EE 330
Lecture 15

Devices in Semiconductor Processes

- Diodes
- Capacitors
- MOSFETs

Review from Last Lecture

Basic Devices and Device Models

- Resistor
- Diode
- Capacitor
- MOSFET
- BJT

Review from Last Lecture

Analysis of Nonlinear Circuits

(Circuits with one or more nonlinear devices)

What analysis tools or methods can be used?

KCL ?

KVL?

~~Superposition?~~

~~Voltage Divider ?~~

~~Current Divider?~~

~~Thevenin and Norton Equivalent Circuits?~~

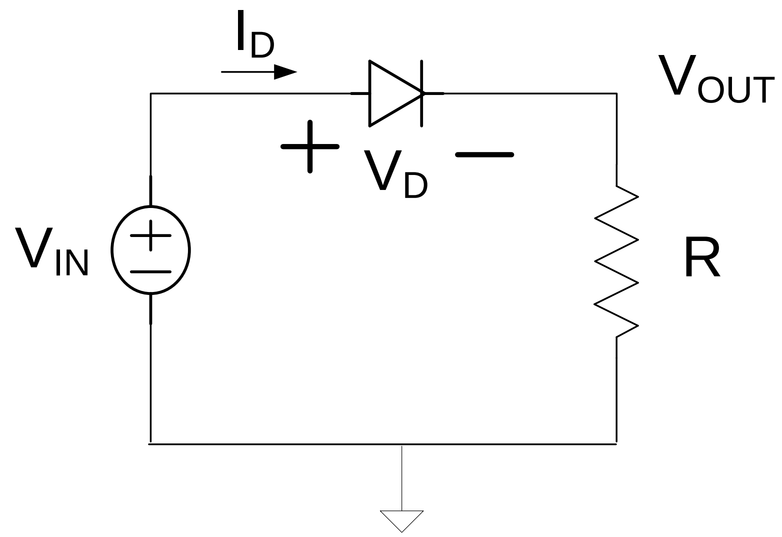
Nodal Analysis

Mesh Analysis

Two-Port Subcircuits

Review from Last Lecture

Consider again the basic rectifier circuit



$$\left.\begin{aligned} V_{IN} &= V_D + I_D R \\ V_{OUT} &= I_D R \\ I_D &= I_S\left(e^{\frac{V_d}{V_t}} - 1\right) \end{aligned}\right\}$$

$$V_{OUT} = I_S R\left(e^{\frac{V_{IN}-V_{OUT}}{V_t}} - 1\right)$$

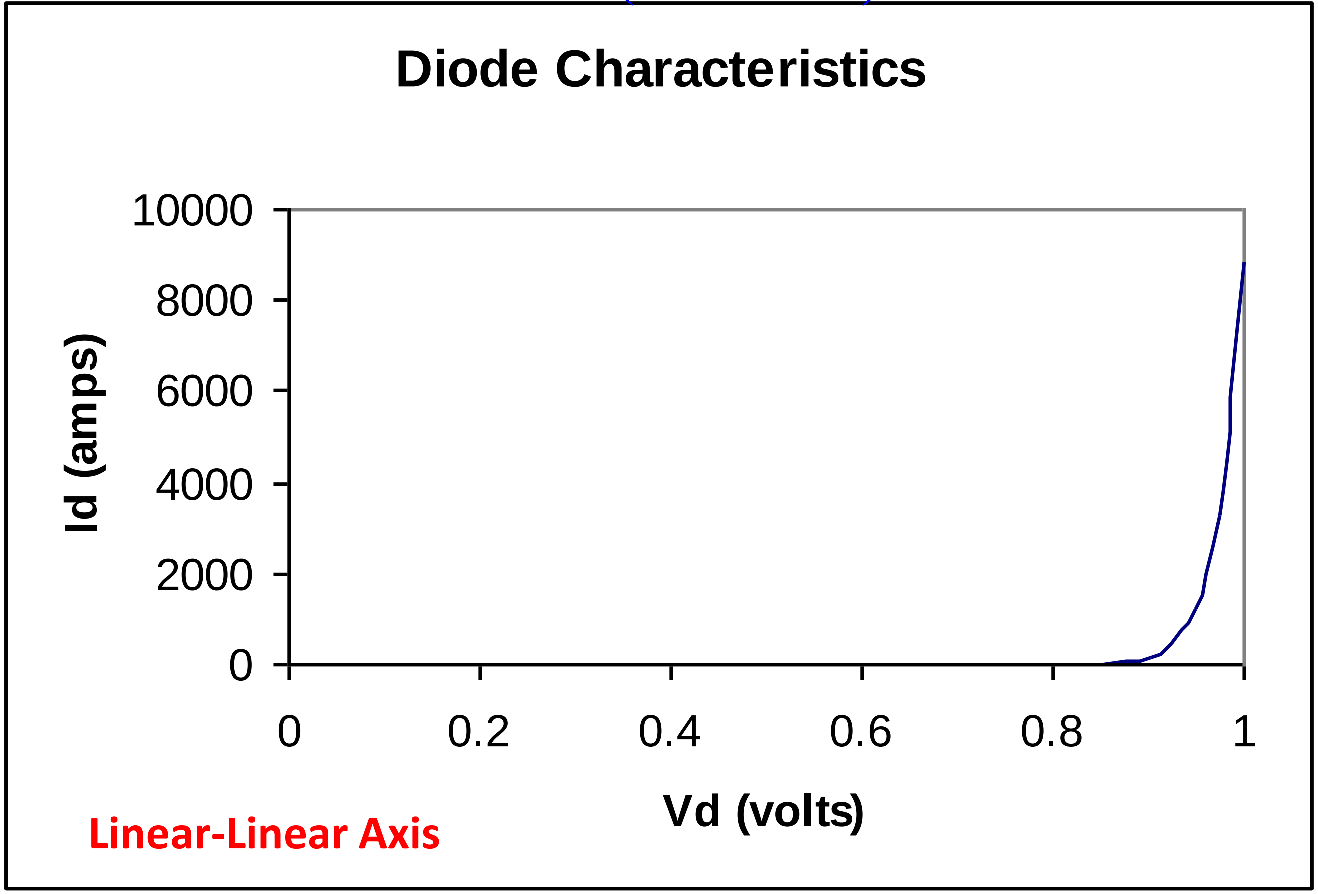
Even the simplest diode circuit does not have a closed-form <u>explicit</u> solution when diode equation is used to model the diode !!

Due to the nonlinear nature of the diode equation

Simplifications are essential if analytical results are to be obtained

Lets study the diode equation a little further

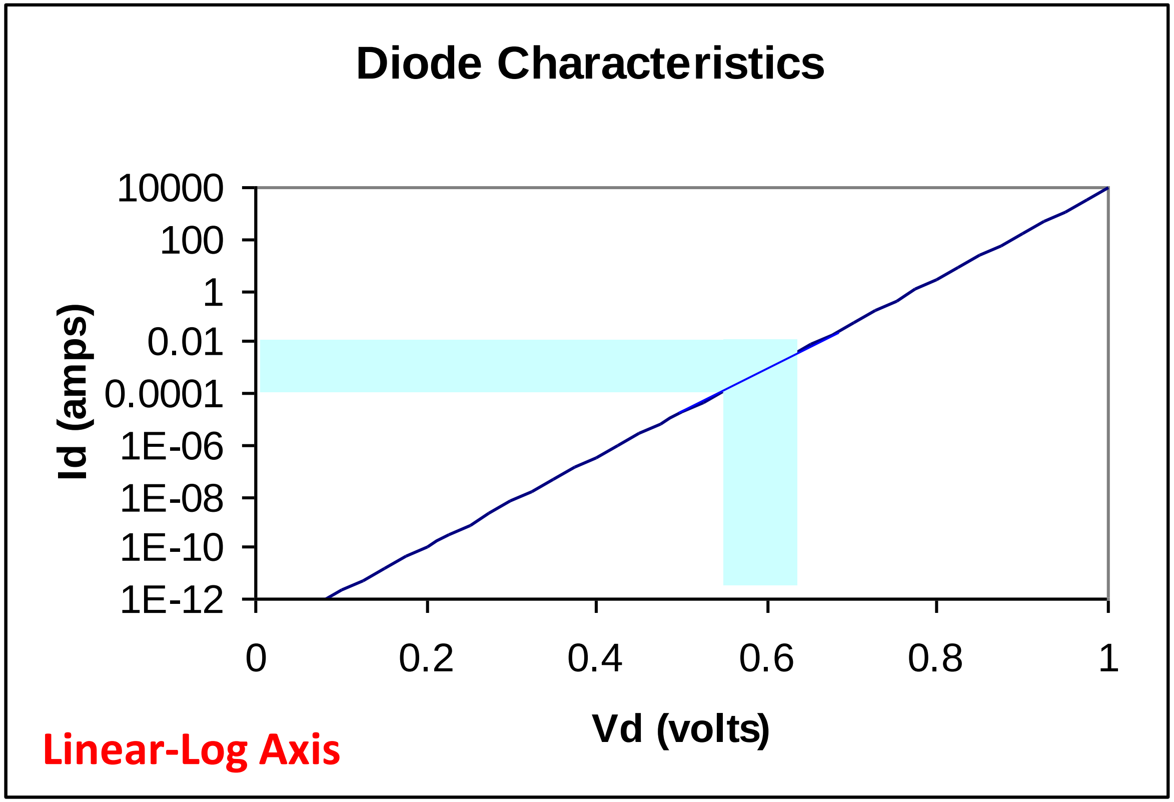
$$I_d = I_S\left(e^{\frac{V_d}{V_t}} - 1\right)$$



