FUNDAMENTAL OF ELECTRICAL AND ELECTRONICS ENGINEERING

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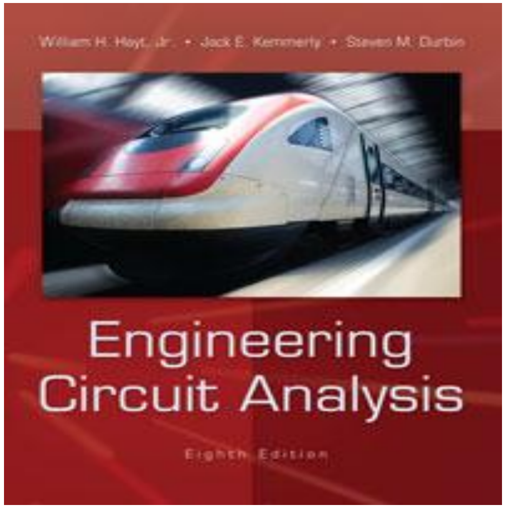
UNIT -I

ELECTRIC CIRCUIT ELEMENTS



The SI System

Base units:

- meter (m), kilogram (kg), second (s), ampere (A)
- also: kelvin, mole, and candela

Derived units:

- work or energy: joule (J)
- power (rate of doing work): watt (W)
- 1 W = 1 J/s

SI: Units and Prefixes

Any measurement can be expressed in terms of a unit, or a unit with a “prefix” modifier.

FACTOR	NAME	SYMBOL
10^{-9}	nano	n
10^{-6}	micro	μ
10^{-3}	milli	m
10^{3}	kilo	k
10^{6}	mega	M

Exam N

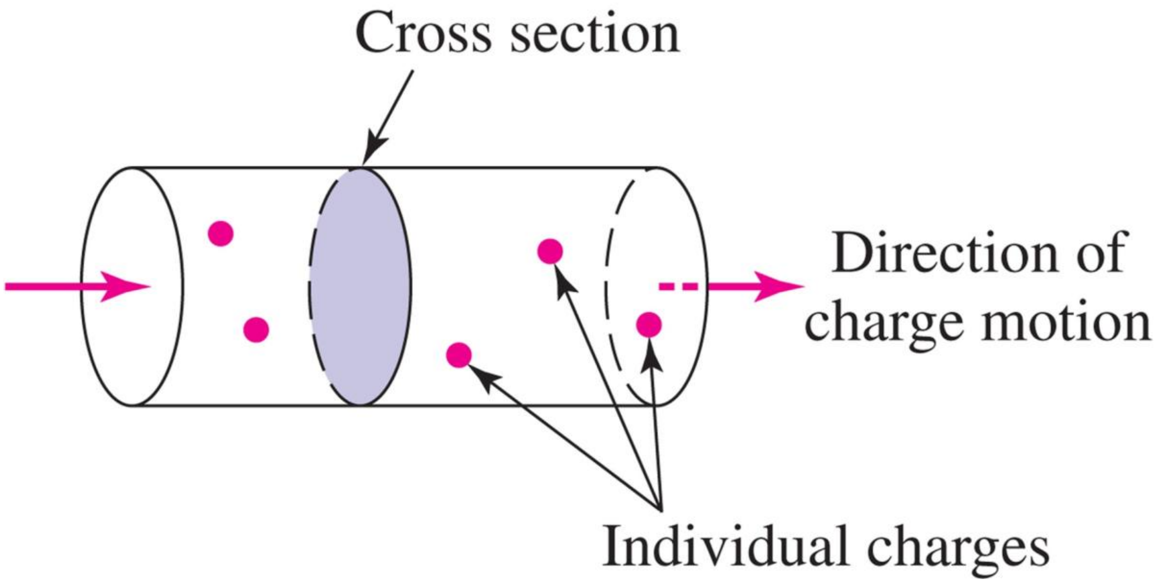
Charge

- charge is *conserved*: it is neither created nor destroyed
- symbol: Q or *q;* units are coulomb (C)
- the smallest charge, the *electronic charge*, is carried by an electron (-1.602×10^{-19} C) or a proton ($+1.602\times10^{-19}$ C)
- in most circuits, the charges in motion are electrons

Current and Charge

Current is the rate of charge flow:

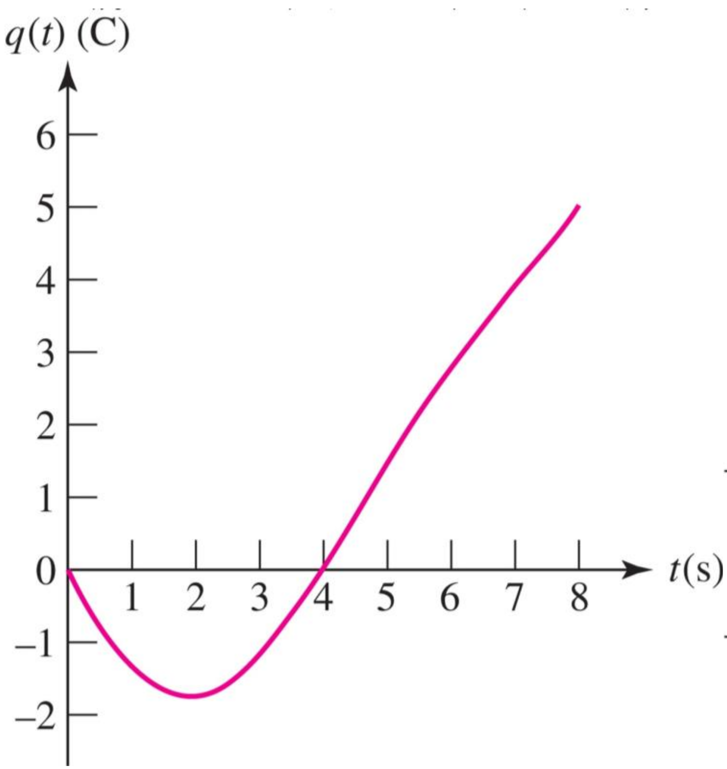
1 ampere = 1 coulomb/second (or 1 A = 1 C/s)

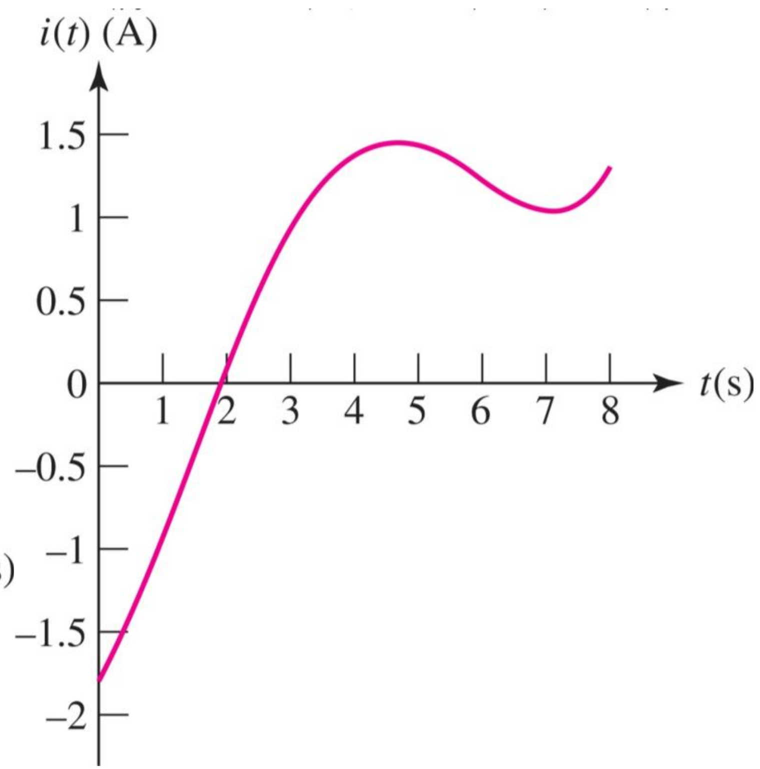


Current and Charge

- Current (designated by *I* or *i*) is the rate of flow of charge
- Current must be designated with both a direction and a magnitude
- These two currents are the same:

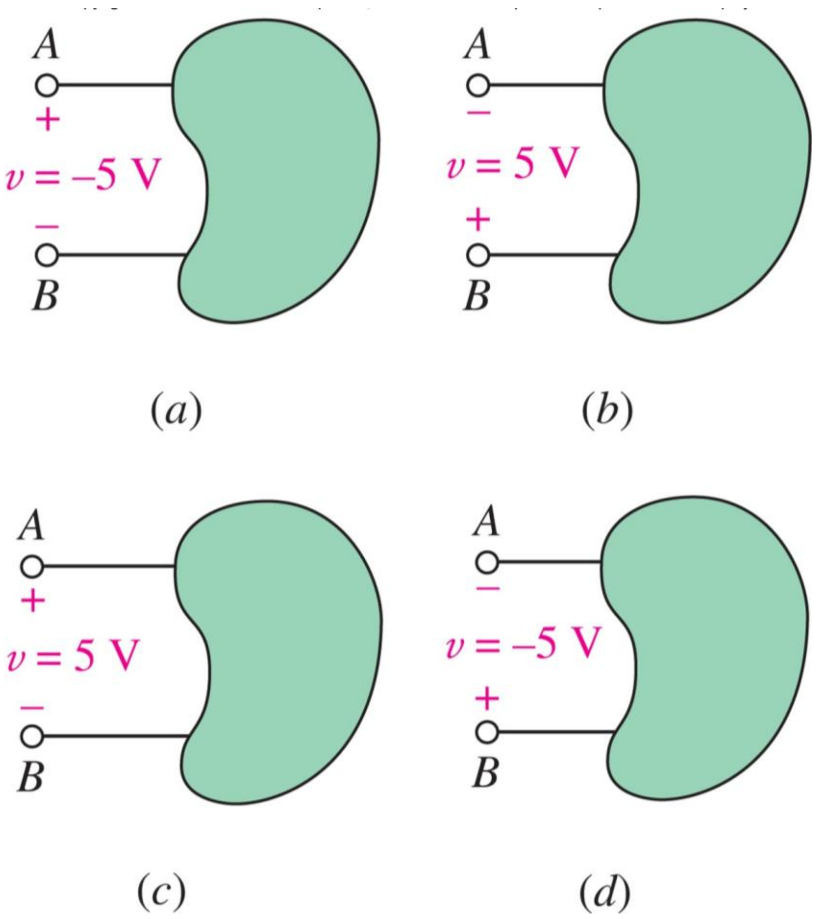
Current and Charge: i=dq/dt





Voltage

- When 1 J of work is required to move 1 C of charge from A to B, there is a voltage of 1 volt between A and B.
- Voltage (V or *v*) across an element requires both a magnitude and a polarity.
- Example: (a)=(b), (c)=(d)

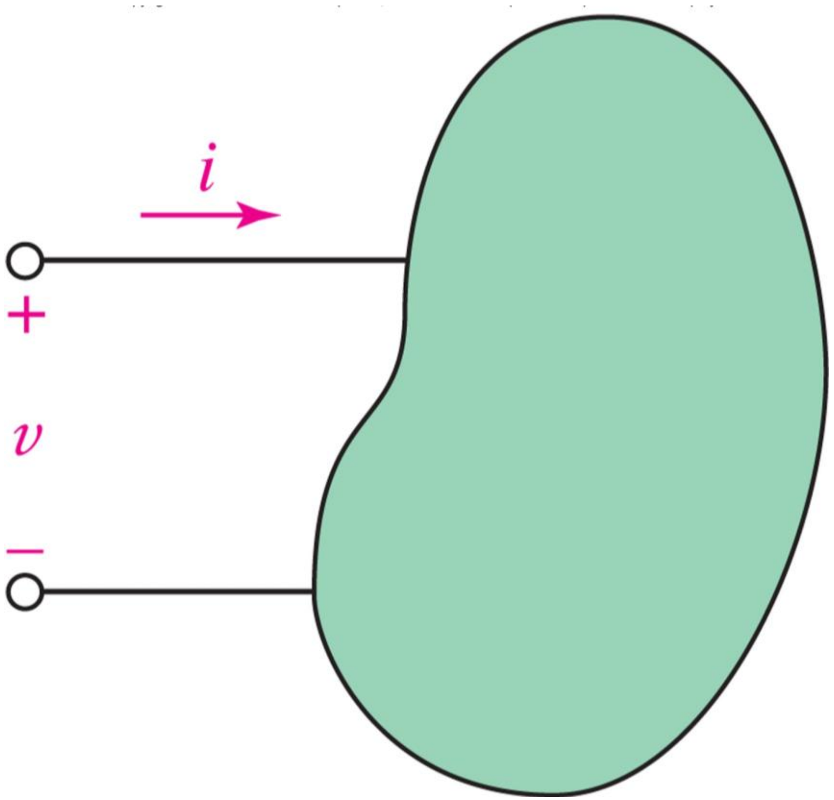


Power: $p = v\, i$

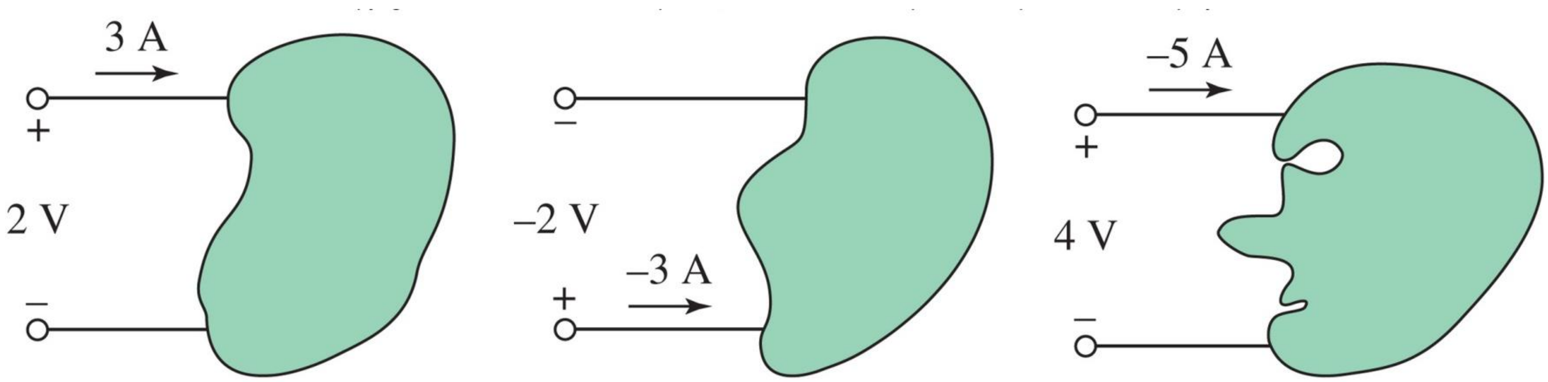
The power required to push a current i (C/s) into a voltage v (J/C) is $p = vi$ (J/s = W).

When power is positive, the element is *absorbing* energy.

When power is negative, the element is *supplying* energy.



Example: Power



(*a*) (*b*) (*c*)

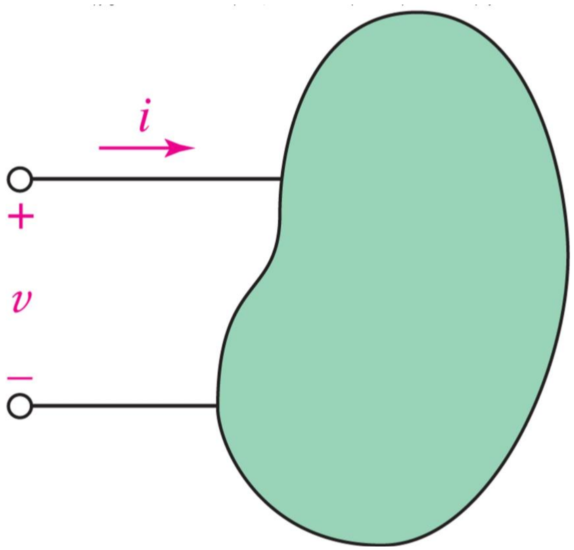
How much power is absorbed by the three elements above?

$P_a = +6$ W, $P_b = +6$ W, $P_c = -20$ W.
(Note: (c) is actually supplying power)

Circuit Elements

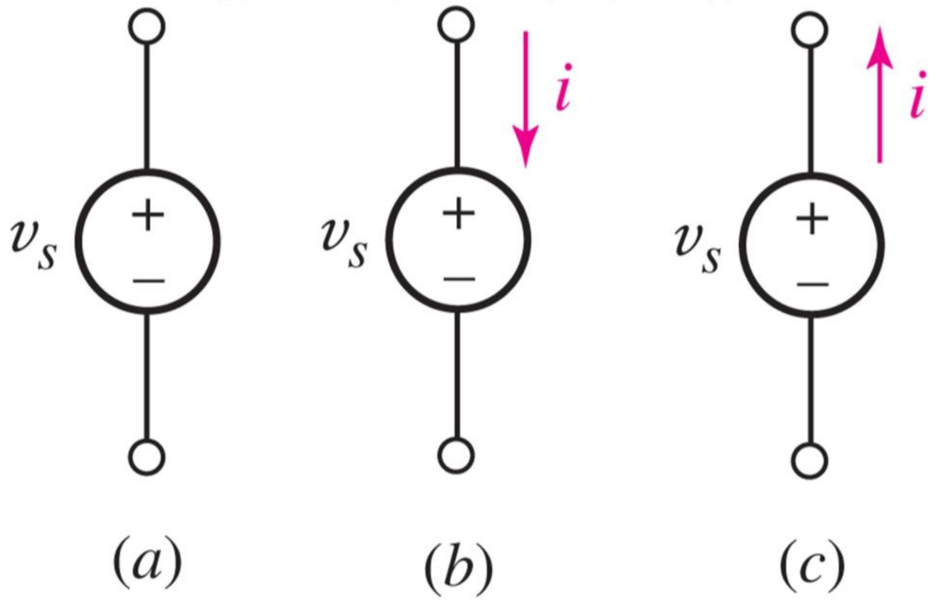
- A circuit element usually has two terminals (sometimes three or more).

