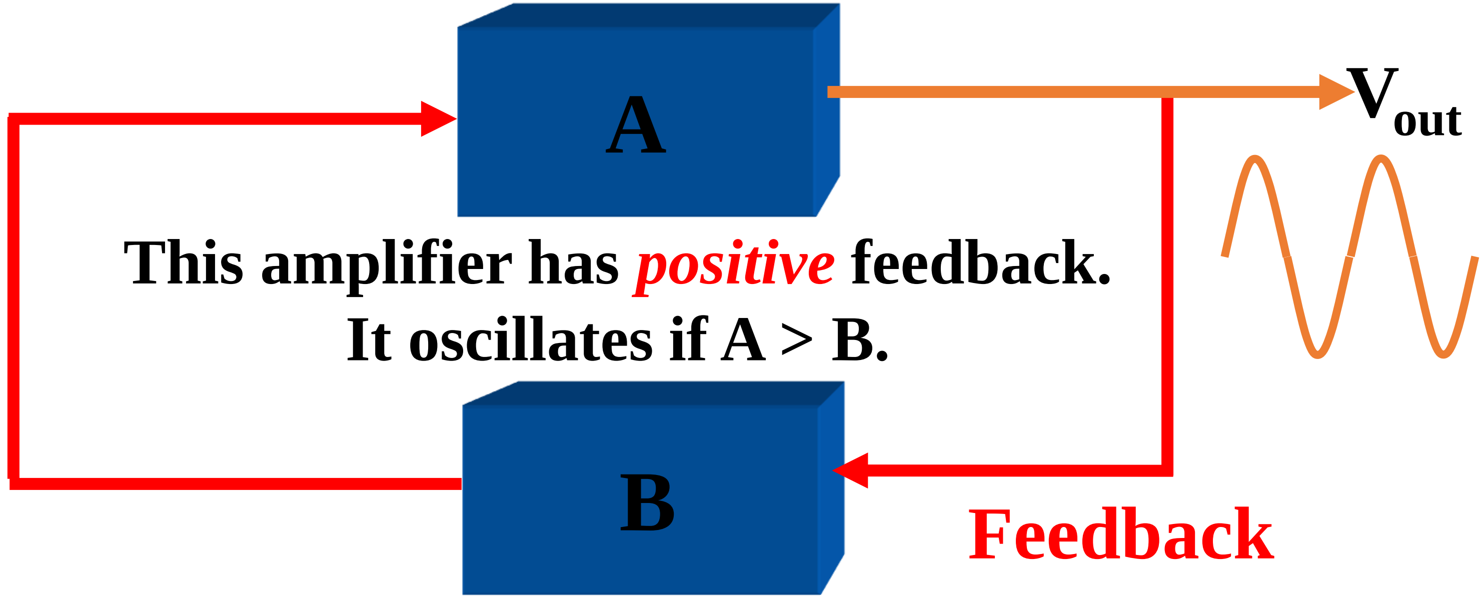


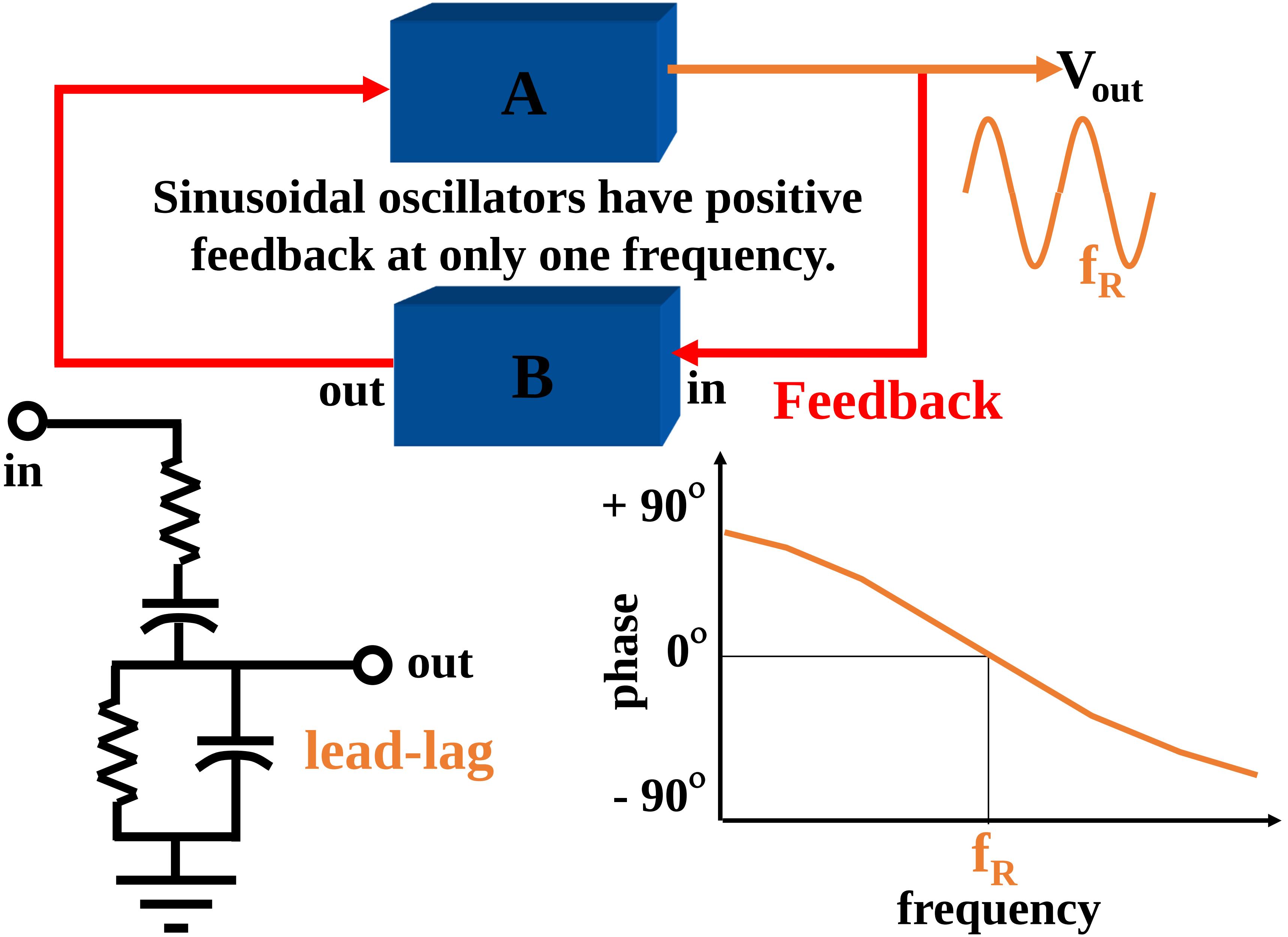


Some possible output waveforms



Recall: A = open-loop gain and B = feedback fraction





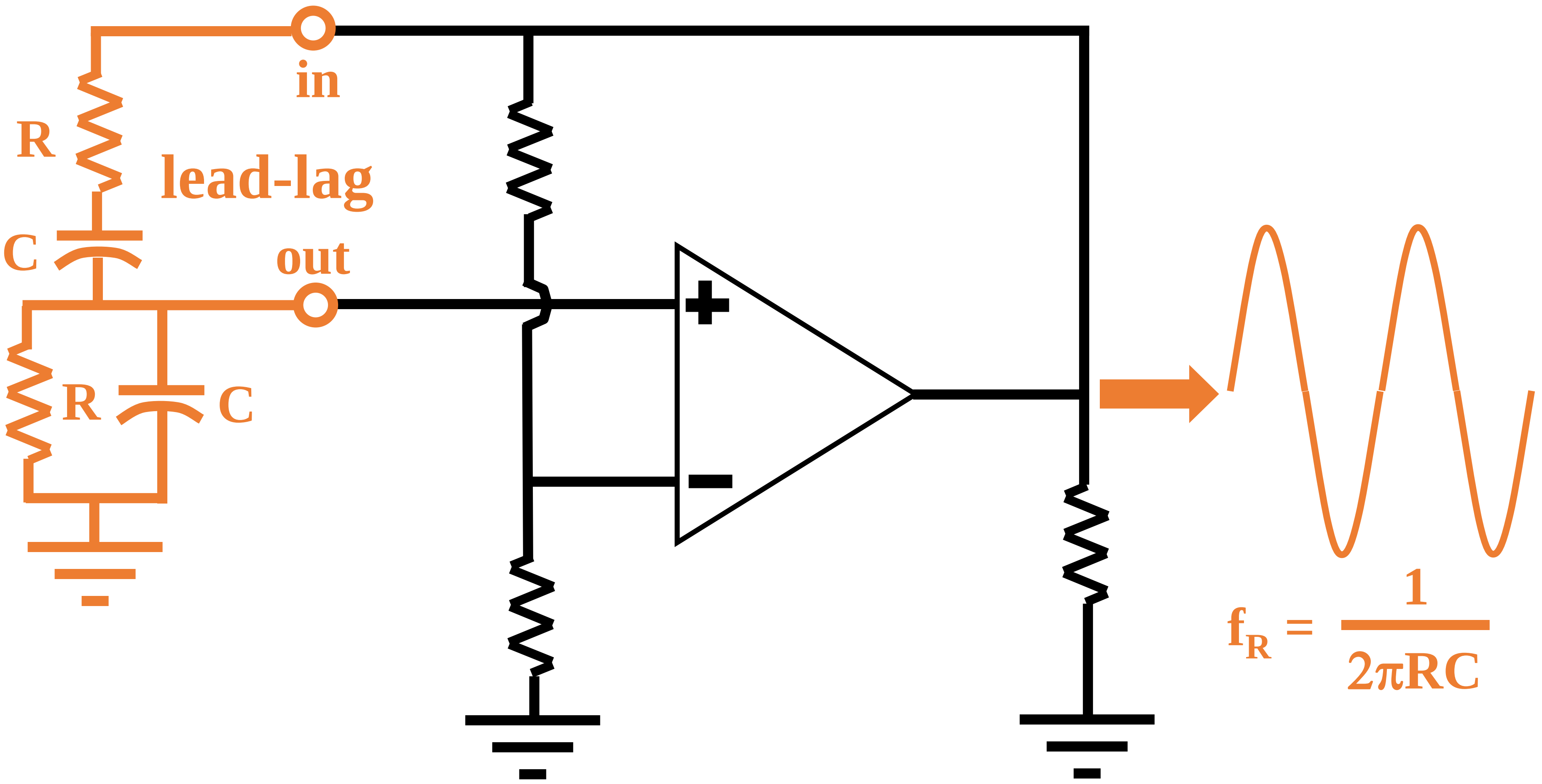
This can be accomplished with RC or LC networks.