Power Dissipation Becomes Destructive if Vd > 0.85V (actually less)

Lets study the diode equation a little further

$$I_d = I_S\left(e^{\frac{V_d}{V_t}} - 1\right)$$

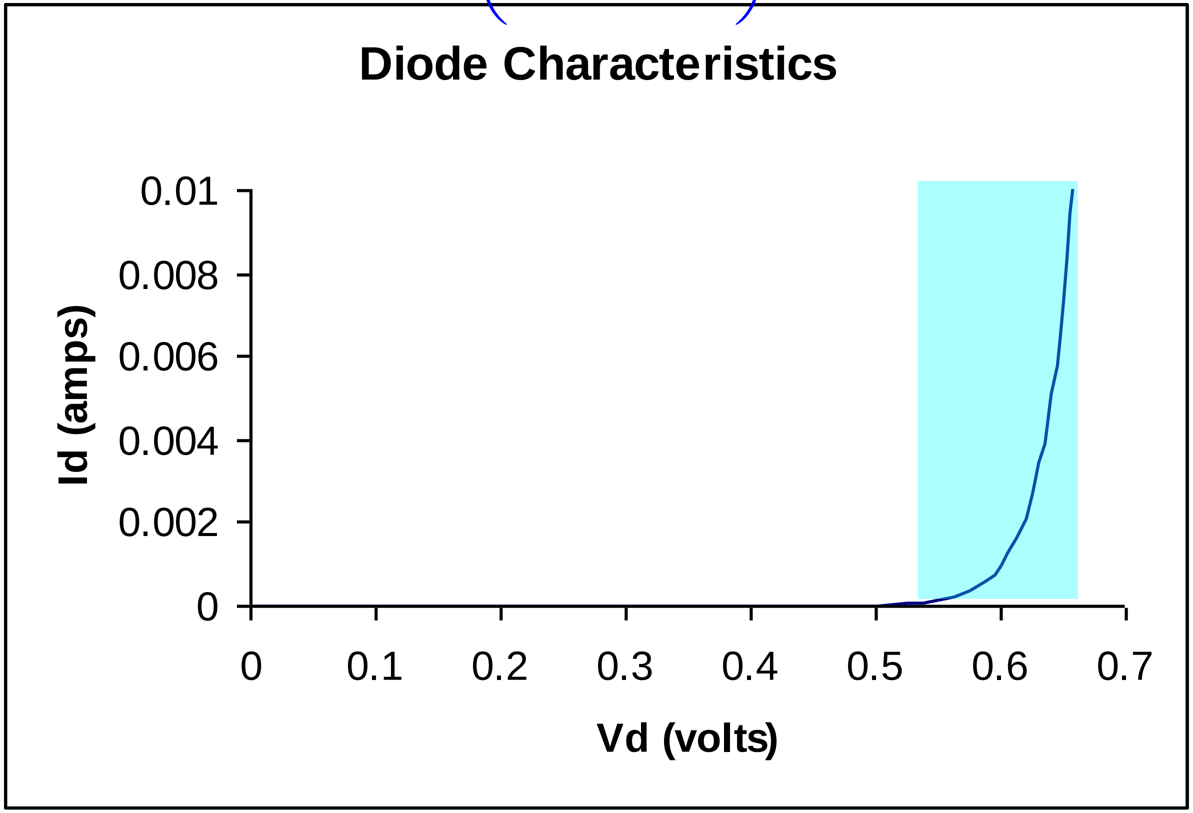


For two decades of current change, Vd is close to 0.6V

This is the most useful conducting current range for many applications

Lets study the diode equation a little further

$$I_d = I_S\left(e^{\frac{V_d}{V_t}} - 1\right)$$



For two decades of current change, Vd is close to 0.6V

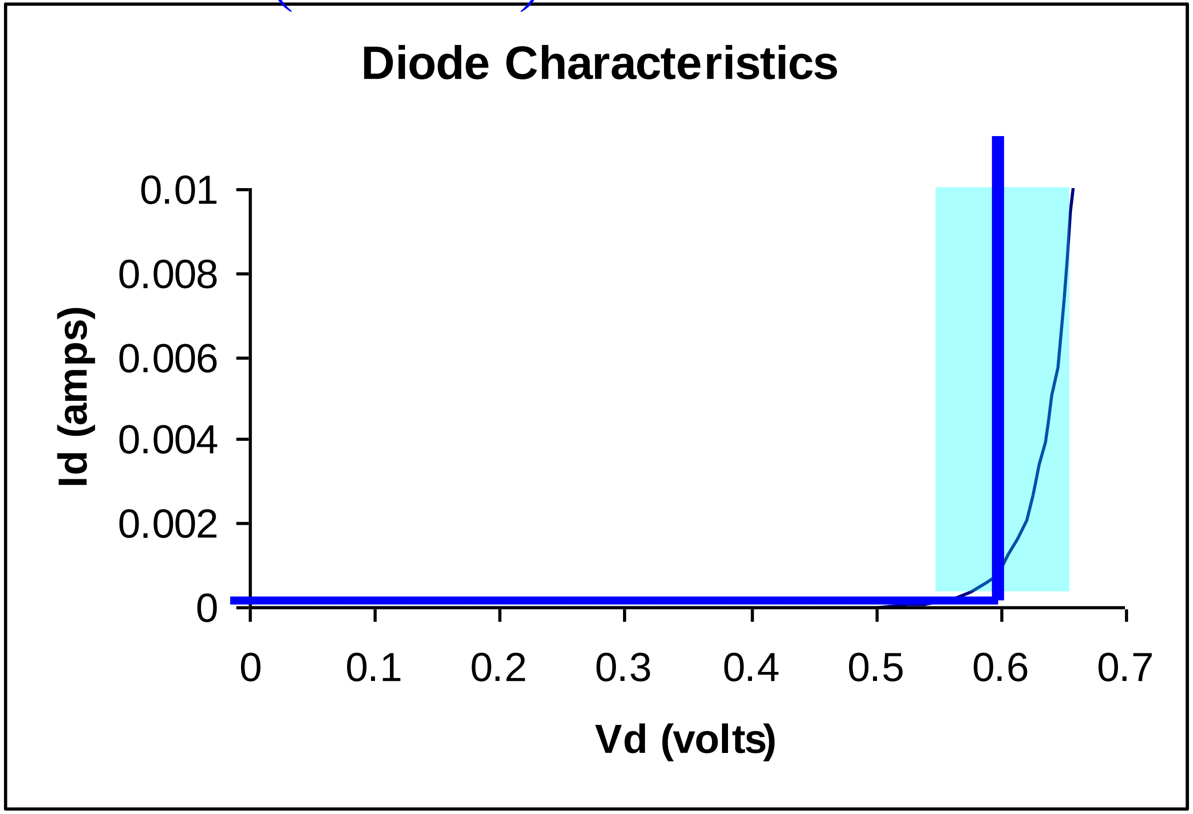
This is the most useful current range when conducting for many applications

