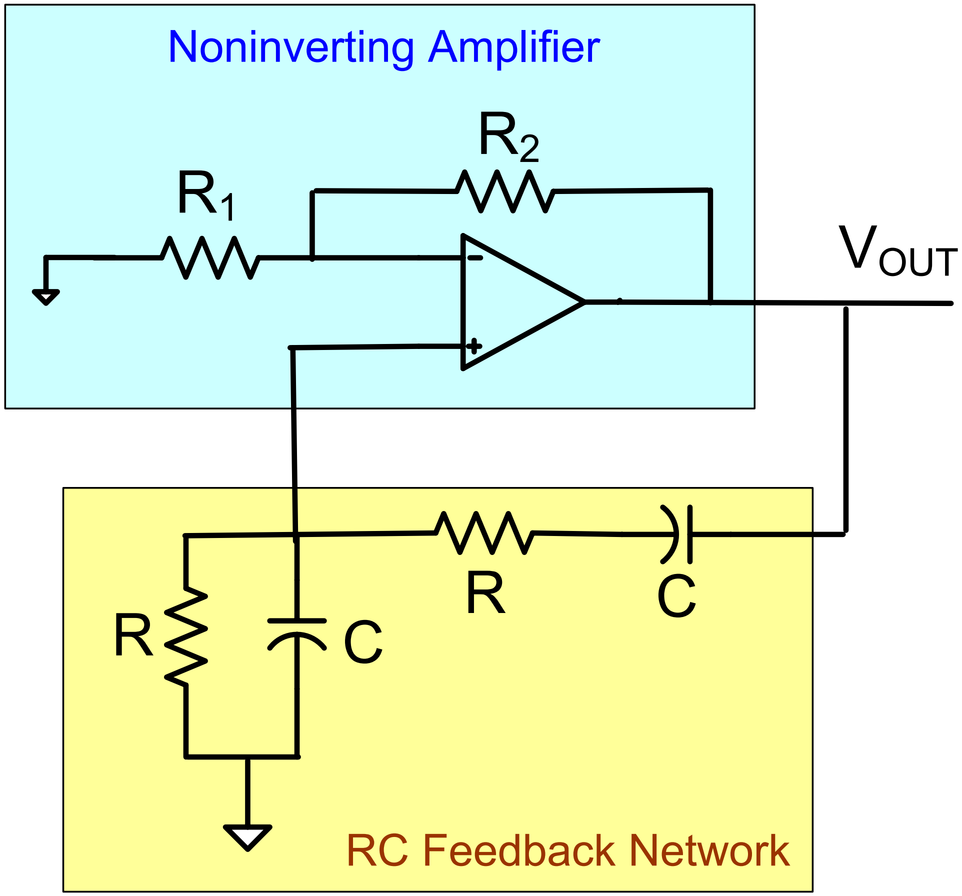
EE 230
Lecture 29

Nonlinear Circuits and Nonlinear Devices

- Diode
- BJT
- MOSFET

Review from Last Time:

Wein-Bridge Oscillator



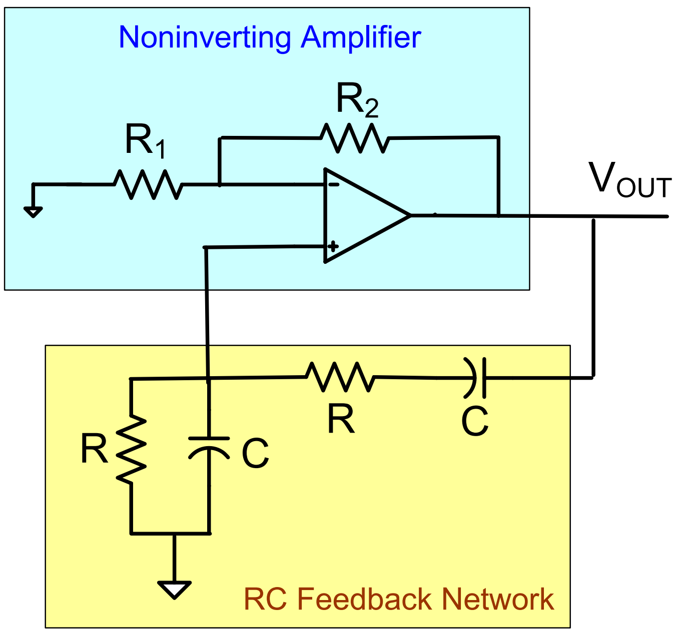
$$K_o = 1 + \frac{R_2}{R_1} = 3 + \varepsilon$$