- The relationship between the voltage *v* across the terminals and the current *i* through the device defines the circuit element model.



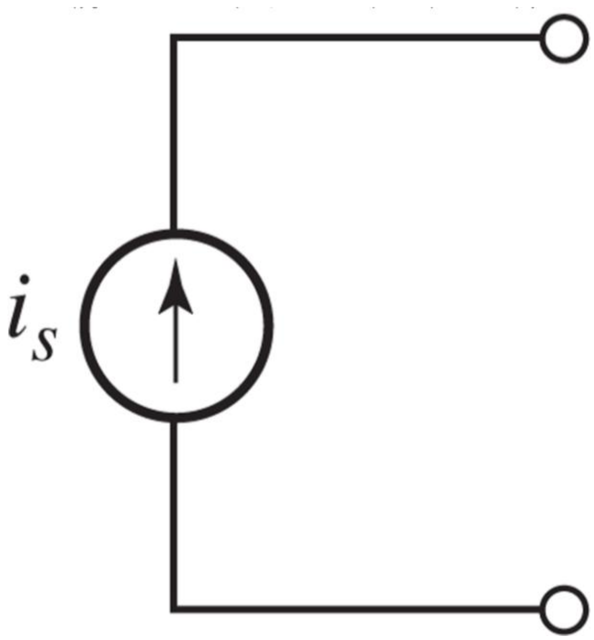
Voltage Sources

- An ideal voltage source is a circuit element that will maintain the specified voltage v_s across its terminals.
- The current will be determined by other circuit elements.



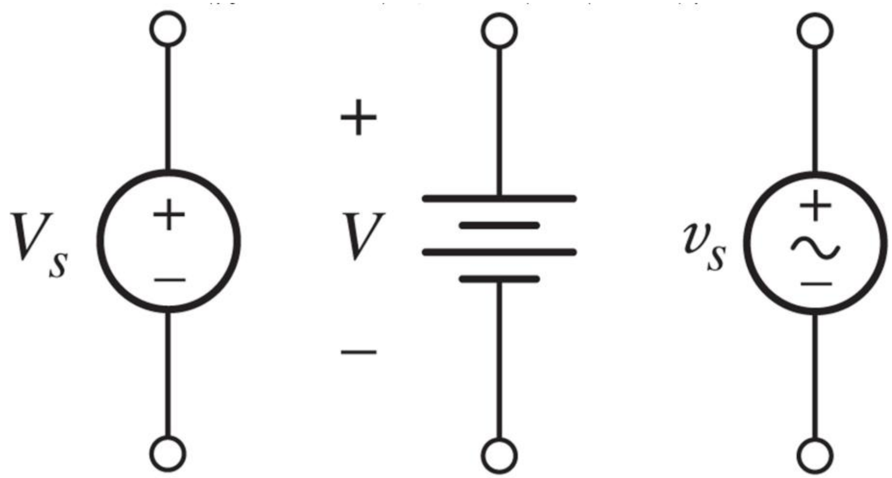
Current Sources

- An ideal current source is a circuit element that maintains the specified current flow i_s through its terminals.
- The voltage is determined by other circuit elements.



Battery as Voltage Source

- A voltage source is an idealization (no limit on current) and generalization (voltage can be time-varying) of a battery.
- A battery supplies a constant “dc” voltage V but in practice a battery has a maximum power.

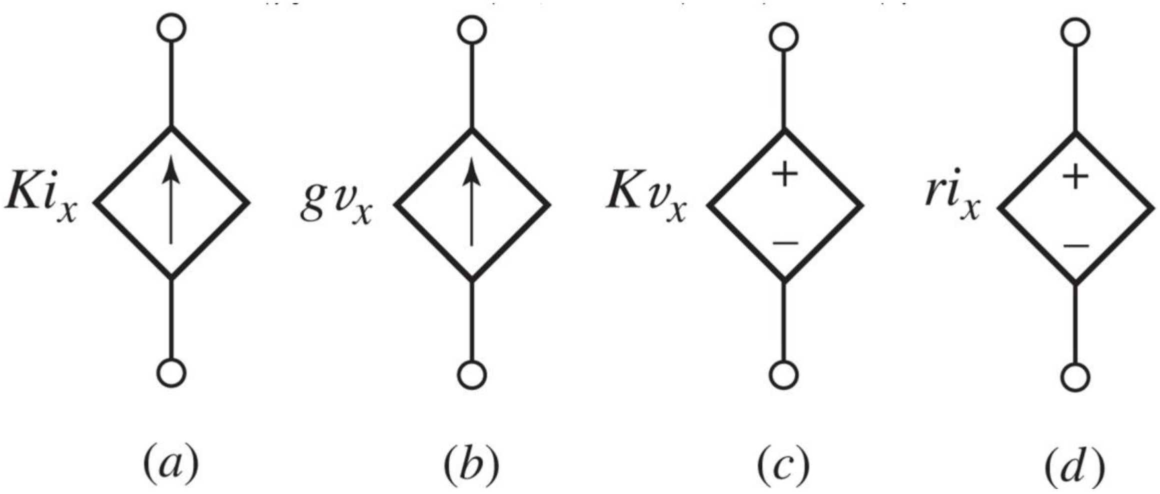


(a) (b) (c)

Dependent Sources

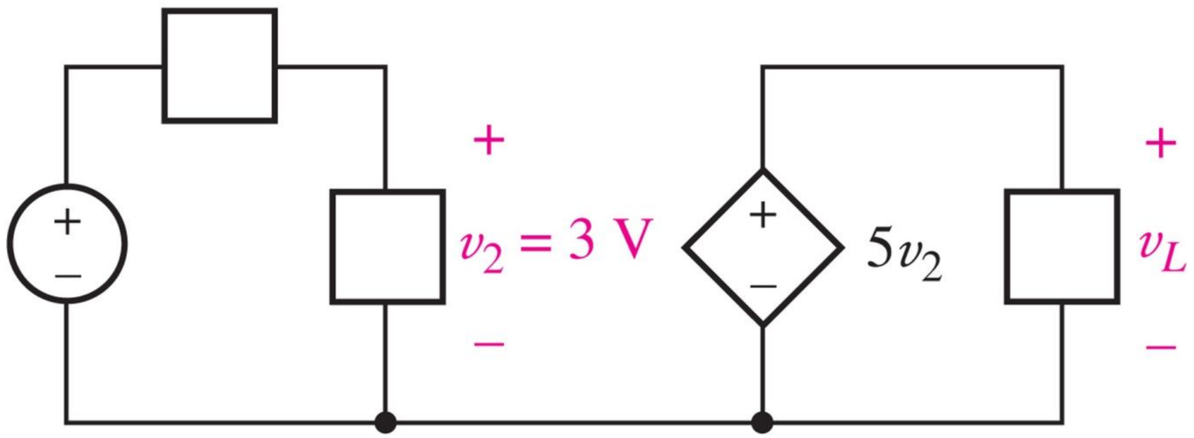
Dependent current sources (a) and (b) maintain a *current* specified by another circuit variable.

Dependent voltage sources (c) and (d) maintain a *voltage* specified by another circuit variable.



Example: Dependent Sources

Find the voltage v_L in the circuit below.

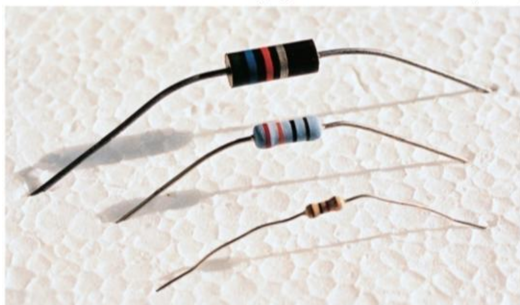


Ohm’s Law: Resistance

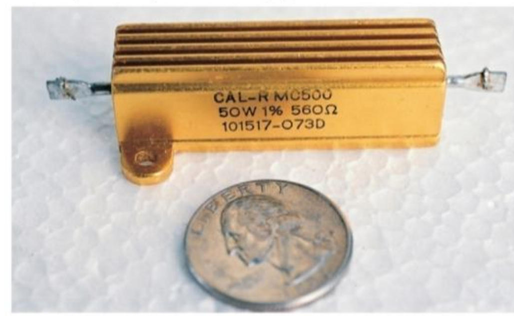
- A (linear) resistor is an element for which
  - *v=iR*
- where the constant R is a resistance.
- The equation is known as “Ohm’s Law.”
- The unit of resistance is ohm (Ω)

Resistors

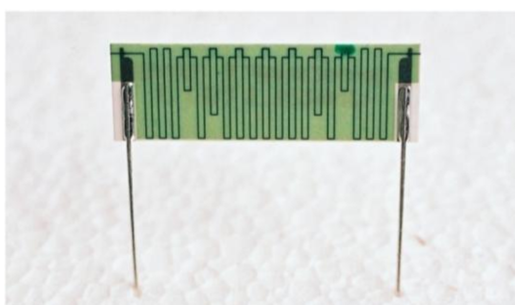
(a) typical resistors (b) power resistor
(c) a 10 TΩ resistor (d) circuit symbol



(*a*)



(*b*)

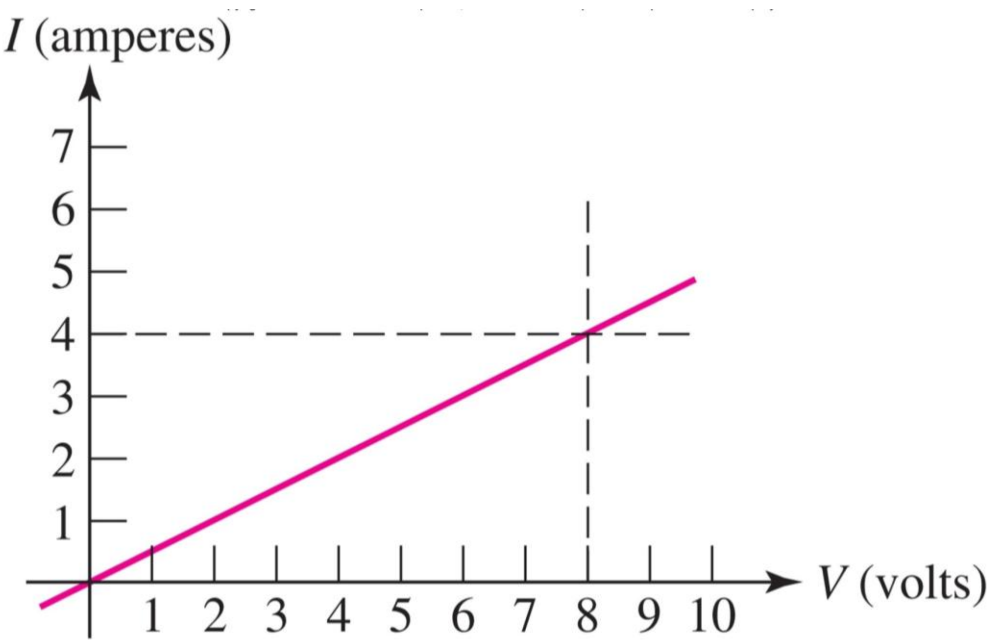


(*c*)

(*d*)

The i-v Graph for a Resistor

For a resistor, the plot of current versus voltage is a straight line:



In this example, the slope is 4 A / 8 V or 0.5 Ω^{-1}.

This is the graph for a 2 ohm resistor.

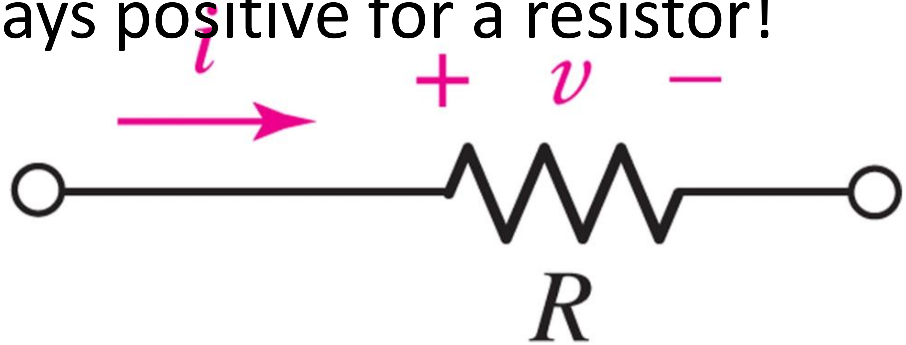
Power Absorption

Resistors absorb power: since $v=iR$

$$p=vi = v^2/R = i^2R$$

Positive power means the device is absorbing energy.

Power is always positive for a resistor!



Example: Resistor Power

A 560 Ω resistor is connected to a circuit which causes a current of 42.4 mA to flow through it.

Calculate the voltage across the resistor and the power it is dissipating.

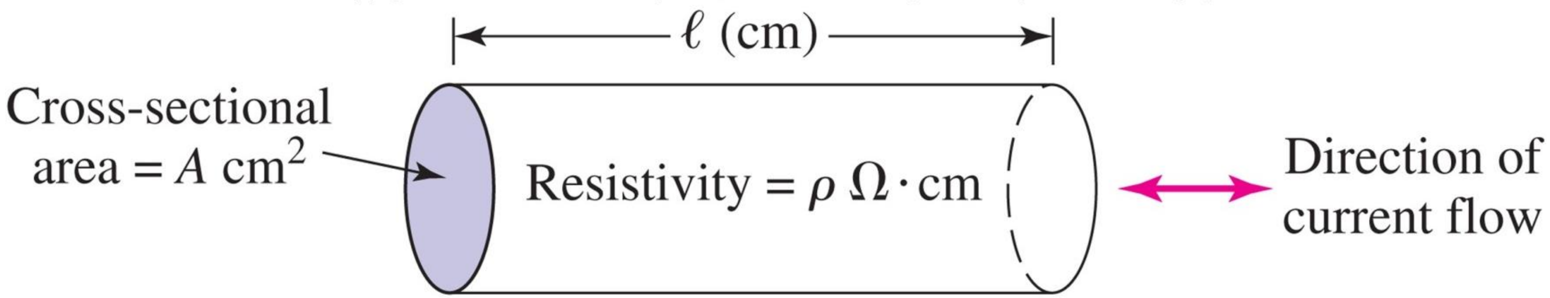
$v = iR = (0.0424)(560) = 23.7\text{ V}$

$p = i^2R = (0.0424)^2(560) = 1.007\text{ W}$

Wire Gauge and Resistivity

The resistance of a wire is determined by the resistivity of the conductor as well as the geometry:

$$R = \rho\, l / A$$



[In most cases, the resistance of wires can be assumed to be 0 ohms.]

Conductance

- We sometimes prefer to work with *the reciprocal of resistance* (1/R), which is called conductance (symbol G, unit siemens (S)).
- A resistor R has conductance G=1/R.
- The *i-v* equation (i.e. Ohm's law) can be written as

$$i = Gv$$

Open and Short Circuits

- An open circuit between A and B means $i=0$.
- *Voltage across* an open circuit: any value.
- An open circuit is equivalent to $R = \infty\ \Omega$.

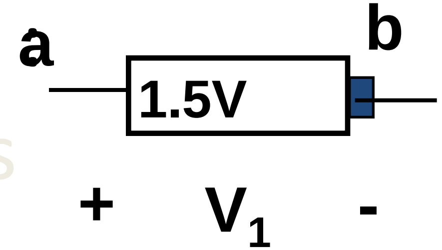
- A short circuit between A and B means $v=0$.
- *Current through* a short circuit: any value.
- A short circuit is equivalent to $R = 0\ \Omega$.

Circuit Analysis Basics

- Fundamental elements
  - Resistor
  - Voltage Source
  - Current Source
  - Air
  - Wire
- Kirchhoff’s Voltage and Current Laws
- Resistors in Series
- Voltage Division

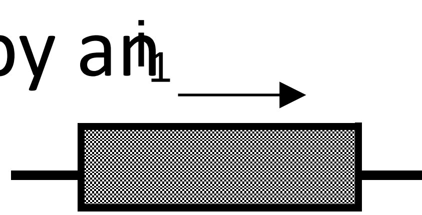
Voltage and Current

- Voltage is the difference in electric potential between two points. To express this difference, we label a voltage with a “+” and “-”



Here, V_1 is the potential at “a” minus the potential at “b”, which is -1.5 V.

- Current is the flow of positive charge. Current has a value and a direction, expressed by an arrow:



Here, i_1 is the current that flows right; i_1 is negative if current actually flows left.

- These are ways to place a frame of reference in

Basic Circuit Elements

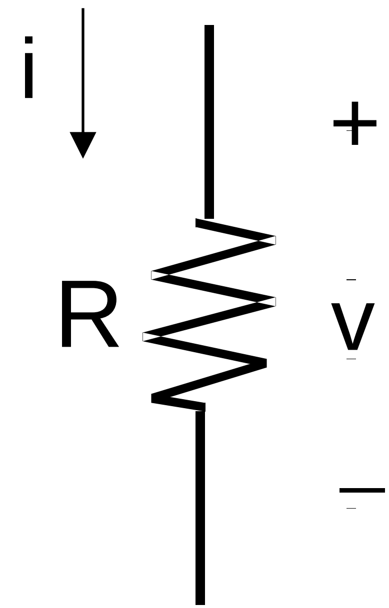
- Resistor
  – Current is proportional to voltage (linear)
- Ideal Voltage Source
  – Voltage is a given quantity, current is unknown
- Wire (Short Circuit)
  – Voltage is zero, current is unknown
- Ideal Current Source
  – Current is a given quantity, voltage is unknown
- Air (Open Circuit)
  – Current is zero, voltage is unknown

Resistor

- The resistor has a current-voltage relationship called Ohm's law:

  $v = i\,R$

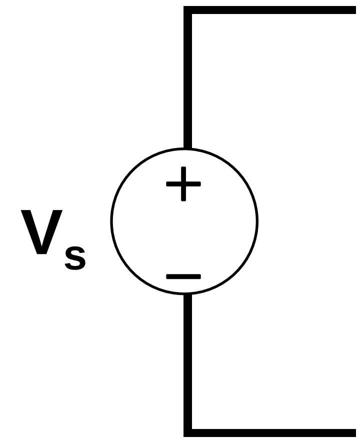
  where R is the resistance in Ω, i is the current in A, and v is the voltage in V, with reference directions **<u>as pictured</u>**.



