Transistor

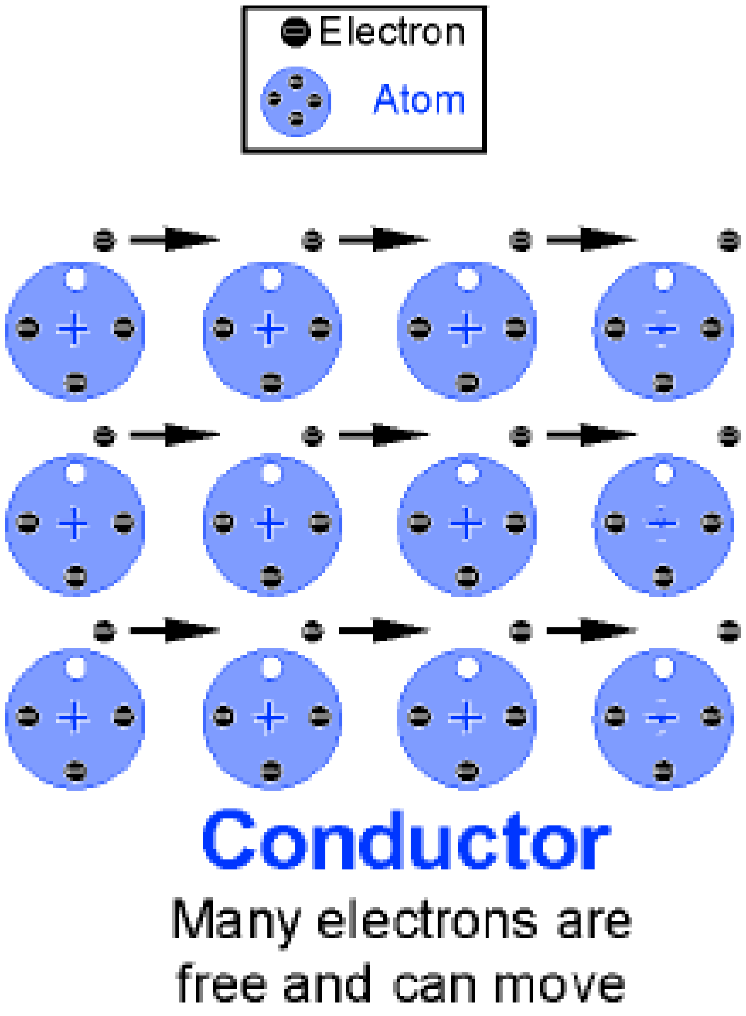
Dr. Cahit Karakuş

Transistors and Diodes

- Transistors and Diodes are solid-state devices or semiconductors.
- They are used in many electronic devices, including amplifiers, computers, and industrial controls.
- Diodes are used to alter information signals, convert AC current into DC current, and as protective devices and switches.

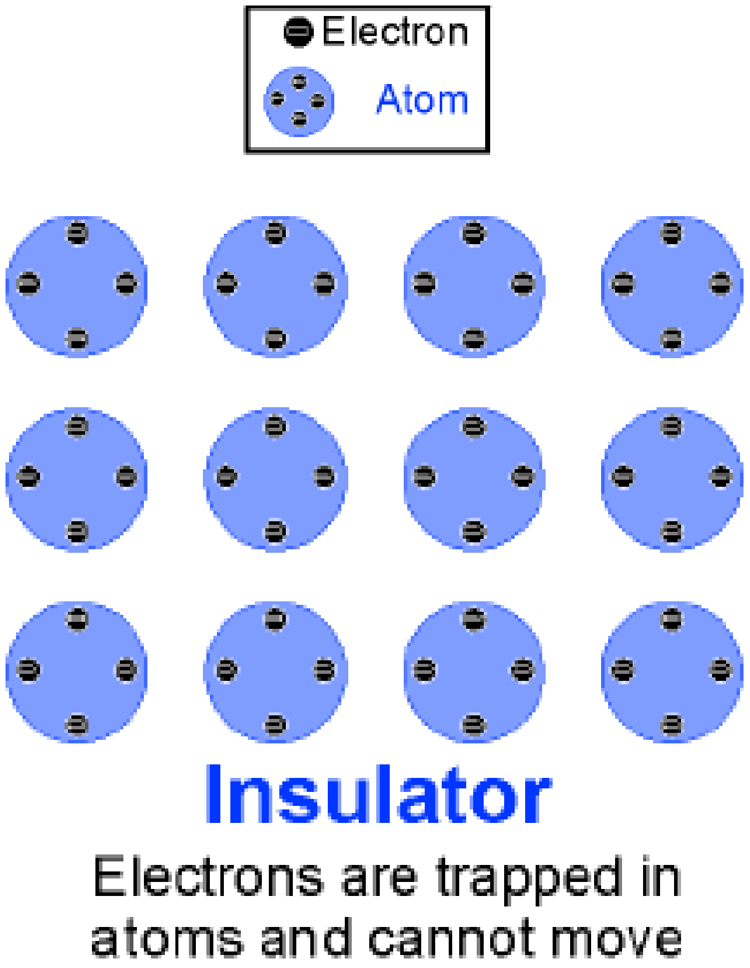
Metals as conductors

- **Metals are good conductors because a small percentage of electrons are free to separate from atoms and move independently.**



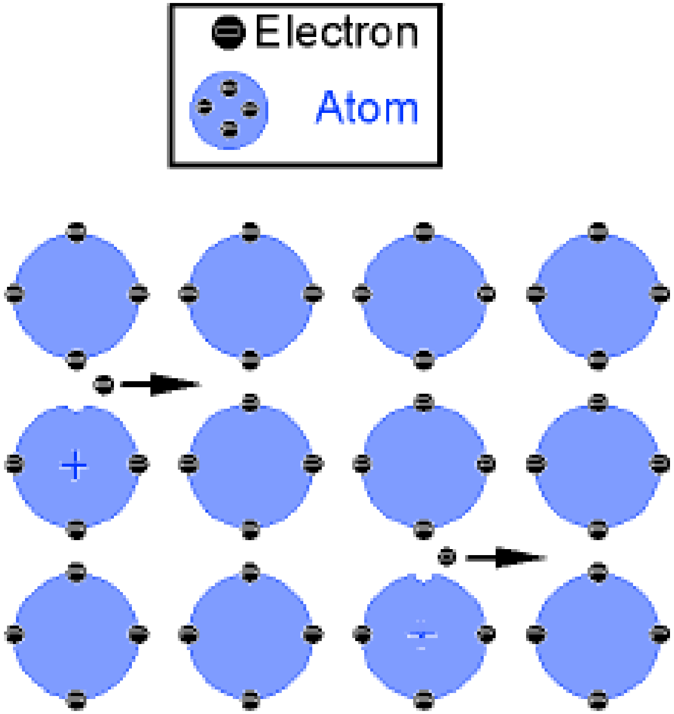
Nonmetals as conductors

- **In an insulator, the electrons are tightly bonded to atoms and cannot move.**
- **Since the electrons cannot move, they cannot carry current.**



Semiconductors

- The electrons in a semiconductor are also bound to atoms, but the bonds are relatively weak.
- The density of free electrons is what determines the conductivity of a semiconductor.

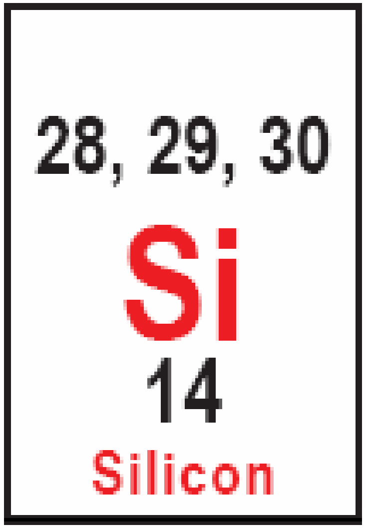


Semiconductor

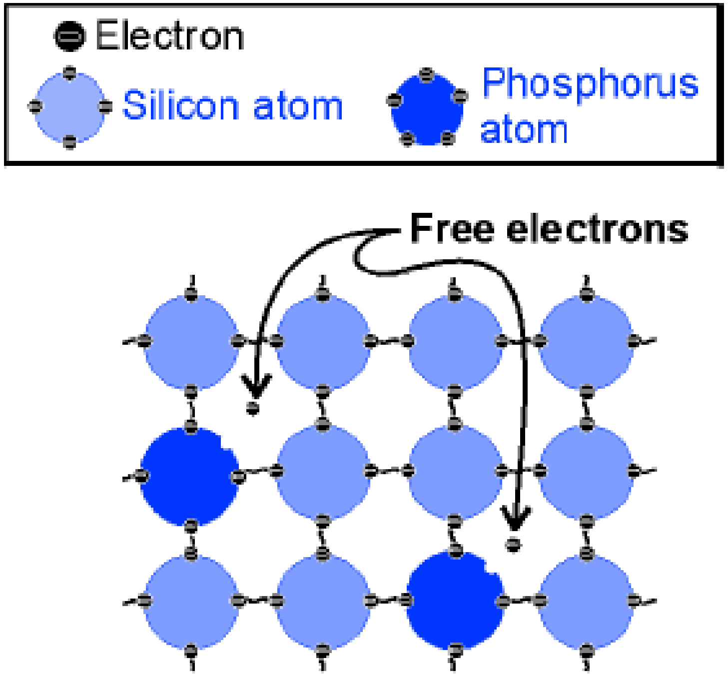
A few electrons are free and can move, but most are weakly bonded to atoms

Semiconductors

- If there are many free electrons to carry current, the semiconductor acts more like a conductor.
- If there are few electrons, the semiconductor acts like an insulator.
- Silicon is the most commonly used semiconductor.
- Atoms of silicon have 14 electrons.
- Ten of the electrons are bound tightly inside the atom.
- Four electrons are near the outside of the atom and only loosely bound.



Changing conductivity



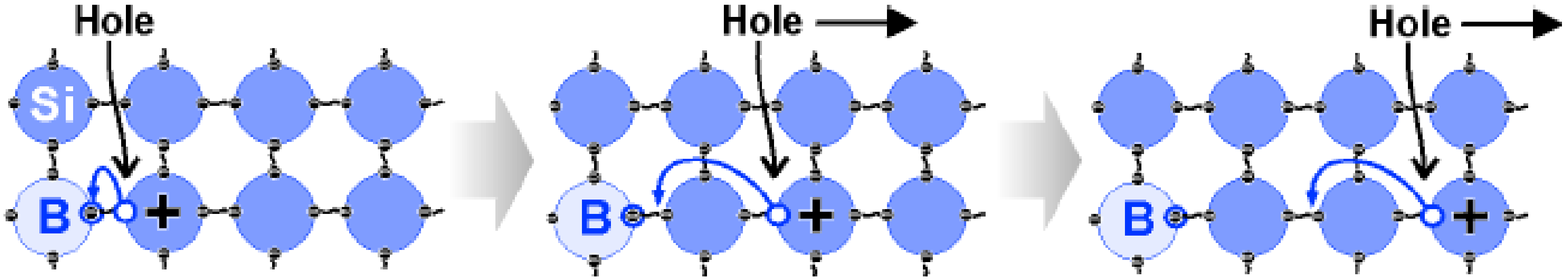
***n*-type** semiconductor

When phosphorus bonds with silicon, one electron is left free

- Anything that changes the number of free electrons has a huge effect on conductivity in a semiconductor.
- Adding a phosphorus impurity to silicon increases the number of electrons that can carry current.
- Silicon with a phosphorus impurity makes an n-type semiconductor with current of negative charge.

Changing conductivity

- When a small amount of boron is mixed into silicon the opposite effect happens.
- When an electron is taken by a boron atom, the silicon atom is left with a positive charge and current is carried as electrons move.

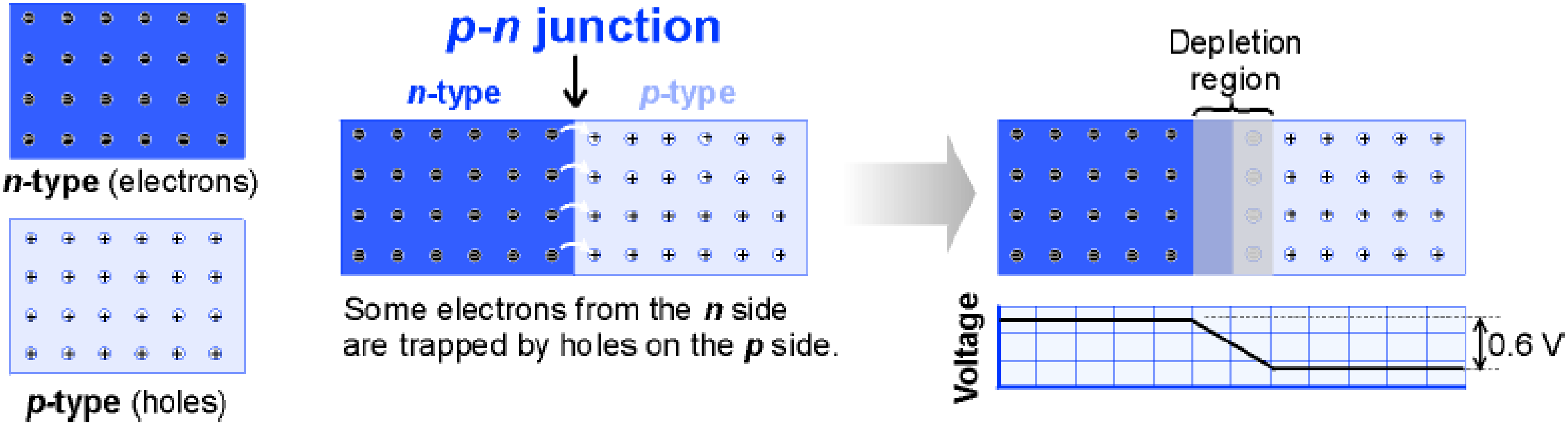


A boron atom creates a hole by taking an electron from a silicon atom

The hole acts like a moving positive charge as electrons jump from atom to atom

The p-n junction

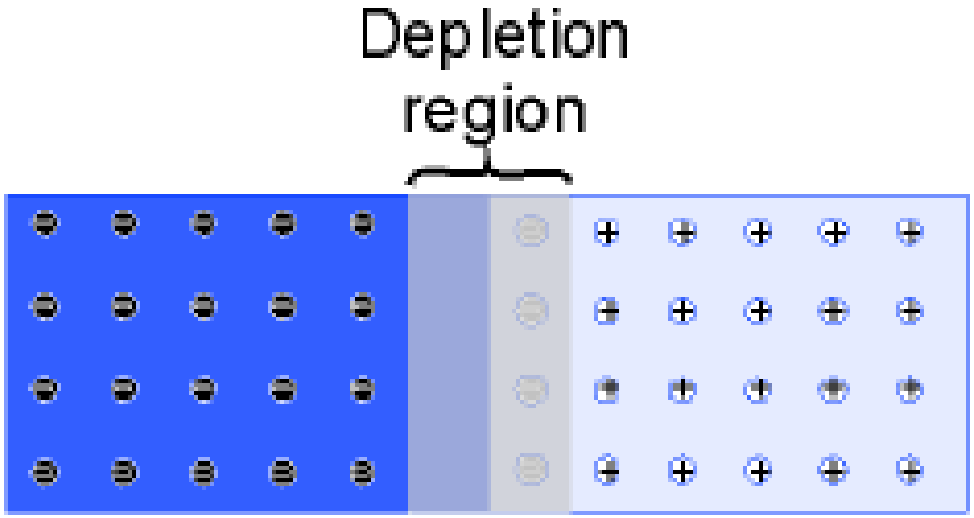
- A p-n junction forms where *p*-type and *n*-type semiconductor materials meet.
- The depletion region becomes an insulating barrier to the flow of current because electrons and holes have combined to make neutral



Some electrons from the *n* side are trapped by holes on the *p* side.

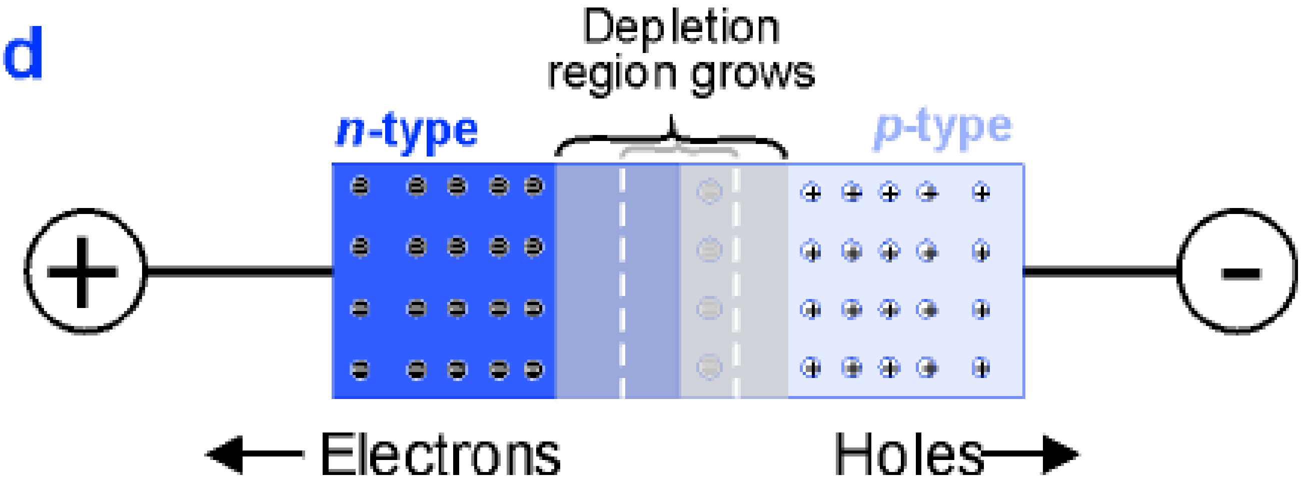
The physics of diodes

- **The depletion region of a p-n junction is what gives diodes, transistors, and all other semiconductors their useful prop**



The physics of diodes

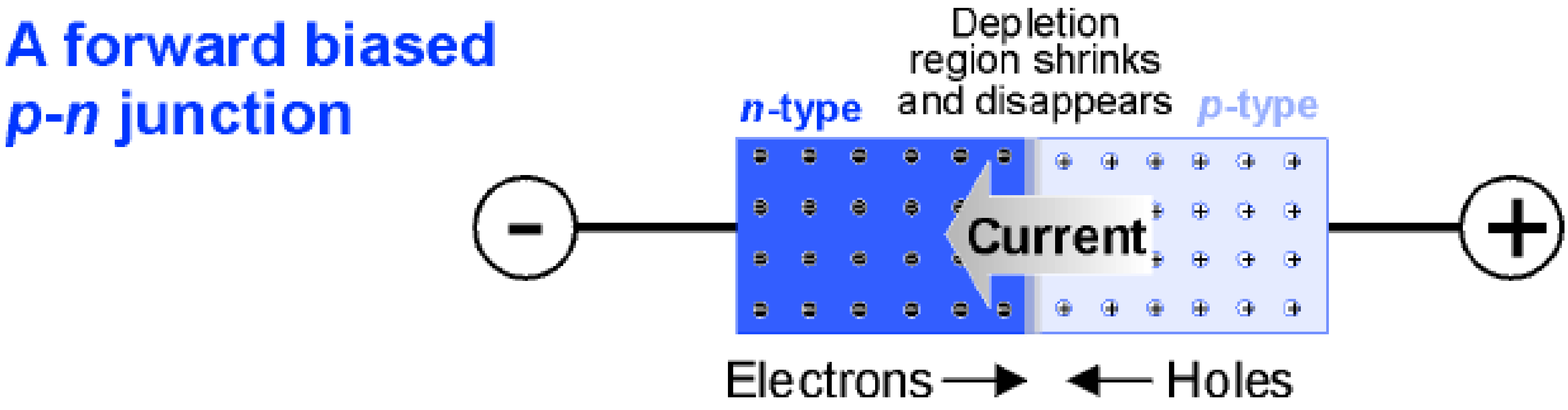
- As the voltage increases, no current can flow because it is blocked by a larger (insulating) depletion region.



A reverse biased *p*-*n* junction

The physics of diodes

- If the opposite voltage is applied, both electrons and holes are repelled <u>toward</u> the depletion region.
- As a result, the depletion region gets smaller.
- Once the depletion region is gone, electrons are



The physics of diodes

- **In short, a p-n junction is a diode.**

1. **The p-n junction <u>blocks</u> the flow of current from the *n* side to the *p* side.**
2. **The p-n junction <u>allows</u> current to flow from the *p* side to the *n* side if the voltage difference is more than 0.6 volts.**

Conductivity and semiconductors

- The relative ease at which electric current flows through a material is known as conductivity.
- Conductors (like copper) have very high conductivity.
- Insulators (like rubber) have very low conductivity.
- The conductivity of a semiconductor depends on its conditions.
- For example, at low temperatures and low voltages a semiconductor acts like an insulator.
- When the temperature and/or the voltage is increased, the conductivity increases and the material acts more like a conductor.

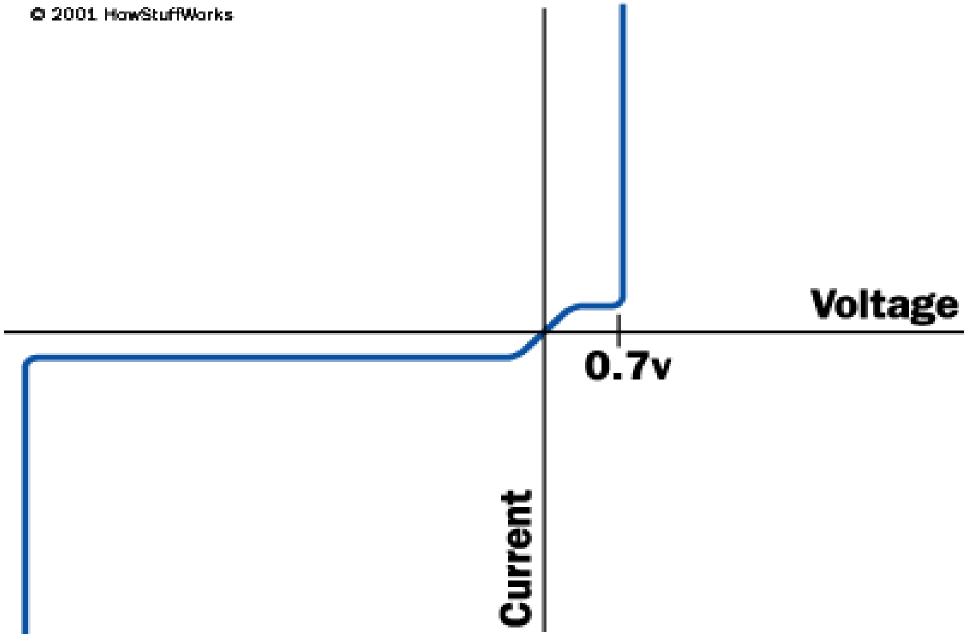
Vocabulary Terms

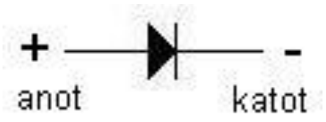
- forward bias
- reverse bias
- bias voltage
- *p*-type
- *n*-type
- depletion region
- hole
- collector
- emitter
- base
- conductivity
- *p*-*n* junction
- logic gate
- rectifier
- diode
- transistor
- amplifier
- gain
- analog
- digital
- AND
- OR
- NAND
- NOR
- binary
- CPU
- program
- memory
- bit
- integrated circuit

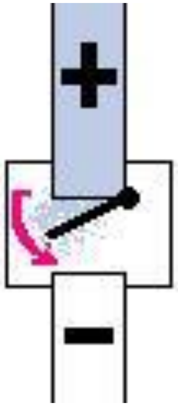
DİYOD

Diyot (D)

Diyot, sadece bir yönde akım geçiren devre elemanıdır. Ters yönde gerilim uygulandığında kesimdedir (iletmez). İletim yönünde kutuplandığında üzerinde ortalama 0.7 voltluk gerilim düşer. Ters yöndeki kutuplamada da belirli bir gerilim seviyesinin aşılması diyodun dayanamamasına yani yanmasına sebep olur. Çizge incelendiğinde, iletim yönünde kutuplanmış olsa bile, diyodun Veşik=0.7 volttan önce iletime geçmediği görülebilir.

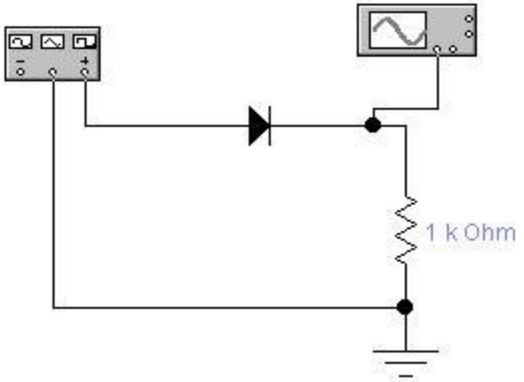


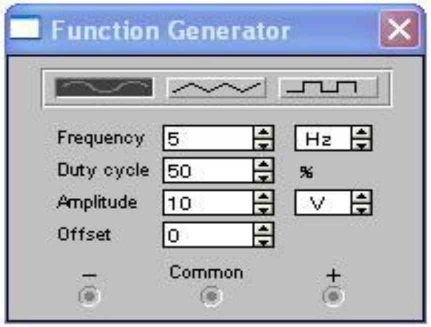




Diyot (D)

Diyot üzerine uygulanan + ve – kutuplar içeren 5 hertzlik Vtt (tepeden tepeye) gerilimi 20 volt olan bir işaret uygulanmakta ve diyot bu işaretin sadece + yarı çevrimini geçirirken tepe gerilimini, üzerinde düşen eşik gerilimi sebebiyle 0,7 volt düşürdüğü gözleniyor.



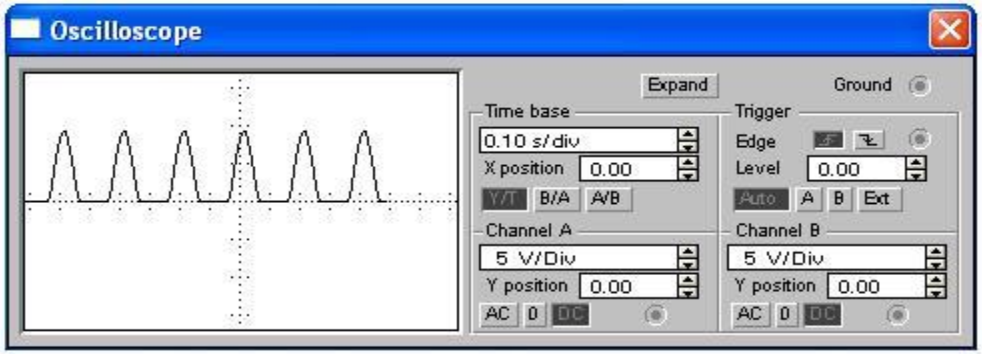

Function Generator

Frequency 5 Hz

Duty cycle 50 %

Amplitude 10 V

Offset 0


Oscilloscope

Time base 0.10 s/div

X position 0.00

Trigger

Level 0.00

Channel A 5 V/Div

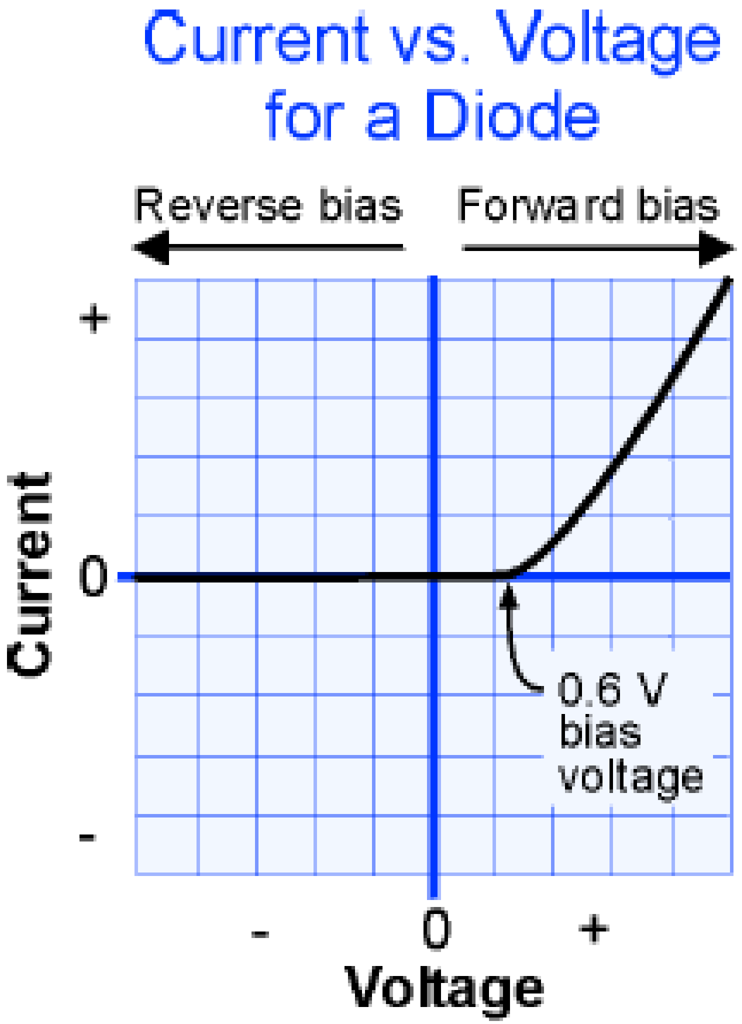
Y position 0.00

Channel B 5 V/Div

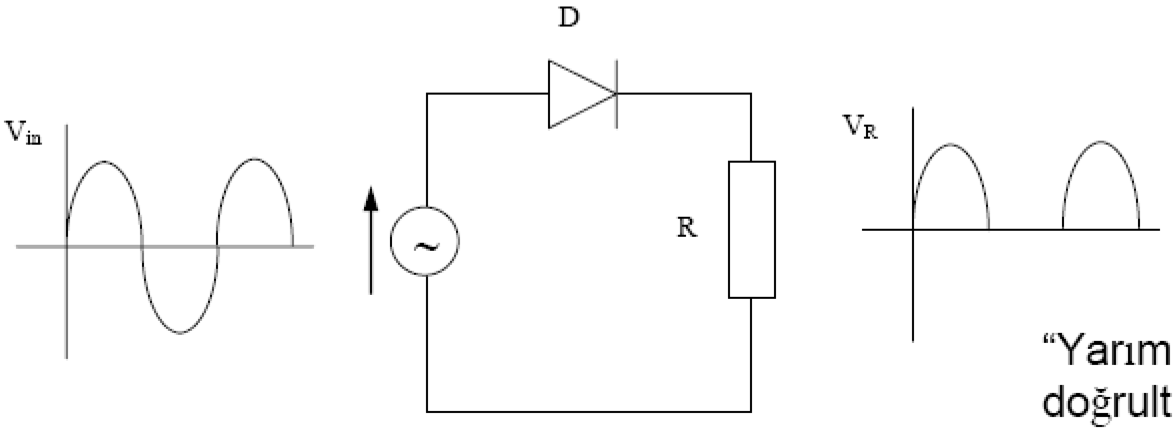
Y position 0.00

Diodes

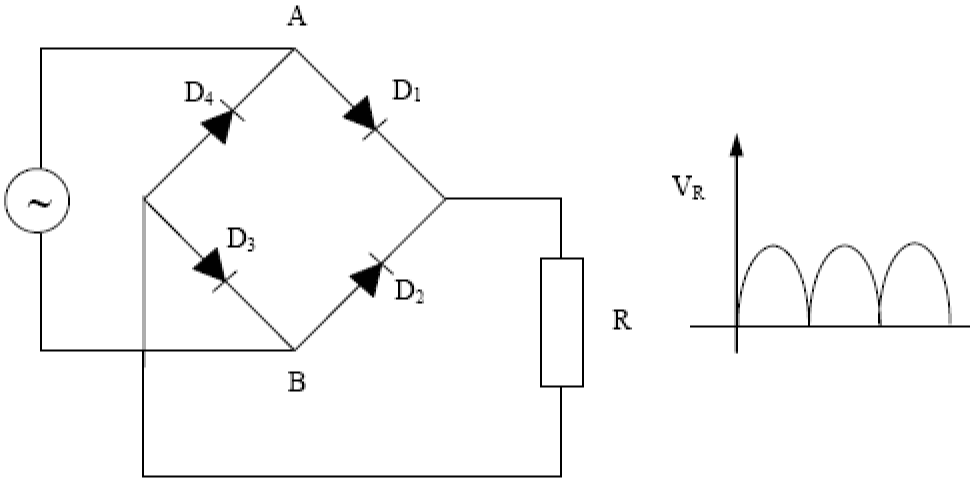
- In a forward-biased diode the current stays at zero until the voltage reaches the bias voltage (Vb), which is 0.6 V for common silicon diodes.
- You can think of the bias voltage as the amount of energy difference it takes to open the diode.



