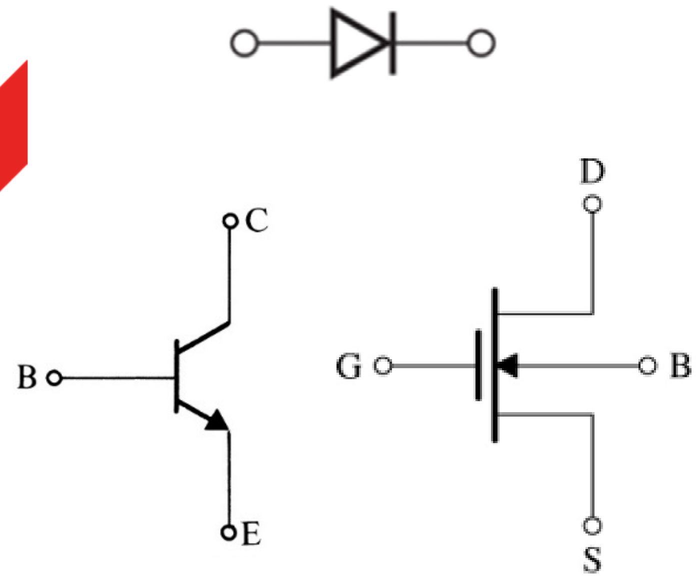
MACQUARIE University

ELEC2005 Electrical and Electronic Systems

DIODES

DAVID PAYNE



Goals of this lecture

- Understand what nonlinearity means
- Understand how we can use nonlinearity
- Be familiar with Diodes and their non-linear characteristics
- Analyse basic diode circuits
- Be able to use models for analysing diode circuits
- Understand diode applications: rectifiers and wave-shaping circuits
- Small signal analysis

Intro to Nonlinear Devices

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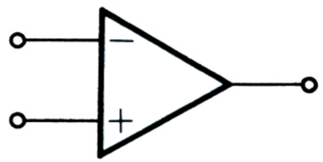
WHAT IS A NONLINEAR DEVICE/CIRCUIT?

- Many systems/subsystems involve complex nonlinear circuits with multiple nonlinear devices

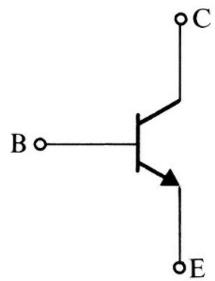
- Four of the most common nonlinear devices are shown here, diodes and transistors and the circuits constructed with them are the focus of part 1 of this unit

- For each of these, the relationship between their output and input characteristics is not linear

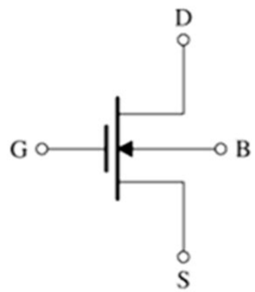


Opamp

Diode



Bipolar Junction Transitor

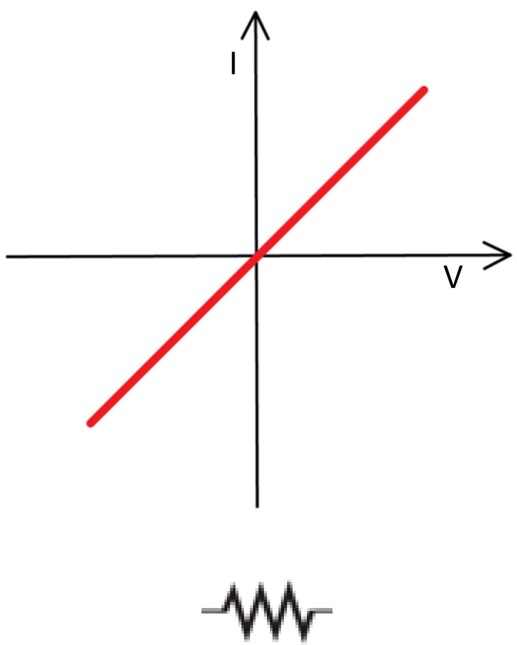


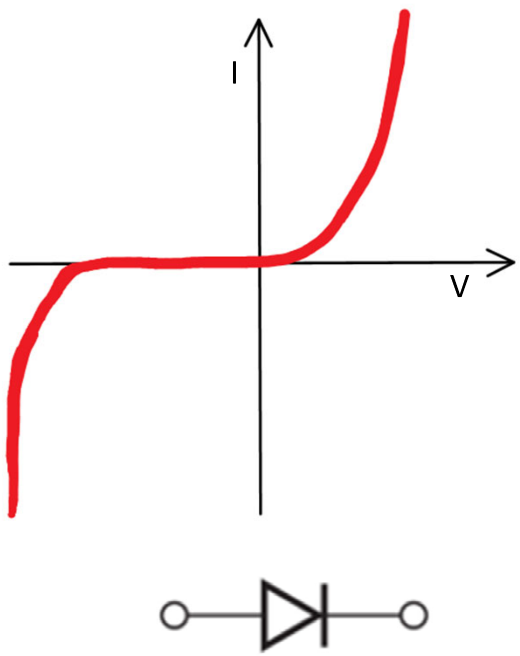
Field Effect Transitor

Intro to Nonlinear Devices

WHAT IS A NONLINEAR DEVICE/CIRCUIT?

- Devices such as *ideal* resistors, capacitors and inductors have a output characteristics that are a linear function of input.
- Diodes and transistors have a more complex relationship between input and output
  - Though they have regions of linearity



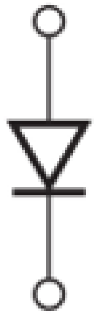


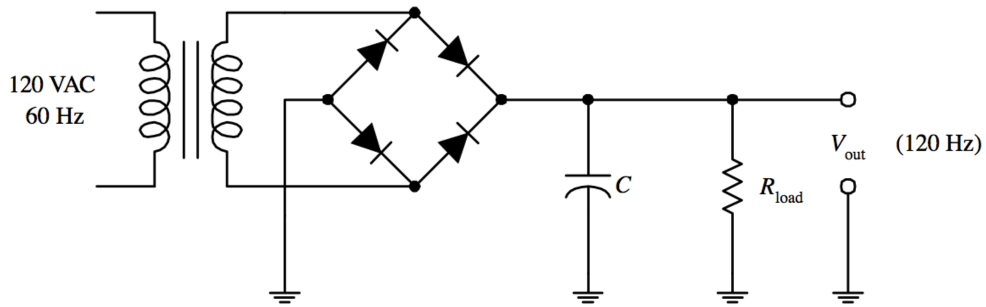
Lecture 2

1. **Diode Fundamentals & Models**
2. Diode Circuits & Applications
3. Small Signal Analysis

Diodes: What is a diode?

- An two terminal device with non-linear IV characteristics
- Exhibits asymmetric conductance - primarily conducts current in one direction
- Fabricated using a semiconductor with a p-n junction (more on this later)
- They have many applications, including:
  - ❖ Power conversion
  - ❖ Over-voltage protection
  - ❖ Detectors
  - ❖ Signal Generation

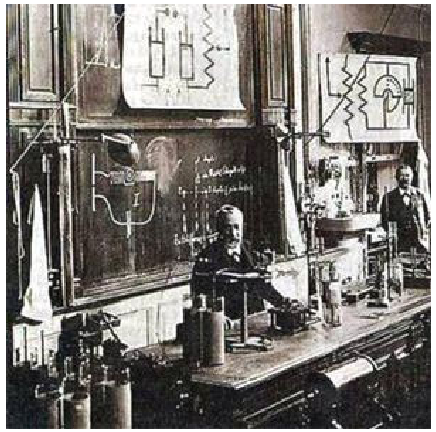




A little bit of history….

- Originally known as rectifiers and were developed as radio receiver detectors in the early 1900s (vacuum-tubes and semiconductors versions simultaneously developed)
- The Thermionic diode (Vacuum tube) effect was first discovered as far back as 1873, by Frederick Guthrie
- The effect was first discovered in a semiconductor in 1874 by Ferdinand Braun
- The term diode was first coined in 1919, from it's Greek roots, it means two (di) paths (ode)

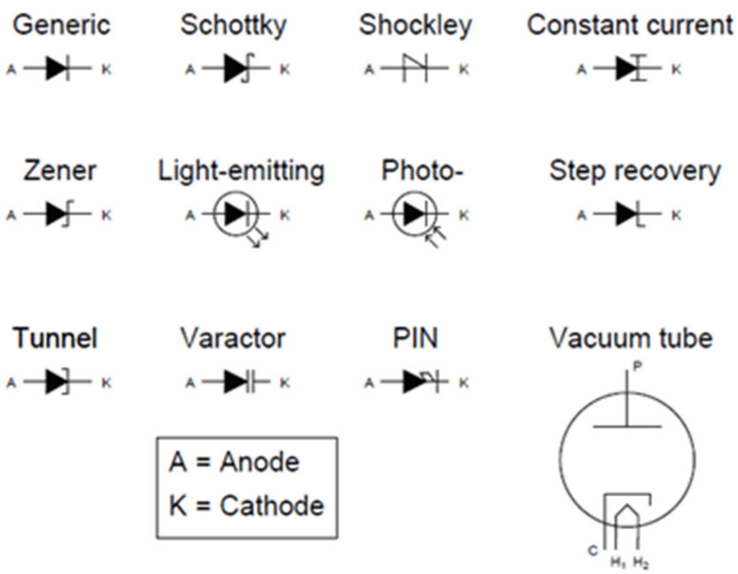
Frederick Guthrie



Ferdinand Braun

Types of diode

- Nowadays, a huge variety of diode technology has been developed, they are widely used!

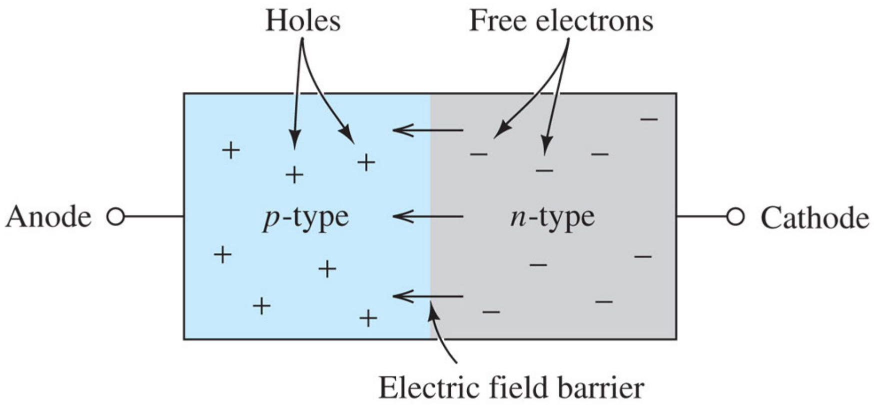


Various symbols of Diode

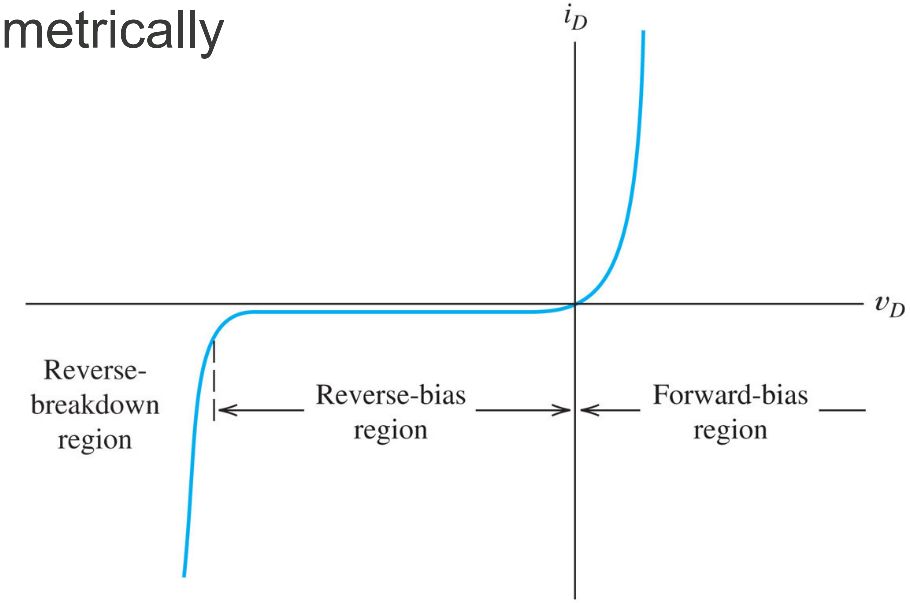
Not all are based on p-n junctions!

The PN Junction

- Modern diodes are typically based on p-n junctions fabricated using semiconductors (commonly silicon)
- These junctions conduct current asymmetrically

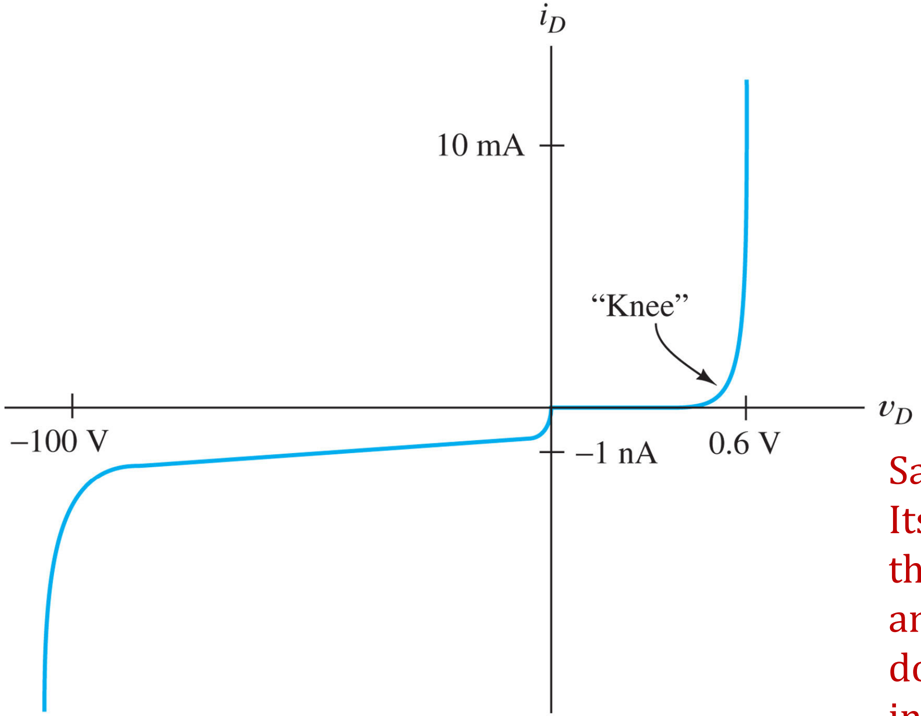


(c) Simplified physical structure



(b) Volt–ampere characteristic

Junction Diode Characteristics



Approximate Shockley Equation
(for forward bias more than several tenths of a volt)

$$i_D \cong I_s \exp\left(\frac{v_D}{nV_T}\right)$$

Much easier to use

Shockley Equation
(for forward bias)

$$i_D = I_s\left(e^{v_D/nV_T} - 1\right)$$

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

Saturation current.
Its value depends on the area of the diode and the temperature, doubling for each 5° increase for silicon diodes.
~10^{-14}A at 300 K

Emission coefficient (ideality factor)
$\mathbf{1 < n < 2}$
$\mathbf{n \cong 1}$

Thermal voltage.
$\mathbf{V_T = kT/q \cong}$
25 mV at 300 K

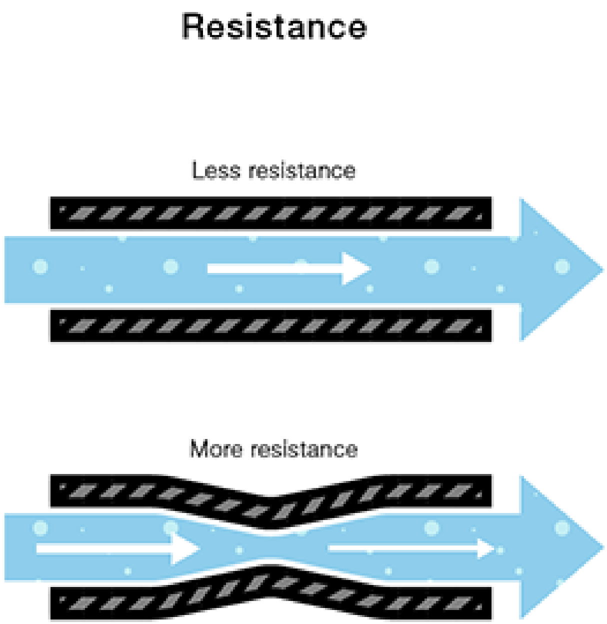
Temperature in K
(273 + temp in °C)