- If R is given, once you know i, it is easy to find v and vice-versa.

- Since R is never negative, a resistor always absorbs power…

Ideal Voltage Source

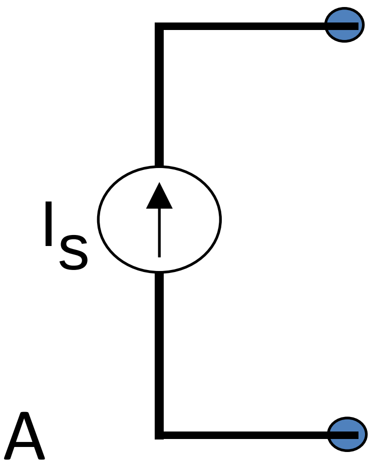


- The ideal voltage source explicitly defines the voltage between its terminals.
  - Constant (DC) voltage source: Vs = 5 V
  - Time-Varying voltage source: Vs = 10 sin(t) V
  - Examples: batteries, wall outlet, function generator, …
- The ideal voltage source does not provide any information about the current flowing through it.
- The current through the voltage source is defined by the rest of the circuit to which the source is attached. Current cannot be determined by the value of the voltage.
- <u>Do not assume that the current is zero!</u>

Wire

- Wire has a very small resistance.
- For simplicity, we will idealize wire in the following way: the potential at all points on a piece of wire is the same, regardless of the current going through it.
  – Wire is a 0 V voltage source
  – Wire is a 0 Ω resistor
- This idealization (and others) can lead to contradictions on paper—and smoke in lab.

Ideal Current Source

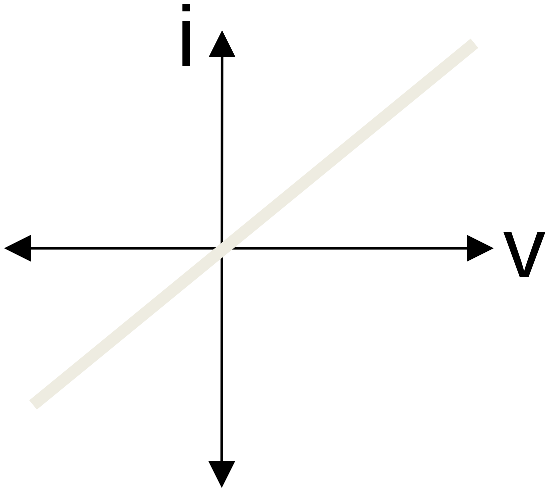


- The ideal current source sets the value of the current running through it.
  - Constant (DC) current source: $I_s = 2$ A
  - Time-Varying current source: $I_s = -3 \sin(t)$ A
  - Examples: few in real life!
- The ideal current source has known current, but unknown voltage.
- The voltage across the voltage source is defined by the rest of the circuit to which the source is attached.
- Voltage cannot be determined by the value of the current.
- <u>Do not assume that the voltage is zero!</u>

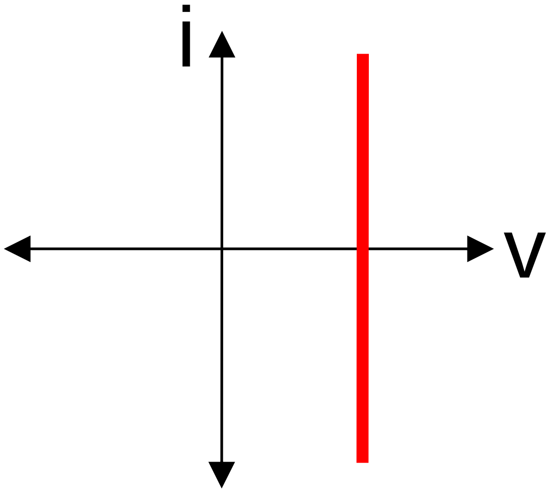
Air

- Many of us at one time, after walking on a carpet in winter, have touched a piece of metal and seen a blue arc of light.
- That arc is current going through the air. So is a bolt of lightning during a thunderstorm.
- However, these events are unusual. Air is usually a good insulator and does not allow current to flow.
- For simplicity, we will idealize air in the following way: current never flows through air (or a hole in a circuit), regardless of the potential difference (voltage) present.
  - Air is a 0 A current source
  - Air is a very very big (infinite) resistor
- <u>There can be nonzero voltage over air or a hole in a circuit!</u>

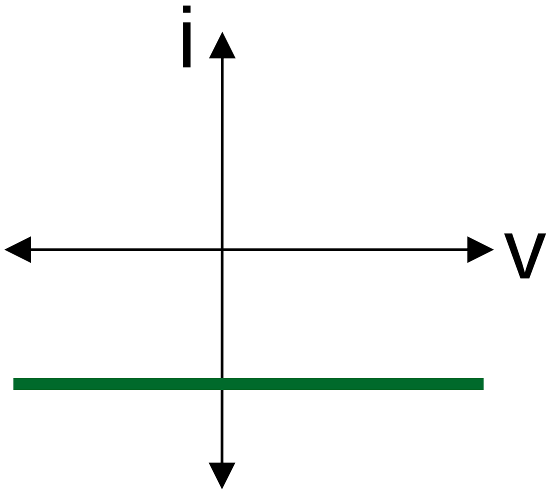
I-V Relationships Graphically



Resistor: Line through origin with slope 1/R



Ideal Voltage Source: Vertical line



Ideal Current Source: Horizontal line

Wire: Vertical line through origin

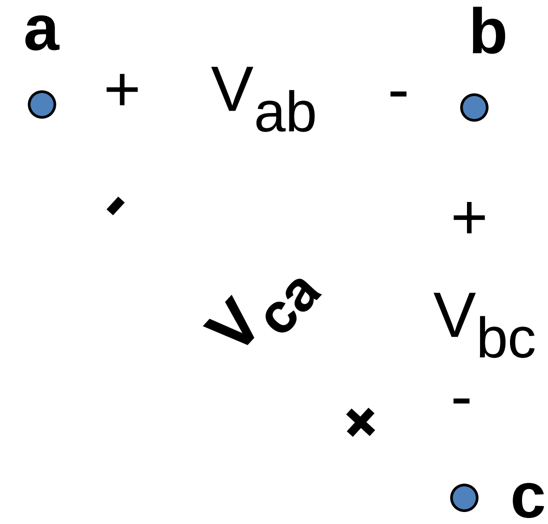
Air: Horizontal line through origin

Kirchhoff’s Laws

- The I-V relationship for a device tells us how current and voltage are related within that device.
- Kirchhoff’s laws tell us how voltages relate to other voltages in a circuit, and how currents relate to other currents in a circuit.
- KVL: The sum of voltage drops around a closed path must equal zero.
- KCL: The sum of currents leaving a closed surface or point must equal zero.

Kirchhoff's Voltage Law (KVL)

- Suppose I add up the potential drops around the closed path, from "a" to "b" to "c" and back to "a".
- Since I end where I began, the total drop in potential I encounter along the path must be zero: $V_{ab} + V_{bc} + V_{ca} = 0$

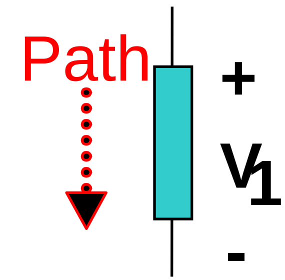


- It would not make sense to say, for example, "b" is 1 V lower than "a", "c" is 2 V lower than "b", and "a" is 3 V lower than "c". I would then be saying that "a" is 6 V lower than "a", which is nonsense!
- We can use potential rises throughout instead of potential drops; this is an alternative statement of KVL.

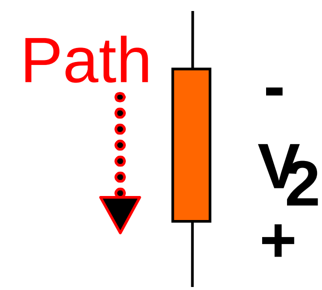
KVL Tricks

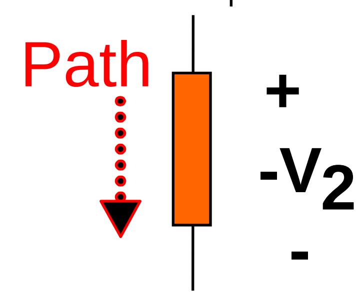
- A voltage rise is a negative voltage drop.

Along a path, I might encounter a voltage which is labeled as a voltage drop (in the direction I'm going). The sum of these voltage drops must equal zero.



I might encounter a voltage which is labeled as a voltage rise (in the direction I'm going). This rise can be viewed as a "negative drop". Rewrite:

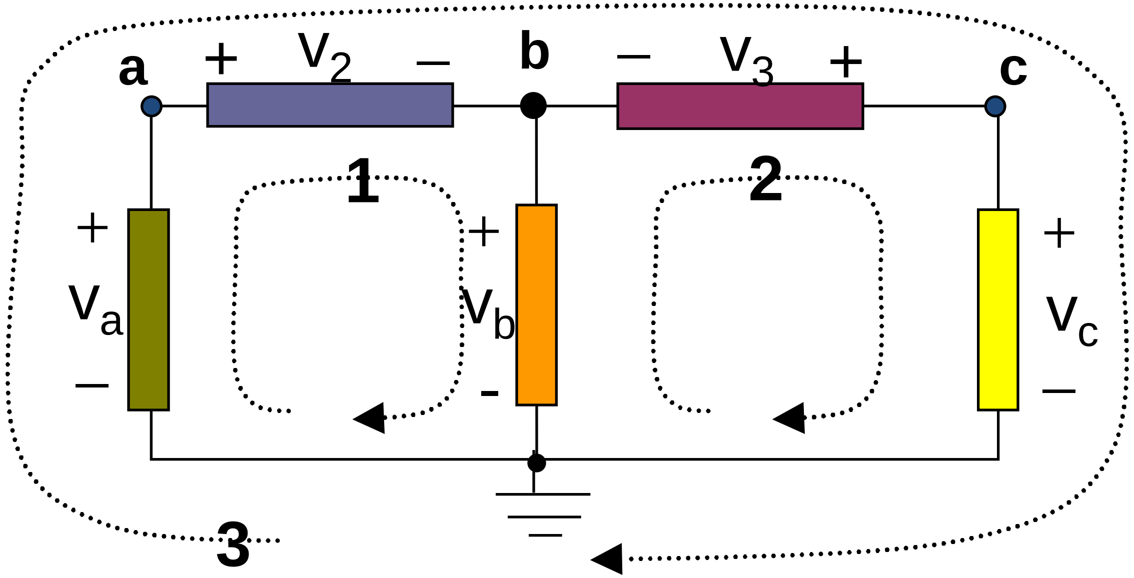




- Look at the first sign you encounter on each element when tracing the closed path. If it is a "-", it is a voltage rise and you will insert a "-" to rewrite as a drop.

Writing KVL Equations

What does KVL say about the voltages along these 3 paths?



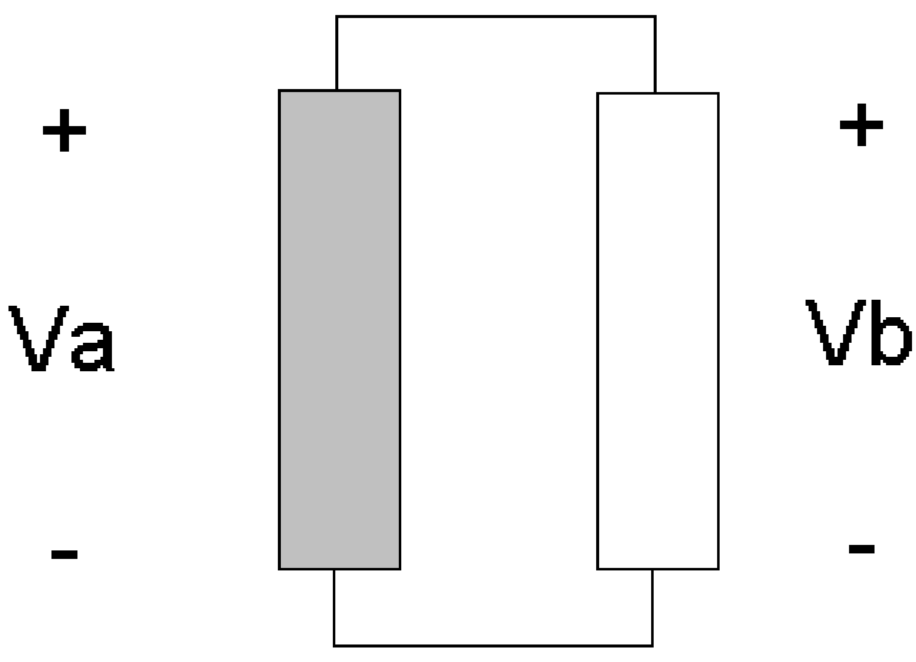
Path 1: $-v_a + v_2 + v_b = 0$

Path 2: $-v_b - v_3 + v_c = 0$

Path 3: $-v_a + v_2 - v_3 + v_c = 0$

Elements in Parallel

- KVL tells us that any set of elements which are **connected at both ends** carry the **same voltage**.
- We say these elements are **in parallel**.



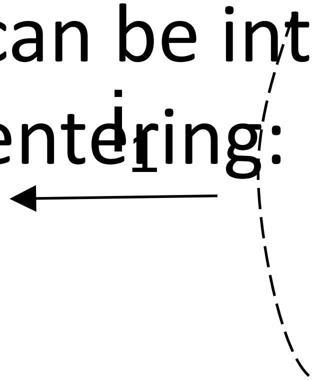
KVL clockwise, start at top:

$V_b - V_a = 0$

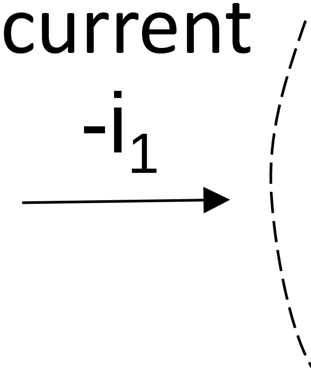
$V_a = V_b$

Kirchhoff's Current Law (KCL)

- Electrons don't just disappear or get trapped (in our analysis).
- Therefore, the sum of all current entering a closed surface or point must equal zero—whatever goes in must come out.
- Remember that current leaving a closed surface can be interpreted as a negative current entering:



is the same statement as



KCL Equations

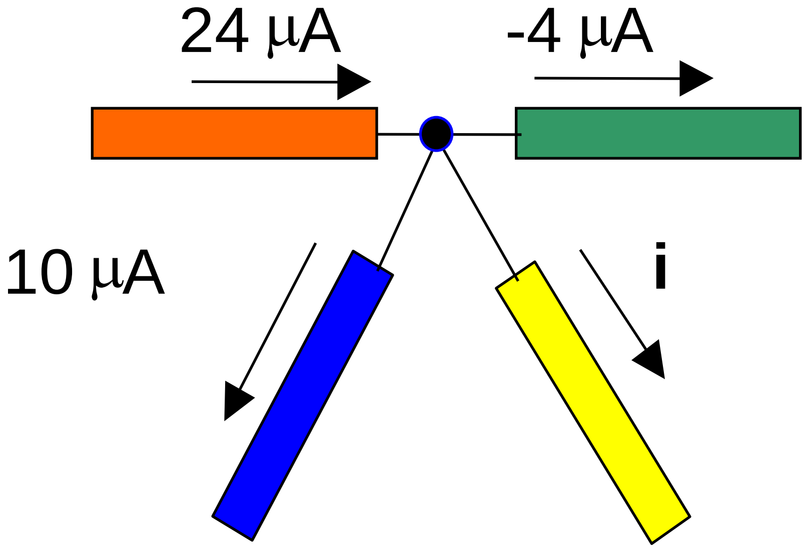
In order to satisfy KCL, what is the value of i?