DOĞRULTUCU DEVRELER:



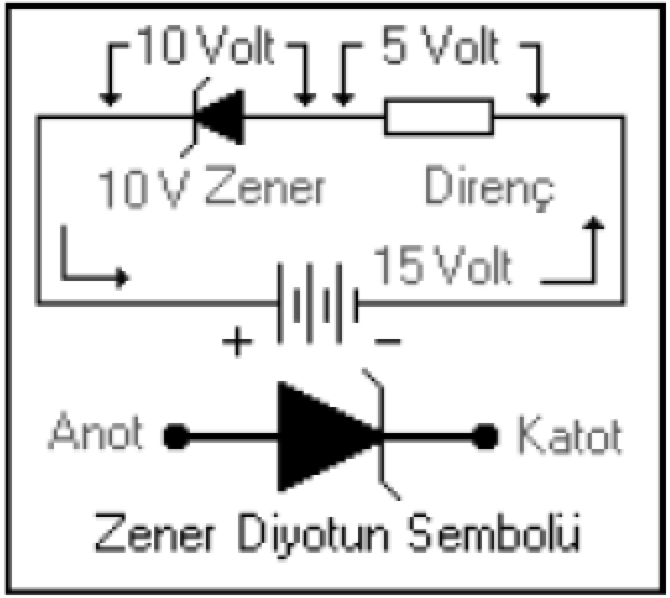
“Yarım dalga”
doğrultma devresi

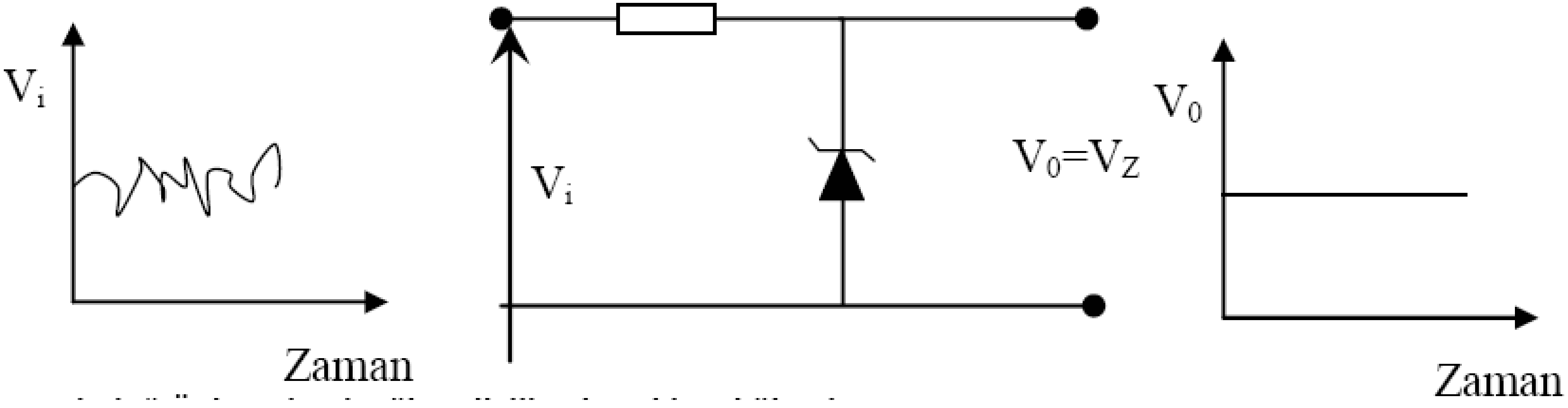


Bir diyot köprü devresi
kullanarak
“tam dalga” doğrultma

Zener diyot:

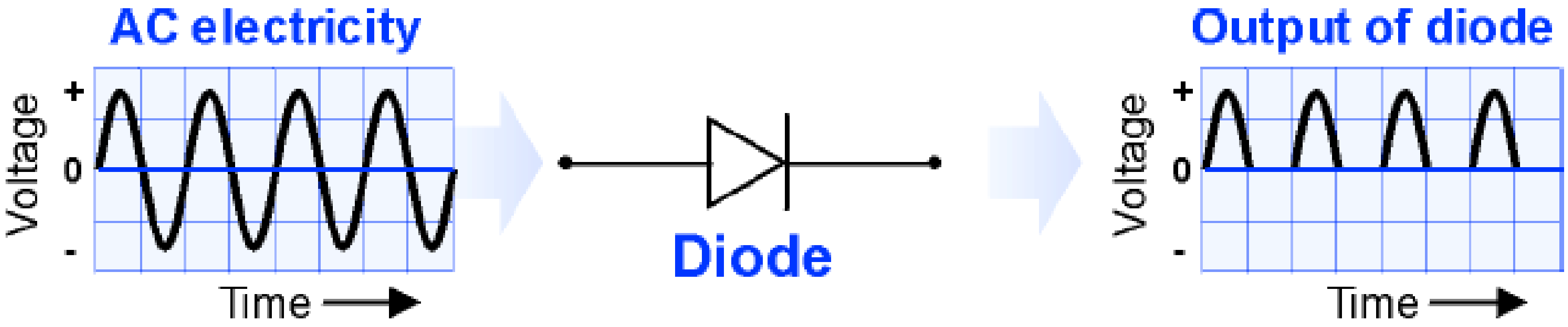
Zener diyotlar, normal diyodun “delinme gerilimi” noktasından faydalanılarak yapılmışlardır. Doğru polarlamada normal diyot gibi, ters polarlamada ise uygulanan gerilim “Zener Voltajı”nın altında ise yalıtıma geçer. Bu voltajın üzerine çıkıldığında ise Zener diyodun uçlarındaki gerilim “Zener Voltajı”nda sabit kalır, üzerine çıkmaz. Zenerden geçen akım değişken olabilir. Arta kalan gerilim ise zener diyoda seri bağlı olan direncin üzerine düşer. *Zener diyotlar gerilimi sabit tutmak istediğimiz devrelerde yani regülasayon devrelerinde* kullanılırlar.





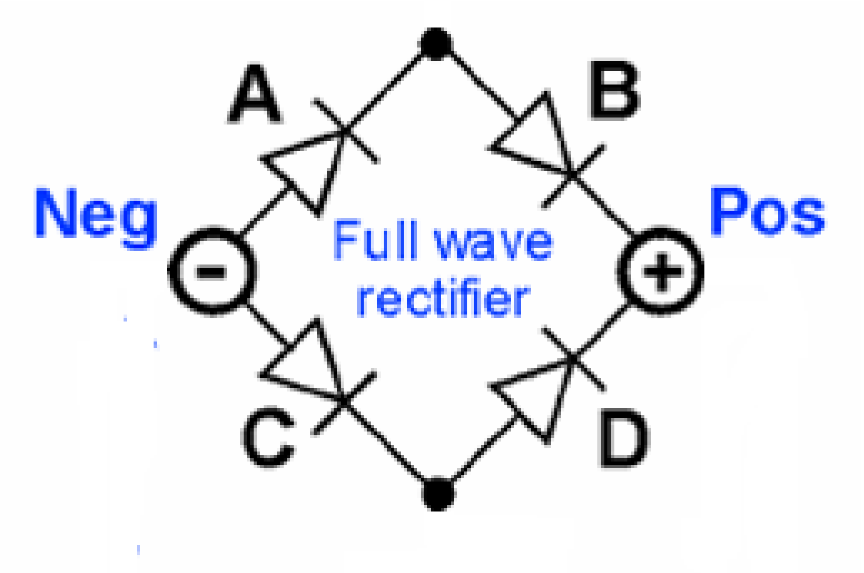
Circuits with diodes

- A diode can convert alternating current electricity to direct current.
- When the AC cycle is positive, the voltage passes through the diode because the diode is conducting and has low resistance.
- A single diode is called a halfwave rectifier since it



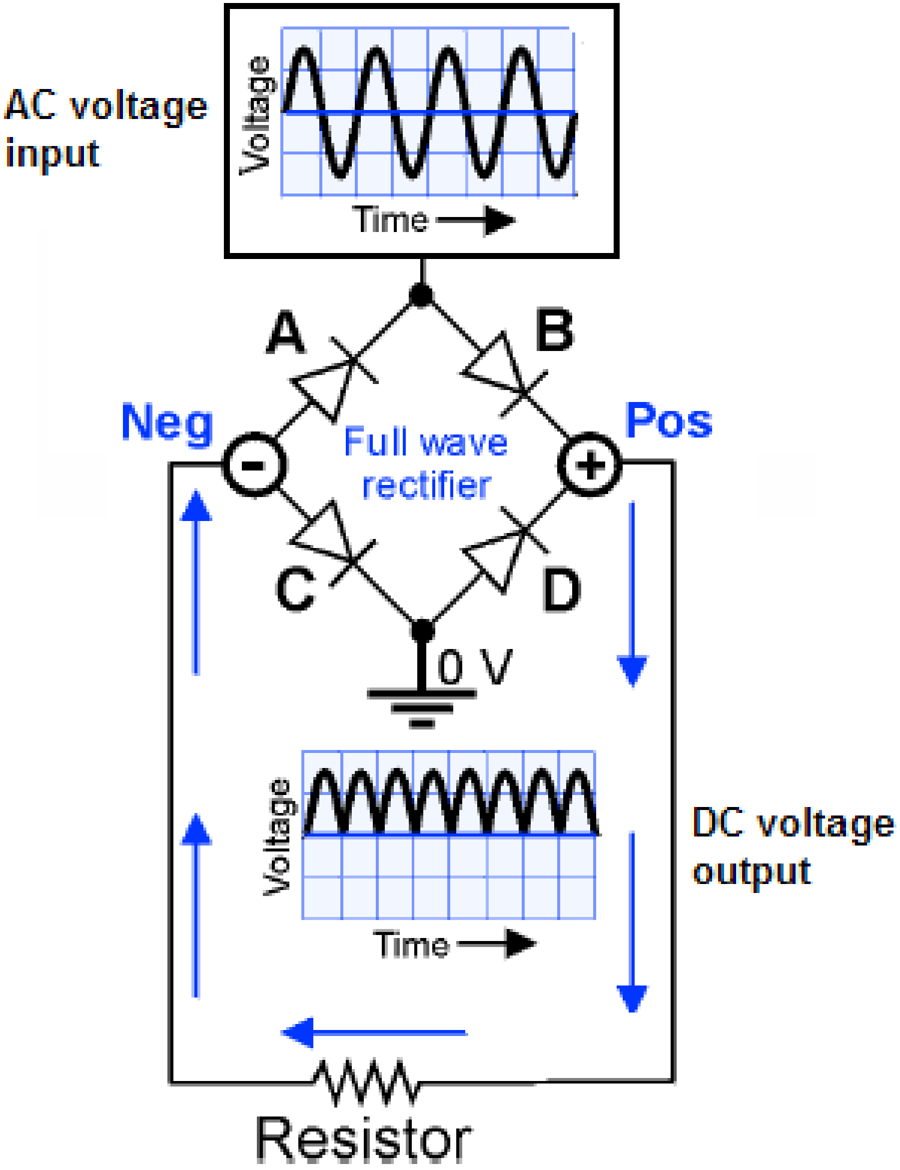
Circuits with Diodes

- **When 4 diodes are arranged in a circuit, the whole AC cycle can be converted to DC and this is called a full-wave rectifier.**



AC into DC

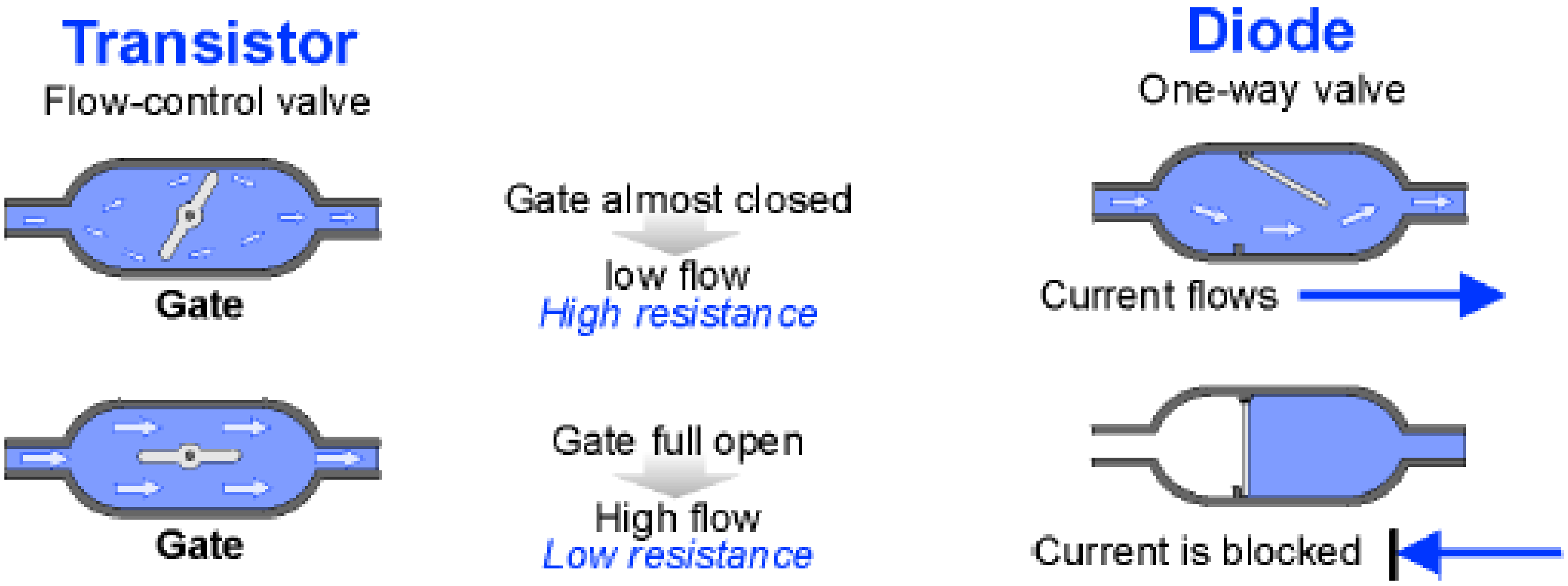
- **A bridge-rectifier circuit** uses the entire AC cycle by inverting the negative portions.
- This version of the full-wave rectifier circuit is in nearly every AC adapter you have ever used.



TRANSİSTOR

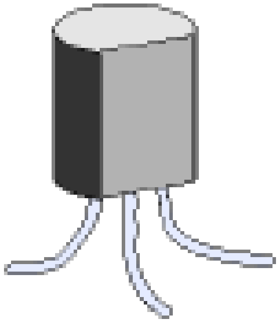
Transistors

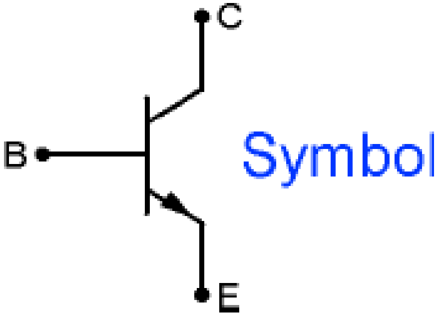
- A transistor allows you to control the current, not just block it in one direction.
- A good analogy for a transistor is a pipe with an adjustable gate.

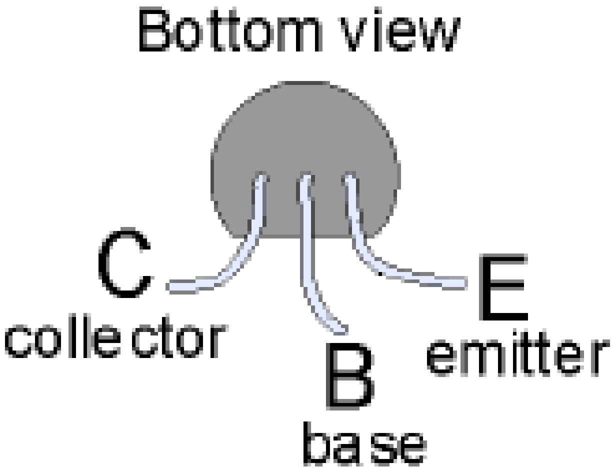


Transistors

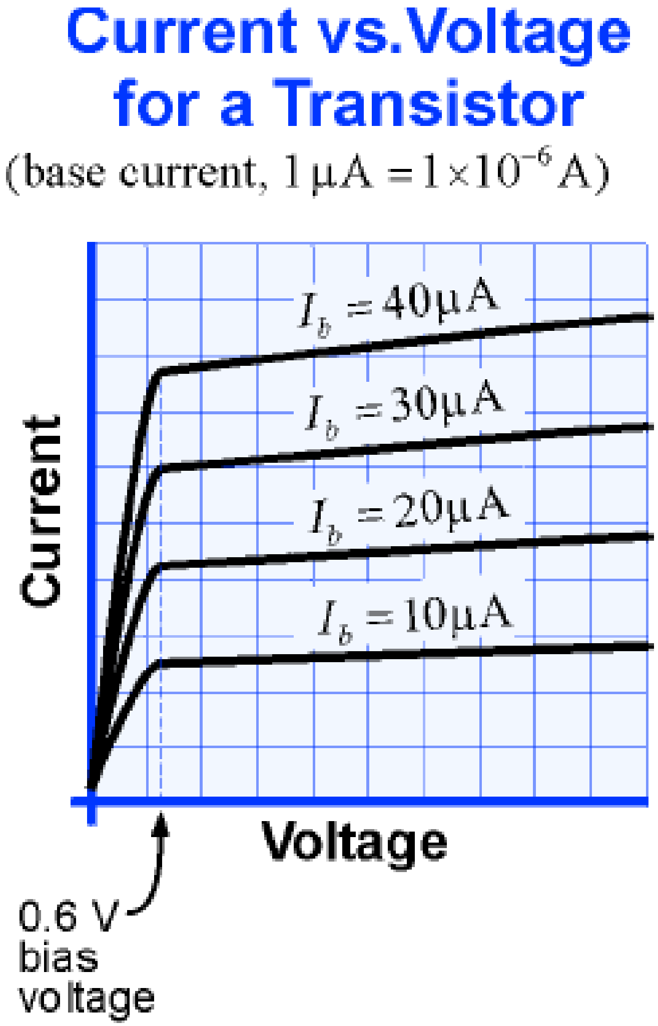
- A transistor has <u>three</u> terminals.
- The main path for current is between the collector and emitter.
- The base controls how much current flows, just like the gate controlled the flow of water in the pipe.





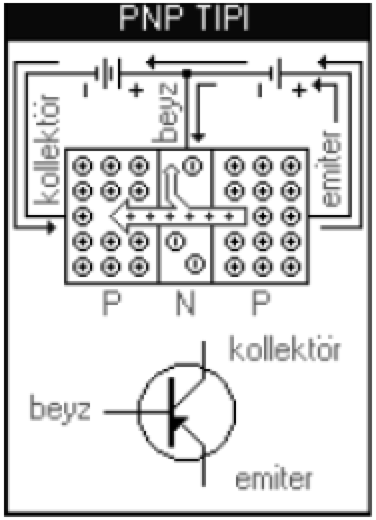


Transistors

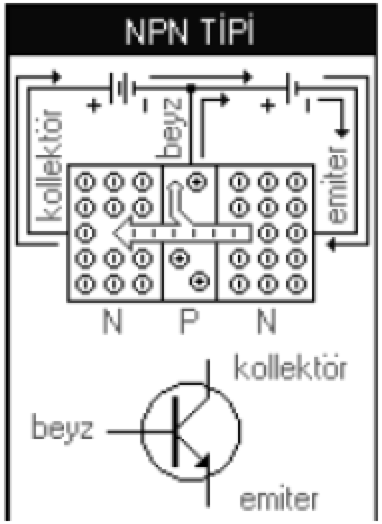


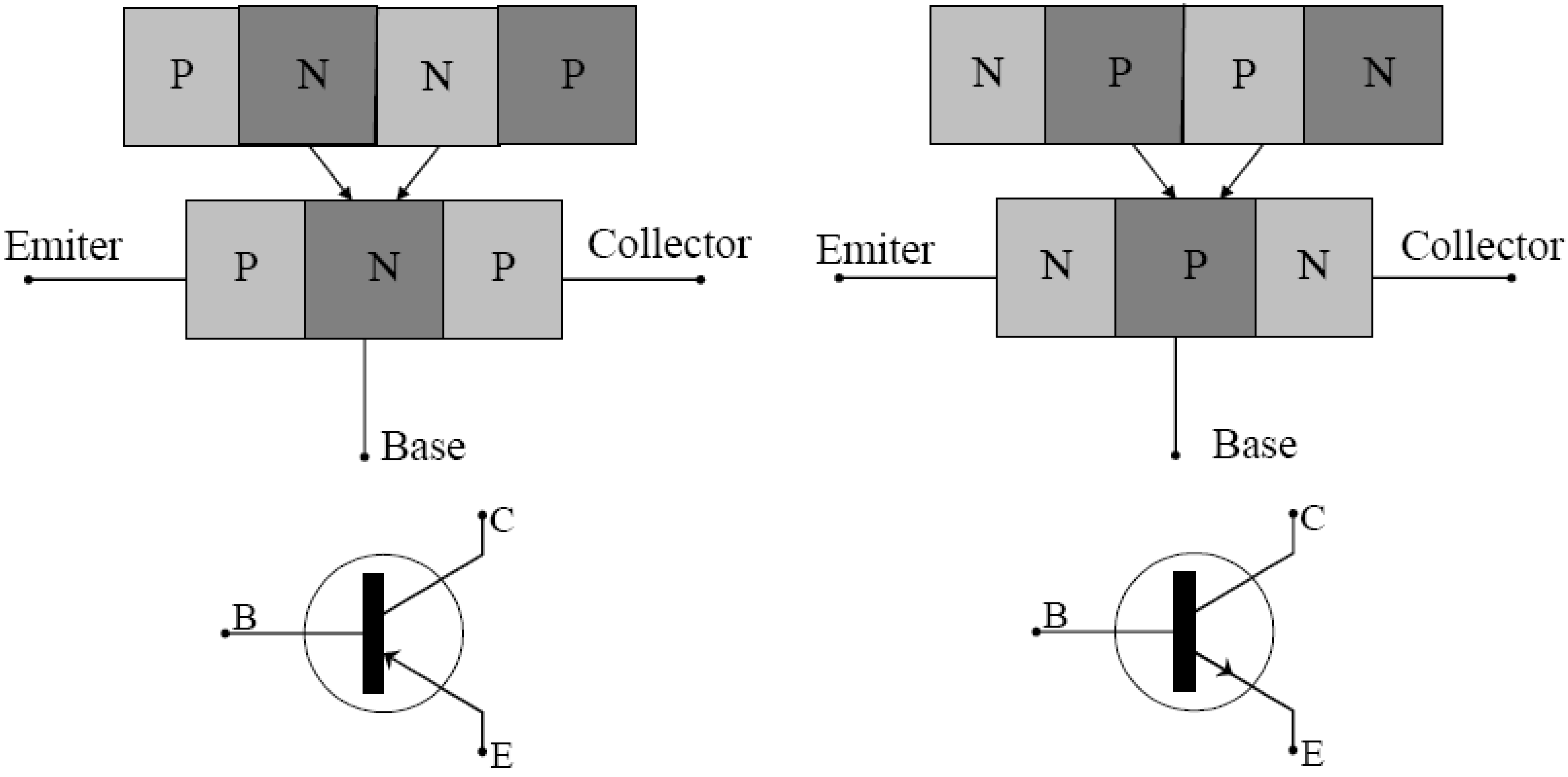
- The current versus voltage graph for a transistor is more complicated than for a simple resistor because there are three variables.
- A transistor is very sensitive; ten-millionths of an amp makes a big difference in the resistance between the collector and emitter.

PNP tipi transistörler, P, N ve P tipi yarıiletkenlerin birleşmesinden meydana gelir. Yandaki şekilde görüldüğü gibi 1 nolu kaynağın (+) kutbundaki oyuklar emiterdeki oyukları beyze doğru iter ve bu oyukların yaklaşık %1'i beyz üzerinden 1 nolu kaynağın (-) kutbuna, geri kalanı ise kollektör üzerinden 2 nolu kaynağın (-) kutbuna doğru hareket eder. Beyz ile emiter arasında dolaşan akım çok küçük, kollektör ile emiter arasında dolaşan akım ise büyüktür.



NPN tipi transistörler, N, P ve N tipi yarıiletkenlerin birleşmesinden meydana gelir. Yandaki şekilde görüldüğü gibi 1 nolu kaynağın (-) kutbundaki elektronlar emitördeki elektronları beyze doğru iter ve bu oyukların yaklaşık %1'i beyz üzerinden 1 nolu kaynağın (+) kutbuna, geri kalanı ise kollektör üzerinden 2 nolu kaynağın (+) kutbuna doğru hareket eder. Beyz ile emiter arasında dolaşan akım çok küçük, kollektör ile emiter arasında dolaşan akım ise büyüktür.

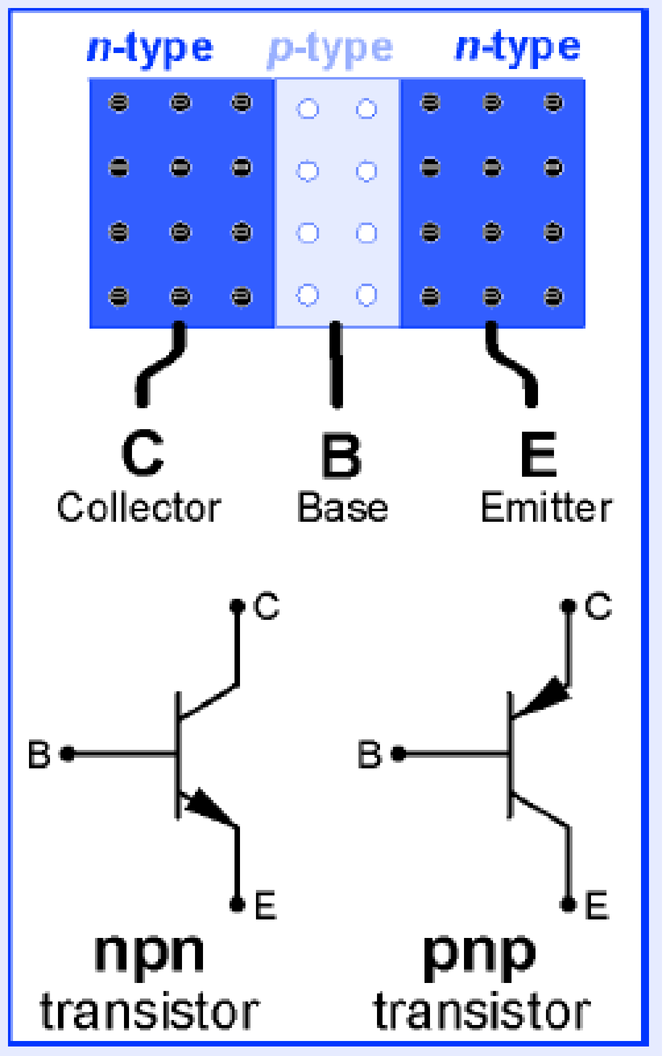




(a) (b)

PNP (a) ve NPN (b) transistor ve sembolleri

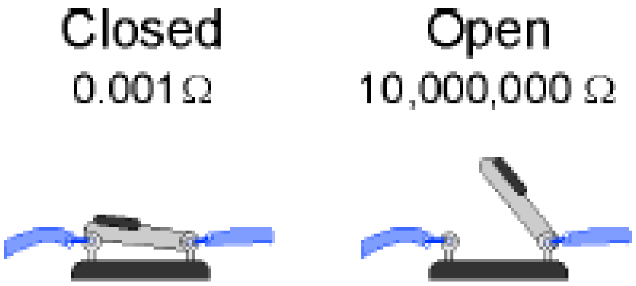
The physics of transistors



- A transistor is made from two *p*-*n* junctions back to back.
- An npn transistor has a *p*-type layer sandwiched between two *n*-type layers.
- A pnp transistor is the inverse.
- An *n*-type semiconductor is between two layers of *p*-type.

A transistor switch

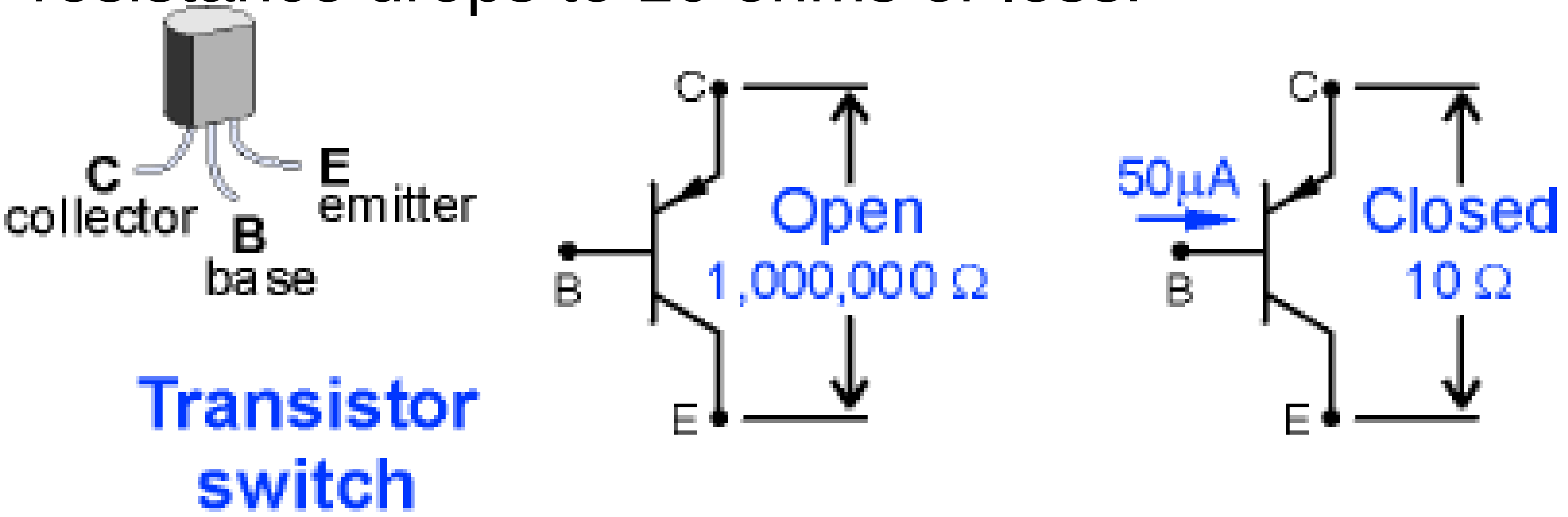
- In many electronic circuits a small voltage or current is used to switch a much larger voltage or current.
- Transistors work very well for this application because they behave like switches that can be turned on and off electronically instead of using manual or mechanical action.



Mechanical switch

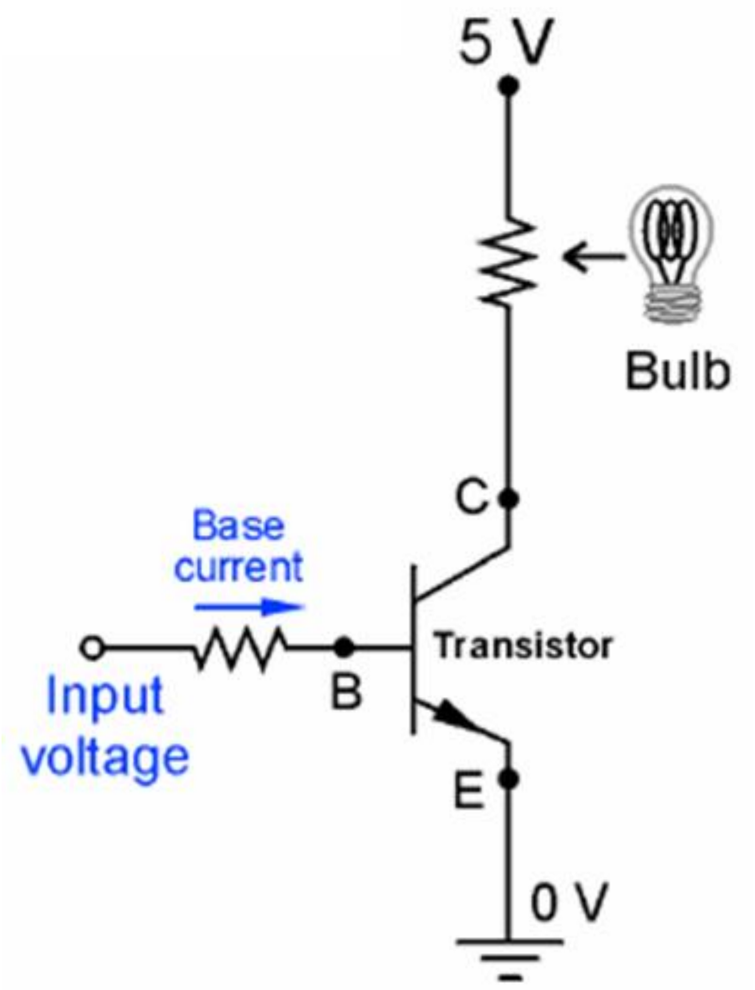
A transistor switch

- When the current into the base is zero, a transistor has a resistance of 100,000 ohms or more.
- When a tiny current flows into the base, the resistance drops to 10 ohms or less.