Oscillator Basics Quiz

Oscillators convert dc to __________.	ac
In order for an oscillator to work, the feedback must be __________.	positive
An oscillator can't start unless gain (A) is __________ than feedback fraction (B).	greater
Sine wave oscillators have the correct feedback phase at one __________.	frequency
The phase shift of an RC lead-lag network at f_R is __________.	0^o

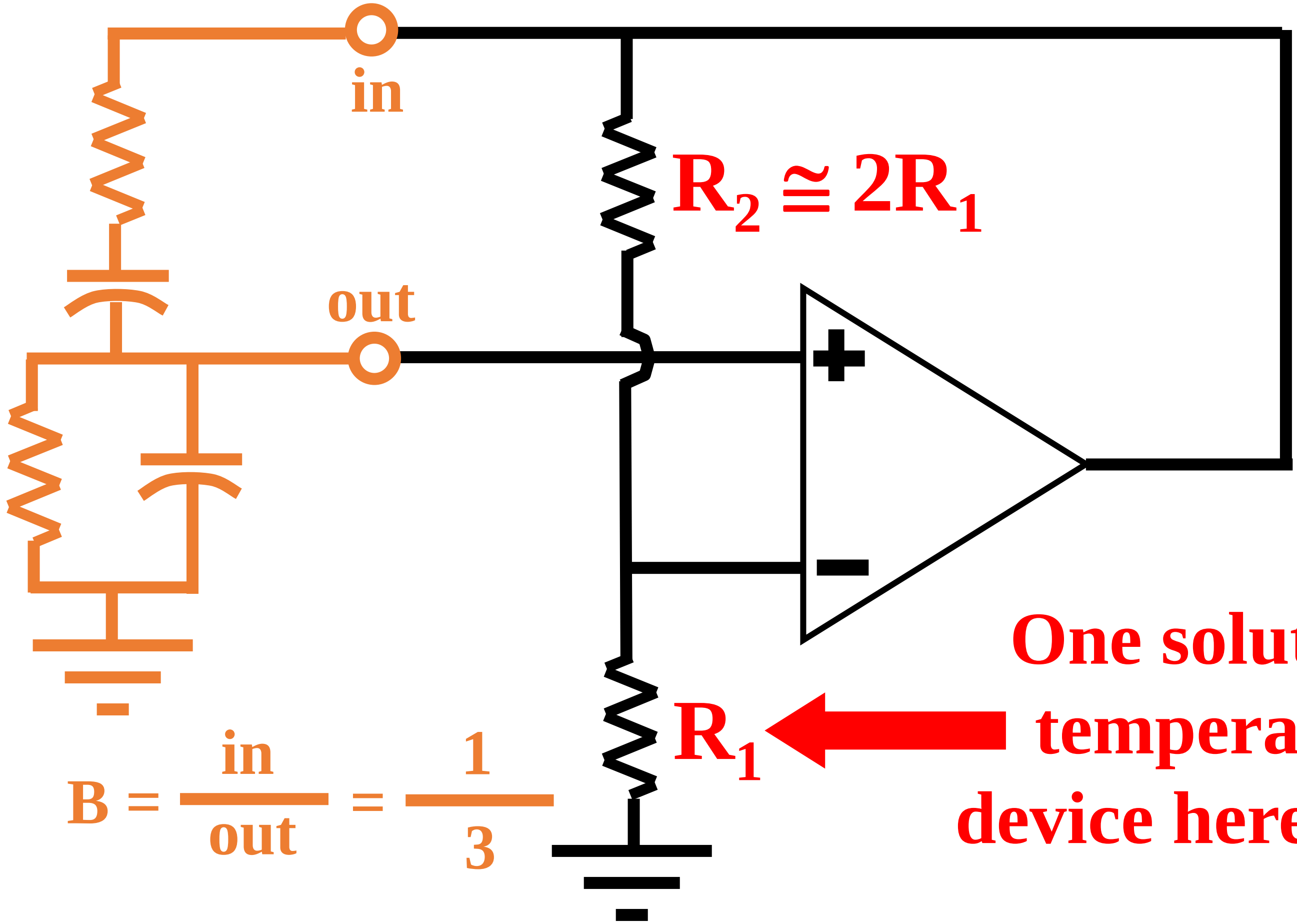
Wien Bridge Oscillator

Only f_R arrives at the + input in phase.



The feedback fraction at f_R in this circuit is one-third:

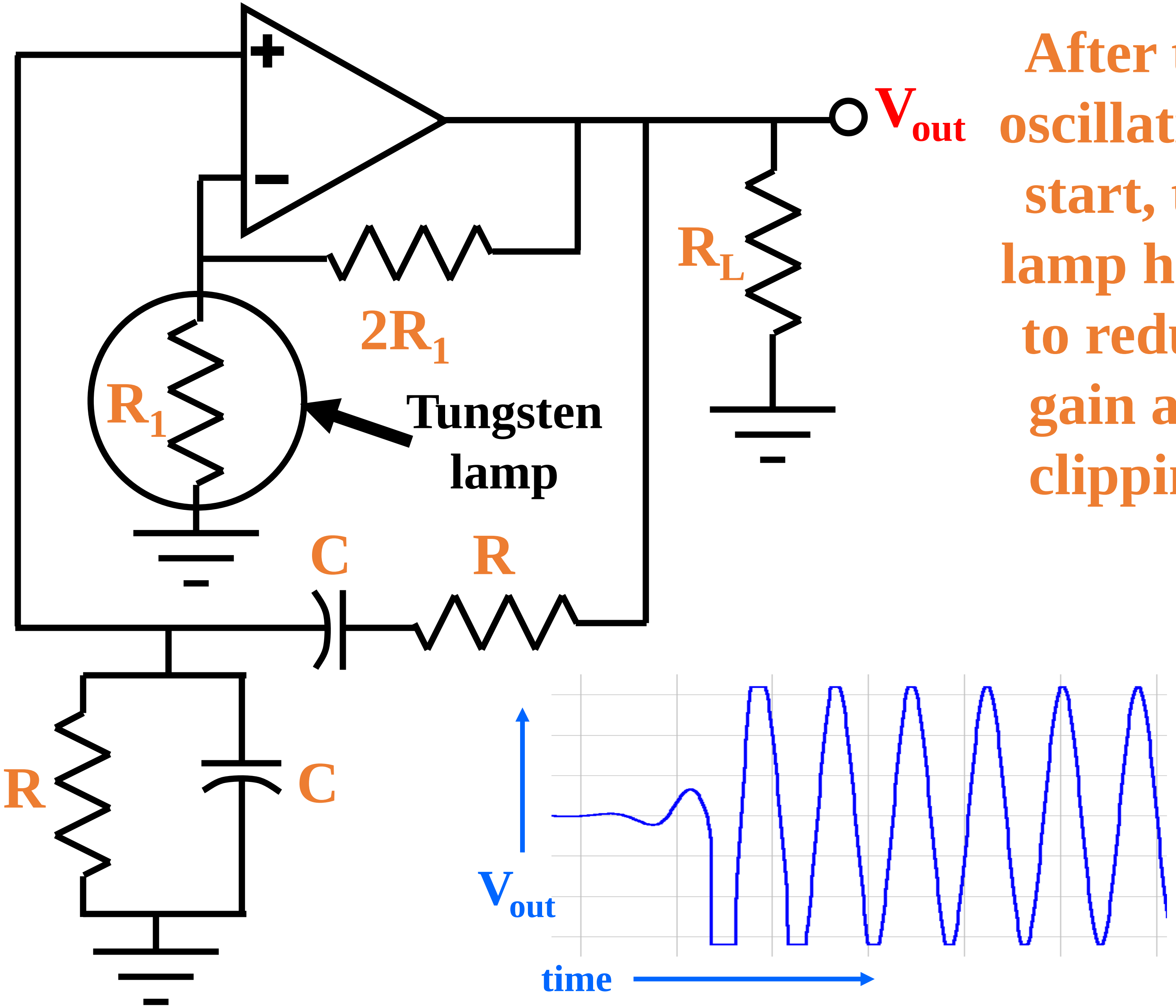
A must be > 3 for oscillations to start. After that, **A** must be reduced to avoid driving the op amp to V_{SAT}.



$$A = 1 + \frac{R_2}{R_1}$$

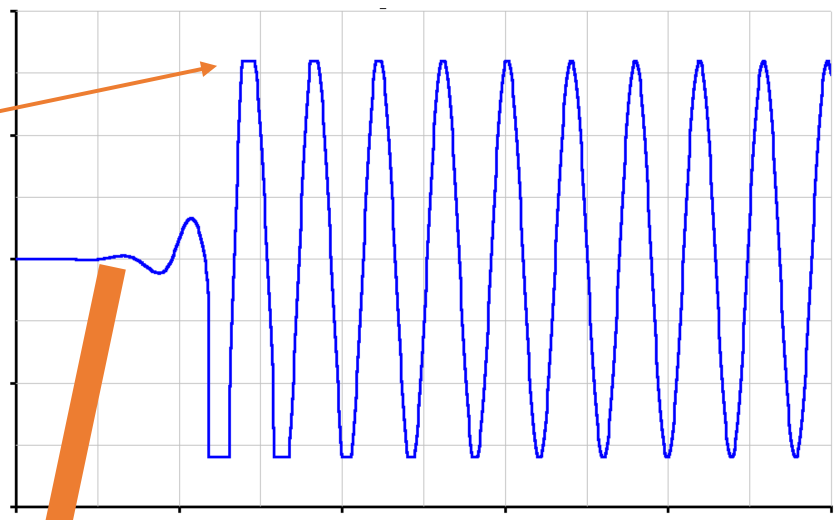
$$B = \frac{in}{out} = \frac{1}{3}$$

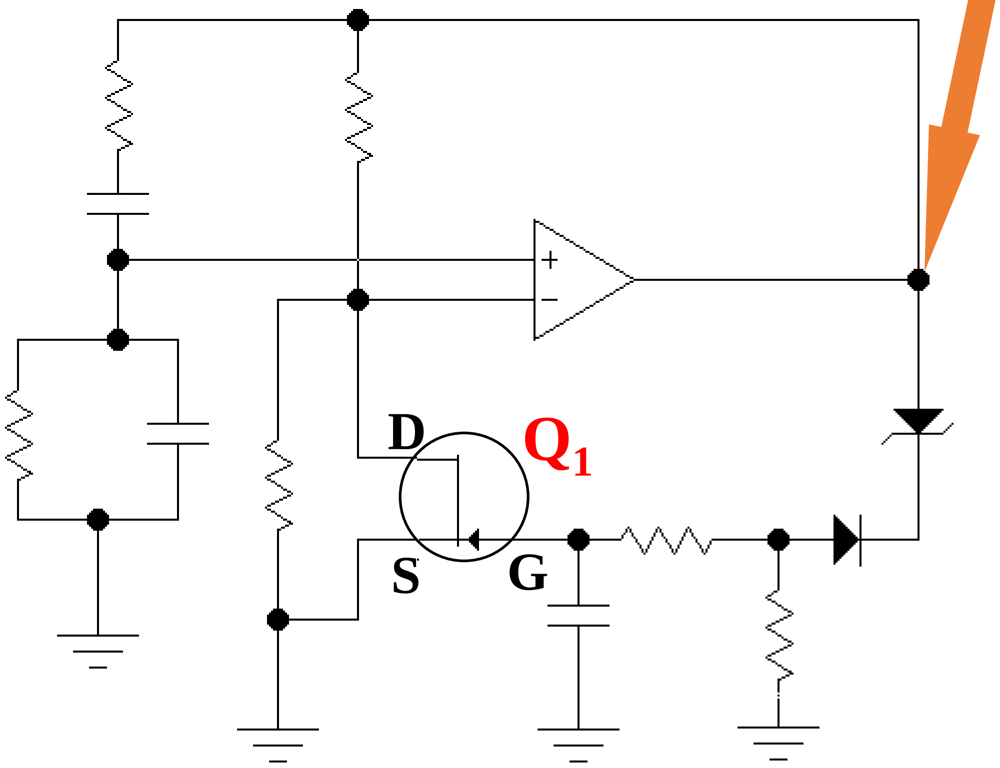
One solution is a positive temperature coefficient device here to decrease gain.



After the oscillations start, the lamp heats to reduce gain and clipping.

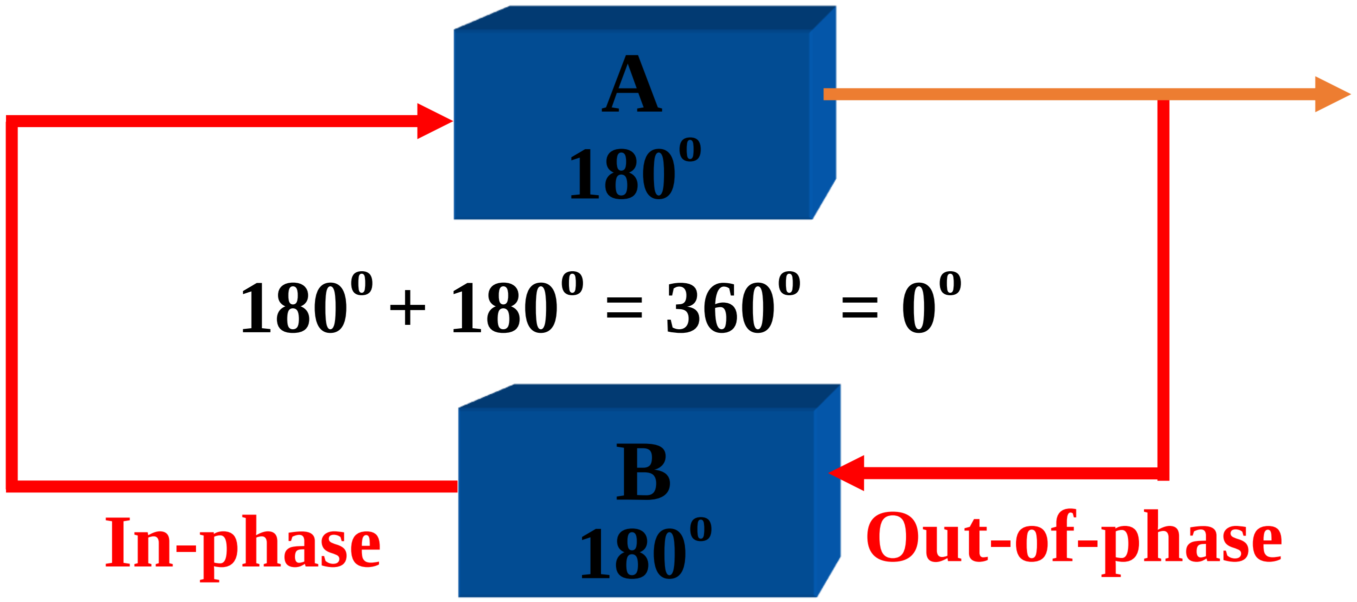
Notice that the clipping subsides as Q_1 reduces the loop gain.