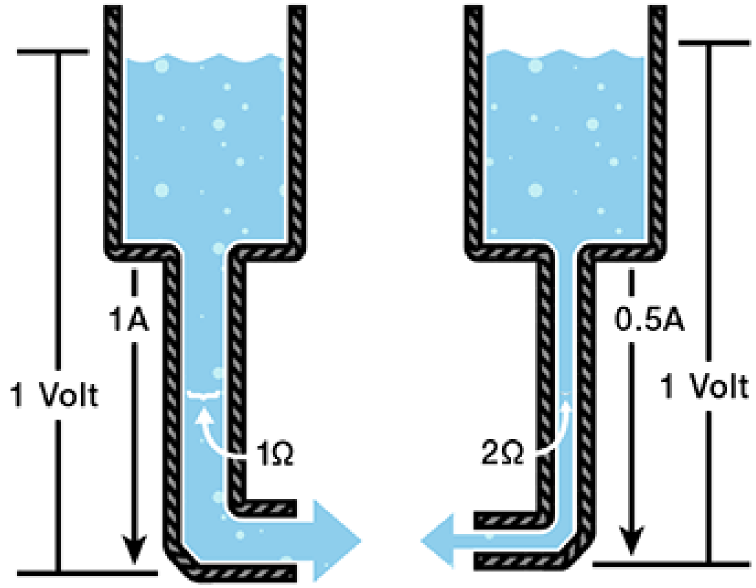
$k = 1.38 \times 10^{-23}$ joules/kelvin Boltzmann's constant

$q = 1.60 \times 10^{-19}$ coulomb magnitude of charge of an electron

The Pipe Analogy

- In the pipe analogy (AKA hydraulic analogy):
- Electric potential is equivalent to pressure. i.e. voltage is equivalent to the difference in pressure between two points
- Current is equivalent to flow rate, and charge is equivalent to quantity of water





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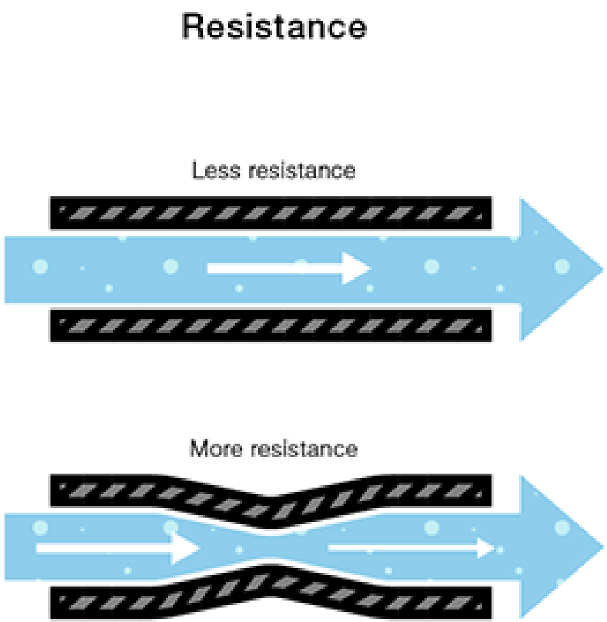

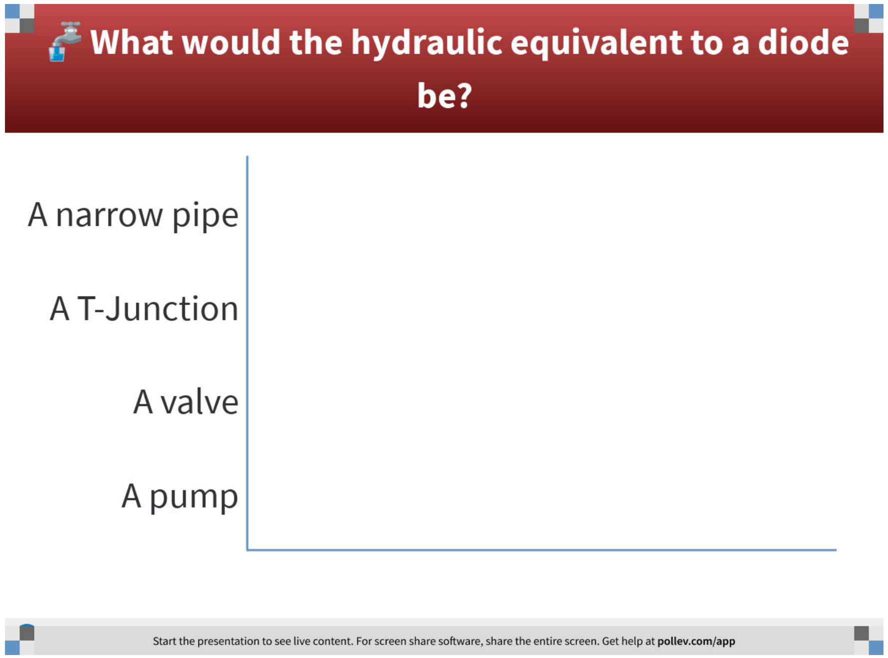

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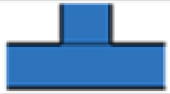
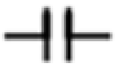
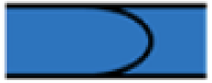
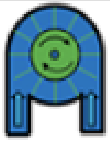
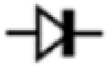
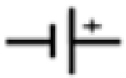
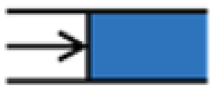
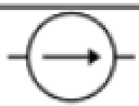
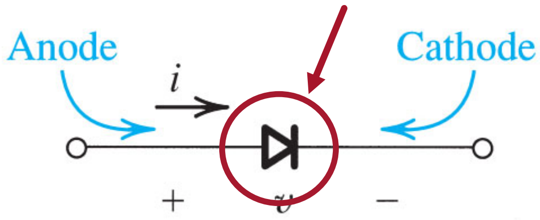
The Pipe Analogy

Element	Circuit Analogy		Pipe Analogy		Flow Equation
Node	Junction		Junction		Total Flow = 0
Path	Wire		Rigid Pipe		Solve Directly
Resistance	Resistor		Aperture		$F = P/R$
Compliance	Capacitor		Diaphram		$F(t) = C\frac{dP(t)}{dt}$
Inertance	Inductor		Heavy Paddle		$F = \frac{1}{L}\int_{t_0}^{t} P\,dt + F(t_0)$
Switch	Switch		Gate Valve		Solve Directly
Valve	Diode		Check Valve		Solve Directly
Pressure Source	Voltage Source		Pump		Solve Directly
Flow Source	Current Source				$F = F$

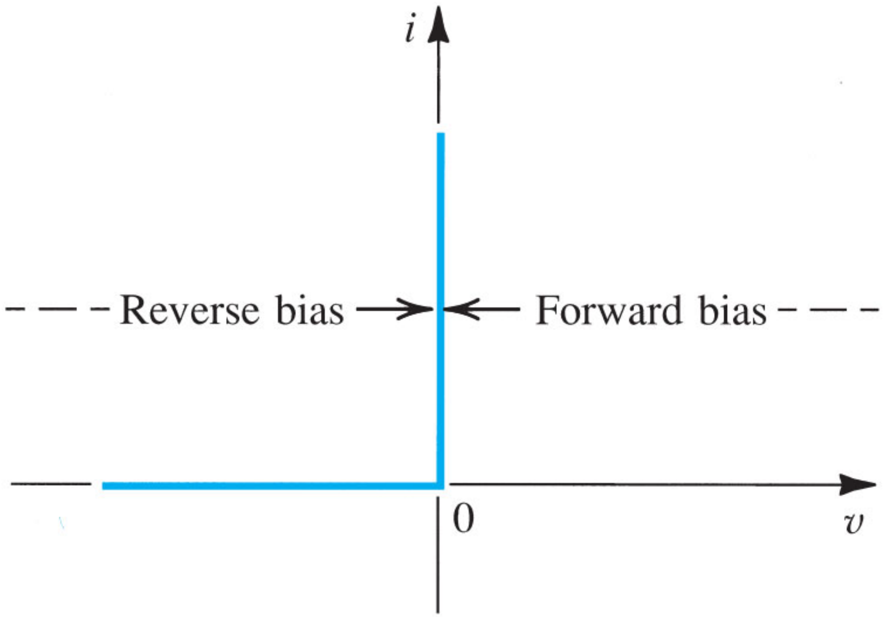
The Ideal Diode

- If a negative voltage is applied (reverse bias), no current flows – open circuit
- If a positive current is applied (forward bias), there is no voltage drop – short circuit

Points in direction of current

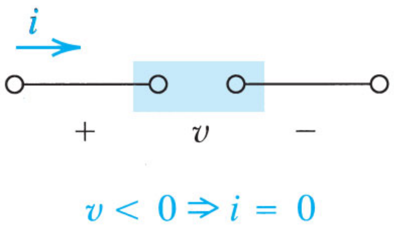


i-v characteristic

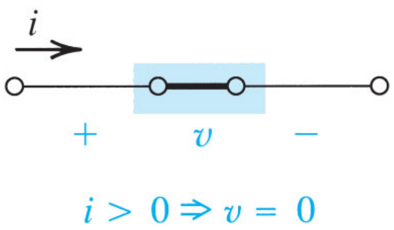


Equivalent Circuits

Reverse Direction



Forward Direction



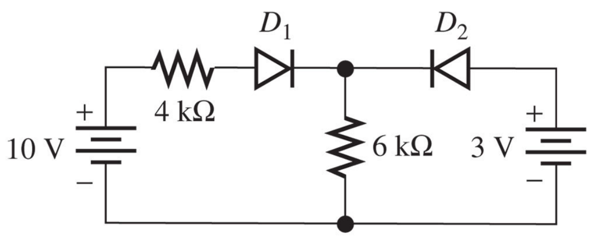
Analysis by Assumed States

In a circuit with a number of diodes:

- Assume a state for each diode (ON or OFF).
- n diodes will require 2^n possible combinations.
- Calculate currents of ON diodes and voltages of OFF diodes.
- Check to see if the calculations are consistent with the assumptions.
- If yes, the assumption works. If not, return to step 1 and make a new assumption.
- Making a table for your assumptions helps!

Example Exercise

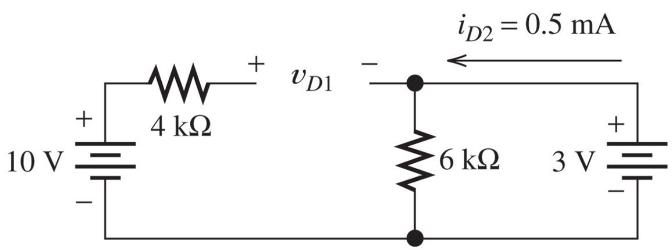
See *Hambley* Example 10.5 for more details



(a) Circuit diagram

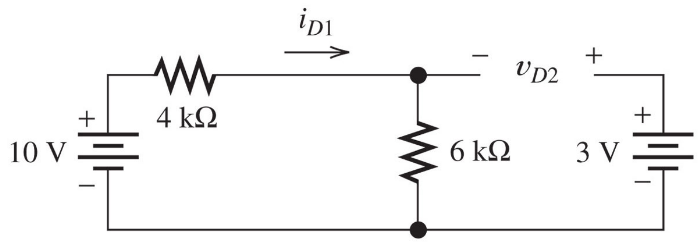
Use the ideal diode model to solve the circuit.

Assume D1 off and D2 on:



(b) Equivalent circuit assuming D_1 off and D_2 on (since $v_{D1} = +7$ V, this assumption is not correct)

Assume D1 on and D2 off:

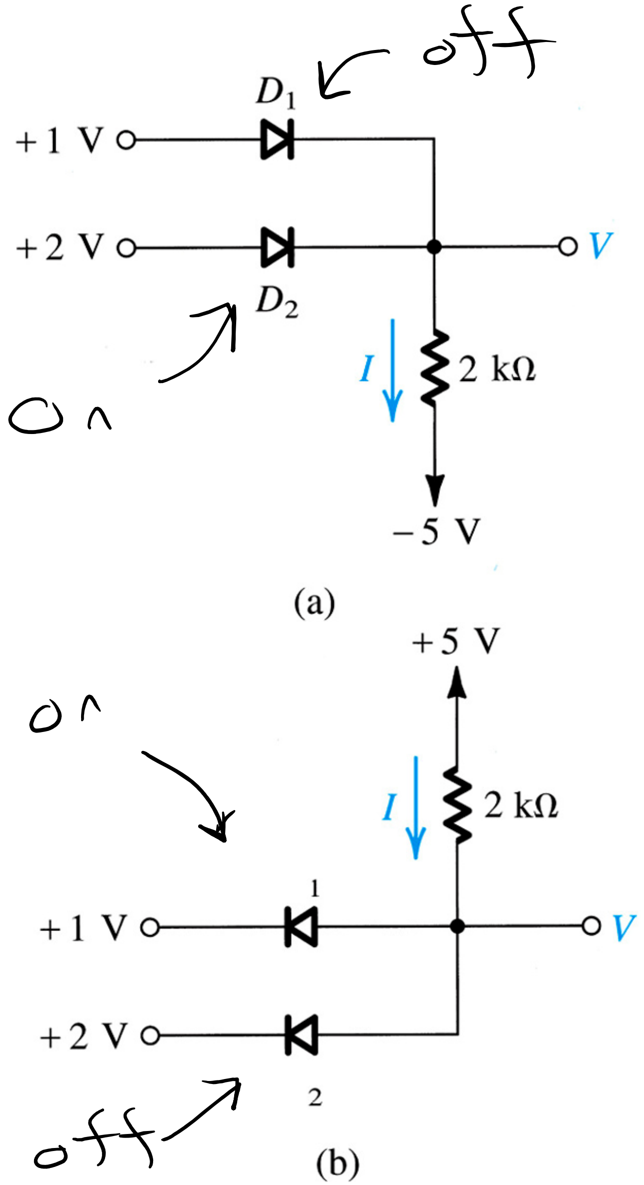


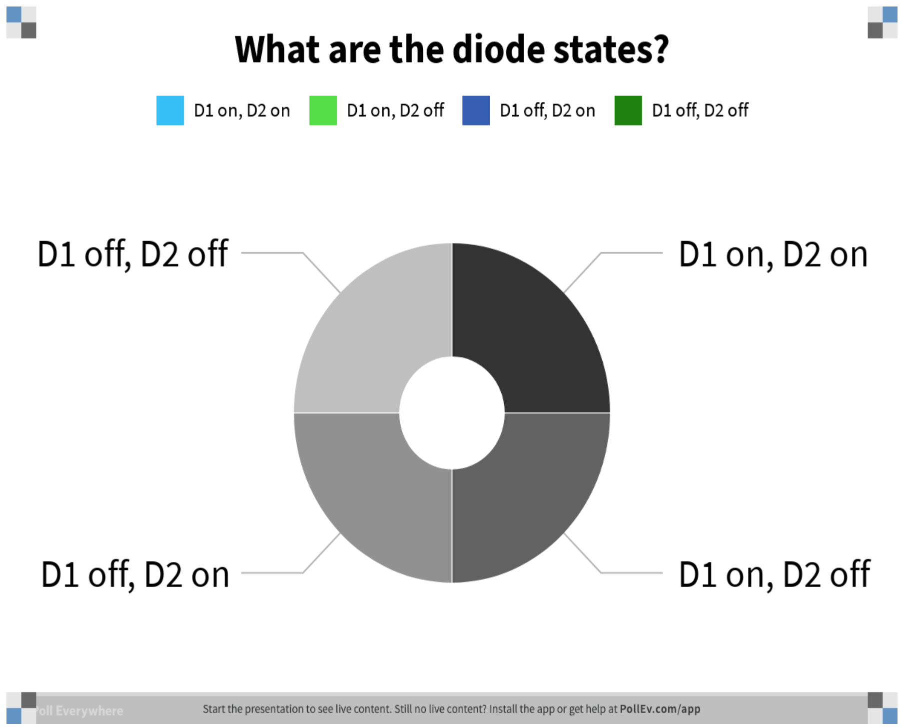
(c) Equivalent circuit assuming D_1 on and D_2 off (this is the correct assumption since i_{D1} turns out to be a positive value and v_{D2} turns out negative)

What about the other two states?

Class Exercise

Use the ideal diode model to solve each circuit.





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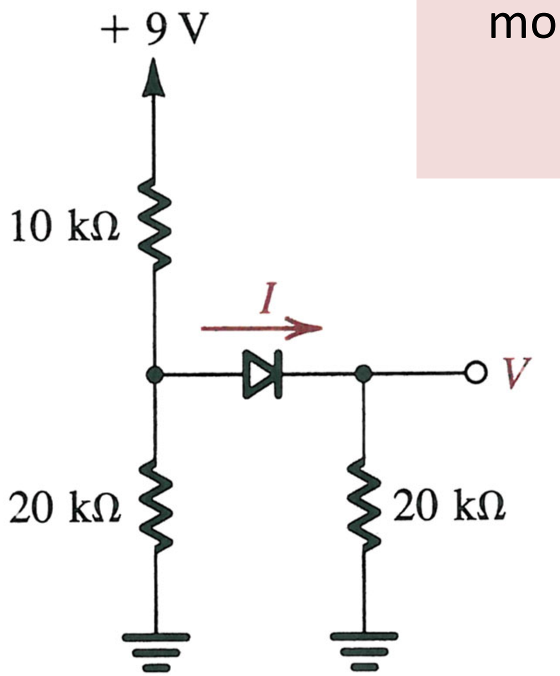
Class Exercise

IDEAL MODEL



(a)

Use the ideal diode model to solve the circuit.