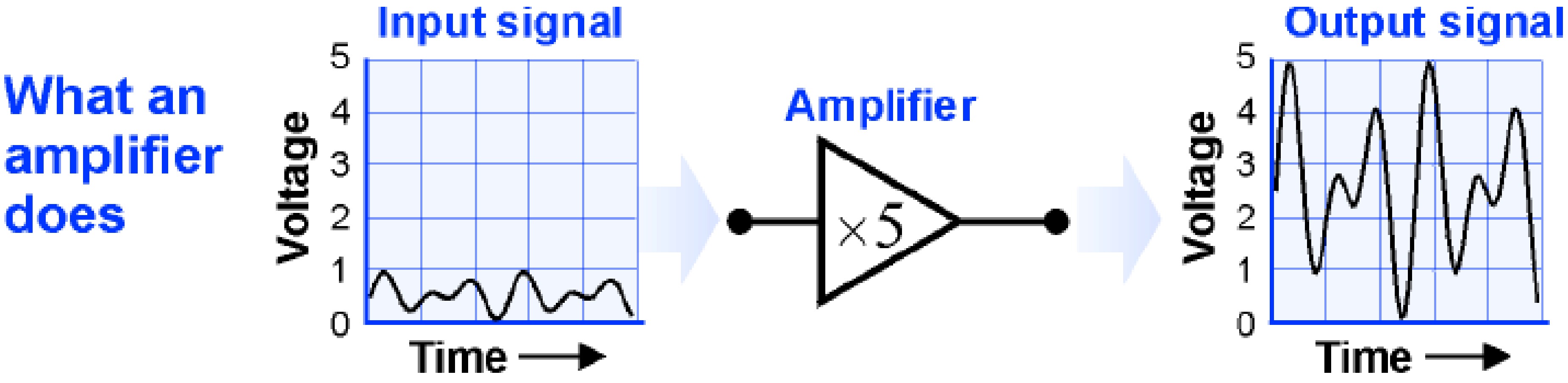
A transistor switch

- **The resistance difference between “on” and “off” for a transistor switch is good enough for many useful circuits such as an indicator light bulb in a mechanical circuit.**



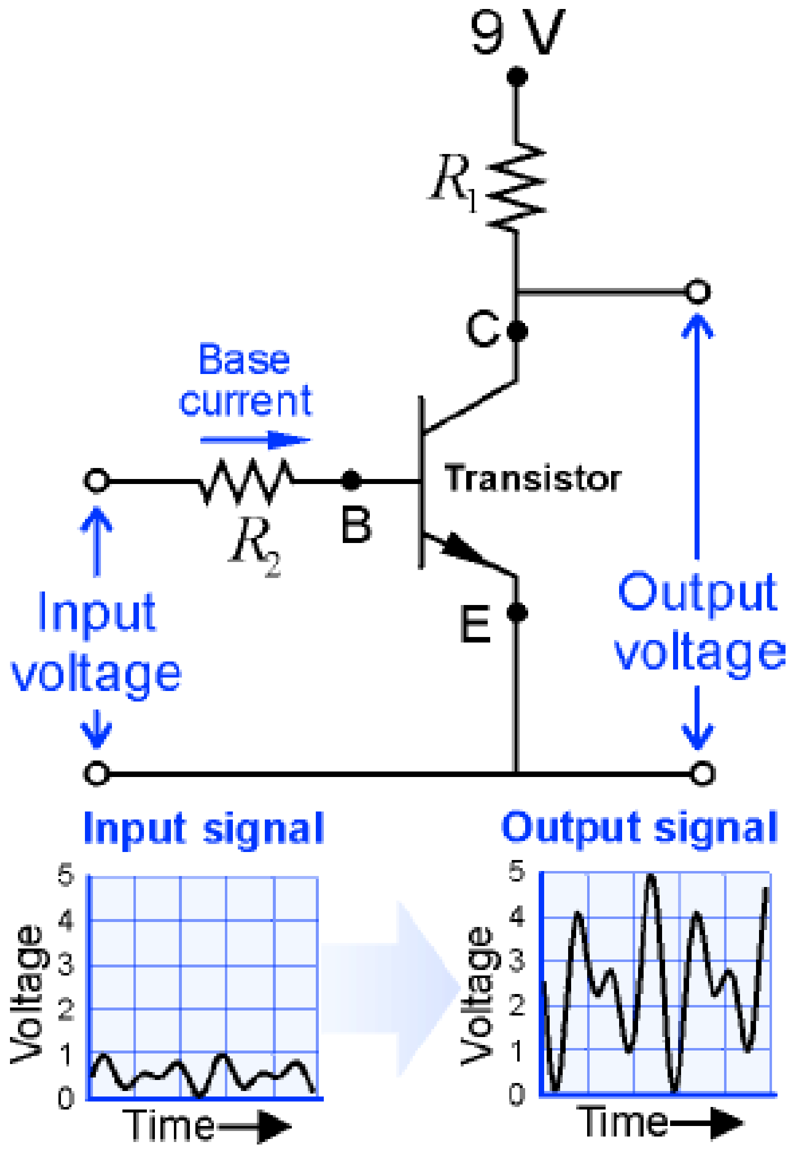
A transistor amplifier

- One of the most important uses of a transistor is to amplify a signal.
- In electronics, the word “amplify” means to make the voltage or current of the input signal larger without changing the shape of the signal.



A transistor amplifier

- In an amplifier circuit, the transistor is not switched fully "on" like it is in a switching circuit.
- Instead, the transistor operates partially on and its resistance varies between a few hundred ohms and about 10,000 ohms, depending on the specific transistor.



Electronic Logic

- **Logic circuits are designed to compare inputs and produce specific output when all the input conditions are met.**
- **Logic circuits assign voltages to the two logical conditions of TRUE (T) and FALSE (F).**
- **For example, the circuit that starts your car only works when a) the car is in park, b) the brake is on, and c) the key is turned.**

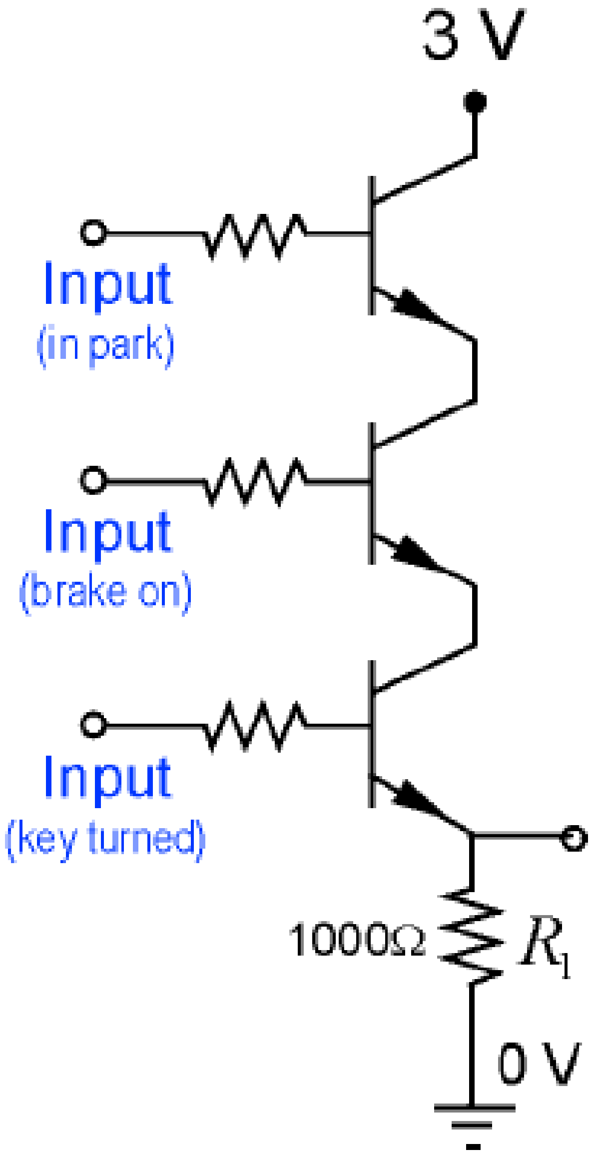
Electronic Logic

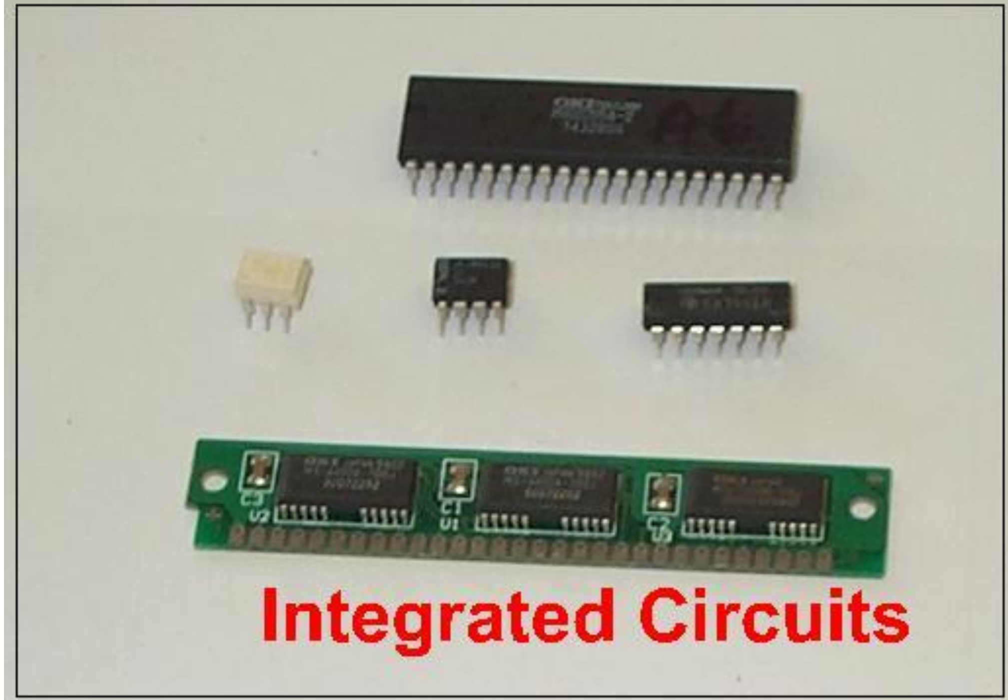
- There is one output which starts the car if TRUE and does not start the car if FALSE.

INPUT Car in park	INPUT Brake on	INPUT Key turned		OUTPUT Start engine
0 V	0 V	0 V		0 V
3 V	0 V	0 V		0 V
3 V	3 V	0 V		0 V
3 V	0 V	3 V		0 V
0 V	3 V	3 V		0 V
3 V	3 V	3 V		3 V

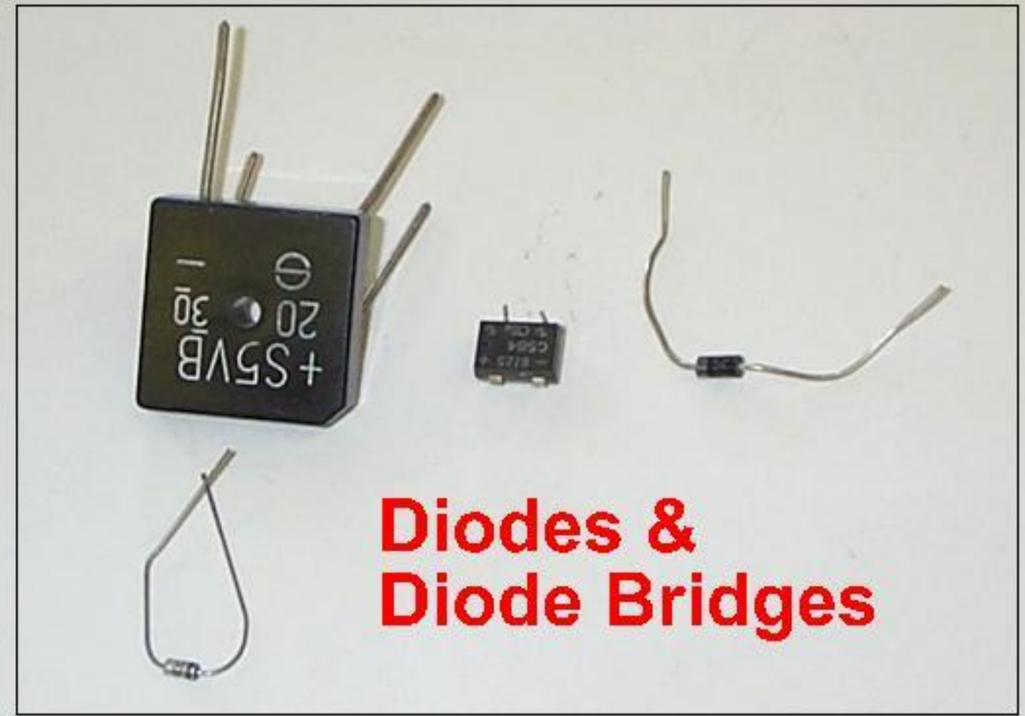
A transistor logic circuit

- The only way for the output to be 3 V is when all three transistors are on, which only happens if all three inputs are TRUE.

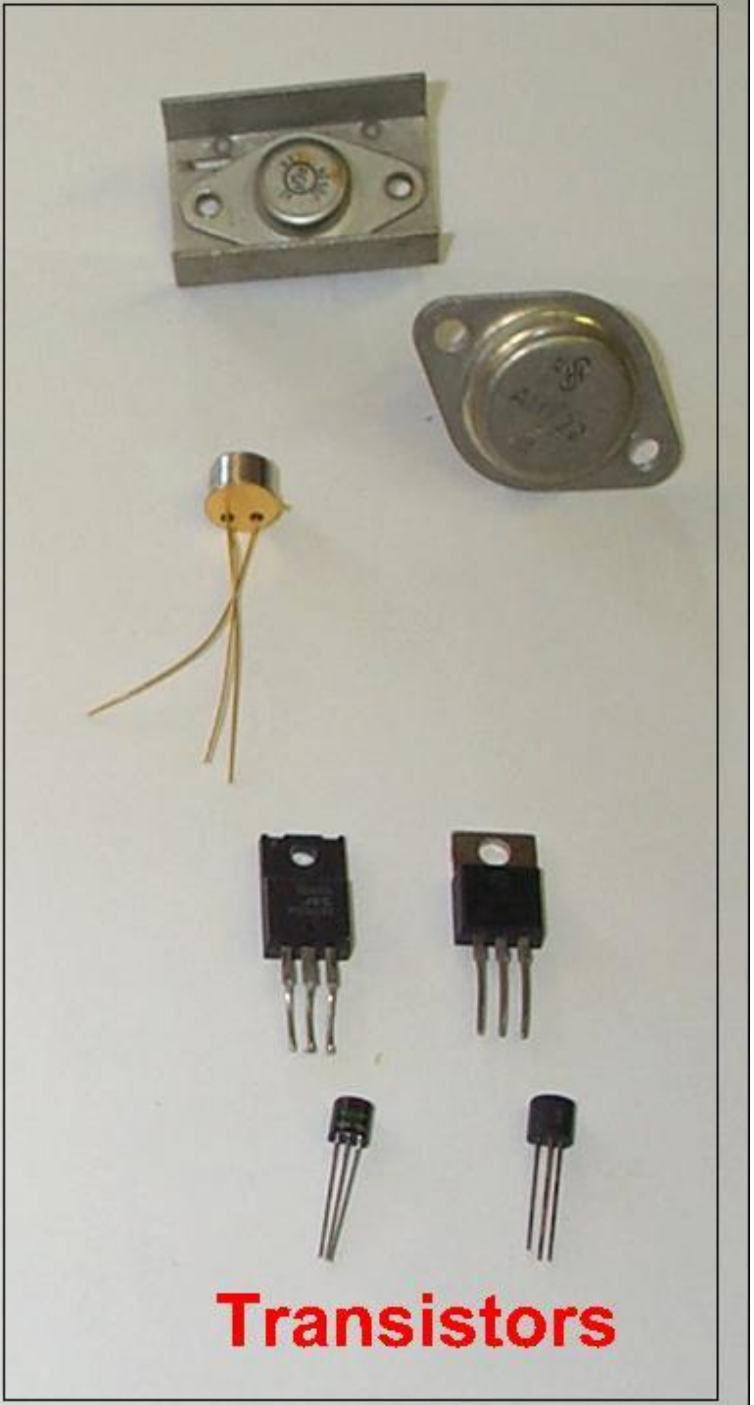




Integrated Circuits



Diodes &
Diode Bridges



Transistors

BİPOLAR TRANSİSTOR
NPN - PNP

NPN Transistor Amplifier

Example

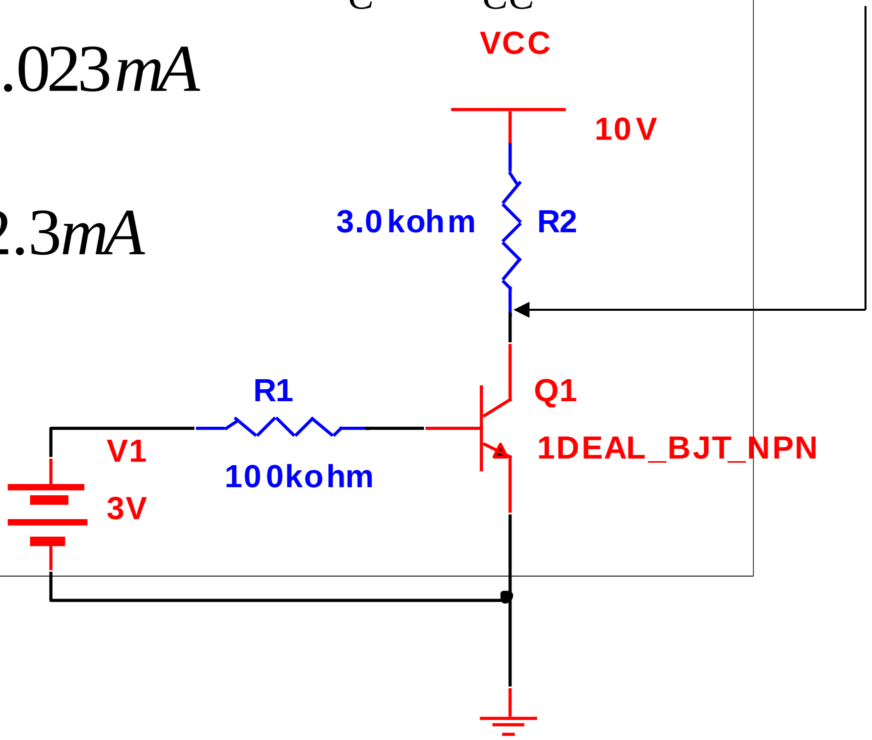
- NPN

•Quiescent point

$$I_B = \frac{V_{BB} - V_{BE}}{R_{BB}} = \frac{3-0.7}{100} = 0.023mA$$

$$I_C \cong \beta I_B = \frac{3-0.7}{100} = 2.3mA$$

$$V_C = V_{CC} - 2.3x3 \;\; = 3.1V$$

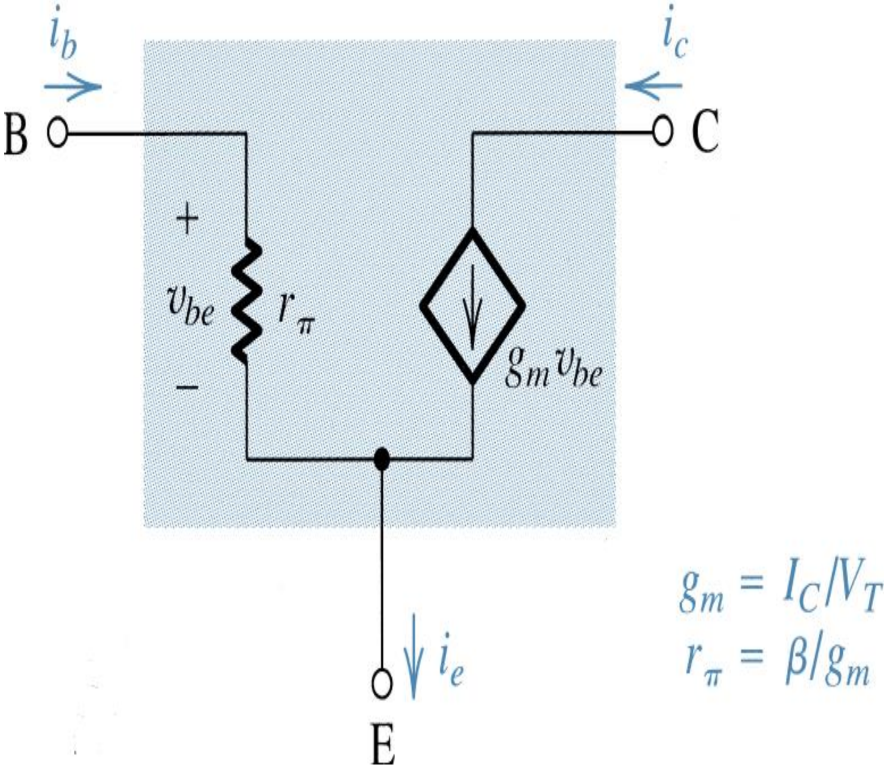


Small Signal Analysis

$$r_e = \frac{V_T}{I_E} = \frac{25mV}{(2.3/0.99)mA} = 10.8\Omega$$

$$g_m = \frac{I_C}{V_T} = \frac{2.3mA}{25mV} = 92mA/V$$

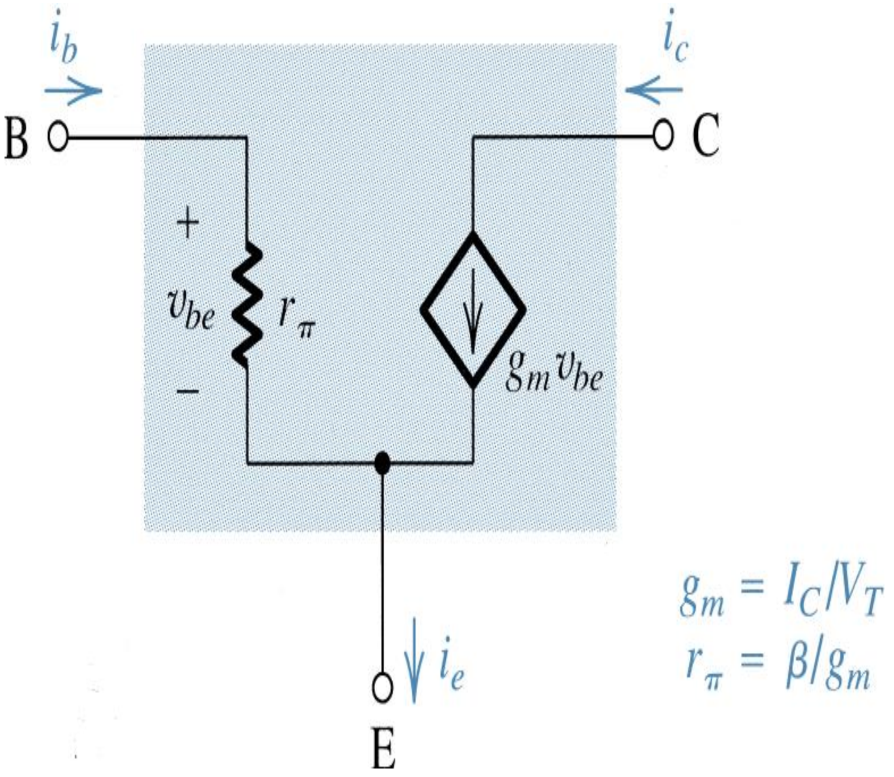
$$r_\Pi = \frac{\beta}{g_m} = \frac{100}{92} = 1.09k\Omega$$

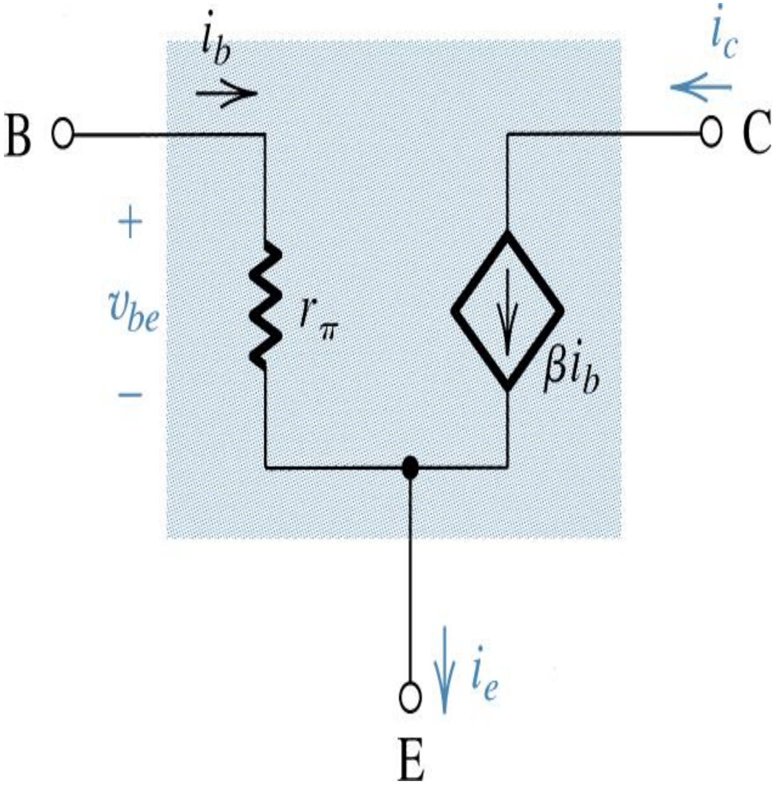


BJT as Amplifier

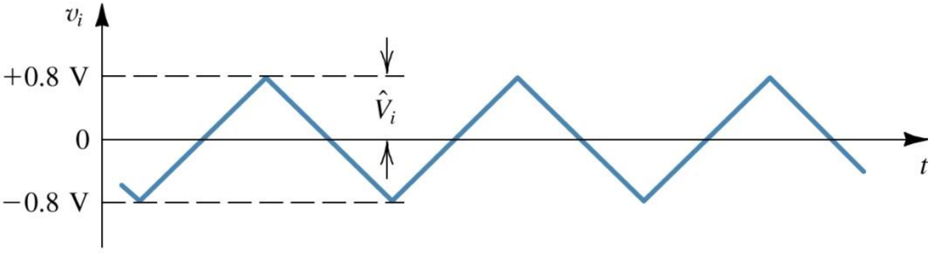
BJT as a voltage-controlled current source (a transconductance amplifier)

BJT as a current-controlled current source (a current amplifier).

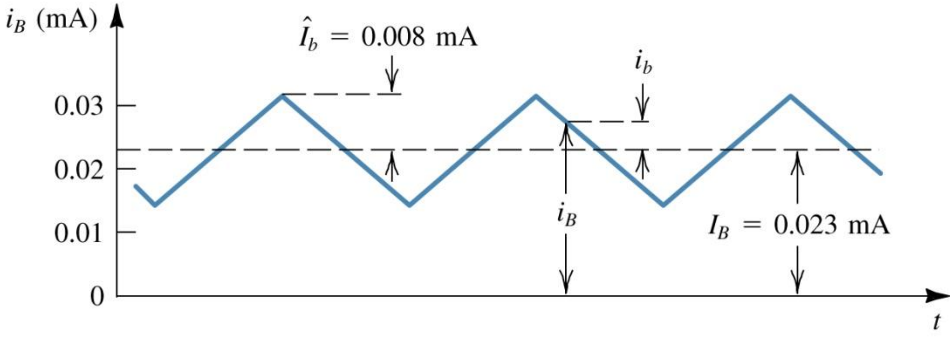




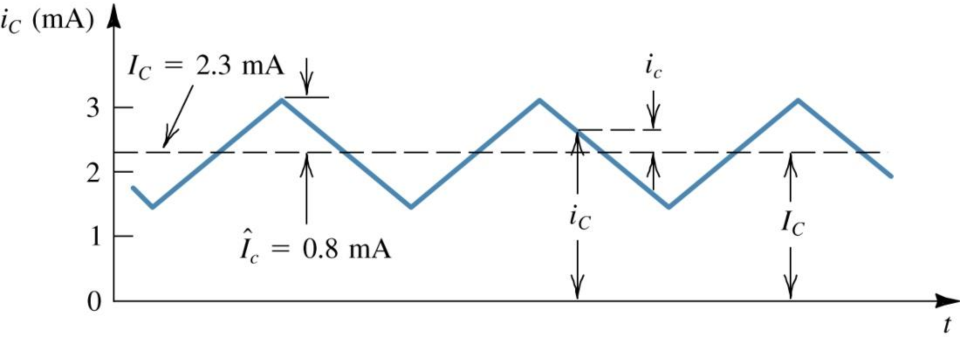
Small Signal



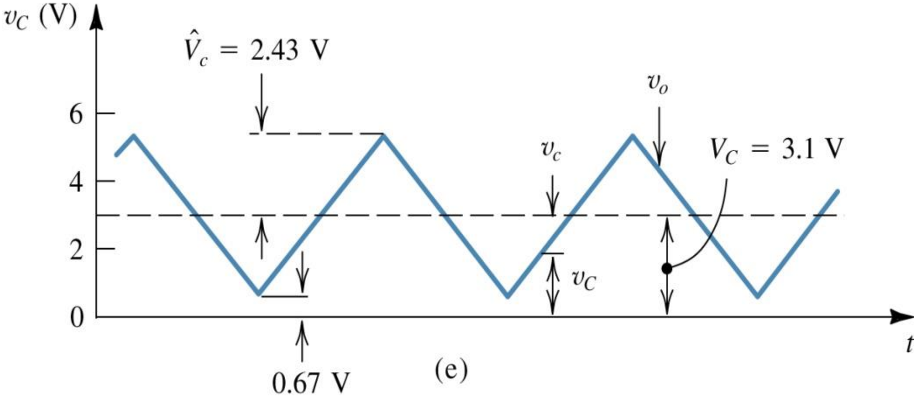
(a)



(b)



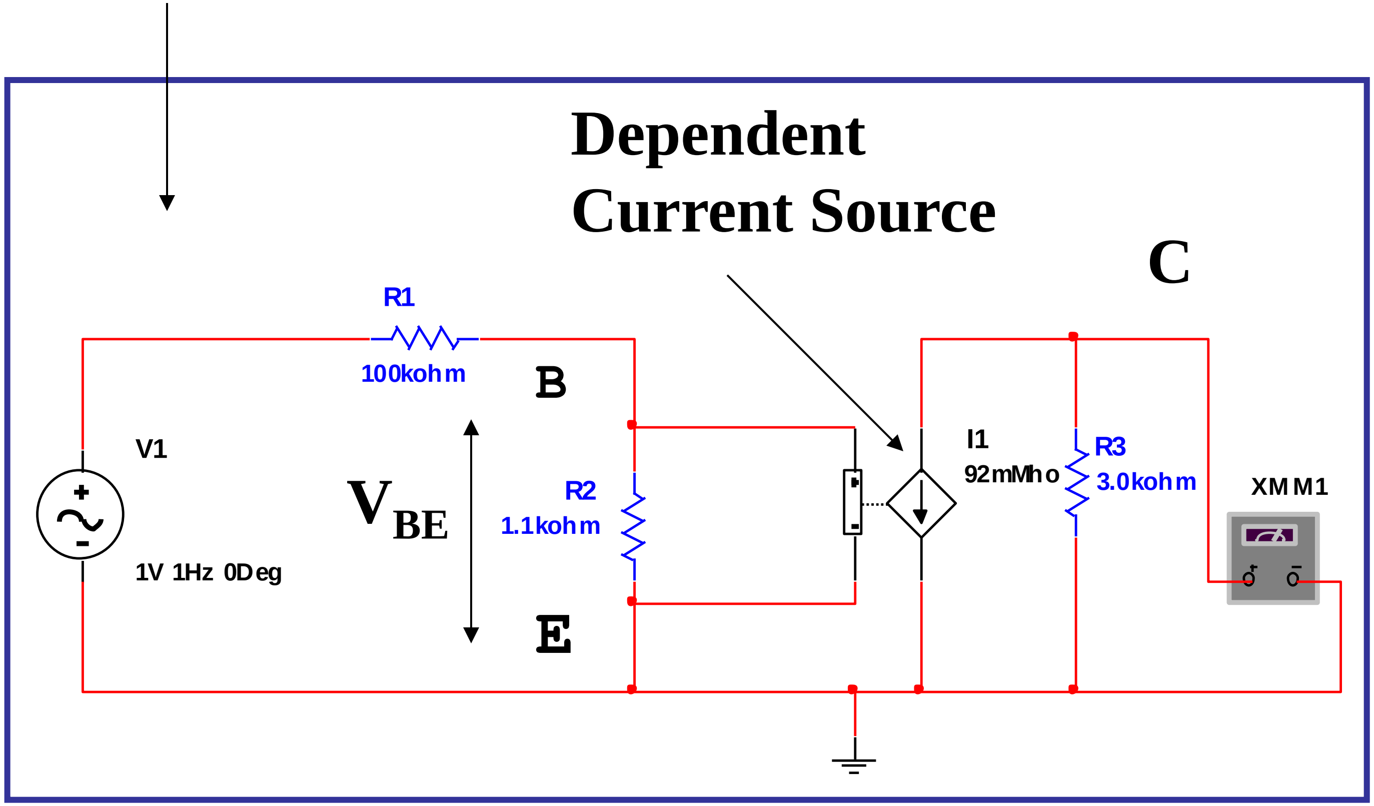
(d)