$$\omega_{OSC} \cong \frac{1}{RC}$$

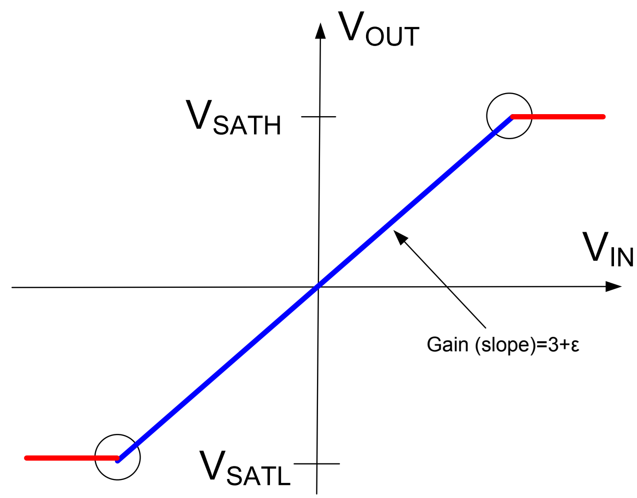
Nonlinearity of Noninverting Amplifier Limits Amplitude of V_{OUT} and when saturation occurs, will cause distortion

Review from Last Time:

Wein-Bridge Oscillator



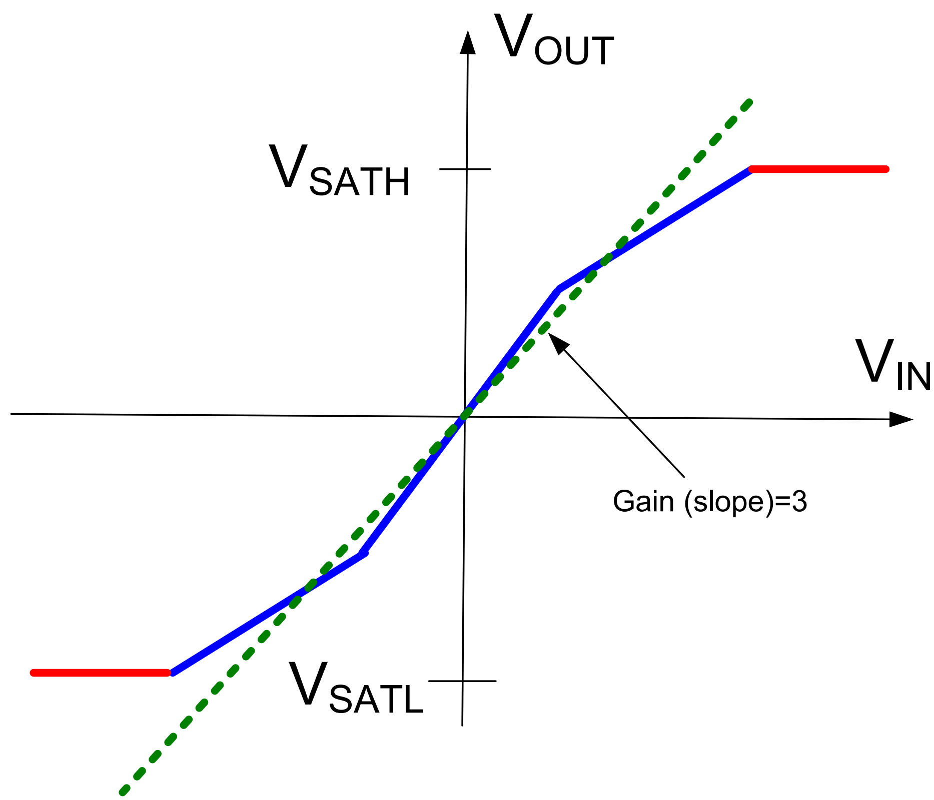
$$K_o = 1 + \frac{R_2}{R_1} = 3 + \varepsilon$$