KCL says:

24 μA + -10 μA + (-)-4 μA + -i =0

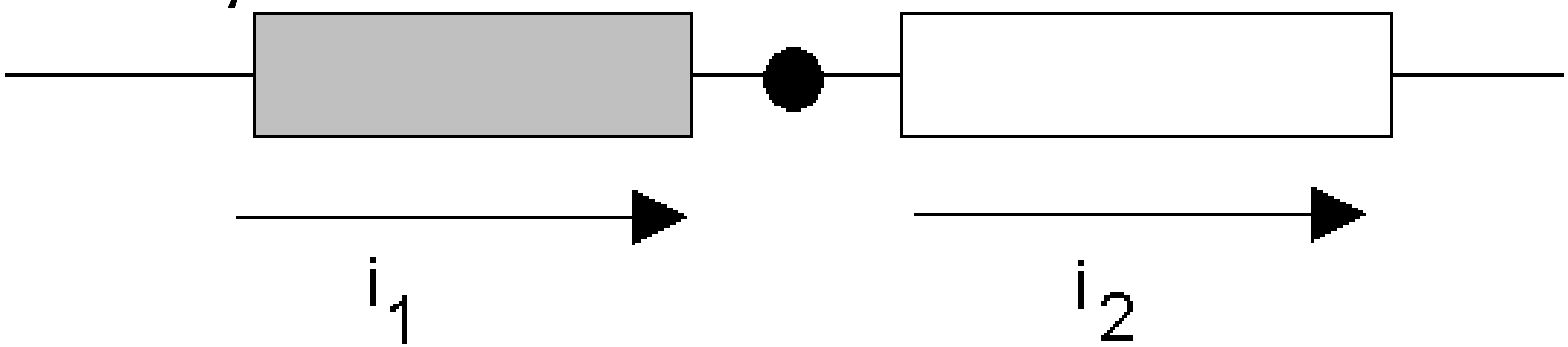
18 μA – i = 0

i = 18 μA



Elements in Series

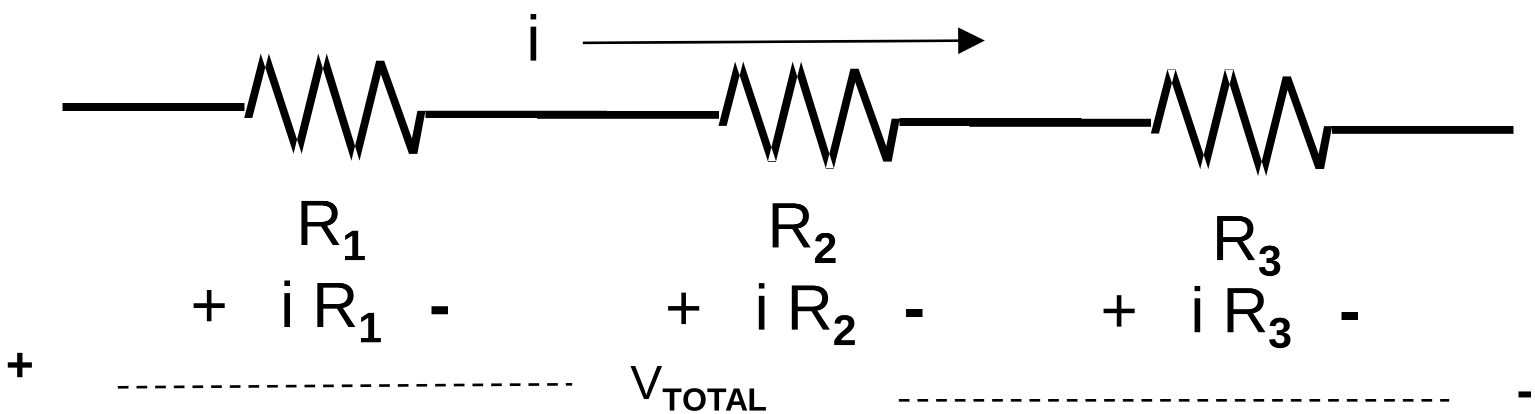
- Suppose two elements are connected with **nothing coming off in between**.
- KCL says that the elements carry the **same current**.
- We say these elements are **in series**.



$$i_1 - i_2 = 0 \qquad i_1 = i_2$$

Resistors in Series

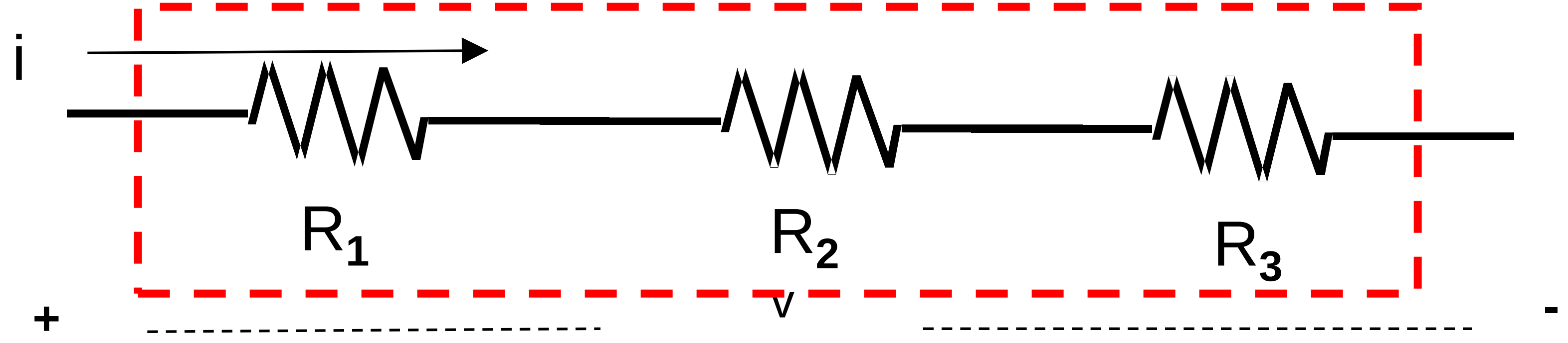
- Consider resistors in series. This means they are attached end-to-end, with nothing coming off in between.



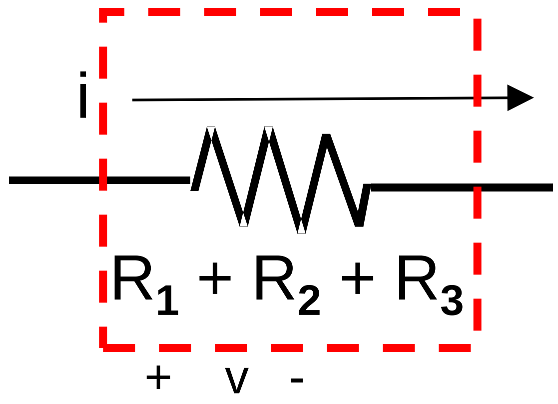
- Each resistor has the same current (labeled i).
- Each resistor has voltage iR, given by Ohm's law.
- The total voltage drop across all 3 resistors is

$$V_{\mathbf{TOTAL}} = i\,R_1 + i\,R_2 + i\,R_3 = i\,(R_1 + R_2 + R_3)$$

Resistors in Series

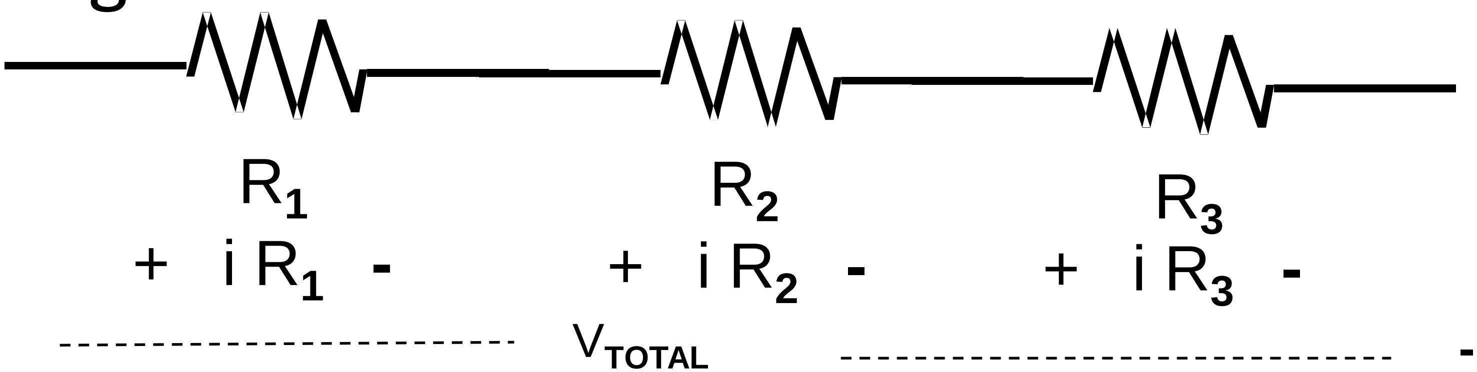


- When we look at all three resistors together as one unit, we see that they have the same I-V relationship as one resistor, whose value is the sum of the resistances:
- So we can treat these resistors as just one **equivalent resistance**, as long as we are not interested in the individual voltages. Their effect on the rest of the circuit is the same, whether lumped together or not.



Voltage Division

- If we know the total voltage over a series of resistors, we can easily find the individual voltages over the individual resistors.



- Since the resistors in series have the same current, the voltage divides up among the resistors in proportion to each individual

Voltage Division

- For example, we know
  $i = V_{\mathbf{TOTAL}} / (R_{\mathbf{1}} + R_{\mathbf{2}} + R_{\mathbf{3}})$
  so the voltage over the **first resistor** is
  $i\ R_{\mathbf{1}} = R_{\mathbf{1}}\ V_{\mathbf{TOTAL}} / (R_{\mathbf{1}} + R_{\mathbf{2}} + R_{\mathbf{3}})$

$$= V_{TOTAL} \frac{R_1}{R_1 + R_2 + R_3}$$

- To find the voltage over an individual resistance in series, take the total series voltage and multiply by the individual resistance over the total resistance.

UNIT II

NETWORK ANALYSIS AND THEOREMS

Superposition Theorem

- Total current through or voltage across a resistor or branch
  - Determine by adding effects due to each source acting independently
- Replace a voltage source with a short

Superposition Theorem

- Replace a current source with an open
- Find results of branches using each source independently
  - Algebraically combine results

Superposition Theorem

- Power
  - Not a linear quantity
  - Found by squaring voltage or current
- Theorem does not apply to power
  - To find power using superposition
  - Determine voltage or current
  - Calculate power

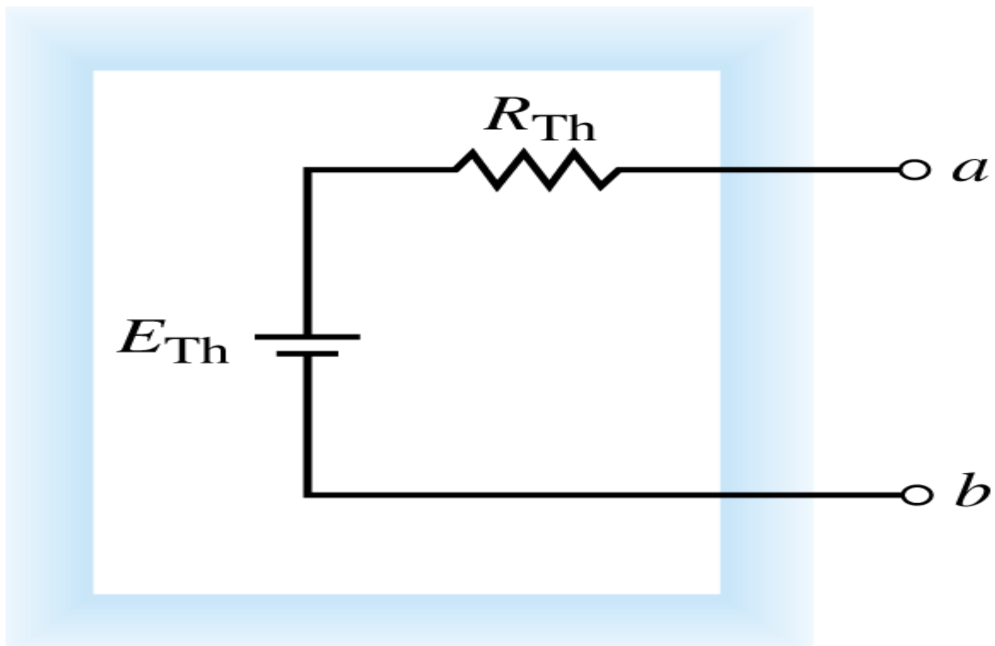
Thévenin's Theorem

- Lumped linear bilateral network
  - May be reduced to a simplified two-terminal circuit
  - Consists of a single voltage source and series resistance

Thévenin's Theorem

- Voltage source
  - Thévenin equivalent voltage, E_{Th}.
- Series resistance is Thévenin equivalent resistance, R_{Th}

Thévenin's Theorem



Thévenin’s Theorem

- To convert to a Thévenin circuit
  - First identify and remove load from circuit
- Label resulting open terminals

Thévenin's Theorem

- Set all sources to zero
- Replace voltage sources with shorts, current sources with opens
- Determine Thévenin equivalent resistance as seen by open circuit

Thévenin’s Theorem

- Replace sources and calculate voltage across open
- If there is more than one source
  - Superposition theorem could be used

Thévenin’s Theorem

- Resulting open-circuit voltage is Thévenin equivalent voltage
- Draw Thévenin equivalent circuit, including load

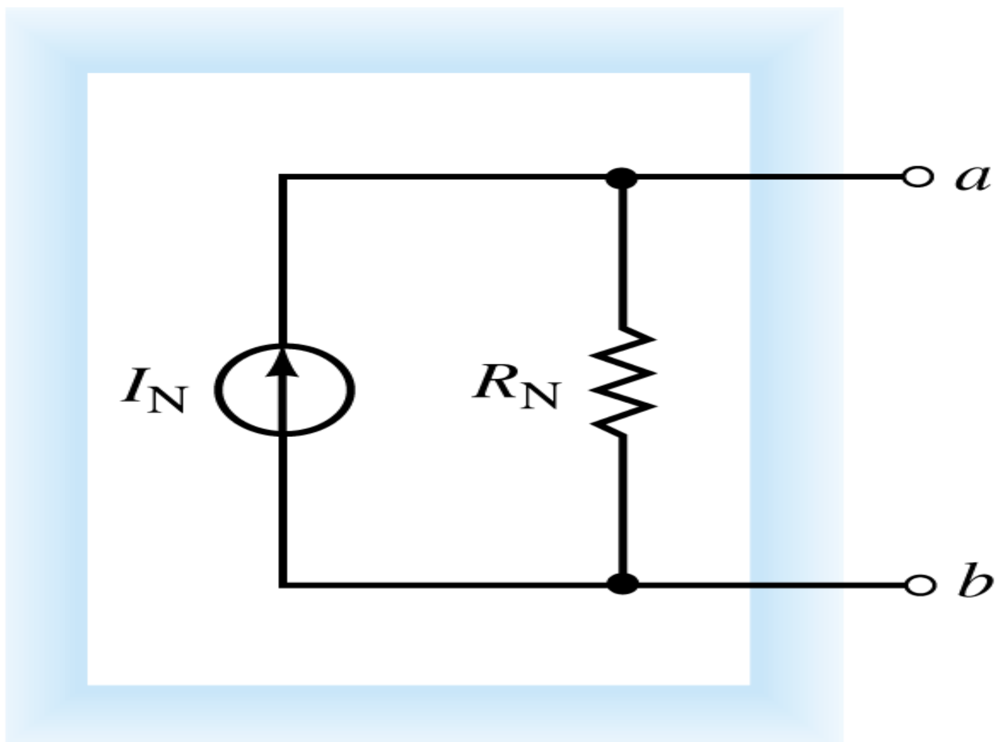
Norton’s Theorem

- Similar to Thévenin circuit
- Any lumped linear bilateral network
  - May be reduced to a two-terminal circuit
  - Single current source and single shunt resistor

Norton's Theorem

- $R_{\mathrm{N}} = R_{\mathrm{Th}}$
- I_{N} is Norton equivalent current

Norton's Theorem



Norton's Theorem

- To convert to a Norton circuit
  - Identify and remove load from circuit
- Label resulting two open terminals
- Set all sources to zero

Norton's Theorem

- Determine open circuit resistance
  - This is Norton equivalent resistance
- Note
  - This is accomplished in the same manner as Thévenin equivalent resistance

Norton’s Theorem

- Replace sources and determine current that would flow through a short place between two terminals
- This current is the Norton equivalent current

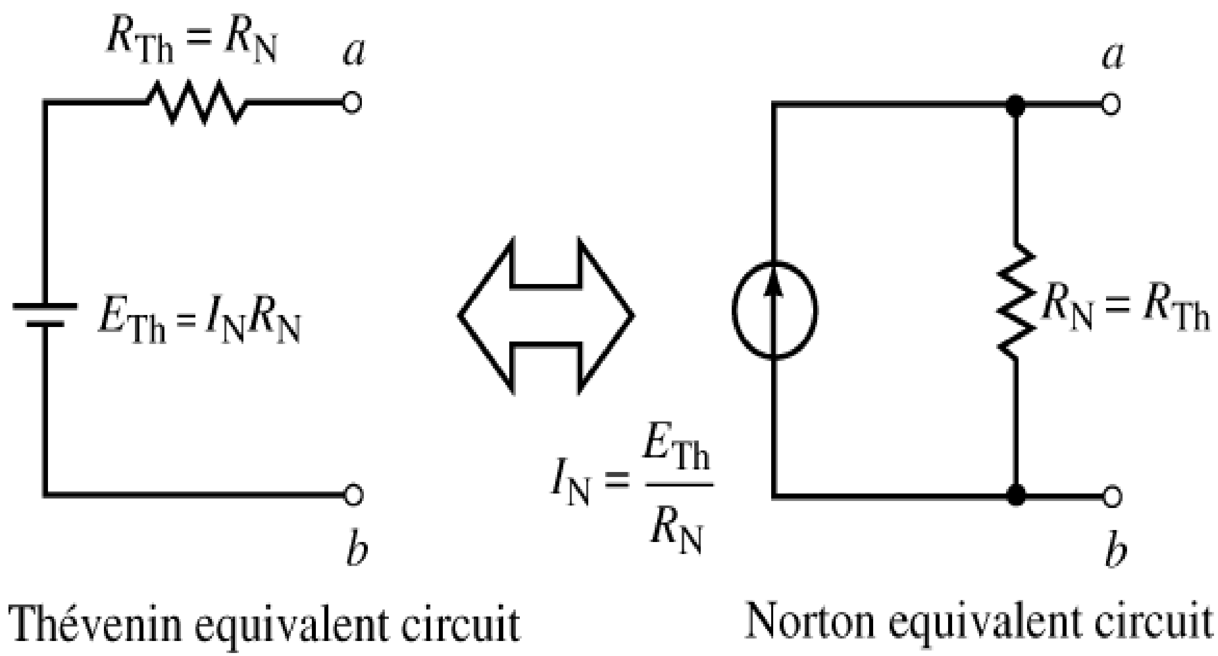
Norton’s Theorem

- For multiple sources
  - Superposition theorem could be used
- Draw the Norton equivalent circuit
  - Including the load

Norton's Theorem

- Norton equivalent circuit
  - May be determined directly from a Thévenin circuit (or vice-versa) by using source transformation theorem

Norton's Theorem



Maximum Power Transfer

- Load should receive maximum amount of power from source
- Maximum power transfer theorem states
  - Load will receive maximum power from a circuit when resistance of the load is exactly the same as Thévenin (or Norton) equivalent resistance of the circuit