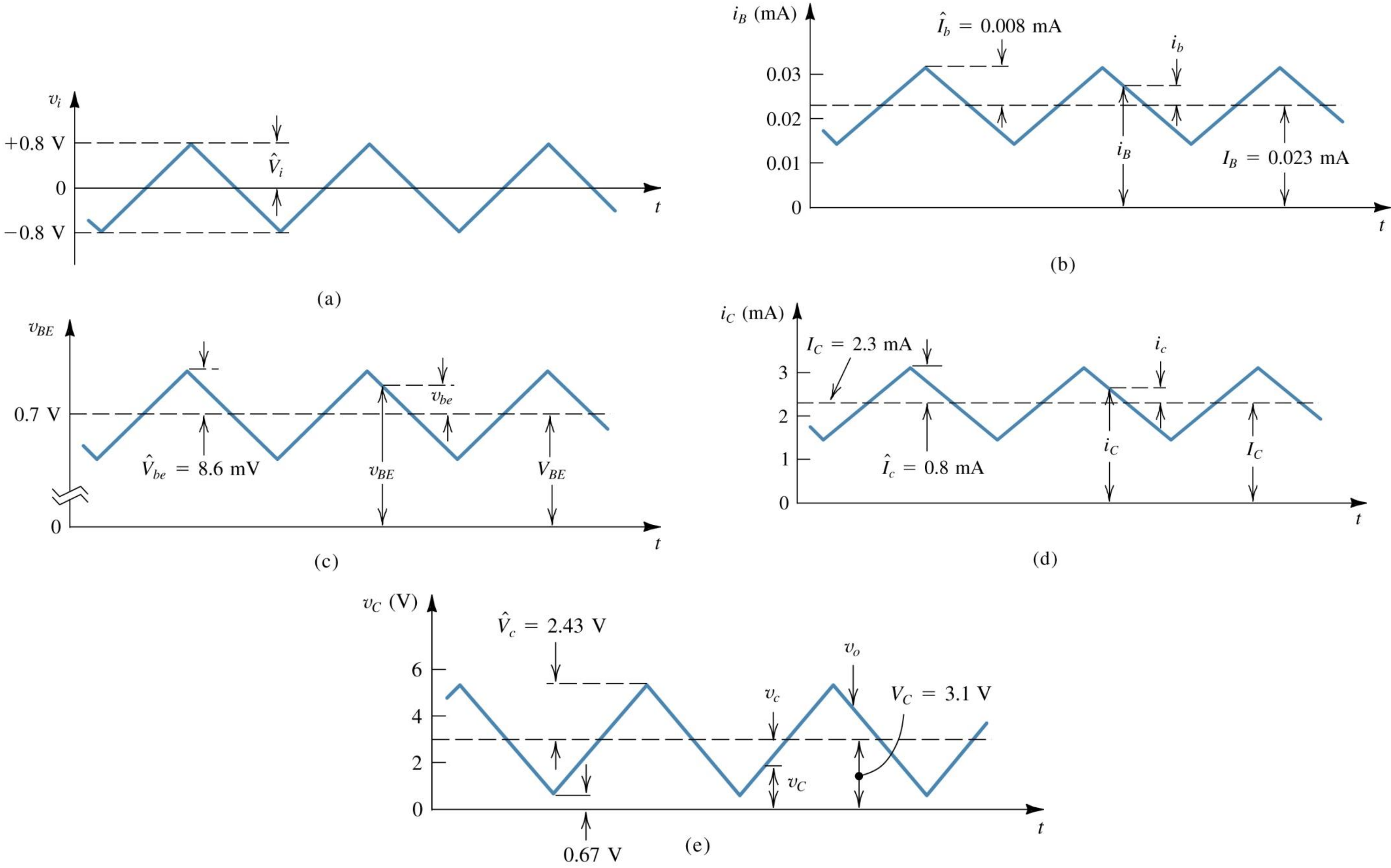
(e)

Small Signal Analysis

- Employ either hybrid-π model.
- Using the first model
- BJT as Amplifier



Signal Waveforms



(a)

(b)

(c)

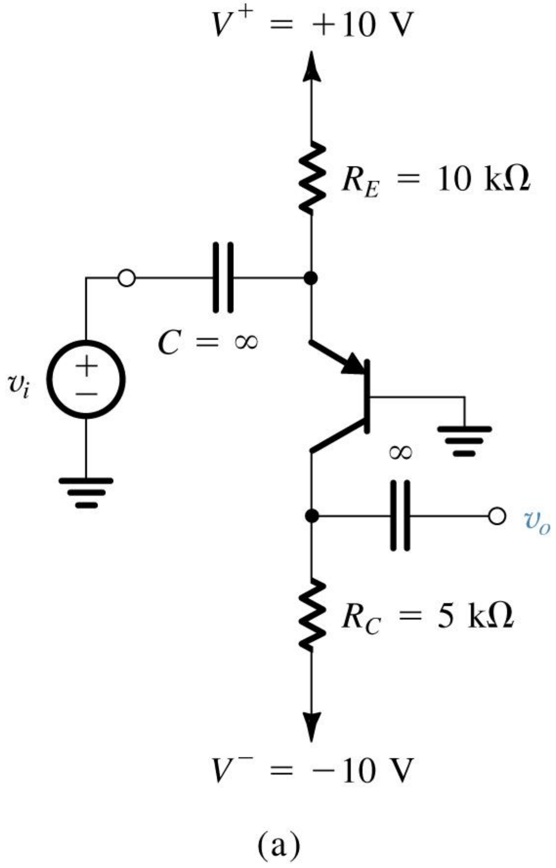
(d)

(e)

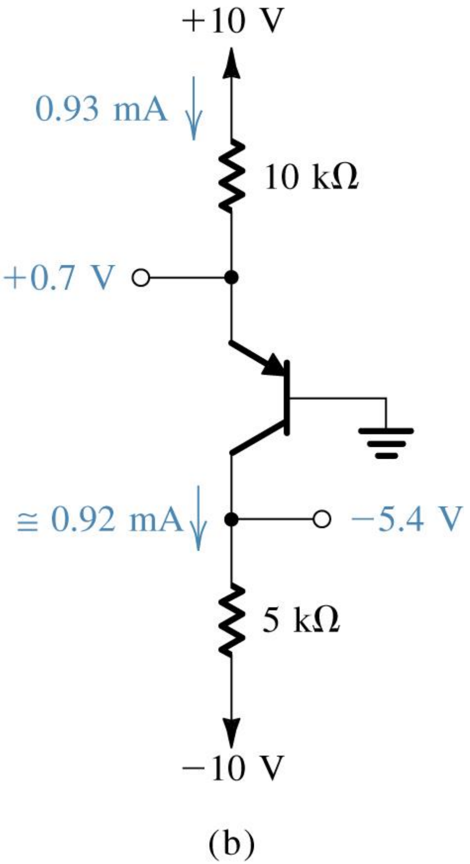
PNP Transistor Amplifier

Example

- Voltage Gain
- Signal Waveforms
- Capacitor couples input signal v_i to emitter
- DC bias with V^+ & V^-



DC Analysis



(b)

- Find operating pt. Q

$$I_E = \frac{10 - V_E}{R_E} \cong \frac{10 - 0.7}{10} = 0.93mA$$

- Let β=100 and α=0.99

$$I_C = 0.99 I_E = 0.92mA$$

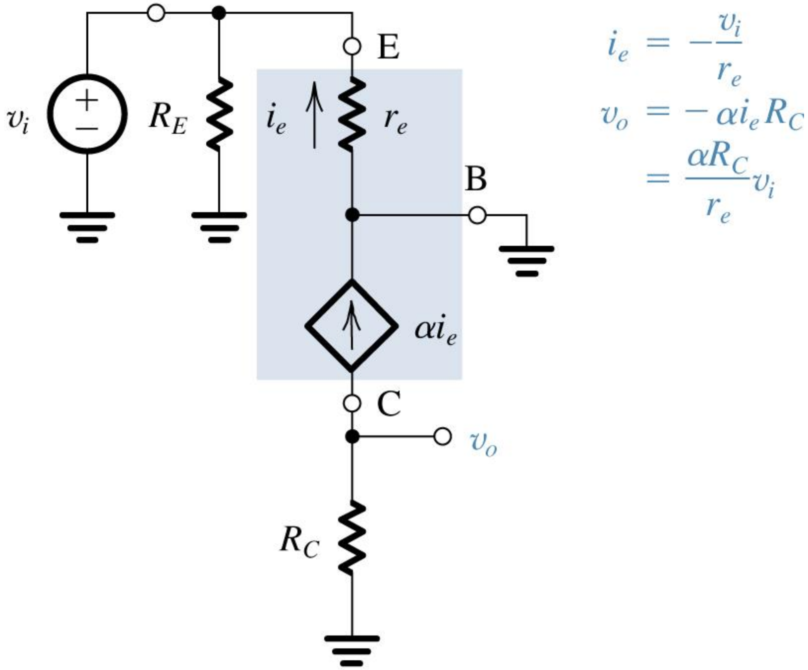
$$V_C = -10 + I_C R_C = -5.4V$$

- The transistor is active
- Max. signal swing depends on bias voltage

Small Signal Analysis

- Replace BJT with T equivalent ckt.
- Why? Base is gnded. More convenient than hybrid π

☐ α= 0.99
r_e=25mV/0.93mA= 27 Ω



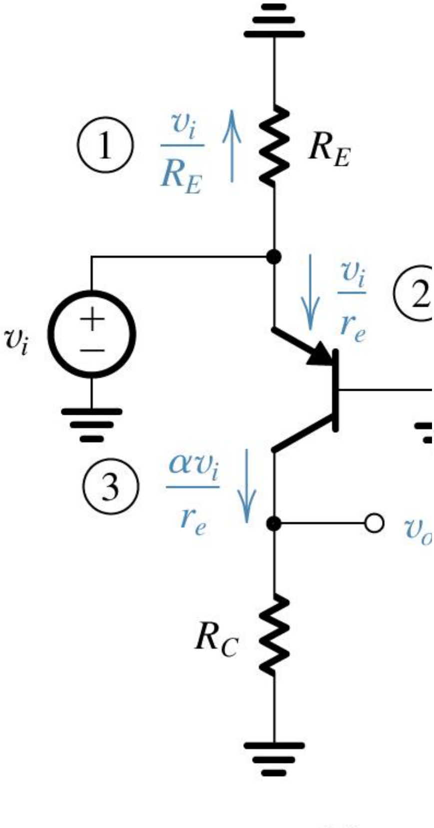
$$\begin{aligned} i_e &= -\frac{v_i}{r_e} \\ v_o &= -\alpha i_e R_C \\ &= \frac{\alpha R_C}{r_e} v_i \end{aligned}$$

(c)

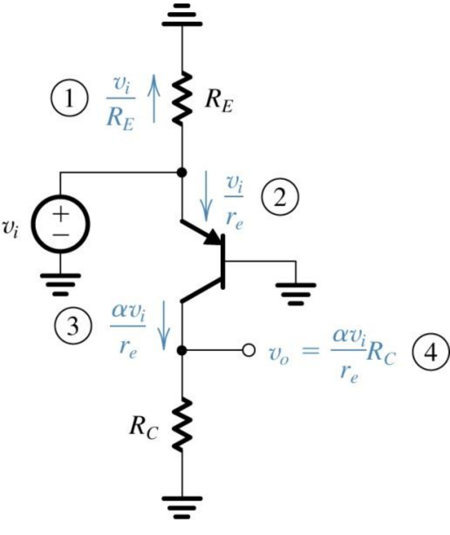
Small Signal Equiv Ckt

- V_O/V_i =0.99x5k/27=183
- Allowable signal magnitude?
- But $v_{eb} = v_i$ For small signal limit to 10mV.

Then, v_c=1.833V



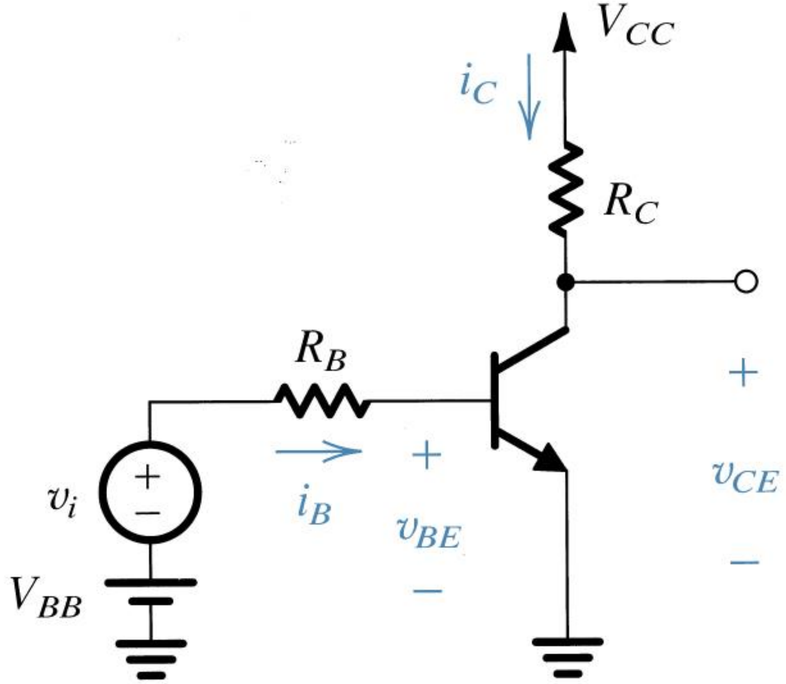
(d)



(d)

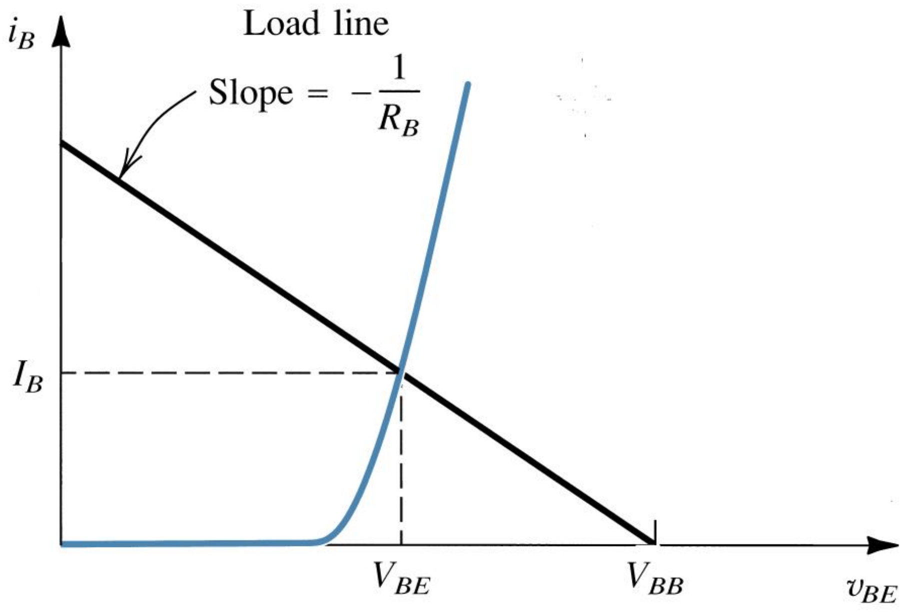
Graphical Analysis

- Find DC bias point
- Set v_i=0 and draw load line to determine dc bias point I_B (similar to diode ckts)



Graphical Construction

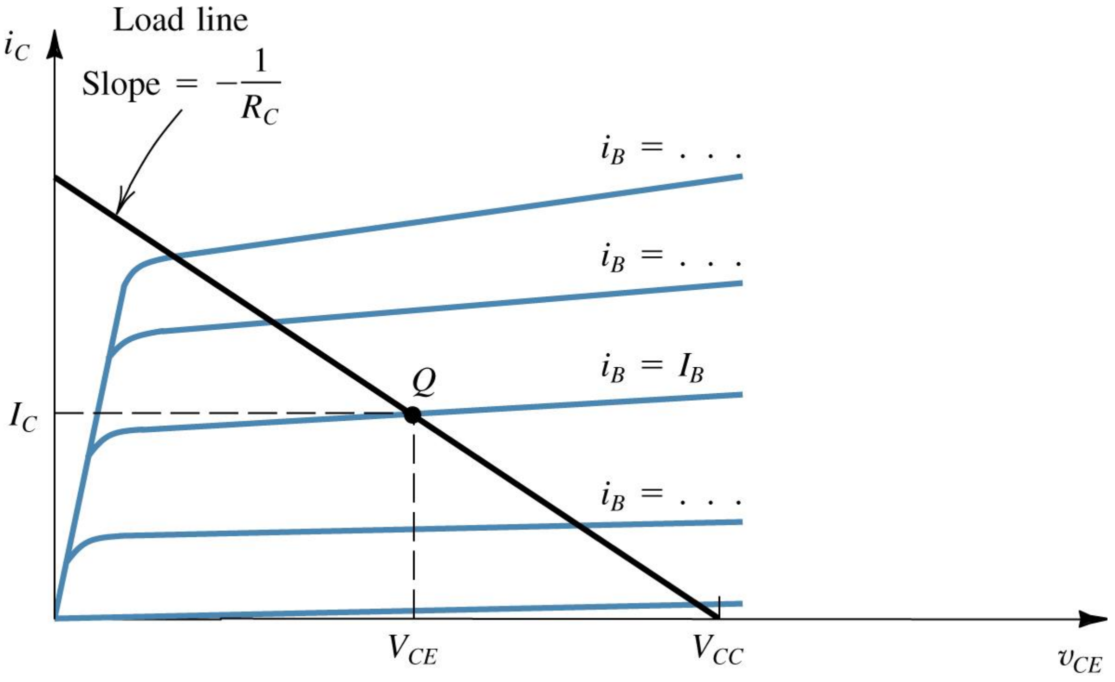
- Load line has a slope of –1/R_B
- i_B vs v_{BE} from forward biased diode eqns



Graphical construction for the determination of the dc base current

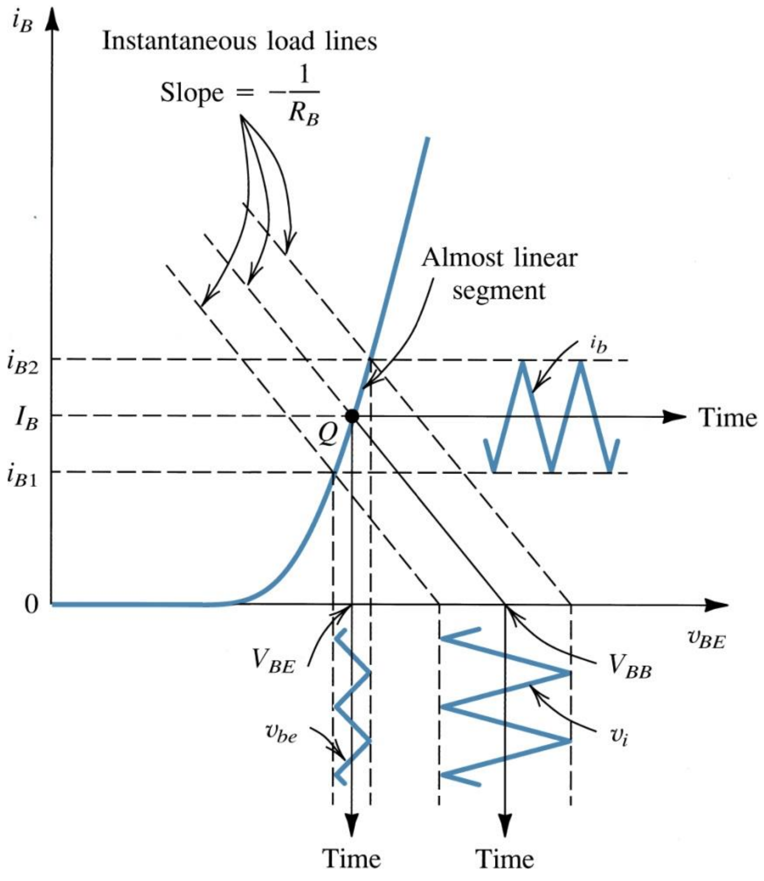
Collector Current

Graphical construction for determining the dc collector current I_C and the collector-to-emmiter voltage



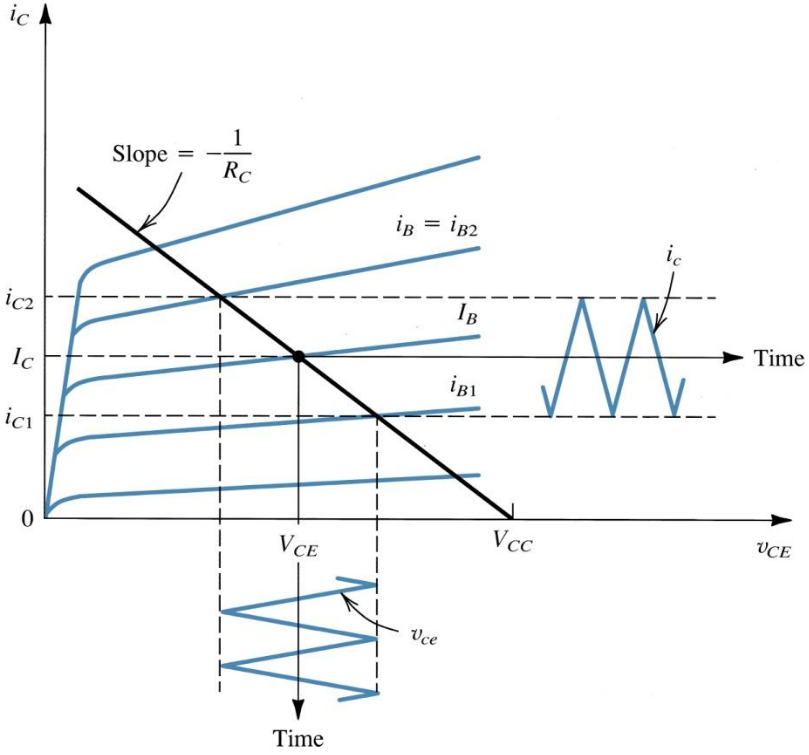
Small Signal Graphical Analysis

- Signal is superimposed on DC voltage V_{BB}
- Corresponding to each instantaneous value of $V_{BB} + v_i(t)$ draw a load line
- Intersection of the i_B - v_{BE} curve with the load lines
- Amplitude $v_i(t)$ small so i_b linear

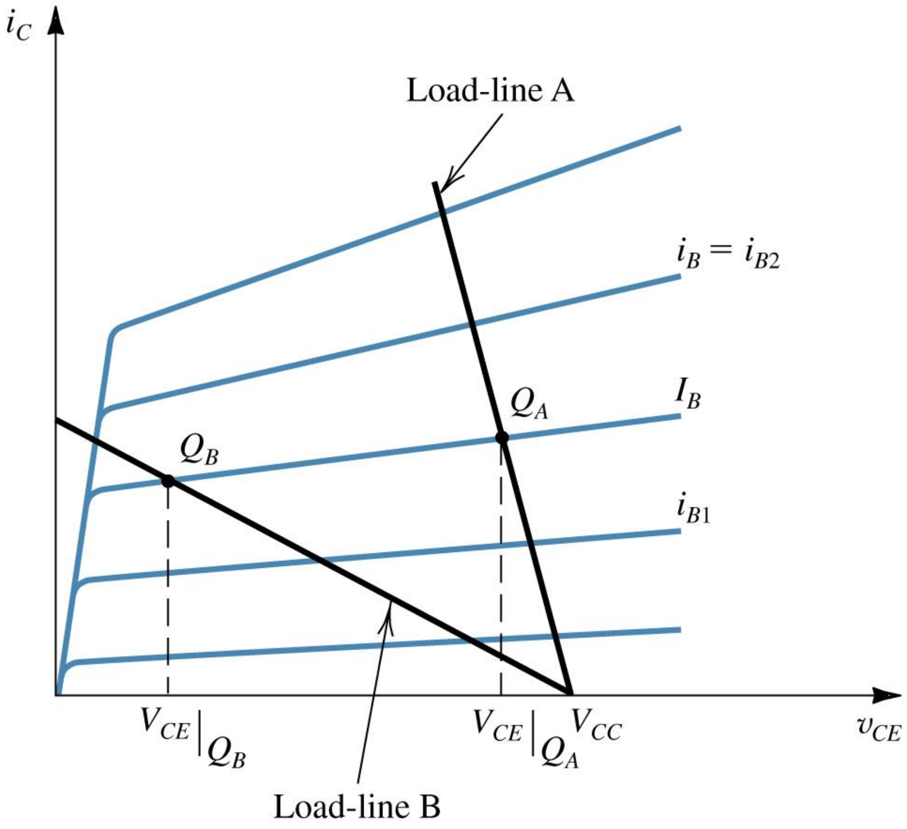


Collector Currrent

- Corresponding to each instantaneous value of $V_{CE} + v_{ce}(t)$ operating point will be on the load line
- Amplitude $v_i(t)$ small so i_c linear

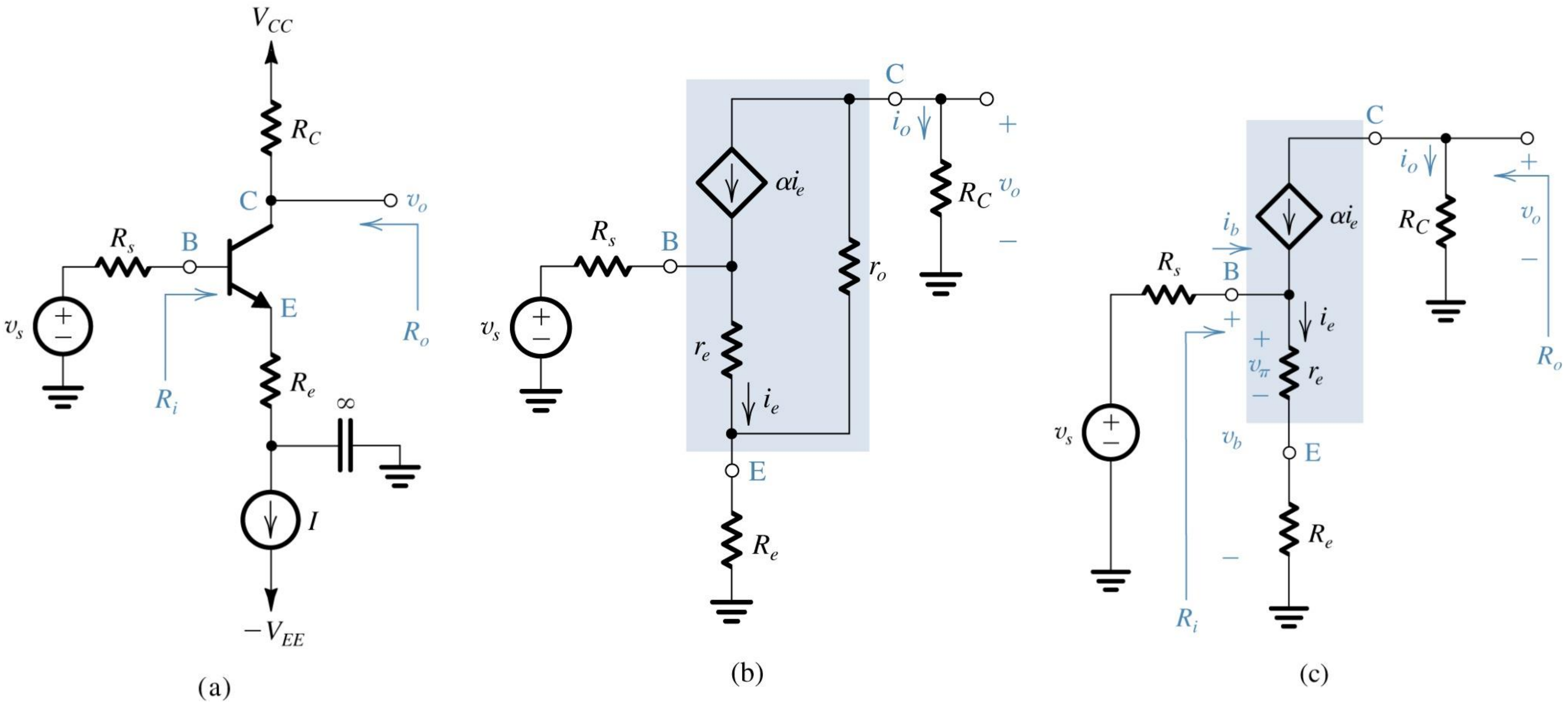


Bias Point vs Signal Swing



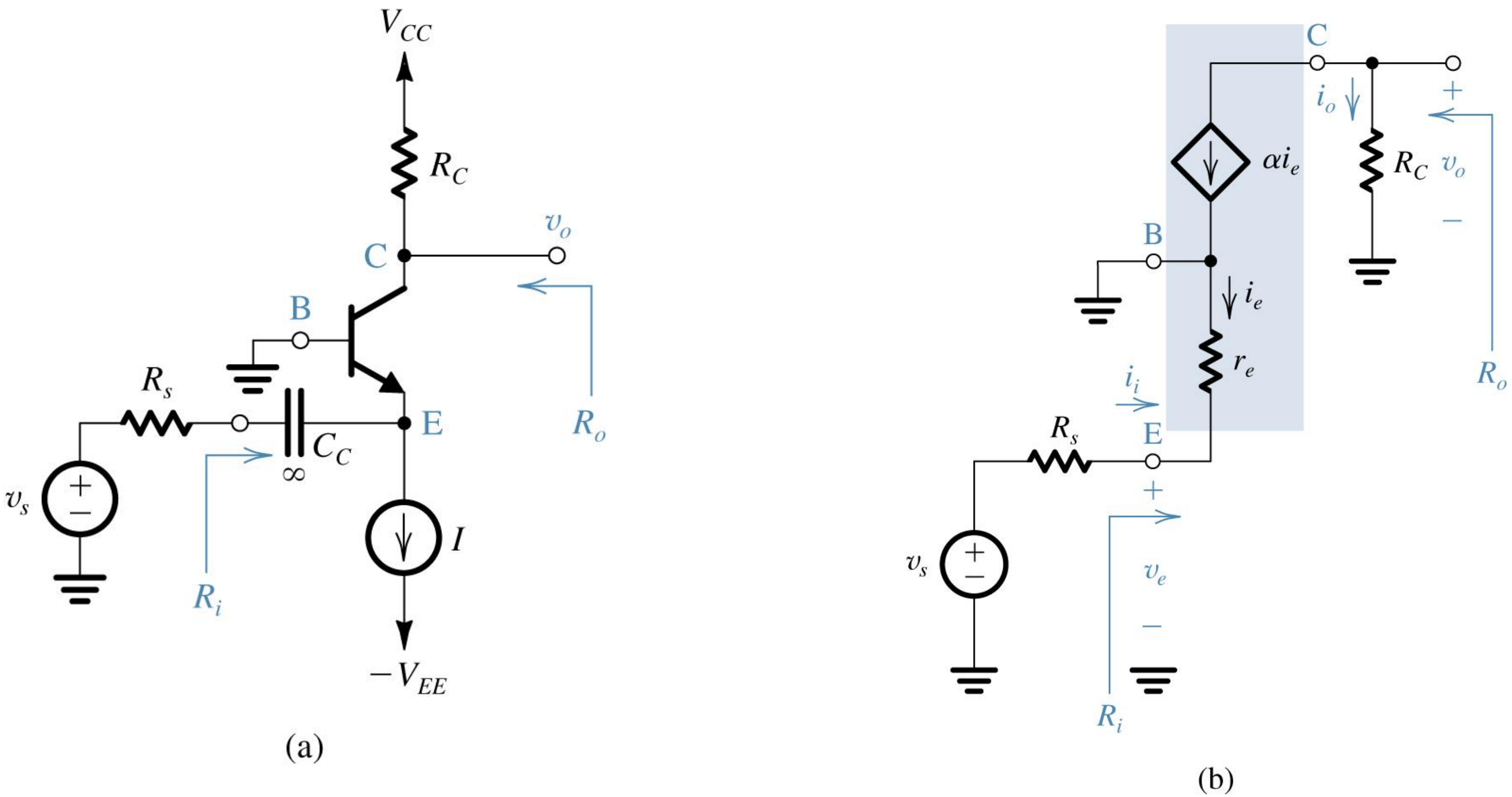
- Bias-point location limits allowable signal swing
- Load-line A results in bias point Q_A with a corresponding V_{CE} which is too close to V_{CC} and thus limits the positive swing of v_{CE}.
- At the other extreme, load-line B results in an operating point too close to the saturation region, thus limiting the negative swing of v_{CE}.

Basic Single Stage Amplifiers



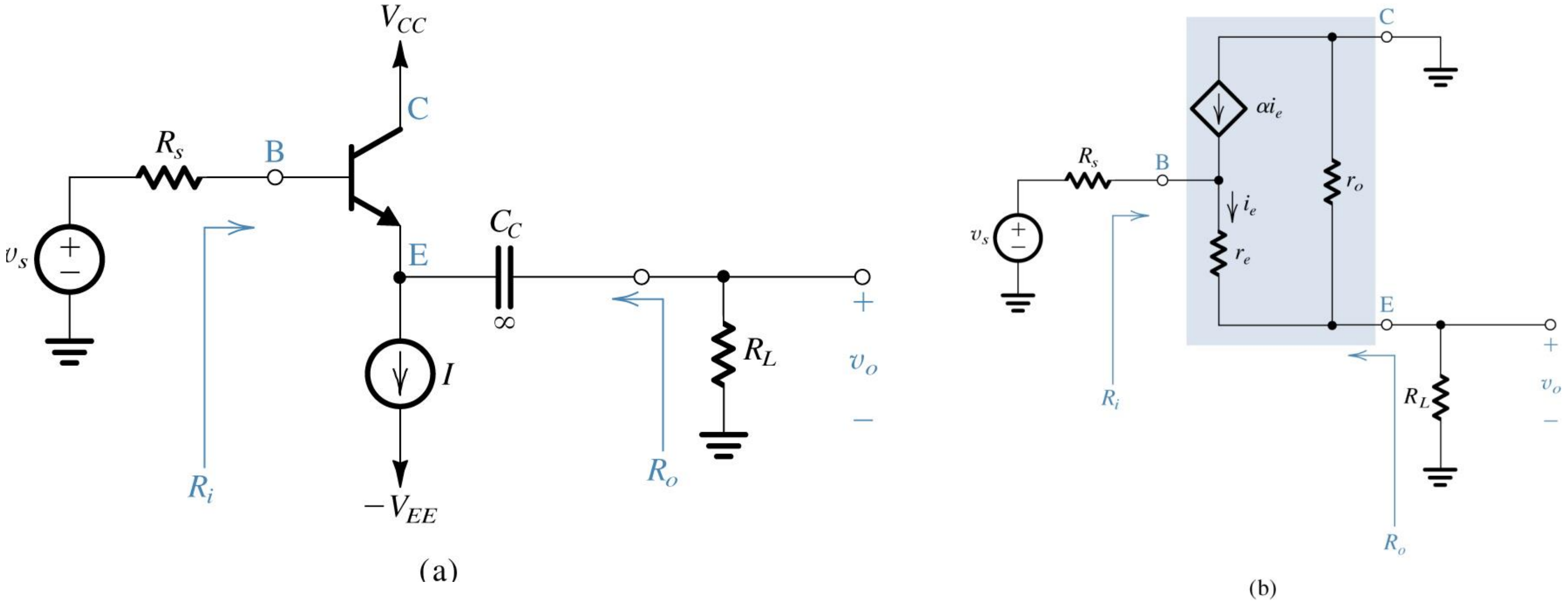
Common-emitter amplifier with a resistance R_e in the emitter. **(a)** Circuit. **(b)** Equivalent circuit with the BJT replaced with its T model **(c)** The circuit in (b) with r_o eliminated.