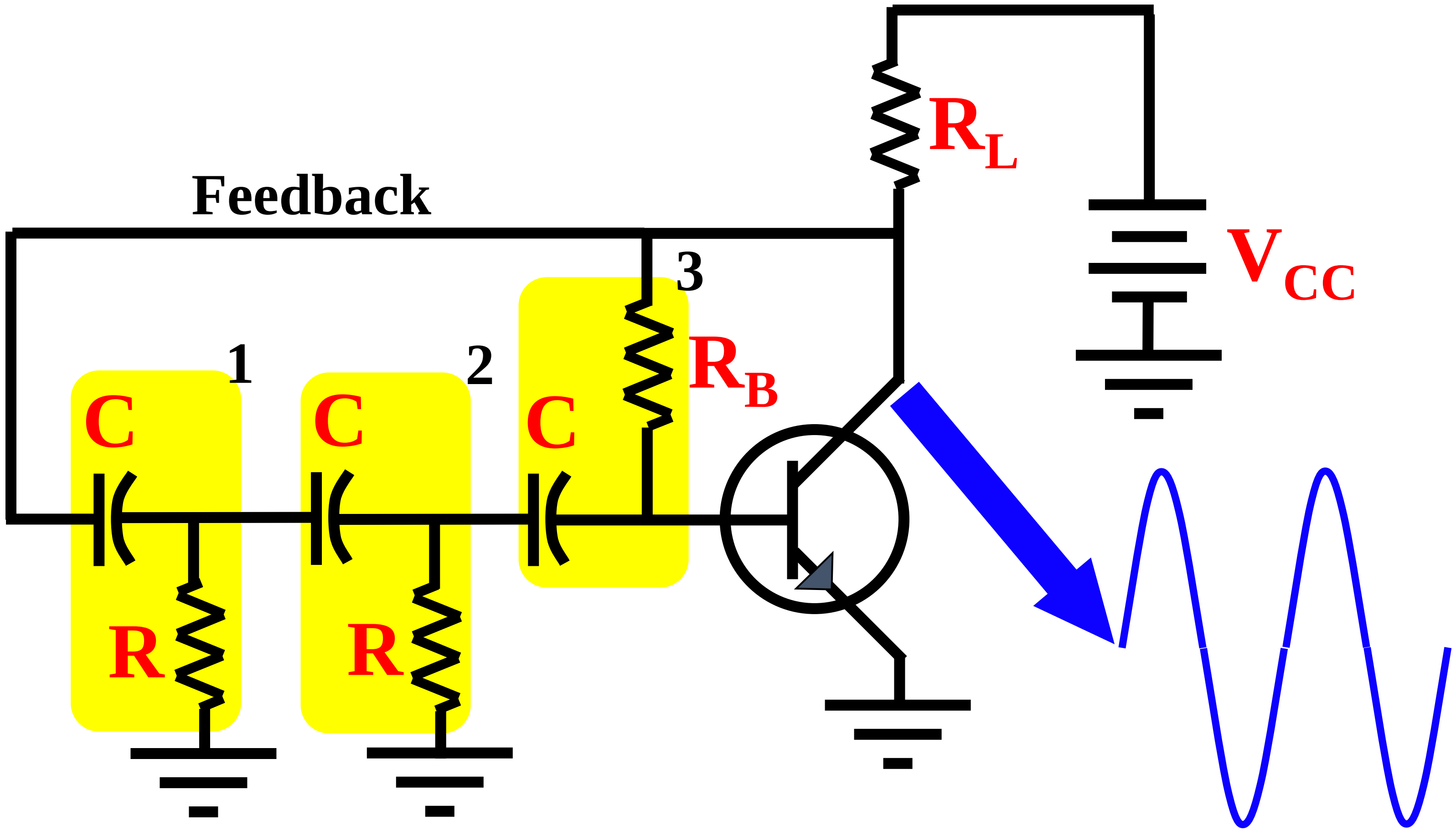


Q_1 is an N-channel JFET. After oscillations start, the output signal is rectified and the negative voltage is applied to the JFET's gate. This increases its D-S resistance which decreases the gain of the op amp.

When common-emitter amplifiers are used as oscillators, the feedback circuit must provide a 180^o phase shift to make the circuit oscillate.



A phase-shift oscillator based on a common-emitter amplifier



3 RC networks provide a total phase shift of 180°.

RC Oscillator Quiz

A properly designed Wien bridge oscillator provides a ___________ waveform. sine

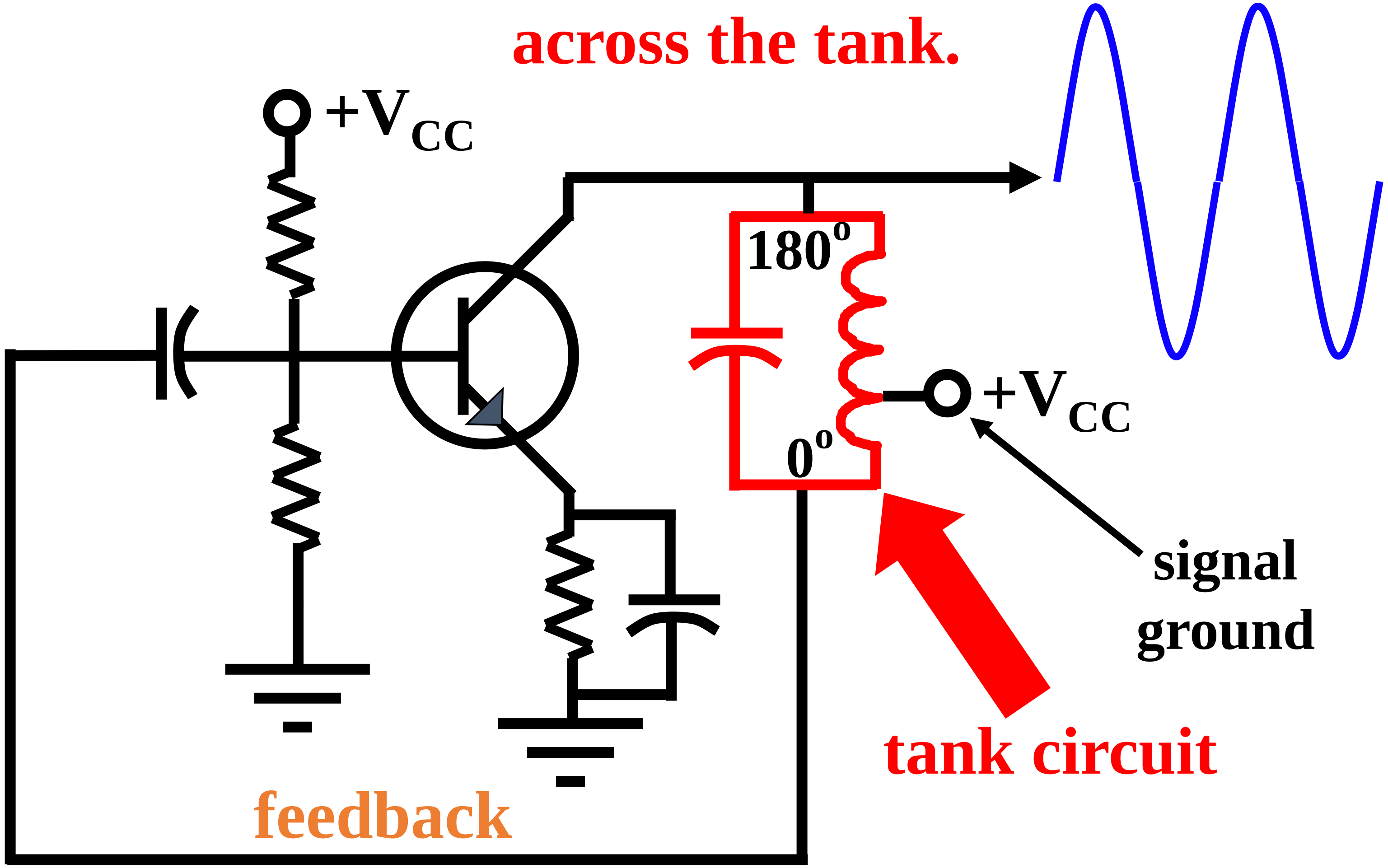
The feedback fraction in a Wien bridge oscillator is ___________. 0.333

A tungsten lamp has a ___________ temperature coefficient. positive

The feedback circuit in a common-emitter oscillator provides ___________ of phase shift. 180^o

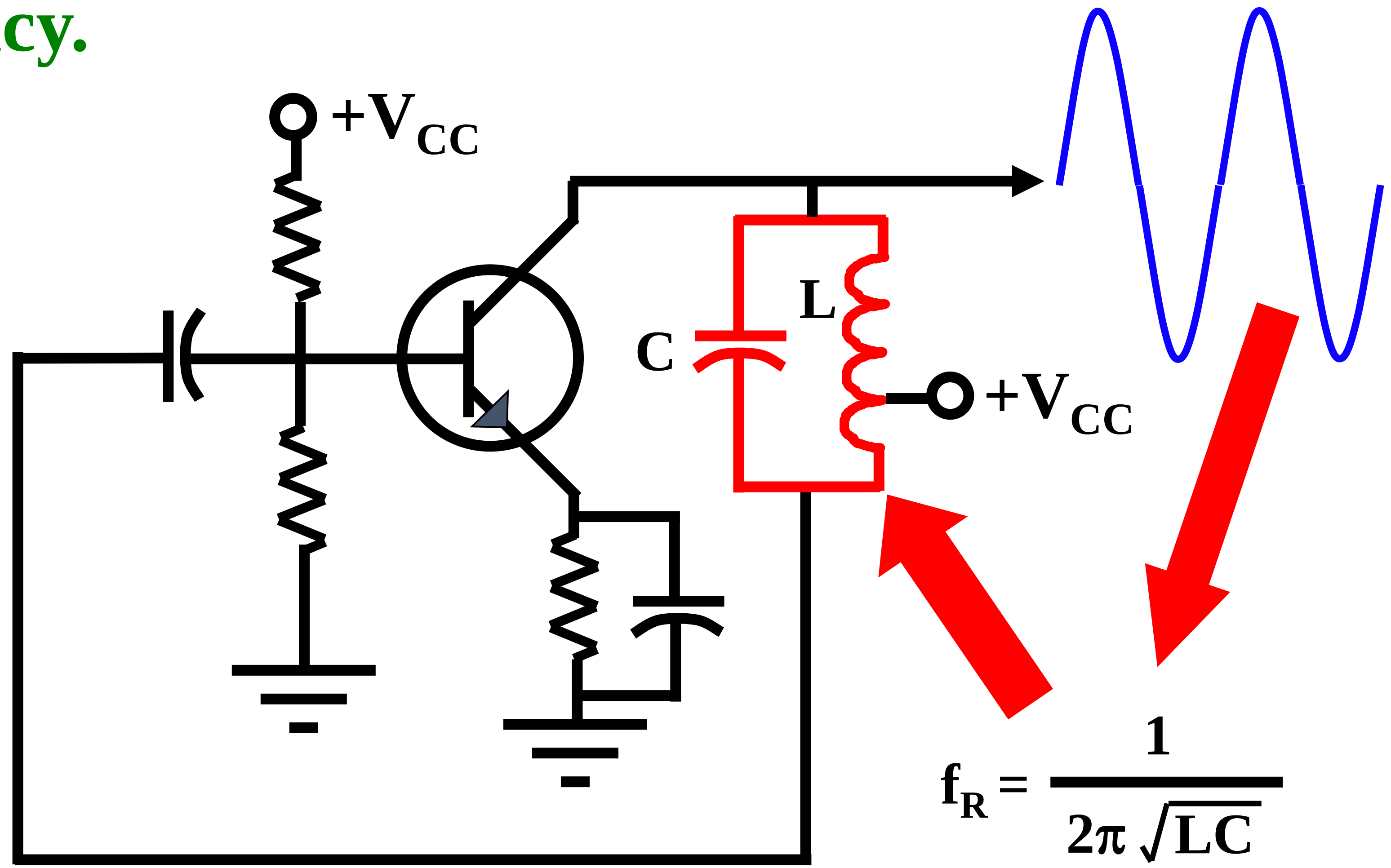
A phase shift oscillator uses three RC sections to provide a total shift of __________. 180^o

The supply tap is a signal ground. There is a 180° phase shift across the tank.



