ECE 3020
Introduction to Electronics

Section 5: Diodes

Spring 2024

Tawfiq Musah, Assistant Professor
Dept. of Electrical & Computer Engineering
The Ohio State University

Acknowledgement

- The instructor would like to acknowledge and thank the following for kindly providing the lecture notes/handouts for this class. Some modifications and/or customizations to the original material is occasionally introduced by the instructor
  - Prof. Nima Ghalichechian
  - Prof. Asimina Kiourti
  - Prof. Ayman Fayed
  - Prof. George Valco

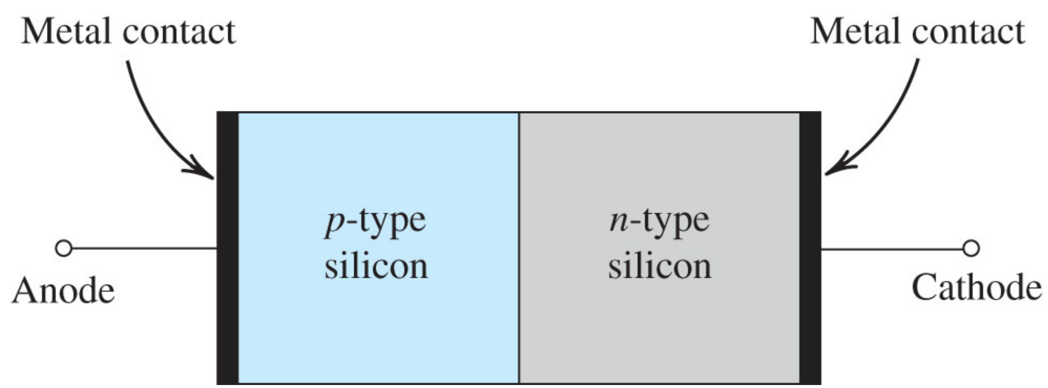
Topics Covered in this Course

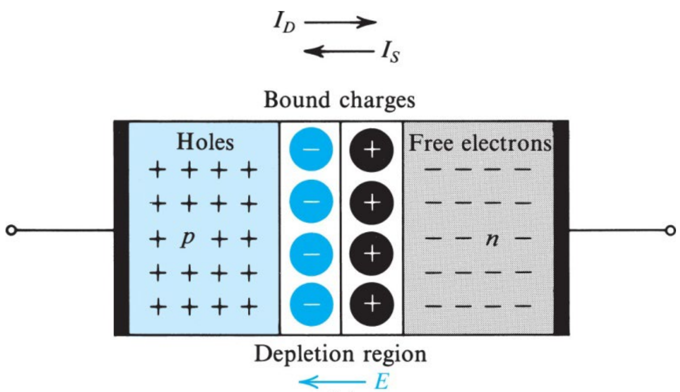
- Section 1: Basic Concepts
- Section 2: Operational Amplifiers (Op-Amps)
- Section 3: Introduction to Feedback
- Section 4: Filters
- **Section 5: Diodes and Applications**
- Section 6: Field Effect Transistors (FETs) and Applications
- Section 7: Bipolar Junction Transistors (BJTs) and Applications
- Section 8: Digital and Mixed-Signal Circuits
- Section 9: Circuit Simulation Software

Reading Assignment

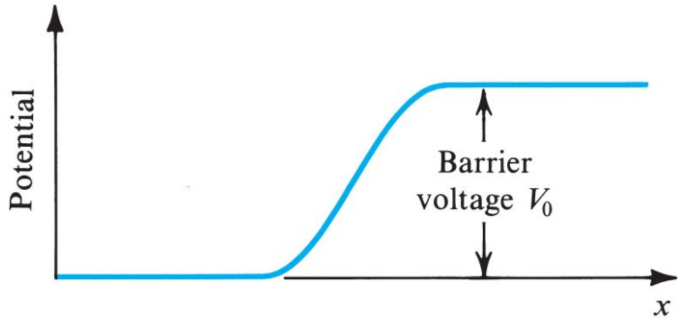
- Text → pp 175-190 (Diode terminal characteristics and models)
- Text → pp 190-200 (Diode models)
- Text → pp 200-207 (Diode application for voltage regulation; Zener diodes)
- Text → pp 207-213 (Diodes & Rectifier Circuits)

PN Junction





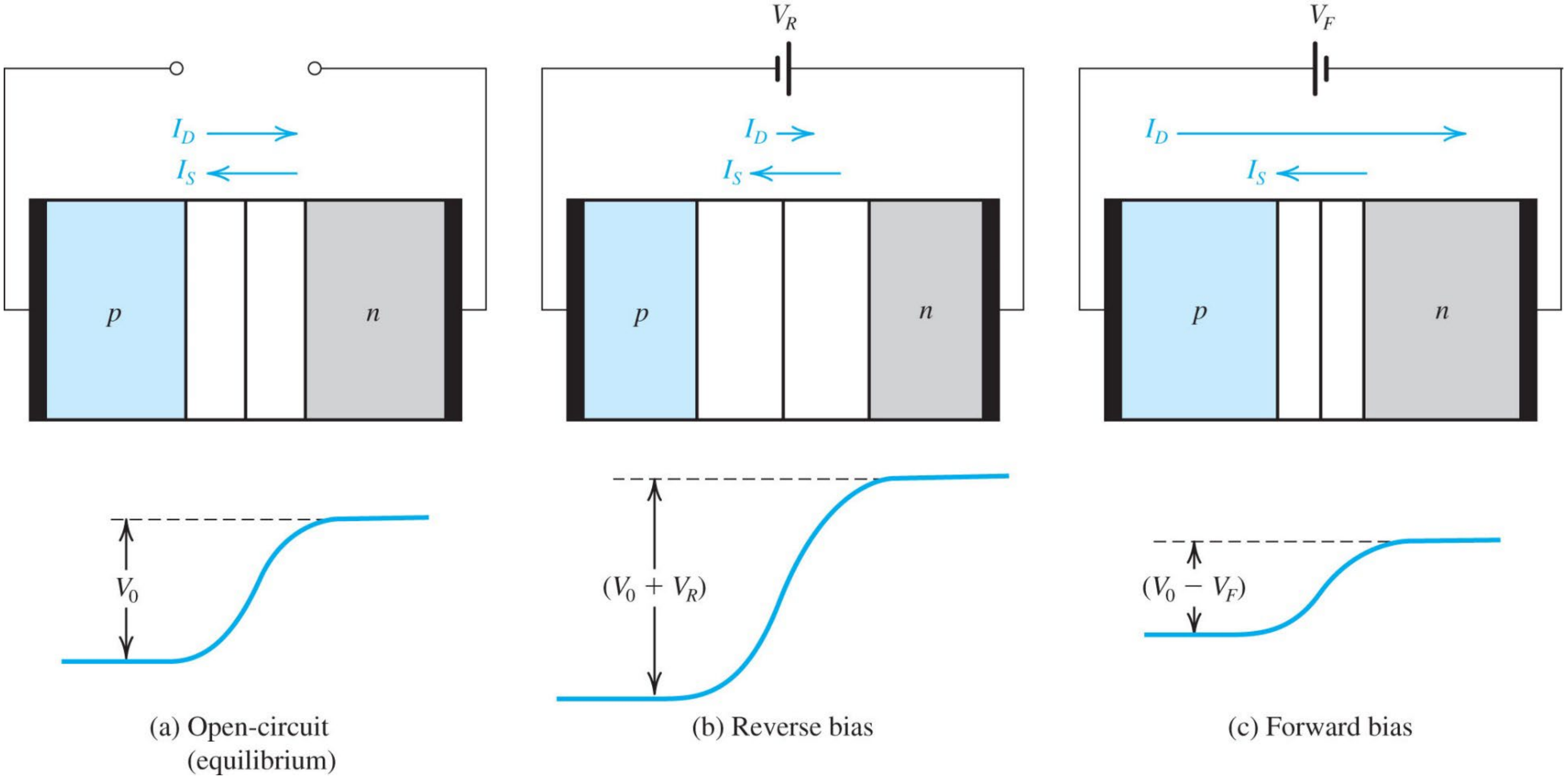
(a)



(b)

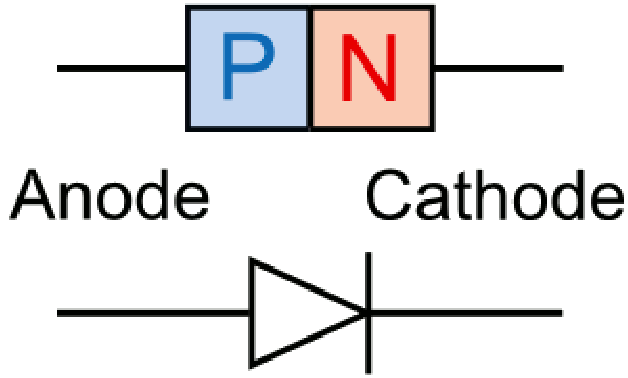
The *pn* junction with no applied voltage (open-circuited terminals). **(b)** The potential distribution along an axis perpendicular to the junction.

PN Junction

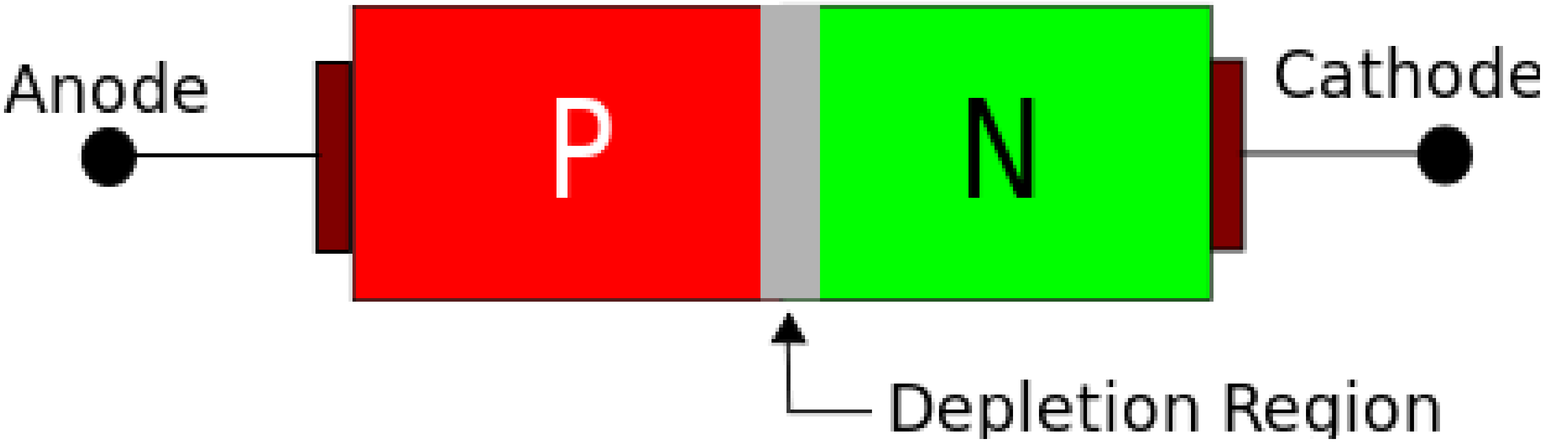


The *pn* junction in: **(a)** equilibrium; **(b)** reverse bias; **(c)** forward bias.

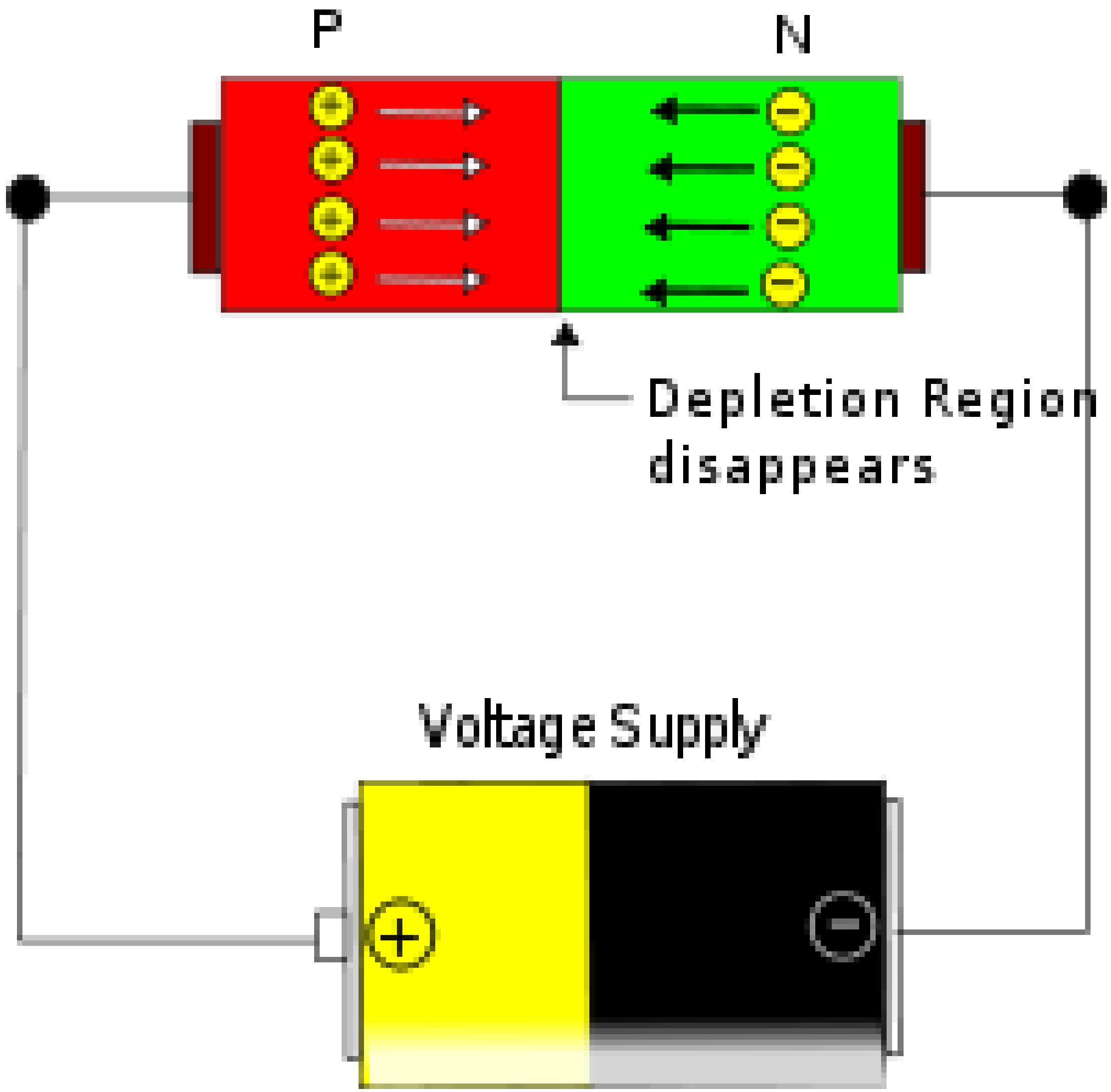
The Semiconductor Diode



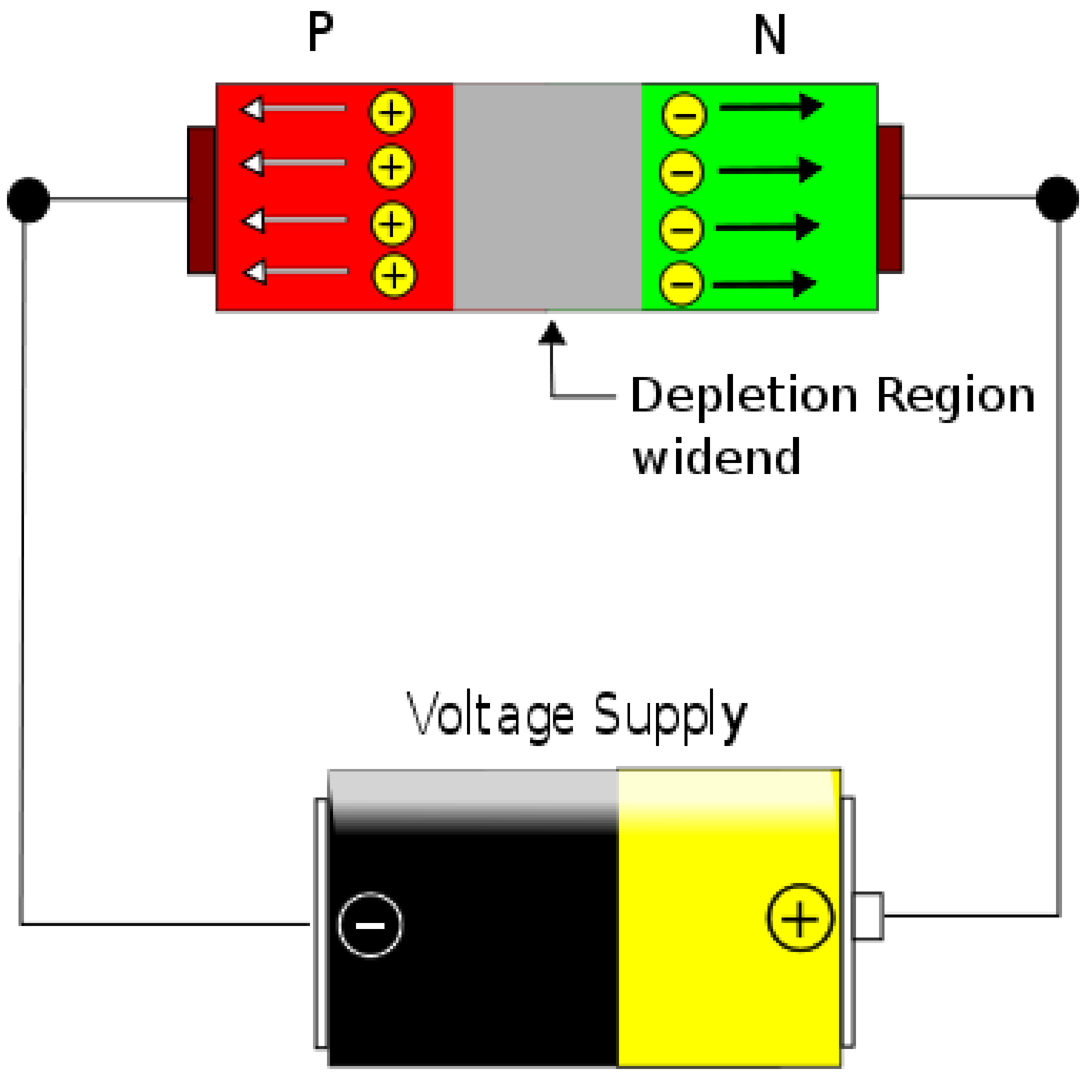
- **Forward-bias operation**
- **Reverse-bias operation**