Hint: use Thévenin equivalents

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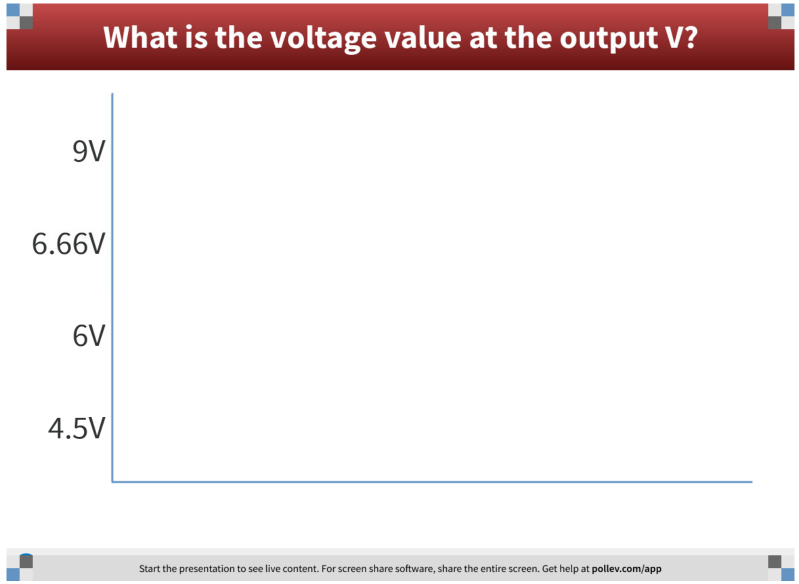
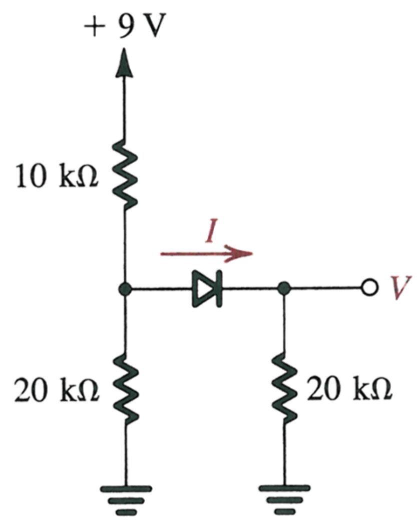


Timer Bar (1 min) :

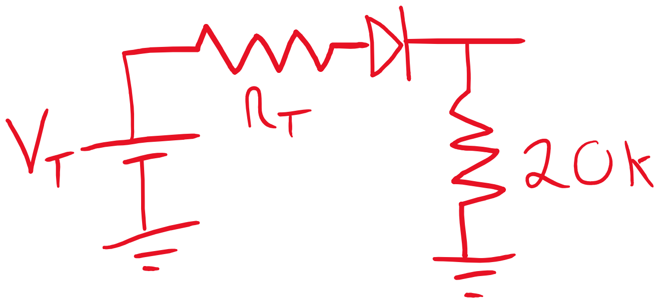
Class Exercise

IDEAL MODEL



(a)

1 Redraw with Thevenin..



$R_T = 10 \| 20 = \frac{10 \times 20}{30} = 6.66k$

$V_T = \frac{20}{30} V_{in} = 6V$

2 Calculate I

$I = \frac{6V}{6.66k + 20k} = 0.225\,mA$

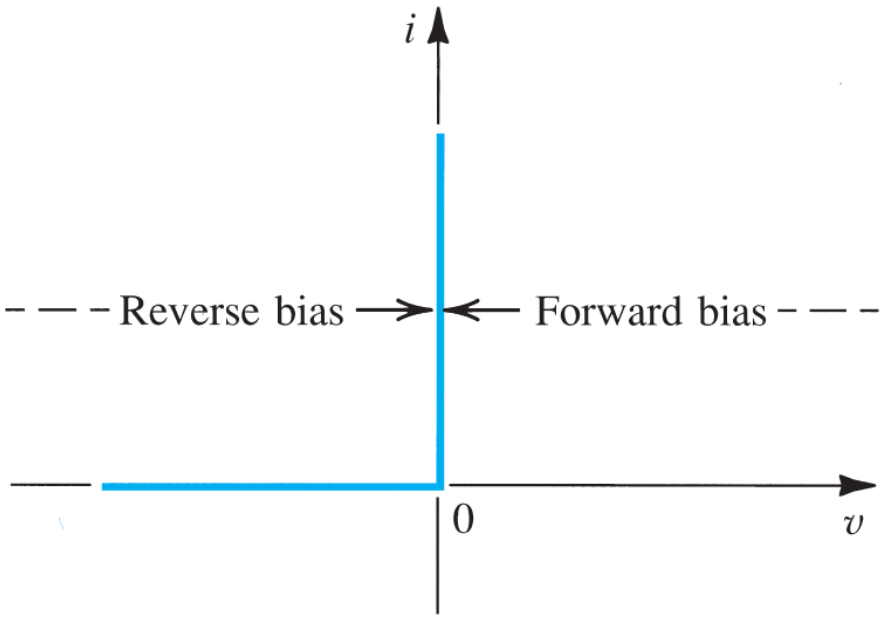
3 Find V

$V = \frac{20k}{20k + 6.66k} \times 6 = 4.5V$

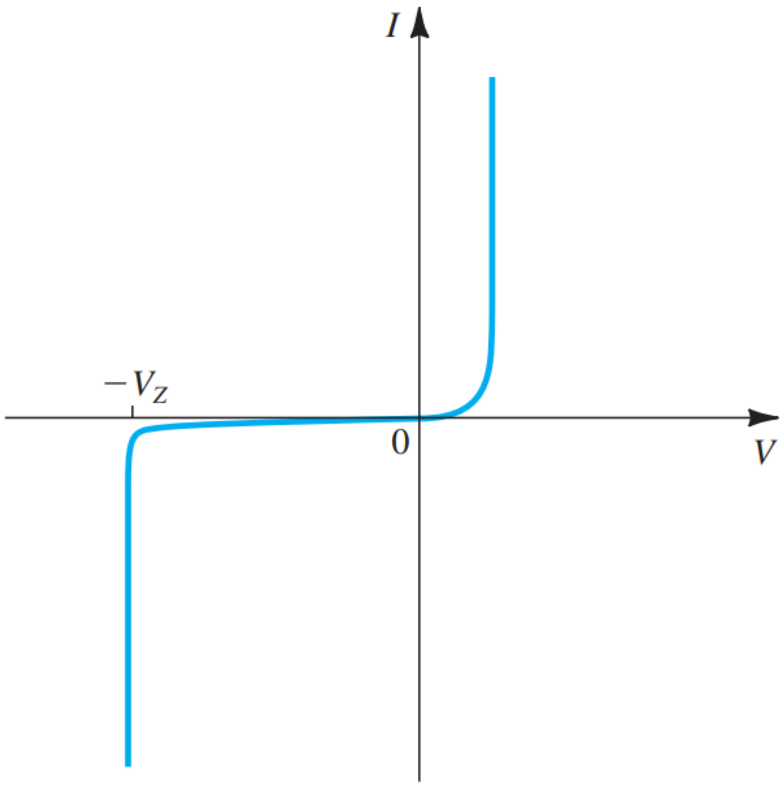
Non-ideal Diodes

In practice diode behaviour is typically more complex

Ideal Characteristics



Realistic Characteristics

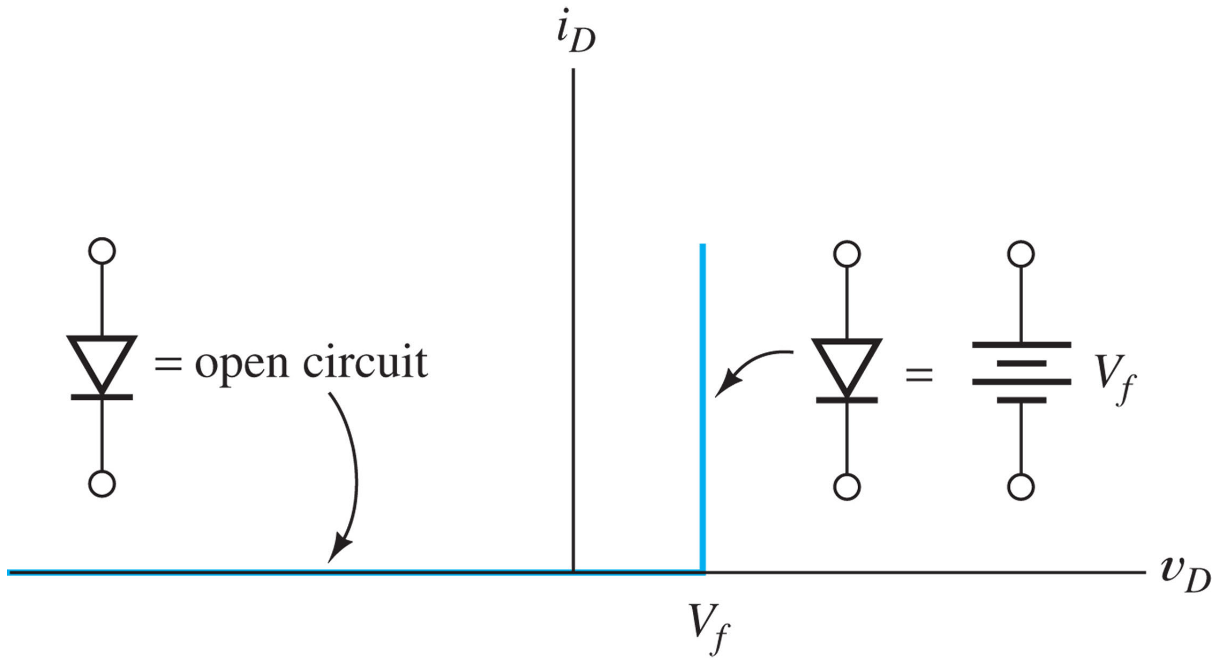


We can improve our model to approximate this!

Accounting for turn on voltage

CONSTANT VOLTAGE DROP MODEL

- A basic model that accounts for the forward turn on voltage of the diode
- Does not account for the slope, or reverse breakdown



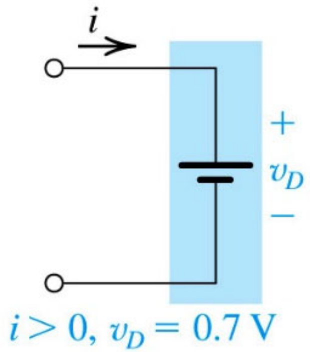
V_f~ 0.7 V
for a silicon signal diode

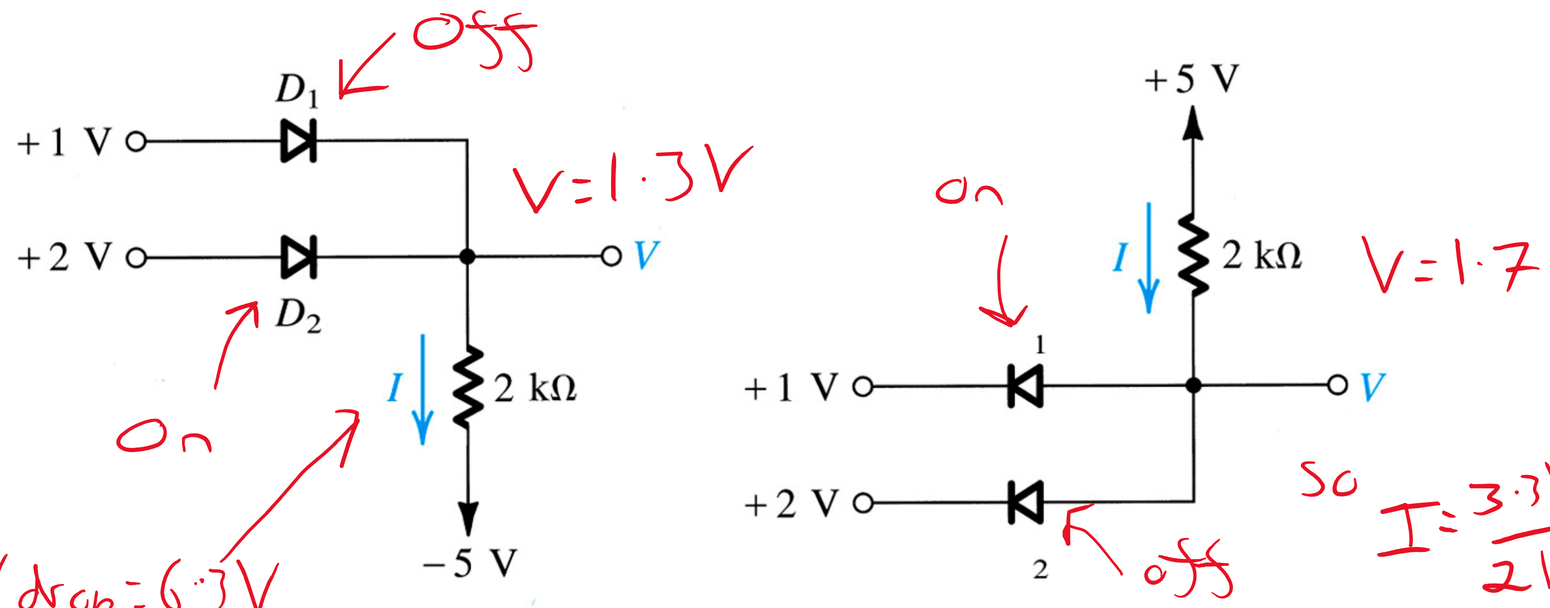
We will use this simple model most of the time.

Example

CONSTANT VOLTAGE DROP MODEL

Use the 0.7V drop diode model to solve each circuit.





(a) (b)

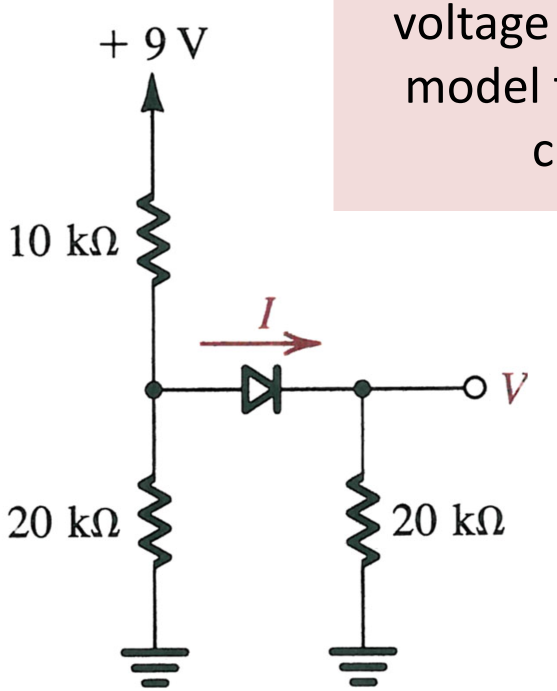
$I = \frac{6.3V}{2k} = 3.15 mA$

$I = \frac{3.3V}{2k}$

$I = 1.65 mA$

Class Exercise

CONSTANT VOLTAGE DROP MODEL



(a)

Use the constant voltage drop (0.7 V) model to solve the circuit.

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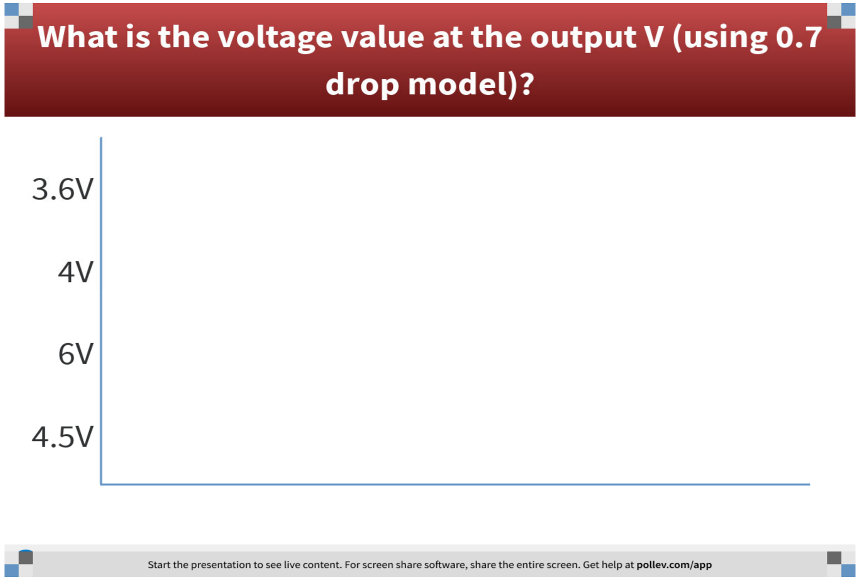
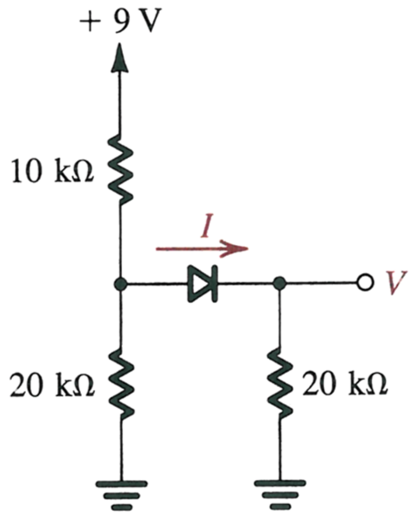


Timer Bar (1 min) :

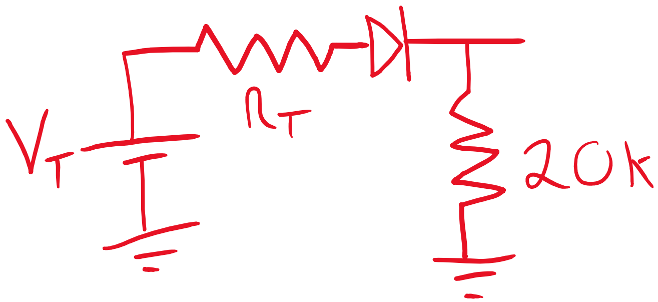
Class Exercise

CONSTANT VOLTAGE DROP MODEL



(a)