The Hartley oscillator is LC controlled.

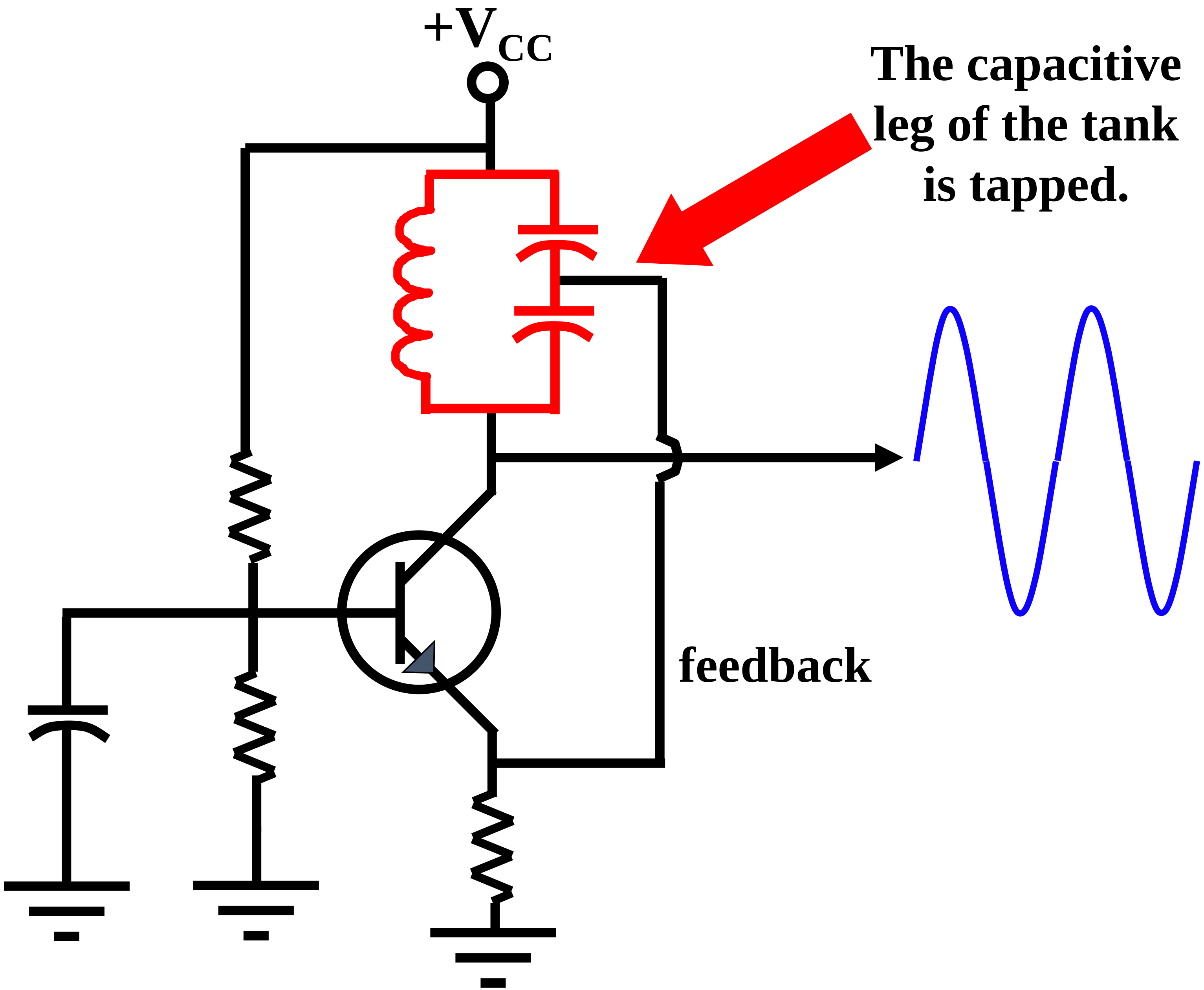
The output frequency is equal to the resonant frequency.

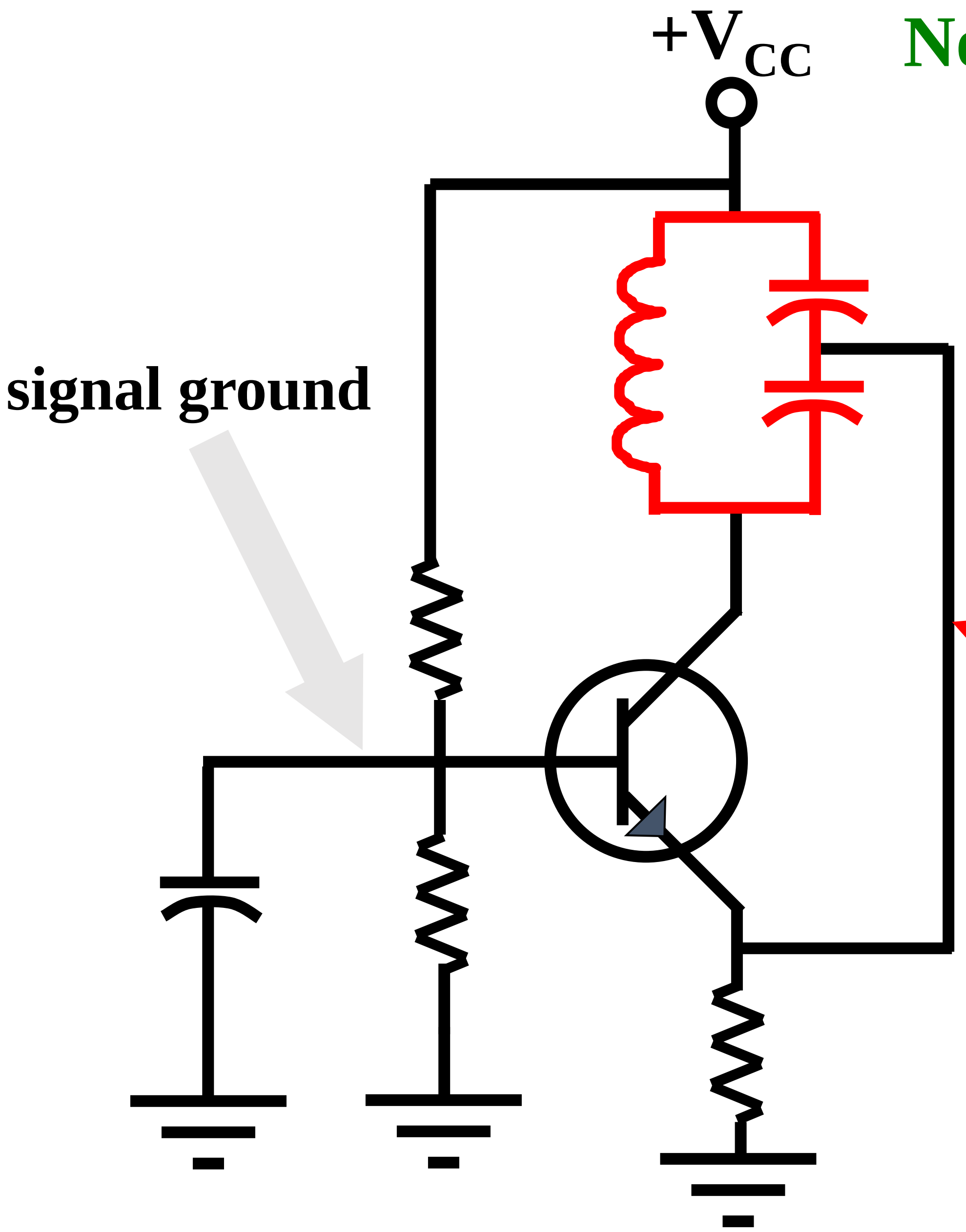


$$f_R = \frac{1}{2\pi\sqrt{LC}}$$

L is the value for the entire coil.

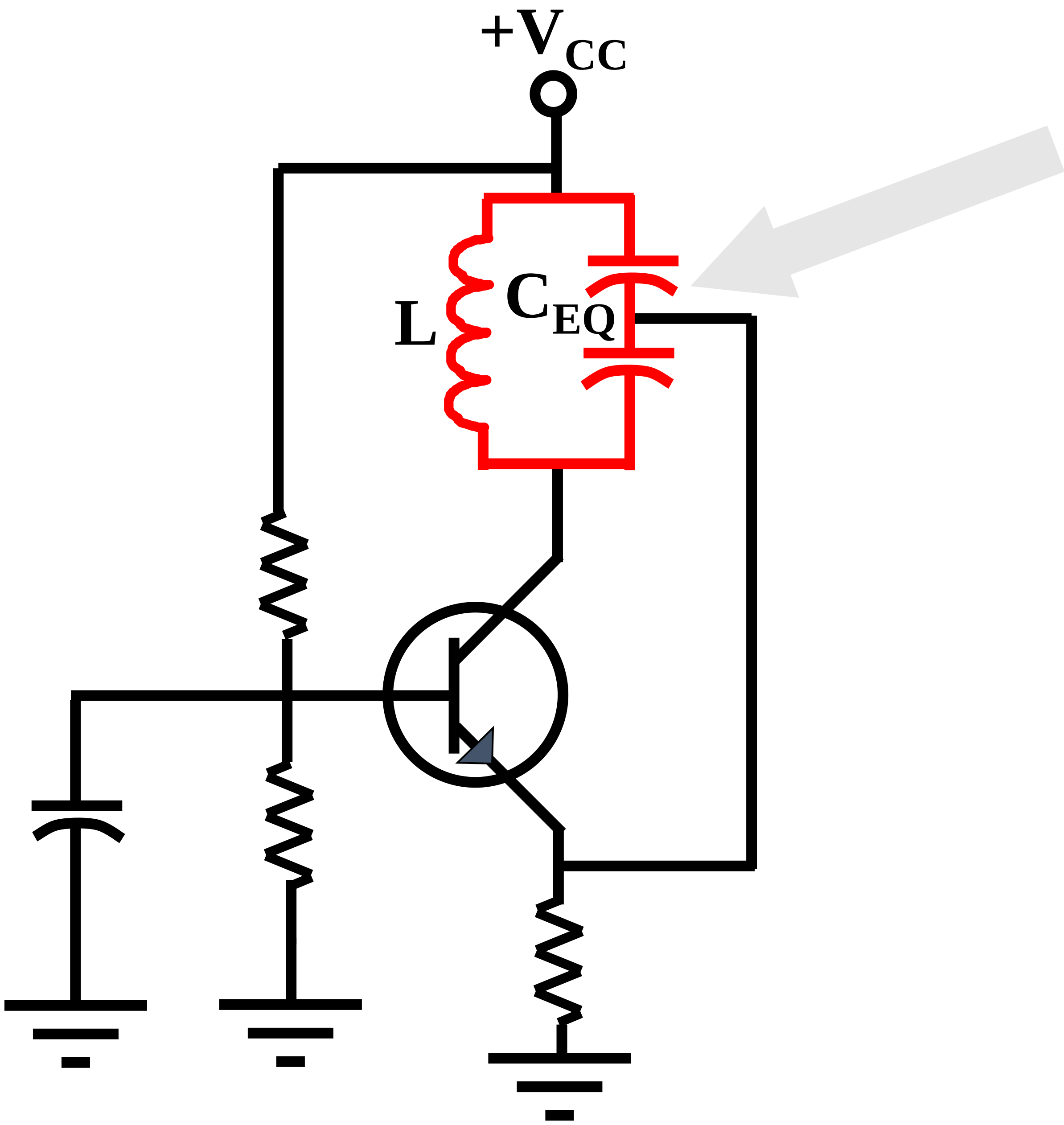
This is called a Colpitts oscillator.