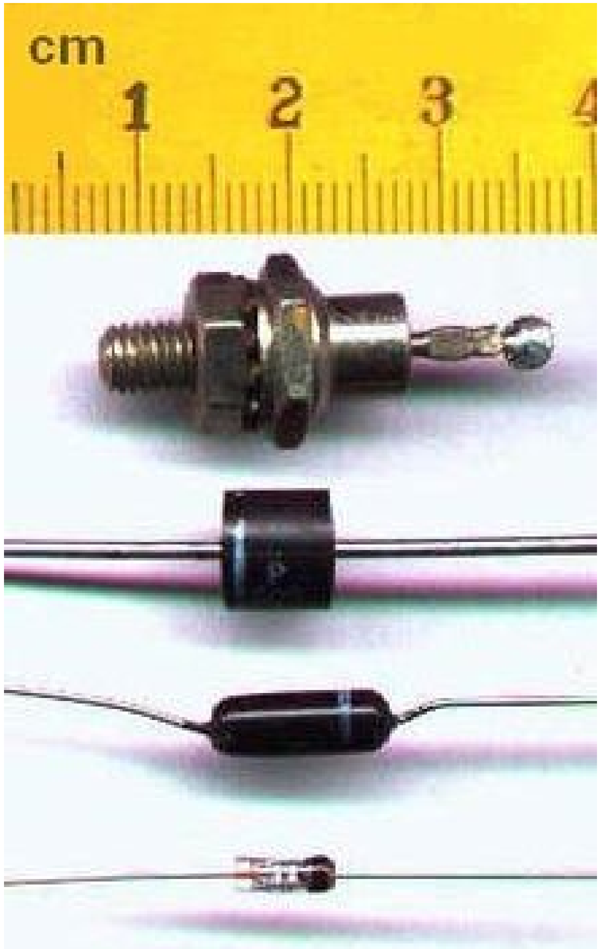
Forward Bias Operation

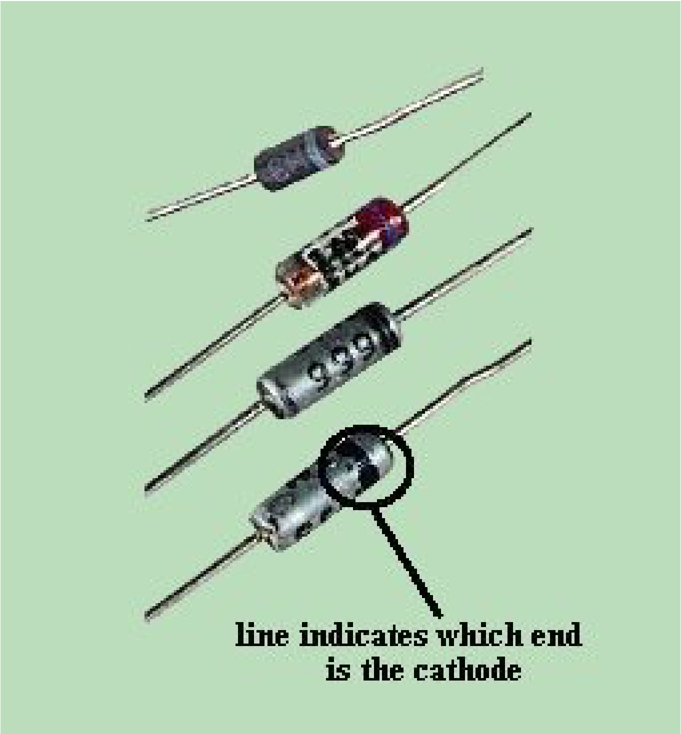


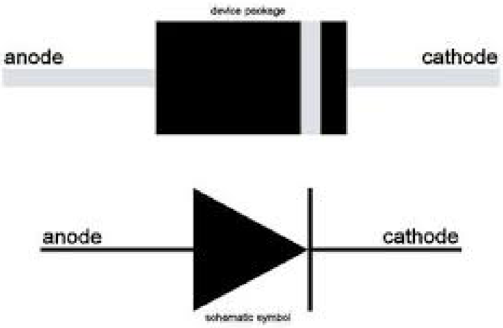
Reverse Bias Operation



Example Semiconductor Diodes



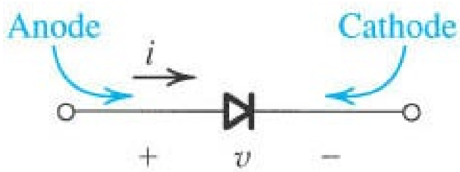




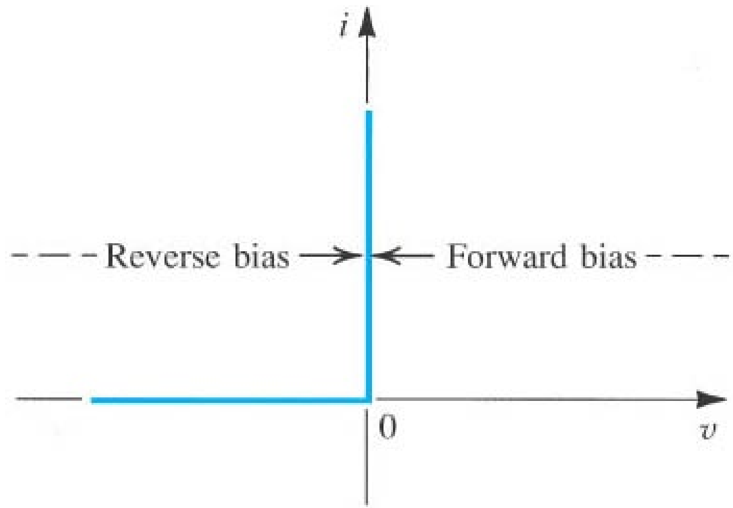
ECE 3020: Introduction to Electronics

THE IDEAL DIODE

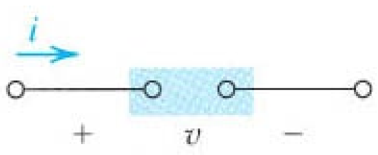
The Ideal Diode Model



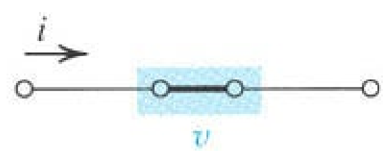
diode circuit symbol



i–*v* characteristic



equivalent circuit
reverse bias (ideal)



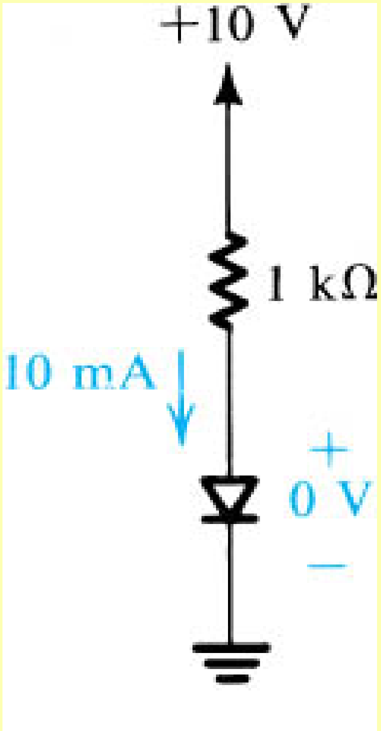
equivalent circuit
forward bias (ideal)

Exercise #1: Modes of Operation of Ideal Diodes

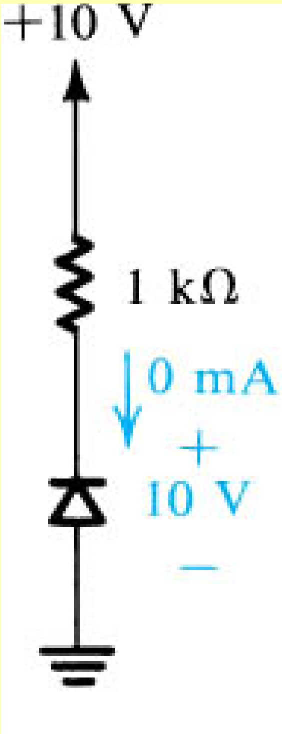
Assuming ideal diodes:

1) **What is the voltage drop and current flowing through the diode in (a)?**

2) **What is the voltage drop and current flowing through the diode in (b)?**



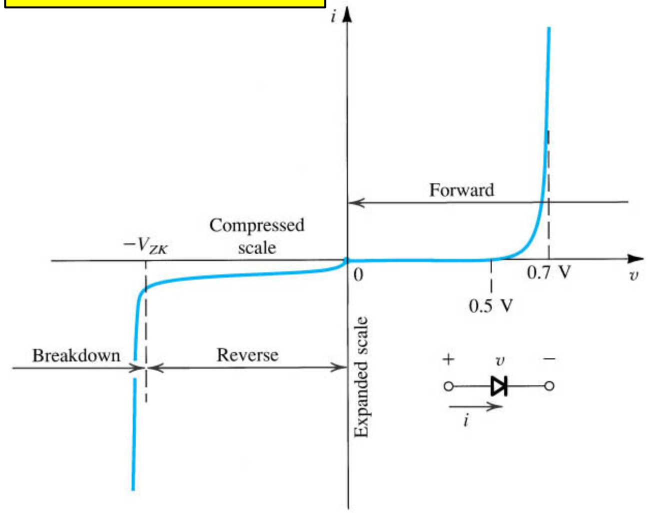
(a)



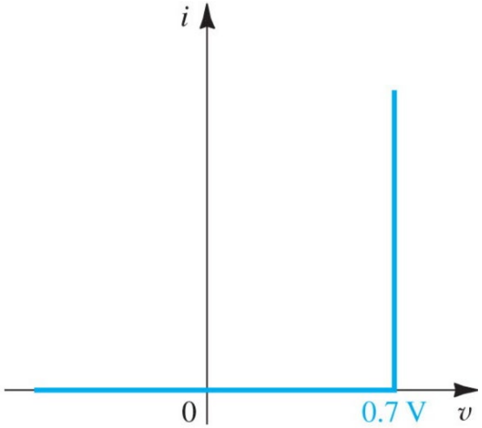
(b)

Diode Models

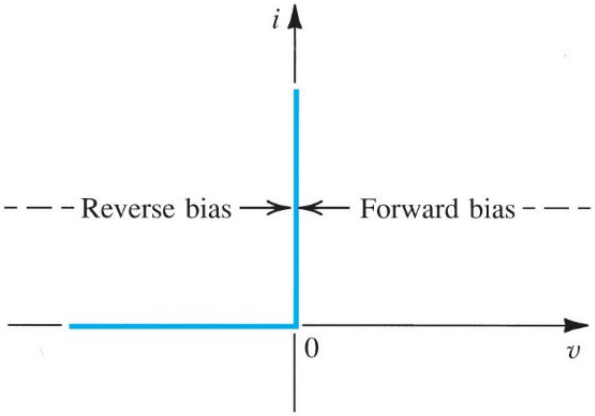
1) Real diode



2) constant-voltage-drop model



3) Ideal diode

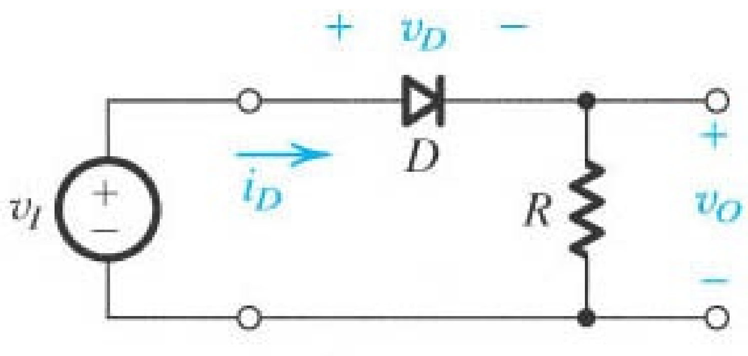


(b)

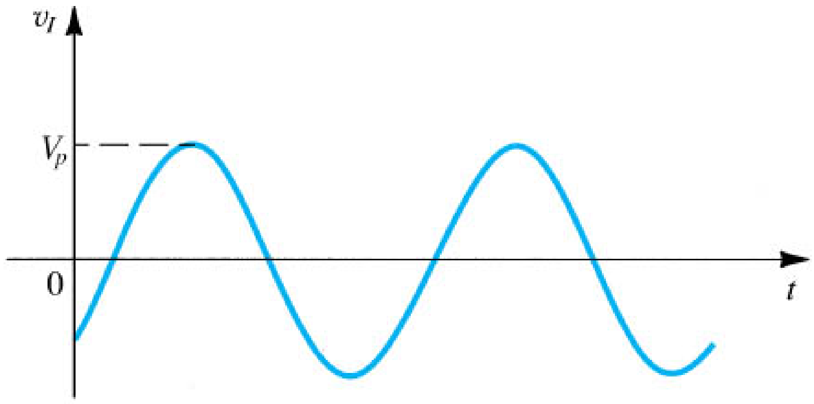
ECE 3020: Introduction to Electronics

A SIMPLE APPLICATION: THE RECTIFIER

A Simple Application: The Rectifier



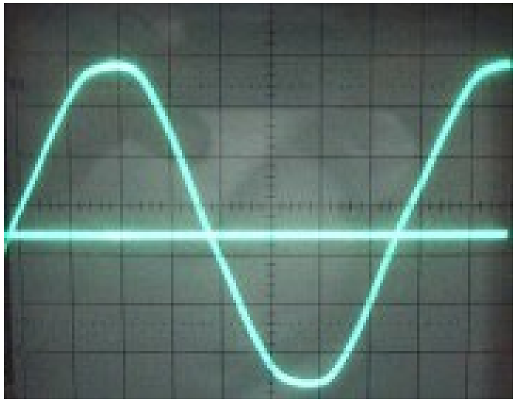
(a) Rectifier circuit



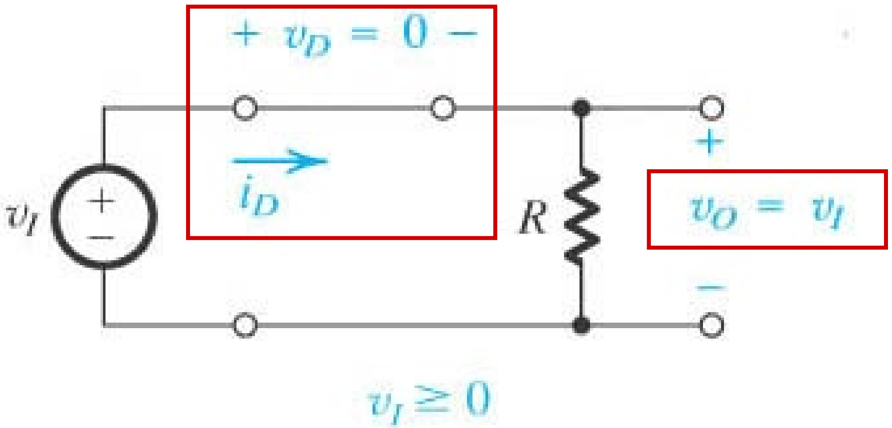
(b) Input waveform

Diode connected in series with load resistor.

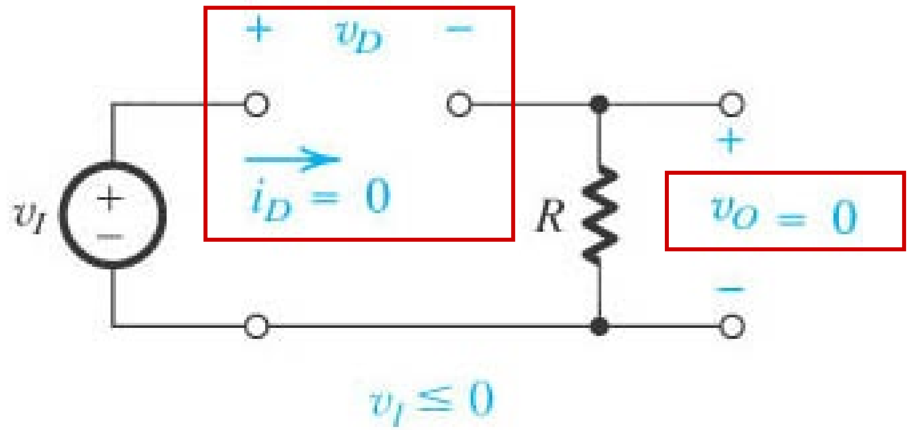
Model used for diode depends on sign of input.



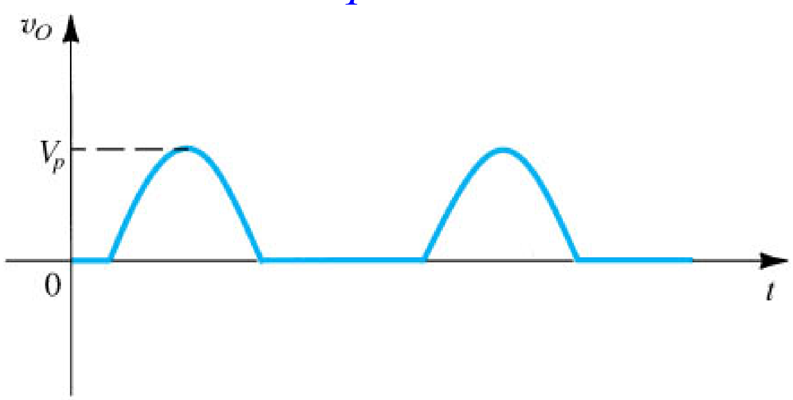
A Simple Application: The Rectifier



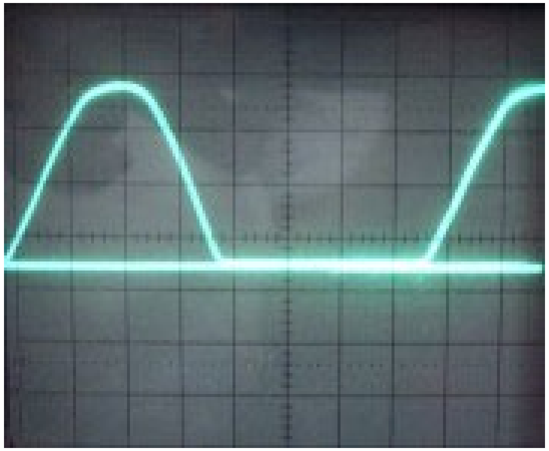
(c) Equivalent circuit when $v_I \geq 0$.