Maximum Power Transfer

- To calculate maximum power delivered by source to load
  - Use $P = V^2/R$
- Voltage across load is one half of Thévenin equivalent voltage

Maximum Power Transfer

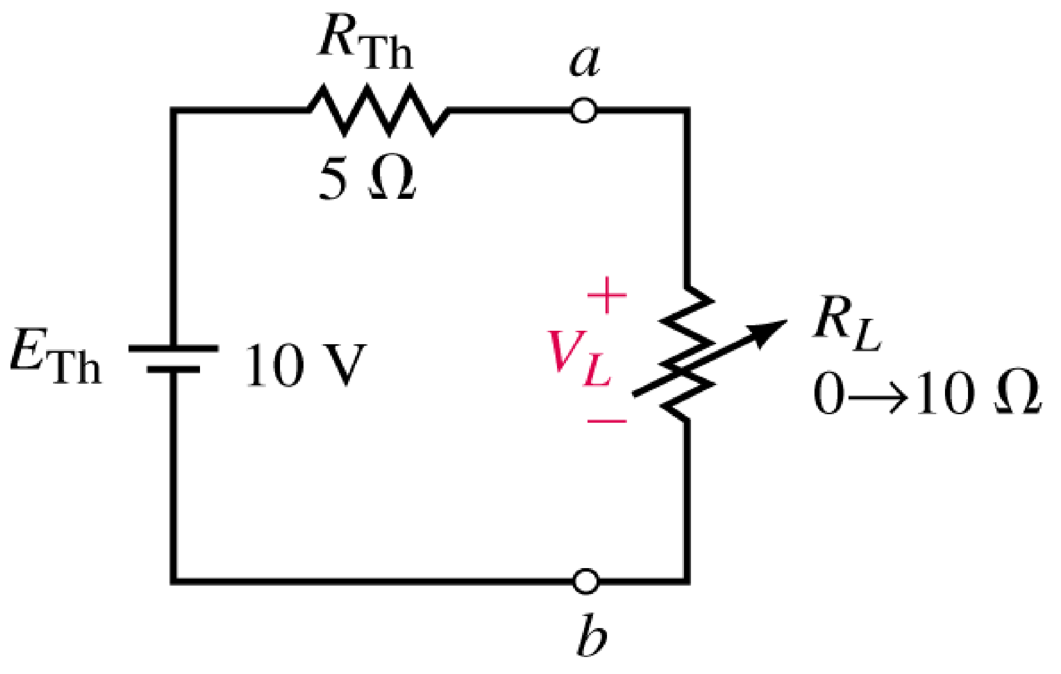
- Current through load is one half of Norton equivalent current

$$P_{\max} = \frac{E_{\mathrm{Th}}{}^{2}}{4R_{\mathrm{Th}}} = \frac{I_{\mathrm{N}}{}^{2} R_{\mathrm{N}}}{4}$$

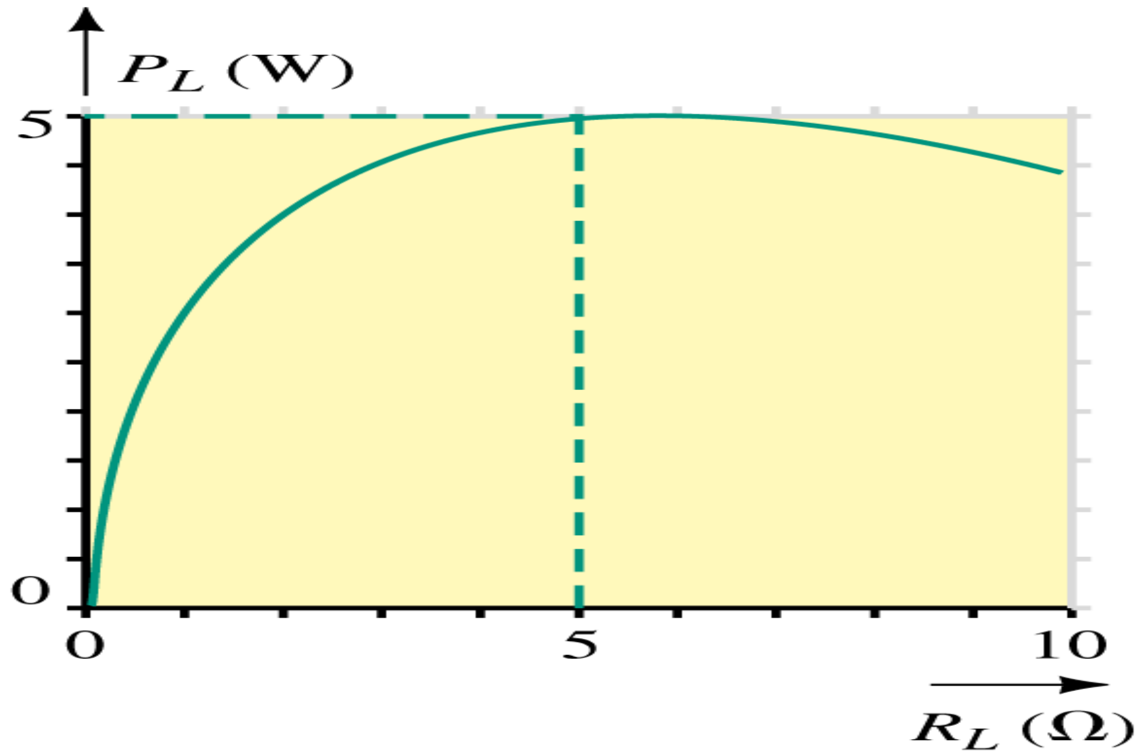
Maximum Power Transfer

- Power across a load changes as load changes by using a variable resistance as the load

Maximum Power Transfer



Maximum Power Transfer



Efficiency

- To calculate efficiency:

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}}$$

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\%$$

$$\eta = \frac{\dfrac{E_{\text{Th}}{}^2}{4R_{\text{Th}}}}{\dfrac{E_{\text{Th}}{}^2}{2R_{\text{Th}}}} \times 100\% = 50\%$$

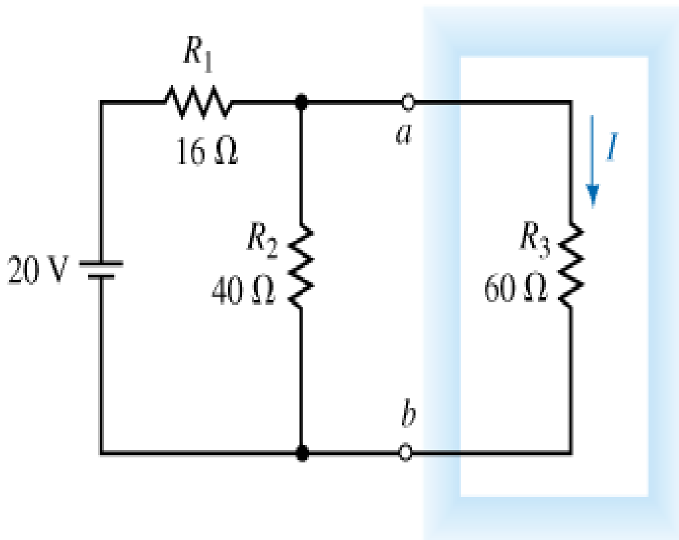
Substitution Theorem

- Any branch within a circuit may be replaced by an equivalent branch
  - Provided the replacement branch has same current voltage
- Theorem can replace any branch with an equivalent branch
- Simplify analysis of remaining circuit

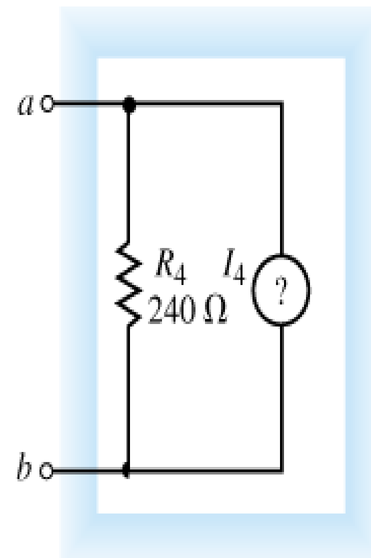
Substitution Theorem

- Part of the circuit shown is to be replaced with a current source and a 240 Ω shunt resistor
  - Determine value of the current source

Substitution Theorem



(a)



(b)

Millman’s Theorem

- Used to simplify circuits that have
  - Several parallel-connected branches containing a voltage source and series resistance
  - Current source and parallel resistance
  - Combination of both

Millman’s Theorem

- Other theorems may work, but Millman’s theorem provides a much simpler and more direct equivalent

Millman’s Theorem

- Voltage sources
  - May be converted into an equivalent current source and parallel resistance using source transformation theorem
- Parallel resistances may now be converted into a single equivalent resistance

Millman's Theorem

- First, convert voltage sources into current sources
- Equivalent current, I_{eq}, is just the algebraic sum of all the parallel currents

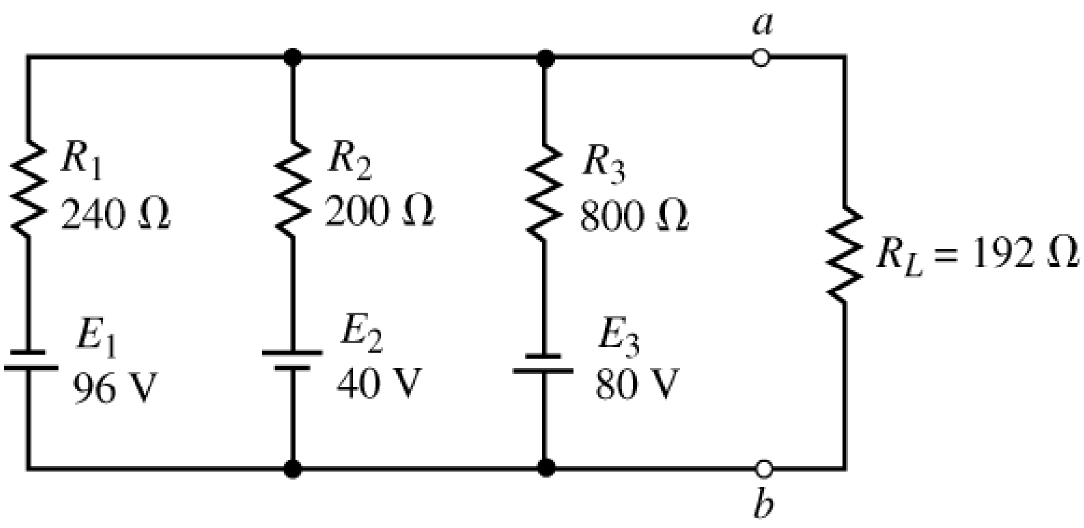
Millman's Theorem

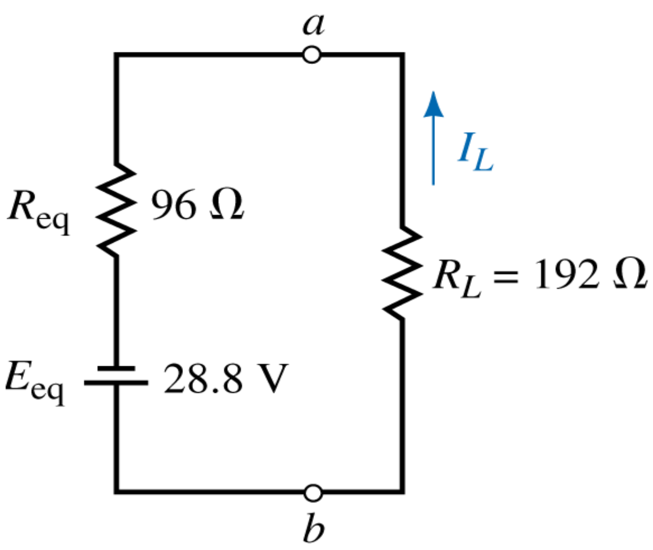
- Next, determine equivalent resistance, R_{eq}, the parallel resistance of all the resistors
- Voltage across entire circuit may now be calculated by:

$$E_{eq} = I_{eq}R_{eq}$$

Millman's Theorem

- We can simplify a circuit as shown:





Reciprocity Theorem

- A voltage source causing a current *I* in any branch
  - May be removed from original location and placed into that branch

Reciprocity Theorem

- Voltage source in new location will produce a current in original source location
  - Equal to the original I

Reciprocity Theorem

- Voltage source is replaced by a short circuit in original location
- Direction of current must not change

Reciprocity Theorem

- A current source causing a voltage *V* at any node
  - May be removed from original location and connected to that node
- Current source in the new location
  - Will produce a voltage in original location equal to *V*

Reciprocity Theorem

- Current source is replaced by an open circuit in original location
- Voltage polarity cannot change

Unit III

AC Series-Parallel Circuits

AC Circuits

- Rules and laws developed for dc circuits apply equally well for ac circuits
- Analysis of ac circuits requires vector algebra and use of complex numbers
- Voltages and currents in phasor form
  – Expressed as RMS (or effective) values

Ohm's Law

- Voltage and current of a resistor will be in phase
- Impedance of a resistor is: $\mathbf{Z}_R = R\angle 0°$

$$I = \frac{V\angle\theta}{R\angle 0^\circ} = I\angle\theta$$

Ohm's Law

- Voltage across an inductor leads the current by 90°(ELI the ICE man)

$$\mathbf{Z}_L = X_L \angle 90^\circ$$

$$\mathbf{I} = \frac{V \angle \theta}{X_L \angle 90^\circ}$$

$$\mathbf{I} = I \angle (\theta - 90^\circ)$$

Ohm's Law

- Current through a capacitor leads the voltage by 90° (ELI the ICE man)

$$\mathbf{Z}_C = X_C \angle -90^\circ$$

$$\mathbf{I} = \frac{V \angle \theta}{X_C \angle -90^\circ}$$

$$\mathbf{I} = I \angle (\theta + 90^\circ)$$

AC Series Circuits

- Current everywhere in a series circuit is the same
- Impedance used to collectively determine how resistance, capacitance, and inductance impede current in a circuit

AC Series Circuits

- Total impedance in a circuit is found by adding all individual impedances vectorially

AC Series Circuits

- Impedance vectors will appear in either the first or the fourth quadrants because the resistance vector is always positive
- When impedance vector appears in first quadrant, the circuit is inductive

AC Series Circuits

- If impedance vector appears in fourth quadrant
  - Circuit is capacitive

Voltage Divider Rule

- Voltage divider rule works the same as with dc circuits
- From Ohm's law:

$$\mathbf{I}_x = \mathbf{I}_T$$

$$\frac{\mathbf{V}_x}{\mathbf{Z}_x} = \frac{\mathbf{V}_T}{\mathbf{Z}_T}$$

$$\mathbf{V}_x = \frac{\mathbf{Z}_x}{\mathbf{Z}_T}\mathbf{V}_T$$

Kirchhoff’s Voltage Law

- KVL is same as in dc circuits
- Phasor sum of voltage drops and rises around a closed loop is equal to zero

Kirchhoff’s Voltage Law

- Voltages
  - May be added in phasor form or in rectangular form
- If using rectangular form
  - Add real parts together
  - Then add imaginary parts together

AC Parallel Circuits

- Conductance, *G*
  - Reciprocal of the resistance
- Susceptance, *B*
  - Reciprocal of the reactance

AC Parallel Circuits

- Admittance, Y
  - Reciprocal of the impedance
- Units for all of these are siemens (S)

AC Parallel Circuits

- Impedances in parallel add together like resistors in parallel
- These impedances must be added vectorially

AC Parallel Circuits

- Whenever a capacitor and an inductor having equal reactances are placed in parallel
  - Equivalent circuit of the two components is an open circuit

Kirchhoff’s Current Law

- KCL is same as in dc circuits
- Summation of current phasors entering and leaving a node
  - Equal to zero

Kirchhoff’s Current Law

- Currents must be added vectorially
- Currents entering are positive
- Currents leaving are negative

Current Divider Rule

- In a parallel circuit
  - Voltages across all branches are equal

$$\mathbf{V}_x = \mathbf{V}_\mathrm{T}$$

$$\mathbf{I}_x \mathbf{Z}_x = \mathbf{I}_\mathrm{T} \mathbf{Z}_\mathrm{T}$$

$$\mathbf{I}_x = \frac{\mathbf{Z}_\mathrm{T}}{\mathbf{Z}_x} \mathbf{I}_\mathrm{T}$$

Series-Parallel Circuits

- Label all impedances with magnitude and the associated angle
- Analysis is simplified by starting with easily recognized combinations

Series-Parallel Circuits

- Redraw circuit if necessary for further simplification
- Fundamental rules and laws of circuit analysis must apply in all cases

Frequency Effects of *RC* Circuits

- Impedance of a capacitor decreases as the frequency increases
- For dc (f = 0 Hz)
  - Impedance of the capacitor is infinite

Frequency Effects of *RC* Circuits

- For a series *RC* circuit
  - Total impedance approaches *R* as the frequency increases
- For a parallel *RC* circuit
  - As frequency increases, impedance goes from *R* to a smaller value

Frequency Effects of *RL* Circuits

- Impedance of an inductor increases as frequency increases
- At dc (f = 0 Hz)
  - Inductor looks like a short
  - At high frequencies, it looks like an open

Frequency Effects of *RL* Circuits

- In a series *RL* circuit
  - Impedance increases from *R* to a larger value
- In a parallel *RL* circuit
  - Impedance increases from a small value to *R*

Corner Frequency

- Corner frequency is a break point on the frequency response graph
- For a capacitive circuit
  - $\omega_C = 1/RC = 1/\tau$
- For an inductive circuit
  - $\omega_C = R/L = 1/\tau$

RLC Circuits

- In a circuit with *R*, *L*, and *C* components combined in series-parallel combinations
  - Impedance may rise or fall across a range of frequencies
- In a series branch
  - Impedance of inductor may equal the capacitor

RLC Circuits

- Impedances would cancel
  - Leaving impedance of resistor as the only impedance
- Condition is referred to as resonance

Applications

- AC circuits may be simplified as a series circuit having resistance and a reactance
- AC circuit
  - May be represented as an equivalent parallel circuit with a single resistor and a single reactance

Applications

- Any equivalent circuit will be valid only at the given frequency of operation

UNIT IV

SEMICONDUCTOR DIODE AND APPLICATIONS

Overview

- Introduction
- What are P-type and N-type semiconductors??
- What are Diodes?
- Forward Bias & Reverse Bias
- Characteristics Of Ideal Diode
- Shockley Equation
- I – V Characteristics of Diodes

Introduction

Semiconductors are materials whose electrical properties lie between Conductors and Insulators.