1 Redraw with Thevenin..



$R_T = 10 \| 20 = \frac{10 \times 20}{30} = 6.66k$

$V_T = \frac{20}{30} V_{in} = 6V$

2 Calculate I

$I = \frac{6 - 0.7}{20k + 6.66k} = 0.199\ mA$

3 Find V

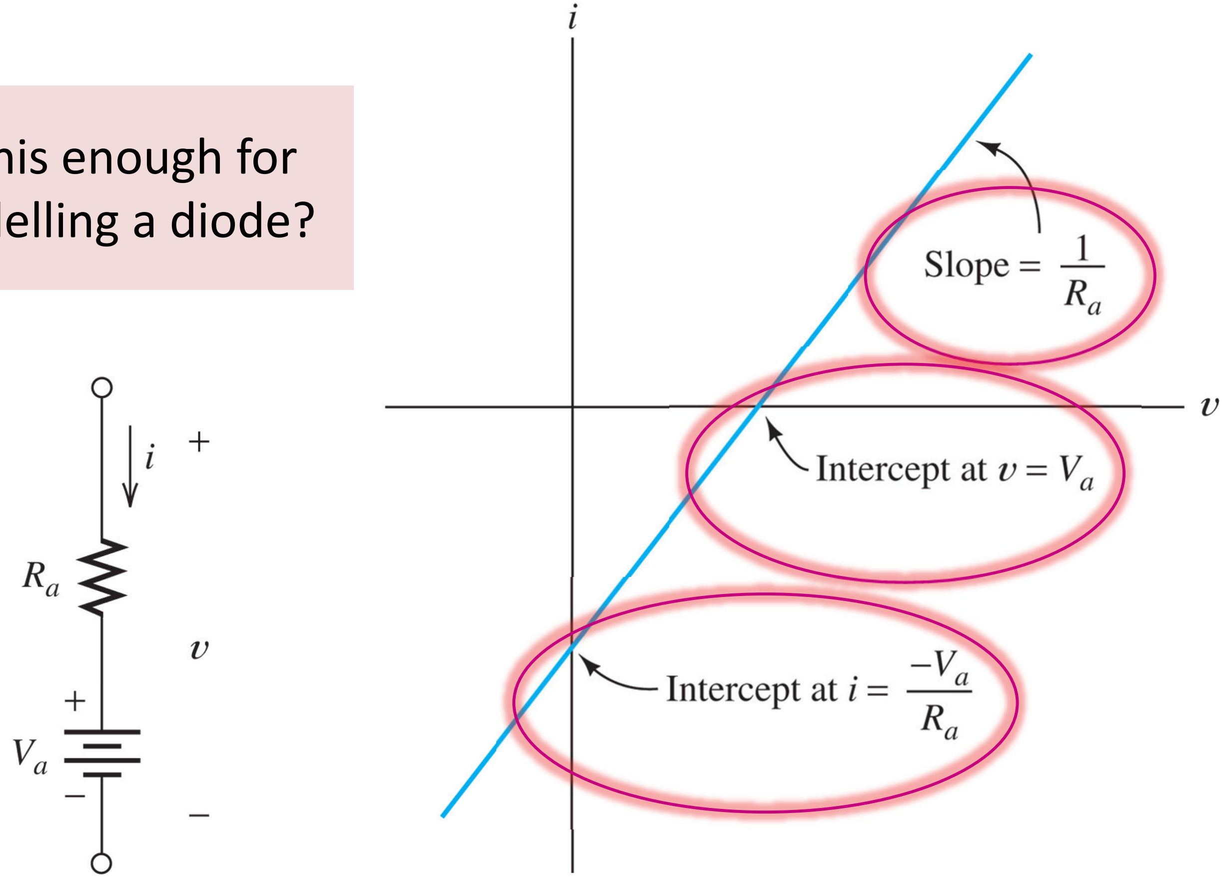
$V = I \times R_L = 20k \times 0.199\ mA = 3.98\ V$

What abount the slope?

A SIMPLE LINEAR MODEL

In practice diode behaviour is typically more complex

Is this enough for modelling a diode?



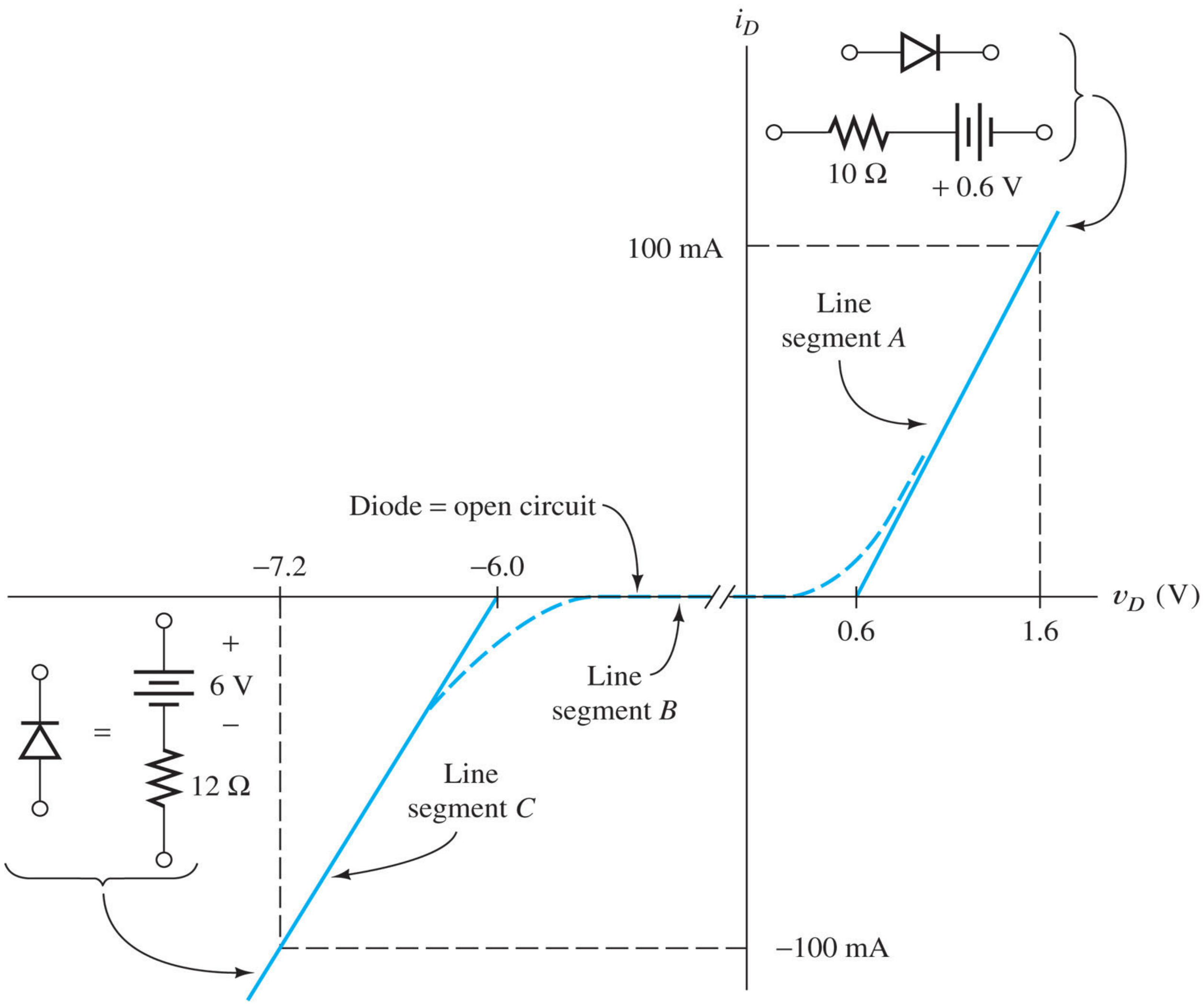
(a) Circuit diagram

(b) Volt–ampere characteristic

What is the mathematical equation for this model?

An Improved Model

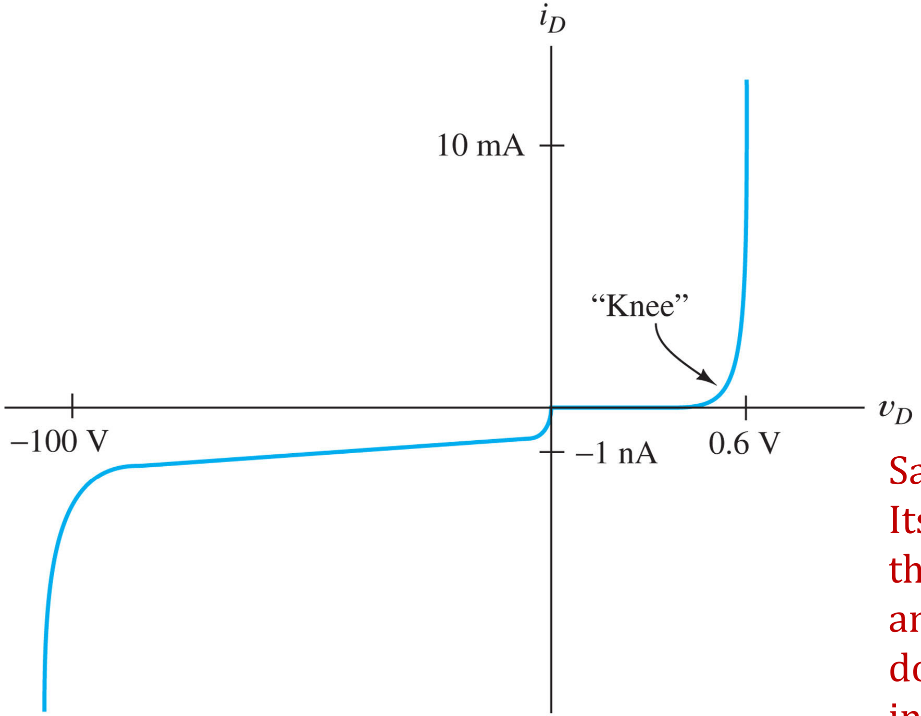
A NONLINEAR BUT PIECE-WISE LINEAR MODEL



This is the graphical model.
Good for load-line analysis.

What is the mathematical model?

The Shockley Equation



Approximate Shockley Equation
(for forward bias more than several tenths of a volt)

$$i_D \cong I_s \exp\left(\frac{v_D}{nV_T}\right)$$

Much easier to use

Shockley Equation
(for forward bias)

$$i_D = I_s\left(e^{v_D/nV_T} - 1\right)$$

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

Saturation current. Its value depends on the area of the diode and the temperature, doubling for each 5° increase for silicon diodes.

$\sim \mathbf{10^{-14}}$ **A at 300 K**

Emission coefficient (ideality factor)

$\mathbf{1 < n < 2}$

$\mathbf{n \cong 1}$

Thermal voltage.
$\boldsymbol{V_T = kT/q \cong}$
25 mV at 300 K

Temperature in K
(273 + temp in °C)

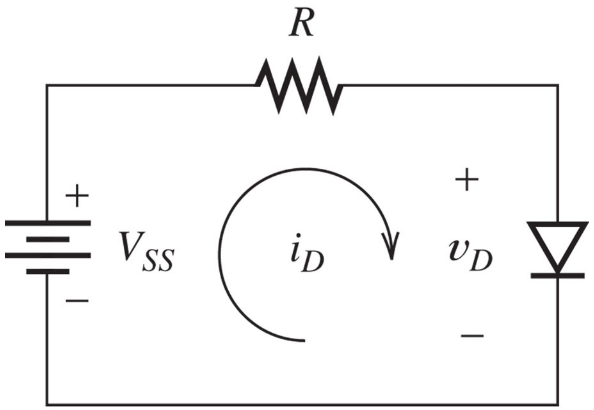
$k = 1.38 \times 10^{-23}$ joules/kelvin Boltzmann's constant

$q = 1.60 \times 10^{-19}$ coulomb magnitude of charge of an electron

Diode Analysis

USING THE SHOCKLEY EQUATION

- We want to find the diode voltage and current (operating point)

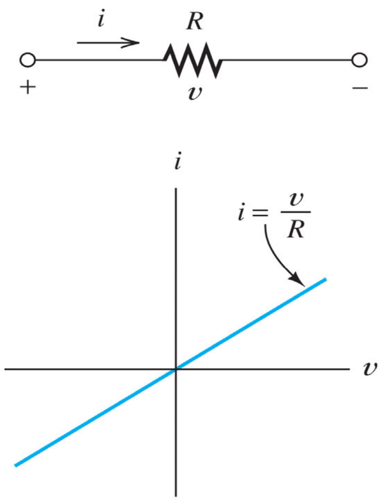


We know the diode I-V equation:

$$i_D = I_s \left[\exp\left(\frac{v_D}{nV_T} \right) - 1 \right] \quad (1)$$

or: $$i_D \cong I_s \exp\left(\frac{v_D}{nV_T} \right)$$

There is no straightforward way to solve these two equations analytically



We know the resistor I-V equation

We know Kirchhoff's voltage law:

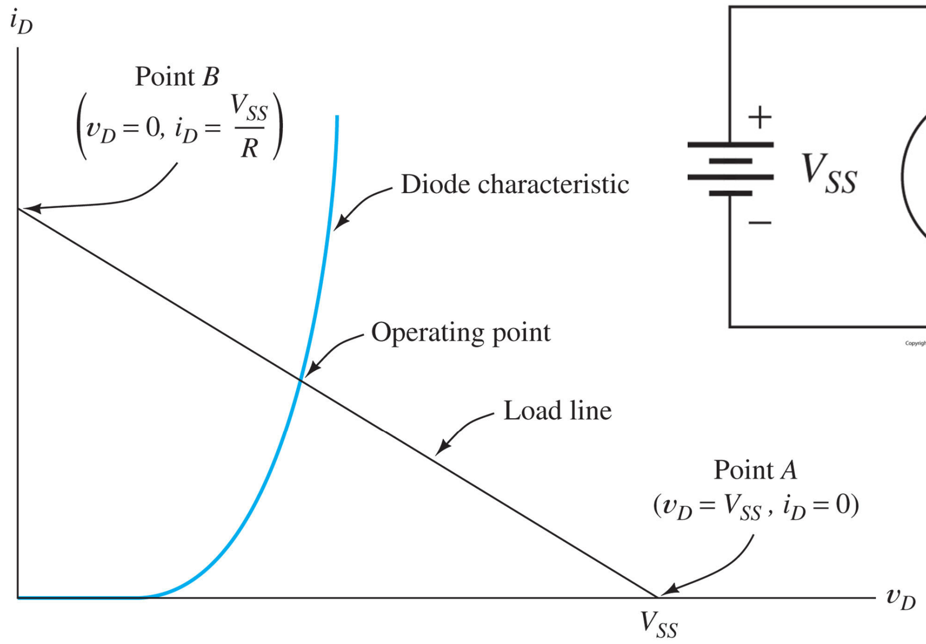
$$V_{SS} = Ri_D + v_D \quad (2)$$

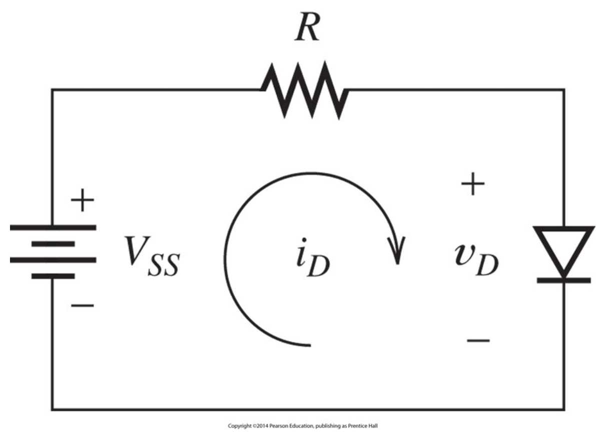
Graphical method called load-line analysis can be used.

Load Line Analysis

EXAMPLE PROBLEM

See *Hambley* Exercise 10.1 for more details





We know the diode I-V equation:

$$i_D = I_s\left[\exp\left(\frac{v_D}{nV_T}\right) - 1\right] \quad (1)$$

or: $$i_D \cong I_s \exp\left(\frac{v_D}{nV_T}\right)$$

We know Kirchhoff's voltage law:

$$V_{SS} = Ri_D + v_D \quad (2)$$

$$i_D = \frac{V_{SS} - v_D}{R}$$

What else do we need to find the operating point?