(d) Equivalent circuit when $v_I \leq 0$



(e) Output waveform

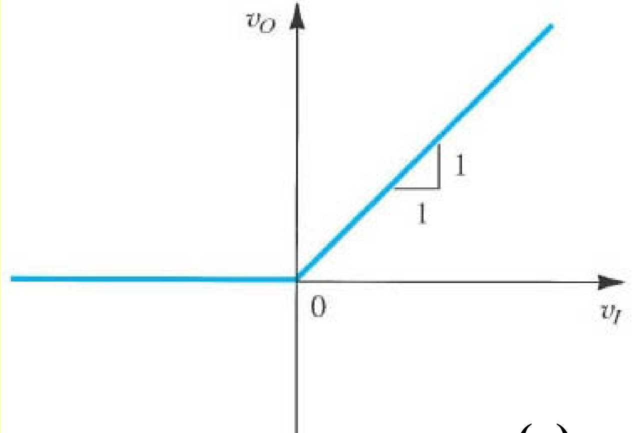


Exercise #2

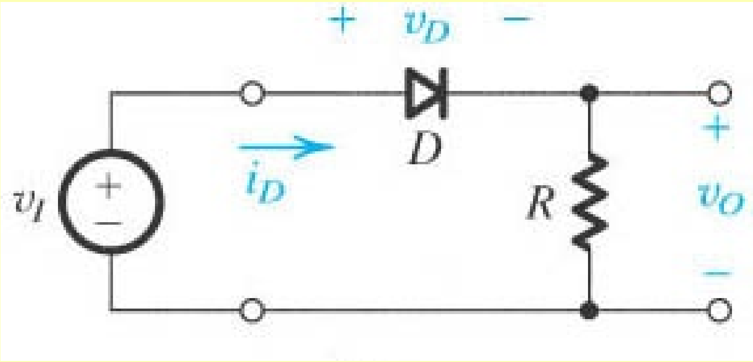
For the single-diode rectifier circuit:

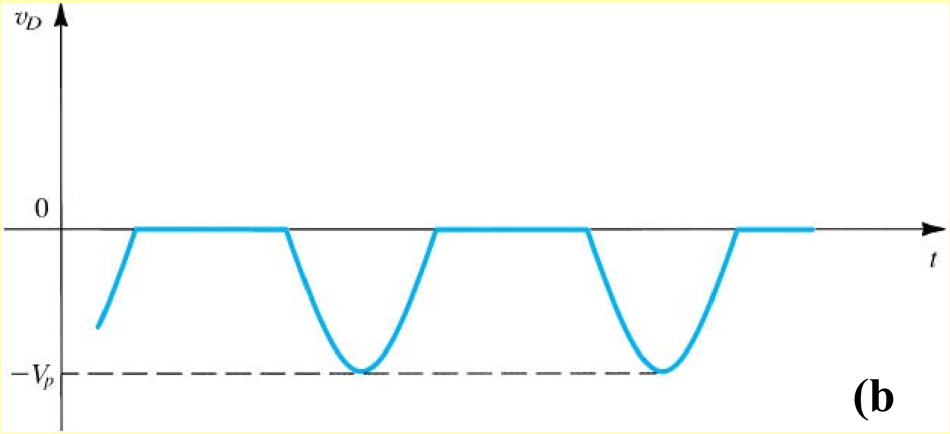
a) **Plot the transfer characteristic (v_o vs. v_I)**

b) **Plot the waveform v_D as a function of time.**



(a)



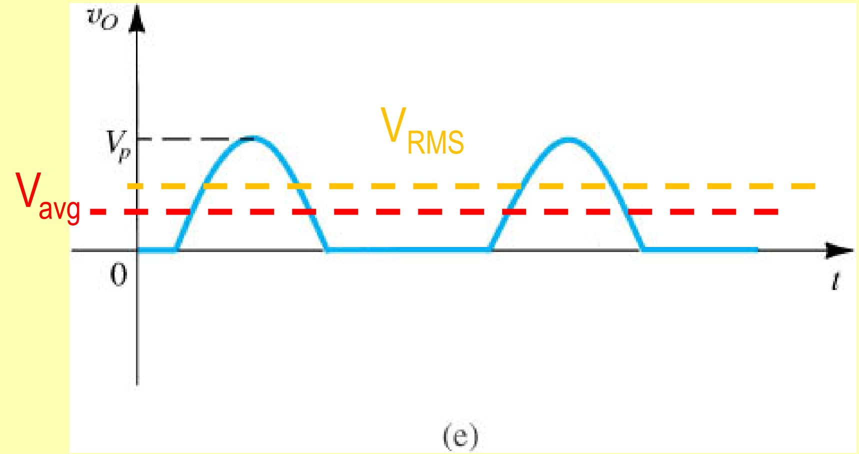


(b)

Exercise #3

For half-wave rectified sine wave with peak voltage of V_P:

1) **Find $V_{average}$ or $V_{dc.}$**
2) **Find V_{RMS}**



Ans:

$V_{average} = V_P / \pi$

$V_{RMS} = V_P / 2$

ECE 3020: Introduction to Electronics

ANALYSIS OF DIODE CIRCUITS: EDUCATED GUESS APPROACH

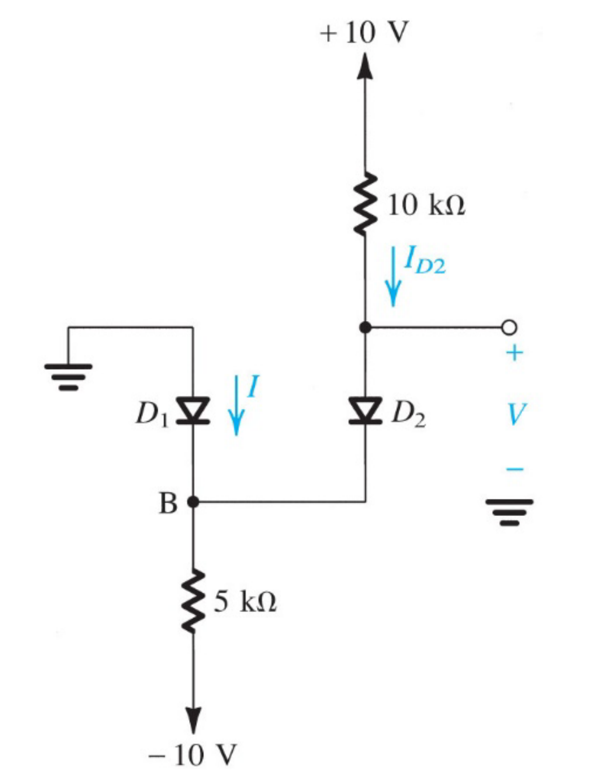
Analysis of Diode Circuits

Educated guess approach

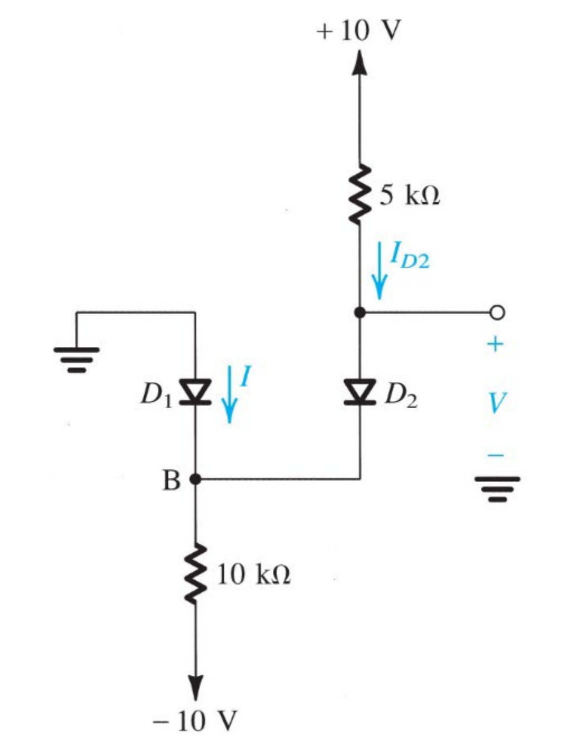
- Relies on piecewise linear nature of our diode model
  - Overall *i*-*v* characteristic of diode is extremely non-linear
  - But each section of our model is a straight line
  - If diode biased so that signal remains in one section ⇒ may use linear analysis
  - If signal crosses break-point linear analysis may not be used
- Make assumptions about "on" or "off" state of each diode
- Analyze circuit and verify assumptions by checking internal consistency
  - If consistent ⇒ done!
  - If inconsistent ⇒ learn from results and revise educated guess

Exercise #4 (solutions provided)

Use the ideal diode model (for Exercise 4-8) to find the labeled unknown voltages and currents.



(a)



(b)

Solutions: Exercise # 4 -7

Exercise # 4

ID_2= 1 mA, I=1 mA, V=0 V
ID_2= 1.3 mA, I=0 mA, V=3.3 V

Exercise #5

V= 3 V, I_1= 4 mA, I_2 = – 0.8 mA

Exercise #6

a) 2 mA and 0 V

b) 0 mA and 5 V

c) 0 mA and – 5 V

d) 2 mA and 0 V

e) 3 mA and 3 V

f) 4 mA and 1 V

Exercise #7

a) 0.6 mA and – 3 V

b) 0 mA and 3 V

c) 0.6 mA and +3 V

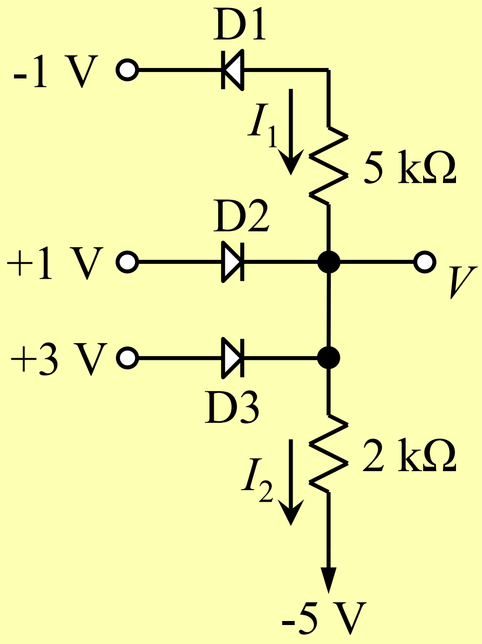
d) 0 mA and – 3 V

e) 2.5 mA and 2 V

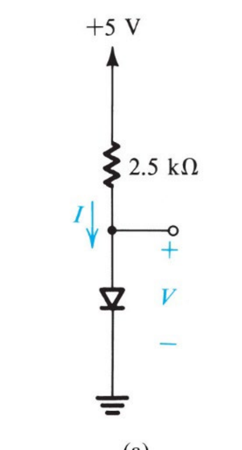
f) 1 mA and 1 V

Exercise #5

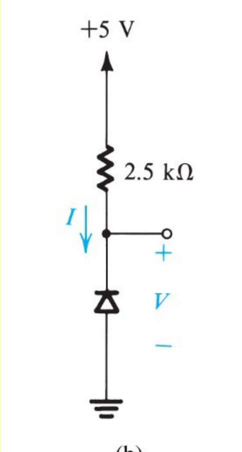
Use the ideal diode model (for Exercise 4-8) to find the labeled unknown voltages and currents.



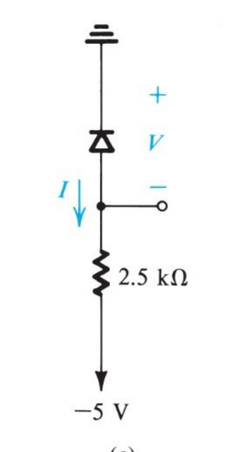
Exercise #6



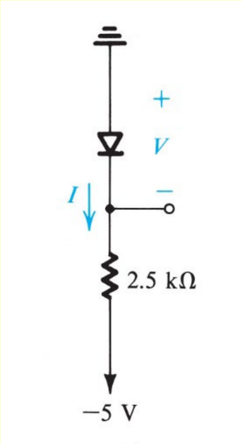
(a)



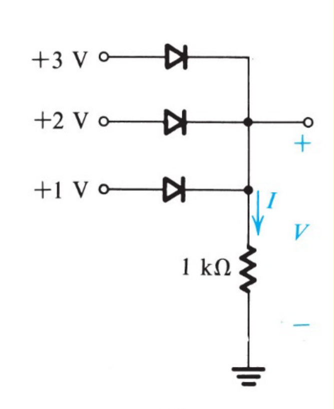
(b)



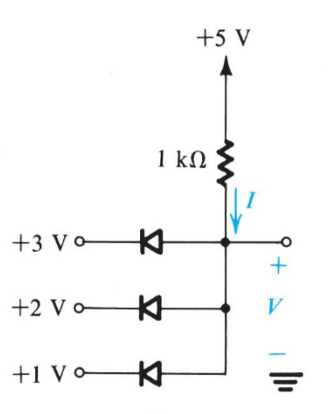
(c)



(d)

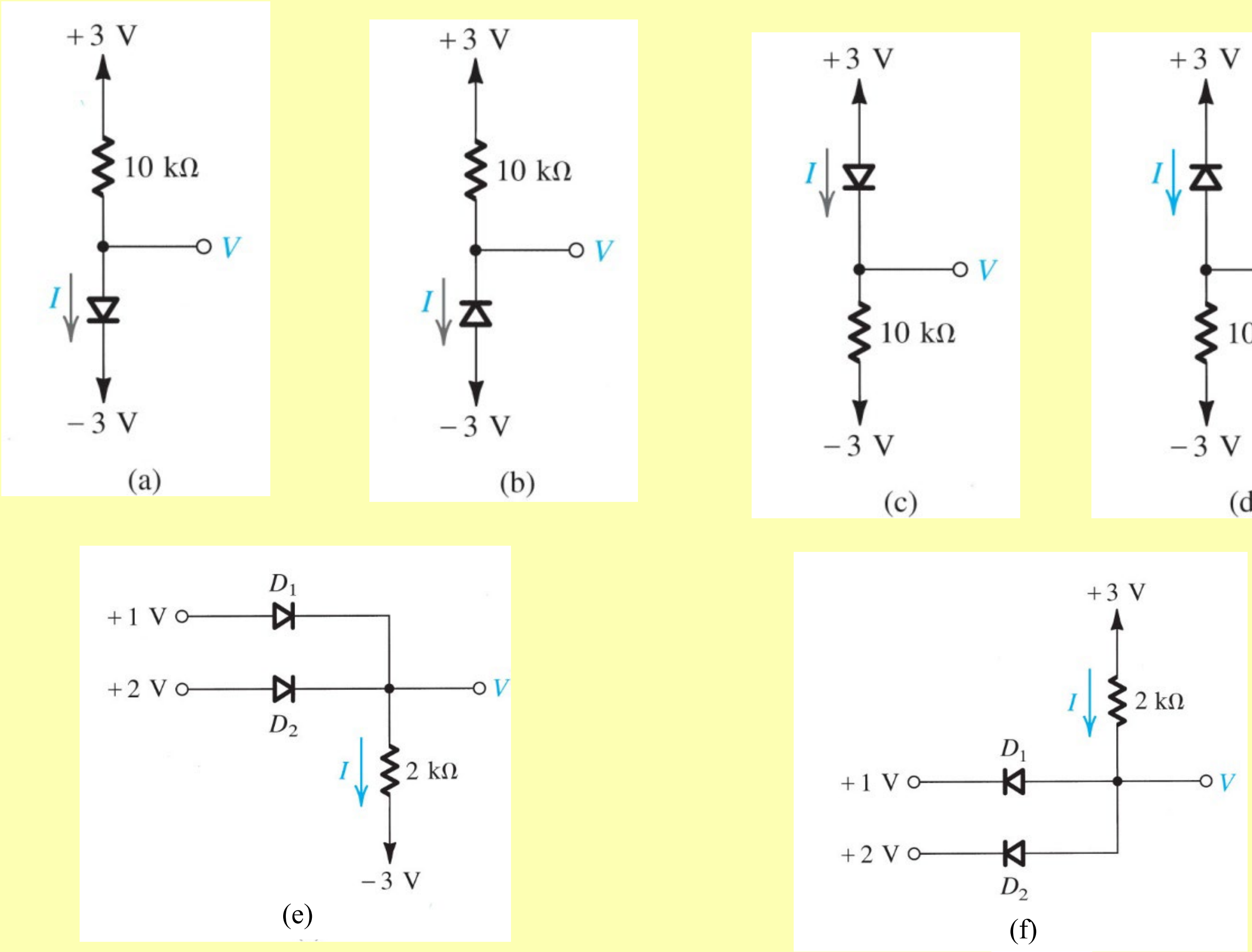


(e)



(f)