Lets study the diode equation a little further

$$I_d = I_S\left(e^{\frac{V_d}{V_t}} - 1\right)$$

$I_d = 0 \qquad V_d < 0.6V$

$V_d = 0.6V \qquad I_d > 0$

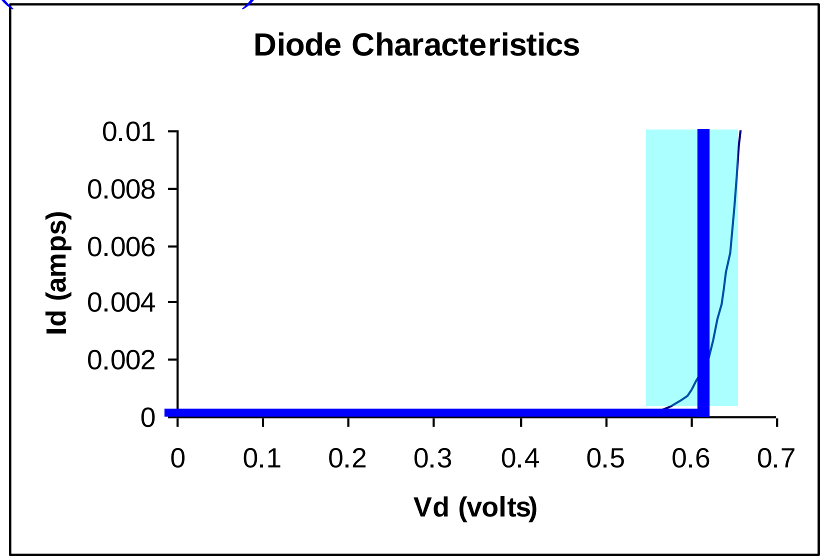


Widely Used **Piecewise Linear** Model

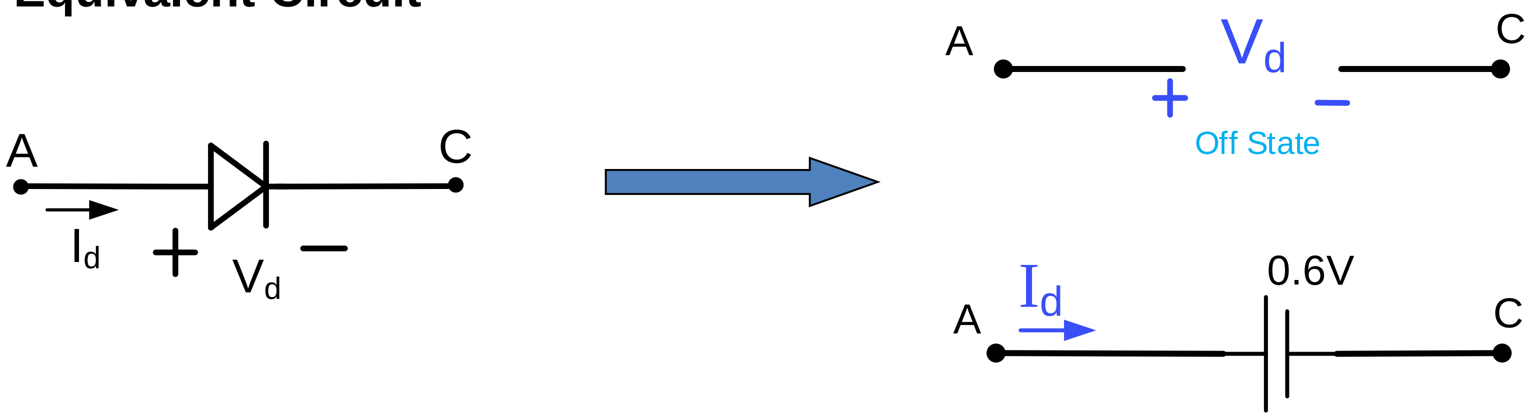
Lets study the diode equation a little further

$$I_d = I_S\left(e^{\frac{V_d}{V_t}} - 1\right)$$

$$I_d = 0 \qquad V_d < 0.6V$$
$$V_d = 0.6V \qquad I_d > 0$$

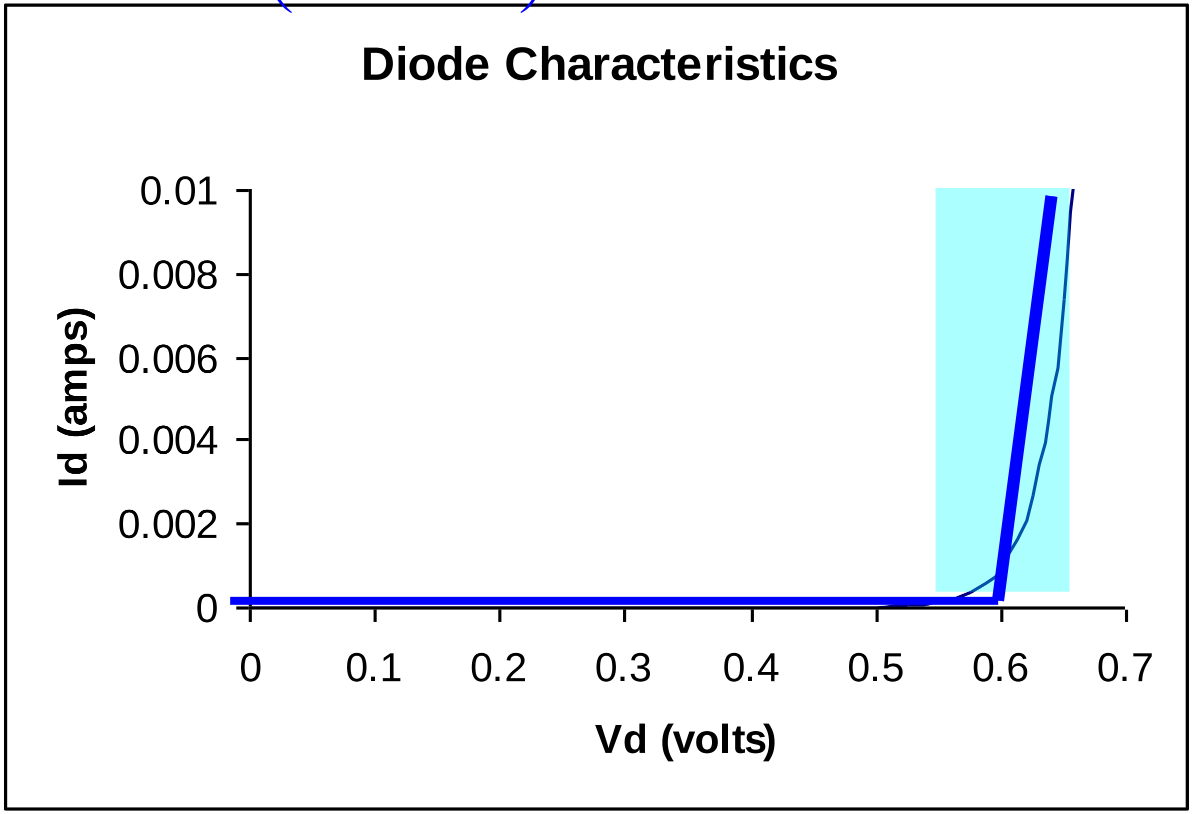


Equivalent Circuit



Lets study the diode equation a little further

$$I_d = I_S\left(e^{\frac{V_d}{V_t}} - 1\right)$$



Better model in “ON” state though often not needed

Includes Diode “ON” resistance

Lets study the diode equation a little further

$$I_d = I_S\left(e^{\frac{V_d}{V_t}} - 1\right)$$

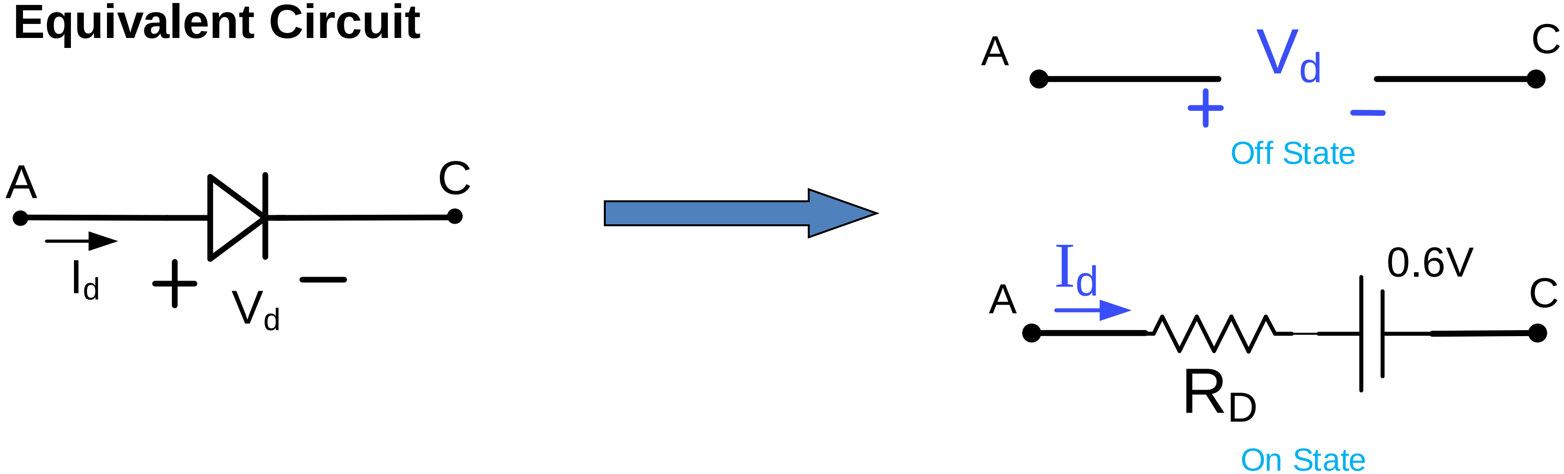
Piecewise Linear Model with Diode Resistance

$$I_d = 0 \qquad \text{if } V_d < 0.6V$$

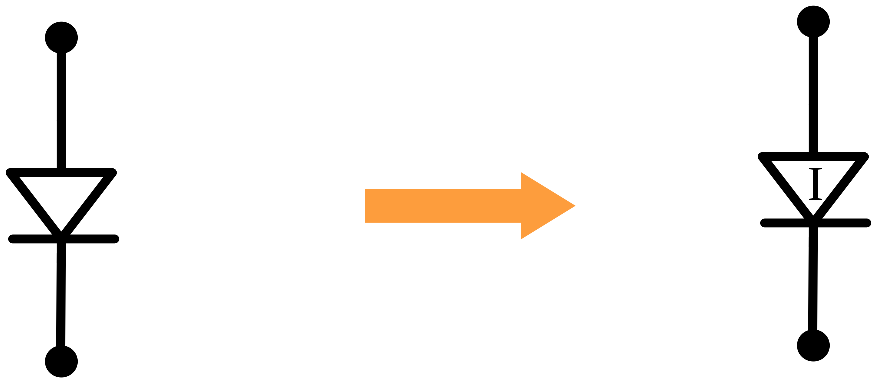
$$V_d = 0.6V + I_d R_D \qquad \text{if } I_d > 0$$