Common Base Amp

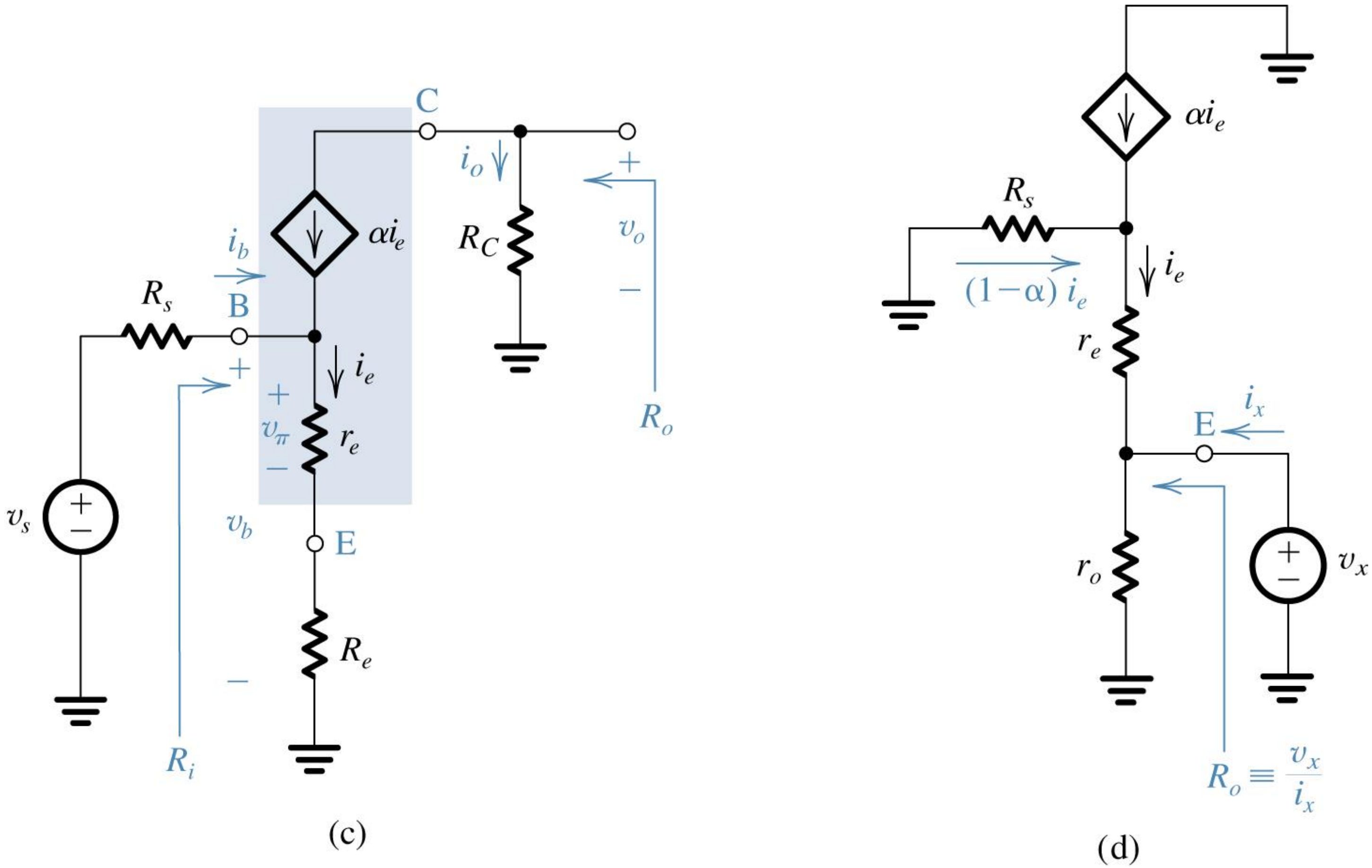


The common-base amplifier. **(a)** Circuit. **(b)** Equivalent circuit obtained by replacing the BJT with its T model.

Common Collector



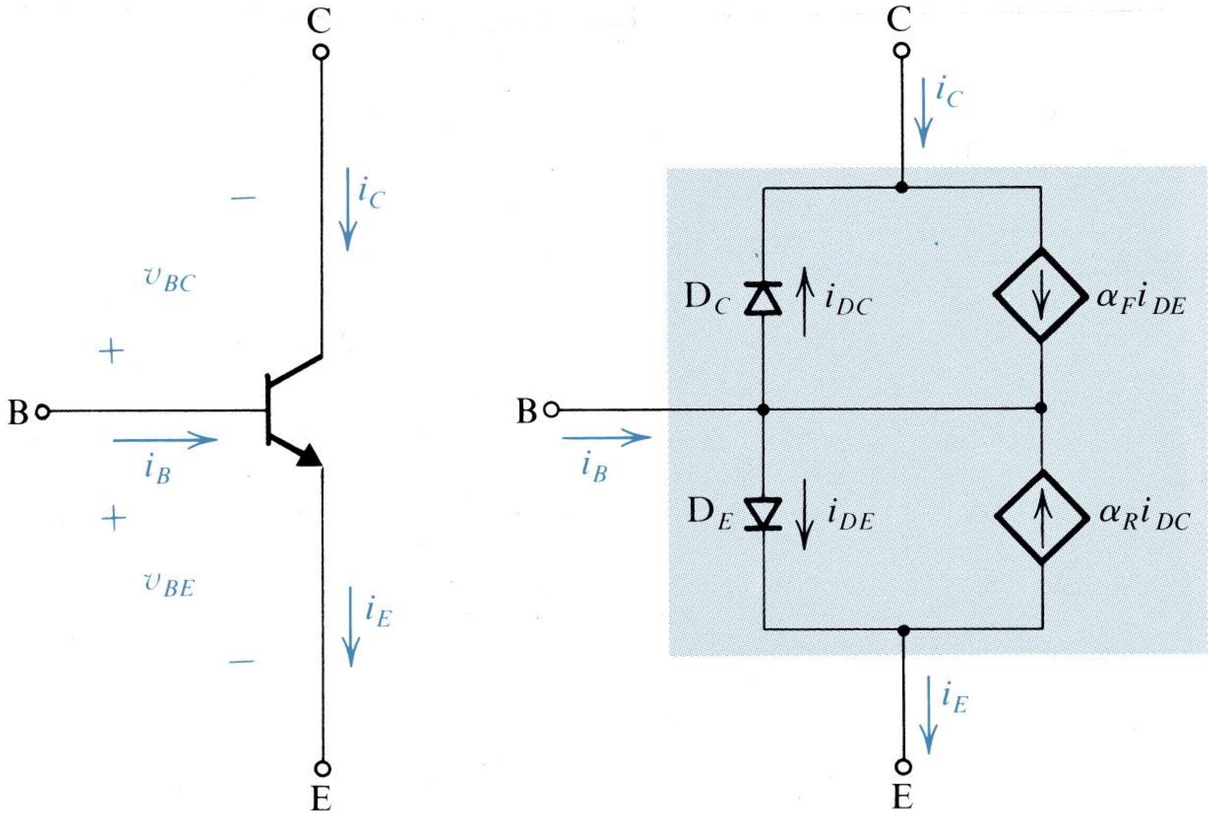
The common-collector or emitter-follower amplifier. **(a)** Circuit. **(b)** Equivalent circuit obtained by replacing the BJT with its T model.



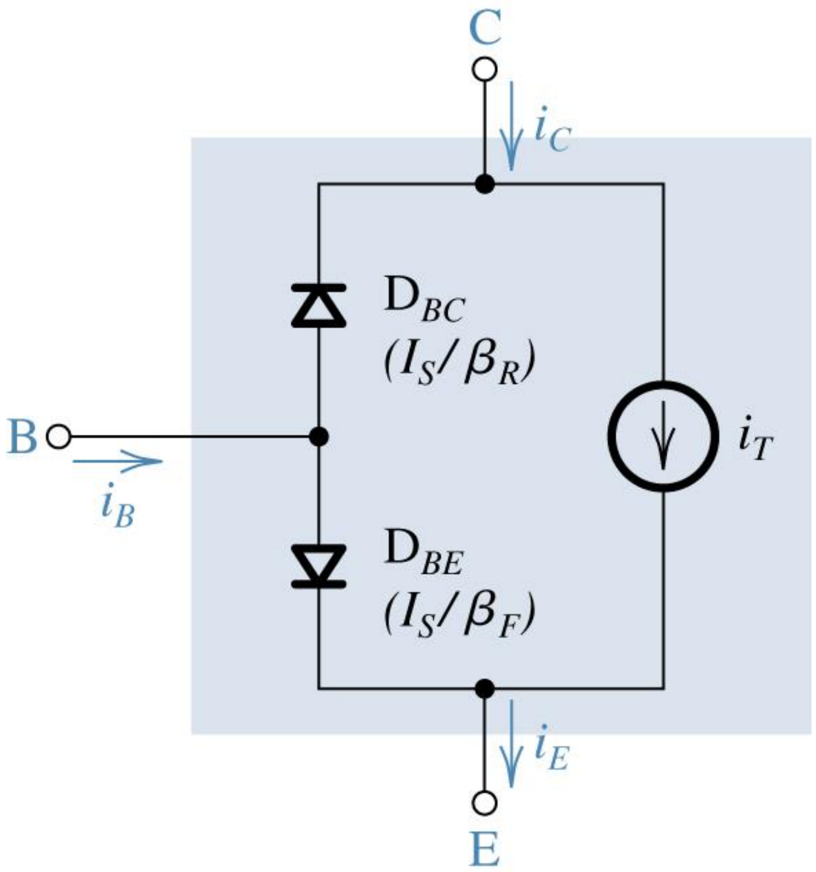
(c) The circuit redrawn to show that r_o is in parallel with R_L.

(d) Circuit for determining R_o.

General Large Signal Model



An *npn* resistor and its Ebers-Moll (EM) model. The scale or saturation currents of diodes D_E (EBJ) and D_C (CBJ) are indicated in parentheses.

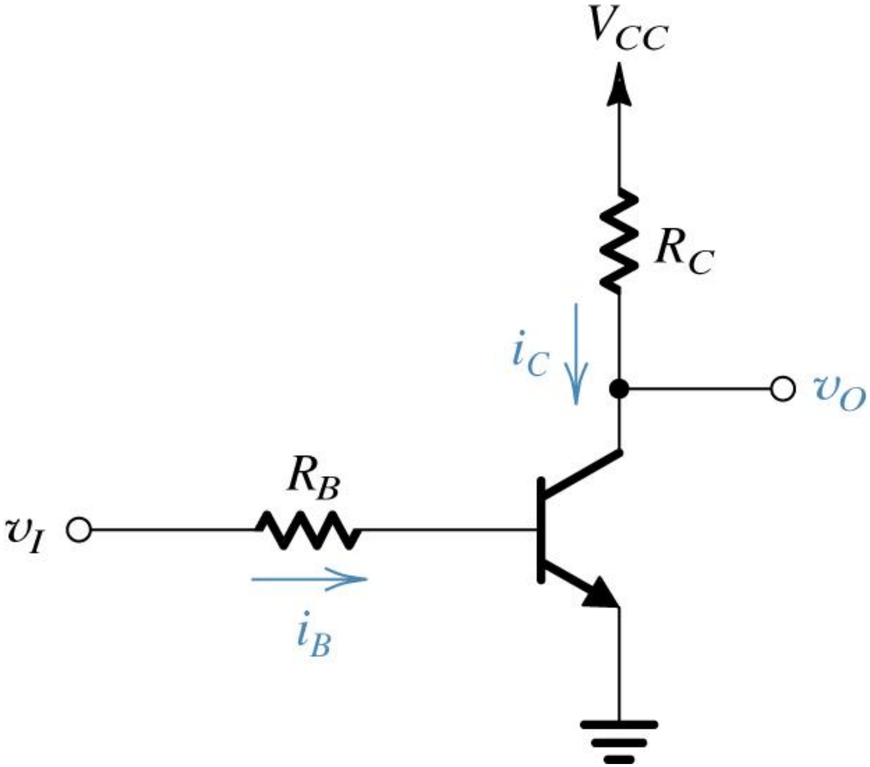


The transport model of the *npn* BJT. This model is exactly equivalent to the Ebers-Moll model

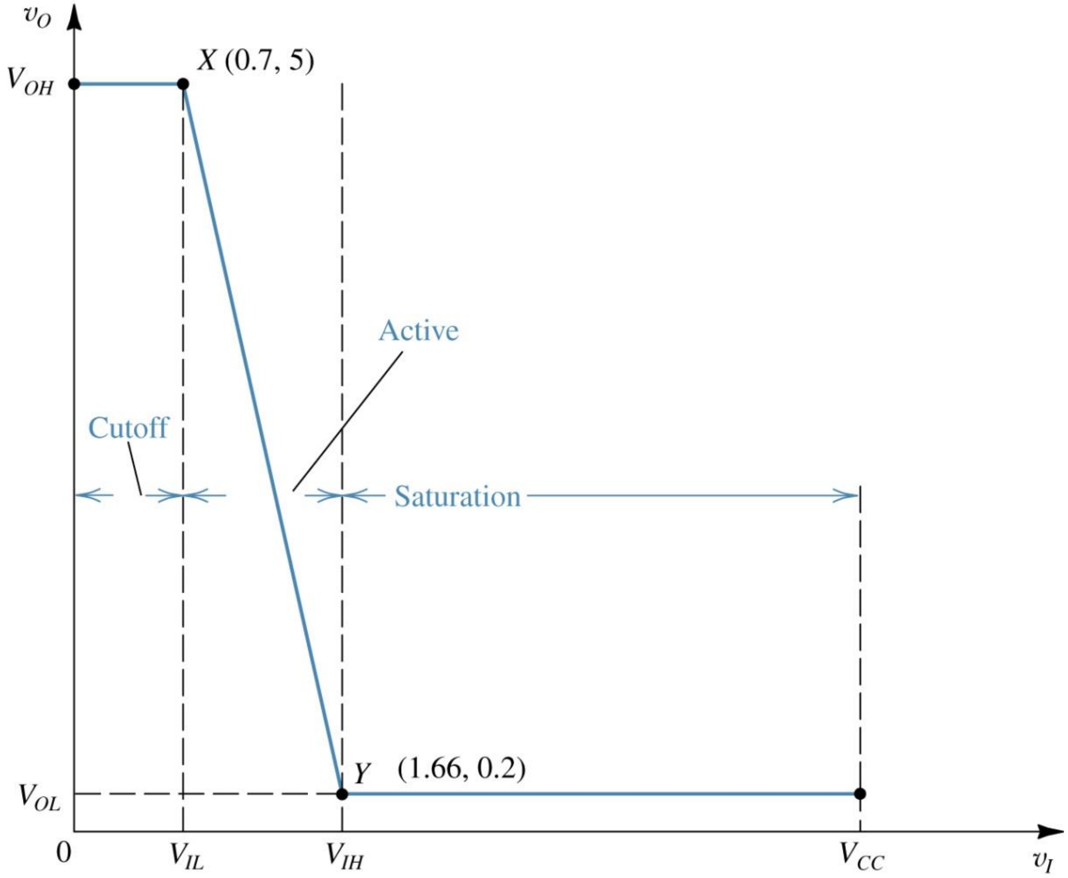
Saturation currents of the diodes in parentheses

BJT Digital Logic

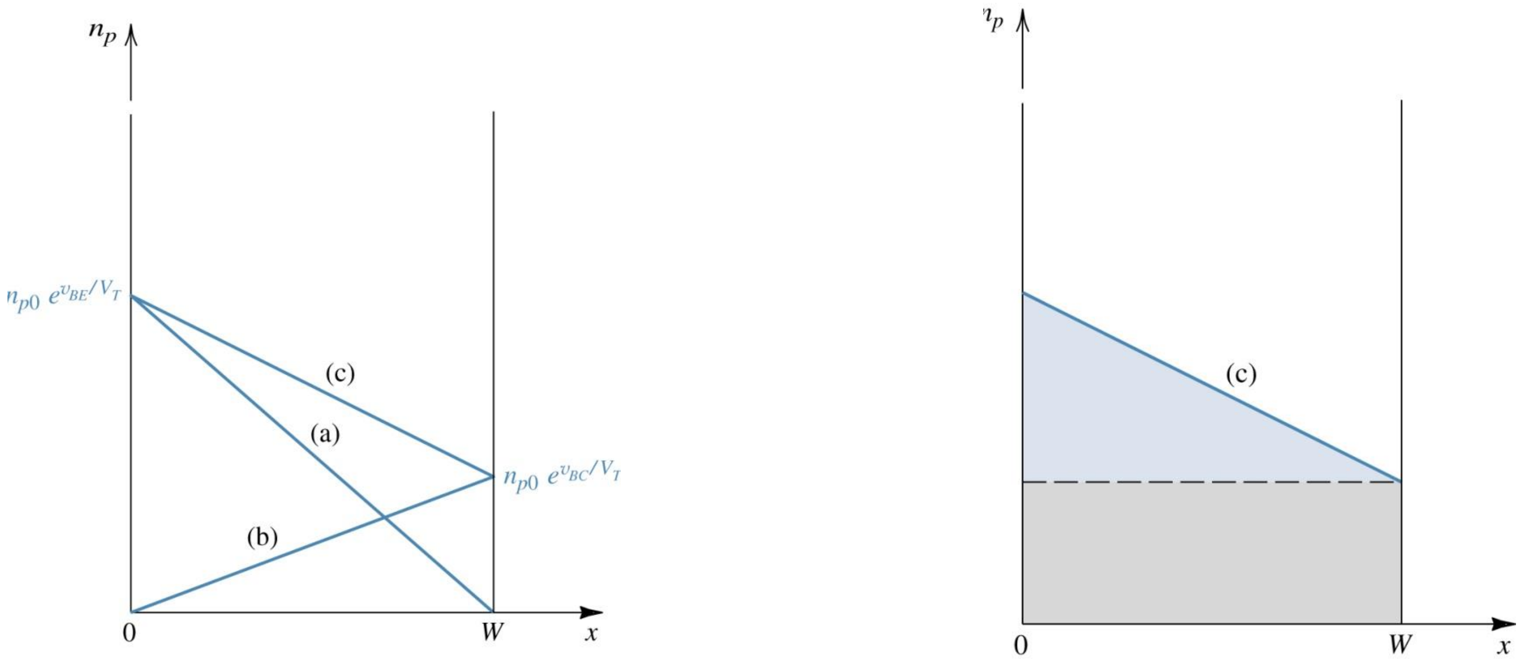
Basic BJT digital logic inverter.



- voltage transfer characteristic of the inverter circuit
- R_B = 10 k□, R_C = 1 k□, □ = 50, and V_{CC} = 5V.



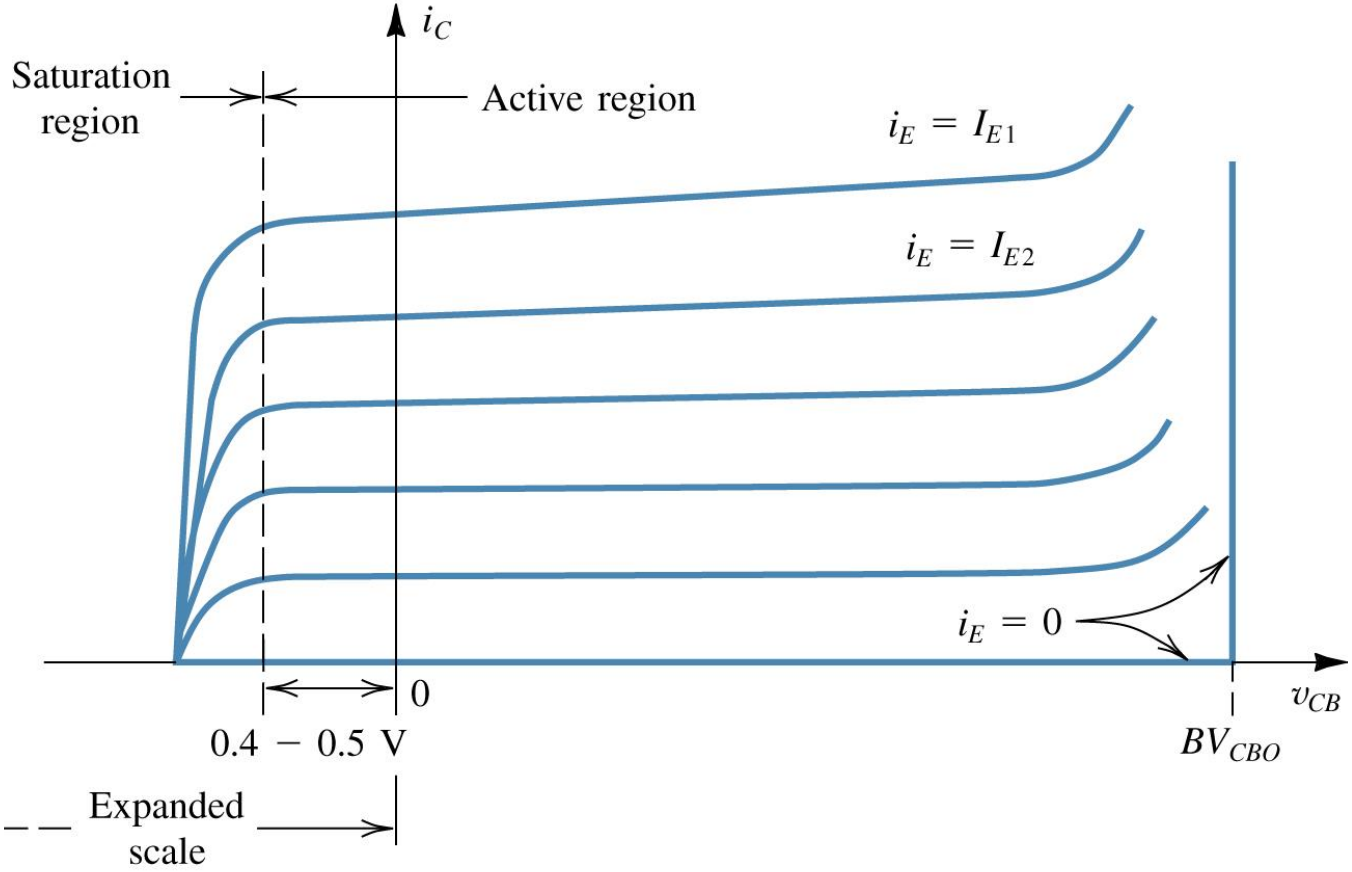
Saturation Region



(a)

(b)

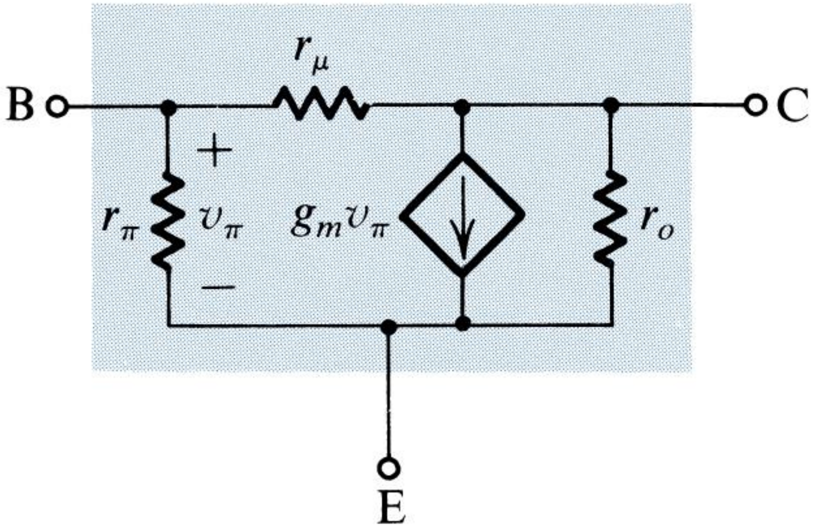
The minority-carrier concentration in the base of a saturated transistor is represented by line (c). **(b)** The minority-carrier charge stored in the base can de divided into two components: That in blue produces the gradient that gives rise to the diffusion current across the base, and that in gray results in driving the transistor deeper into saturation.



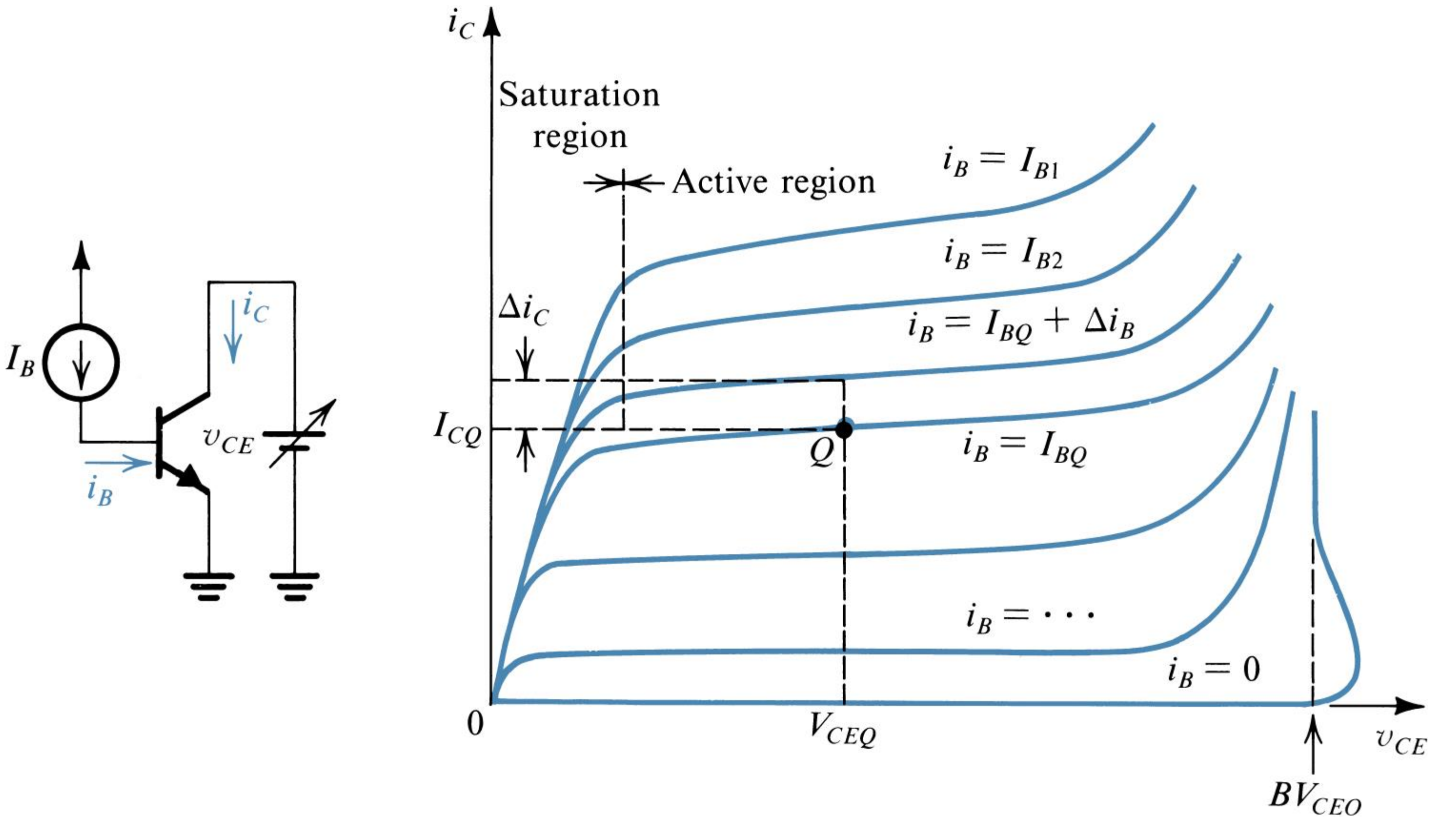
The i_c-v_{cb} or common-base characteristics of an *npn* transistor. Note that in the active region there is a slight dependence of i_C on the value of v_{CB}. The result is a finite output resistance that decreases as the current level in the device is increased.

Common Base Characteristic

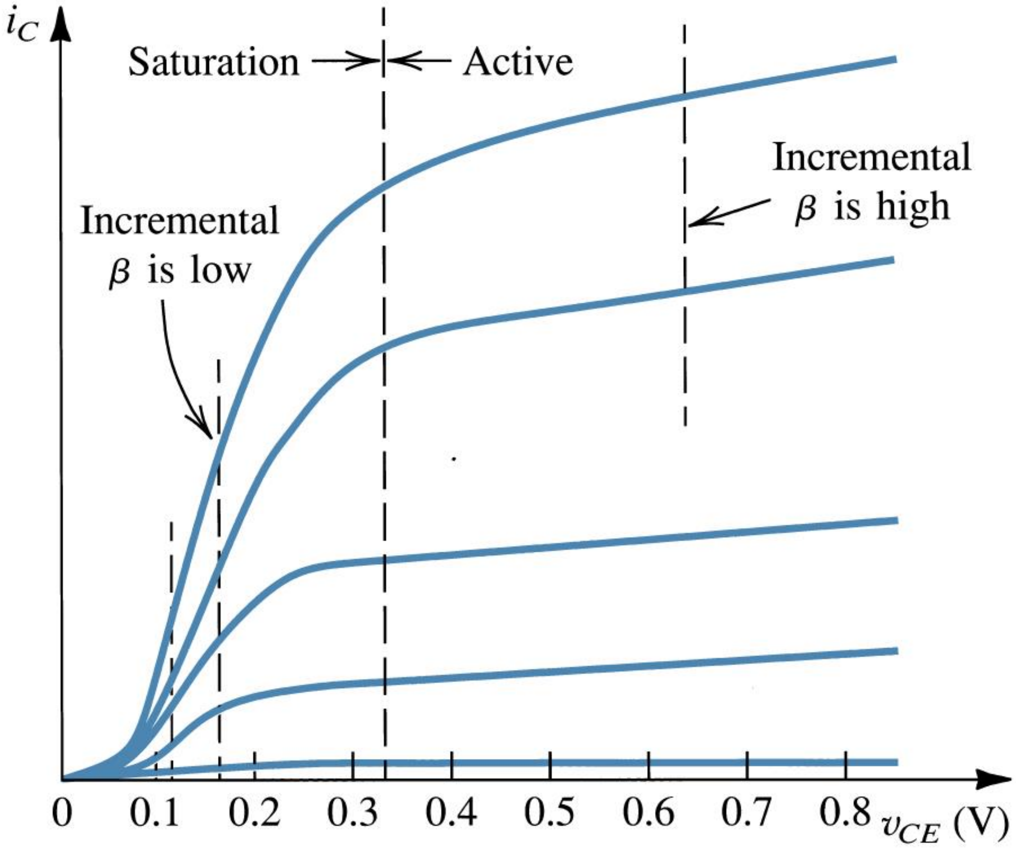
The hybrid-p model, including the resistance $r_{\square}$, which models the effect of v_c on i_b.



Common-emitter characteristics.