Nonlinearity of Noninverting Amplifier

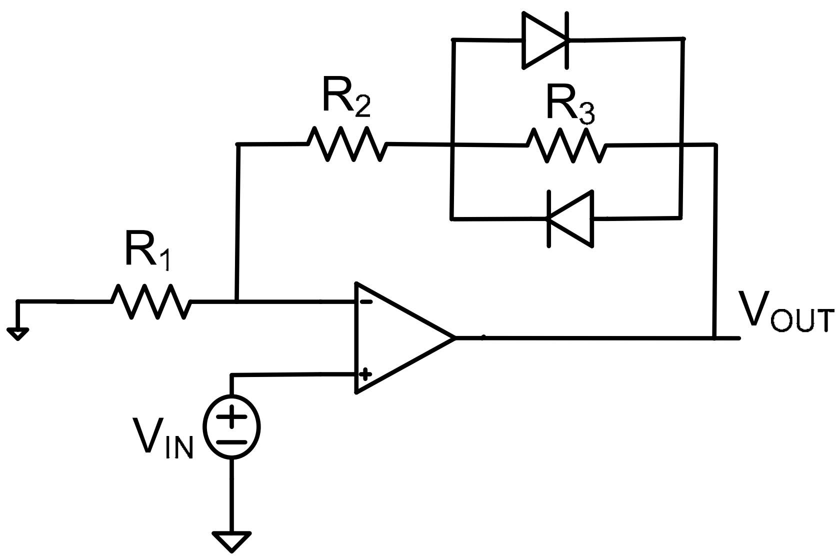
Review from Last Time:

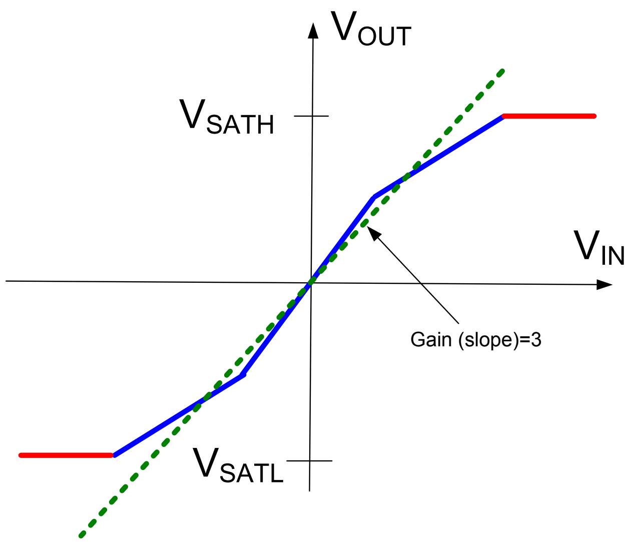
Amplifiers with less abrupt change in slope will reduce distortion



Review from Last Time:

Amplifiers with less abrupt change in slope

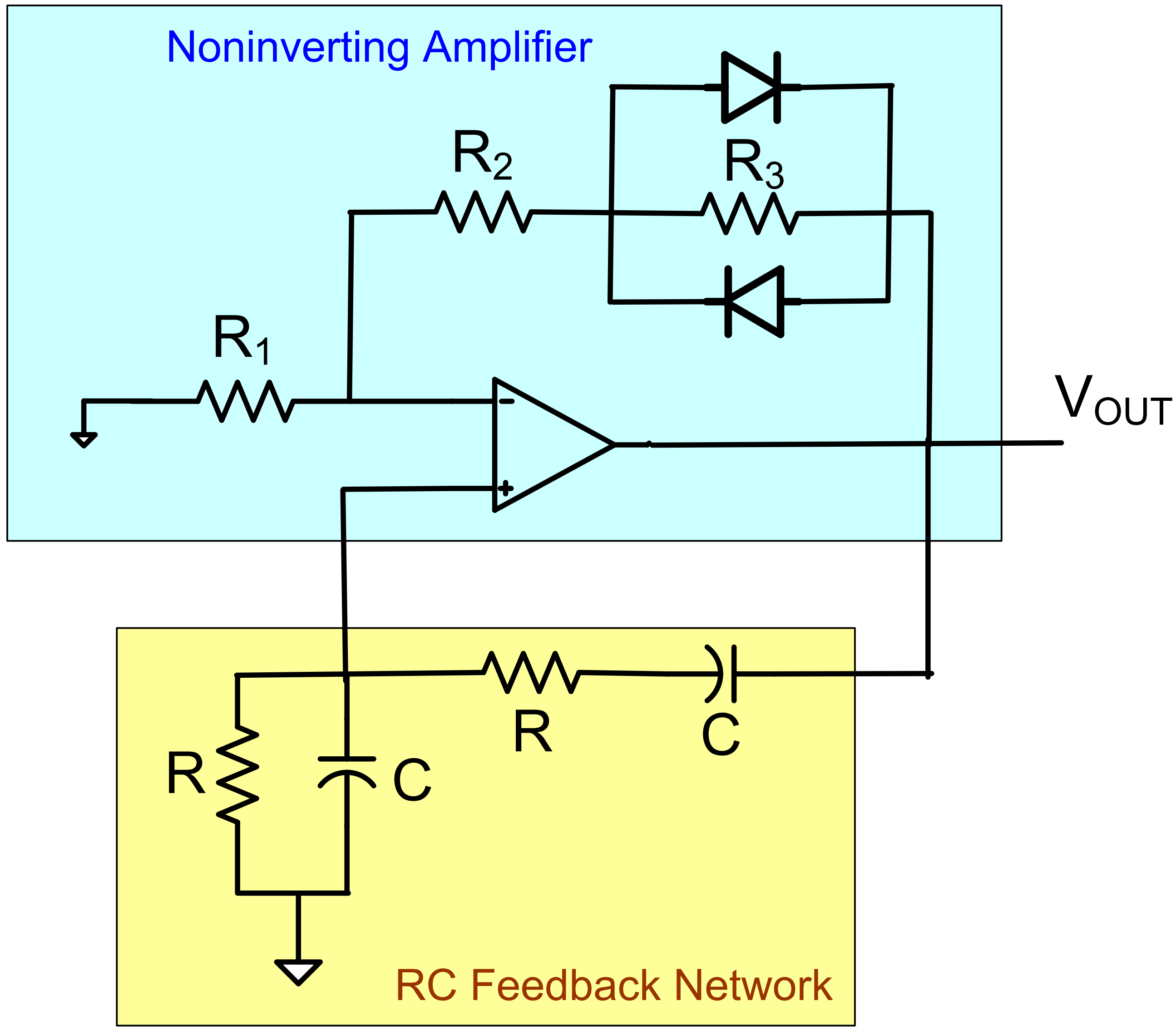




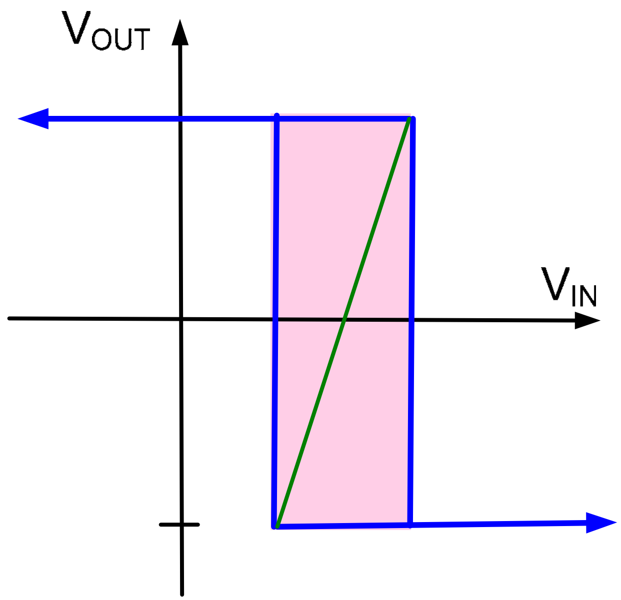
$$V_{OUT}=\begin{cases}\left(1+\frac{R_2}{R_1}\right)V_{IN}+V_\gamma & V_{IN}\geq\frac{R_1}{R_3}V_\gamma \\ \left(1+\frac{R_2}{R_1}\right)V_{IN} & -\frac{R_1}{R_3}V_\gamma<V_{IN}<\frac{R_1}{R_3}V_\gamma \\ \left(1+\frac{R_2}{R_1}\right)V_{IN}-V_\gamma & V_{IN}\leq-\frac{R_1}{R_3}V_\gamma\end{cases}$$

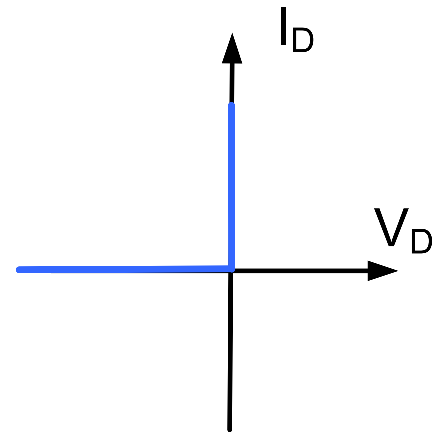
Review from Last Time:

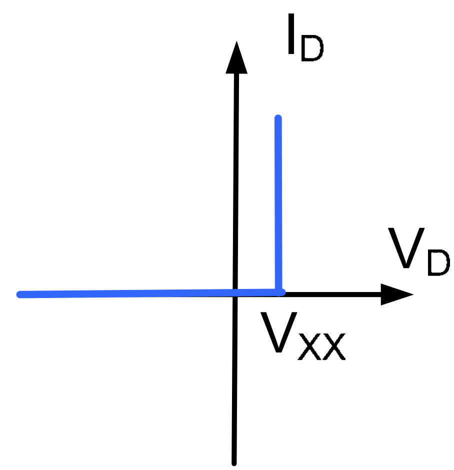
Wein-Bridge Oscillator with Low Distortion Amplitude Limiting



Observation: Nonlinear Devices Have Provided Very Useful Performance Capabilities Not Obtainable with Linear Circuits





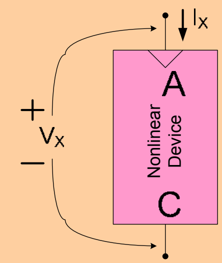


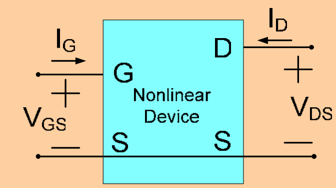
The Electronics World as We See It Until Now

Linear Circuits

- Resistive Networks
- Amplifiers (Dependent Sources)
- Passive Filters (RLC Networks)
- Active Filters
- Waveform Generators
- Sensor Interfaces
- Analog to Digital Converters (ADC)
- Digital to Analog Converters (DAC)