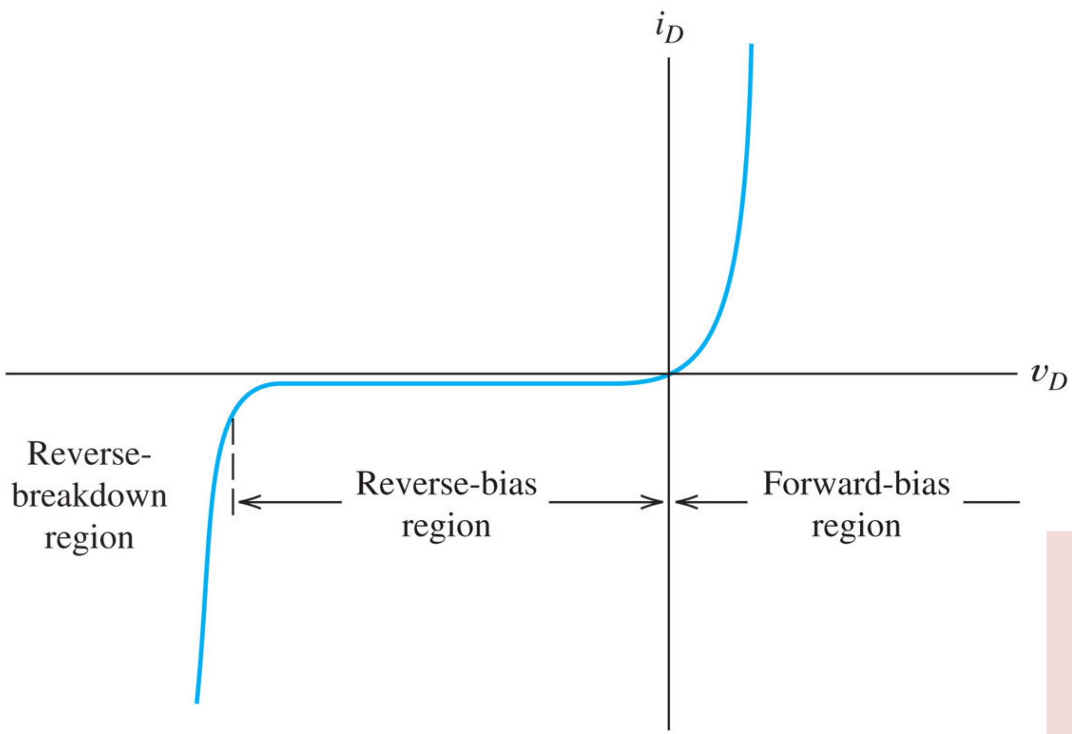
$V_{SS} = 2\ \text{V}$

$R = 1\ \text{k}\Omega$

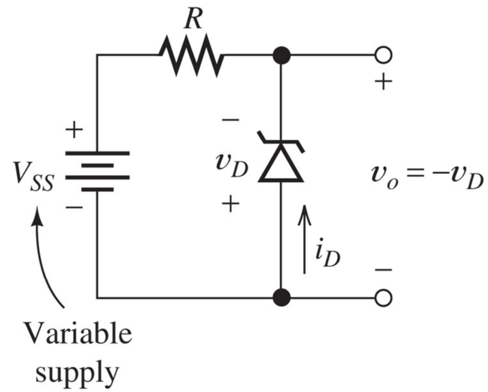
$V_{DQ} \cong 0.7\ \text{V} \quad I_{DQ} \cong 1.3\ \text{mA}$

The Zener Diode

Diodes that are designed to work at the reverse breakdown region are Zener diodes.



(b) Volt–ampere characteristic



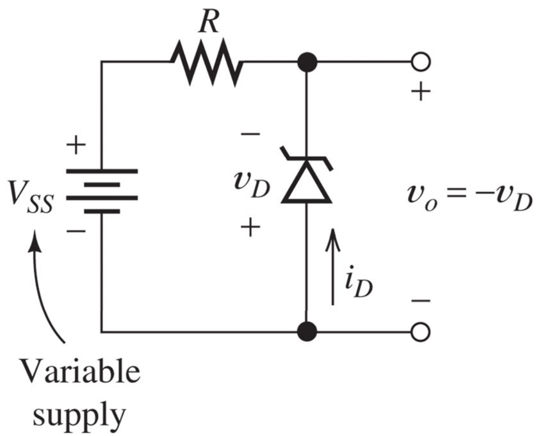
Commonly used for voltage regulator circuits – constant output from variable supply

Zener Diode Voltage Regulator

LOAD-LINE ANALYSIS IN THE REVERSE BREAKDOWN REGION

See *Hambley* Exercise 10.3 for more details

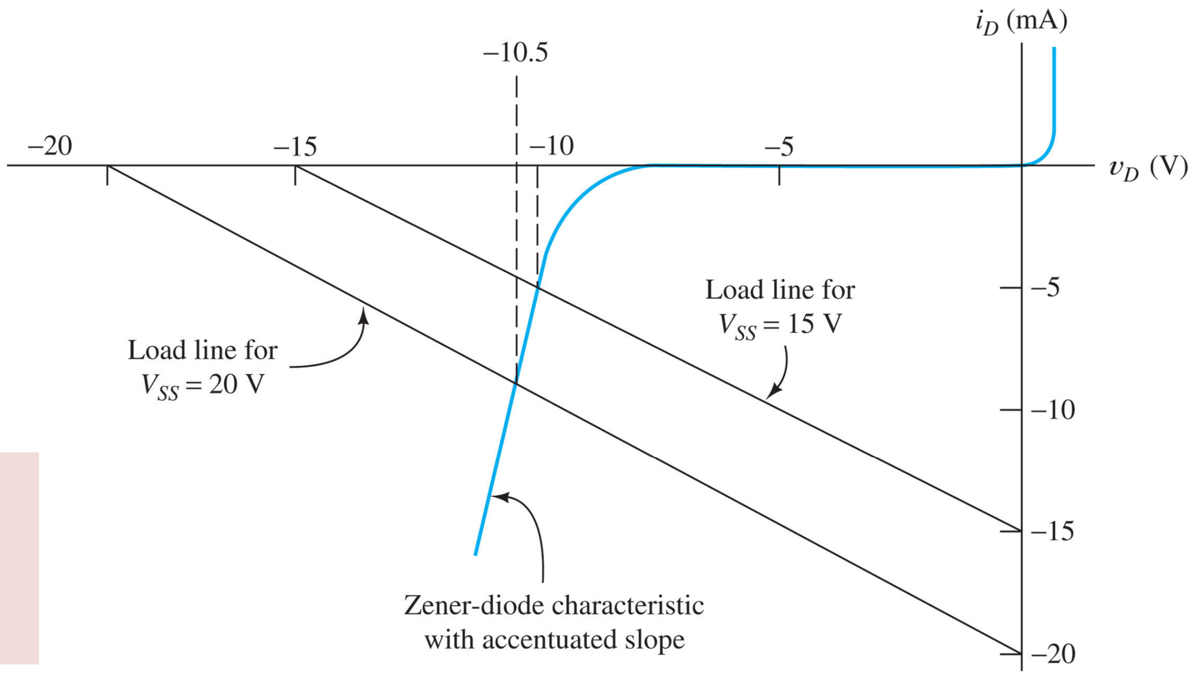
Actual Zener diodes can do much better than this



5V change in the supply voltage results in only a 0.5V change the regulated output voltage.

$$V_{SS} = 15 \text{ V and } 20 \text{ V}$$

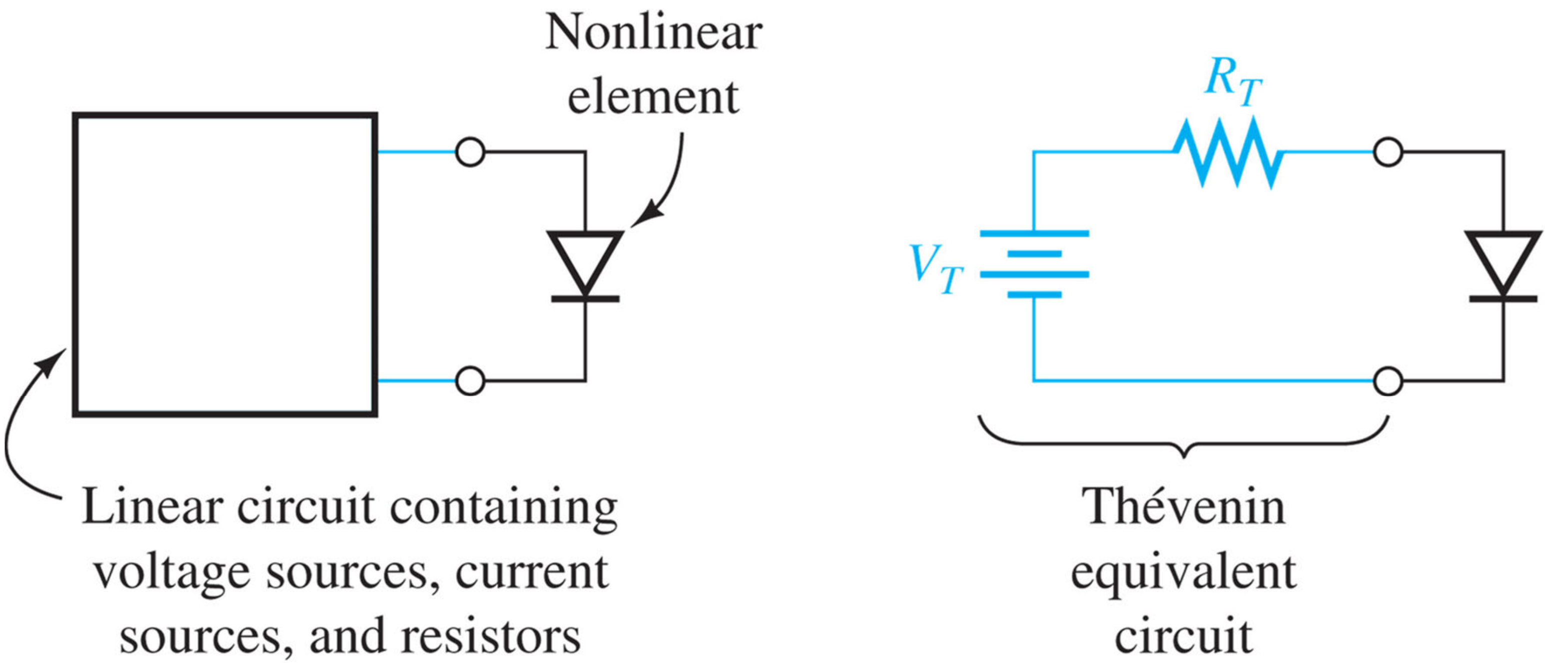
$$R = 1 \text{ k}\Omega$$



Notice the slope of the load line did not change. Why?

L-L Analysis of complex circuits

MACQUARIE University



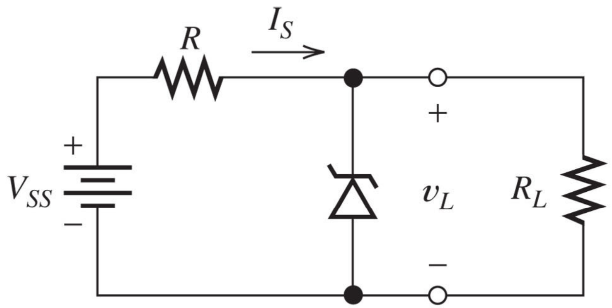
(a) Original circuit

(b) Simplified circuit

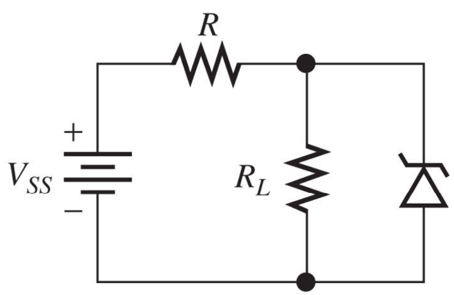
Example

See *Hambley* Exercise 10.4 for more details

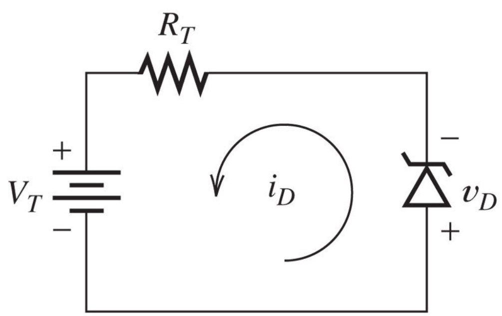
Find the load voltage and source current



(a) Regulator circuit with load



(b) Circuit of (a) redrawn

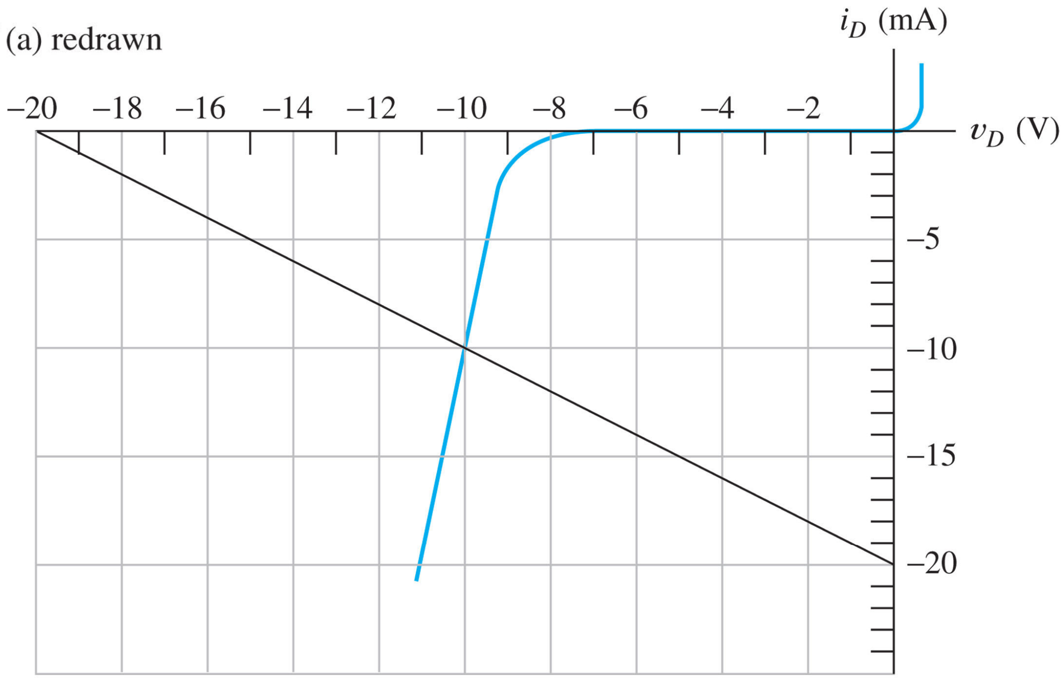


(c) Circuit with linear portion replaced by Thévenin equivalent

$V_{SS} = 24\ \mathrm{V}$

$R = 1.2\ \mathrm{k\Omega}$

$R_L = 6\ \mathrm{k\Omega}$



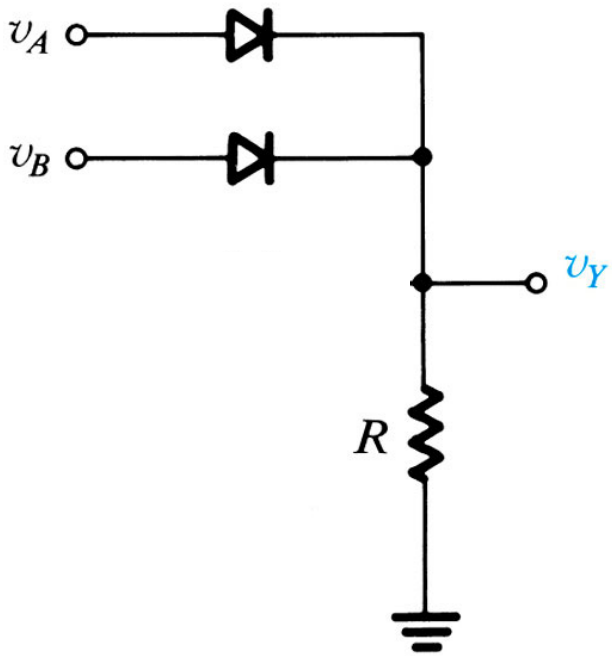
Lecture 2

1. Diode Fundamentals & Models
2. **Diode Circuits & Applications**
3. Small Signal Analysis

Logic Gates

LOGIC GATES WITH DIODES

What kind of logic gate is this?



(a)

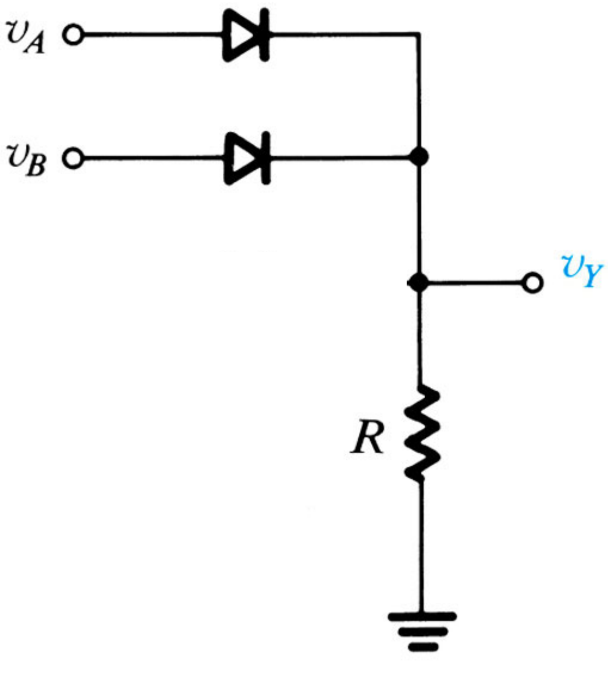
Assuming ideal diodes

v_A (V)	v_B (V)	v_Y (V)
5	0	
0	5	
5	5	
0	0	

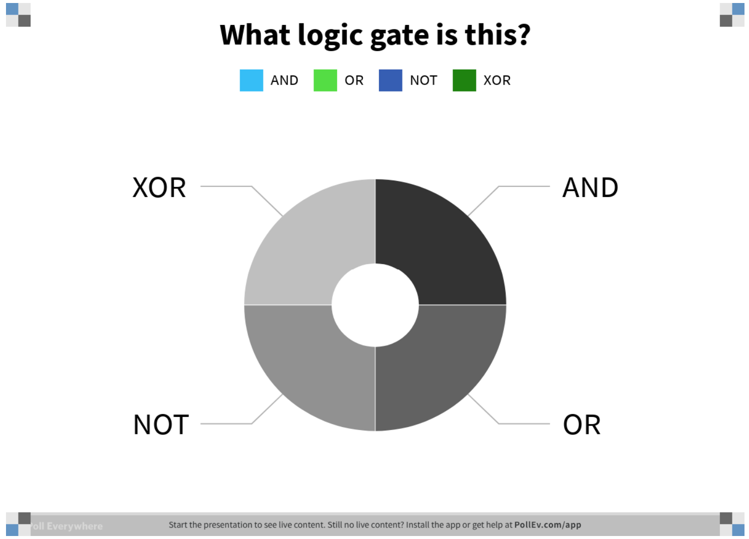
Logic Gates

LOGIC GATES WITH DIODES

What kind of logic gate is this?