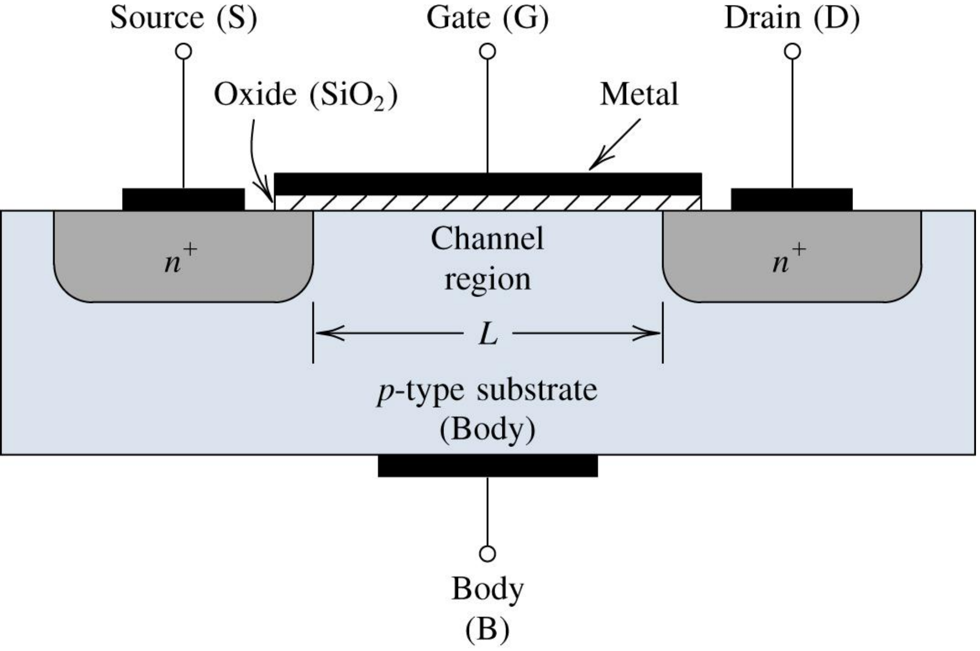


Common Emitter in Saturation Region

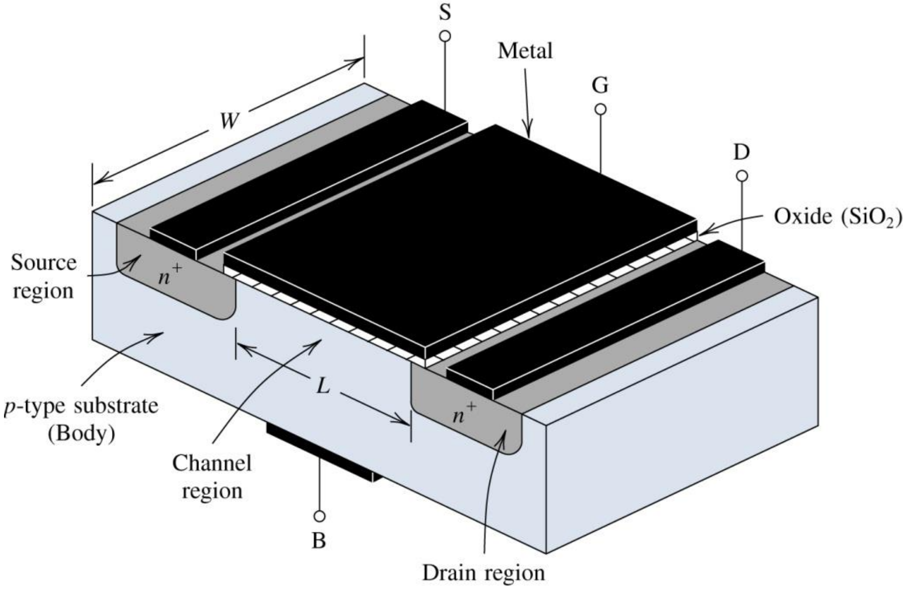


Field Effect Transistors (FET)

Field Effect (MOS) Transistor



(b)

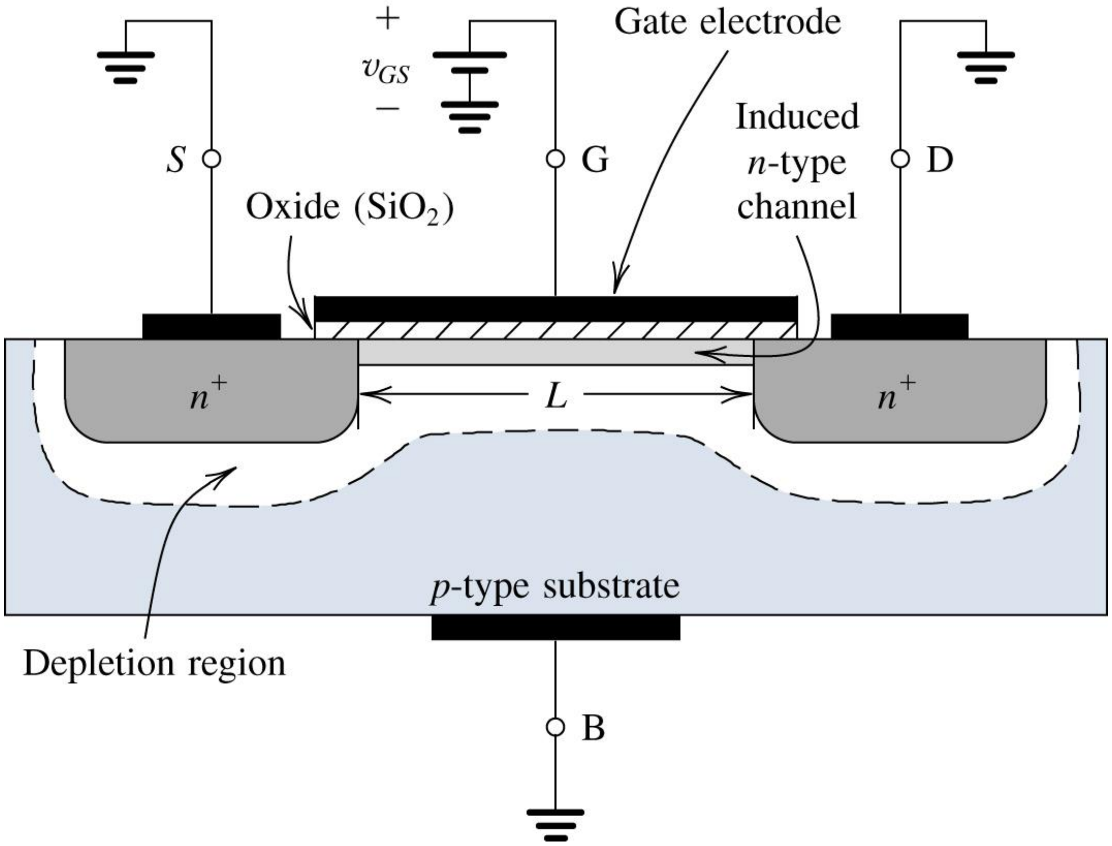


(a)

Typically L = 1 to 10 μm, W = 2 to 500 μm, and the thickness of the oxide layer is in the range of 0.02 to 0.1 μm.

Operation

The enhancement-type NMOS transistor with a positive voltage applied to the gate.

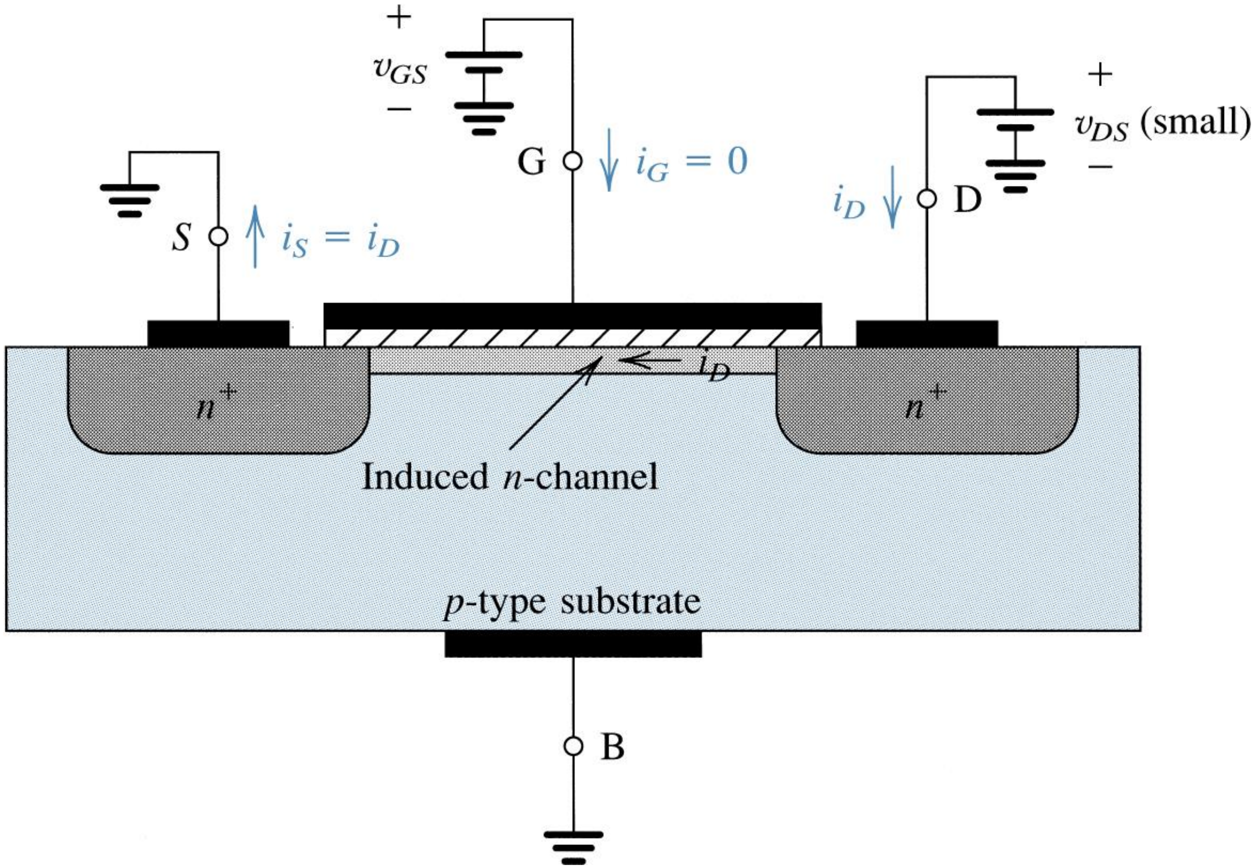


An n channel is induced at the top of the substrate beneath the gate.

Triode Region

$v_{GS} > V_t$, small v_{DS} applied.

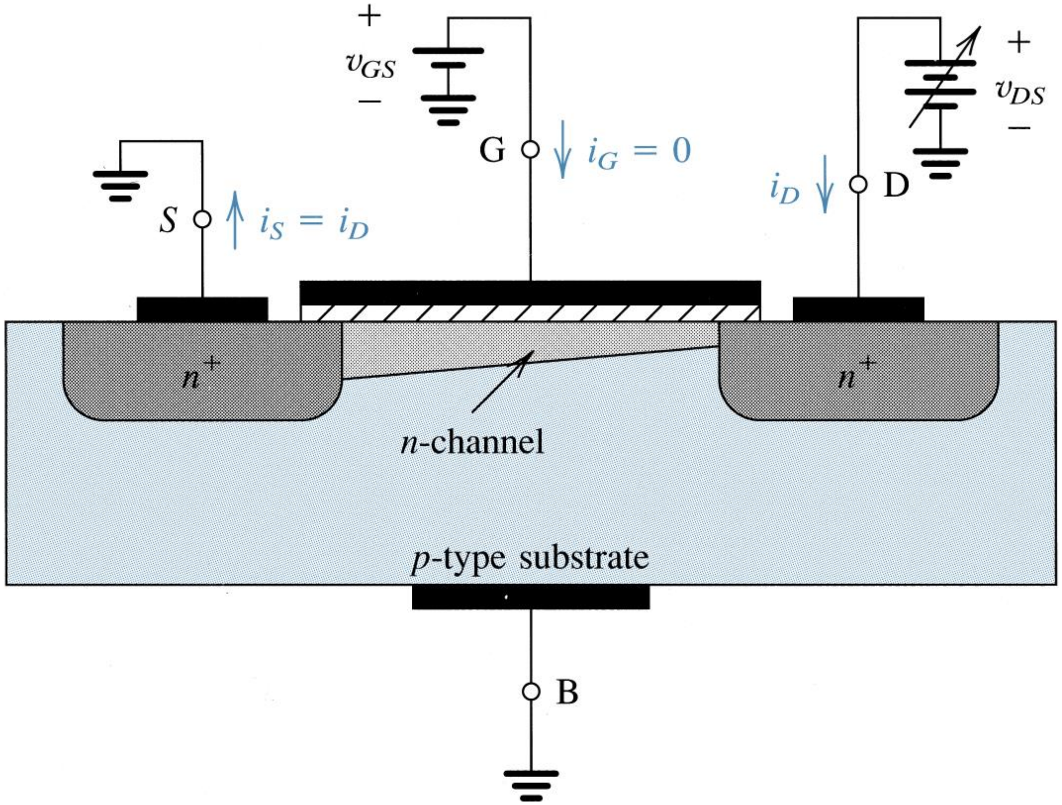
the channel conductance is proportional to v_{GS} - V_t, and is proportional to (v_{GS} - Vt) v_{DS}.



Saturation Region

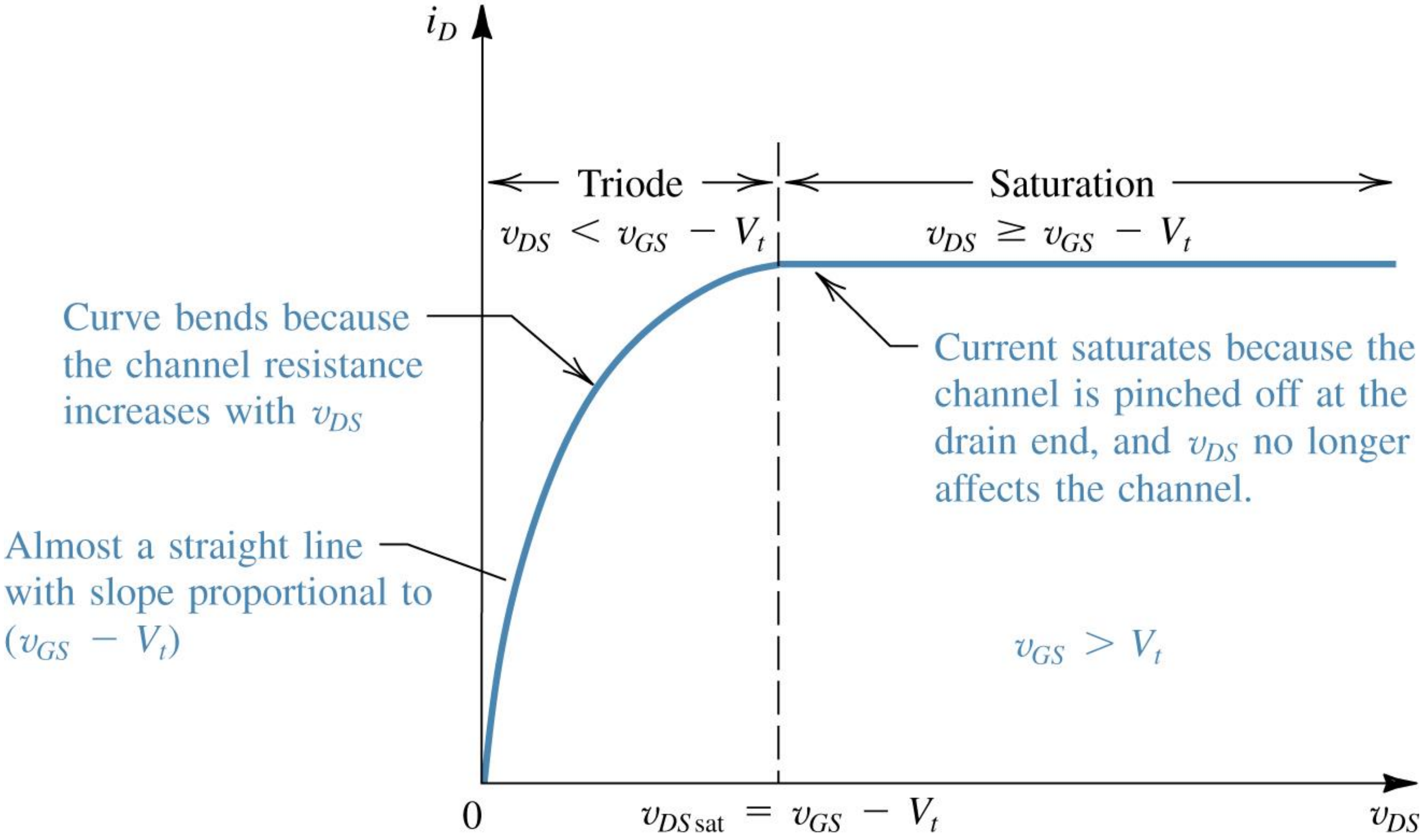
$v_{GS} > V_t.$

The induced channel acquires a tapered shape and its resistance increases as v_{DS} is increased.

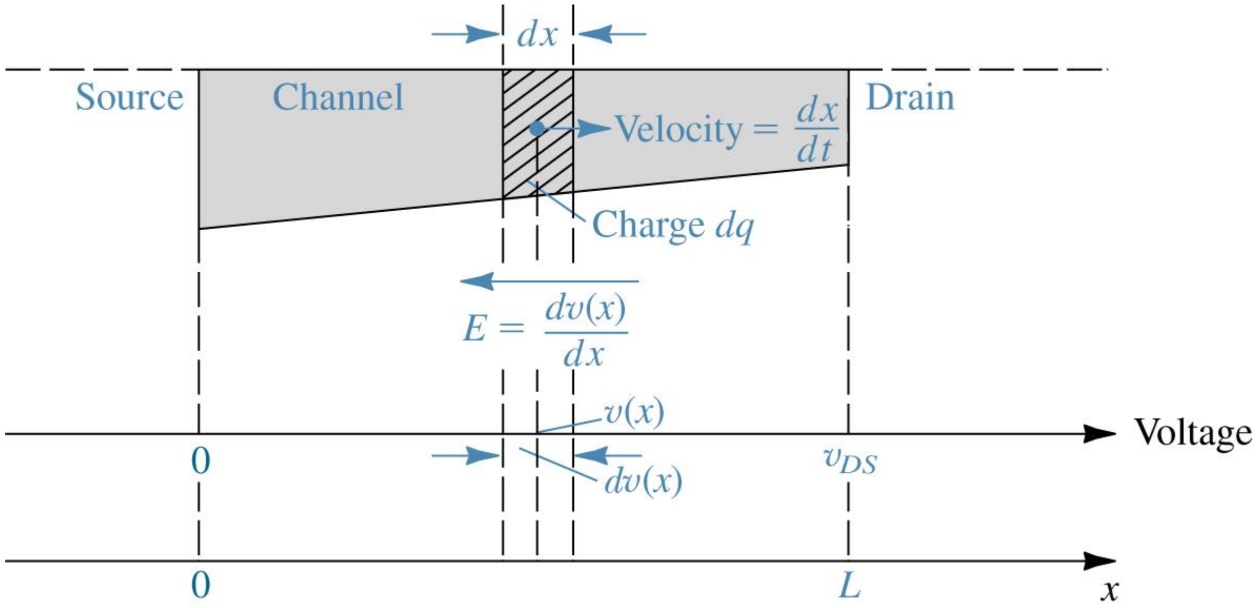


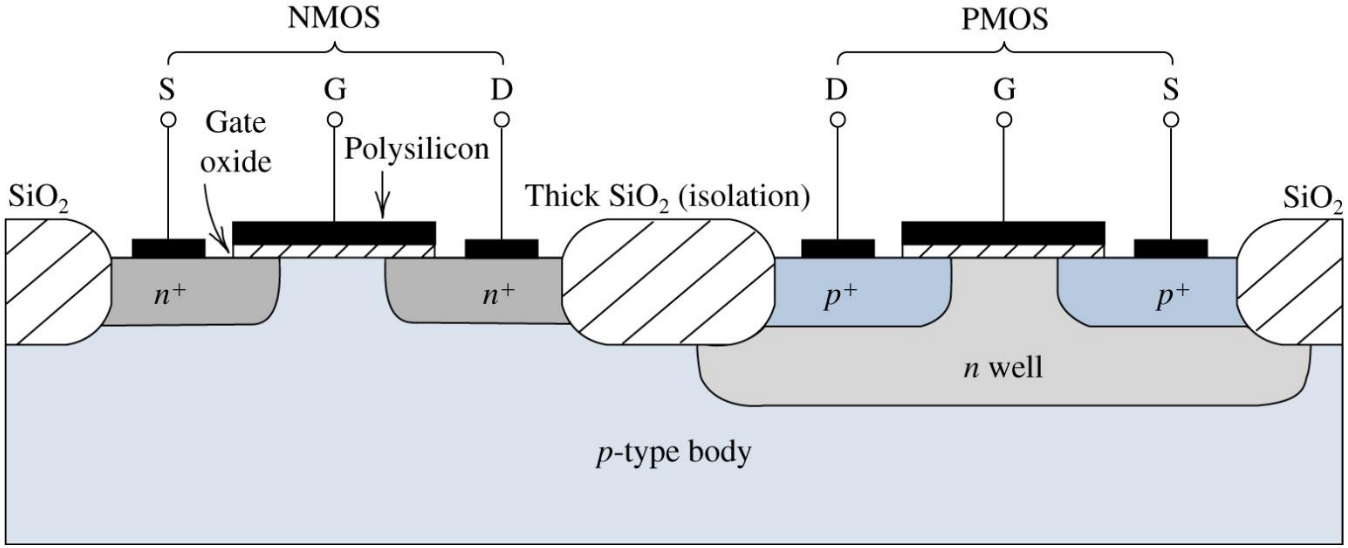
Drain current i_D versus v_{DS}

Enhancement-type NMOS transistor operated with $v_{GS} > V_t$.



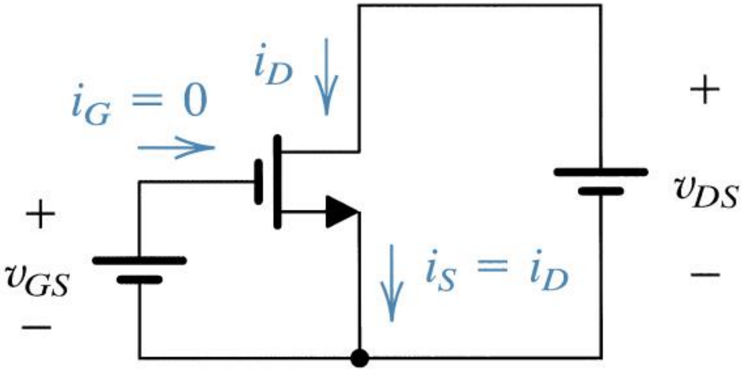
Derivation of the i_D - v_{DS} characteristic of the NMOS transistor.



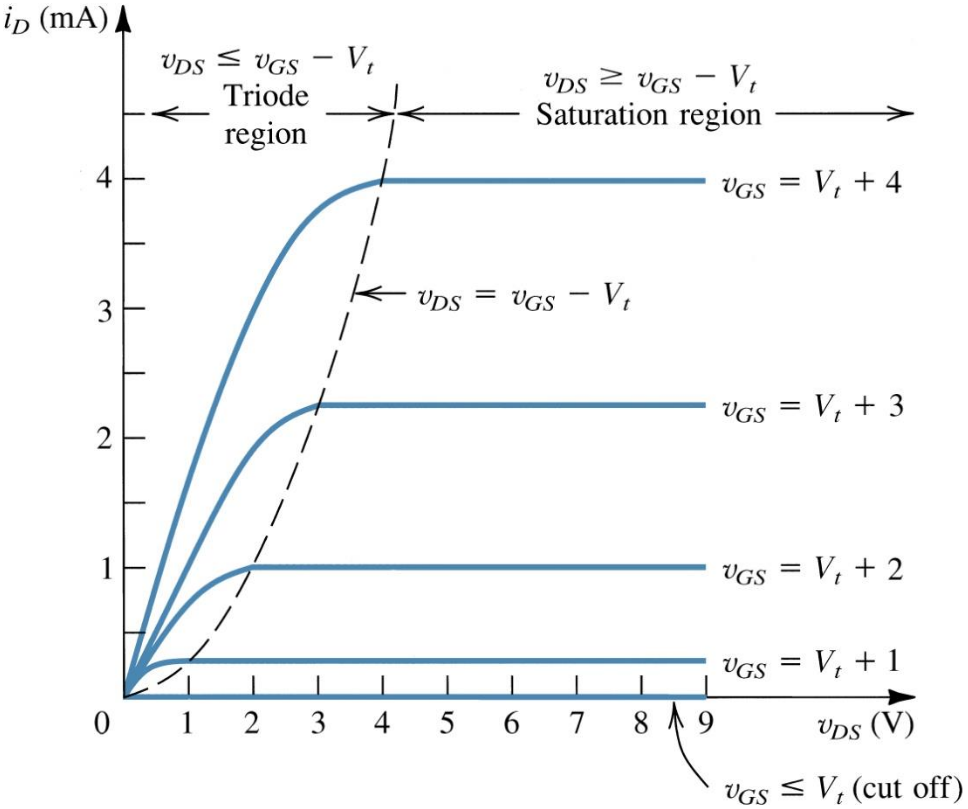


Cross section of a CMOS integrated circuit. Note that the PMOS transistor is formed in a separate *n*-type region, known as an *n* well. Another arrangement is also possible in which an *n*-type body is used and the *n* device is formed in a *p* well.

n-channel enhancement-type MOSFET with v_{GS} and v_{DS} applied and with the normal directions of current flow

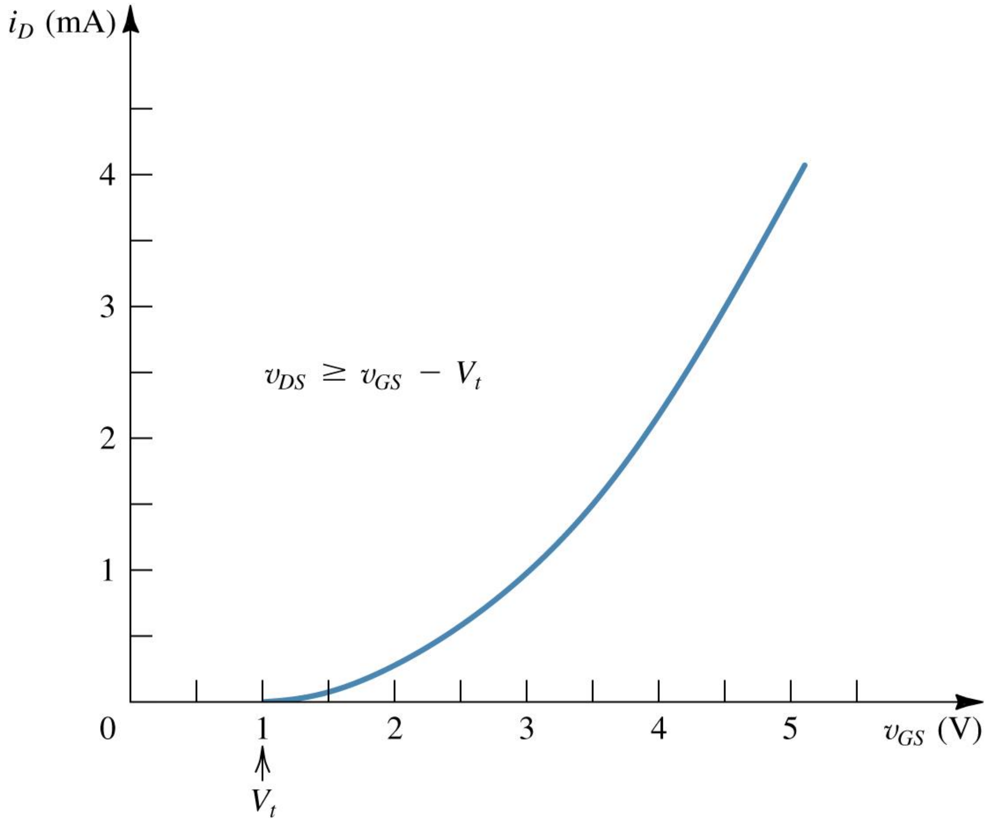


(a)

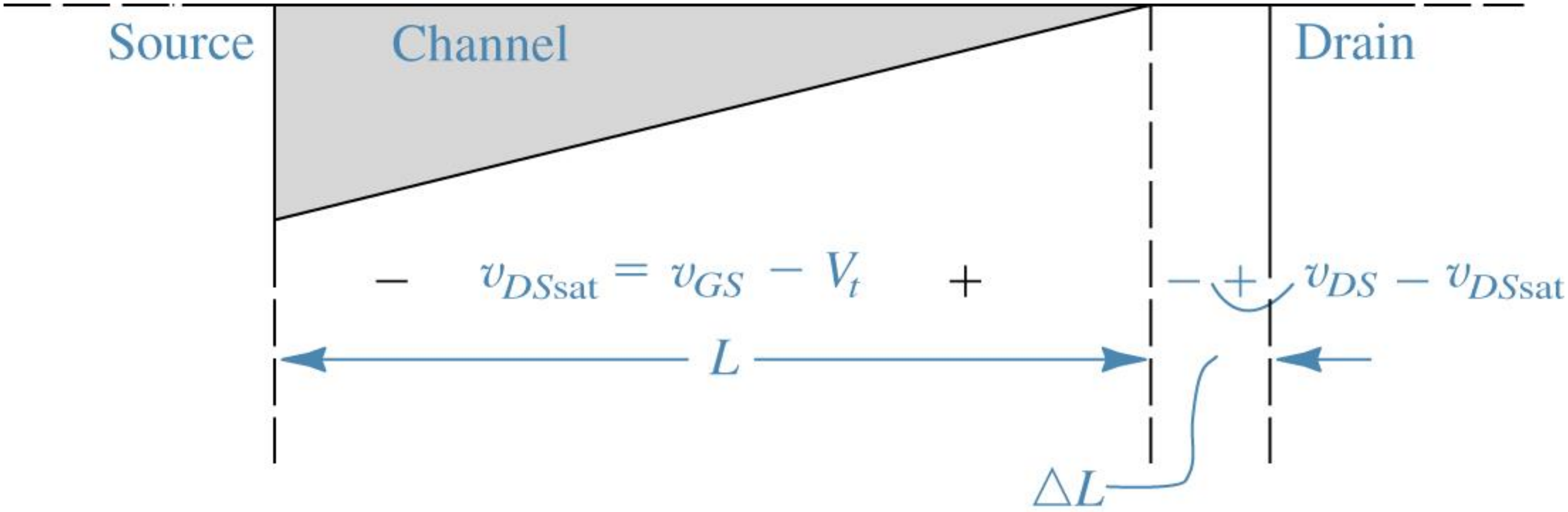


The i_D - v_{DS} characteristics for a device with $V_t = 1$ V and $k'_n(W/L) = 0.5$ mA/V^2.

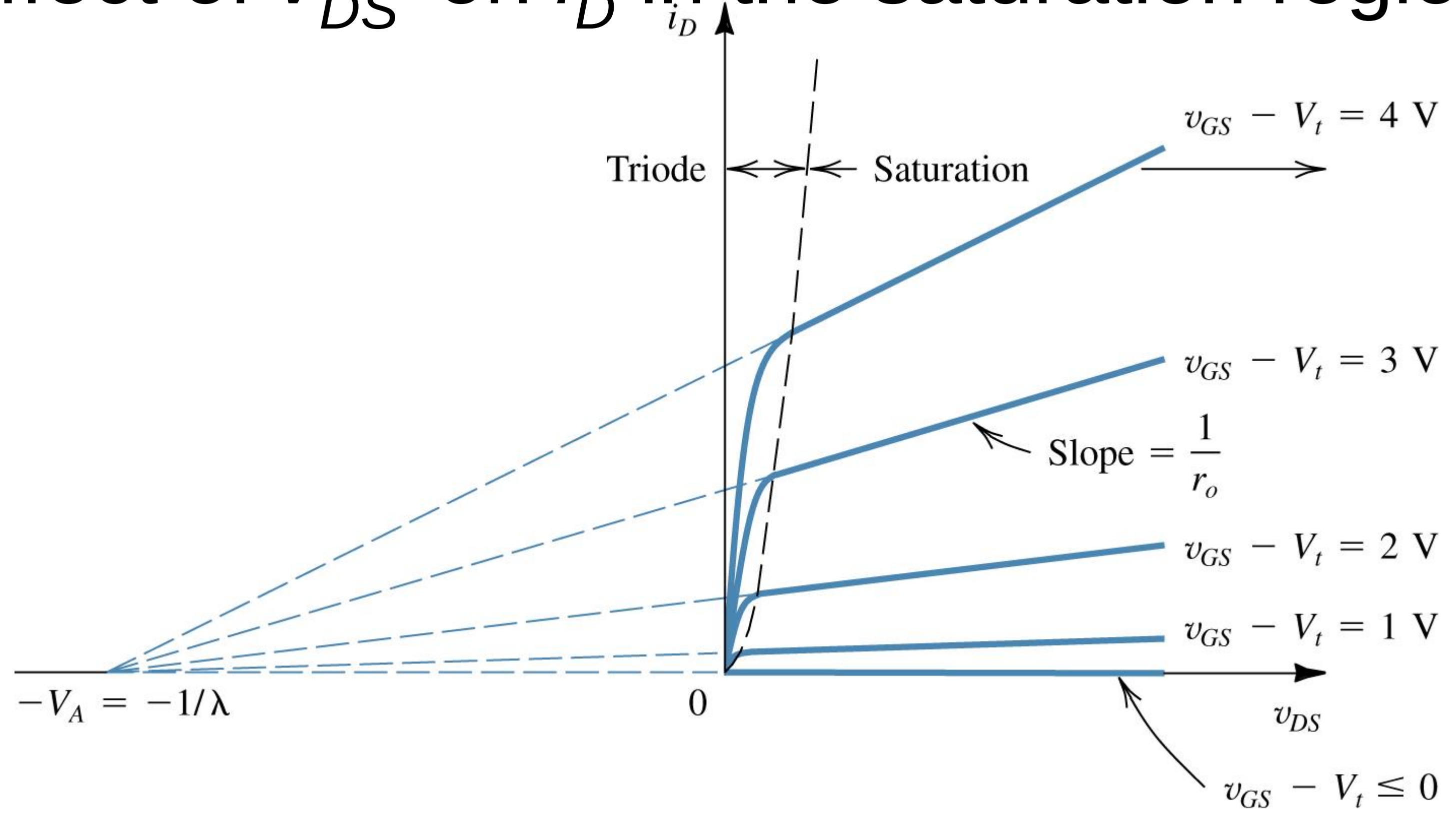
i_D - v_{GS} characteristic for an enhancement-type NMOS transistor in saturation (V_t = 1 V and $k'_n(W/L)$ = 0.5 mA/V^2).



Increasing v_{DS} beyond v_{DSsat} causes the channel pinch-off point to move slightly away from the drain, thus reducing the effective channel length (by ΔL).