Note that the amplifier configuration is common-base.

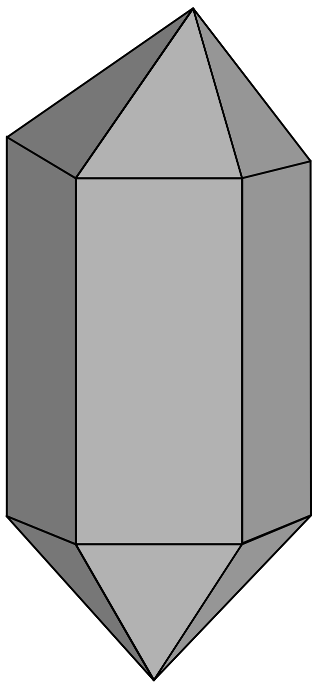
The emitter is the input and the collector is the output. The feedback circuit returns some of the collector signal to the input with no phase shift.



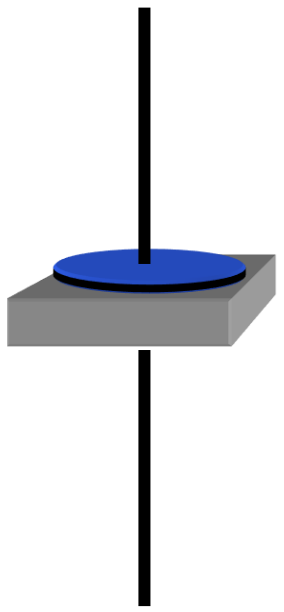
$$f_R = \frac{1}{2\pi\sqrt{LC_{EQ}}}$$

Quartz is a piezoelectric material.

Quartz crystal

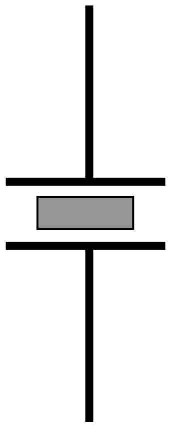


Slab cut from crystal

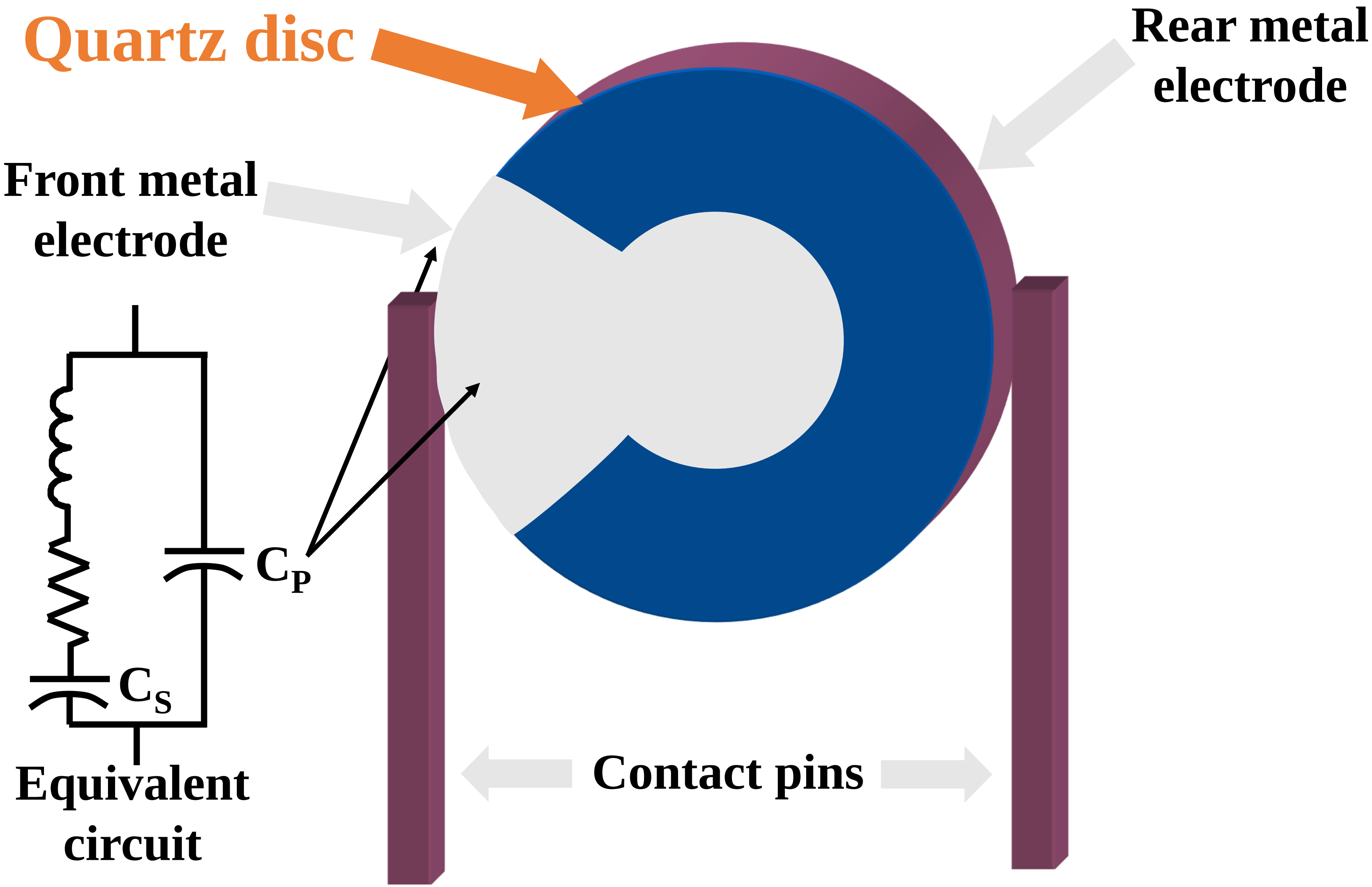


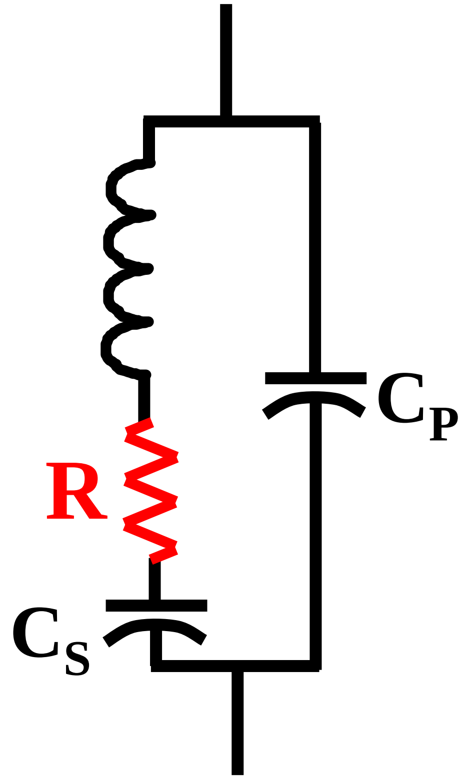
Electrodes and leads

Schematic symbol



Quartz crystals replace LC tanks when frequency accuracy is important.





The equivalent R is very small and the Q is often several thousand.

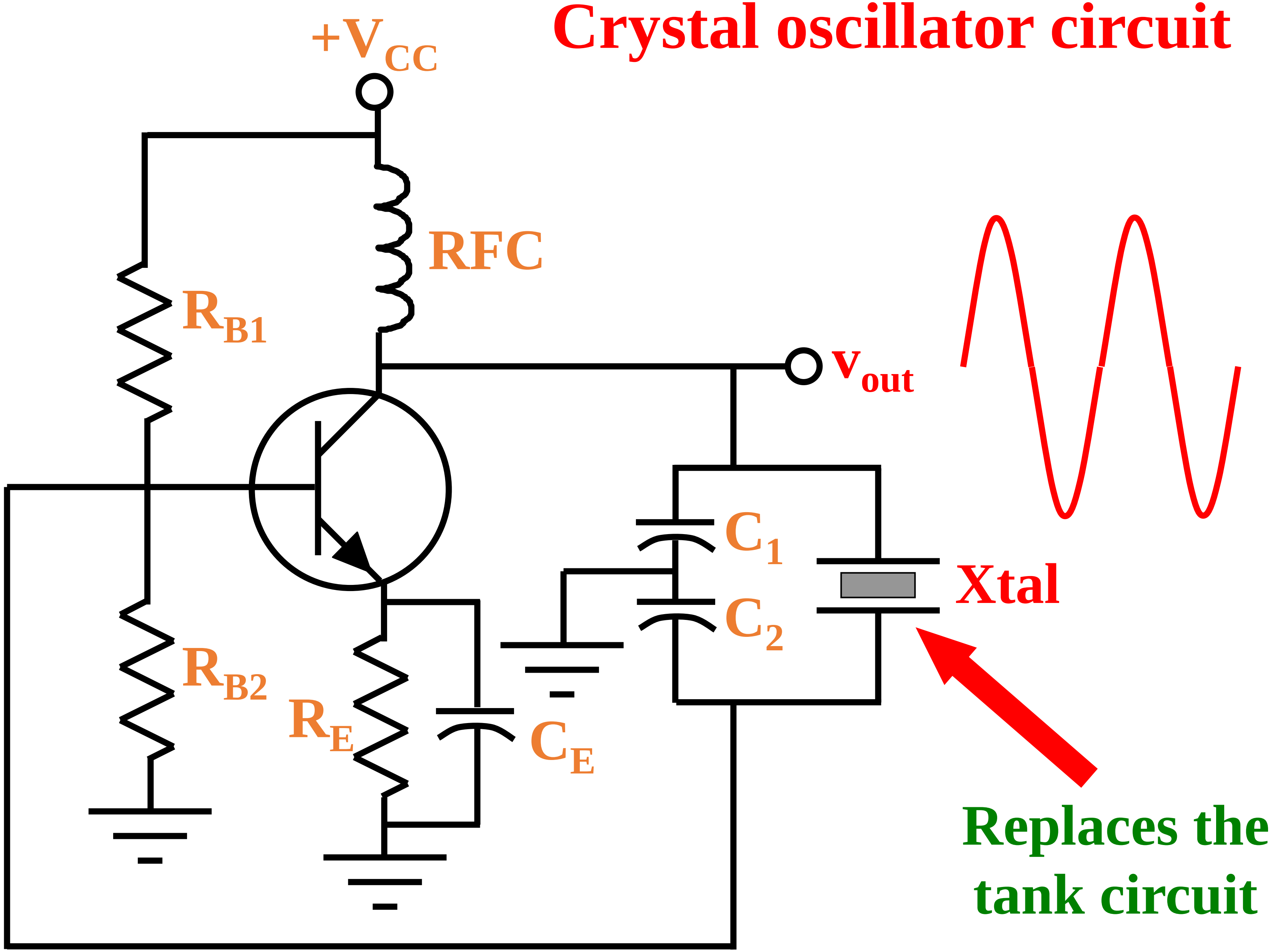
High-Q tuned circuits are noted for narrow bandwidth and this translates to frequency stability.

The equivalent circuit also predicts *two* resonant frequencies: series and parallel. A given oscillator circuit is designed to use one or the other.

Crystals

- The fundamental frequency (series resonance) is controlled by the quartz slab or quartz disk thickness.
- Higher multiples of the fundamental are called overtones.
- The electrode capacitance creates a parallel resonant frequency which is slightly higher.
- Typical frequency accuracy is measured in parts per million (ppm).

Crystal oscillator circuit



Packaged oscillators contain a quartz crystal and the oscillator circuitry in a sealed metal can.