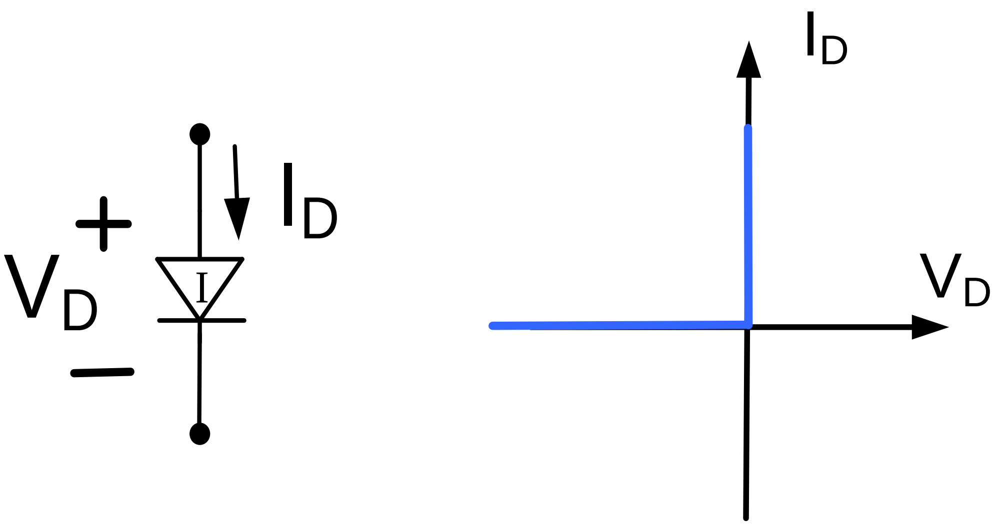
(R_D is rather small: often in the 20Ω to 100Ω range):

Equivalent Circuit



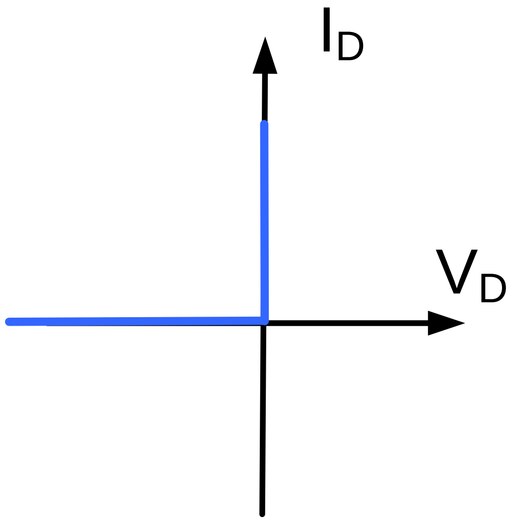
The Ideal Diode





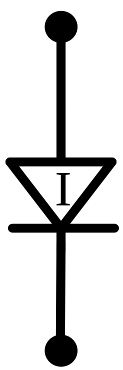
$$I_D = 0 \quad \text{if} \quad V_D \leq 0$$
$$V_D = 0 \quad \text{if} \quad I_D > 0$$

The Ideal Diode

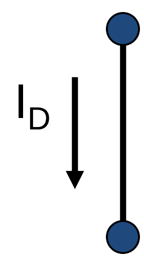


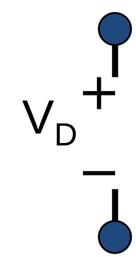
$$I_D = 0 \quad \text{if} \quad V_D \le 0 \qquad \text{“OFF”}$$

$$V_D = 0 \quad \text{if} \quad I_D > 0 \qquad \text{“ON”}$$



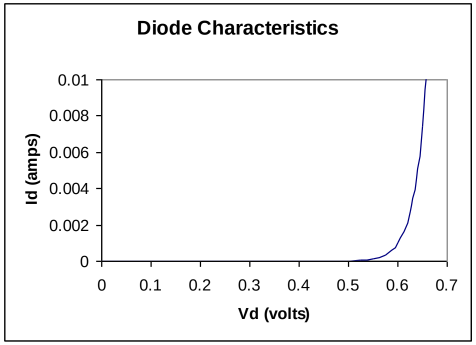
“ON” “OFF”

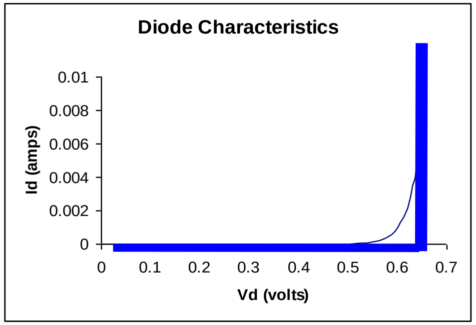


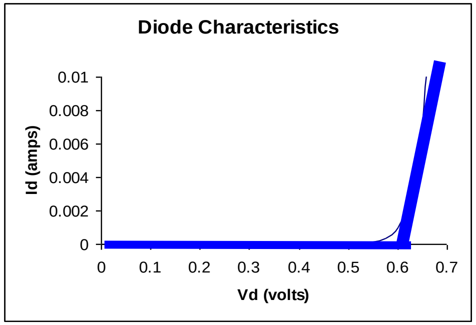


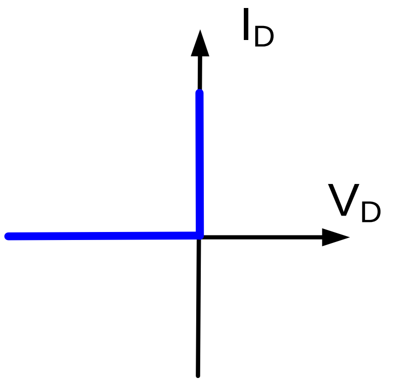
Valid for $I_D > 0$ $V_D \le 0$

Diode Models







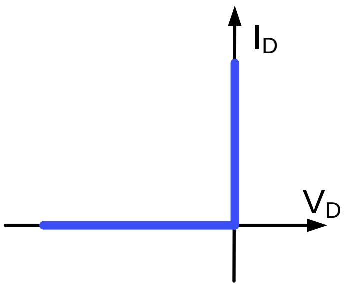


Which model should be used?

The simplest model that will give acceptable results in the analysis of a circuit

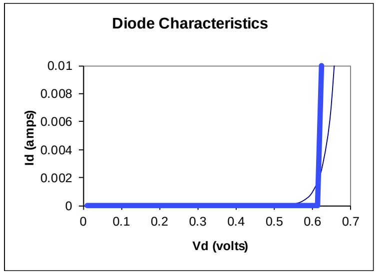
Diode Model Summary

Piecewise Linear Models



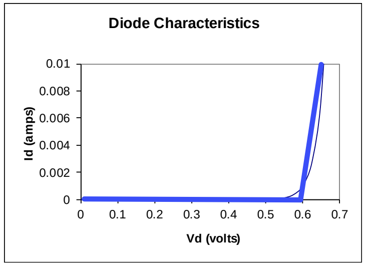
$I_d = 0$ if $V_d < 0$

$V_d = 0$ if $I_d > 0$



$I_d = 0$ if $V_d < 0.6V$

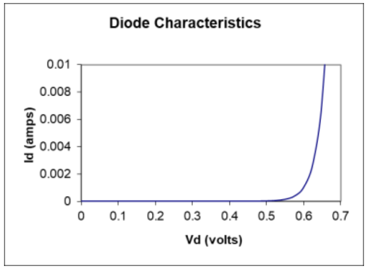
$V_d = 0.6V$ if $I_d > 0$



$I_d = 0$ if $V_d < 0.6$

$V_d = 0.6 + I_d R_d$ if $I_d > 0$

Diode Equation



$$I_d = I_S\left(e^{\frac{V_d}{V_t}} - 1\right)$$

Diode Model Summary

Piecewise Linear Models

$I_d = 0$ if $V_d < 0$

$V_d = 0$ if $I_d > 0$

$I_d = 0$ if $V_d < 0.6V$

$V_d = 0.6V$ if $I_d > 0$

$I_d = 0$ if $V_d < 0.6$

$V_d = 0.6 + I_d R_d$ if $I_d > 0$

Diode Equation

$$I_d = I_S \left(e^{\frac{V_d}{V_t}} - 1 \right)$$

When is the ideal model adequate?

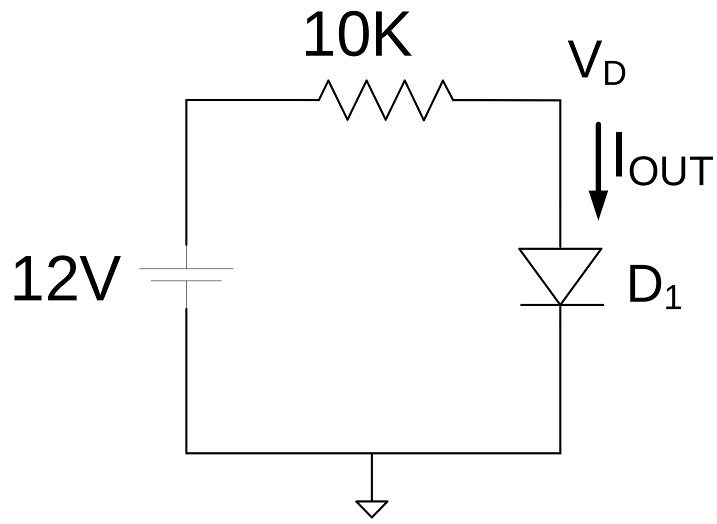
When it doesn't make much difference whether V_d=0V or V_d=0.6V

When is the second piecewise-linear model adequate?