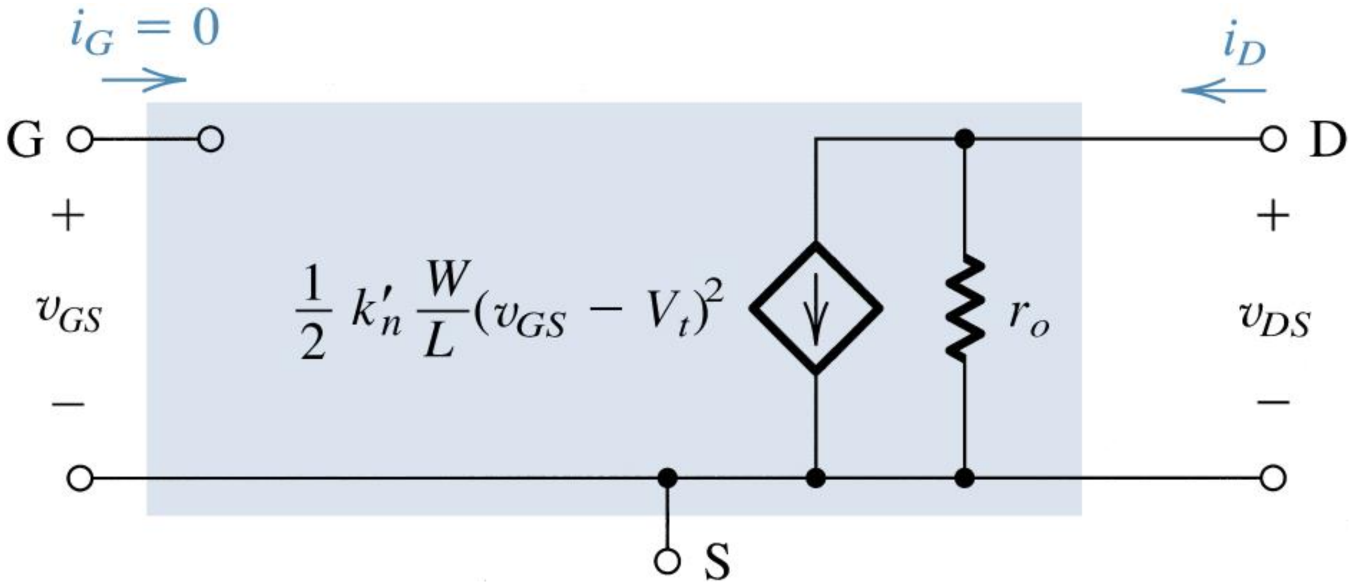


Effect of v_{DS} on i_D in the saturation region.



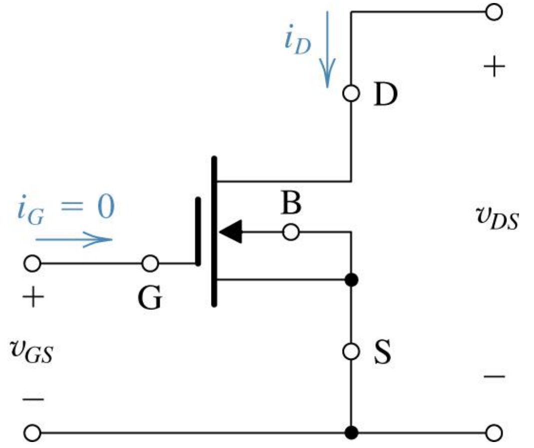
The MOSFET parameter V_A is typically in the range of 30 to 200 V.

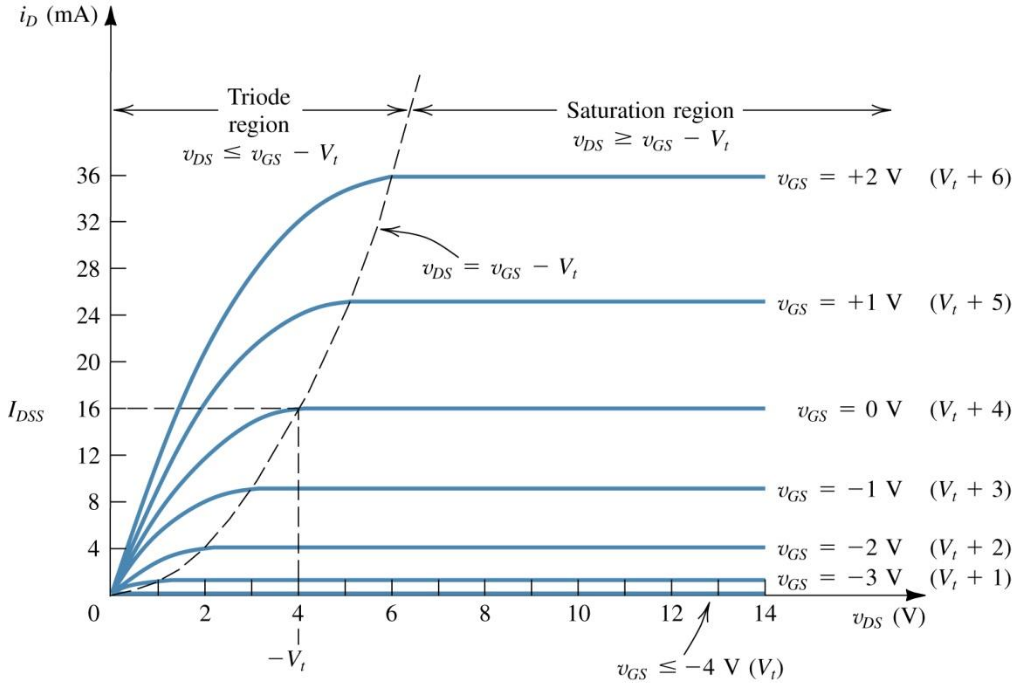
Large-signal equivalent circuit model



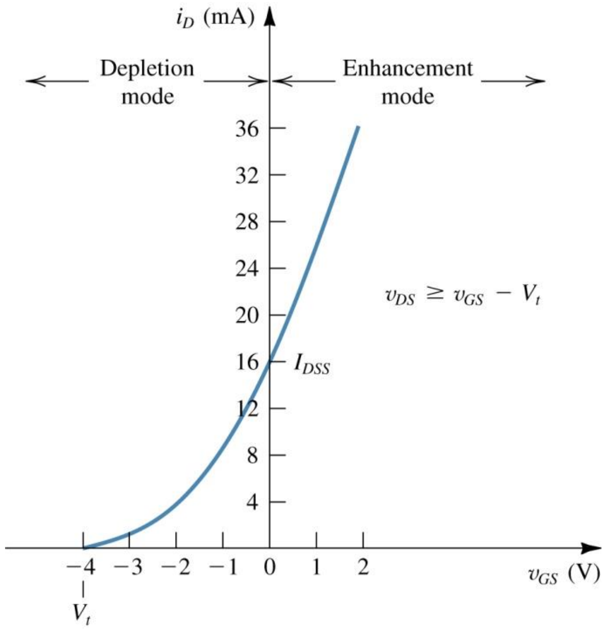
- n-channel MOSFET in saturation, incorporating the output resistance r_o.
- The output resistance $r_o \cong V_A/I_D$.

The current-voltage characteristics of a depletion-type *n*-channel MOSFET for which $V_t = -4$ V and $k'_n(W/L) = 2$ mA/V^2



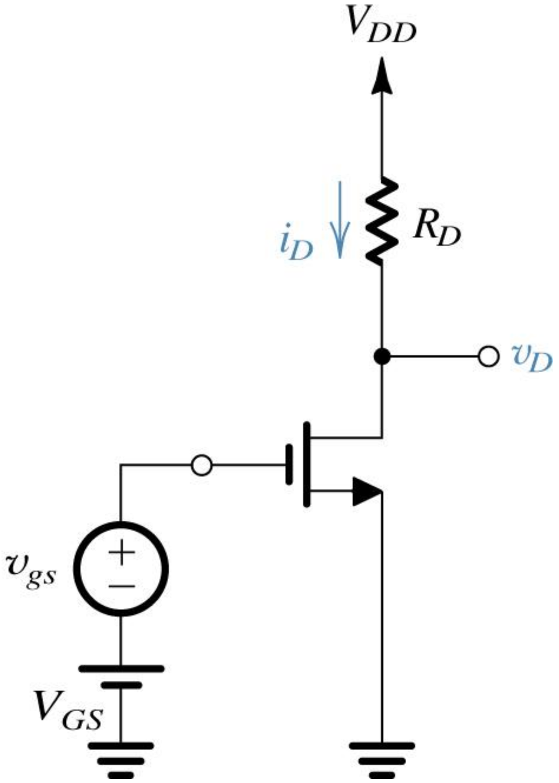


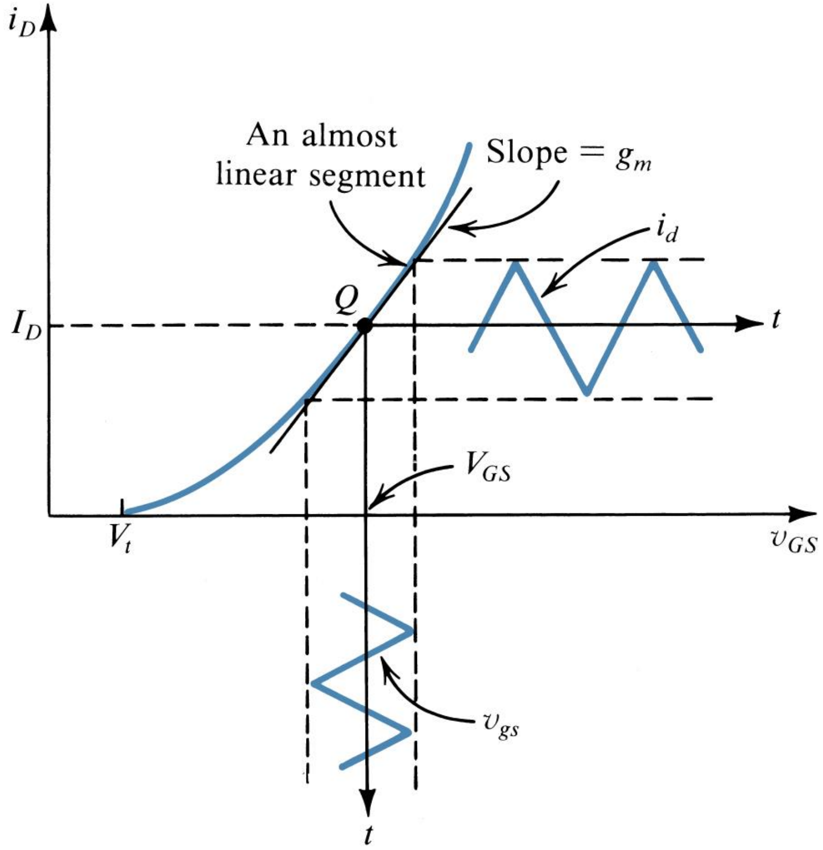
i_D - v_{DS} characteristics



i_D - v_{GS} saturation

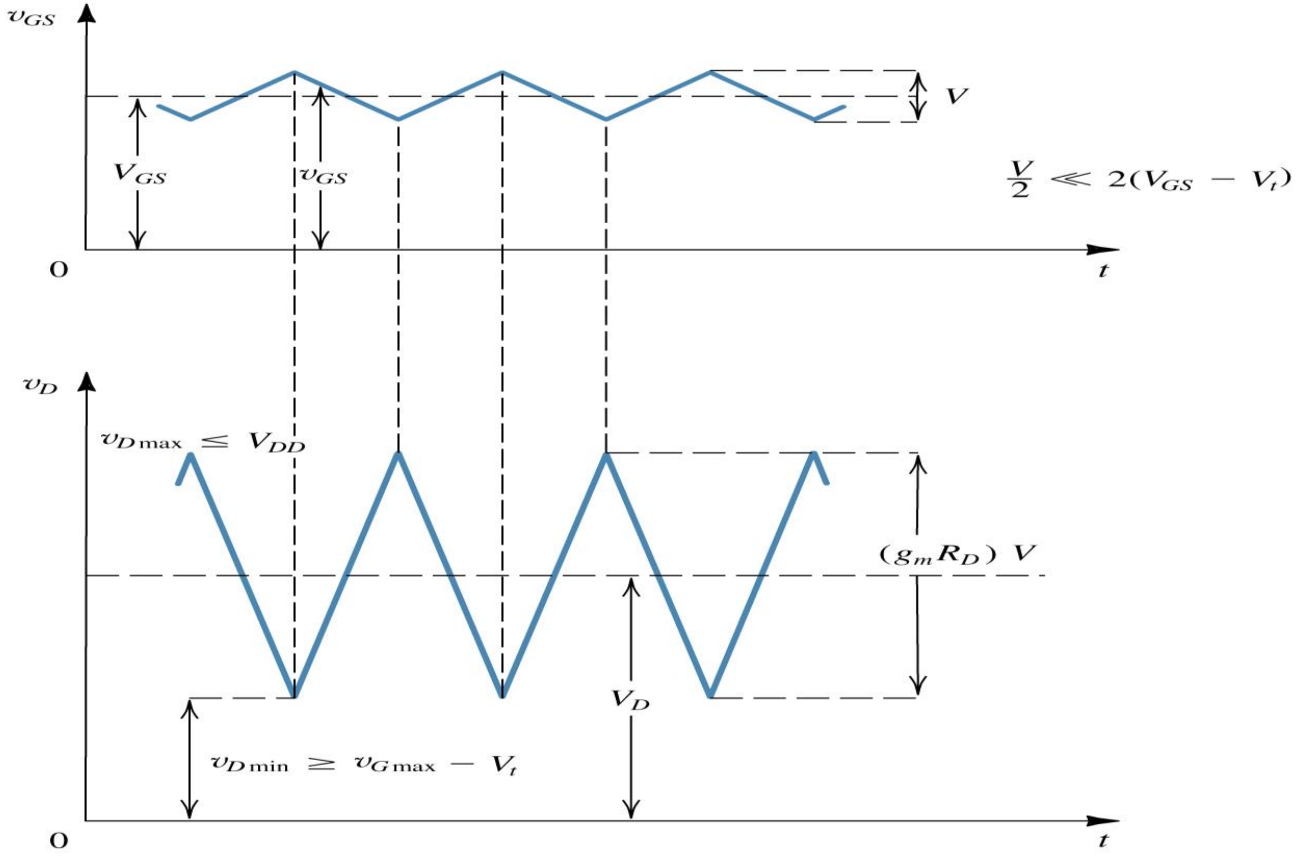
MOSFET as an amplifier.





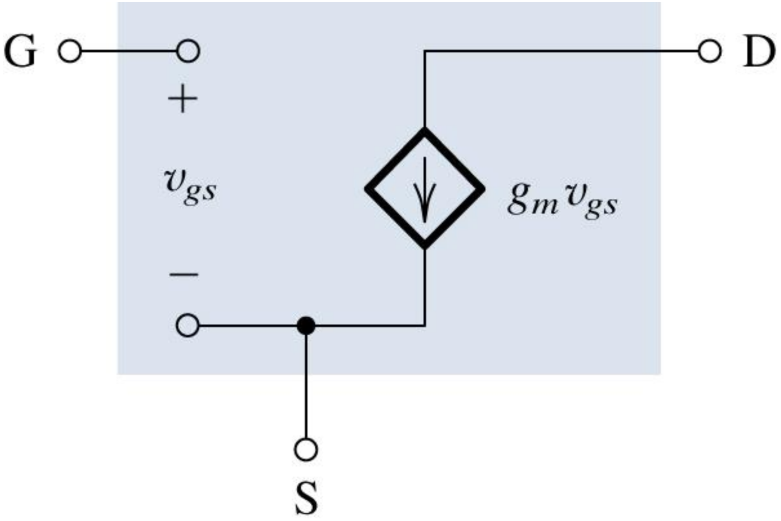
Small Signal

Instantaneous voltages v_{GS} and v_D



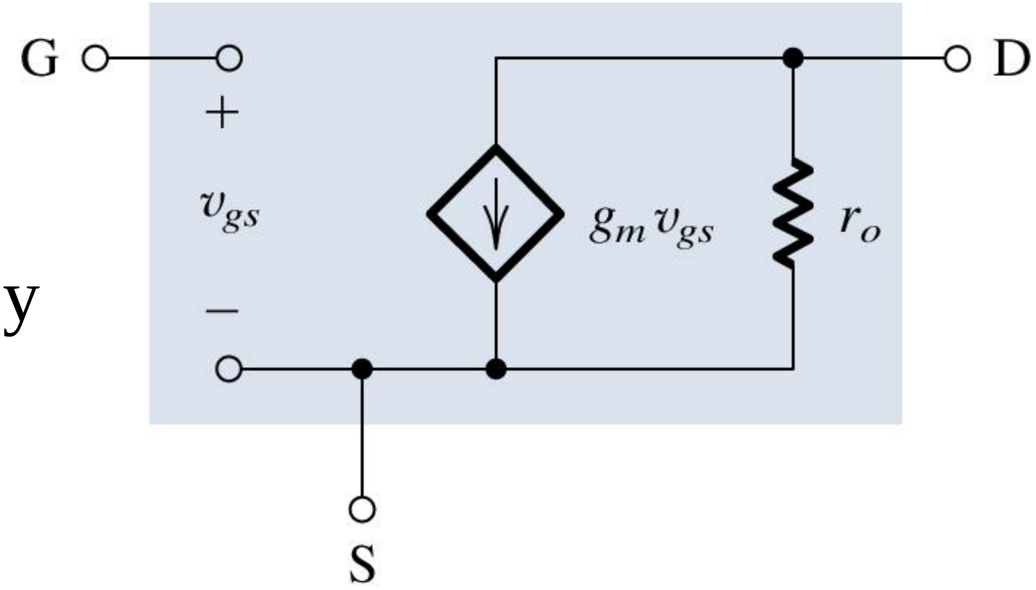
Models for MOSFET

neglecting the dependence of i_D on v_{DS} in saturation (channel-length modulation effect)



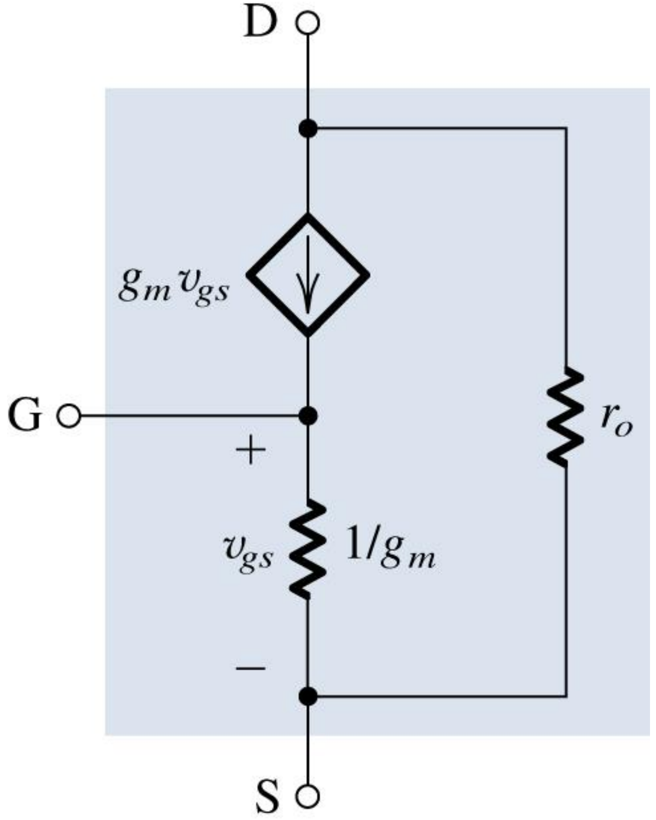
Model with Output Resistance

Including the effect of channel-length modulation modeled by output resistance $r_o = |V_A| / I_D$.



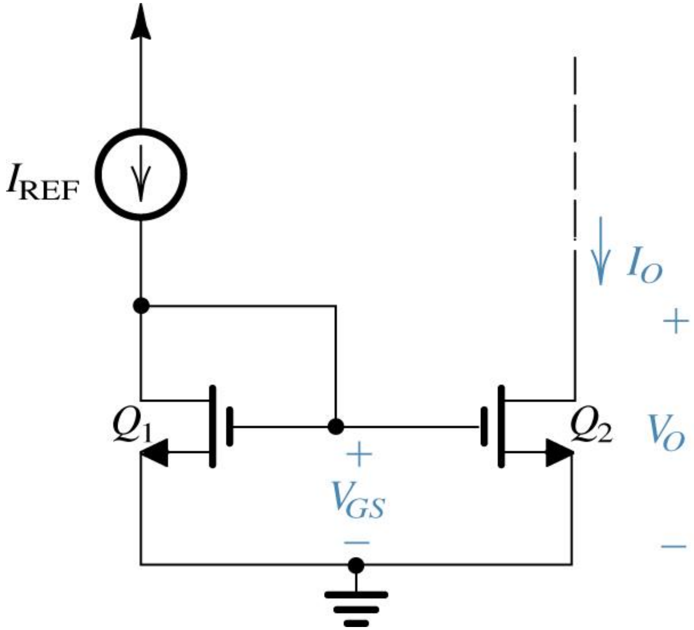
T model of the MOSFET

T model of the MOSFET augmented with the drain-to-source resistance $r_{o.}$

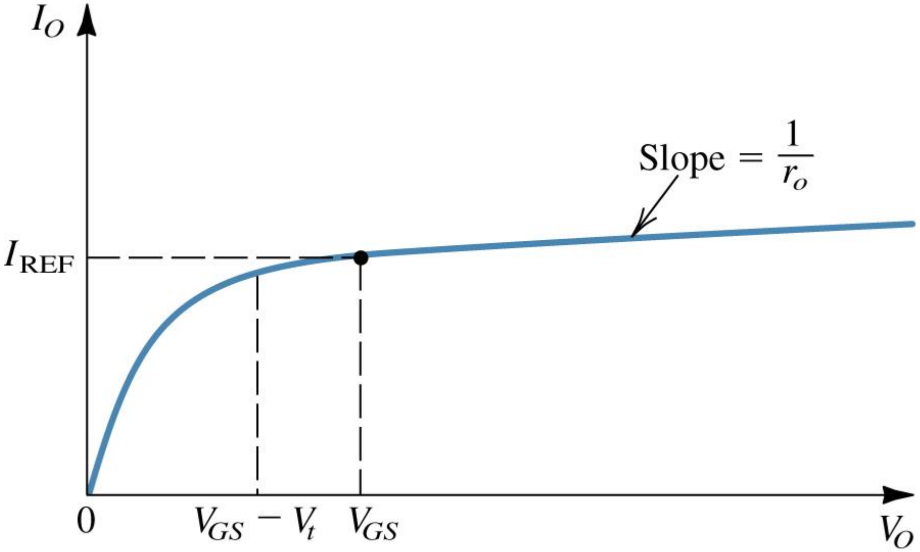


Sample Circuit

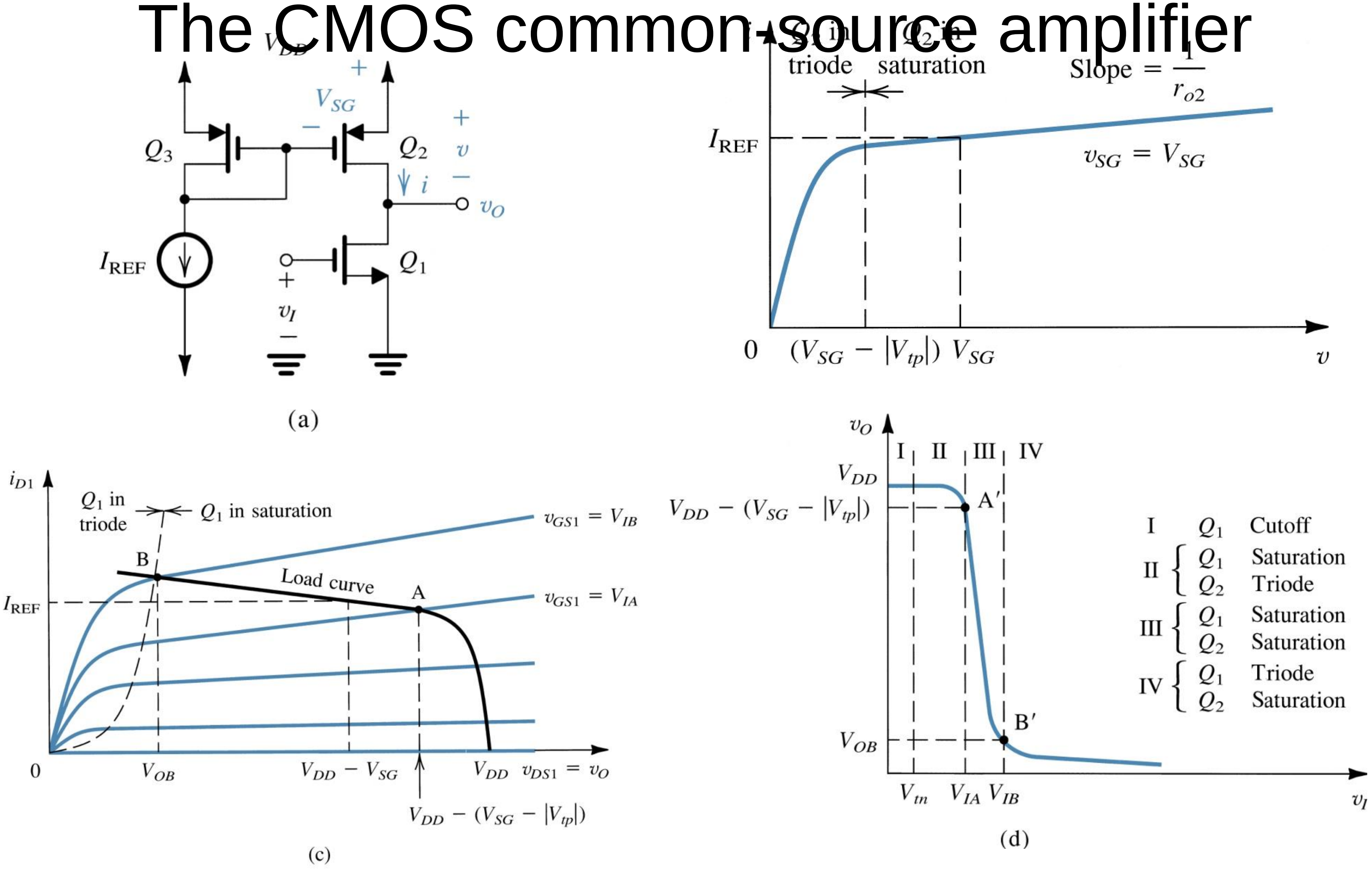
MOSFET current mirror.



Output characteristic of the current mirror Q_2 is matched to Q_1.



The CMOS common-source amplifier

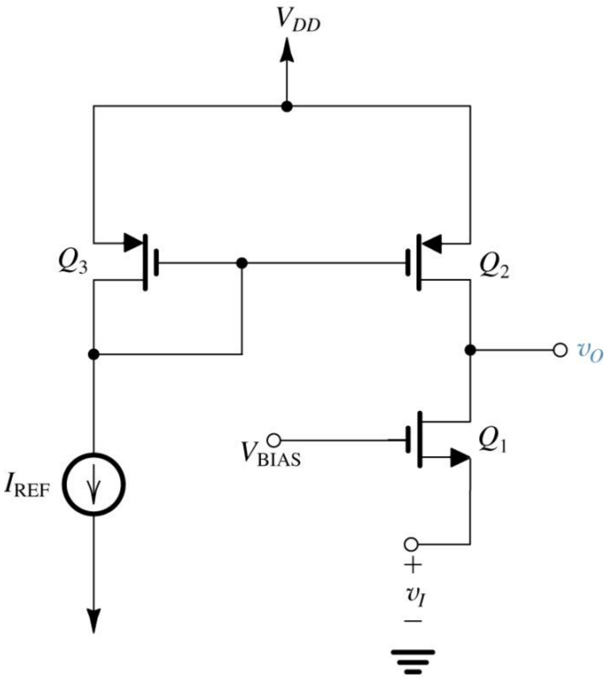


(a)

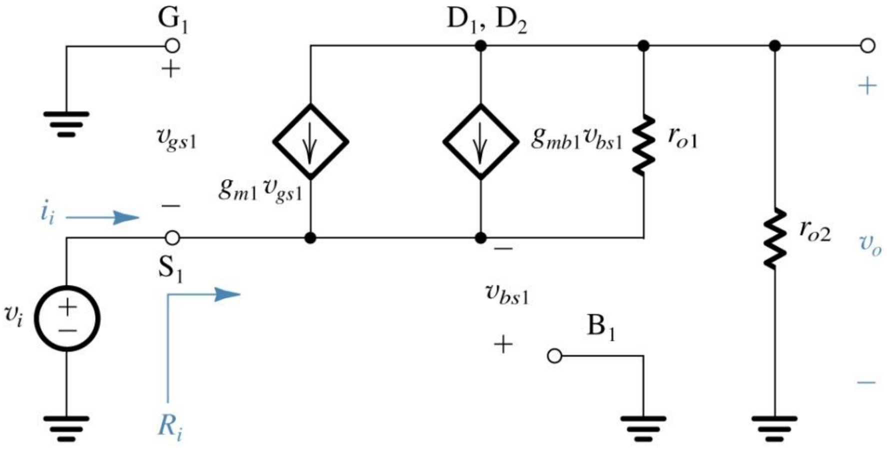
(c)

(d)

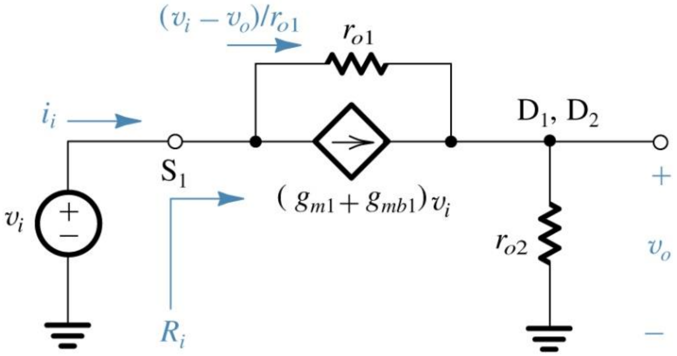
The CMOS common-gate amplifier



(a)

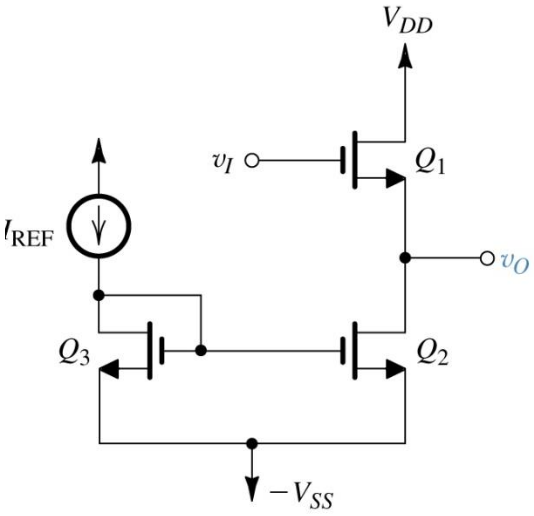


(b)

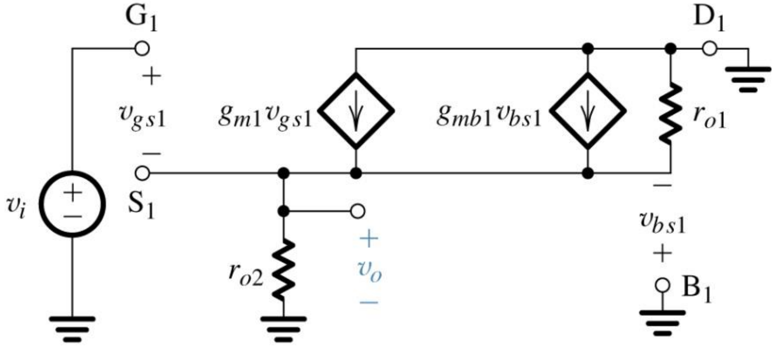


(c)

The source follower

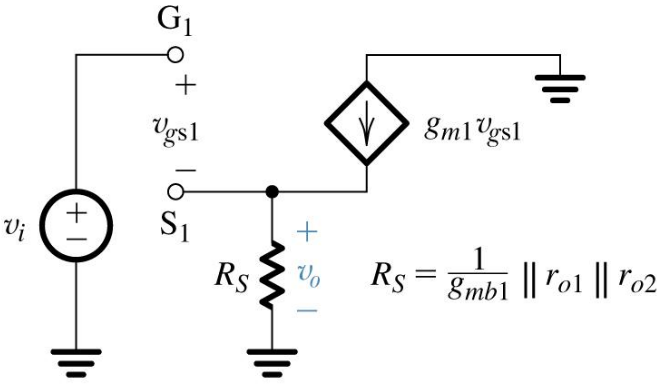


(a)



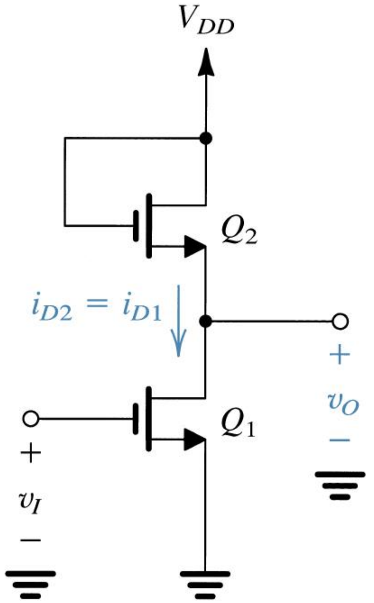
(b)

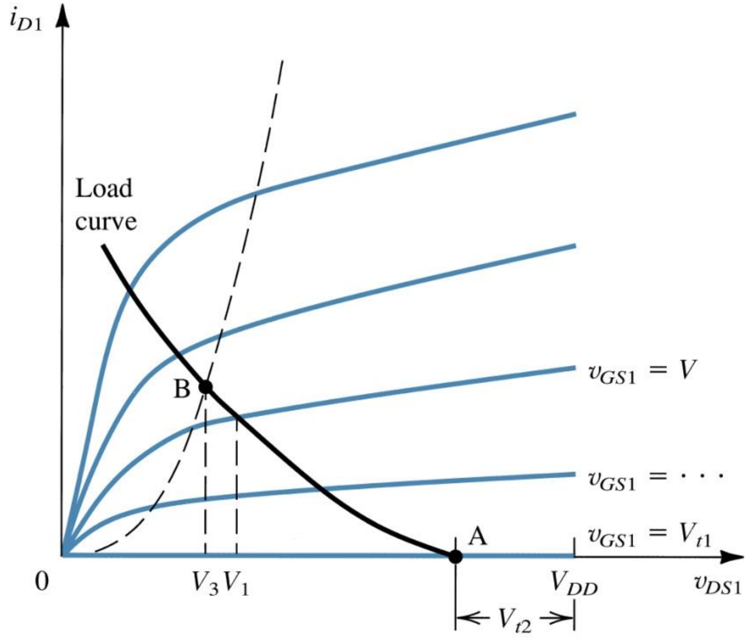
1. (a) circuit;
2. (b) small-signal equivalent circuit
3. (c) simplified version of the equivalent circuit.