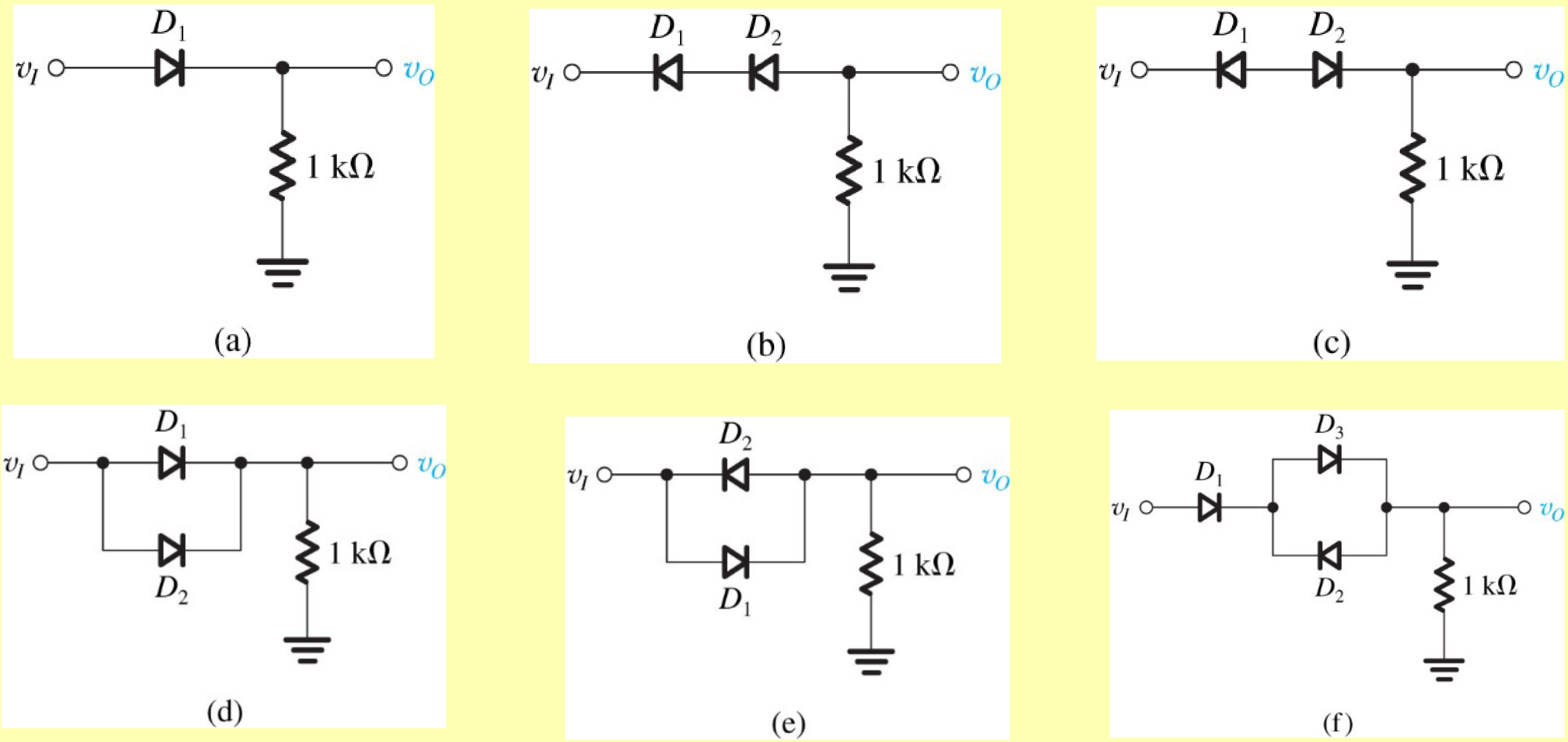
Exercise #7



+3 V
10 kΩ
V
I
−3 V
(a)
+3 V
10 kΩ
V
I
−3 V
(b)
+3 V
I
V
10 kΩ
−3 V
(c)
+3 V
I
V
10 kΩ
−3 V
(d)
D1
+1 V
+2 V
D2
V
I
2 kΩ
−3 V
(e)
+3 V
I
2 kΩ
D1
+1 V
V
+2 V
D2
(f)

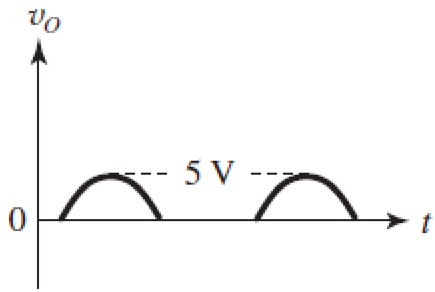
Exercise #8

Assume: v_i is 1 kHz, 5V peak sine wave. Find v_o.



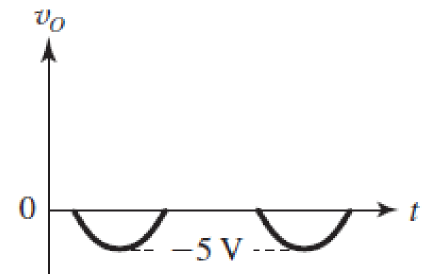
Exercise #8: Solution

(a)



$V_{p+} = 5$ V $V_{p-} = 0$ V $f = 1$ kHz

(b)



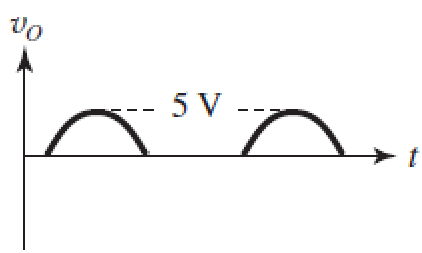
$V_{p+} = 0$ V $V_{p-} = -5$ V $f = 1$ kHz

(c)

$v_O = 0$ V

Neither D_1 nor D_2 conducts, so there is no output.

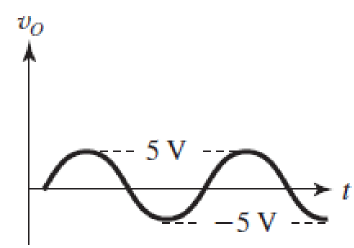
(d)



$V_{p+} = 5$ V, $V_{p-} = 0$ V, $f = 1$ kHz

Both D_1 and D_2 conduct when $v_I > 0$

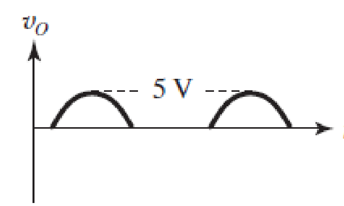
(e)



$V_{p+} = 5$ V, $V_{p-} = -5$ V, $f = 1$ kHz

D_1 conducts when $v_I > 0$ and D_2 conducts when $v_I < 0$. Thus the output follows the input.

(f)

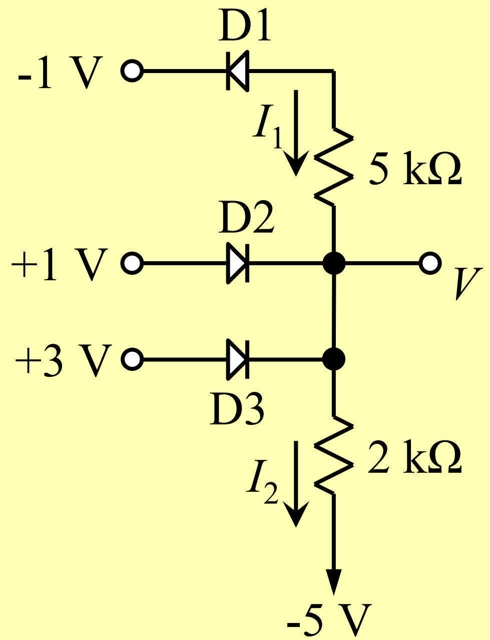


$V_{p+} = 5$ V, $V_{p-} = 0$ V, $f = 1$ kHz

Exercise #9: Non-ideal Diodes

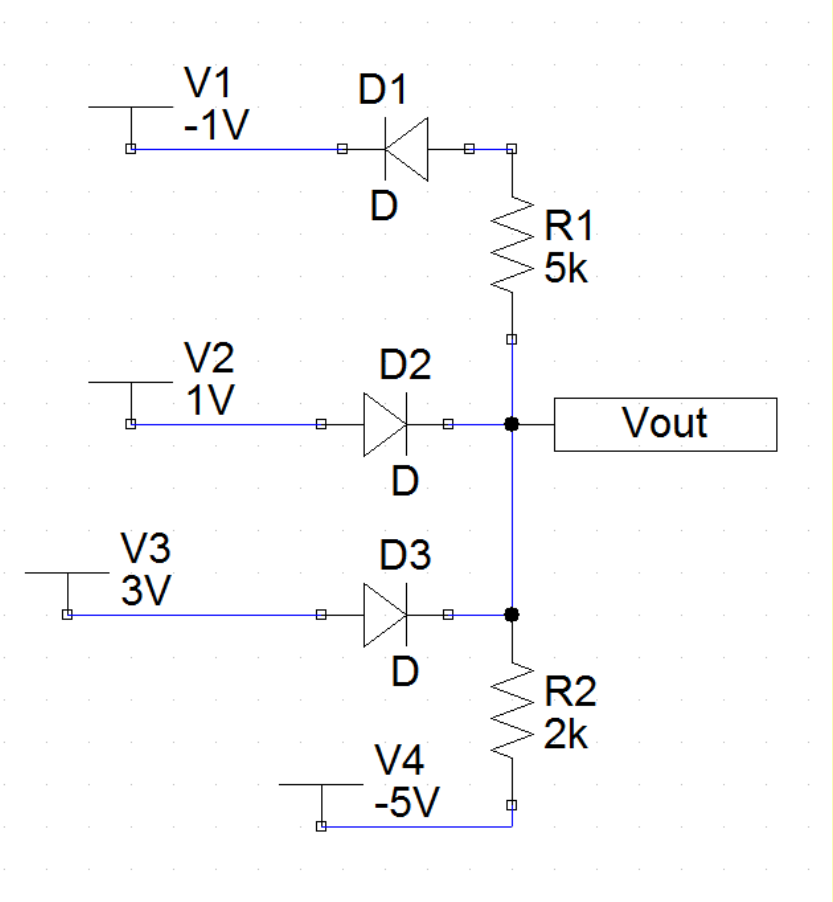
Find V, I_1 and I_2 (use: constant voltage model of 0.7 V)

Compare your results to Exercise #5.



Ans: I_1= – 0.52 mA, I_2= 3.65 mA, V=2.3 V

Exercise #10: Spice Verification



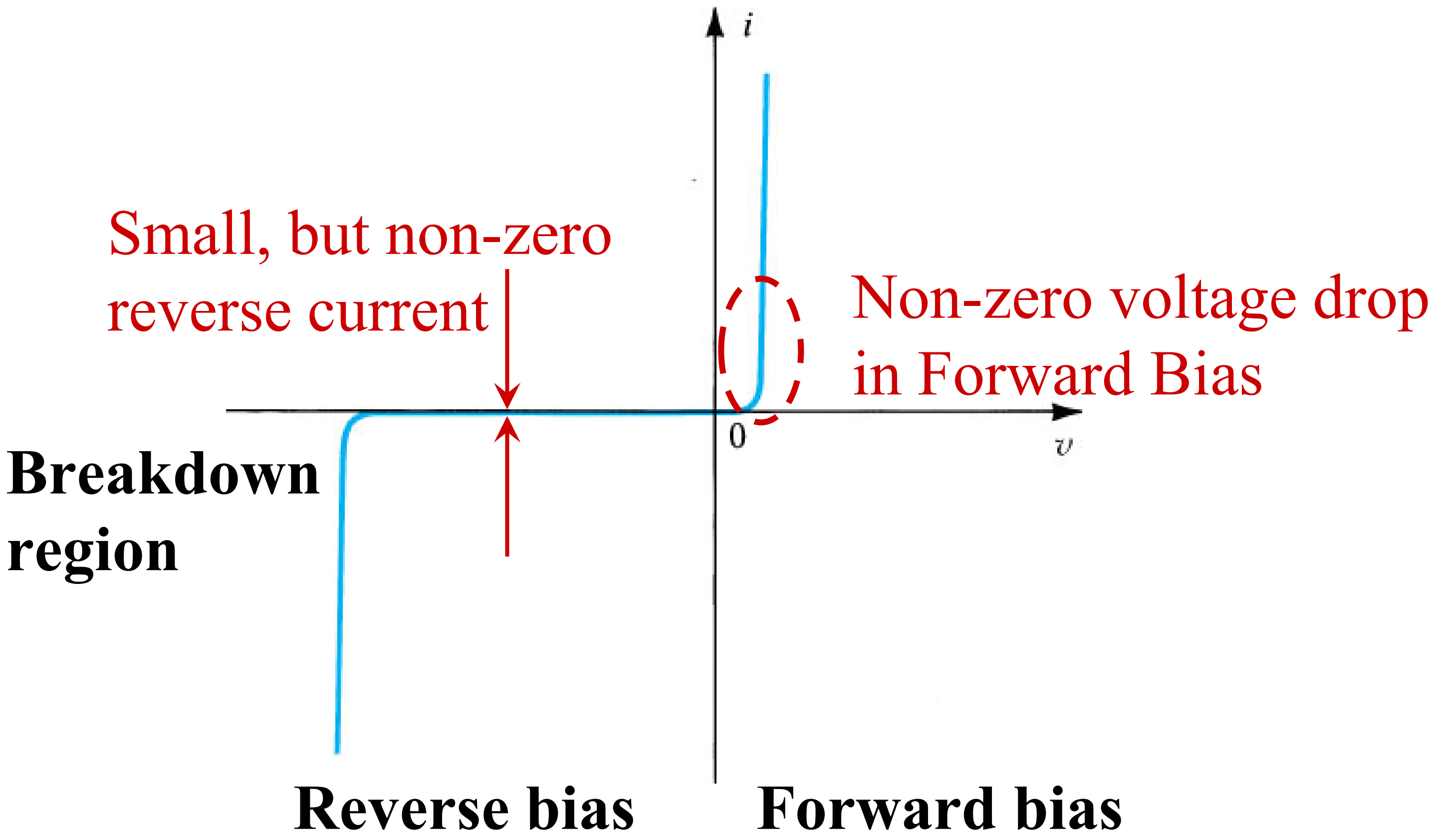

```
SMALL SIGNAL BIAS SOLUTION        TEMPE

************************************

     NODE         VOLTAGE

     V(1)       -3.61136484E-01
    V(V1)       -1.00000000E+00
    V(V2)        1.00000000E+00
  V(VOUT)        2.30785900E+00
    V(V3)        3.00000000E+00
    V(V4)       -5.00000000E+00

   SOURCE         CURRENT

    I(V2)        1.31785889E-12
    I(V3)       -4.18772860E-03
    I(V4)        3.65392950E-03
    I(V1)        5.33799096E-04

   RESISTOR        CURRENT

    I(R1)        5.33799096E-04
    I(R2)        3.65392950E-03
```

Compare your results to Exercise #9.

ECE 3020: Introduction to Electronics

REAL DIODES

Terminal Characteristics of Real Diodes



ECE 3020: Introduction to Electronics

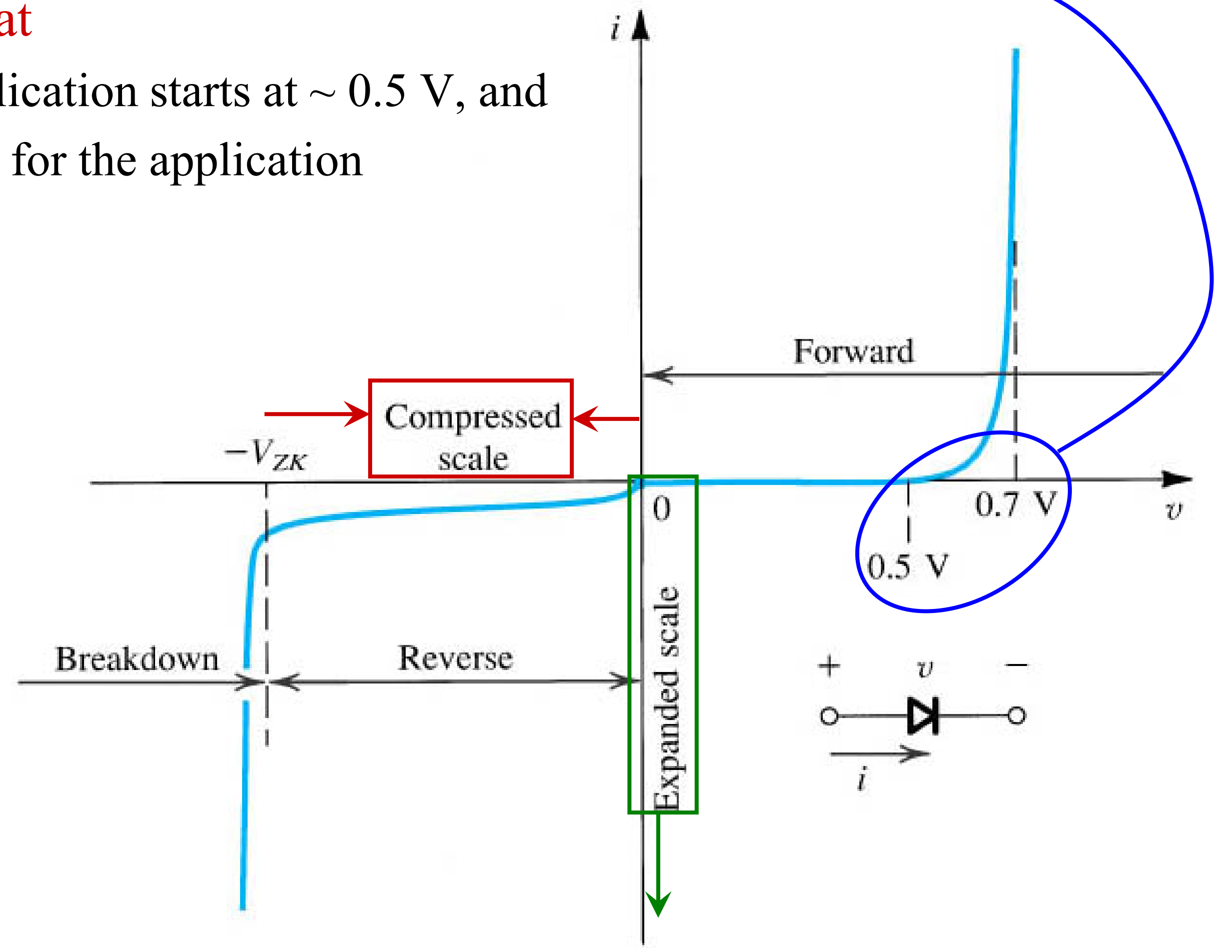
REAL DIODES:
THE FORWARD BIAS REGION

Terminal Characteristics of Real Diodes

Forward current is actually ~exponential, but

Diode typically sized so that

- Significant current for application starts at ~ 0.5 V, and
- By ~0.7 V, current is large for the application