When it doesn't make much difference whether V_d=0.6V or V_d=0.7V

Example:

Determine I_{OUT} for the following circuit



Solution:

If the diode equation model is used will obtain:

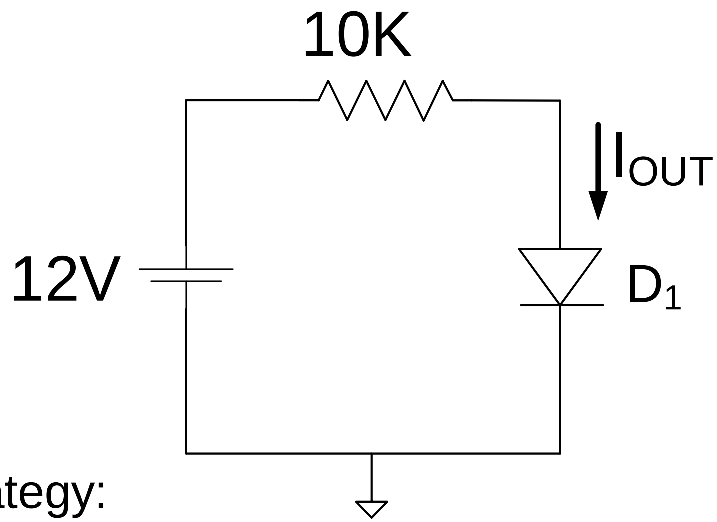
$$\left.\begin{aligned} 12 &= I_{OUT} \bullet 10K + V_D \\ I_{OUT} &= I_S\left(e^{\frac{V_D}{V_t}} - 1\right) \end{aligned}\right\} \Rightarrow \quad I_{OUT} = I_S\left(e^{\frac{-I_{OUT} \bullet 10K}{V_t}} e^{\frac{12}{V_t}} - 1\right)$$

As in previous example, a closed-form explicit expression for I_{OUT} does not exist

Will now establish alternate approach for solving this (and other) nonlinear circuits !

Example:

Determine I_{OUT} for the following circuit



Alternate Solution Strategy:

1. Assume PWL model with V_D=0.6V, R_D=0
2. Guess state of diode (ON)
3. Analyze circuit with model
4. Validate state of guess in step 2 (verify the "if" condition in model)

Select Model

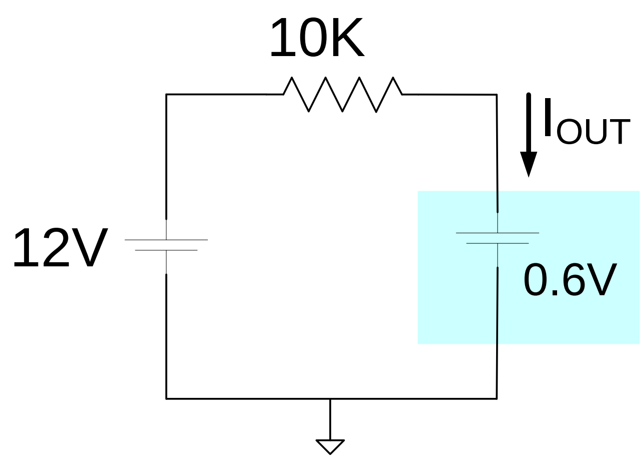
5. Assume PWL with V_D=0.7V
6. Guess state of diode (ON)
7. Analyze circuit with model
8. Validate state of guess in step 6 (verify the "if" condition in model)
9. Show difference between results using these two models is small

Validate Model

10. If difference is not small, must use a different model

Solution:

1. Assume PWL model with V_D=0.6V, R_D=0
2. Guess state of diode (ON)



3. Analyze circuit with model

$$I_{OUT} = \frac{12V-0.6V}{10K} = 1.14mA$$

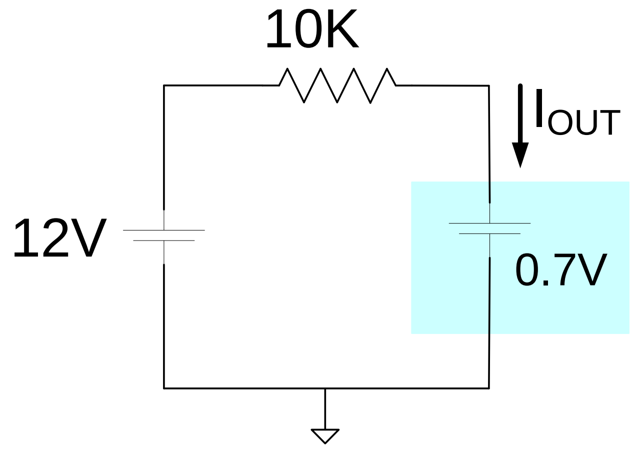
4. Validate state of guess in step 2

To validate state, must show I_D>0

$$I_D = I_{OUT} = 1.14mA > 0$$

Solution:

5. Assume PWL model with V_D=0.7V, R_D=0
6. Guess state of diode (ON)



7. Analyze circuit with model

$$I_{OUT} = \frac{12V - 0.7V}{10K} = 1.13mA$$

8. Validate state of guess in step 6

To validate state, must show I_D>0

$$I_D = I_{OUT} = 1.13mA > 0$$

Solution:

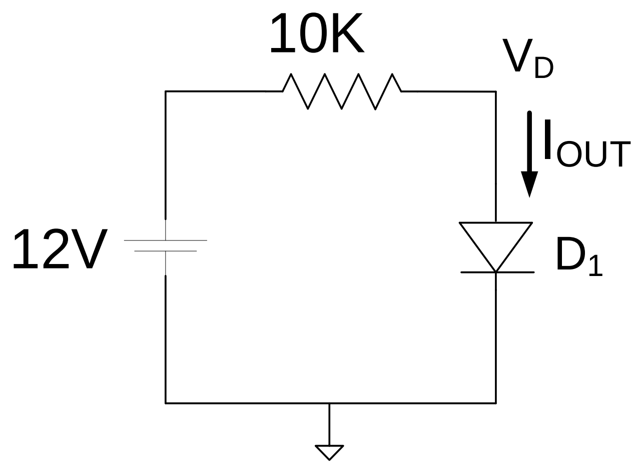
9. Show difference between results using these two models is small

I_{OUT} =1.14mA and I_{OUT} =1.13 mA are close

Thus, can conclude $\boxed{I_{OUT} \cong 1.14mA}$

Example:

Determine I_{OUT} for the following circuit



How do the two solutions compare?

With diode equation model :

$$I_{OUT} = I_S \left(e^{\frac{-I_{OUT} \bullet 10K}{V_t}} e^{\frac{12}{V_t}} - 1 \right)$$

With PWL model:

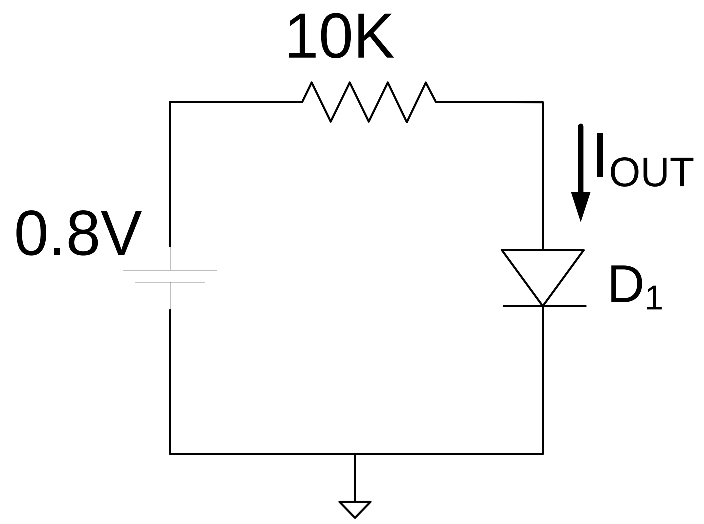
$$I_{OUT} \cong 1.14mA$$

What was the major reason the PWL model simplified the analysis?