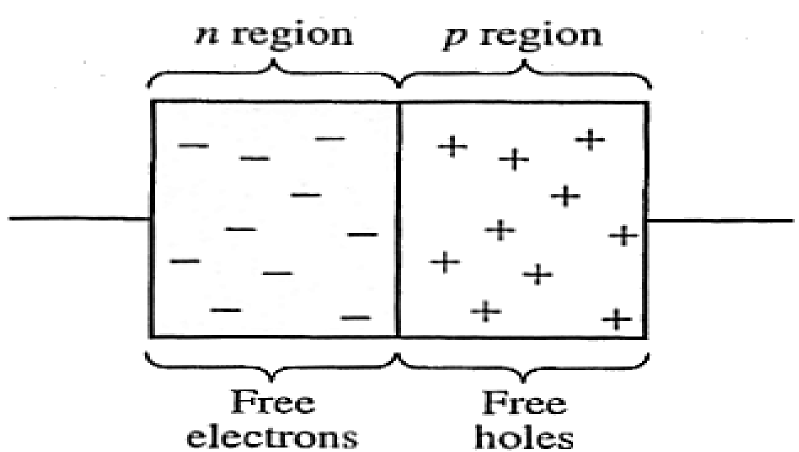
Ex : Silicon and Germanium

What are P-type and N-type ?

- Semiconductors are classified in to P-type and N-type semiconductor
- P-type: A P-type material is one in which holes are majority carriers i.e. they are positively charged materials (++++)
- N-type: A N-type material is one in which electrons are majority charge carriers i.e. they are negatively charged materials (-----)

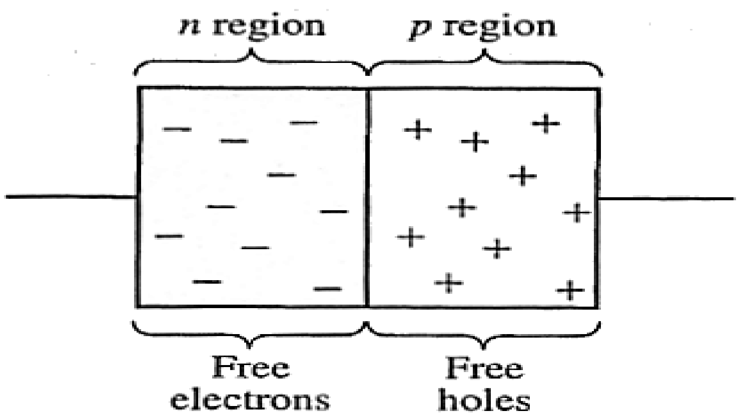
Diodes

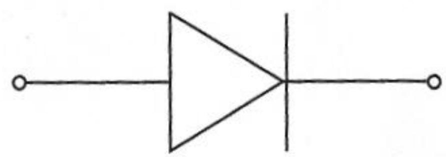
Electronic devices created by bringing together a *p*-type and *n*-type region within the same semiconductor lattice. Used for rectifiers, LED etc



Diodes

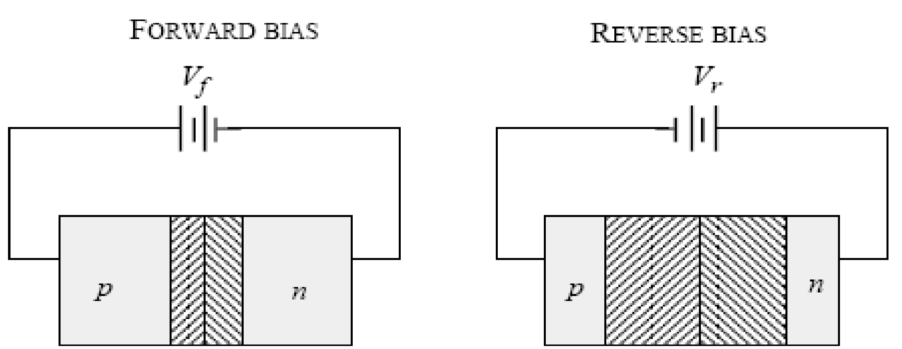
It is represented by the following symbol, where the arrow indicates the direction of positive current flow.





Forward Bias and Reverse Bias

- Forward Bias : Connect positive of the Diode to positive of supply…negative of Diode to negative of supply
- Reverse Bias: Connect positive of the Diode to negative of supply…negative of diode to positive of supply.

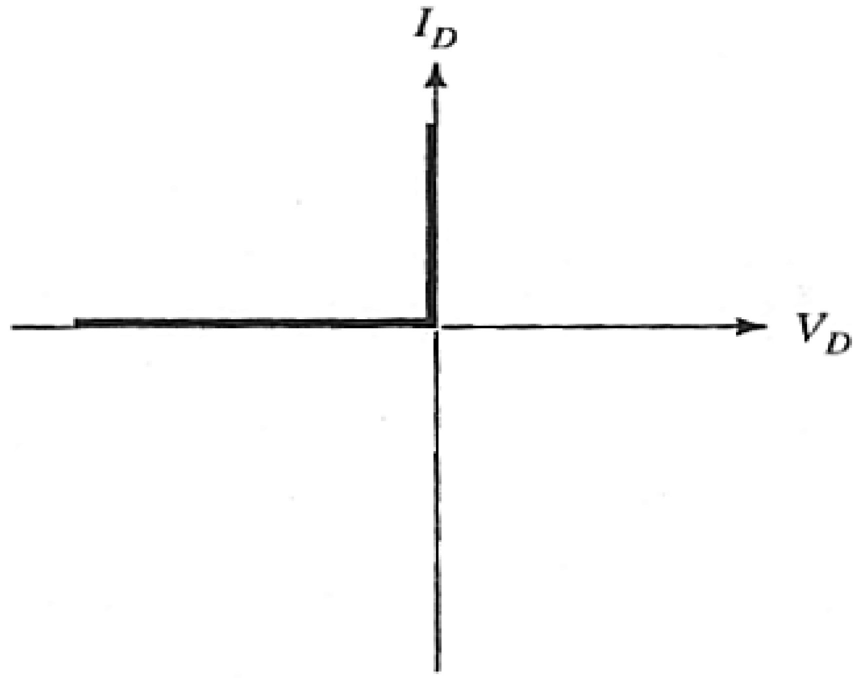


Characteristics of Diode

- Diode always conducts in one direction.
- Diodes always conduct current when “Forward Biased” (Zero resistance)
- Diodes do not conduct when Reverse Biased

  (Infinite resistance)

I-V characteristics of Ideal diode



I-V Characteristics of Practical Diode

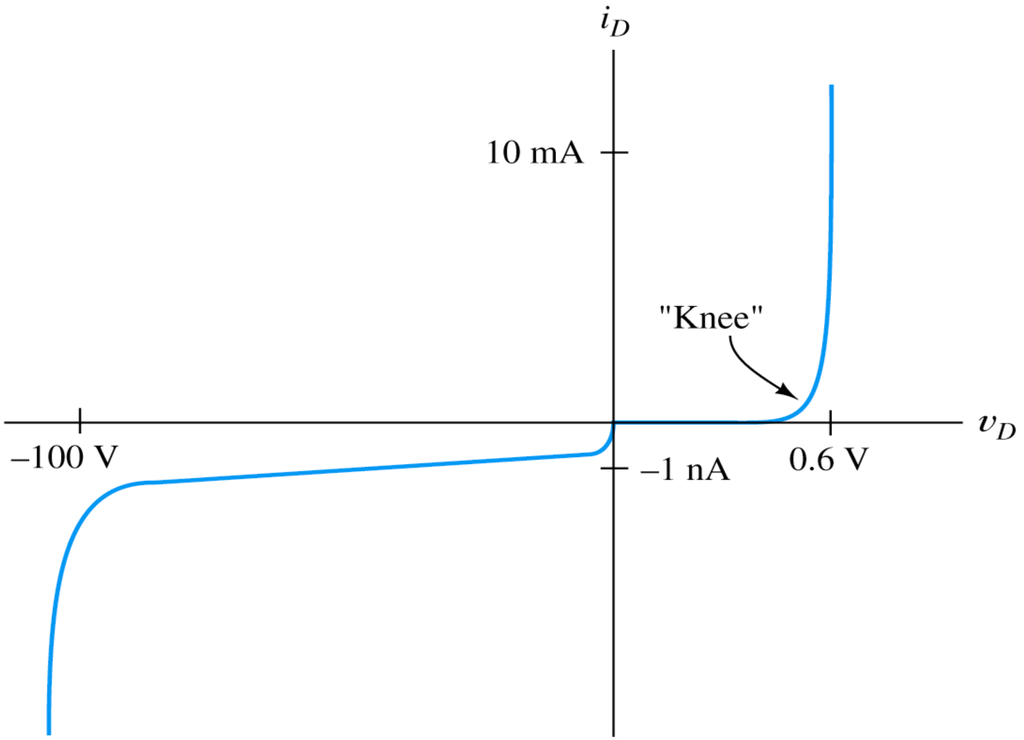


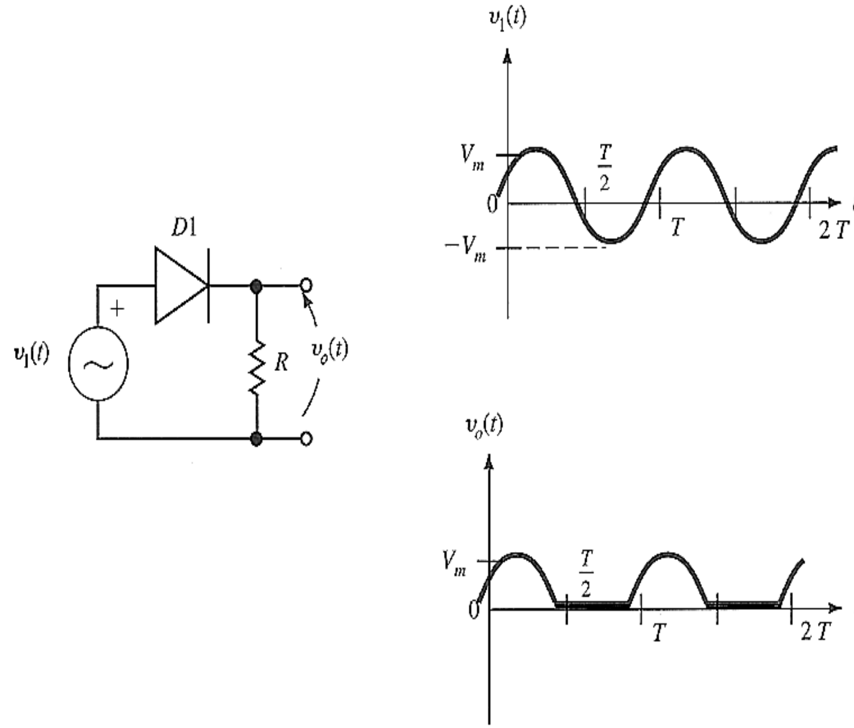
Figure 10.2 Volt–ampere characteristic for a typical small-signal silicon diode at a temperature of 300 K. Notice the change of scale for negative current and voltage.

Rectification

- Converting ac to dc is accomplished by the process of rectification.
- Two processes are used:
  - Half-wave rectification;
  - Full-wave rectification.

Half-wave Rectification

- Simplest process used to convert ac to dc.
- A diode is used to clip the input signal excursions of one polarity to zero.



Shockley Equation

$$i_D = I_s \left[\exp\left(\frac{v_D}{nV_T} \right) - 1 \right] \qquad V_T = \frac{kT}{q}$$

$$V_T \cong 26 \text{ mV}$$

I_s is the saturation current ~10 $^{-14}$
V_d is the diode voltage
n – emission coefficient (varies from 1 - 2)
$k = 1.38 \times 10^{-23}$ J/K is Boltzmann's constant
$q = 1.60 \times 10^{-19}$ C is the electrical charge of an electron.
At a temperature of 300 K, we have

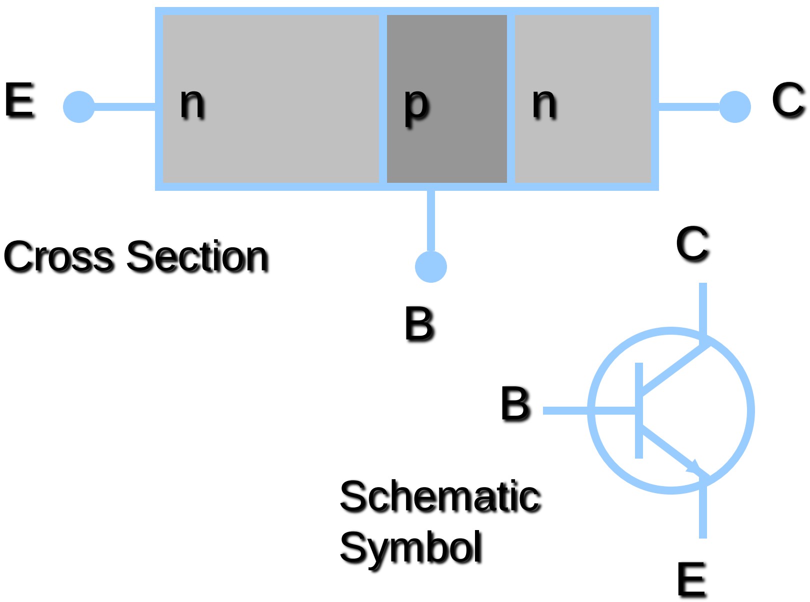
UNIT V

BIPOLAR JUNCTION TRANSISTOR AND APPLICATIONS

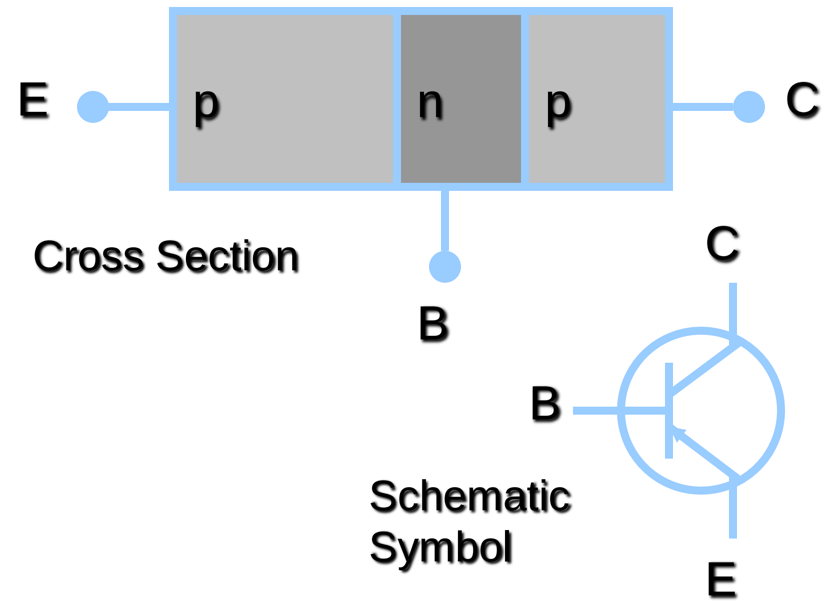
The BJT – Bipolar Junction Transistor

The Two Types of BJT Transistors:

npn

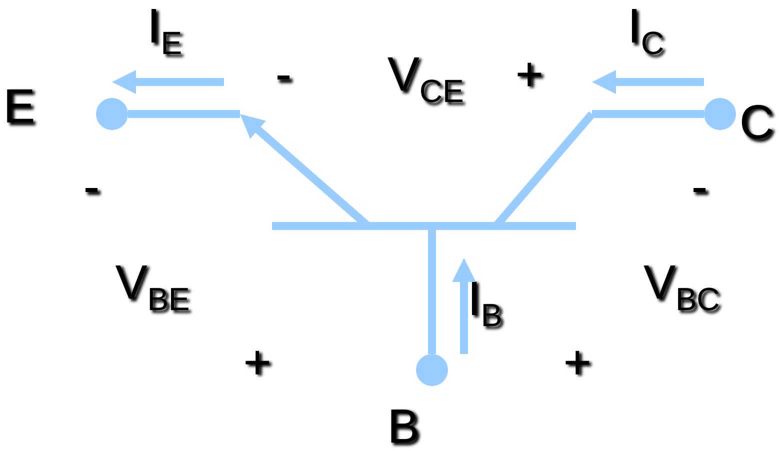


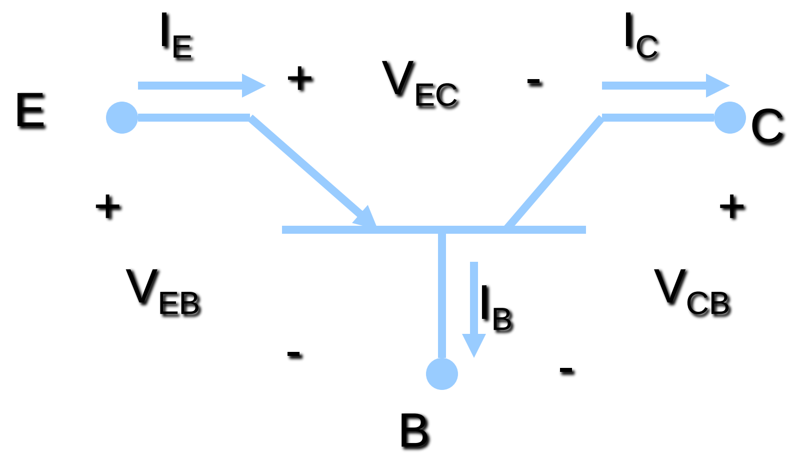
pnp



- Collector doping is usually ~ 10^6
- Base doping is slightly higher ~ $10^7 - 10^8$
- Emitter doping is much higher ~ 10^{15}

BJT Relationships - Equations





npn

$$I_E = I_B + I_C$$

$$V_{CE} = -V_{BC} + V_{BE}$$

pnp

$$I_E = I_B + I_C$$

$$V_{EC} = V_{EB} - V_{CB}$$

Note: The equations seen above are for the transistor, not the circuit.