High-frequency Oscillator Quiz

A Hartley oscillator has a tapped ___________ in its tank circuit. coil

When the capacitive leg is tapped, the circuit might be called ___________. Colpitts

A quartz crystal is a solid-state replacement for the ___________ circuit. tank

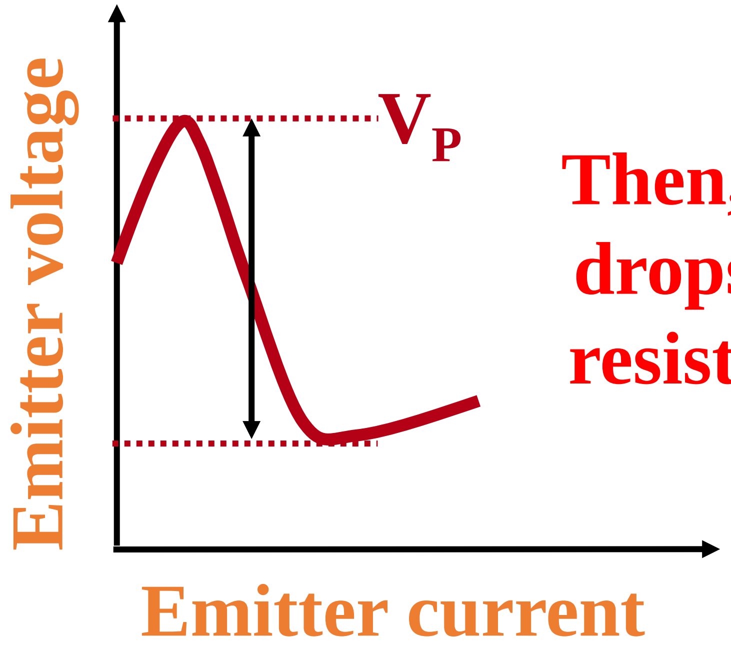
Crystals are more stable than LC tanks due to their very high ___________. Q

Higher multiples of a crystal's resonant frequency are called ___________. overtones

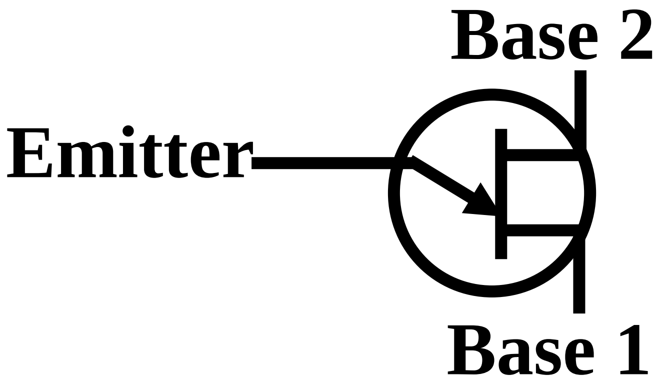
So far, we have learned that:

- **Oscillators can be RC controlled by using phase-shifts.**
- **Oscillators can be LC controlled by using resonance.**
- **Oscillators can be crystal controlled by using resonance or overtones.**
- **There is another RC type called relaxation oscillators. These are *time-constant controlled*.**

RECALL that a unijunction transistor fires when its emitter voltage reaches V_P.



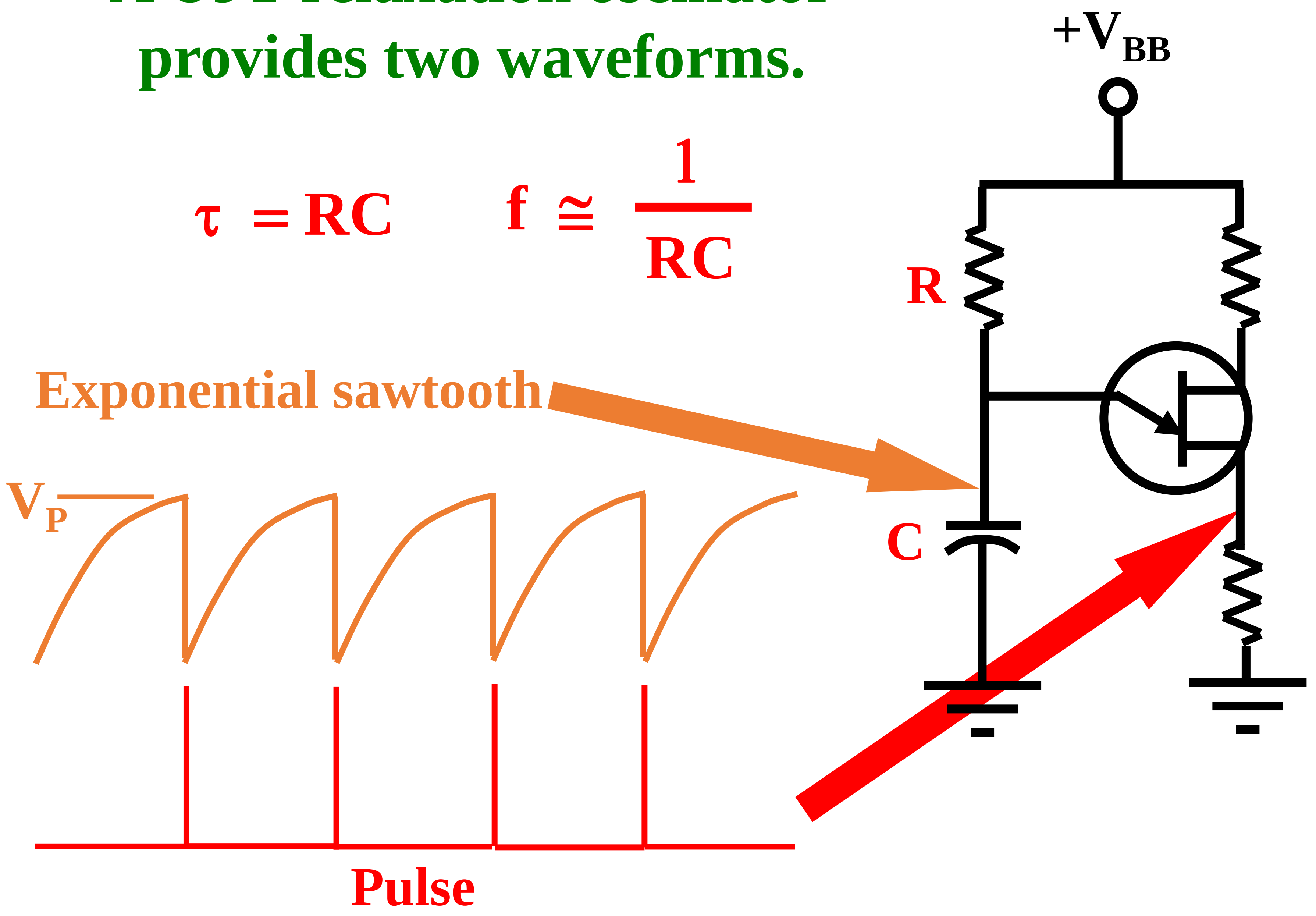
Then, the emitter voltage drops due to its negative resistance characteristic.



UJTs can be used in relaxation oscillators.

A UJT relaxation oscillator provides two waveforms.

$$\tau = RC \qquad f \cong \frac{1}{RC}$$



This multivibrator is also RC controlled.

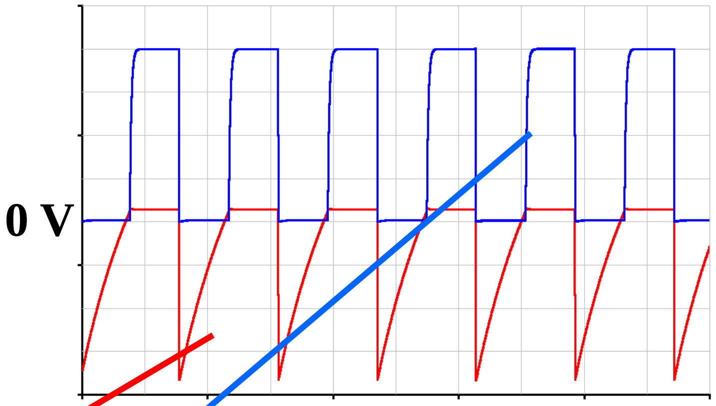
$\tau = 0.69RC$

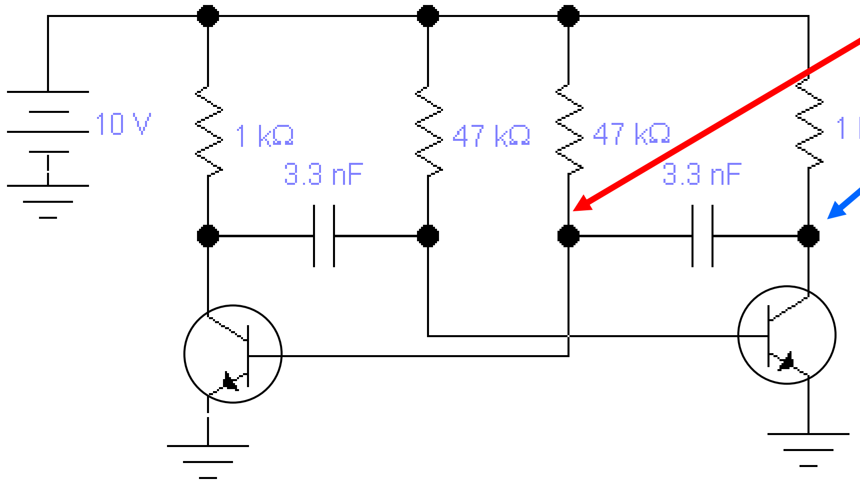
$= 0.69 \times 47\ k\Omega \times 3.3\ nF$