Piecewise Linear Model

Example:

Determine I_{OUT} for the following circuit



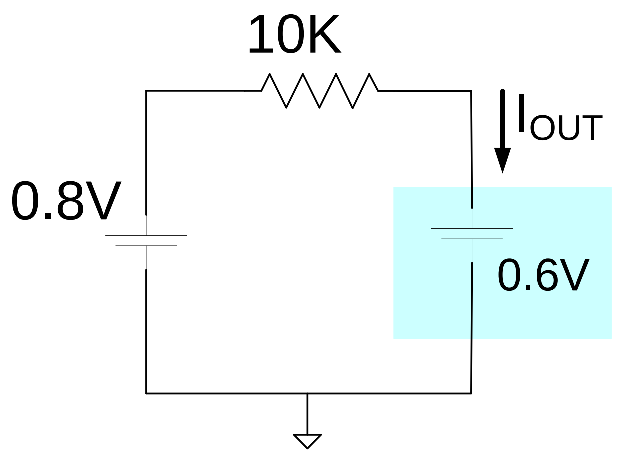
Solution:

Strategy:

1. Assume PWL model with V_D=0.6V, R_D=0
2. Guess state of diode (ON)
3. Analyze circuit with model
4. Validate state of guess in step 2
5. Assume PWL with V_D=0.7V
6. Guess state of diode (ON)
7. Analyze circuit with model
8. Validate state of guess in step 6
9. Show difference between results using these two models is small
10. If difference is not small, must use a different model

Solution:

1. Assume PWL model with V_D=0.6V, R_D=0
2. Guess state of diode (ON)



3. Analyze circuit with model

$$I_{OUT} = \frac{0.8 - 0.6V}{10K} = 20\mu A$$

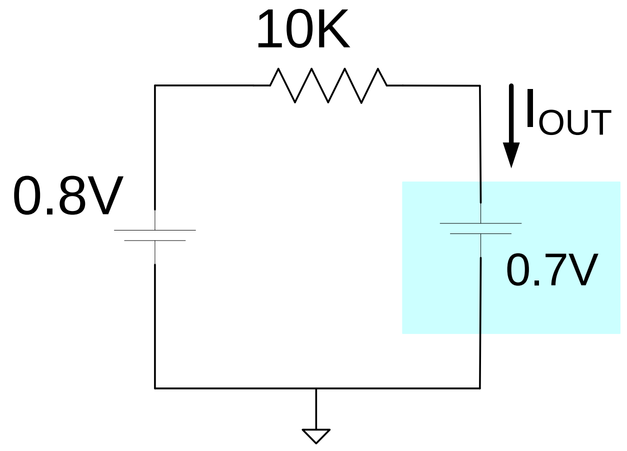
4. Validate state of guess in step 2

To validate state, must show I_D>0

$$I_D = I_{OUT} = 20\mu A > 0$$

Solution:

5. Assume PWL model with V_D=0.7V, R_D=0
6. Guess state of diode (ON)



7. Analyze circuit with model

$$I_{OUT} = \frac{0.8V - 0.7V}{10K} = 10\mu A$$

8. Validate state of guess in step 6

To validate state, must show I_D>0

$$I_D = I_{OUT} = 10\mu A > 0$$

Solution:

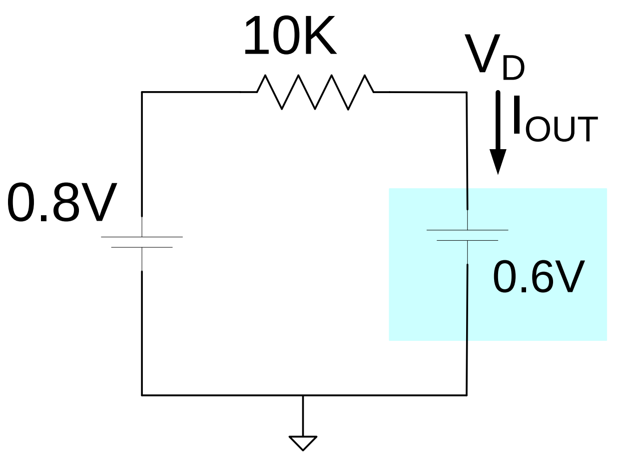
9. Show difference between results using these two models is small

$I_{OUT}=10\mu A$ and $I_{OUT}=20\mu A$ are not close

10. If difference is not small, must use a different model

Thus must use diode equation to model the device

$$\left.\begin{aligned} I_{OUT} &= \frac{0.8-V_D}{10K} \\ I_{OUT} &= I_S e^{\frac{V_D}{V_t}} \end{aligned}\right\}$$



Solve simultaneously, assume V_t=25mV, I_S=1fA

Solving these two equations by iteration, obtain V_D= 0.6148V and $\boxed{I_{OUT}=18.60\mu A}$

Use of Piecewise Models for Nonlinear Devices when Analyzing Electronic Circuits

Process:

1. Guess state of the device
2. Analyze circuit
3. Verify State
4. Repeat steps 1 to 3 if verification fails
5. Verify model (if necessary)

Observations:

- Analysis generally simplified dramatically (particularly if piecewise model is linear)
- Approach applicable to wide variety of nonlinear devices
- Closed-form solutions give insight into performance of circuit
- Usually much faster than solving the nonlinear circuit directly
- Wrong guesses in the state of the device do not compromise solution (verification will fail)
- Helps to guess right the first time
- Detailed model is often not necessary with most nonlinear devices
- For practical circuits, the simplified approach usually applies

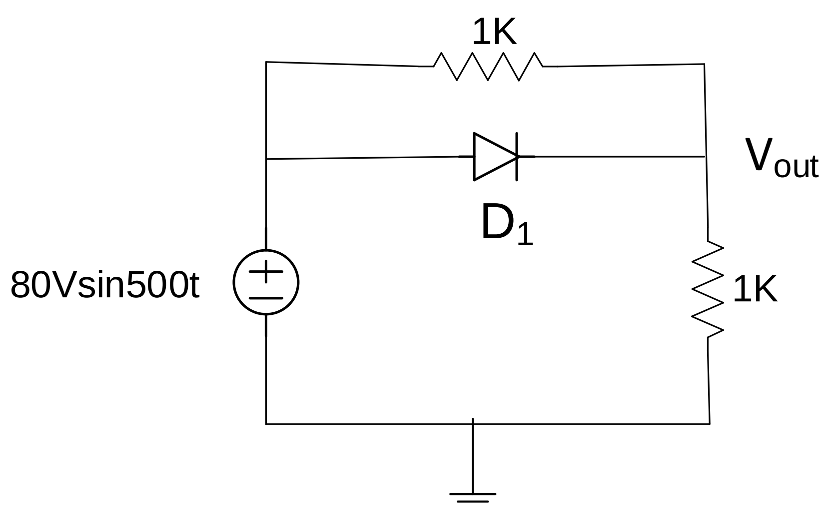
Key Concept For Analyzing Circuits with Nonlinear Devices

Use of <u>Piecewise</u> Models for Nonlinear Devices when Analyzing Electronic Circuits

Process:

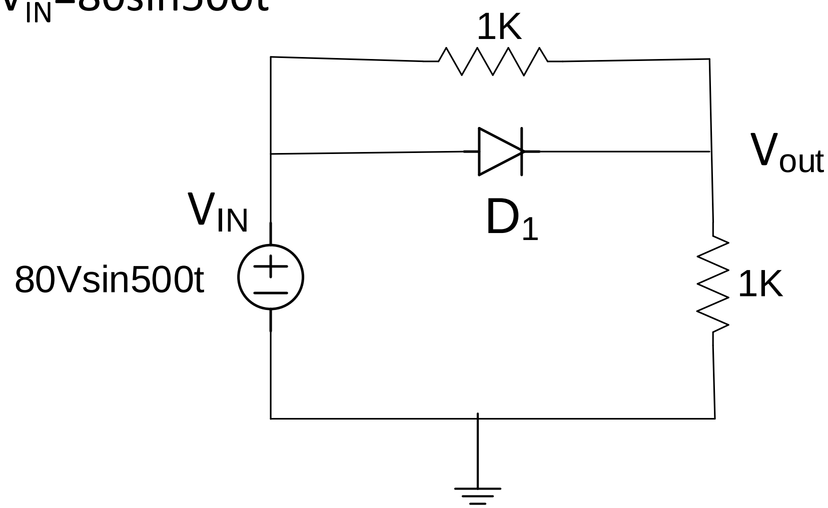
1. Guess state of the device
2. Analyze circuit
3. Verify State
4. Repeat steps 1 to 3 if verification fails
5. Verify model (if necessary)

What about nonlinear circuits (using piecewise models) with time-varying inputs?

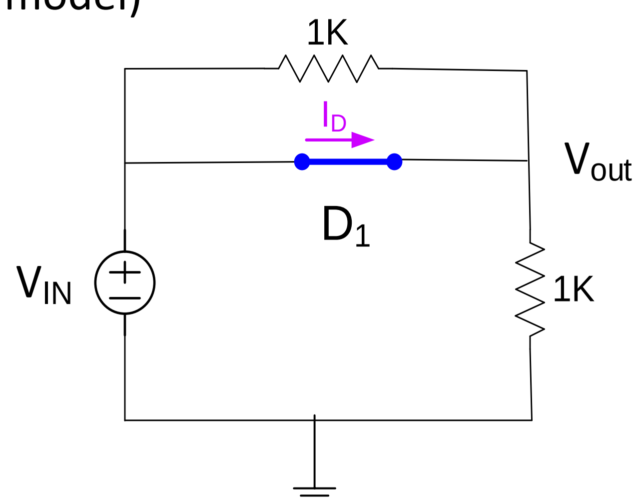


Same process except state verification (step 3) may include a range where solution is valid

Example: Determine V_{OUT} for V_{IN}=80sin500t



Guess D_1 ON (will use ideal diode model)