The Forward Bias Region

$$i = I_S\left[\exp\left(\frac{v}{nV_T}\right) - 1\right]$$

- $I_S(T)$ "saturation" current (proportional to diode area)
- $V_T = kT/q$ is the thermal voltage
  - k is Boltzmann's constant

$= 1.38\times10^{-23}$ J/K
$= 8.617 \times 10^{-5}$ eV/K

  - T is the diode temperature (Kelvin)
  - q is the electron charge: 1.6×10^{-19} C = 1 e

- $I_S(T)$ "rule of thumb" $\Rightarrow$ doubles for each ~ +5° C ΔT
- V_T = 25 mV at 17°C; 25.2 mV at 20°C; 25.9 mV at 300 K
- n = 1 to 2 (ideality factor) [assume 1 unless otherwise specified]

The Forward Bias Region

$$i = I_S \exp\left(\frac{v}{nV_T}\right) \quad \text{for} \quad \boxed{i >> I_S}$$

Solving for v:

$$v = nV_T \ln\left(\frac{i}{I_S}\right) \quad = 2.3\ nV_T \log\left(\frac{i}{I_S}\right) \quad \text{using} \quad \frac{1}{\log(e)} = 2.3$$

$2.3\ nV_T = 60$ or 120 mV for $n = 1$ or 2 respectively at 20 °C

Logarithmic Rate of Change

Consider two different voltages; V_1 and V_2 (assume n=1)

$$I_1 = I_S \exp\left(\frac{V_1}{V_T}\right) \qquad I_2 = I_S \exp\left(\frac{V_2}{V_T}\right)$$

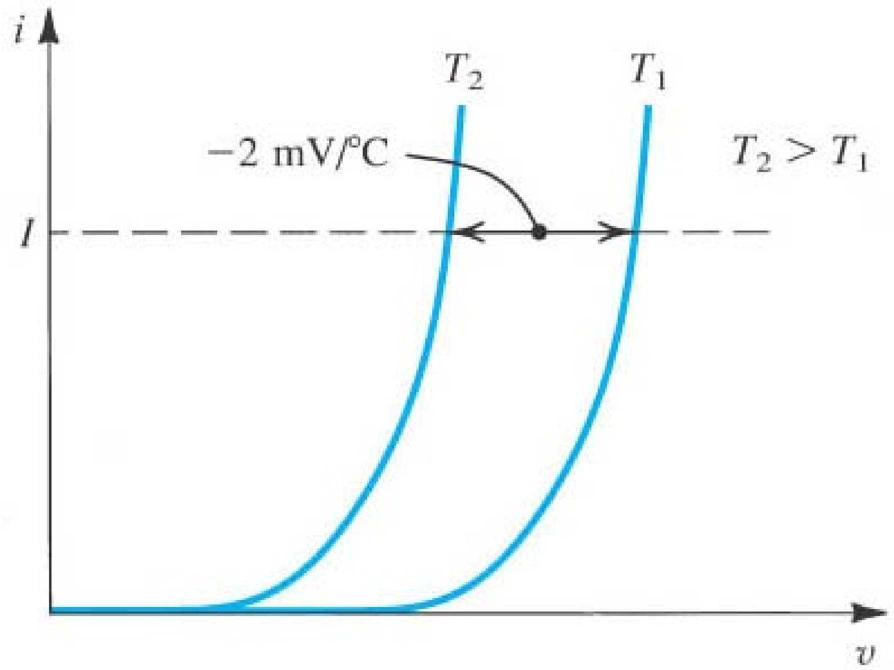
We have: $V_2 - V_1 = 2.3\, V_T \log\left(\frac{I_2}{I_1}\right)$

If diode is sized such that at 0.7 V the current is 1 mA

V	I
0.7 V	1 mA
0.758 V	10 mA

So for a decade change of current, we have $2.3\ V_T \approx 60$ mV change in voltage

Temperature Dependence of Diode Forward Characteristic



At a constant current, the voltage drop decreases by approximately 2 mV for every 1°C increase in temperature

ECE 3020: Introduction to Electronics

REAL DIODES:
THE REVERSE BIAS REGION

Reverse-Bias Region

Starting from: $$i = I_S\left[\exp\left(\frac{v}{nV_T}\right) - 1\right]$$

If v is made negative and a few times larger than V_T: $$\boxed{i \approx -I_S}$$

Hence the name "saturation" current
(a.k.a. *reverse* saturation current)

I_S is typically 10^{-15} to 10^{-14} A (1 to 10 fA)
Real diodes have larger "leakage" current: e.g. 1 nA
But depends on diode size

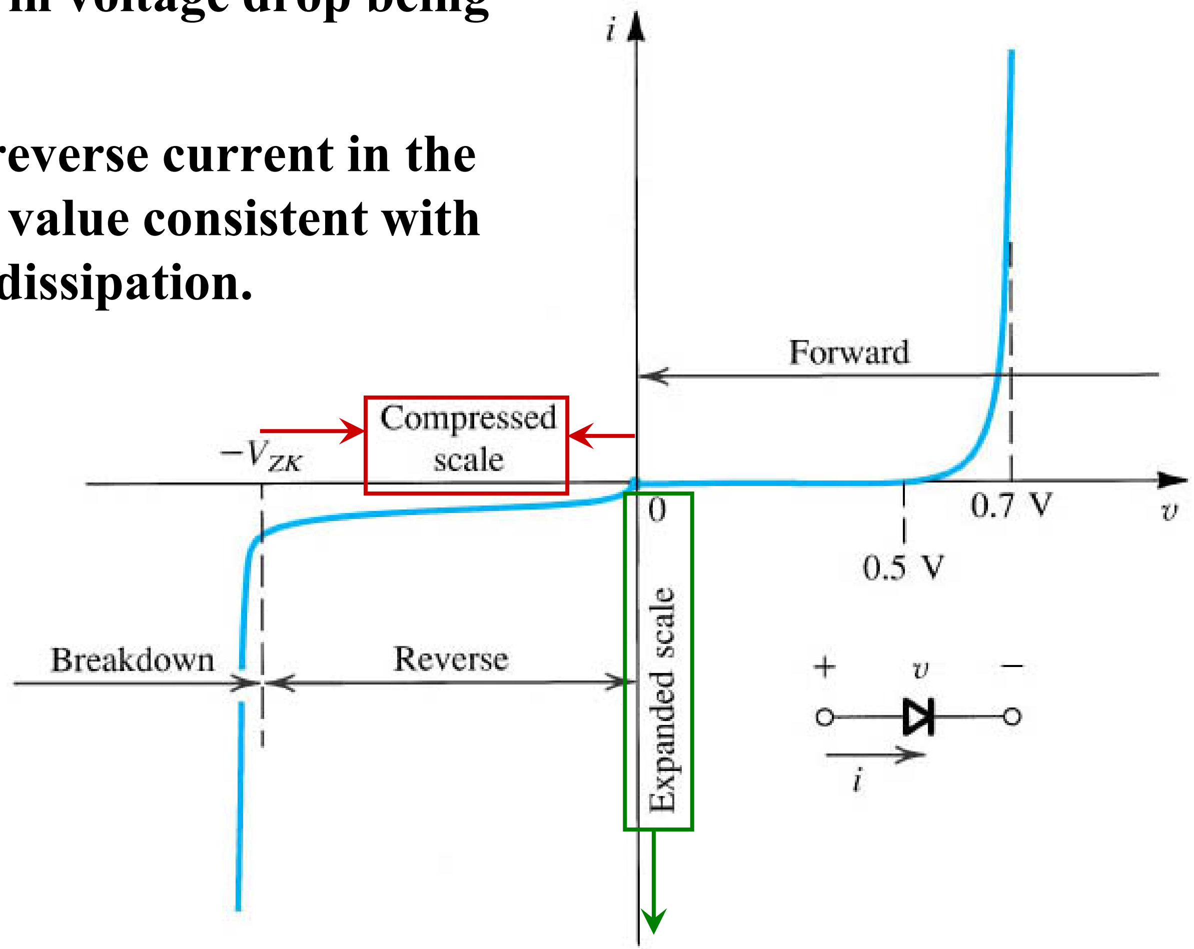
While I_S doubles every ~ 5°C rise in T
Leakage current doubles every ~10°C rise in T

ECE 3020: Introduction to Electronics

REAL DIODES:
THE BREAKDOWN REGION

The Breakdown Region

- The reverse current increases rapidly, with the associated increase in voltage drop being very small.
- Necessary to limit the reverse current in the breakdown region to a value consistent with the permissible power dissipation.

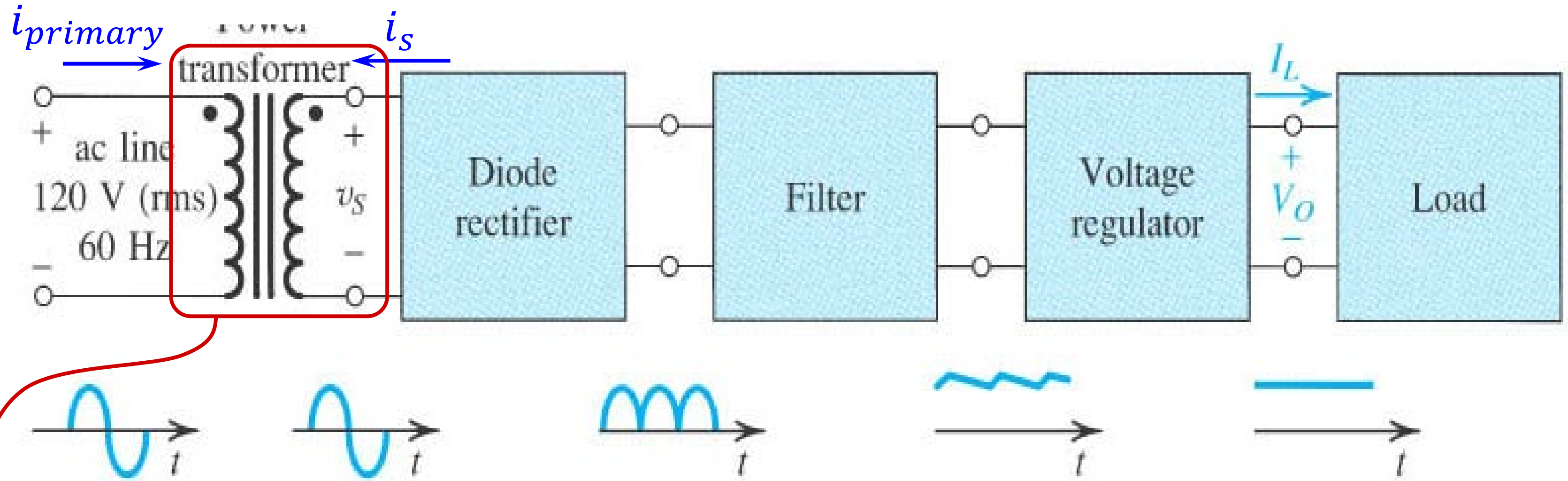


ECE 3020: Introduction to Electronics

RECTIFIER CIRCUITS

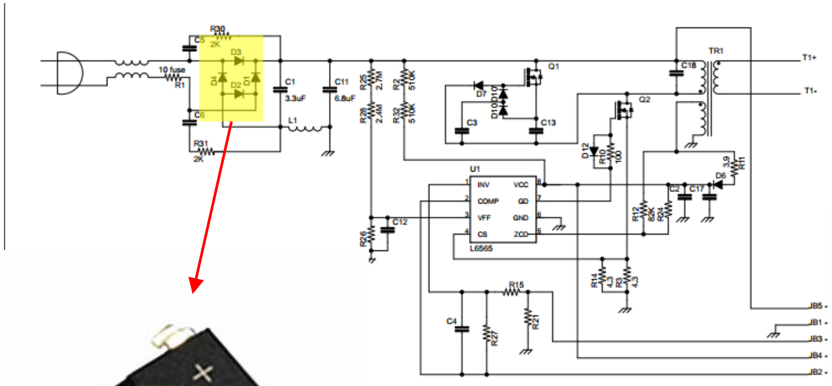
Rectifier Circuits

Block diagram of a dc power supply



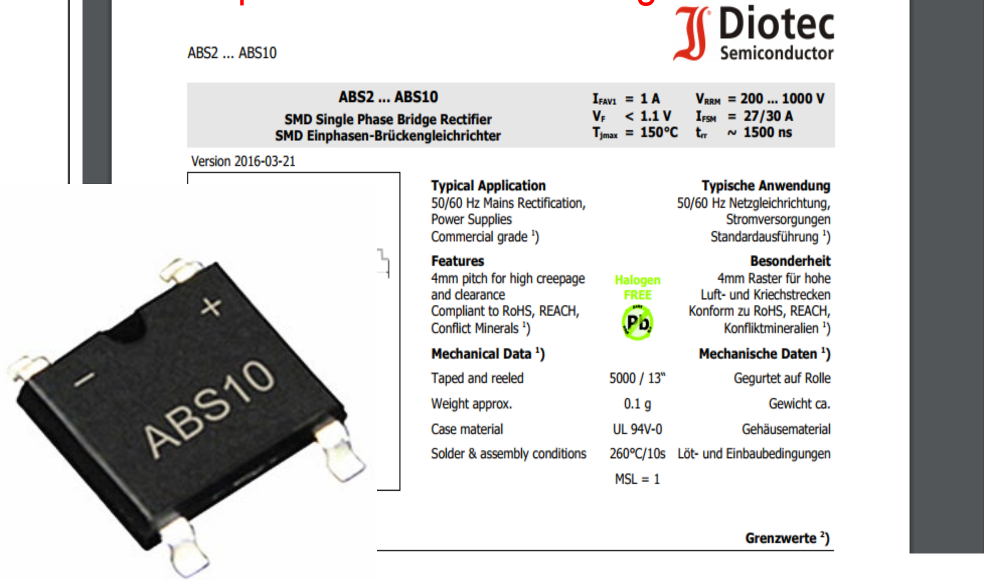
- Two separate coils wound on iron core that couples magnetic flux between coils
- Primary: N_1 turns [e.g. 120 V(rms) line supply]
- Secondary: N_2 turns
  - Ideally: $v_s = \frac{N_2}{N_1} v_{primary}$; $i_s = \pm \frac{N_1}{N_2} i_{primary}$ (+ for ref. direction into dots)
  - E.g. $\frac{N_2}{N_1} = \frac{1}{6}$ turns ratio yields $v_s = 20$ V(rms)

Example: iPhone Charger



Example of bridge application

Example of Commercial Bridge Diode



Diotec Semiconductor

ABS2 ... ABS10

ABS2 ... ABS10

SMD Single Phase Bridge Rectifier

SMD Einphasen-Brückengleichrichter

I_{FAV1} = 1 A **V_{RRM} = 200 ... 1000 V**

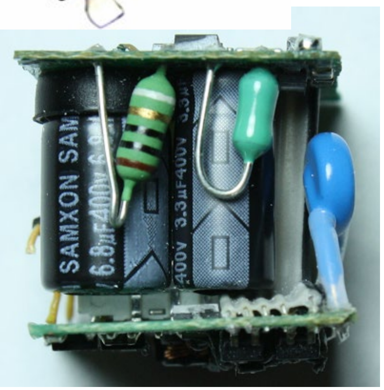
V_F < 1.1 V **I_{FSM} = 27/30 A**

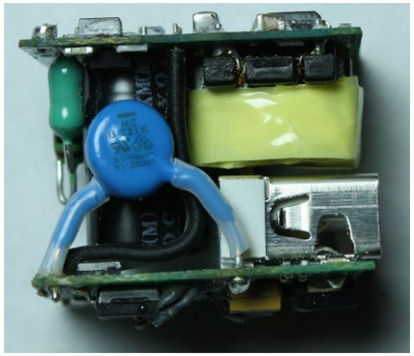
T_{jmax} = 150°C **t_{rr} ~ 1500 ns**

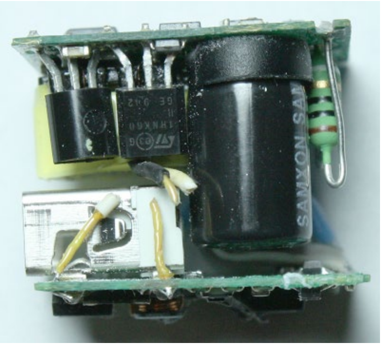
Version 2016-03-21

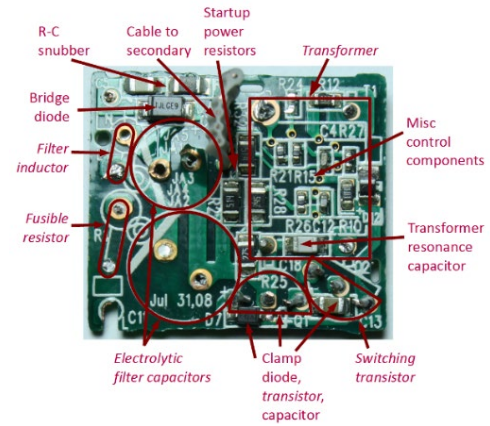
Typical Application 50/60 Hz Mains Rectification, Power Supplies Commercial grade [1])		**Typische Anwendung** 50/60 Hz Netzgleichrichtung, Stromversorgungen Standardausführung [1])
Features 4mm pitch for high creepage and clearance Compliant to RoHS, REACH, Conflict Minerals [1])	Halogen FREE Pb	**Besonderheit** 4mm Raster für hohe Luft- und Kriechstrecken Konform zu RoHS, REACH, Konfliktmineralien [1])
Mechanical Data [1])		**Mechanische Daten [1])**
Taped and reeled	5000 / 13"	Gegurtet auf Rolle
Weight approx.	0.1 g	Gewicht ca.
Case material	UL 94V-0	Gehäusematerial
Solder & assembly conditions	260°C/10s MSL = 1	Löt- und Einbaubedingungen

Grenzwerte [2])