$= 0.107\ ms$

$t = 2\tau = 0.214\ ms$

$f = 1/t = 4.67\ kHz$

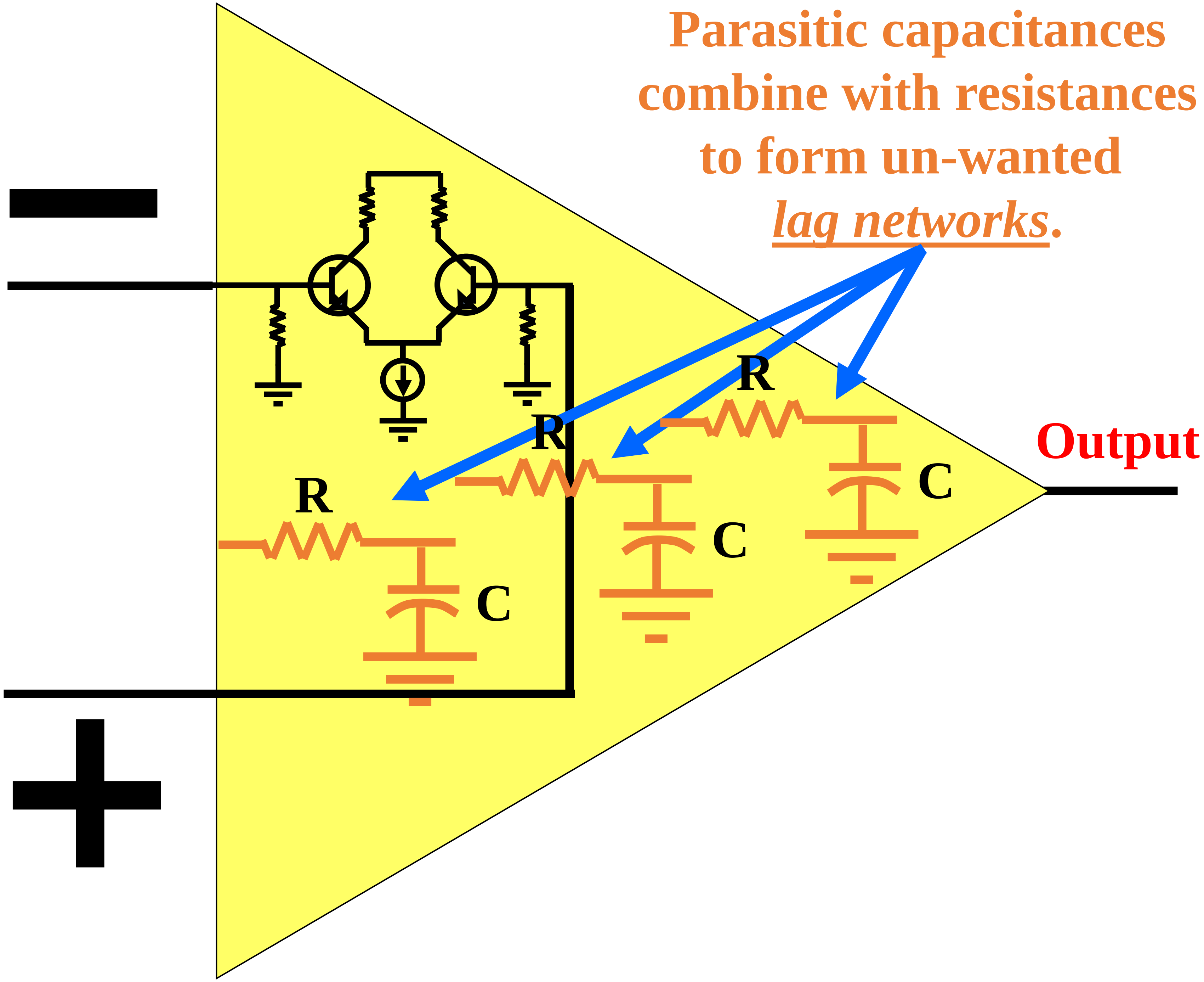




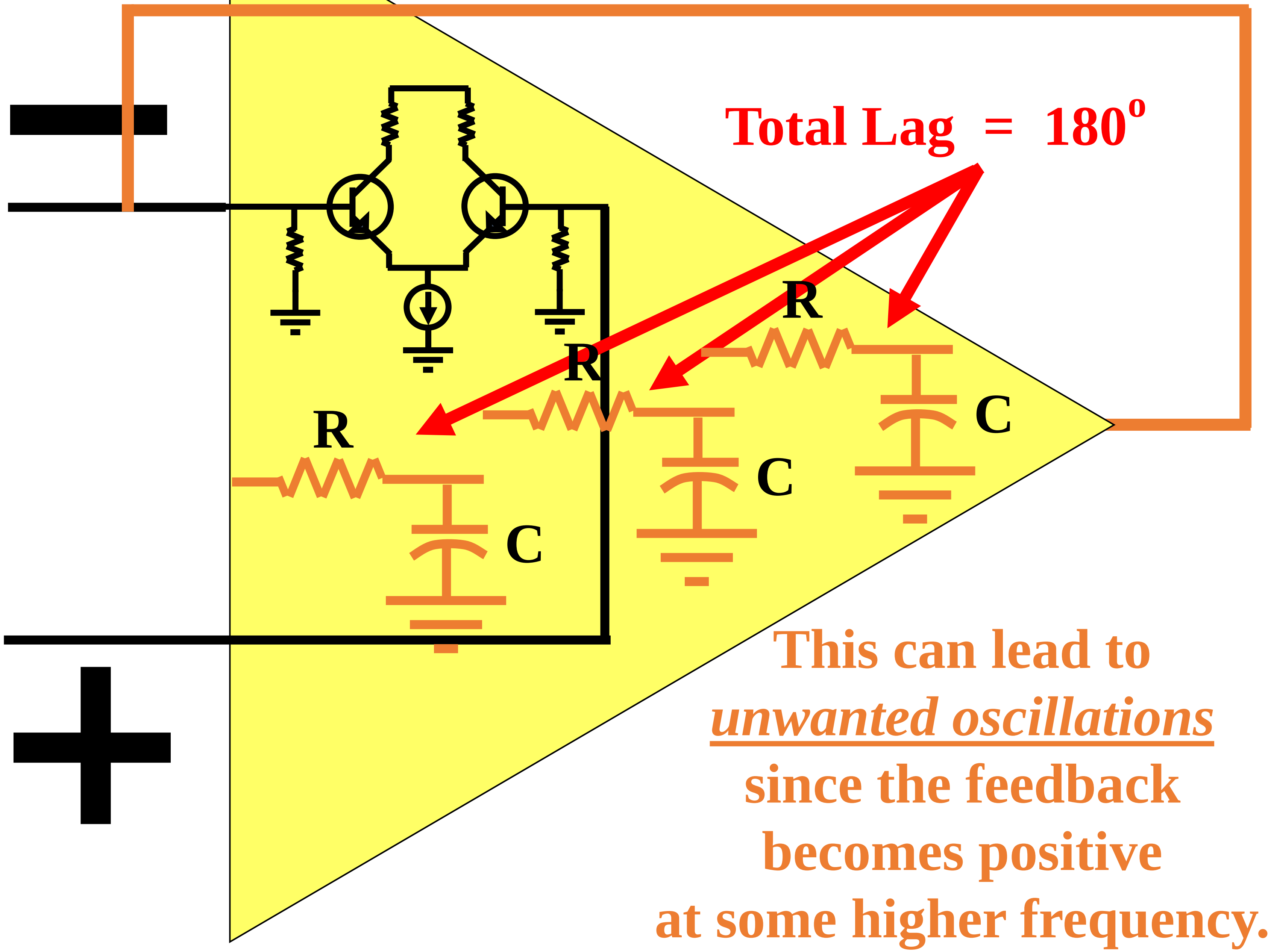
Undesired oscillations:

make amplifiers *useless*.

Why is this a problem?

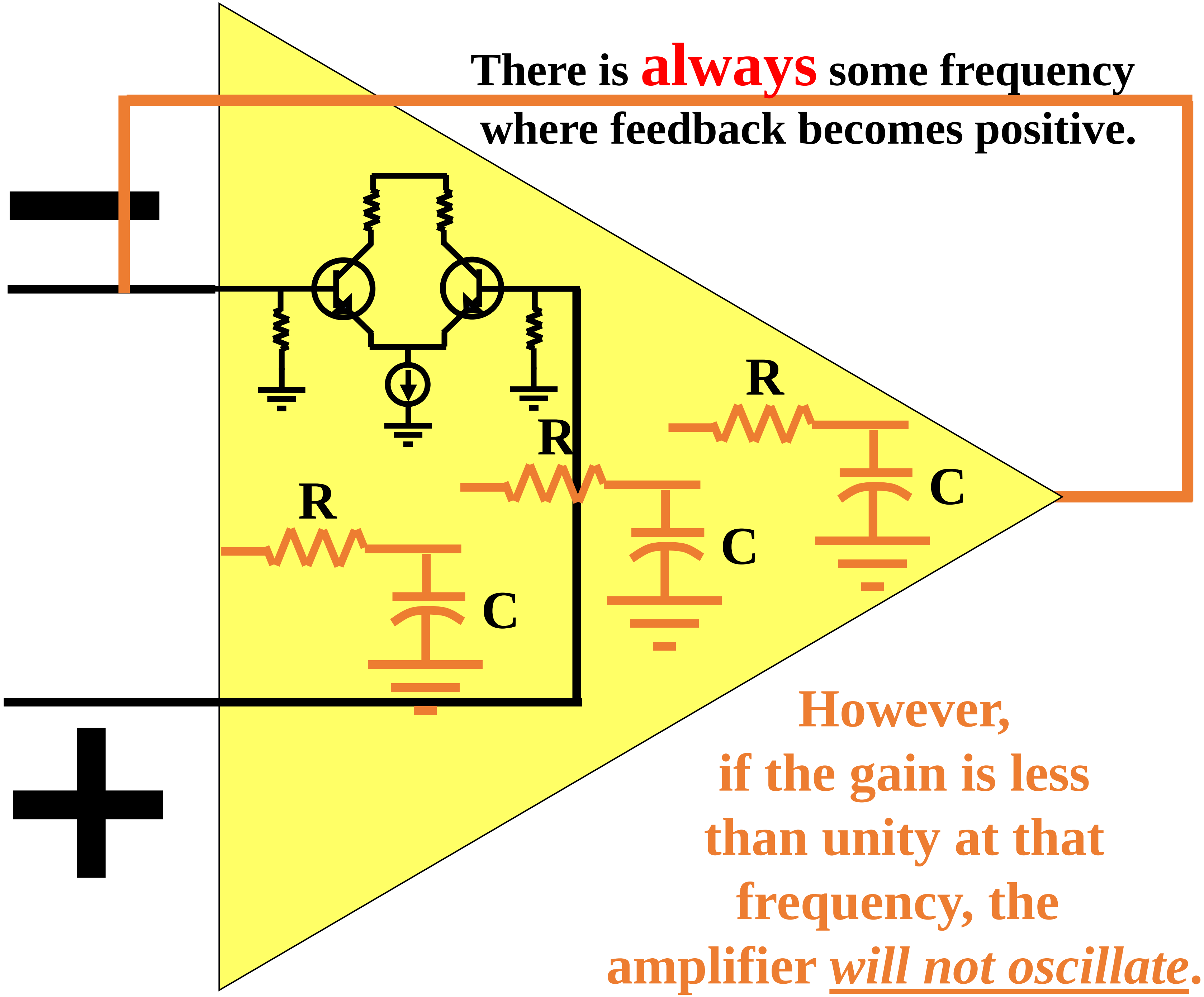

Parasitic capacitances
combine with resistances
to form un-wanted
lag networks.
R
R
R
C
C
C
Output
−
+

It's the equivalent of a phase-shift oscillator.



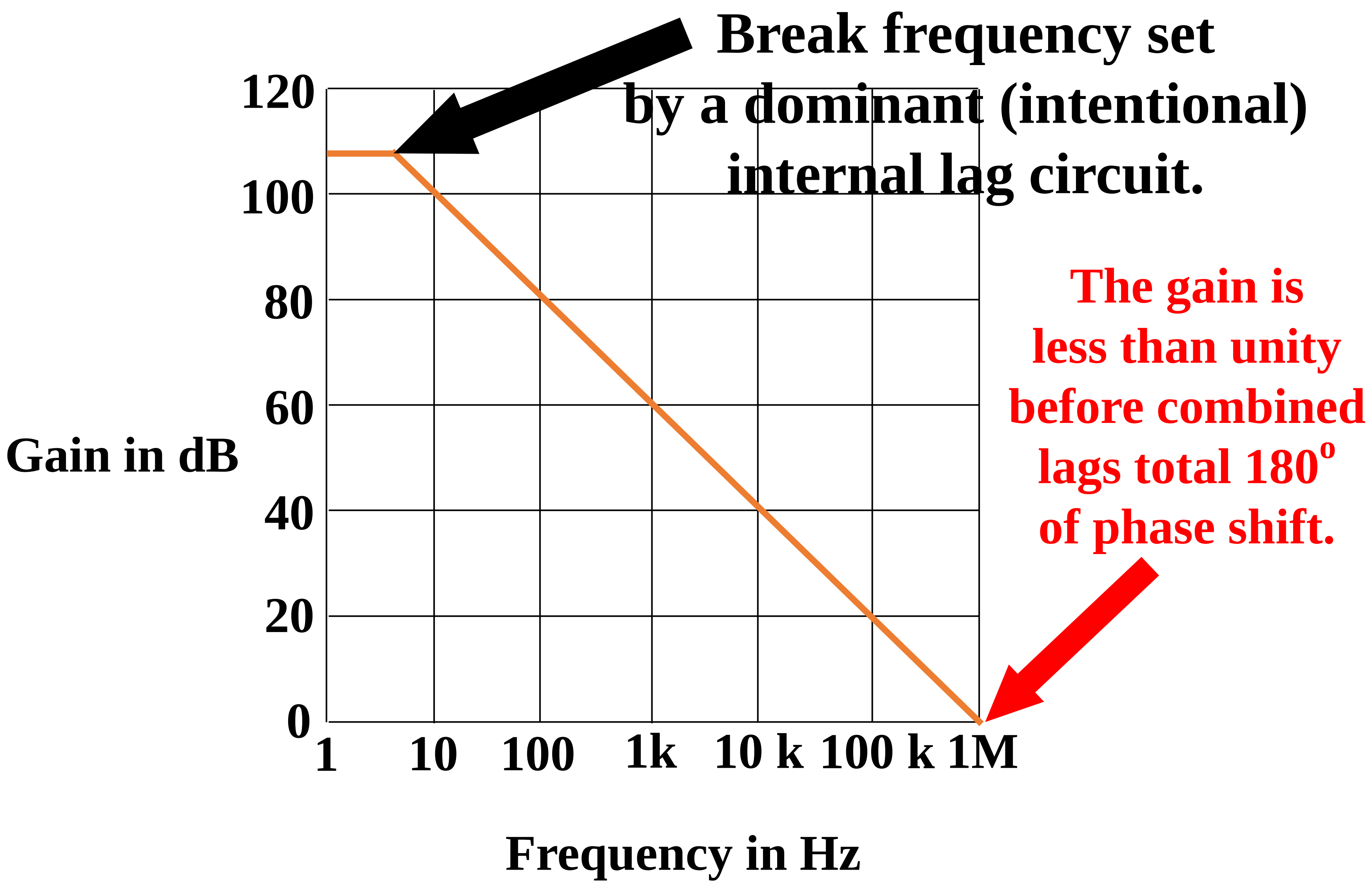
This can lead to
unwanted oscillations
since the feedback
becomes positive
at some higher frequency.