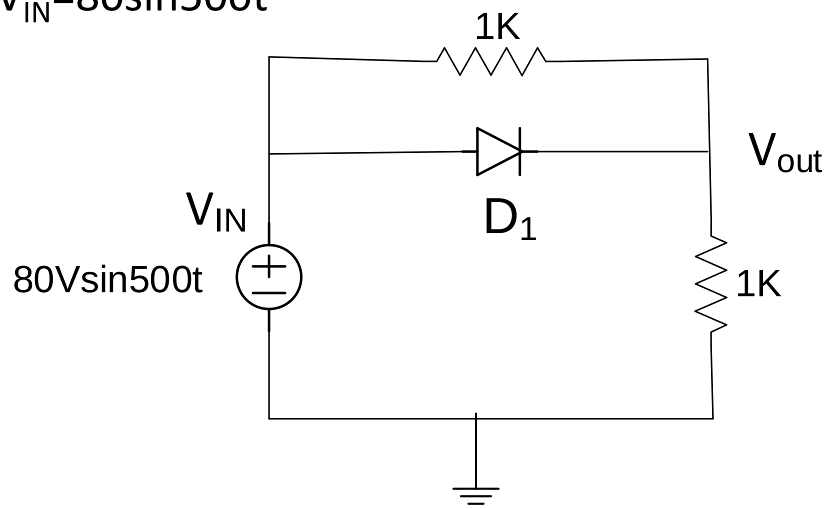


V_{OUT}=V_{IN}=80sin(500t)

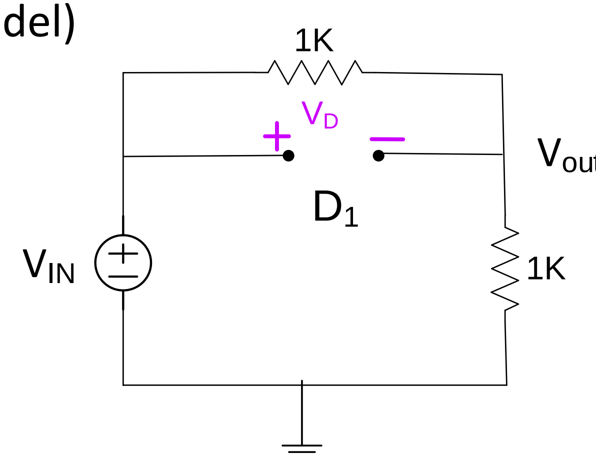
Valid for I_D>0 $$I_D = \frac{V_{IN}}{1K}$$

Thus valid for $V_{IN} > 0$

Example: Determine V_{OUT} for V_{IN}=80sin500t



Guess D_1 OFF (will use ideal diode model)

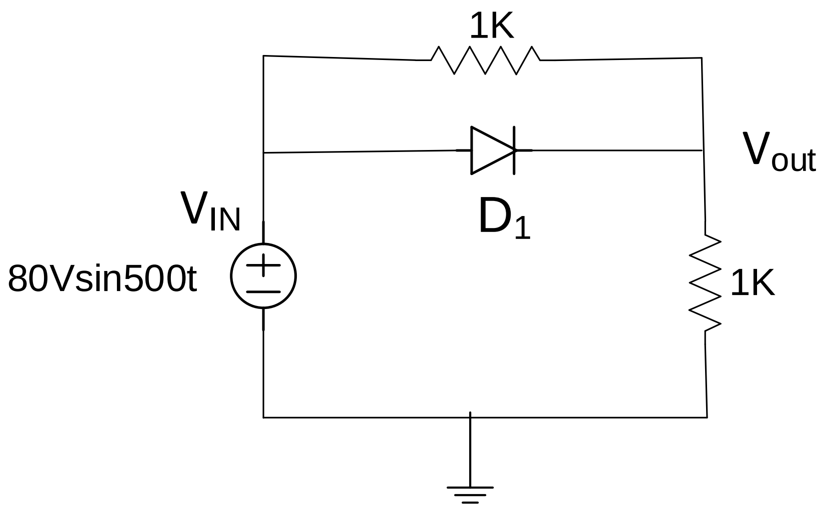


$V_{OUT}=V_{IN}/2=40\sin(500t)$

Valid for $V_D<0$ $\quad V_D = \dfrac{V_{IN}}{2}$

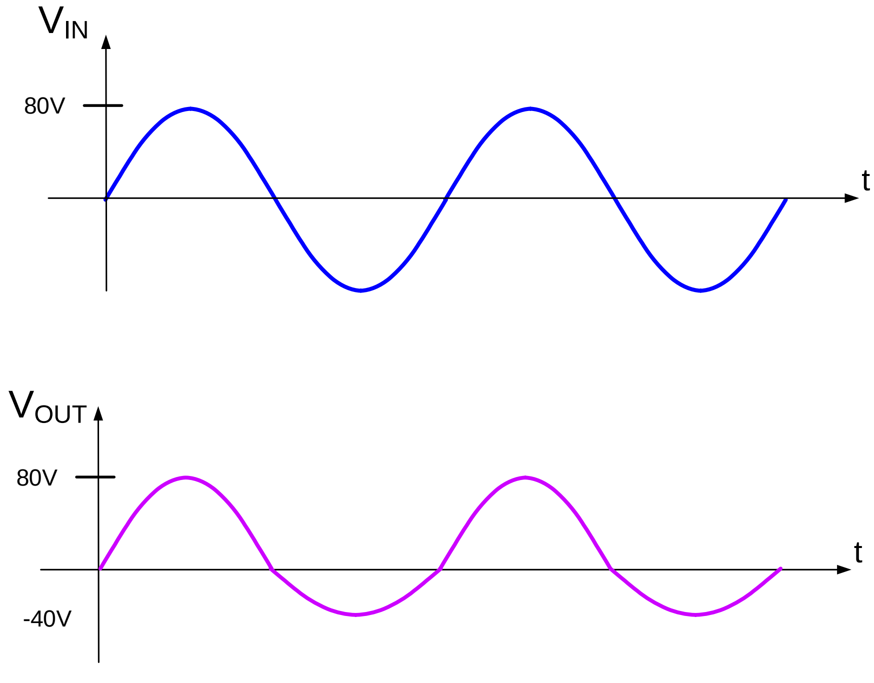
Thus valid for $V_{IN} < 0$

Example: Determine V_{OUT} for V_{IN}=80sin500t



Thus overall solution

$$V_{OUT} = \begin{cases} 80\sin 500t & for\ V_{IN} > 0 \\ 40\sin 500t & for\ V_{IN} < 0 \end{cases}$$

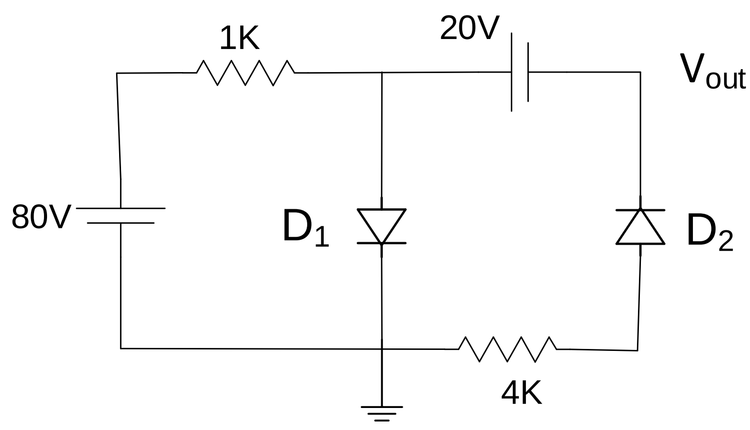


Use of Piecewise Models for Nonlinear Devices when Analyzing Electronic Circuits

Process:

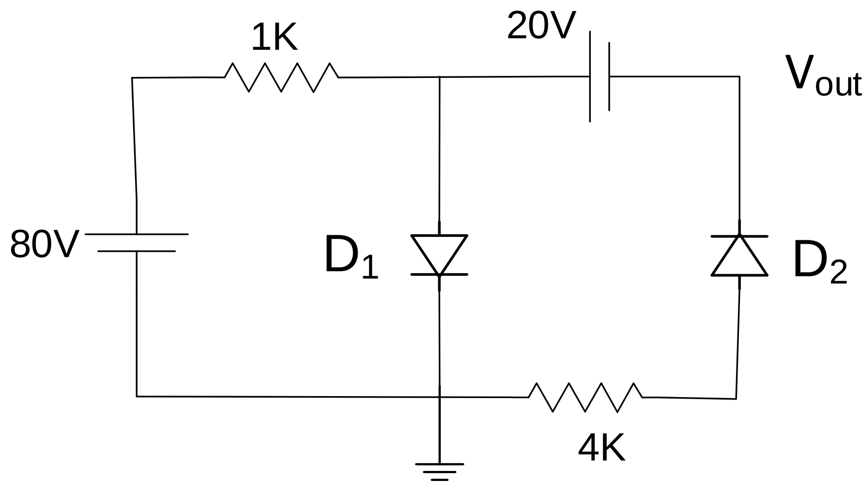
1. Guess state of the device
2. Analyze circuit
3. Verify State
4. Repeat steps 1 to 3 if verification fails
5. Verify model (if necessary)

What about circuits (using piecewise models) with multiple nonlinear devices?