(c)

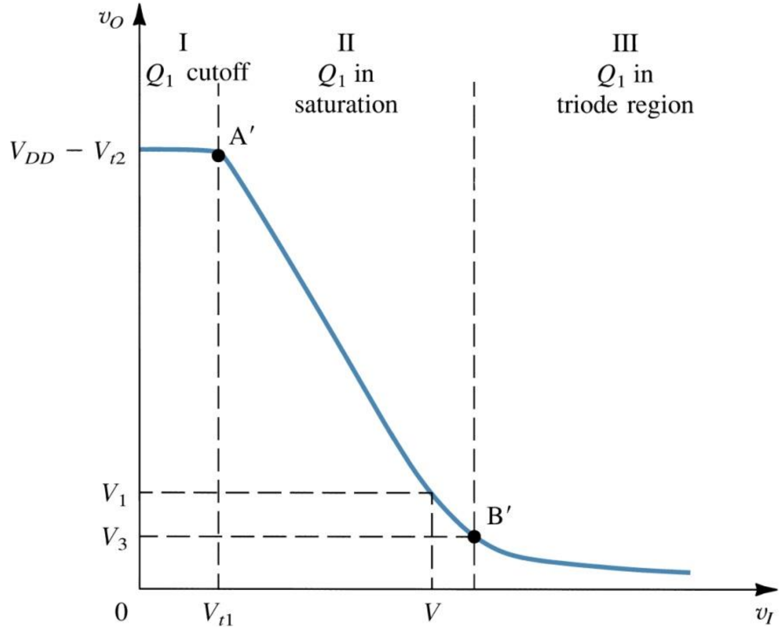
NMOS amplifier with enhancement load



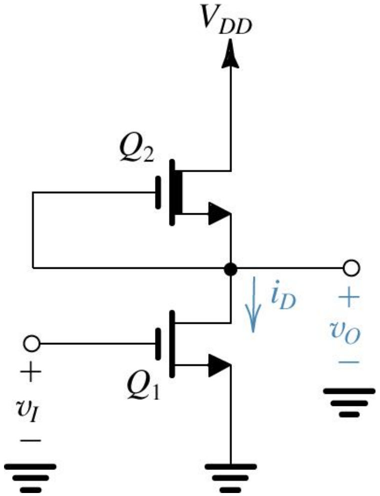


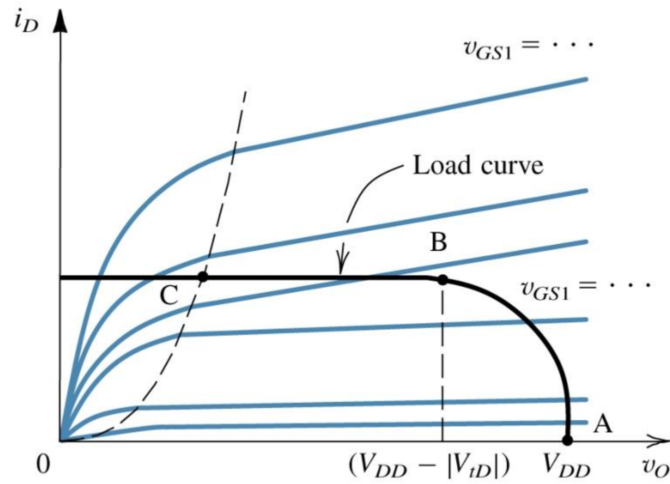
(b)

graphical determination of the transfer characteristic

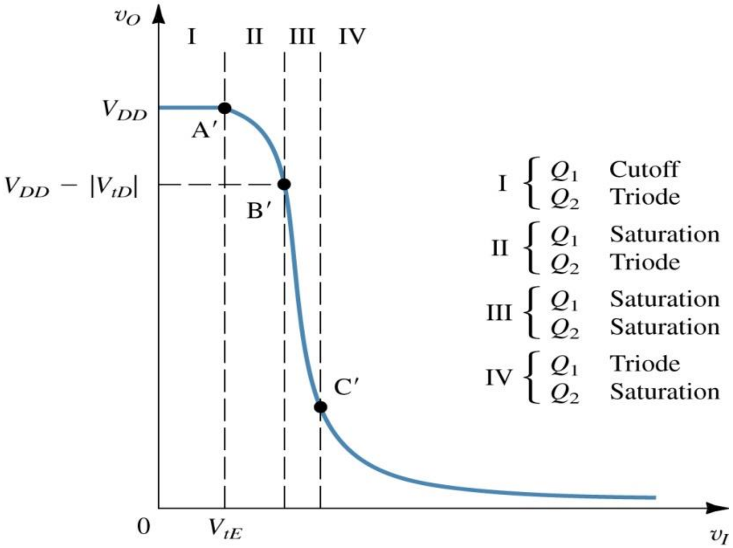


transfer characteristic.



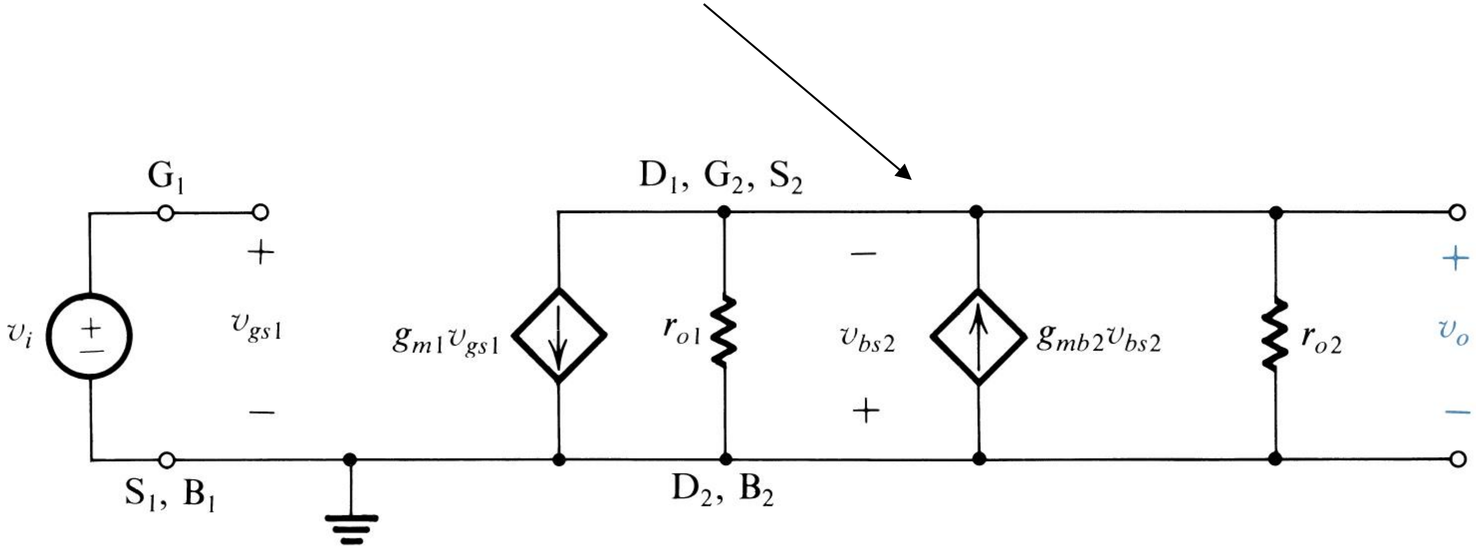


The NMOS amplifier with depletion load: **(a)** circuit; **(b)** graphical construction to determine the transfer characteristic; and **(c)** transfer characteristic.

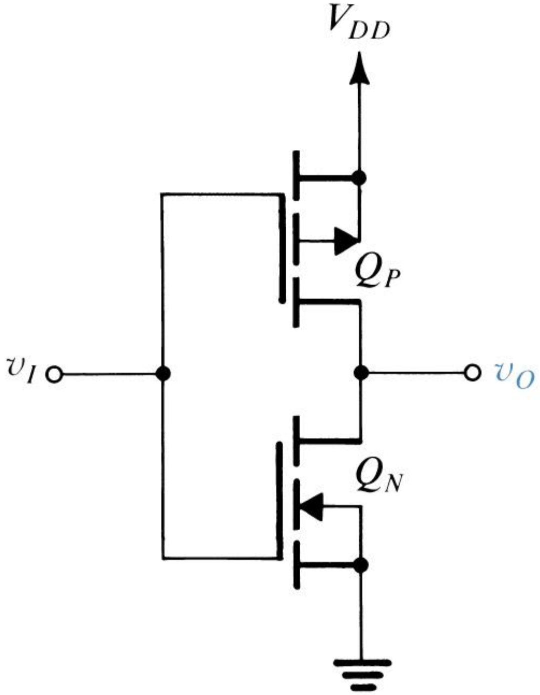


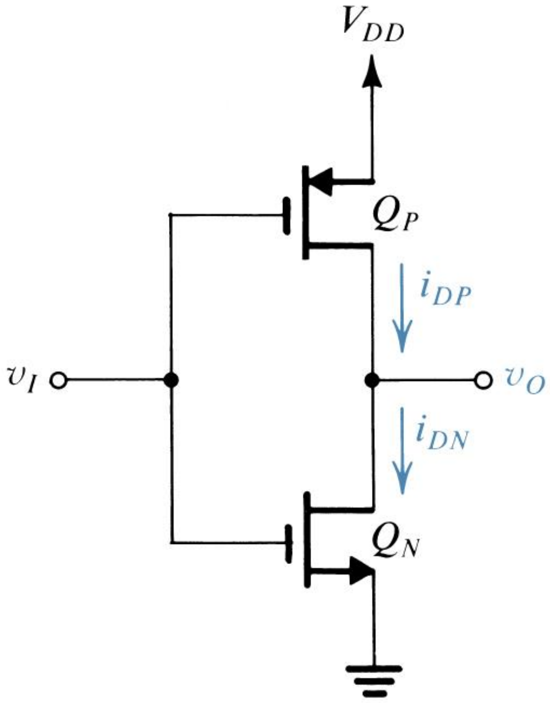
Small-signal equivalent circuit of the depletion-load amplifier

With the body effect of Q_2.



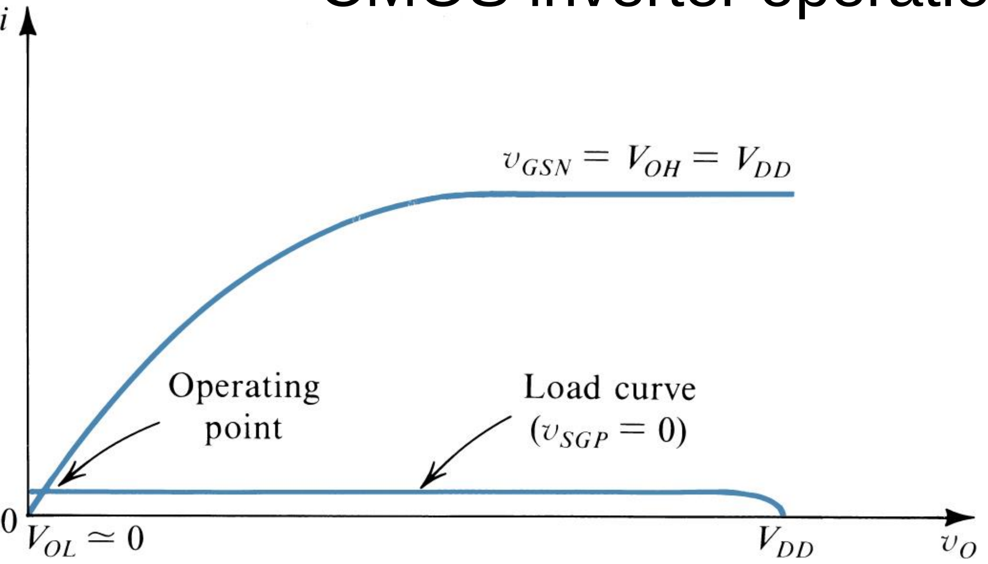
The CMOS inverter

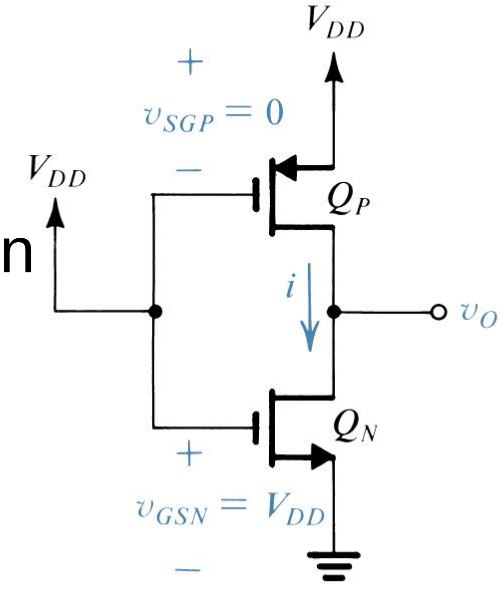




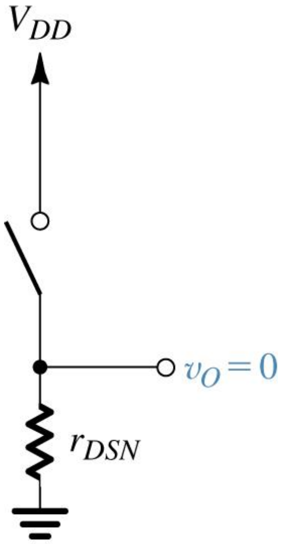
Simplified circuit schematic for the inverter.

CMOS inverter operation





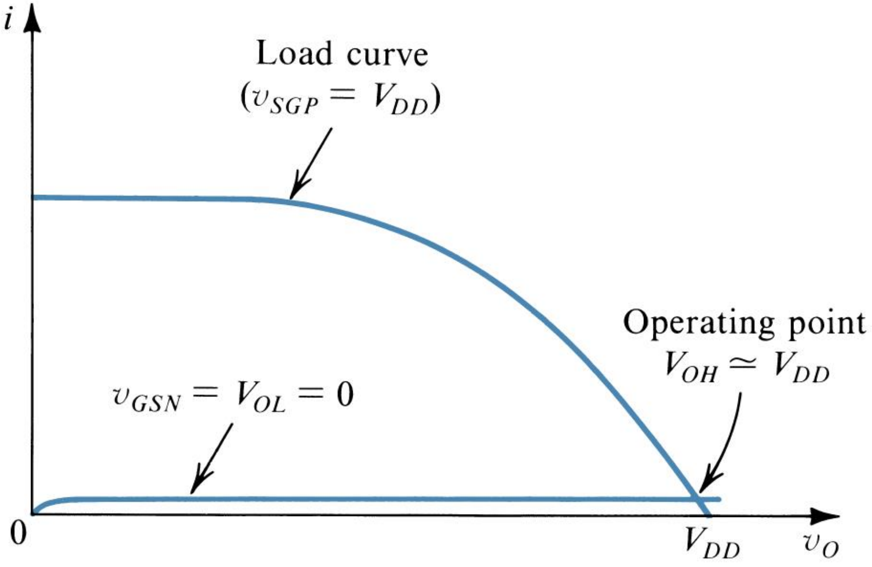
(a)

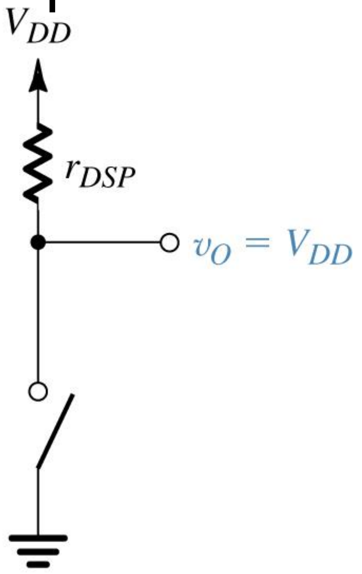


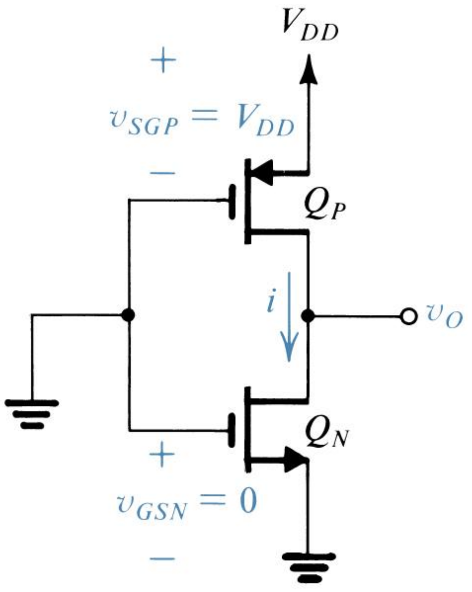
(c)

v_1 is high: (a) circuit with $v_1 = V_{DD}$ (logic-1 level, or V_{OH}); (b) graphical construction to determine the operating point; and (c) equivalent circuit.

CMOS inverter operation



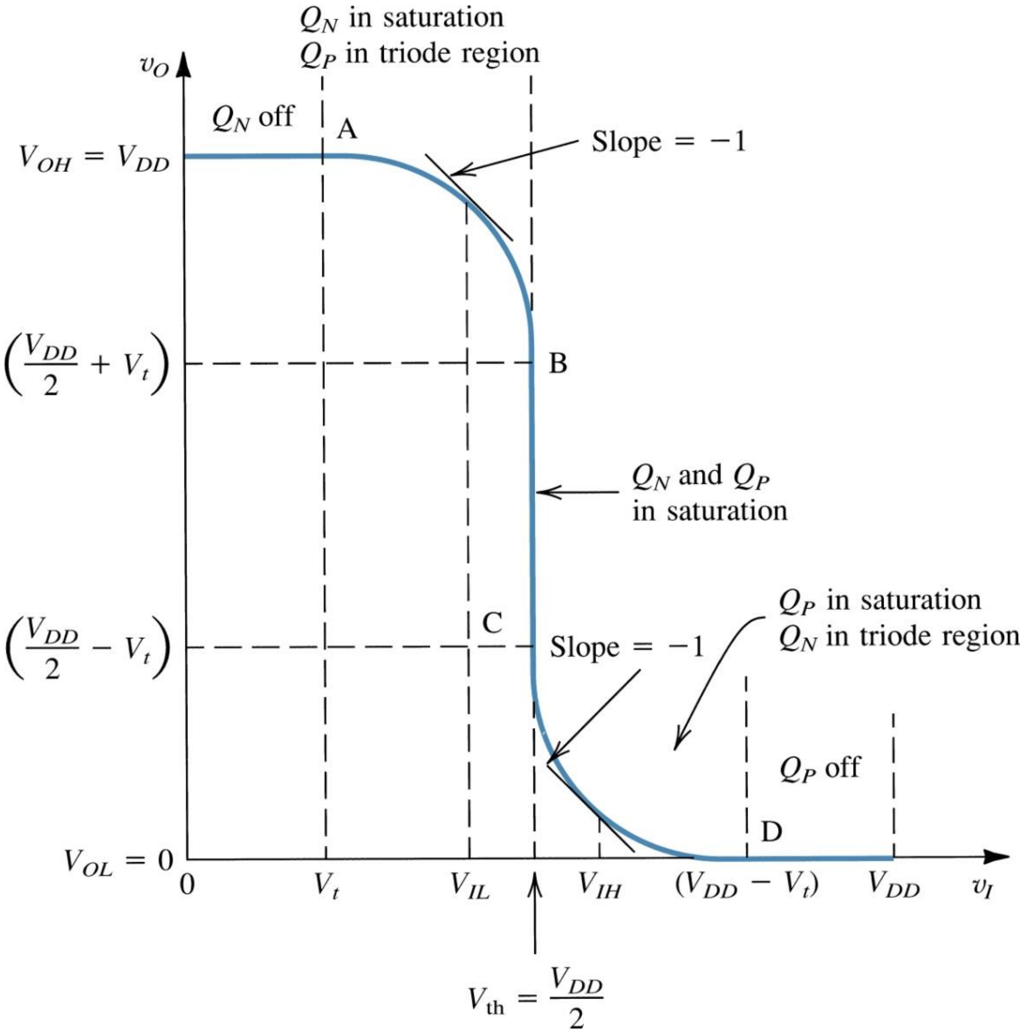




(c)

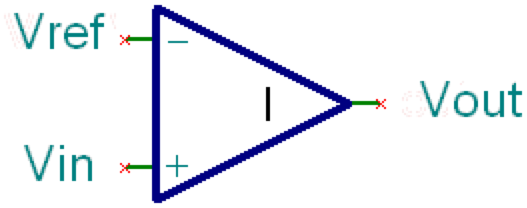
v_1 is low: graphical construction to determine the operating point; and (c) equivalent circuit.

Voltage transfer characteristic of the CMOS inverter.



OPAMP

OPAMP: COMPARATOR



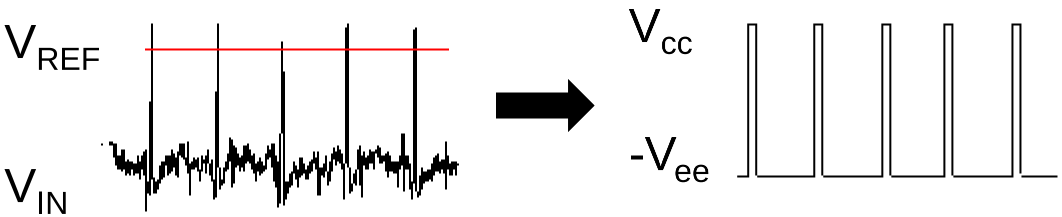
A (gain)
very high

$V_{out}=A(V_{in} - V_{ref})$

If $V_{in}>V_{ref}$, $V_{out} = +\infty$ but practically hits +ve power supply = V_{cc}

If $V_{in}<V_{ref}$, $V_{out} = -\infty$ but practically hits –ve power supply = $-V_{ee}$

Application: detection of QRS complex in ECG



OPAMP: ANALYSIS

The key to op amp analysis is simple

1. No current can enter op amp input terminals.

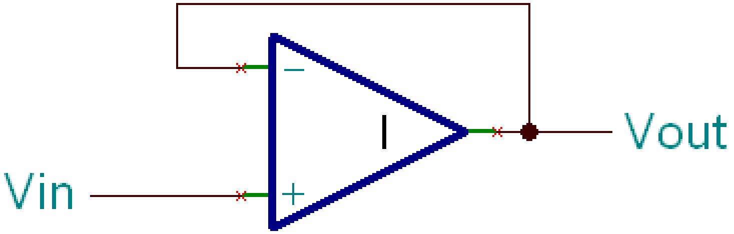
   => Because of infinite input impedance

2. The +ve and –ve (non-inverting and inverting) inputs are forced to be at the same potential.

   => Because of infinite open loop gain

3. These property is called "virtual ground"
4. Use the ideal op amp property in all your analyses

OPAMP: VOLTAGE FOLLOWER



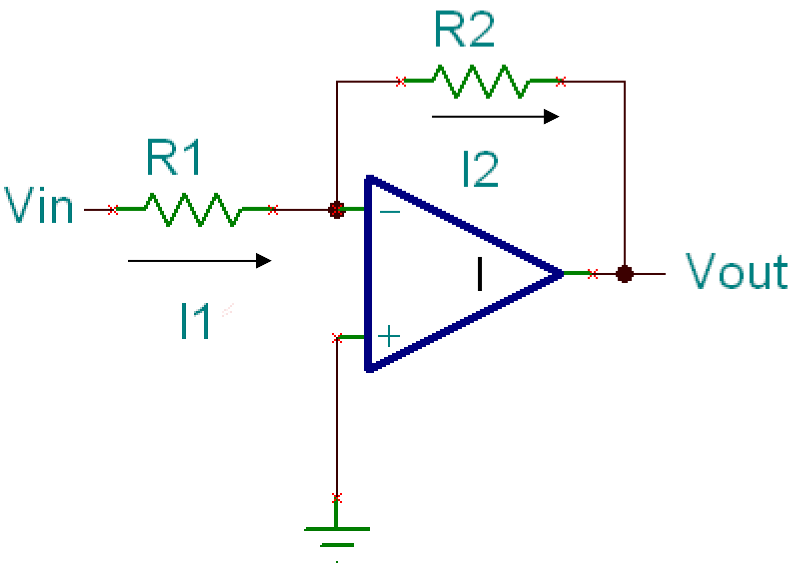
$V_+ = V_{IN}$.

By virtual ground, $V_- = V_+$

Thus $V_{out} = V_- = V_+ = V_{IN}$!!!!

So what's the point ? The point is, due to the infinite input impedance of an op amp, no current at all can be drawn from the circuit before V_{IN}. Thus this part is effectively isolated. Very *useful for interfacing to high impedance sensors such as microelectrode, microphone…*

OPAMP: INVERTING AMPLIFIER



1. $V_- = V_+$

2. As $V_+ = 0$, $V_- = 0$

3. As no current can enter V_- and from Kirchoff's Ist law, $I_1 = I_2$.

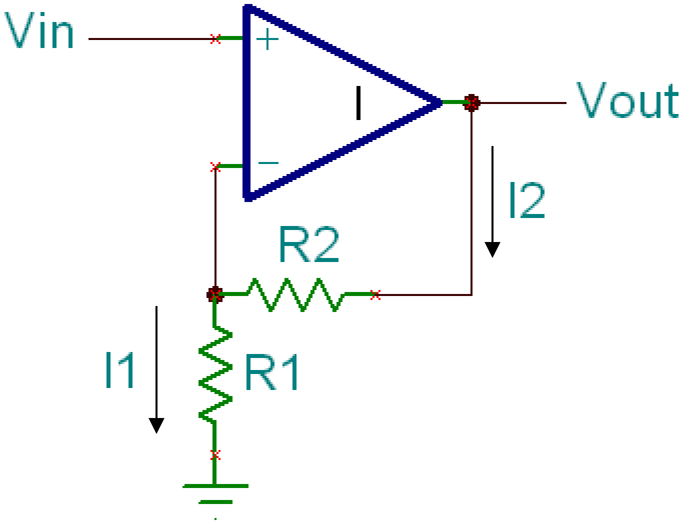
4. $I_1 = (V_{IN} - V_-)/R_1 = V_{IN}/R_1$

5. $I_2 = (0 - V_{OUT})/R_2 = -V_{OUT}/R_2 \Rightarrow V_{OUT} = -I_2R_2$

6. From 3 and 6, $V_{OUT} = -I_2R_2 = -I_1R_2 = -V_{IN}R_2/R_1$

7. Therefore $V_{OUT} = (-R_2/R_1)V_{IN}$

OPAMP: NON - INVERTING AMPLIFIER



1. $V_- = V_+$

2. As $V_+ = V_{IN}$, $V_- = V_{IN}$

3. As no current can enter V_- and from Kirchoff's Ist law, $I_1 = I_2$.

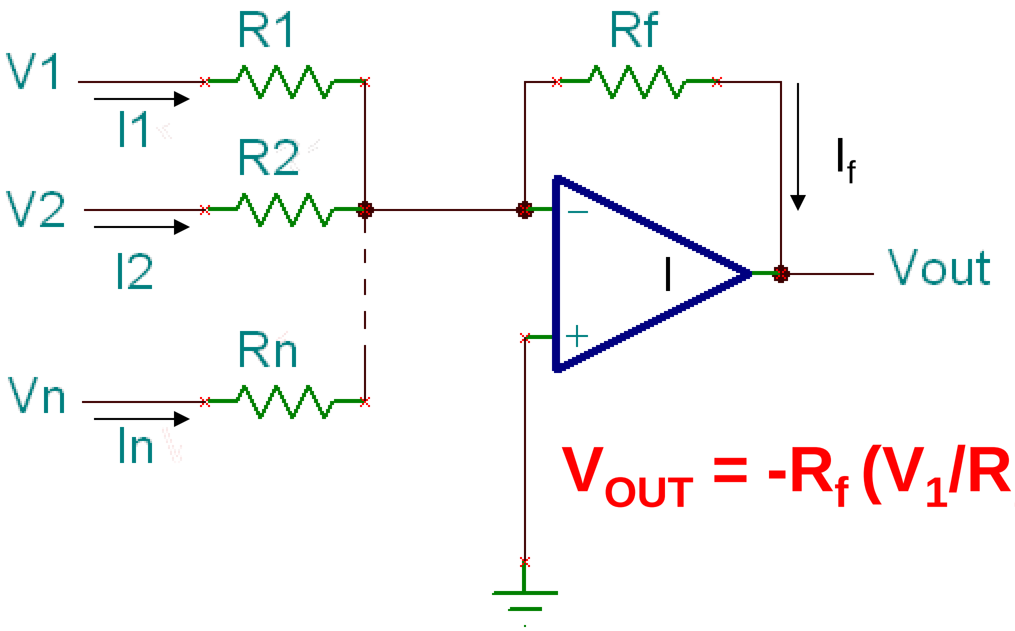
4. $I_1 = V_{IN}/R_1$

5. $I_2 = (V_{OUT} - V_{IN})/R_2 \Rightarrow V_{OUT} = V_{IN} + I_2R_2$

6. $V_{OUT} = I_1R_1 + I_2R_2 = (R_1+R_2)I_1 = (R_1+R_2)V_{IN}/R_1$

7. Therefore $V_{OUT} = (1 + R_2/R_1)V_{IN}$

SUMMING AMPLIFIER



Recall inverting amplifier and
$I_f = I_1 + I_2 + \ldots + I_n$

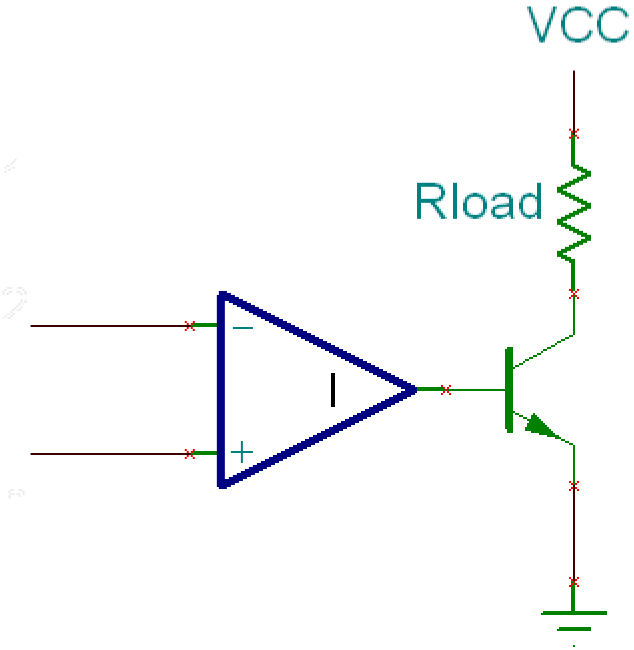
$$V_{OUT} = -R_f\,(V_1/R_1 + V_2/R_2 + \ldots + V_n/R_n)$$

Summing amplifier is a good example of analog circuits serving as analog computing amplifiers (analog computers)!

Note: analog circuits can add, subtract, multiply/divide (using logarithmic components, differentiate and integrate – in real time and continuously.

DRIVING OPAMPS

- For certain applications (e.g. driving a motor or a speaker), the amplifier needs to supply high current. Opamps can't handle this so we modify them thus

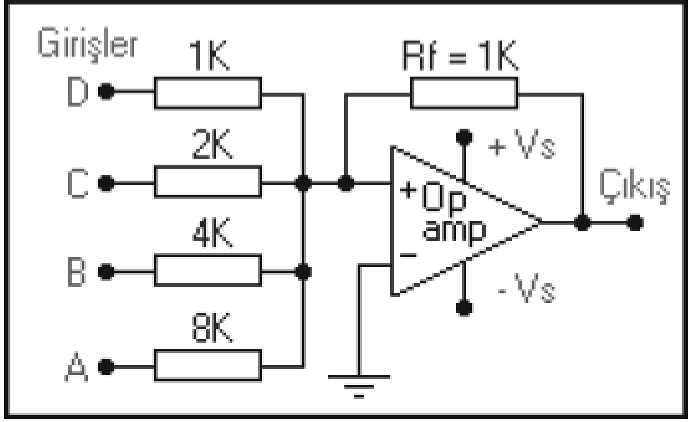


Irrespective of the opamp circuit, the small current it sources can switch ON the BJT giving orders of magnitude higher current in the load.

DAC - ADC Çeviriciler

Dijital ve analog devrelerin ayrı kullanılabileceği gibi aynı devrede de kullanılmaları mümkündür.
Bu tür devrelerde analog sinyali dijital bilgiye, dijital bilgiyi de analog sinyale dönüştürmek gerekebilir. Bu durumlarda da DAC-ADC devreleri kullanılır. Örneğin bilgisayara ses kaydı yapıldığında, bu ses ilk önce mikrofon sayesinde analog sinyal olarak bilgisayara iletilir. Bilgisayarda ise analog sinyal dijital bilgiye çevrilir ve harddiskte depolanır. Daha sonra bu sesi dinlemek istediğinizde dijital bilgi tekrar analog sinyale çevrilir ve hoparlörlerden ses olarak duyulur.

Ağırlık Dirençli DAC



Merdiven Tipi DAC