(a)



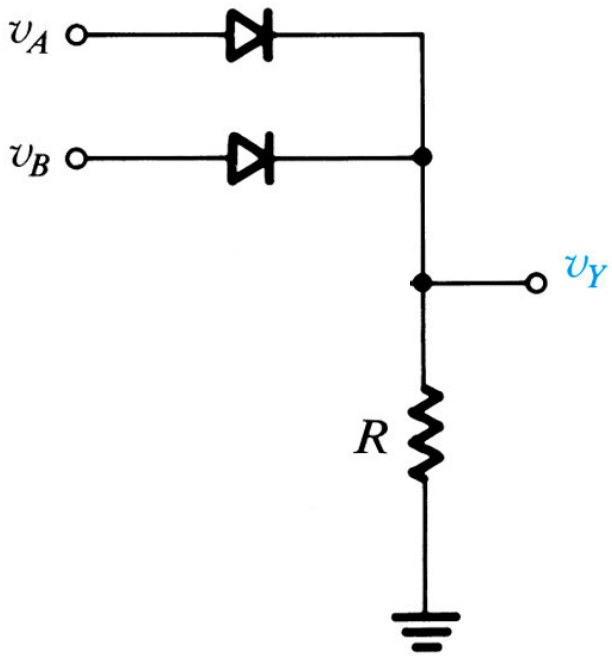
Assuming ideal diodes

v_A (V)	v_B (V)	v_Y (V)
5	0	
0	5	
5	5	
0	0	

Logic Gates

LOGIC GATES WITH DIODES

Y = A **OR** B
(A+B in Boolean notation)



(a)

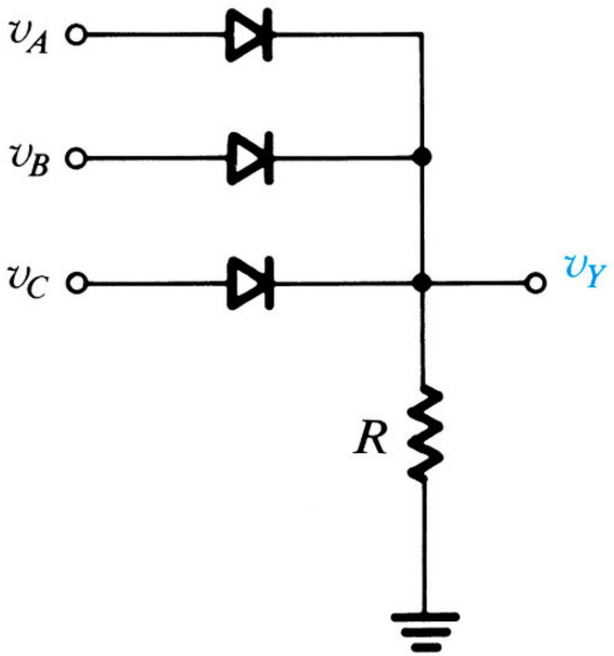
Assuming ideal diodes

v_A (V)	v_B (V)	v_Y (V)
5	0	5
0	5	5
5	5	5
0	0	0

Logic Gates

LOGIC GATES WITH DIODES – OR GATE

Y = A **OR** B **OR** C
(A+B+C in Boolean notation)

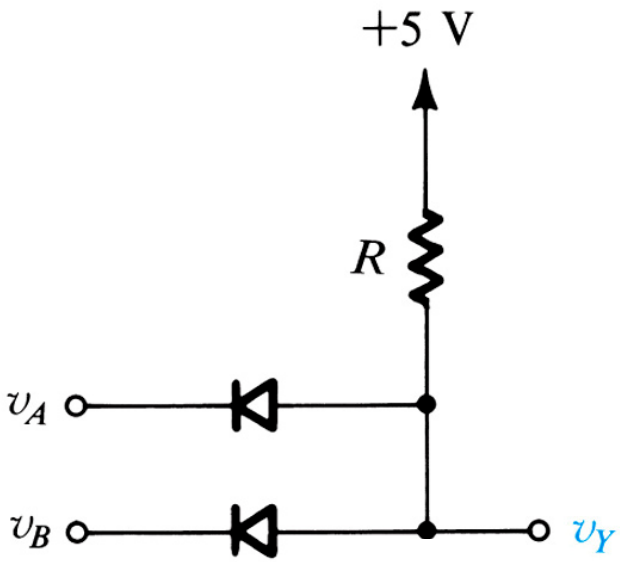


(a)

Logic Gates

LOGIC GATES WITH DIODES

What kind of gate is this?



(b)

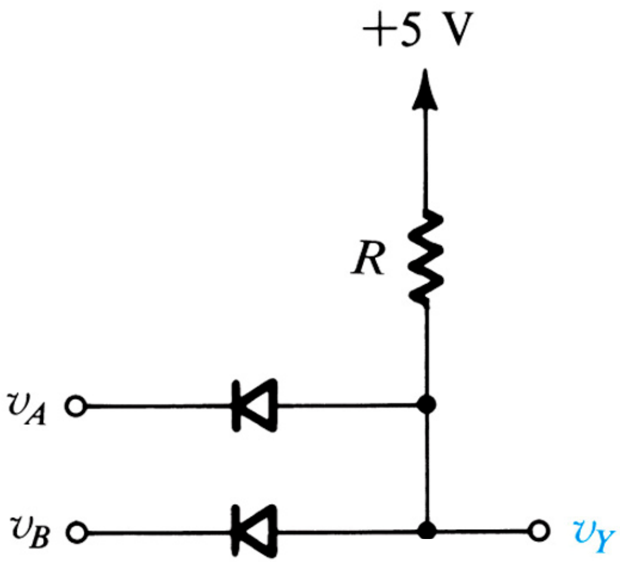
Assuming ideal diodes

v_A (V)	v_B (V)	v_Y (V)
5	0	
0	5	
5	5	
0	0	

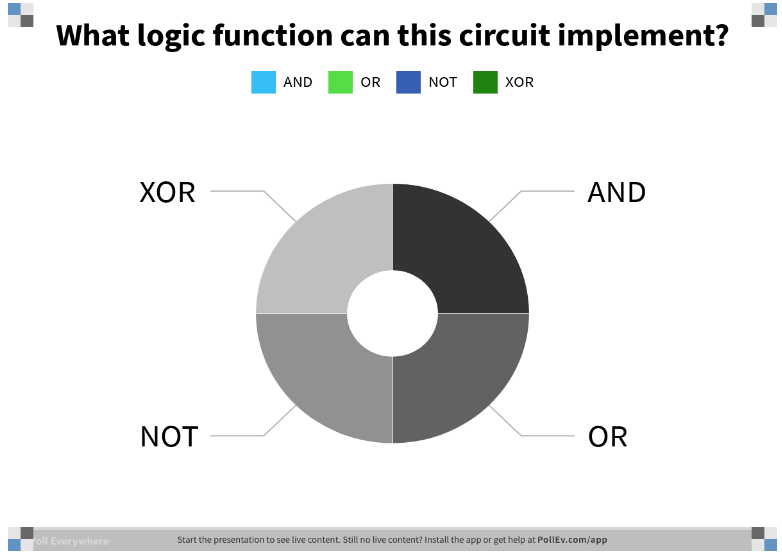
Logic Gates

LOGIC GATES WITH DIODES

What kind of gate is this?



(b)



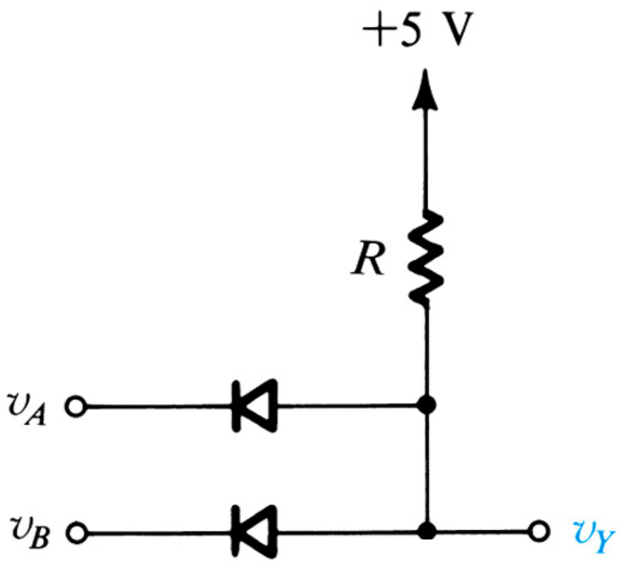
Assuming ideal diodes

v_A (V)	v_B (V)	v_Y (V)
5	0	
0	5	
5	5	
0	0	

Logic Gates

LOGIC GATES WITH DIODES

Y = A **AND** B
(A·B in Boolean notation)



(b)

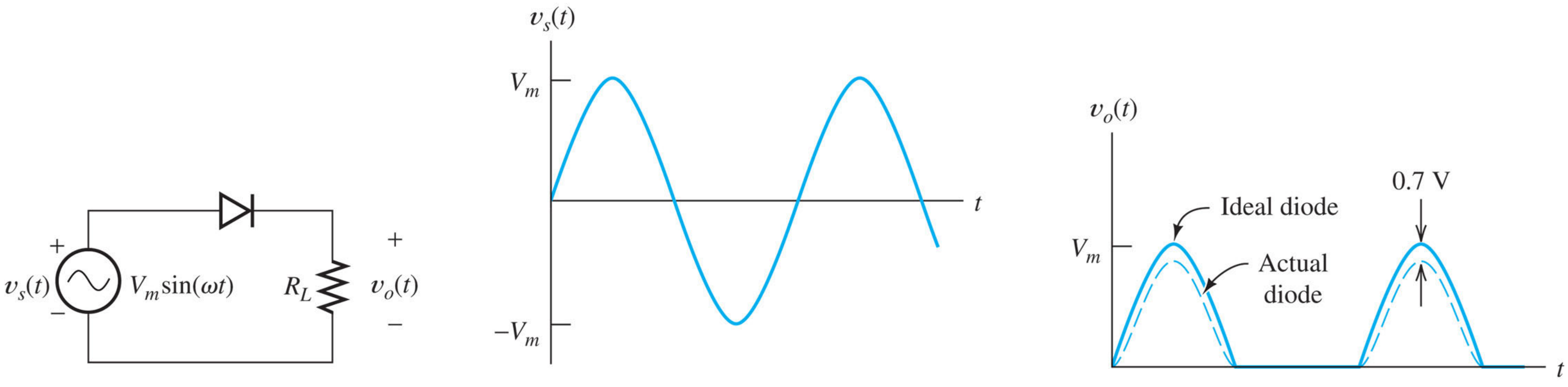
Assuming ideal diodes

v_A (V)	v_B (V)	v_Y (V)
5	0	0
0	5	0
5	5	5
0	0	0

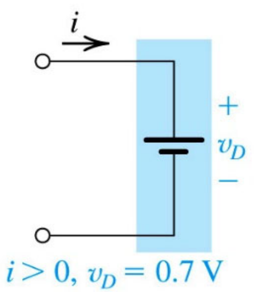
Rectifier Circuits

HALF-WAVE RECTIFIER

- Used to convert AC power to DC power



(a) Circuit diagram (b) Source voltage versus time (c) Load voltage versus time

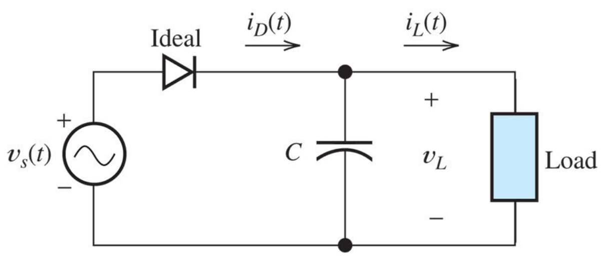


We can use the 0.7V drop model or ideal diode model without losing much accuracy because voltage levels >> 0.7V

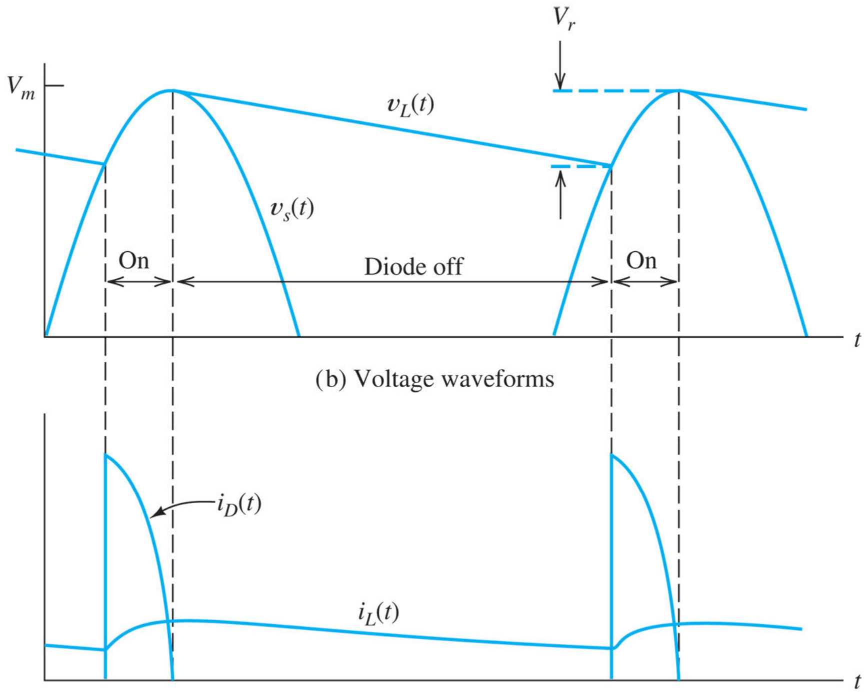
Rectifier Circuits

HALF-WAVE RECTIFIER – WITH SMOOTHING

- We can add a capacitor to smoothen the output



(a) Circuit diagram



(b) Voltage waveforms

(c) Current waveforms

Average load current

Period of the ac voltage

$$C \cong \frac{I_L T}{V_r}$$

Ripple voltage

Choose diode to withstand Peak Inverse Voltage

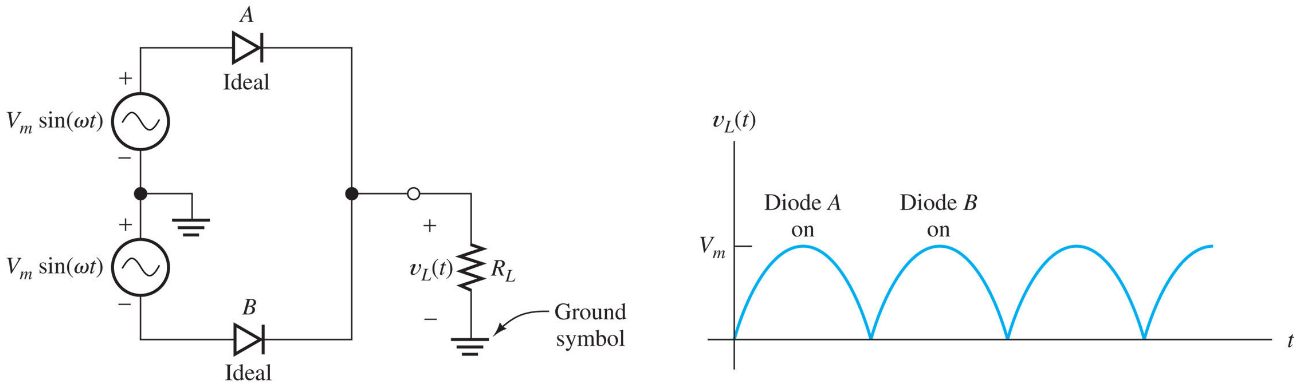
$$\text{PIV} \cong 2V_m$$

PIV needs to be less than the breakdown voltage of the diode.