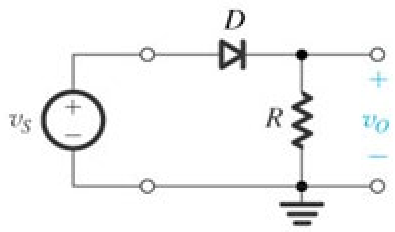




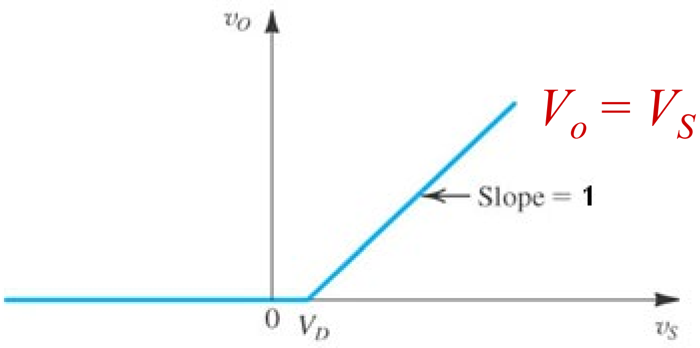


http://www.righto.com/2012/05/apple-iphone-charger-teardown-quality.html

[1] The Half-Wave Rectifier



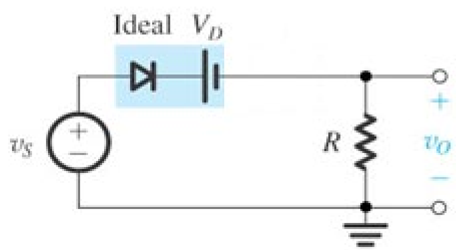
(a)



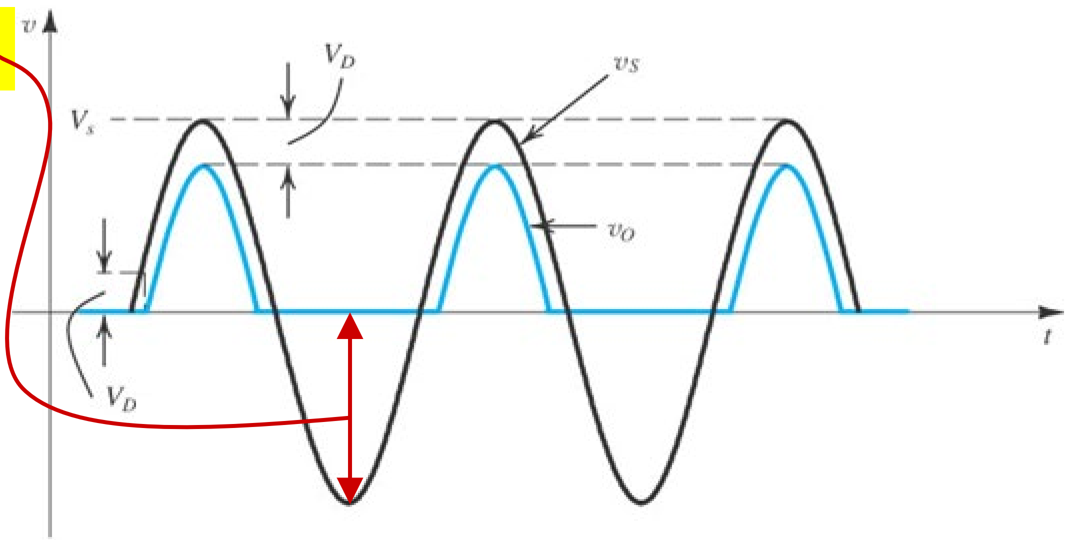
$V_o = V_S - V_D$

Transfer characteristic

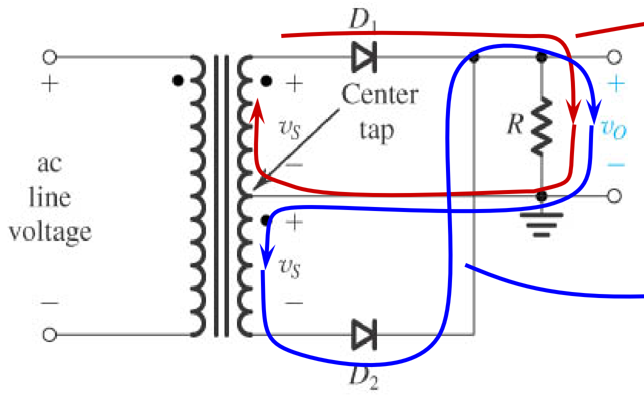
Peak Inverse Voltage: PIV=V_S

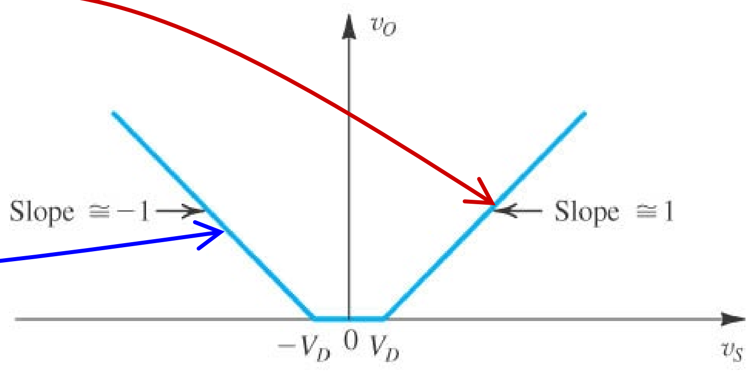


Equivalent circuit

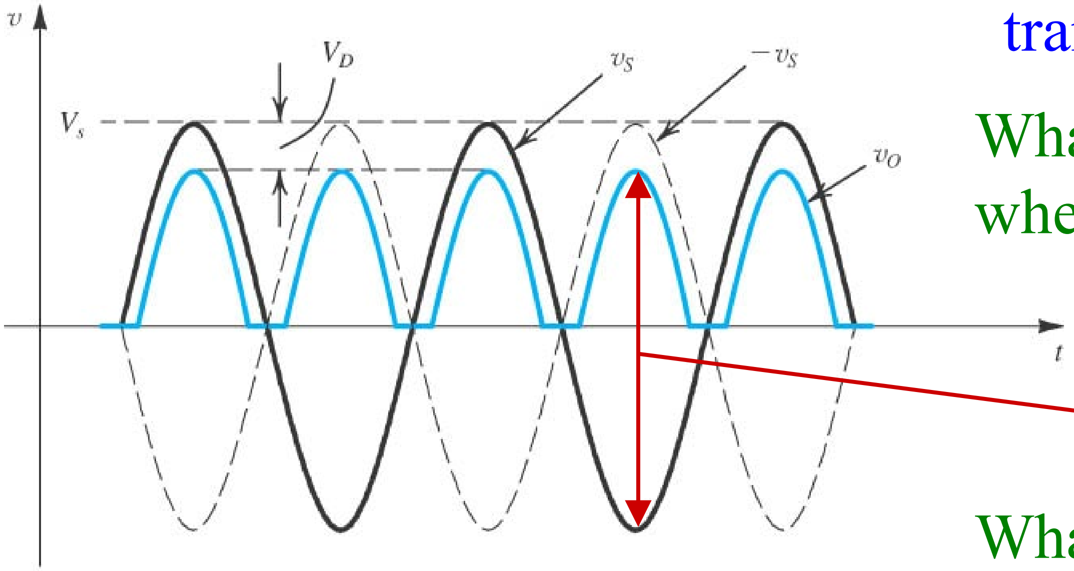


[2] The Full-Wave Rectifier





transfer characteristic



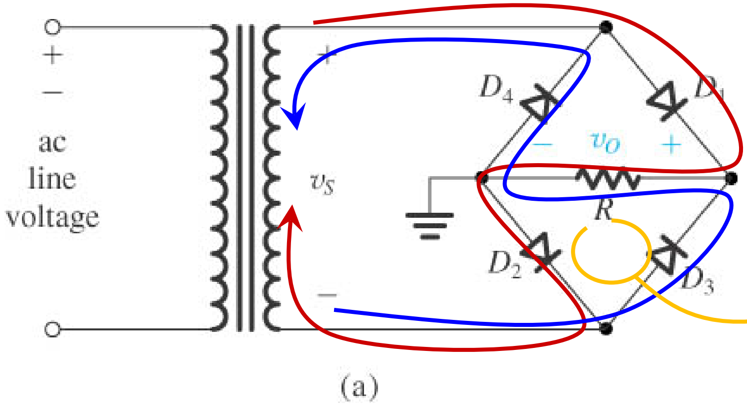
input and output waveforms

What is path of current when v_s is positive?

Peak Inverse Voltage:
$PIV = 2V_S - V_D$

What is path of current when v_s is negative?

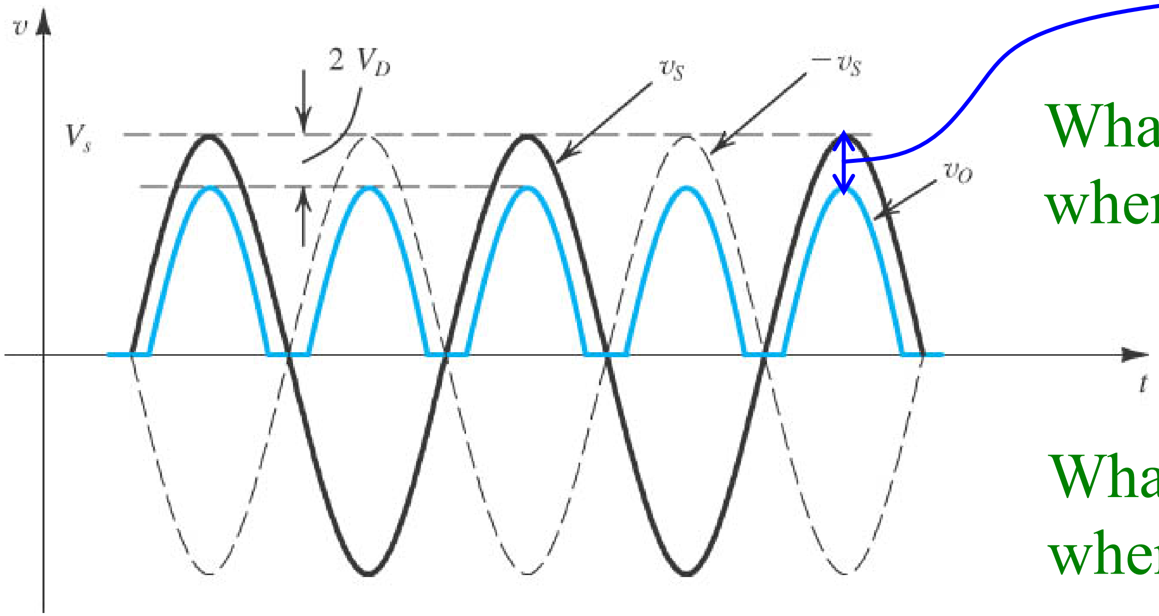
[3] The Bridge Rectifier



Peak Inverse Voltage:
$PIV = V_O + V_D = V_S - V_D$

mesh equation

$$V_O = V_S - 2V_D$$

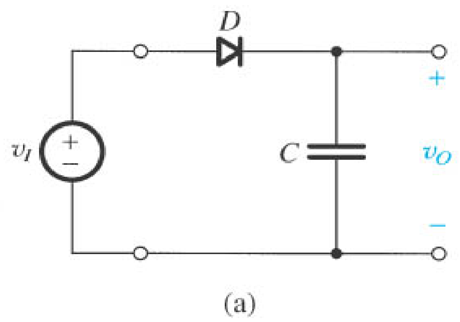


input and output waveforms

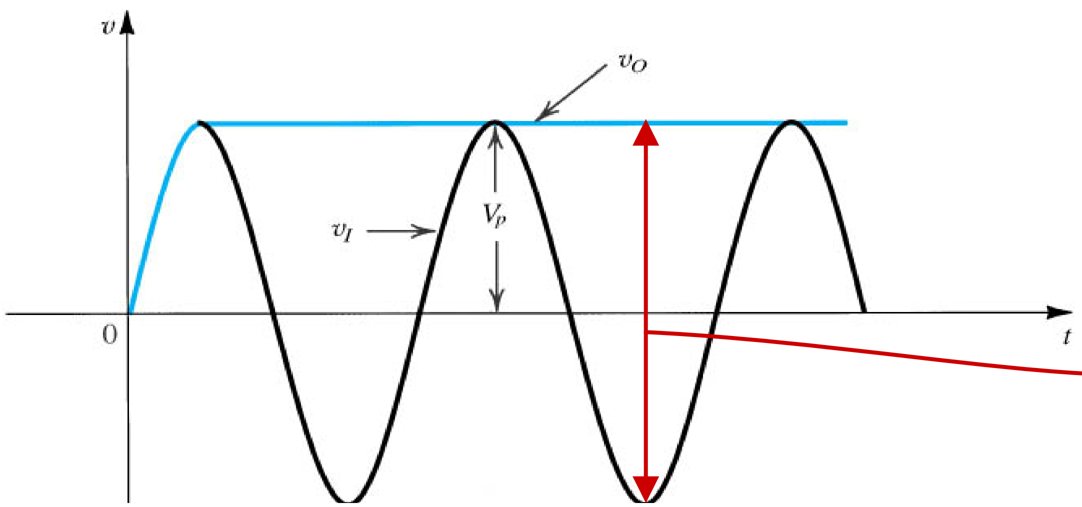
What is path of current when v_s is positive?

What is path of current when v_s is negative?

Effect of a Filter Capacitor



Peak Inverse Voltage: PIV=V_I+V_O



Input and output waveforms for no load current, and assuming an ideal diode

The circuit is known as a peak detector

ECE 3020: Introduction to Electronics

MODELING THE DIODE FORWARD CHARACTERISTIC

Modeling The Diode Forward Characteristic

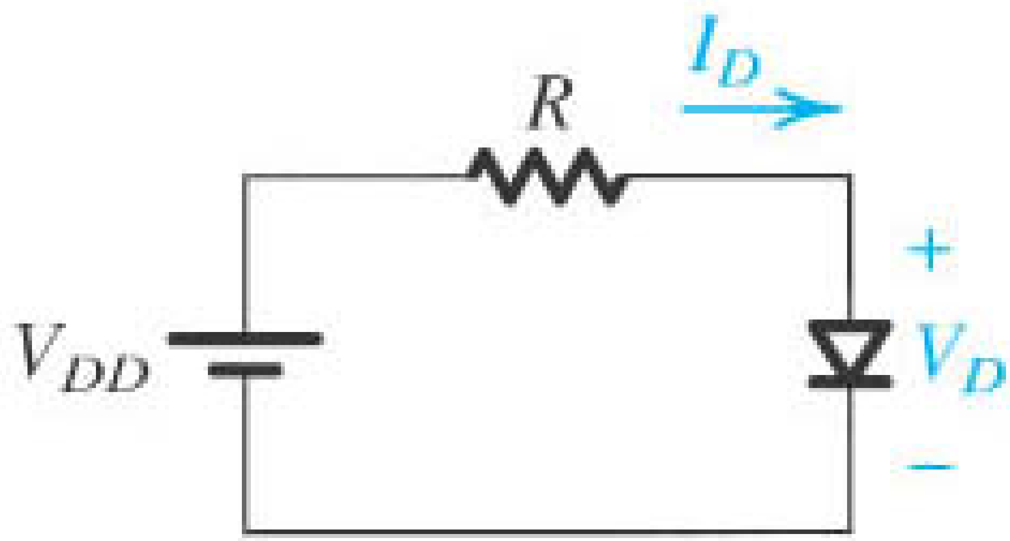
Two unknowns: V_D & I_D

Need two equations:

$$I_D = I_S\left[\exp\left(\frac{V_D}{V_T}\right) - 1\right]$$

$$I_D = \frac{V_{DD} - V_D}{R}$$

Equate I_D



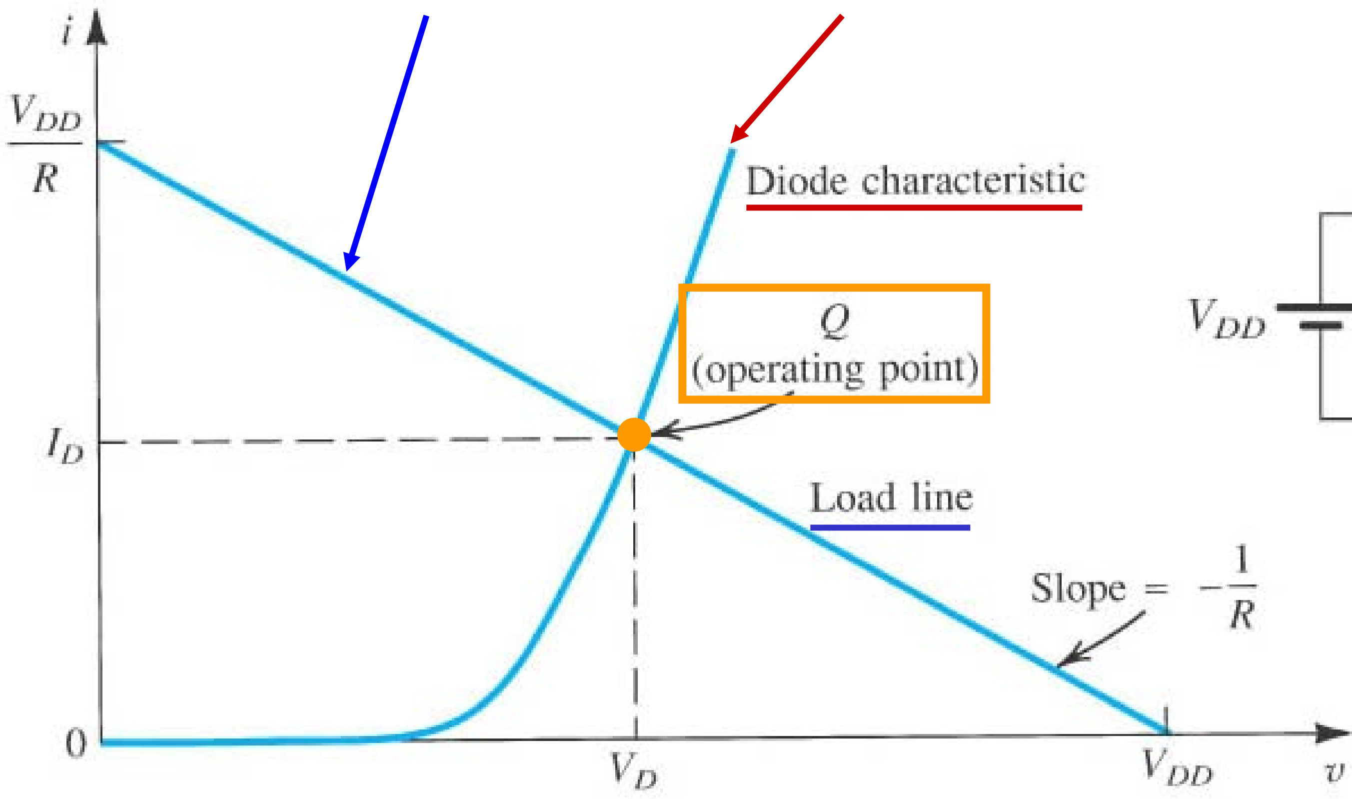
A simple circuit used to illustrate the analysis in which the diode is forward conducting.