There is **always** some frequency where feedback becomes positive.



However,
if the gain is less than unity at that frequency, the amplifier ***will not oscillate***.

The typical op amp has this characteristic:



Methods of Preventing Oscillation

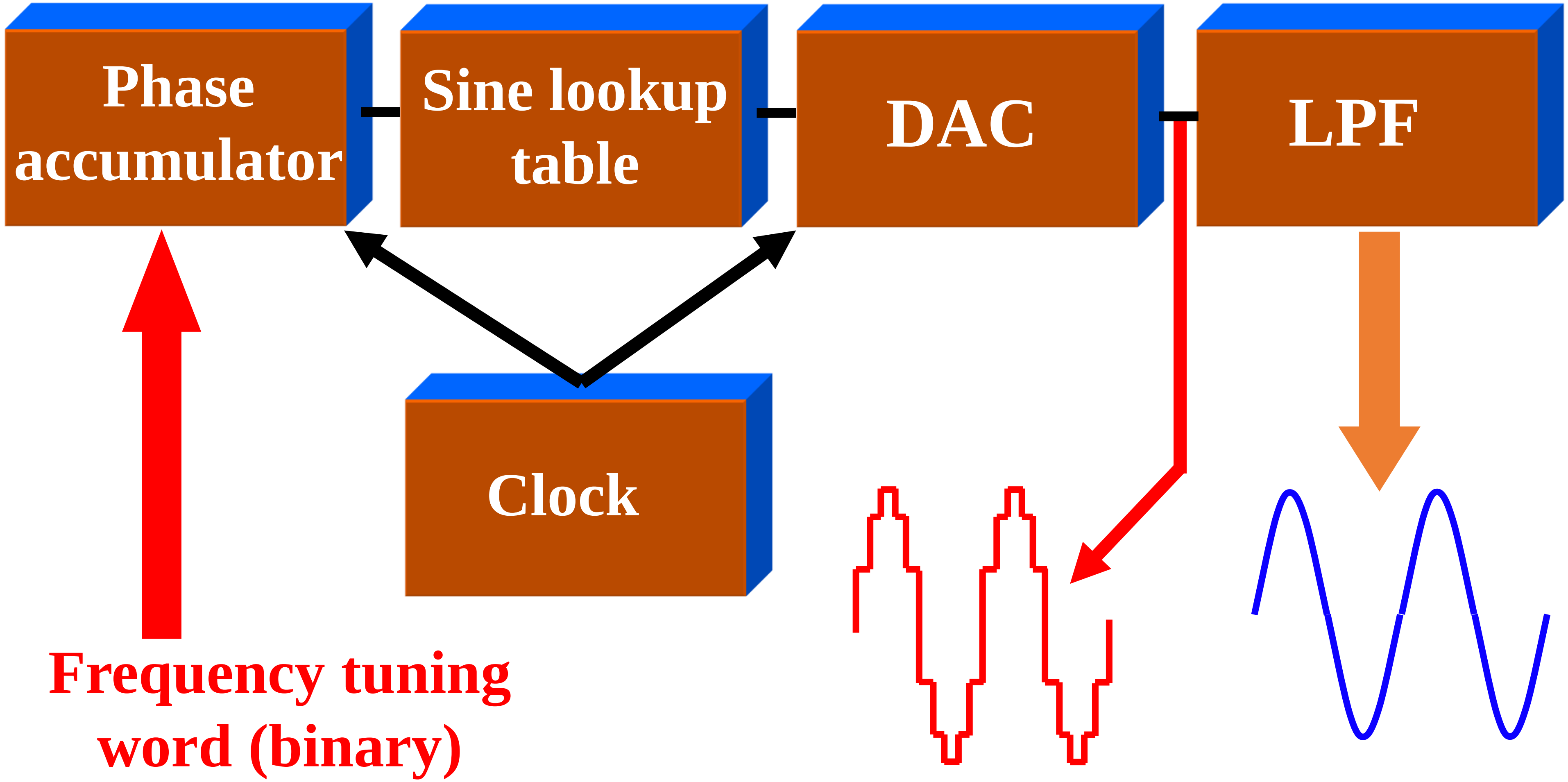
- Reduce the feedback with bypass circuits, shields, and careful circuit layout.
- Cancel feedback with a second path … this is called **neutralization**.
- Reduce the gain for frequencies where the feedback becomes positive … this is called **frequency compensation**.
- Reduce the total phase shift … this is called **phase compensation**.

Oscillator Troubleshooting

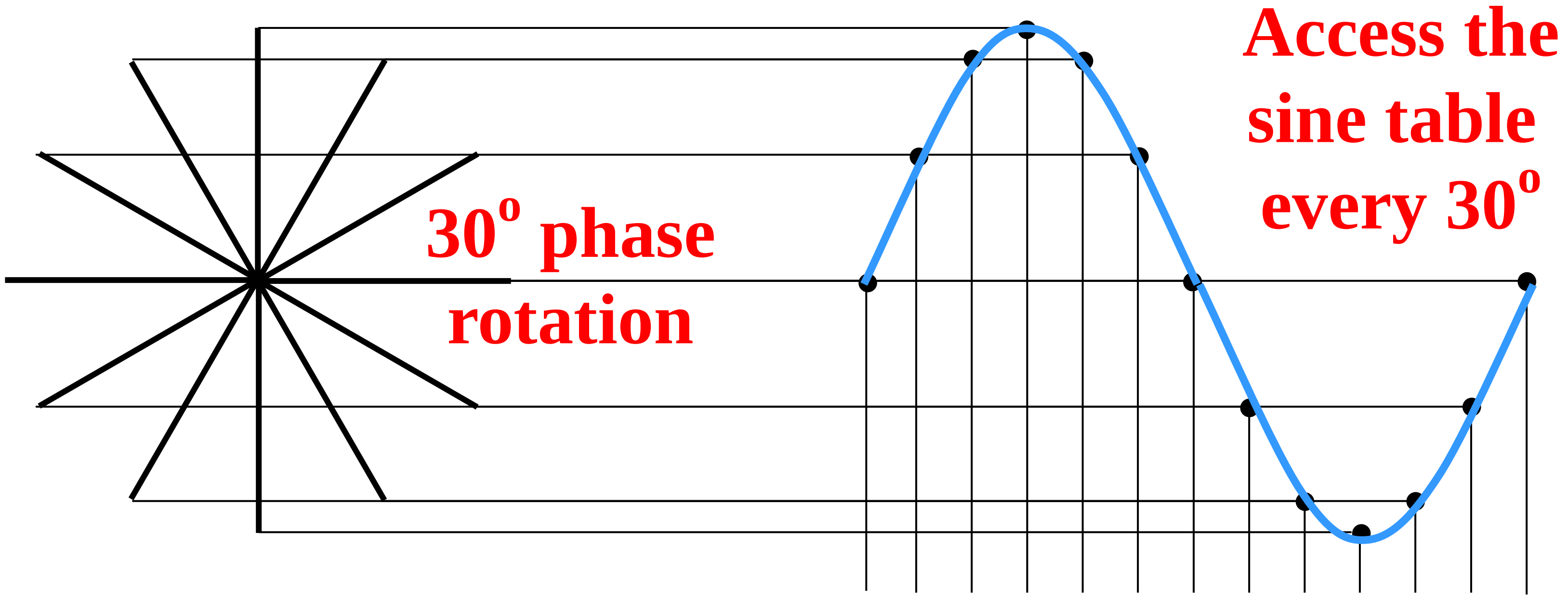
- **No output:** supply voltage; component failure; oscillator is overloaded.
- **Reduced output:** low supply voltage; bias; component defect; loading.
- **Frequency instability:** supply voltage; poor connection or contact; temperature; RC, LC, or crystal.
- **Frequency error:** supply voltage; loading; RC, LC, or crystal.

Direct Digital Synthesizer

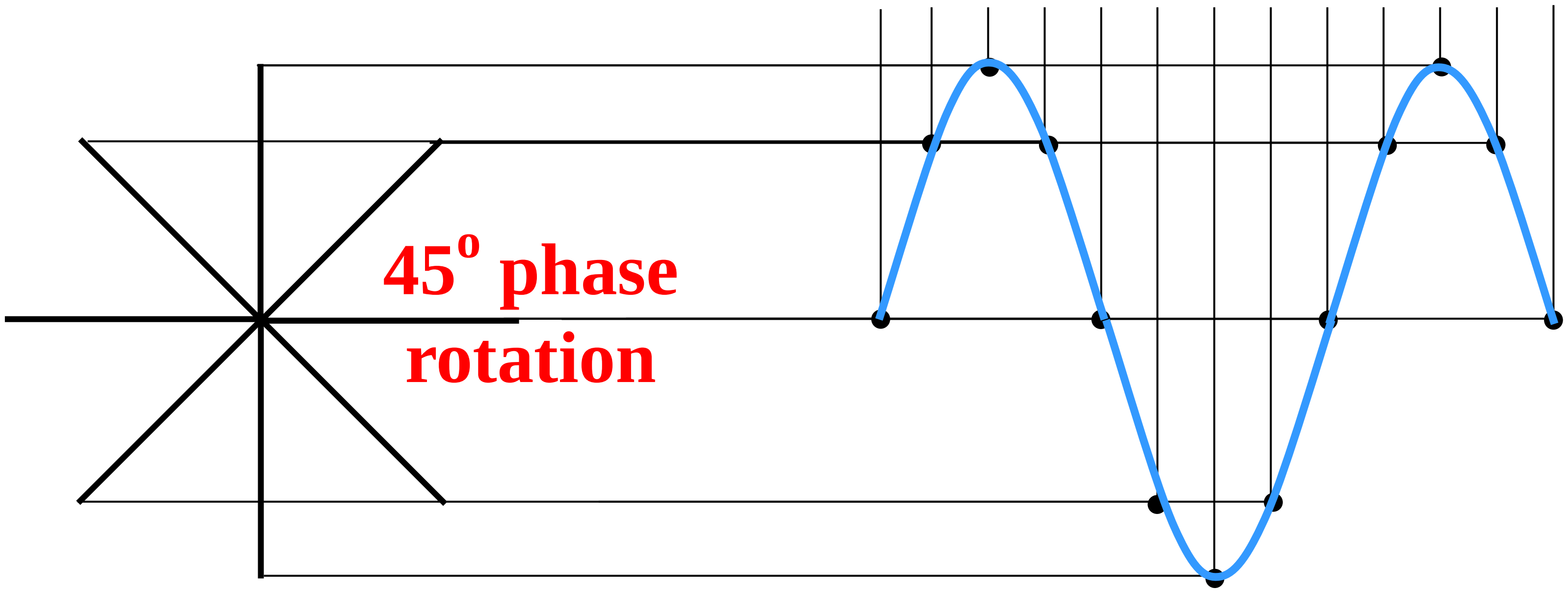
(also called a numerically controlled oscillator)



The tuning word changes the phase increment value.



NOTE: Increasing the phase increment increases the frequency.



Oscillator Wrap-up Quiz

Relaxation oscillators are controlled by RC __________ __________. — time constants

Negative feedback becomes positive at some frequency due to _______ _______. — RC lags

Gain rolloff to prevent oscillation is called __________ compensation. — frequency

Direct digital synthesizers are also called ________ ________ oscillators. — numerically controlled

Direct digital synthesizers use a sine __________ table. — lookup

REVIEW

- Oscillator Characteristics
- RC Circuits
- LC Circuits
- Crystal Circuits
- Relaxation Oscillators
- Undesired Oscillations
- Troubleshooting
- Direct Digital Synthesis

Thank You