DC β and DC α

β = Common-emitter current gain

α = Common-base current gain

$$\beta = \frac{I_C}{I_B} \qquad \alpha = \frac{I_C}{I_E}$$

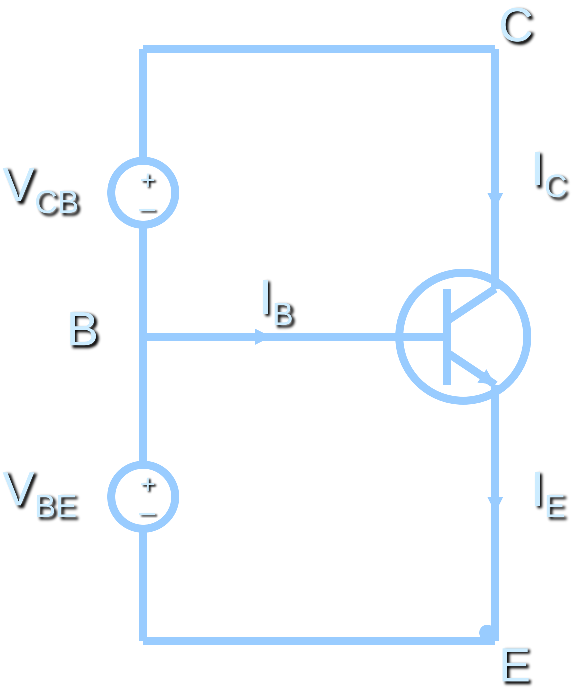
The relationships between the two parameters are:

$$\alpha = \frac{\beta}{\beta + 1} \qquad \beta = \frac{\alpha}{1 - \alpha}$$

Note: α and β are sometimes referred to as α_{dc} and β_{dc} because the relationships being dealt with in the BJT are DC.

BJT Example

Using Common-Base NPN Circuit Configuration



Given: $I_B = 50\ \mu A$, $I_C = 1$ mA
Find: I_E , β , and α

Solution:

$I_E = I_B + I_C = 0.05$ mA + 1 mA = 1.05 mA

$\beta = I_C / I_B = 1$ mA / 0.05 mA = 20

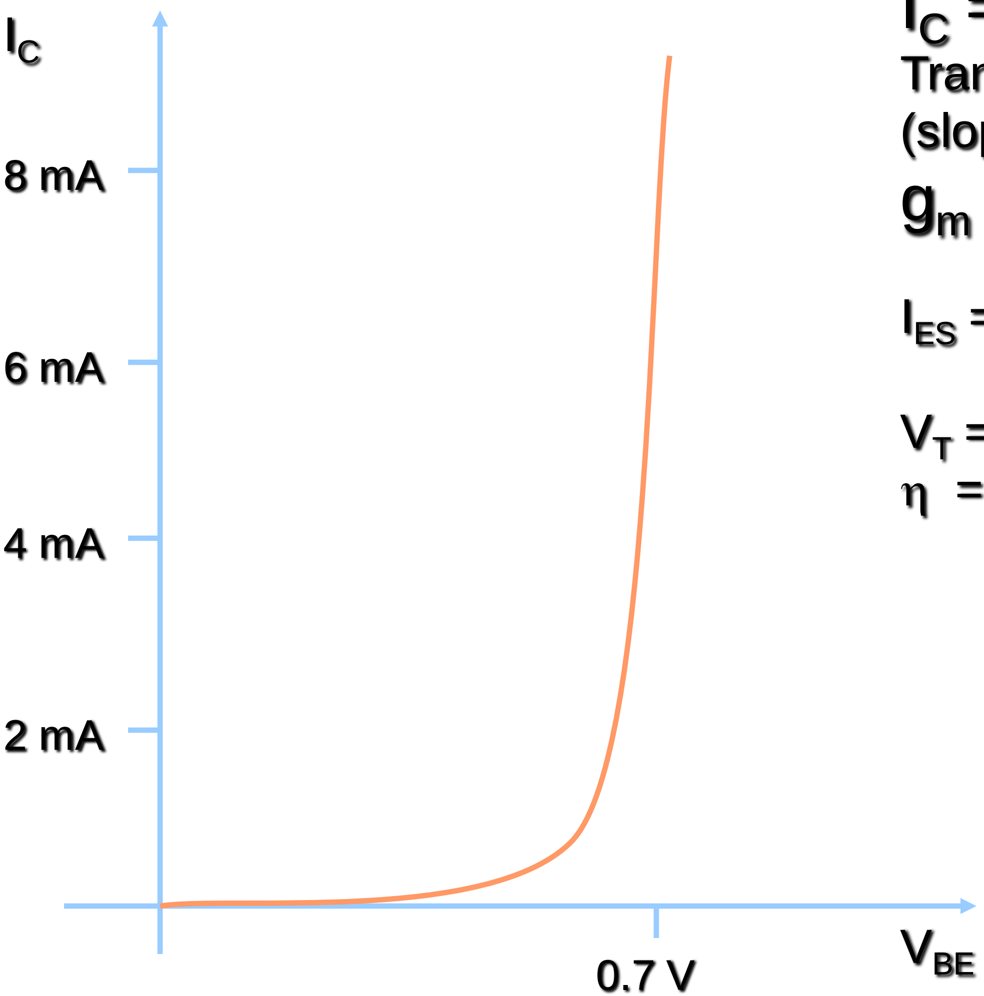
$\alpha = I_C / I_E = 1$ mA / 1.05 mA = 0.95238

α could also be calculated using the value of β with the formula from the previous slide.

$$\alpha = \frac{\beta}{\beta + 1} = \frac{20}{21} = 0.95238$$

BJT Transconductance Curve

Typical NPN Transistor [1]



Collector Current:

$$I_C = \alpha\, I_{ES}\, e^{V_{BE}/\eta V_T}$$

Transconductance:
(slope of the curve)

$$g_m = \Delta I_C \,/\, \Delta V_{BE}$$

I_{ES} = The reverse saturation current of the B-E Junction.

V_T = kT/q = 26 mV (@ T=300K)

η = the emission coefficient and is usually ~1

Modes of Operation

Active:

- Most important mode of operation
- Central to amplifier operation
- The region where current curves are practically flat

Saturation:

- Barrier potential of the junctions cancel each other out causing a virtual short

Cutoff:

- Current reduced to zero
- Ideal transistor behaves like an open switch

* Note: There is also a mode of operation called inverse active, but it is rarely used.

Three Types of BJT Biasing

Biasing the transistor refers to applying voltage to get the transistor to achieve certain operating conditions.

Common-Base Biasing (CB) : input = V_{EB} & I_E
output = V_{CB} & I_C

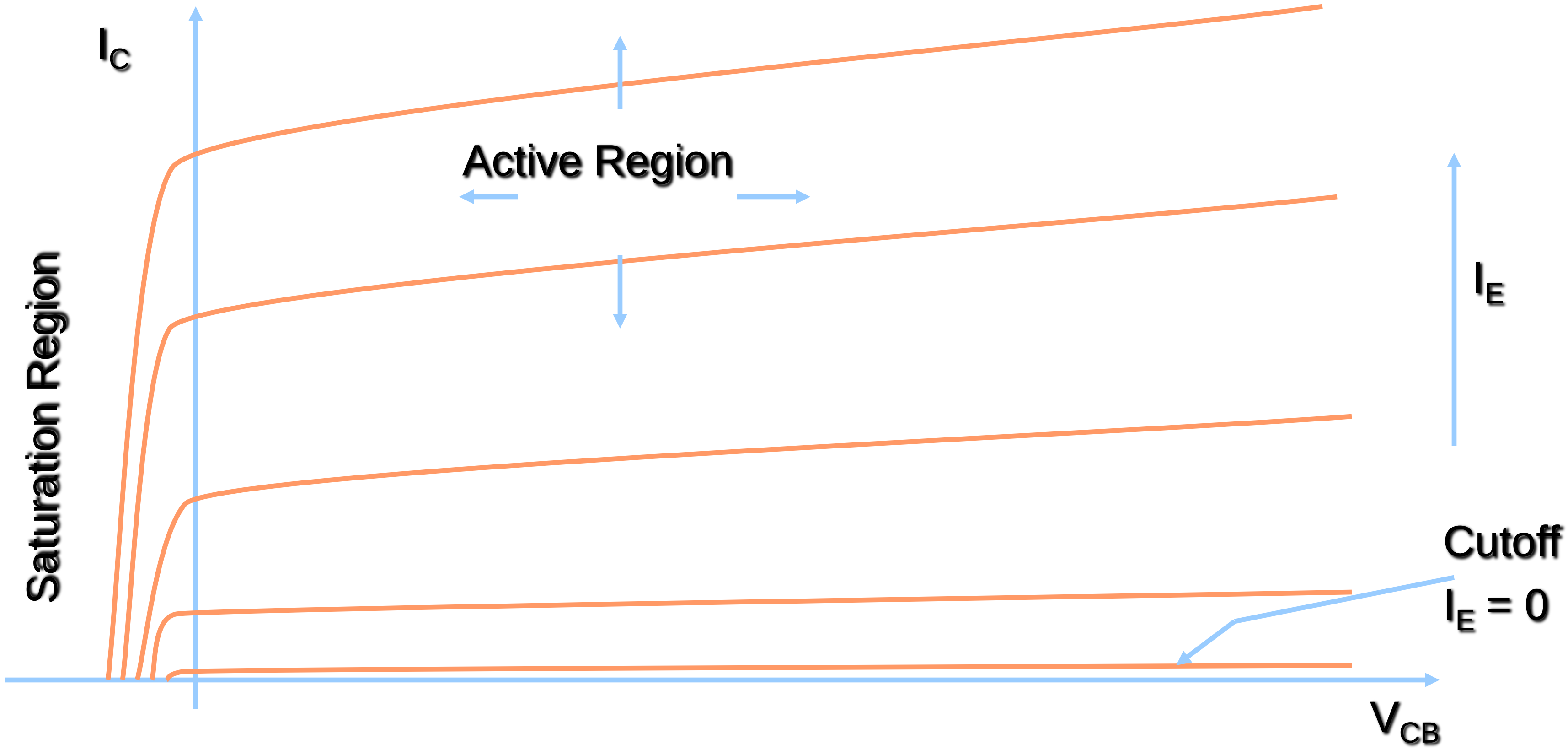
Common-Emitter Biasing (CE): input = V_{BE} & I_B
output = V_{CE} & I_C

Common-Collector Biasing (CC): input = V_{BC} & I_B
output = V_{EC} & I_E

Common-Base

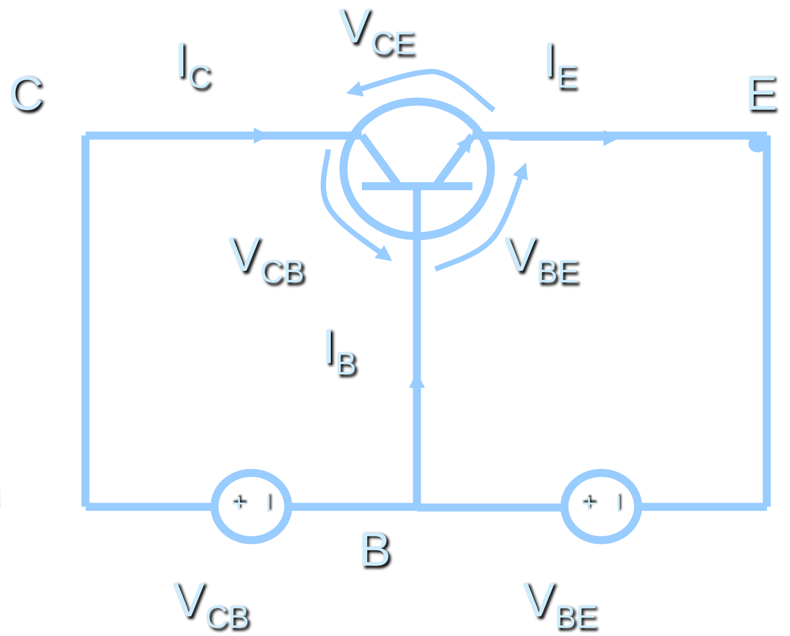
Although the Common-Base configuration is not the most common biasing type, it is often helpful in the understanding of how the BJT works.

Emitter-Current Curves



Common-Base

Circuit Diagram: NPN Transistor

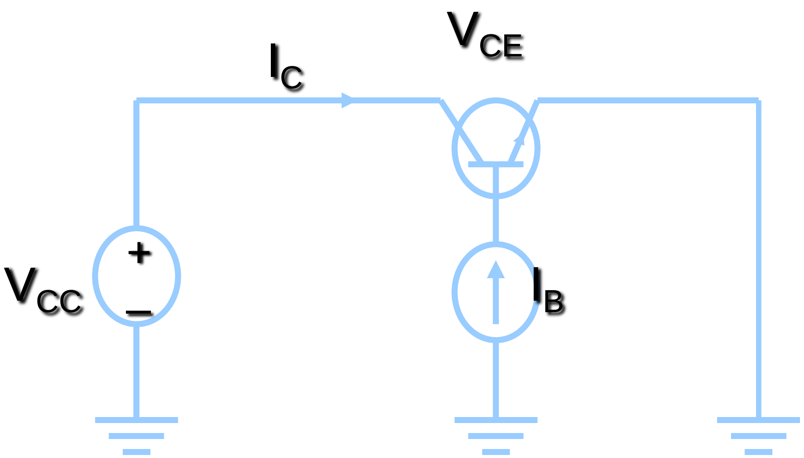


The Table Below lists assumptions that can be made for the attributes of the common-base biased circuit in the different regions of operation. Given for a Silicon NPN transistor.

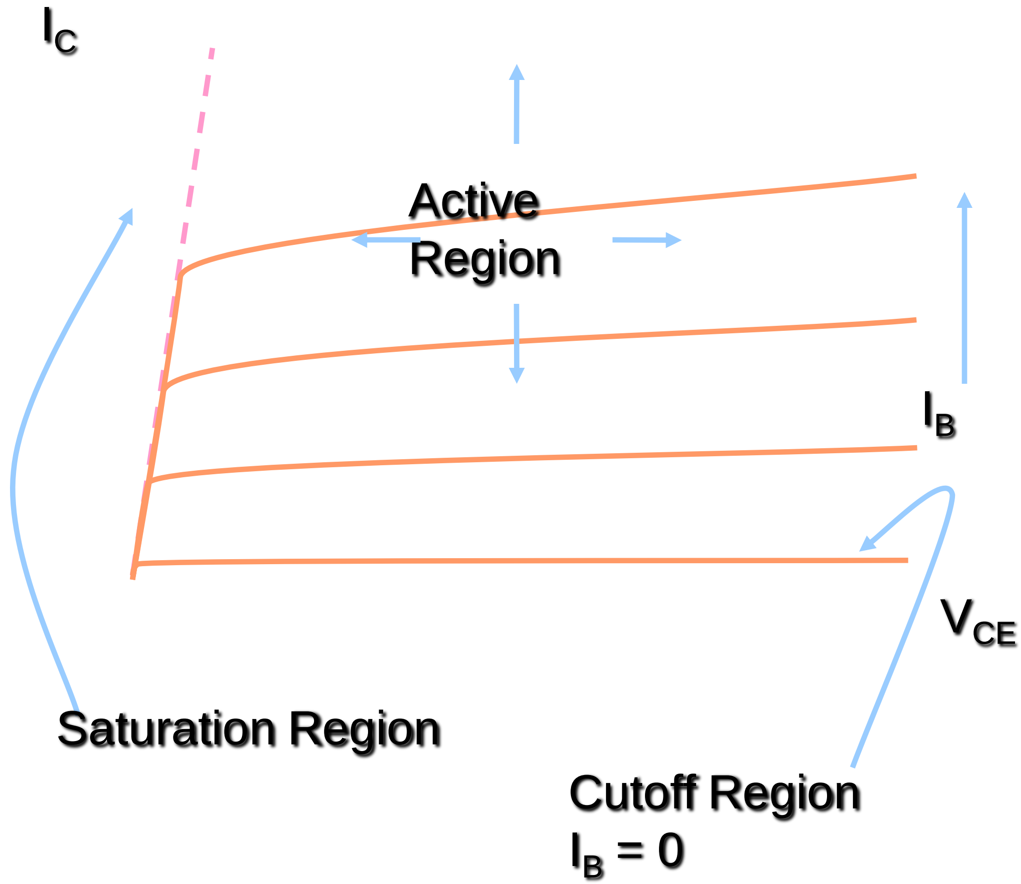
Region of Operation	I_C	V_{CE}	V_{BE}	V_{CB}	C-B Bias	E-B Bias
Active	βI_B	$=V_{BE}+V_{CE}$	~0.7V	❍ 0V	Rev.	Fwd.
Saturation	Max	~0V	~0.7V	$-0.7V<V_{CE}<0$	Fwd.	Fwd.
Cutoff	~0	$=V_{BE}+V_{CE}$	☯ 0V	❍ 0V	Rev.	None /Rev.