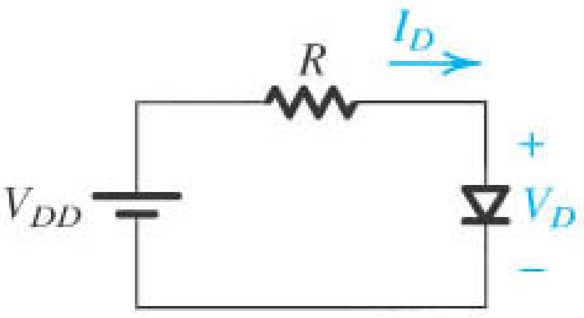
Two methods of solutions possible: graphical & iterative

Graphical Solution

$$I_D = \frac{V_{DD} - V_D}{R}$$

$$I_D = I_S\left[\exp\left(\frac{V_D}{V_T}\right) - 1\right]$$

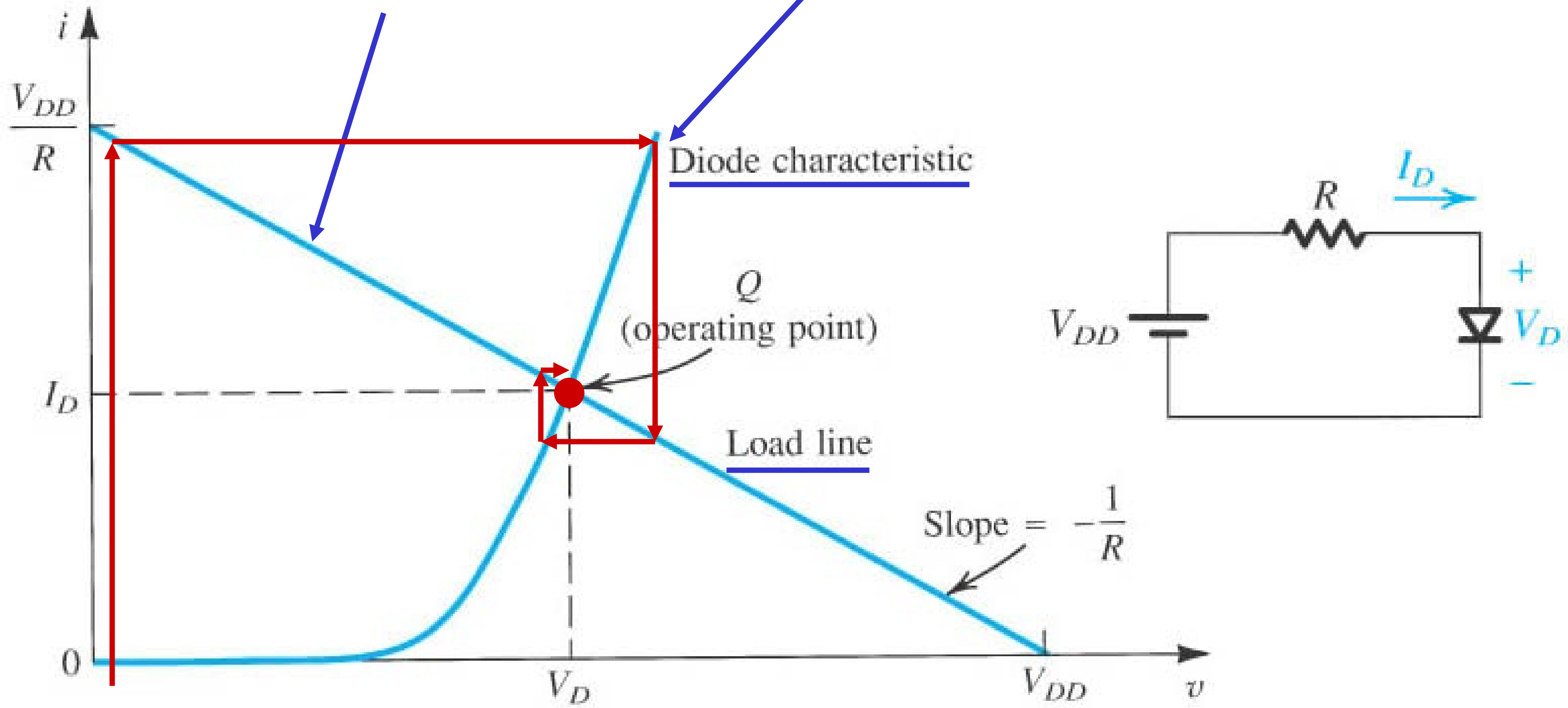




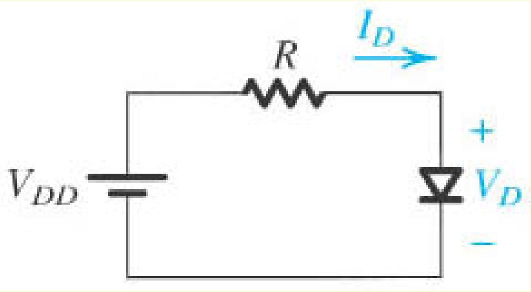
Iterative Analysis

$$I_D = \frac{V_{DD} - V_D}{R}$$

$$I_D = I_S \exp\left(\frac{V_D}{V_T}\right)$$



Iterative Analysis --- Example



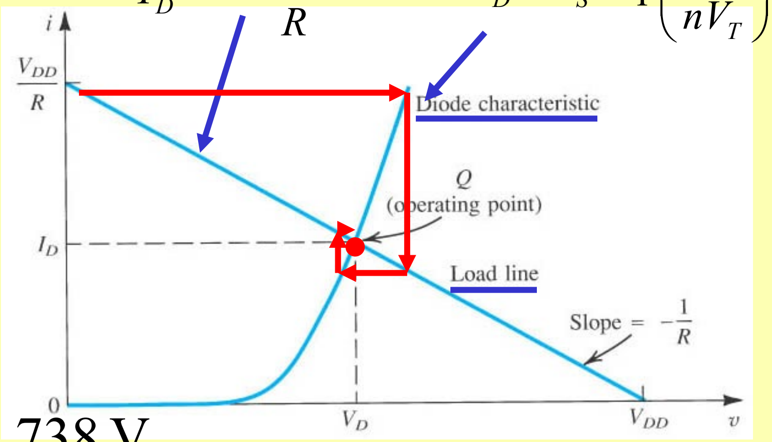
Circuit data: $V_{DD} = 5\text{ V}$ and $R = 1\text{ k}\Omega$

Diode has I_D=1 mA for V_D=0.7 V

Start with $V_1 = 0.7$ V and calculate I_D

$$I_D = \frac{V_{DD} - V_D}{R} = \frac{5-0.7}{1} = 4.3\text{ mA}$$

$$I_D = \frac{V_{DD} - V_D}{R} \qquad I_D = I_S \exp\left(\frac{V_D}{nV_T}\right)$$



Calculate V_D:

$$V_2 - V_1 = 2.3\, V_T \log\left(\frac{I_2}{I_1}\right)$$

$$V_2 = V_1 + 0.06 \times \log\left(\frac{I_2}{I_1}\right) = .7 + 0.06 \times \log\left(\frac{4.3}{1}\right) = 0.738\text{ V}$$

Next iteration we get

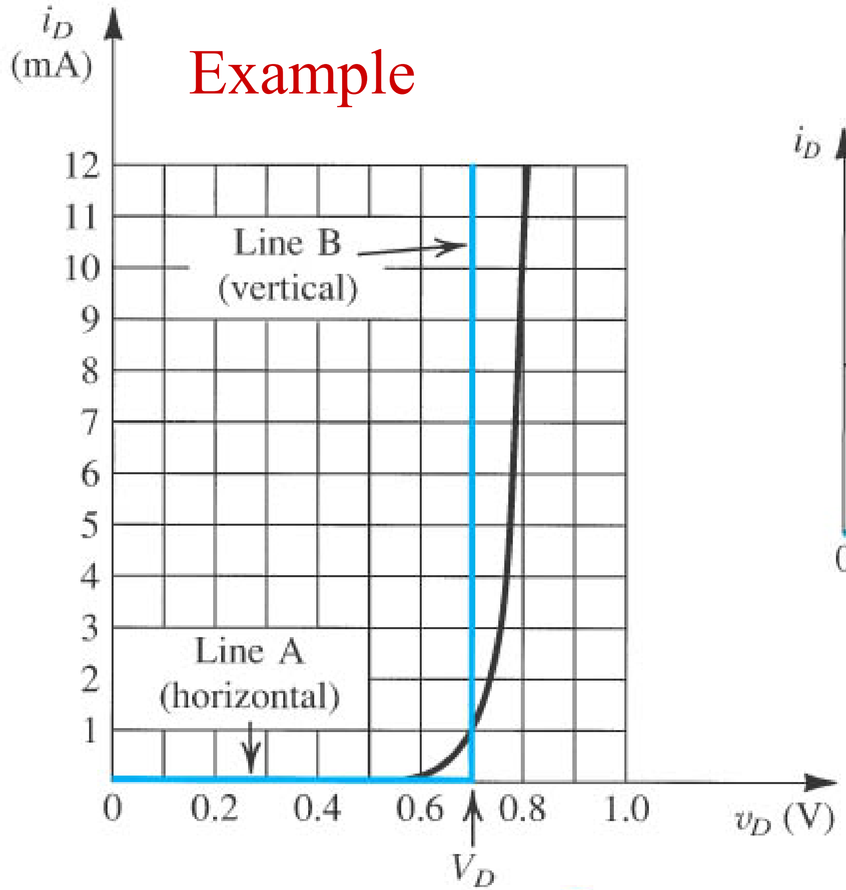
$$I_D = \frac{5-0.738}{1} = 4.262\text{ mA} \quad \text{and} \quad V_3 = .738 + 0.06 \times \log\left(\frac{4.262}{4.3}\right) = 0.738\text{ V}$$

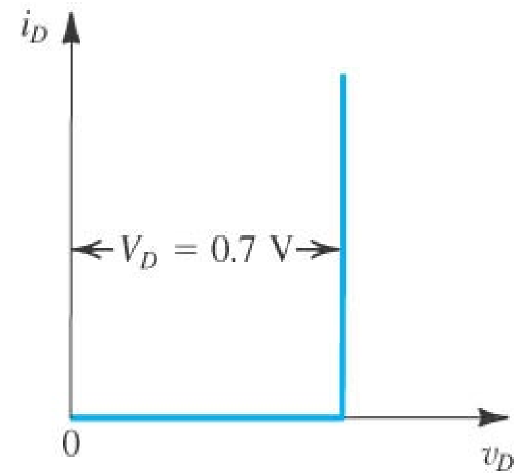
Need For Rapid Analysis

- The graphical and iterative analysis is too time consuming for complex circuits
- A simpler model is desired for a rapid analysis permitting to develop a first cut design
- More accurate analysis can then be performed using circuit simulation CAD tools such as TopSPICE to fine tune the circuit

Constant-Voltage-Drop Model

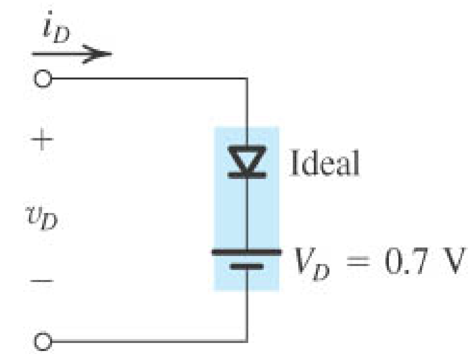
Example





(a)

equivalent-circuit representation

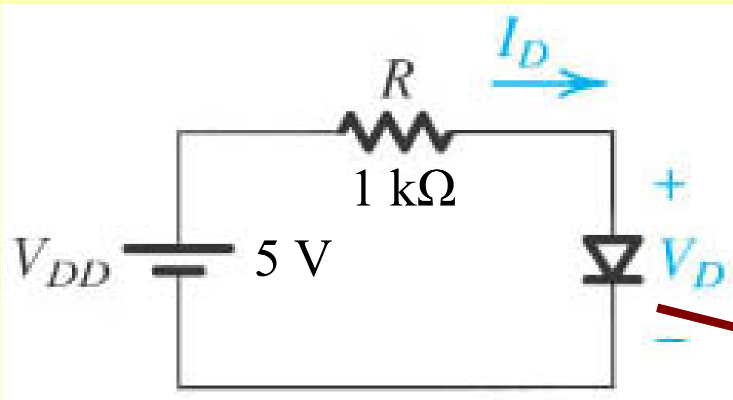


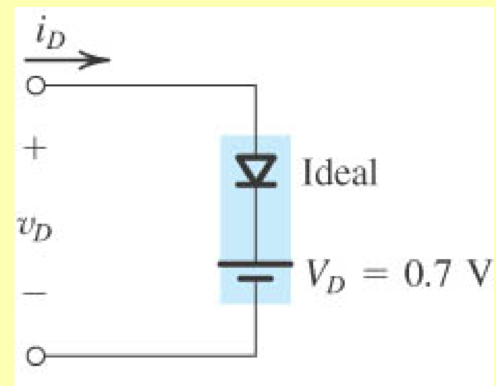
(b)

This simple model predicts V_D to within ±0.1 V over the current range of 0.1 mA to 10 mA (for this example)

Exercise #10

What is the current flowing through the diode?





Assuming V_D=0.7 V. Therefore

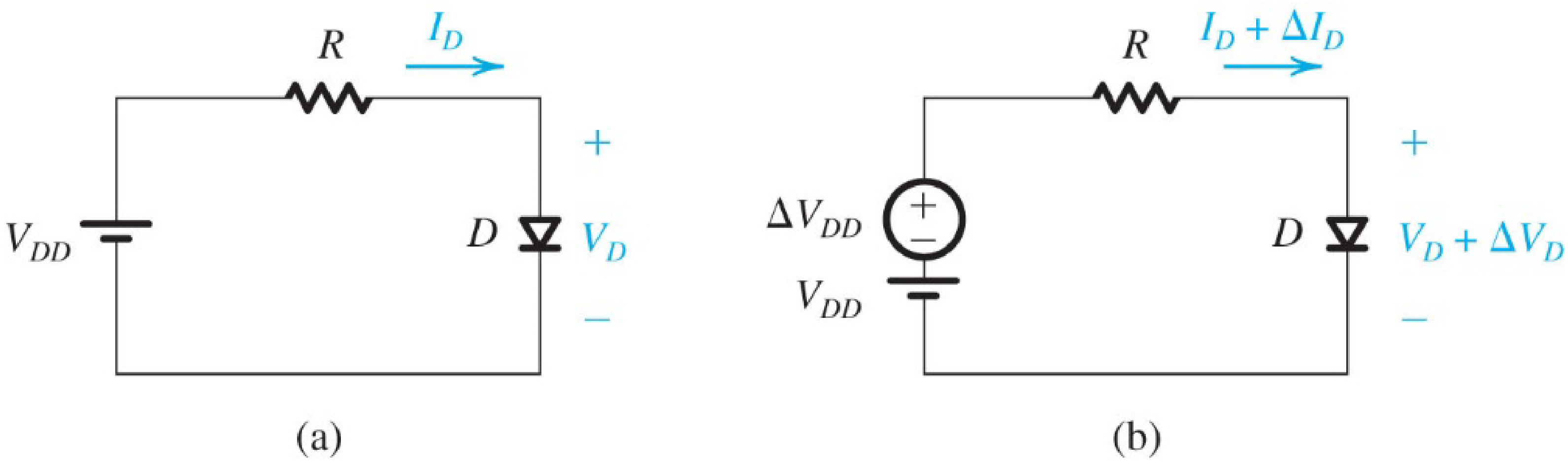
$$I_D = \frac{V_{DD} - V_D}{R} = \frac{5 - 0.7}{1} = 4.3\,\text{mA}$$

ECE 3020: Introduction to Electronics

SMALL SIGNAL MODEL

Small Signal Model

When V_{DD} undergoes a small change ΔV_{DD}, the current I_D changes by an increment ΔI_D, and the diode voltage V_D changes by an increment ΔV_D. We wish to find a **quick way to determine the values of these incremental changes.**



Small Signal Model

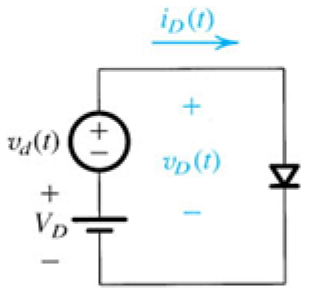
Consider the forward bias approximation:

$$i_D = I_S \exp\left(\frac{v_D}{V_T}\right) = \underbrace{I_S \exp\left(\frac{V_D}{V_T}\right)}_{I_D} \times \exp\left(\frac{v_d}{V_T}\right) \approx I_D\left(1 + \frac{v_d}{V_T}\right)$$