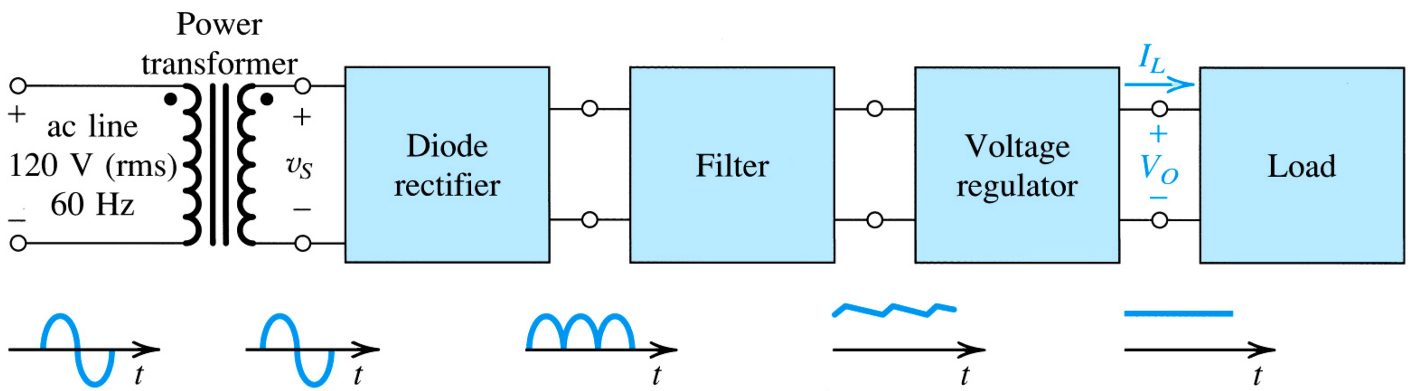
Rectifier Circuits

FULL-WAVE RECTIFIER

A transformer can provide this (out-of-phase ac voltages)



(a) Circuit diagram (b)

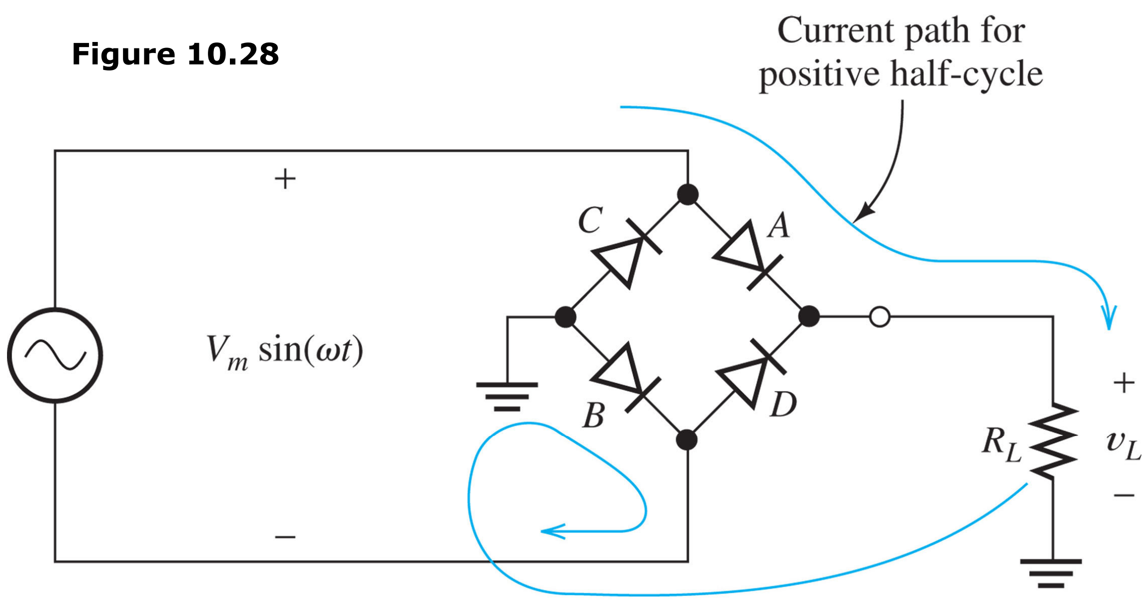


Block diagram of a dc power supply.

Rectifier Circuits

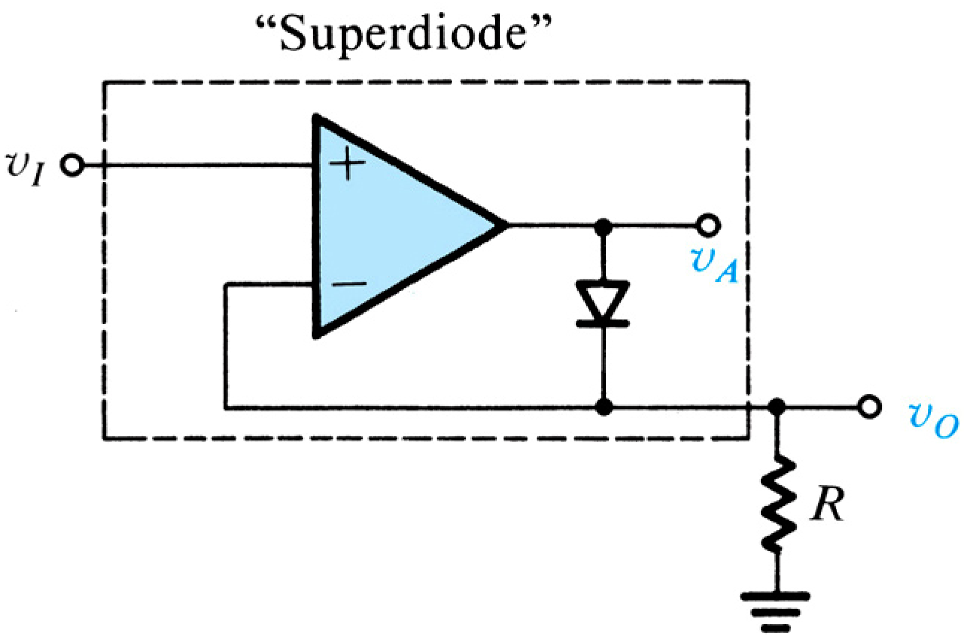
DIODE-BRIDGE FULL-WAVE RECTIFIER

Figure 10.28

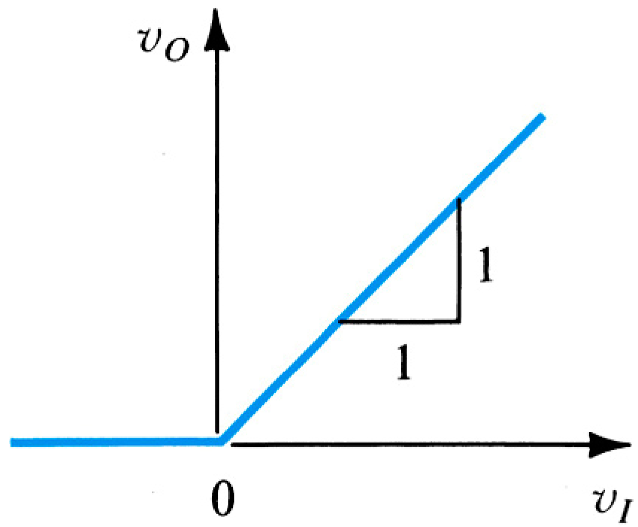


Rectifier Circuits

PRECISION RECTIFIER – THE "SUPERDIODE"

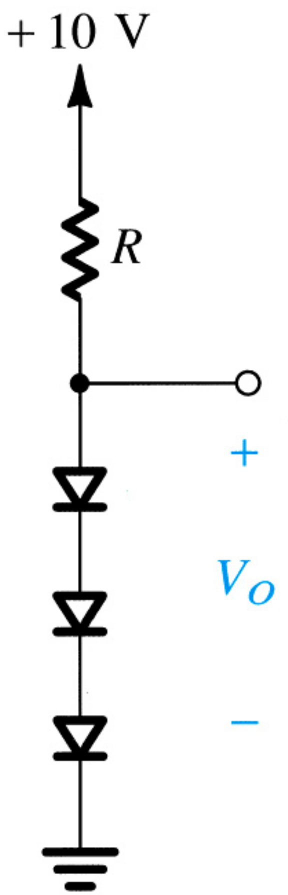


(a)



(b)

Voltage Regulator

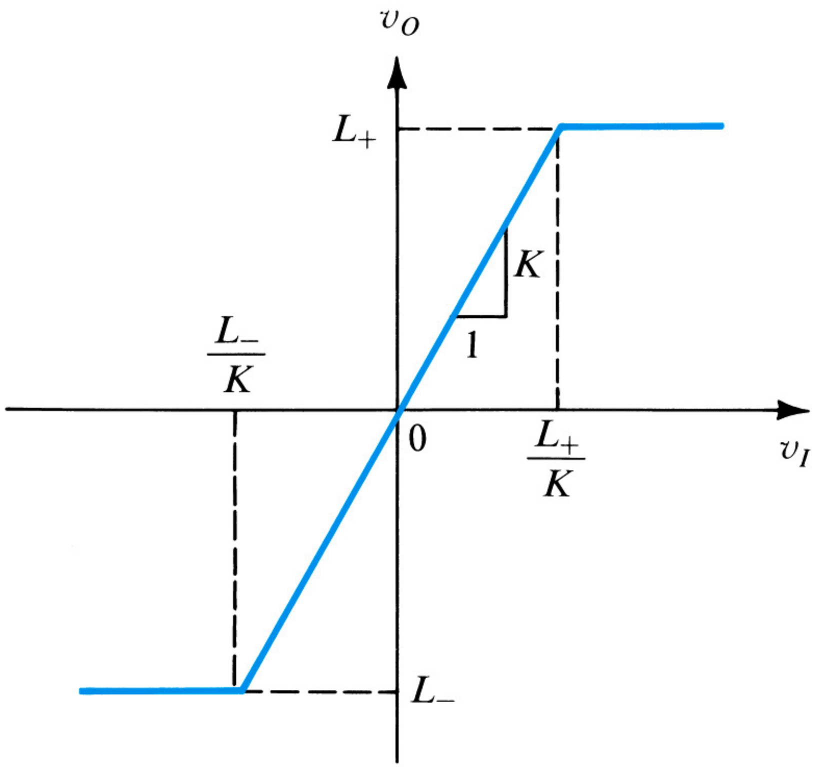


Using Si diodes (0.7V constant Voltage drop)

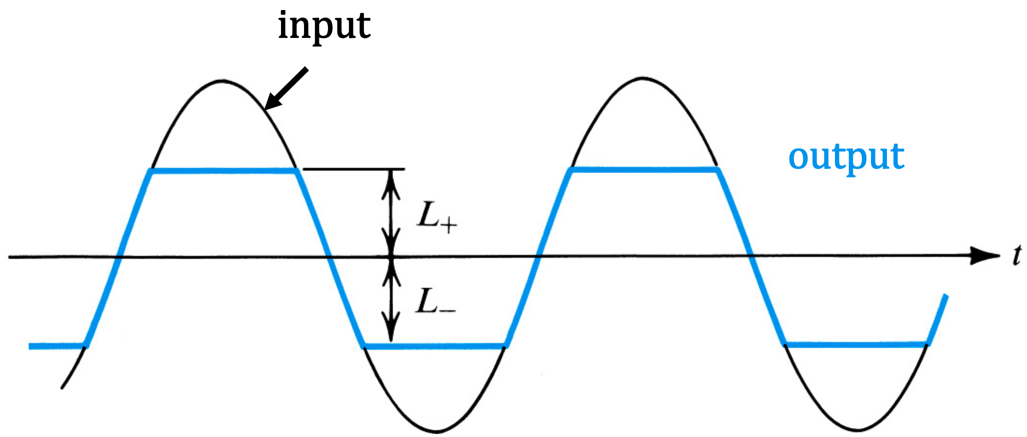
$$V_O \simeq 2.1 \text{ V}$$

Wave Shaping Circuits

LIMITING CIRCUITS



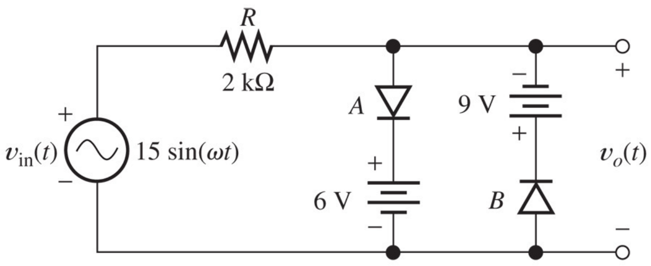
Voltage transfer characteristic
of a limiting circuit (a "limiter")



Example: "clipped" output

Wave Shaping Circuits

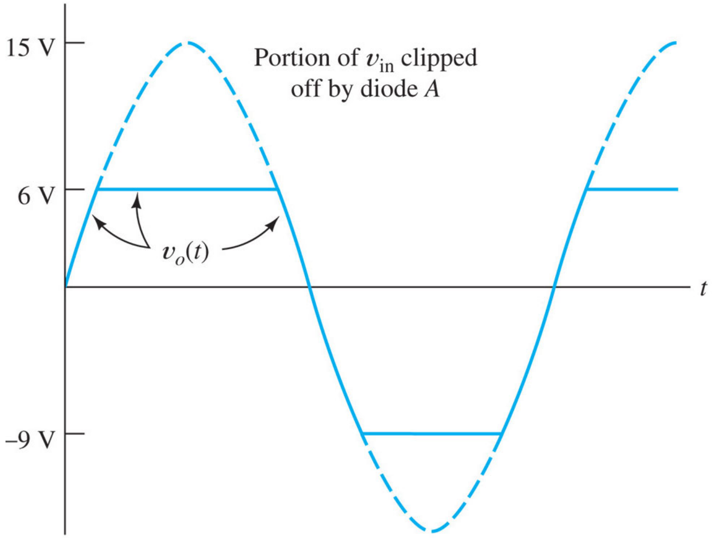
CLIPPER CIRCUITS



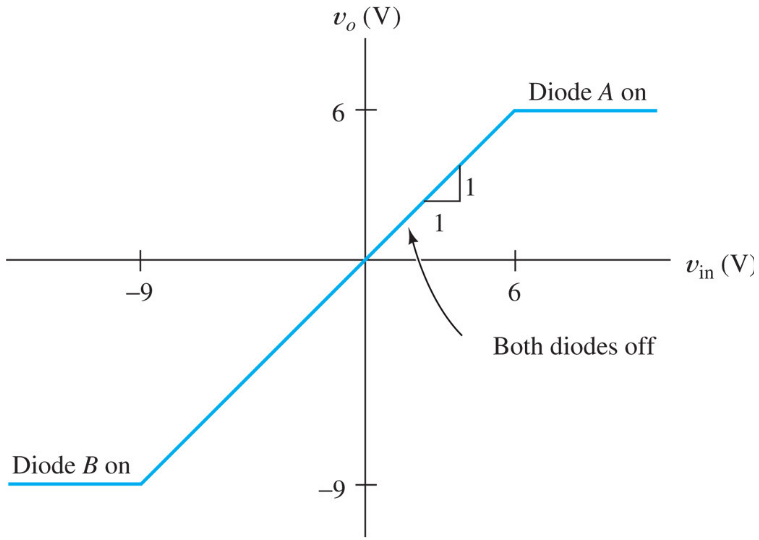
(a) Circuit diagram

Ideal diodes.

You need to practice drawing these by hand!



(b) Waveforms

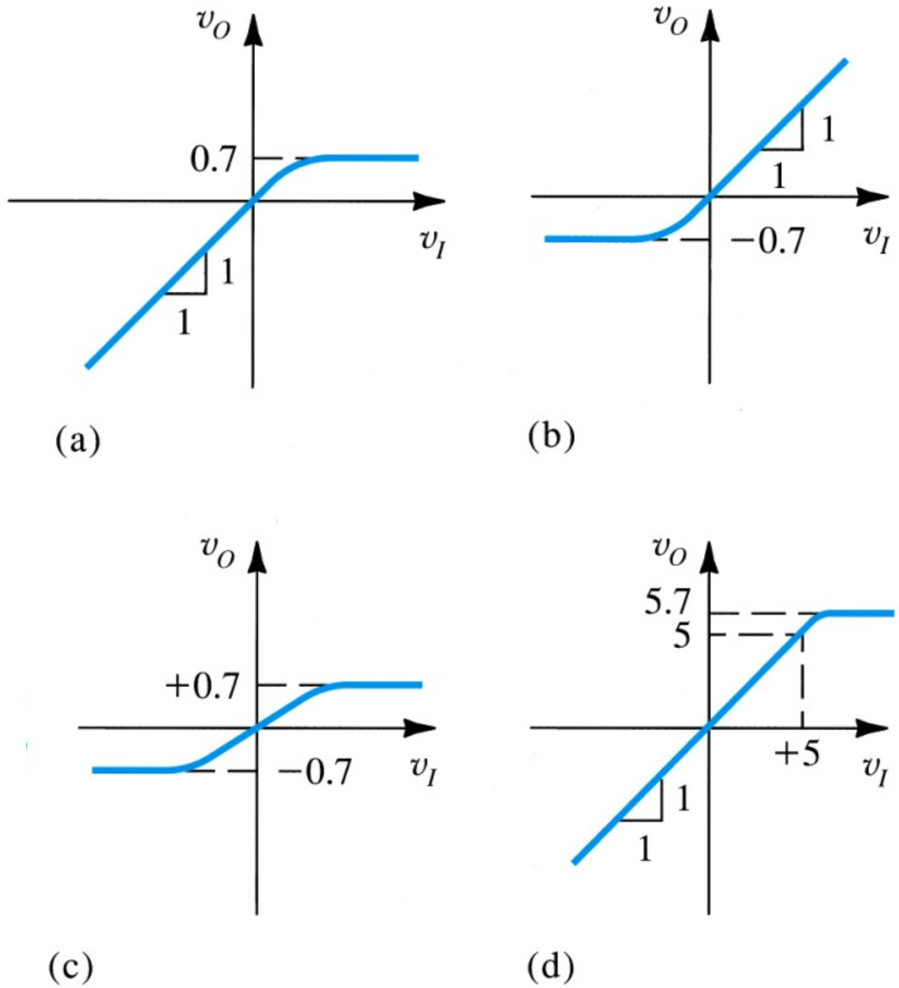


(c) Transfer characteristic

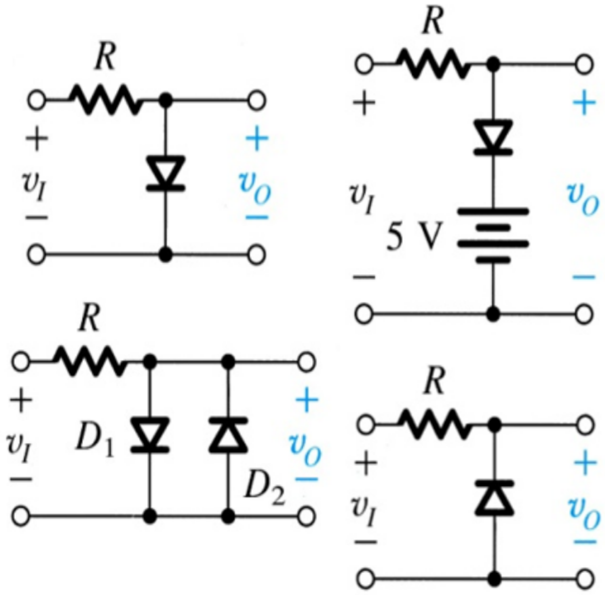
Voltage transfer characteristic !