Common-Emitter

Circuit Diagram



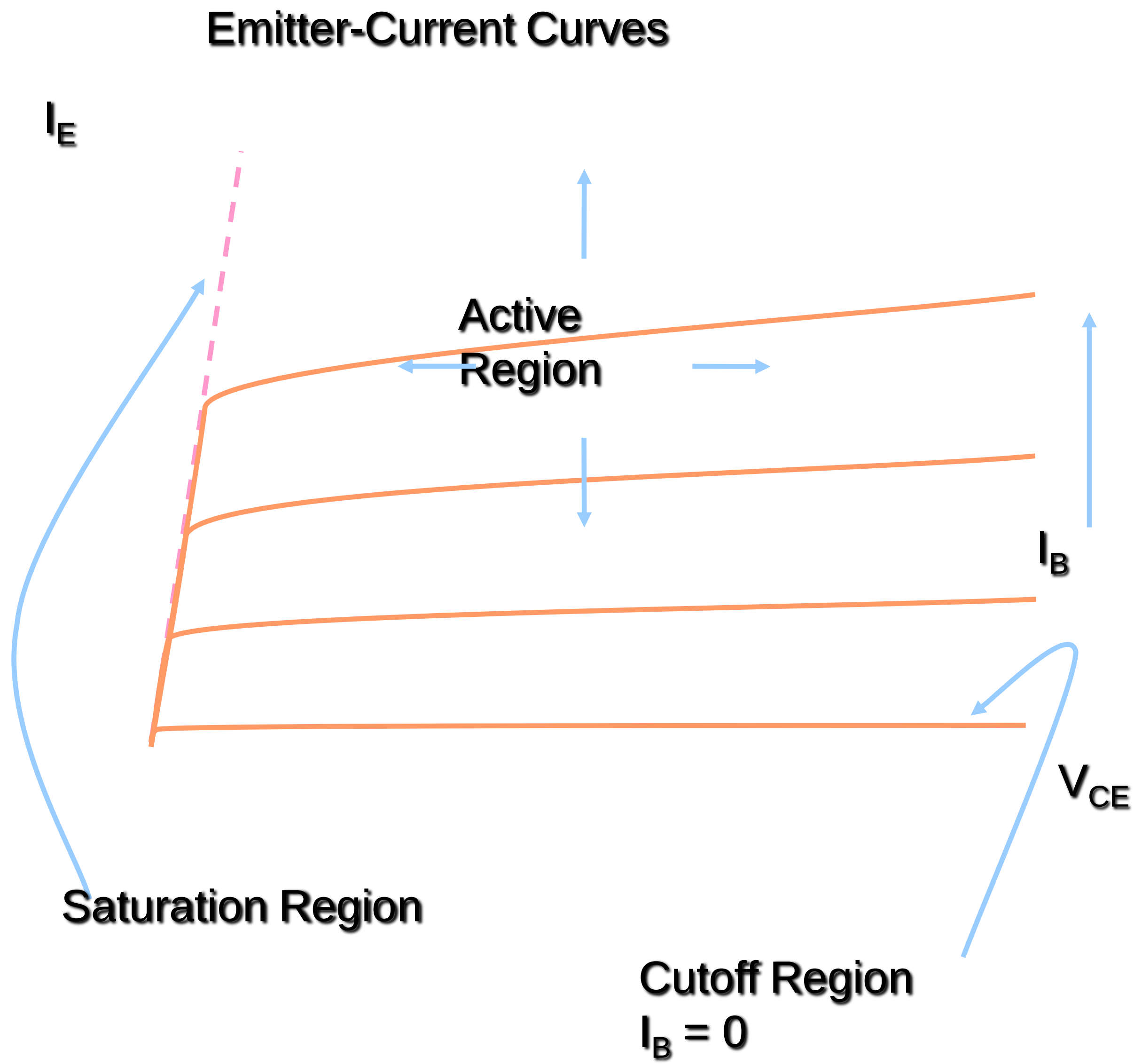
Collector-Current Curves



Region of Operation	Description
Active	Small base current controls a large collector current
Saturation	$V_{CE(sat)}$ ~ 0.2V, V_{CE} increases with I_C
Cutoff	Achieved by reducing I_B to 0, Ideally, I_C will also equal 0.

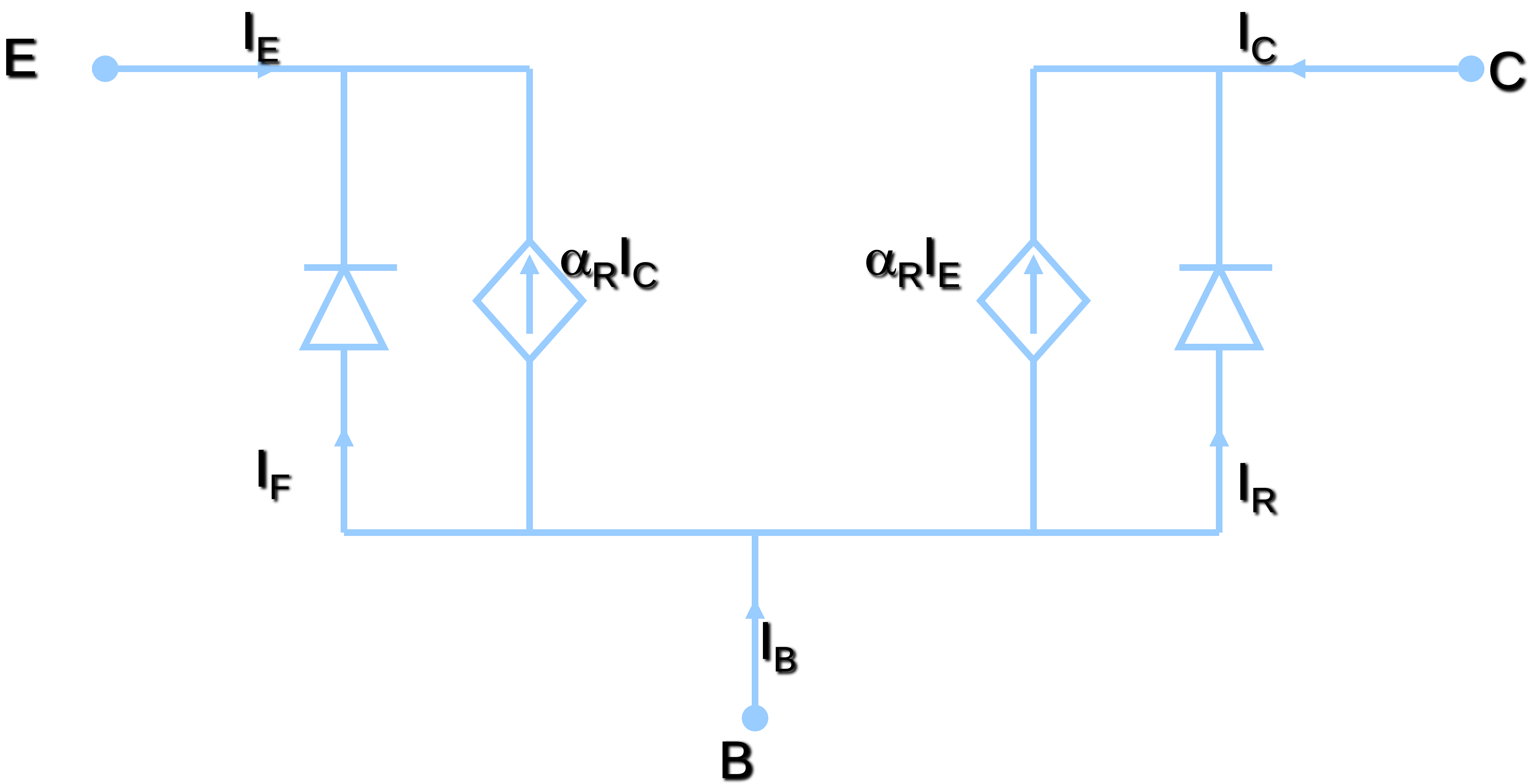
Common-Collector

The Common-Collector biasing circuit is basically equivalent to the common-emitter biased circuit except instead of looking at I_C as a function of V_{CE} and I_B we are looking at I_E. Also, since $\alpha \sim 1$, and $\alpha = I_C/I_E$ that means $I_C \sim I_E$



Eber-Moll BJT Model

The Eber-Moll Model for BJTs is fairly complex, but it is valid in all regions of BJT operation. The circuit diagram below shows all the components of the Eber-Moll Model:



Eber-Moll BJT Model

α_R = Common-base current gain (in forward active mode)
α_F = Common-base current gain (in inverse active mode)
I_{ES} = Reverse-Saturation Current of B-E Junction
I_{CS} = Reverse-Saturation Current of B-C Junction

$I_C = \alpha_F I_F - I_R$ $\qquad$ $I_B = I_E - I_C$

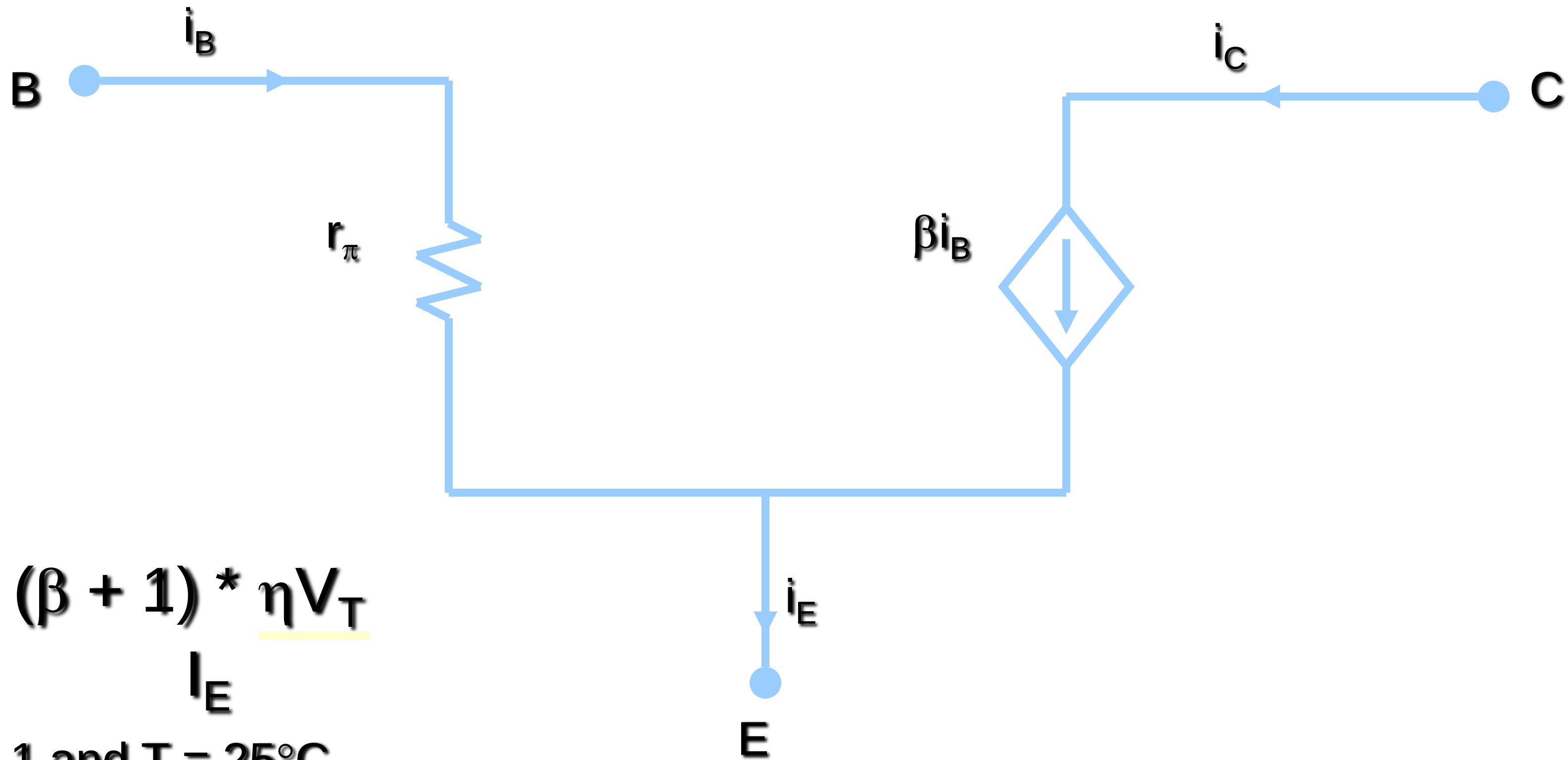
$I_E = I_F - \alpha_R I_R$

$I_F = I_{ES}\,[\exp(qV_{BE}/kT) - 1]$ $\qquad$ $I_R = I_C\,[\exp(qV_{BC}/kT) - 1]$

- If I_{ES} & I_{CS} are not given, they can be determined using various BJT parameters.

Small Signal BJT Equivalent Circuit

The small-signal model can be used when the BJT is in the active region. The small-signal active-region model for a CB circuit is shown below:



$$r_\pi = (\beta + 1) * \frac{\eta V_T}{I_E}$$

@ $\eta = 1$ and T = 25°C

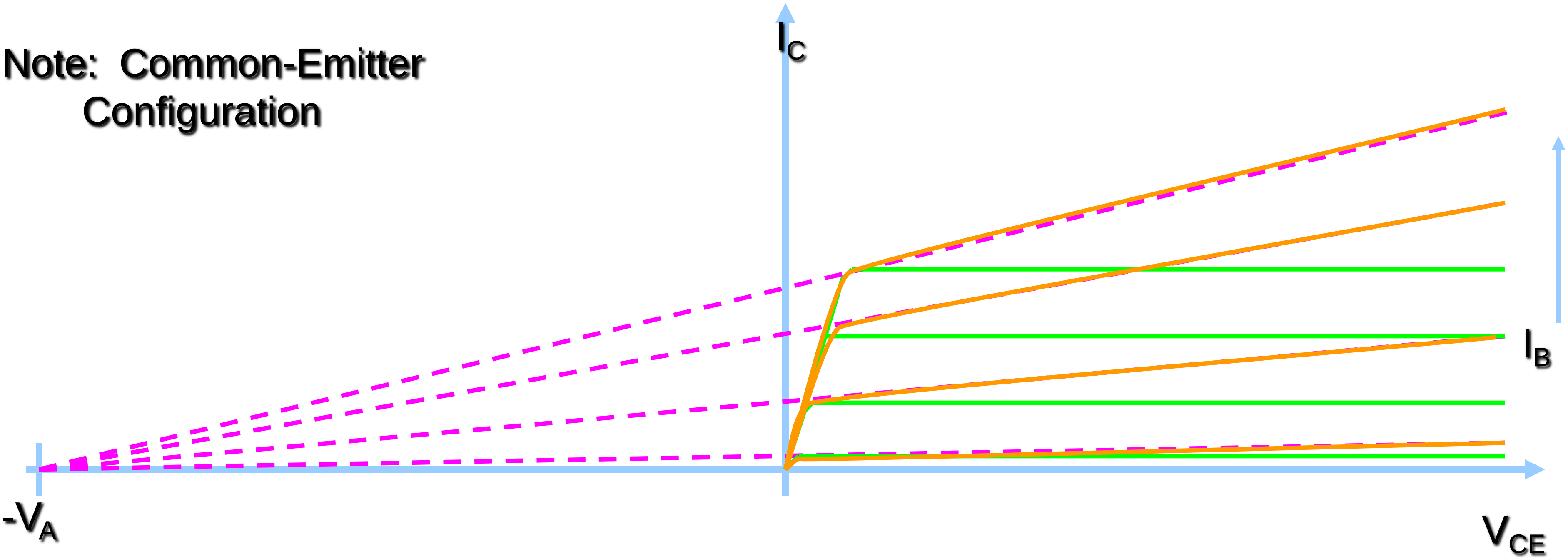
$$r_\pi = (\beta + 1) * \frac{0.026}{I_E}$$

Recall:

$\beta = I_C / I_B$

The Early Effect (Early Voltage)

Note: Common-Emitter Configuration



Green = Ideal I_C
Orange = Actual I_C (I_C')

$$I_C' = I_C \left(\frac{V_{CE}}{V_A} + 1 \right)$$

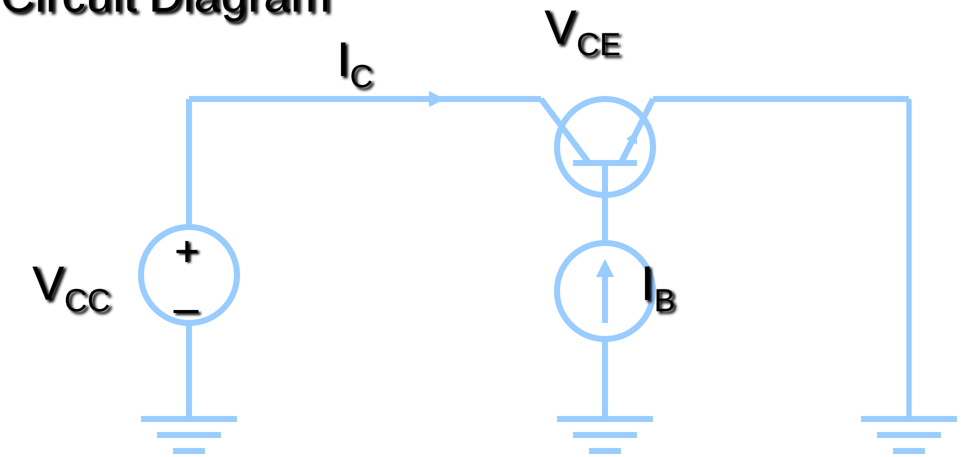
Early Effect Example

Given: The common-emitter circuit below with $I_B = 25\mu A$, $V_{CC} = 15V$, $\beta = 100$ and $V_A = 80$.

Find: a) The ideal collector current

b) The actual collector current

Circuit Diagram



$\beta = 100 = I_C/I_B$

a)

$I_C = 100 * I_B = 100 * (25x10^{-6}\ A)$

$I_C = 2.5\ mA$

b) $$I_C' = I_C\left(\frac{V_{CE}}{V_A} + 1\right) = 2.5x10^{-3}\left(\frac{15}{80} + 1\right) = 2.96\ mA$$

$I_C' = 2.96\ mA$