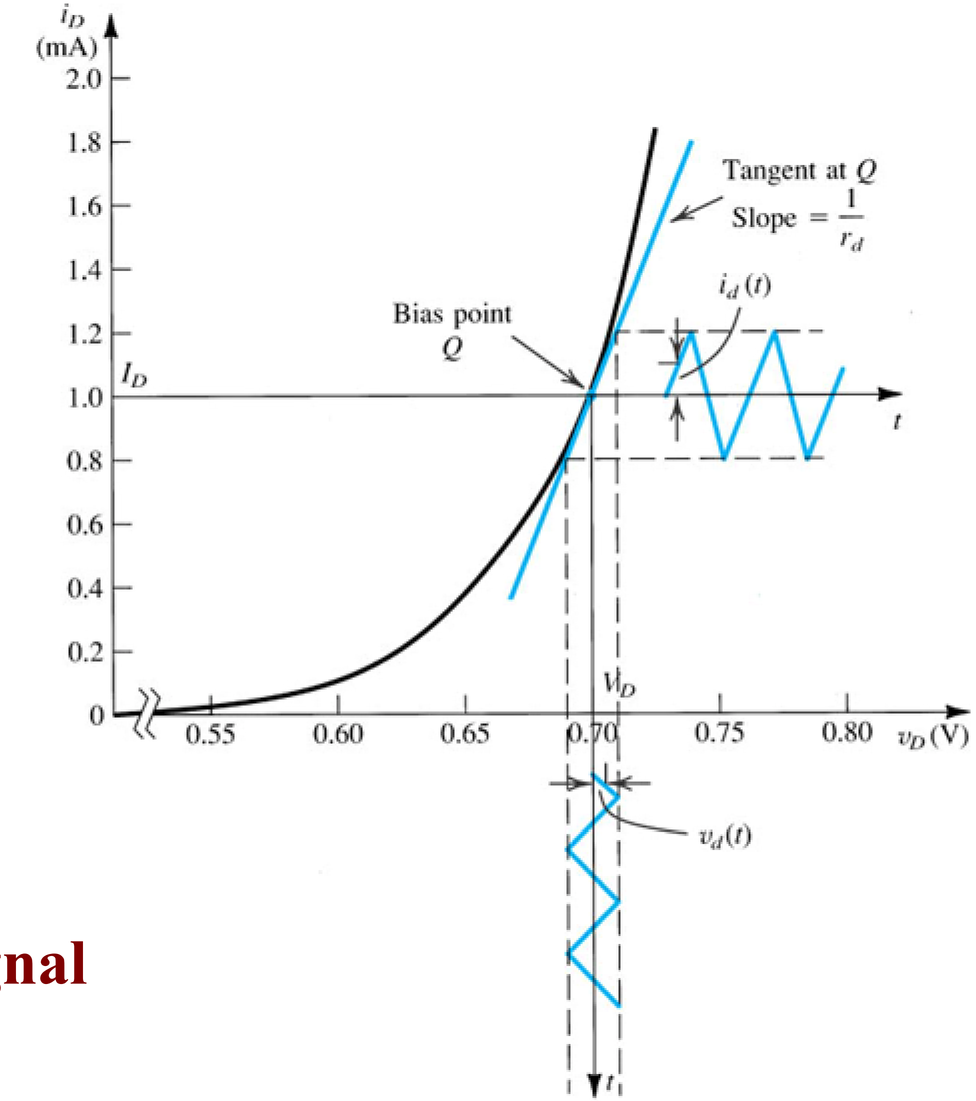
using $\boxed{v_D = V_D + v_d}$ and $\exp(x) \approx 1 + x$ for $x << 1$

$$i_D = I_D + i_d \Rightarrow \boxed{i_d = \frac{I_D v_d}{V_T} = \frac{v_d}{r_d}} \text{ with } r_d = \frac{V_T}{I_D} = \left[\left|\frac{\partial i_D}{\partial v_D}\right|_{i_D = I_D}\right]^{-1}$$

Development of Diode Small-Signal Model



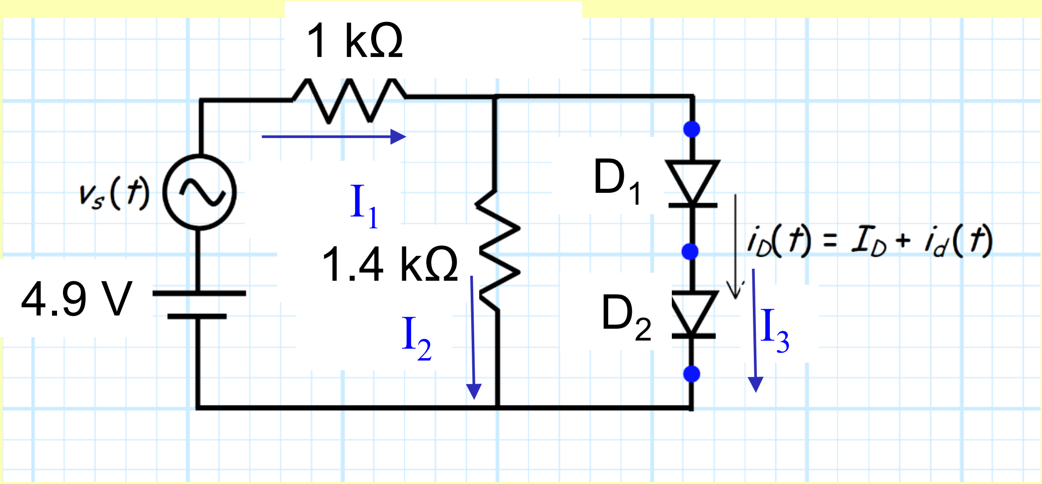
(a)



Diode behaves as a resistor for a small signal perturbation!

Exercise #11: Small Signal Model

$v_s(t)$= 0.100 Sinω_0t V



Assume constant-voltage-drop model (V_D=0.7 V) and V_T=25 mV for both diodes,

1) **Determine r_d for D_1 and D_2.**
2) ***Build a small signal model for the circuit***
3) ***Find $i_d(t)$ and $v_d(t)$ [note the subscript!]***

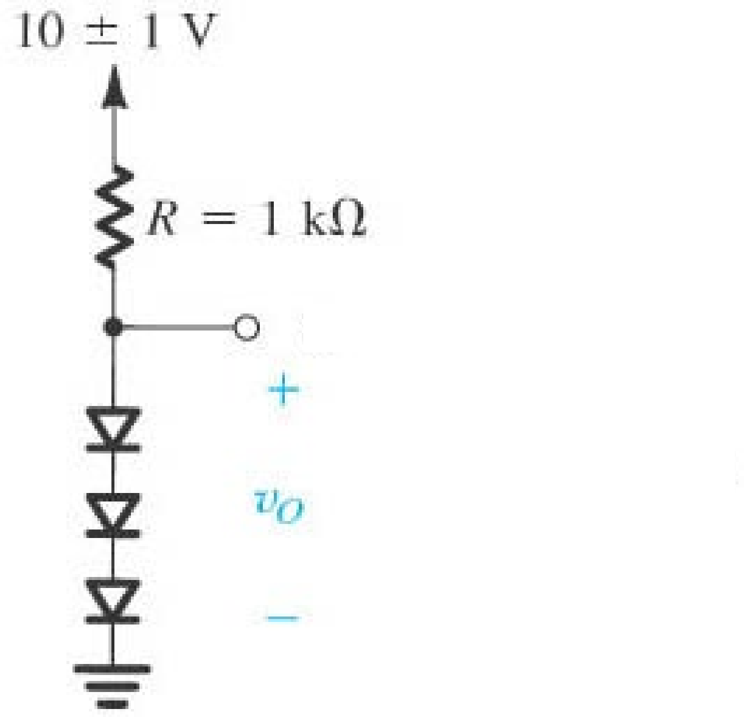
Ans:

1) $r_d = 10\ \Omega$

3) $v_d(t)= 0.97$ Sinω_0t mV *and* $i_d(t)= v_d(t) / r_d = 0.097Sin\omega_0$t mA

Or $v_d(t) \simeq$ Sinω_0t mV *and* $i_d(t) \simeq 0.1$Sinω_0t mA

Exercise #12



What is the output voltage fluctuation for 2 volt peak to peak fluctuation of the supply voltage?

(assume real diodes and use the constant voltage drop model of 0.7 V per diode)

Ans: $v_o = 2.1\ V \pm 9.5\ mV$

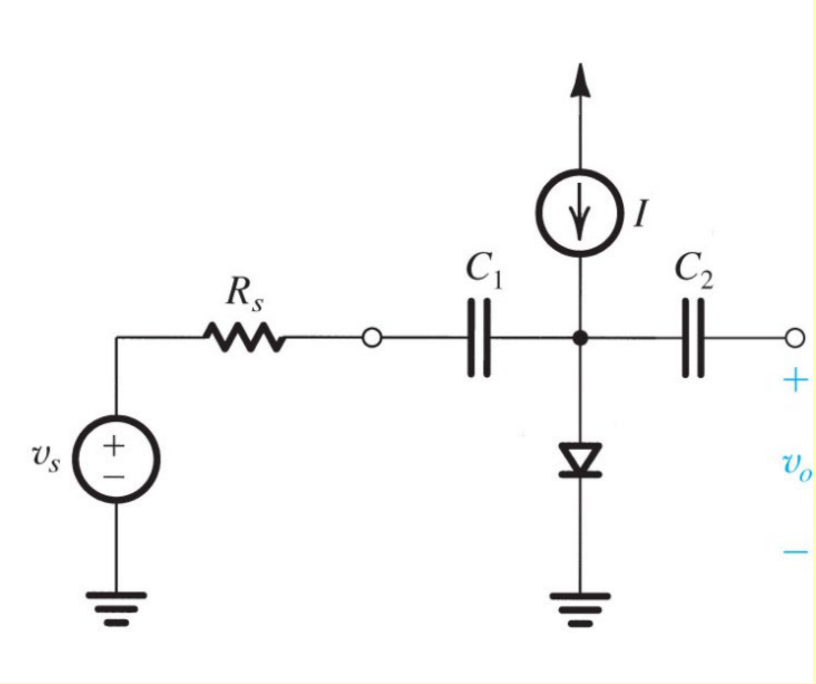
Exercise #13

1) Find v_o/v_s ?
Assume that

- **C_1 and C_2 are very large**
- ***I* is DC**

Ans: $v_o = v_s \frac{V_T}{V_T + IR_S}$

2) Convince yourself that the circuit is the small-signal attenuator.
3) How can this circuit act as a variable attenuator?
Ans: By changing dc bias I.

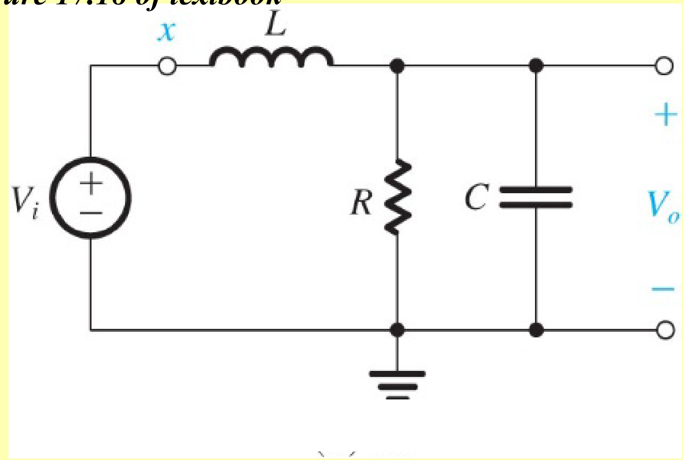


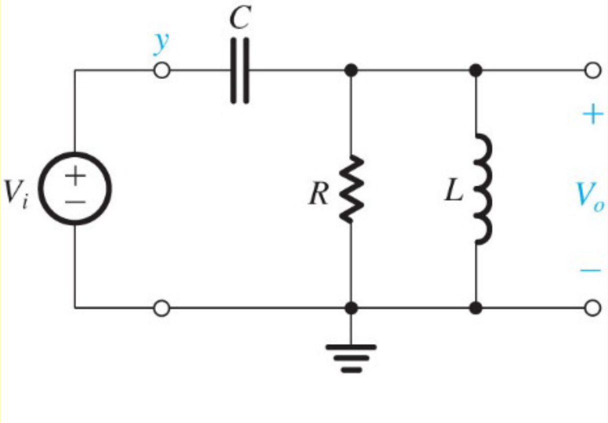
Based on Problem 4.48

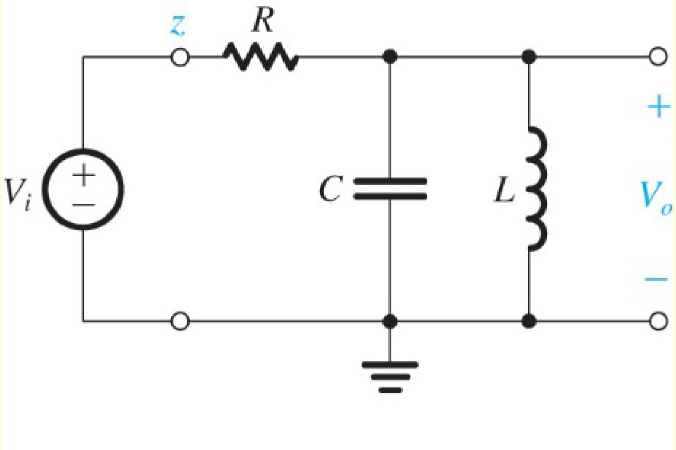
Filter Review - Intuitive Analysis

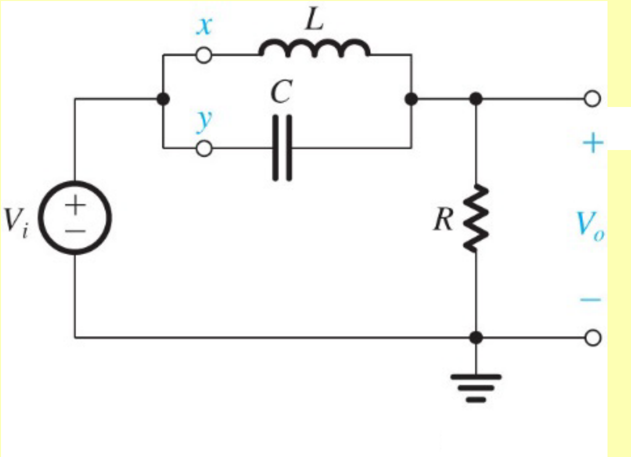
For each circuit: 1) find T(0), 2) T(∞), 3) identify the filter type, and 4) draw bode plot for T(ω).

Based on Figure 17.18 of textbook

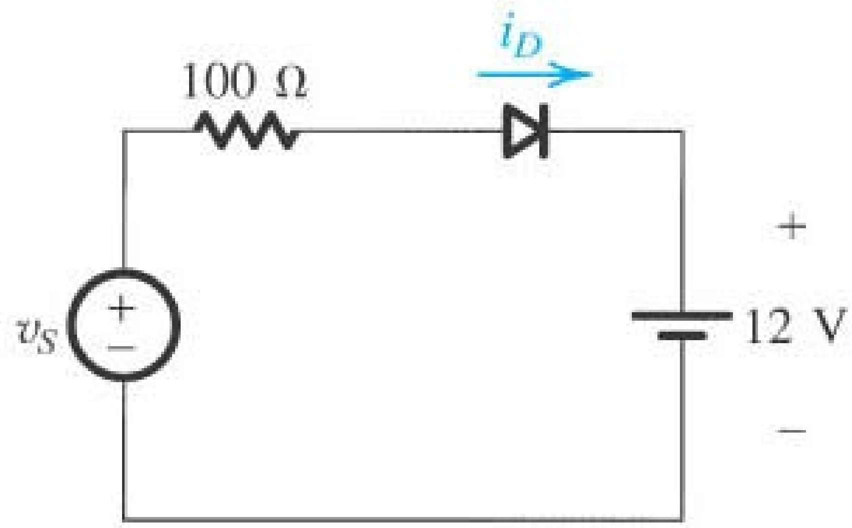








Exercise #14: 12 V Battery Charger



Based on Example 4.1 of textbook

v_S = 24 V peak sinusoid

Find

a) **Fraction of each cycle diode conducts**

b) **Peak diode current**

c) **Max reverse voltage across diode**

Exercise #14: 12 V Battery Charger

Ans.

a) $\dfrac{\frac{2\pi}{3}}{2\pi} = \dfrac{1}{3}$ **or 33%**

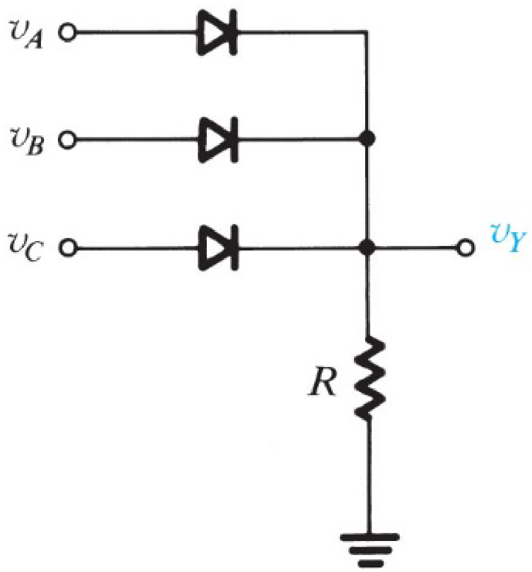
b) 0.12 A

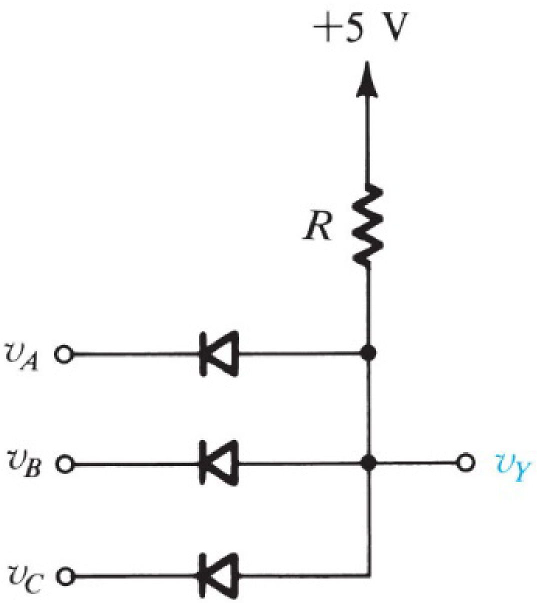
c) PIV=36 V

ECE 3020: Introduction to Electronics

ANOTHER APPLICATION: DIODE LOGIC GATES

Diode Logic Gates





OR gate:
Y = A + B + C

AND gate:
Y = A • B • C