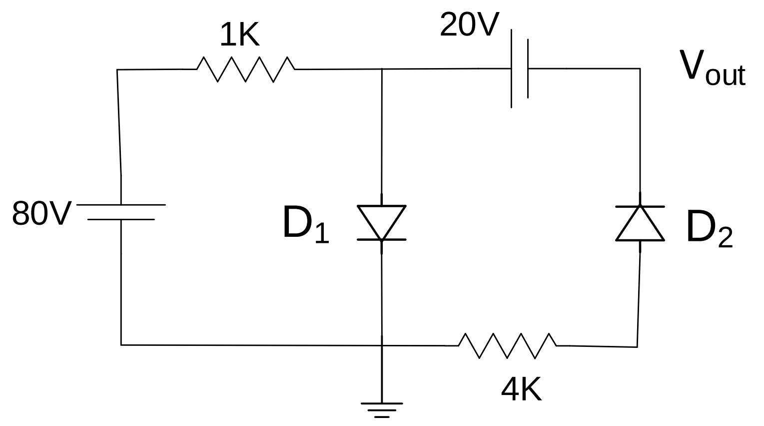


Guess state for each device (multiple combinations possible)

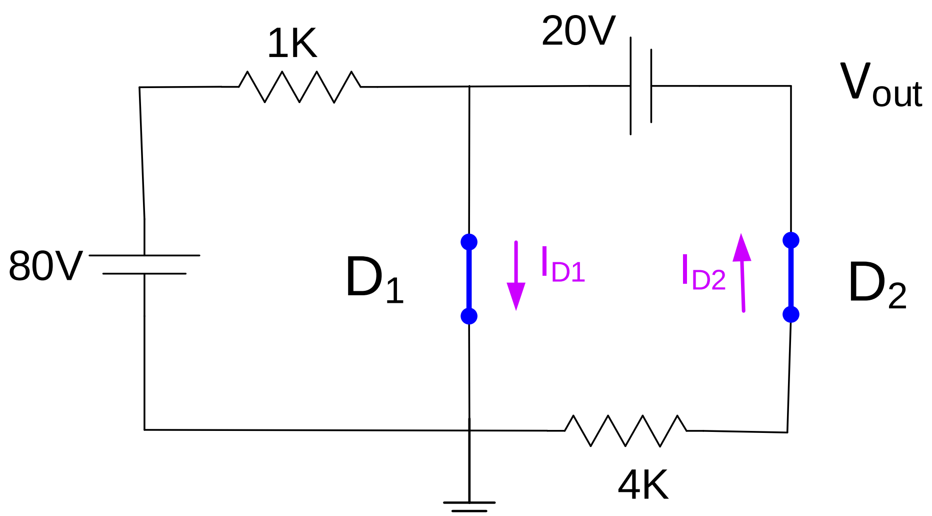
Example: Obtain V_{OUT}



Example: Obtain V_{OUT}



Guess D_1 and D_2 on



V_{OUT}=-20V

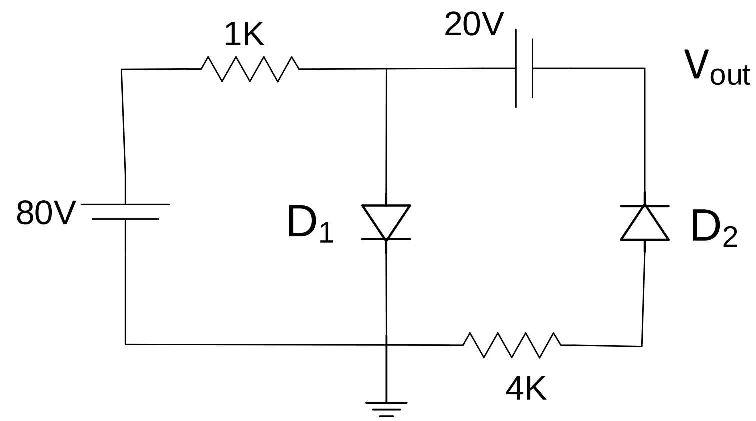
Valid for $I_{D1}>0$ and $I_{D2}>0$

$$I_{D2} = \frac{20V}{4K} = 5mA > 0$$

$$I_{D1} = \frac{80V}{1K} + I_{D2} = 85mA > 0$$

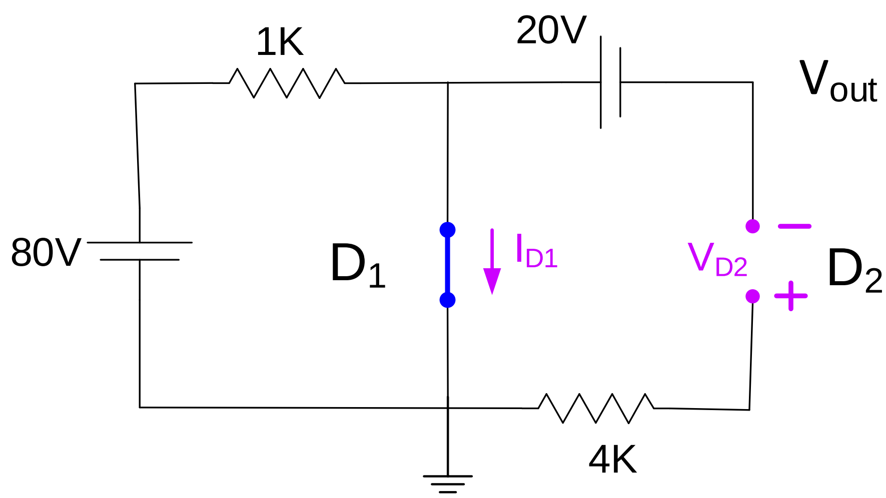
Since validates, solution is valid

Example: Obtain V_{OUT}



If we had guessed wrong

Guess D_1 and D_2 off



V_{OUT}=-20V

Valid for $I_{D1}>0$ and $V_{D2}<0$

$$I_{D2} = \frac{20V}{4K} = 5mA > 0$$

V_{D2}=+20

$$I_{D1} = \frac{80V}{1K} + I_{D2} = 85mA > 0$$

Since fails to validate, solution is not valid so guess is wrong !

Use of Piecewise Models for Nonlinear Devices when Analyzing Electronic Circuits

Single Nonlinear Device

Process:

1. Guess state of the device
2. Analyze circuit
3. Verify State
4. Repeat steps 1 to 3 if verification fails
5. Verify model (if necessary)

Multiple Nonlinear Devices

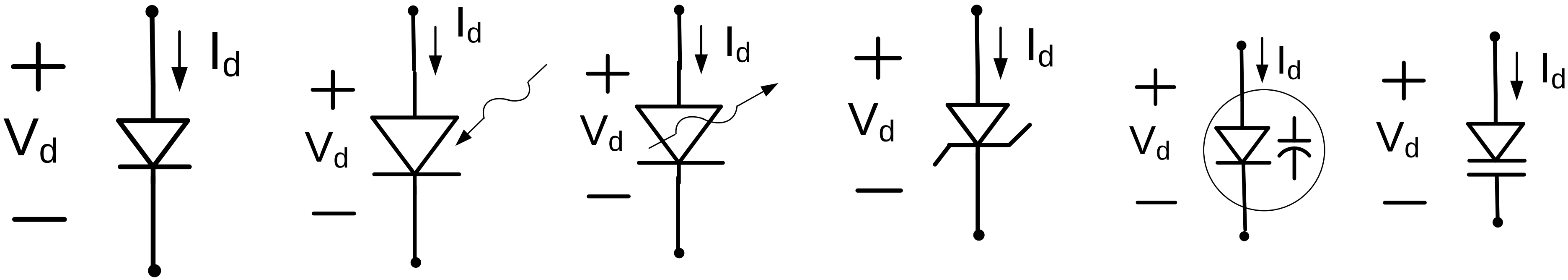
Process:

1. Guess state of each device (may be multiple combinations)
2. Analyze circuit
3. Verify State
4. Repeat steps 1 to 3 if verification fails
5. Verify models (if necessary)

Analytical solutions of circuits with multiple nonlinear devices are often impossible to obtain if detailed non-piecewise nonlinear models are used

Types of Diodes

pn junction diodes



Signal or Rectifier

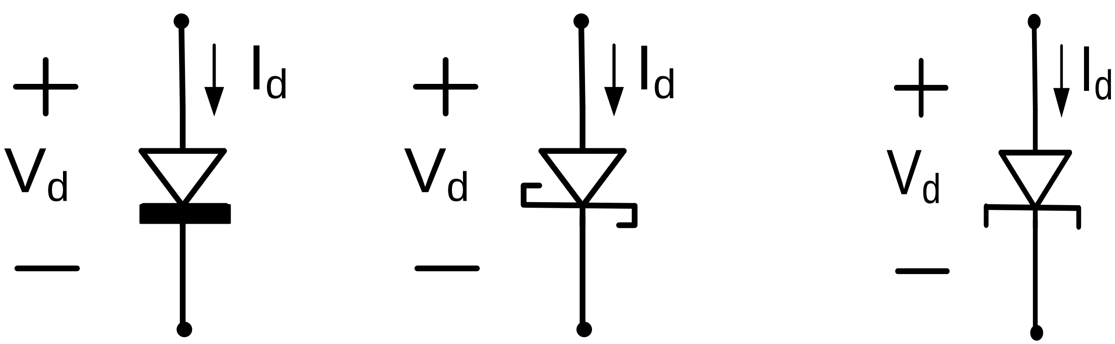
Pin or Photo

Light Emitting LED Laser Diode

Zener

Varactor or Varicap

Metal-semiconductor junction diodes



Schottky Barrier

End of Lecture 15