Wave Shaping Circuits

LIMITING CIRCUITS WITH DIODES



Which circuit will give the shown transfer characteristic?



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Answers: Top-left = a
Top right = d
Bottom left = c
Bottom right = b

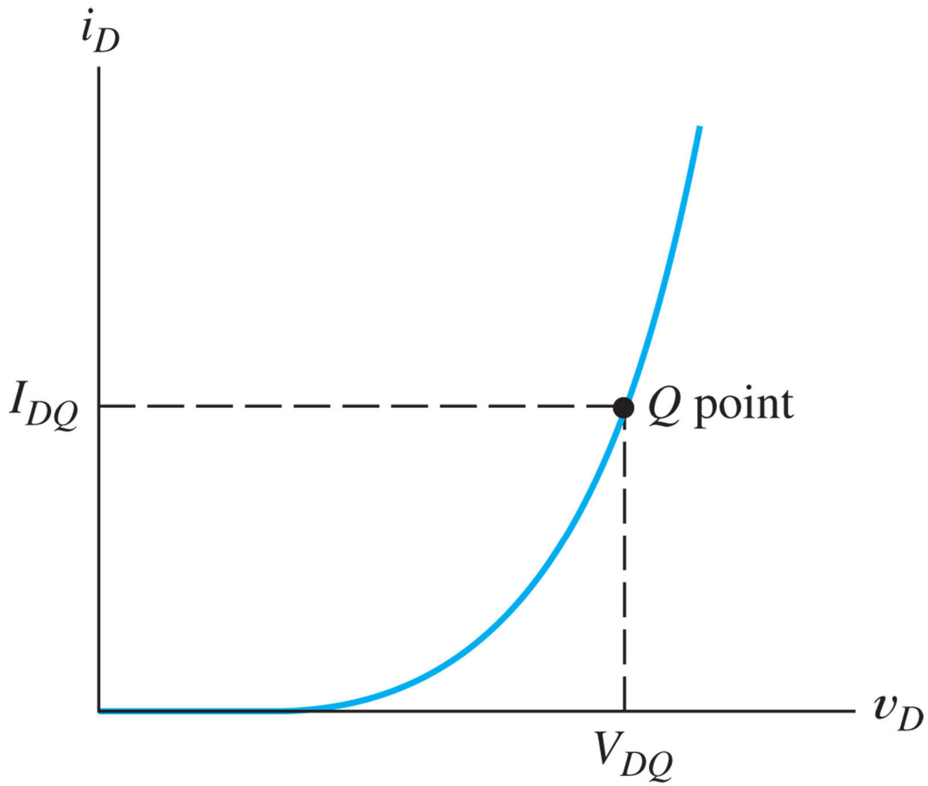
Lecture 2

1. Diode Fundamentals & Models
2. Diode Circuits & Applications
3. **Small Signal Analysis**

Diode Analysis – Small Signals

STEADY STATE AC ANALYSIS

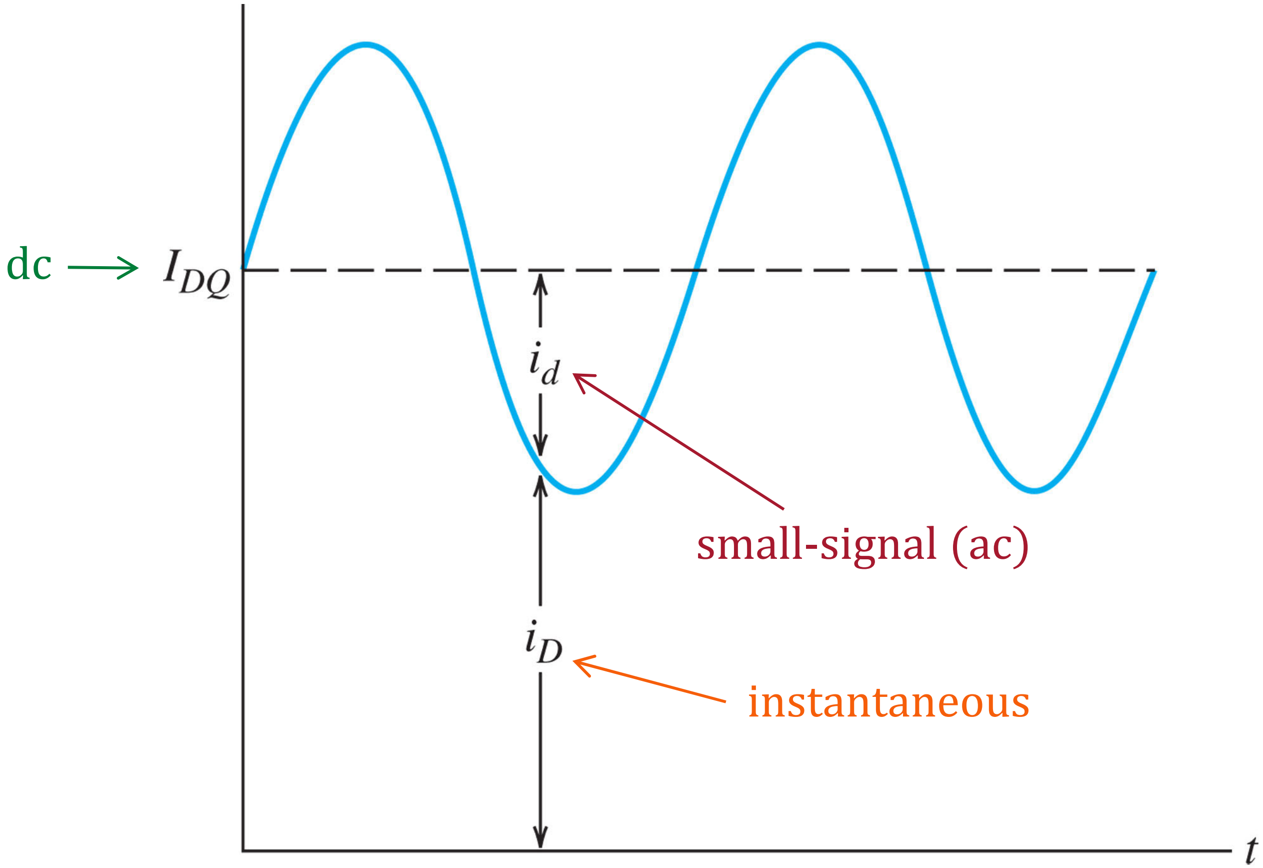
- So far we analysed the diode circuits in the time domain
- We calculated and plotted instantaneous voltages and currents
- We applied dc voltages (or currents) to the diodes and found the operating points (Q point)
- Q stands for quiescent (i.e. quiet or no- signal point)



If the Q point is known (using the nonlinear diode characteristic), the linear ac analysis method can be applied to find the response to small (ac) signals.

Diode Analysis – Small Signals

CURRENT AND VOLTAGE NOTATION

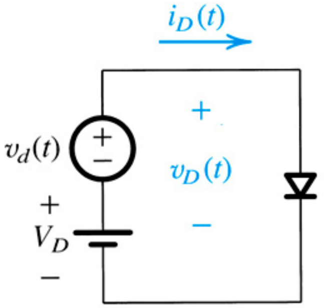


$$i_D(t) = I_{DQ} + i_d(t)$$

$$i_d(t) = I_d \cos(2\pi f t - 90°)$$

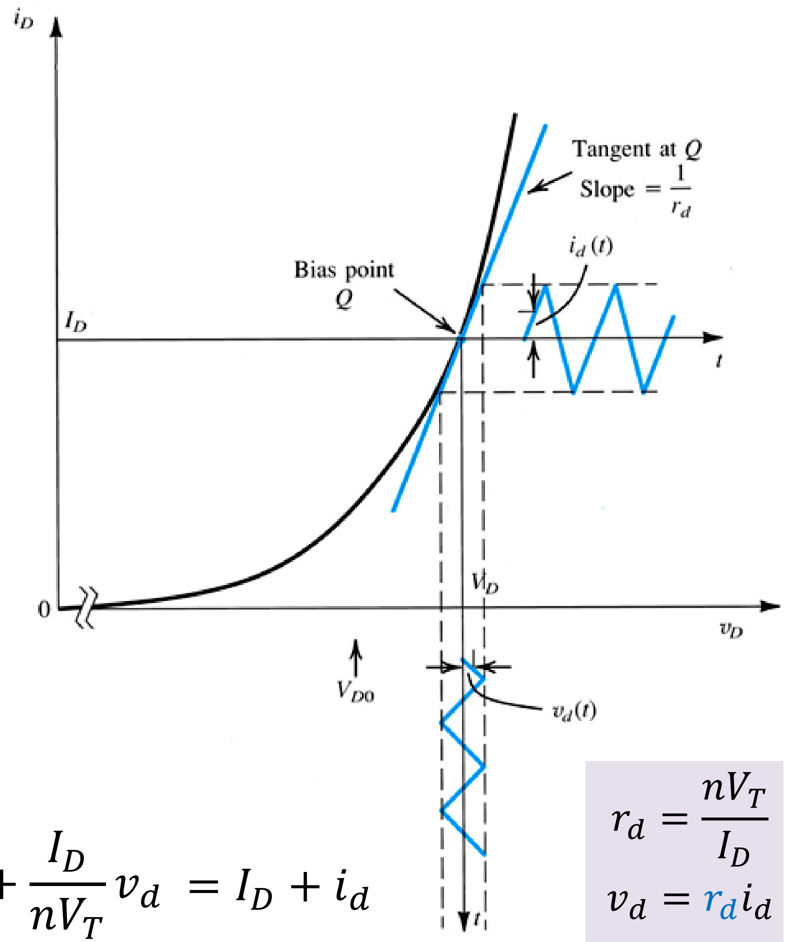
Diode Analysis – Small Signals

SMALL SIGNAL DIODE MODEL



$$v_D(t) = \overset{\text{dc}}{V_D} + \overset{\text{small-signal (ac)}}{v_d(t)}$$

$$i_D(t) = I_D + i_d(t)$$



The exponential diode characteristic in the forward region:

$$i_D = I_S\, e^{v_D/nV_T} = I_S\, e^{(V_D+v_d)/nV_T} = \underbrace{I_S\, e^{V_D/nV_T}}_{I_D}\; e^{v_d/nV_T}$$

$$i_D = I_D\, e^{v_d/nV_T}$$

Taylor series approximation: $e^x \cong 1 + x$, with $x << 1$

if $\frac{v_d}{nV_T} \ll 1$ ➡ $i_D \cong I_D\left(1 + \frac{v_d}{nV_T}\right) = I_D + \underbrace{\frac{I_D}{nV_T}}_{1/r_d} v_d = I_D + i_d$

$$r_d = \frac{nV_T}{I_D}$$

$$v_d = r_d i_d$$

dynamic resistance

So …… $i_d = \frac{I_D}{nV_T} v_d$ $\qquad$ $i_d = \frac{v_d}{r_d}$ Linear!

Diode Analysis – Small Signals

EXAMPLE 1

Calculate the **dynamic resistance** of a junction diode having $n = 1$ at a temperature of 300 K for $I_{DQ} = 0.1\text{ mA} \;\; 1\text{ mA} \;\; 10\text{ mA}$

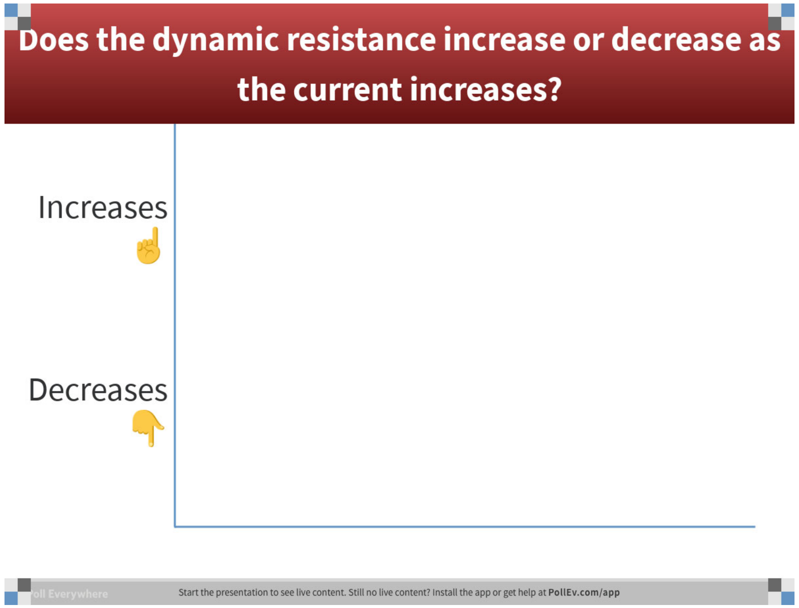
We know $r_d = \dfrac{nV_T}{I_{DQ}}$

take V_T at 300K to be 25mV

$\therefore$ if $I_{DQ} = 0.1\text{mA}$, $r_d = 250\Omega$

$I_{DQ} = 1\text{mA}$, $r_d = 25\Omega$

$I_{DQ} = 10\text{mA}$, $r_d = 2.5\Omega$

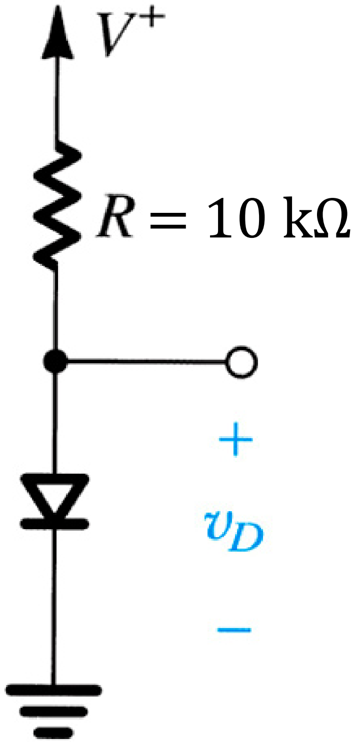


Answer: Rd decreases as IDQ increases

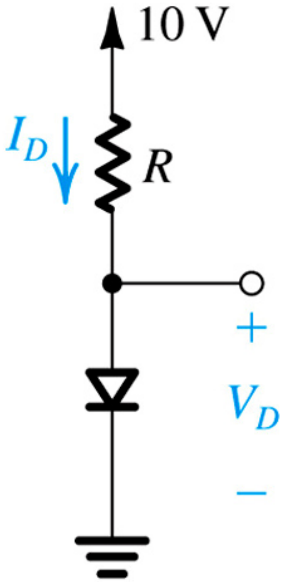
Diode Analysis – Small Signals

EXAMPLE 2 – VOLTAGE REGULATOR

The power supply of the circuit below has a dc value of +10V and a ripple of 1V. Calculate the dc voltage of the diode and its variation caused by the power supply ripple. Assume the diode to have 0.7V drop at 1 mA current and $n = 1$.



Step 1: find the DC operating point



$$I_D = \frac{10 - 0.7}{10k}$$

$$I_D = 0.93\,mA$$

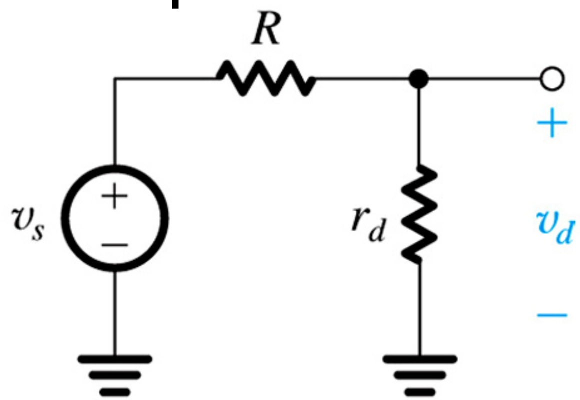
Step 2: calculate r_d

$$r_d = \frac{nV_T}{I_D}$$

$$r_d = 26.9\,\Omega$$

resistance around operating point

Step 3: ac equivalent circuit



Now we just have potential divider

$$v_d = V_s \frac{r_d}{R + r_d} = 2.68\,mV$$

Where Vs is the 1V ripple voltage (the 'small signal')

Preparation for Lab 1

LTSPICE AND ANALOG DISCOVERY 2

Preparation before the lab:

- The worksheet has been available for several days now
- Do at least the pre-lab section before coming to the timetabled support session
- Record your worksheet answers in a digital logbook and upload individual answers to the iLearn submission before 11:55pm on the day of the timetabled lab session