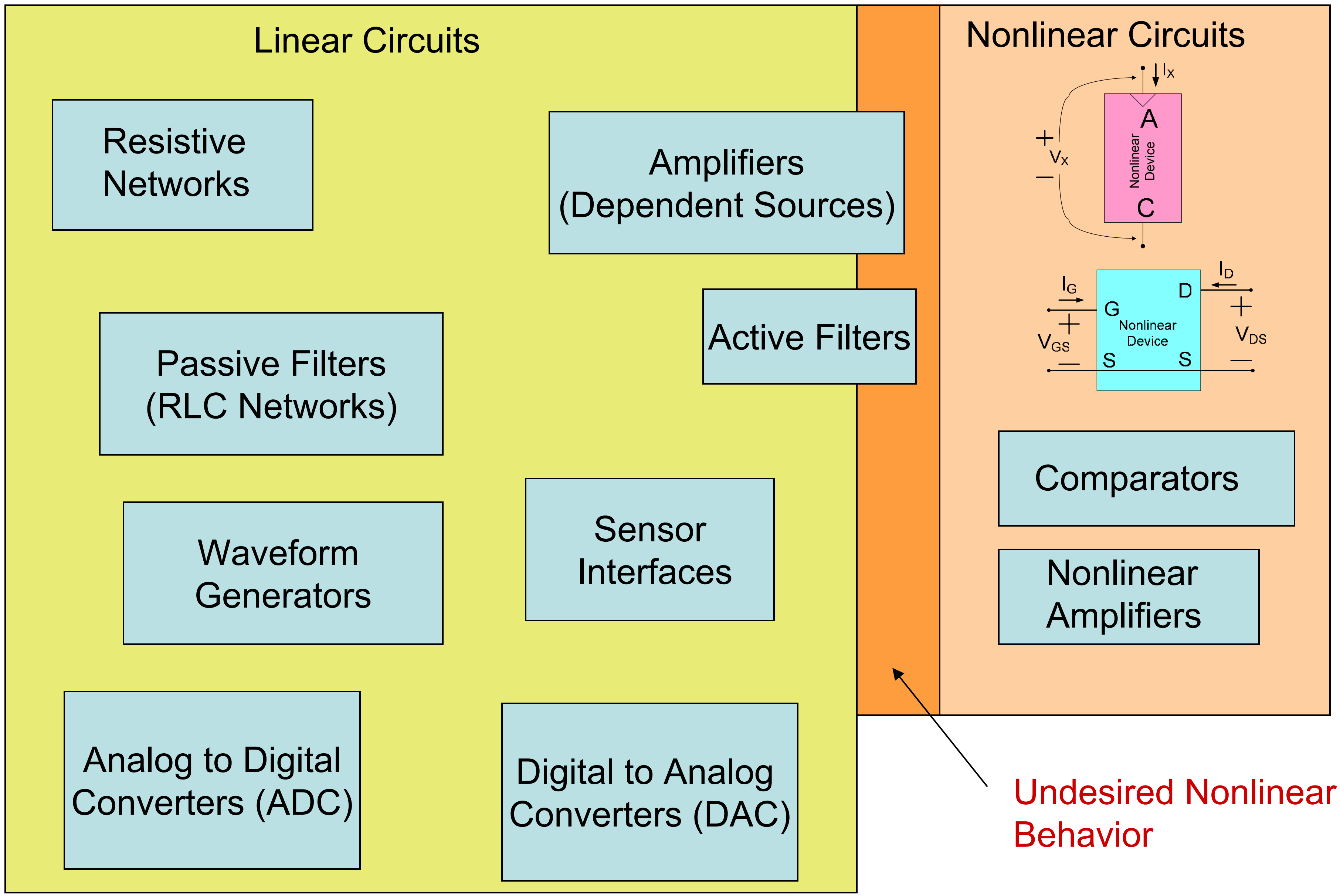
Nonlinear Circuits





- Comparators
- Nonlinear Amplifiers

The Electronics World as We See It Until Now

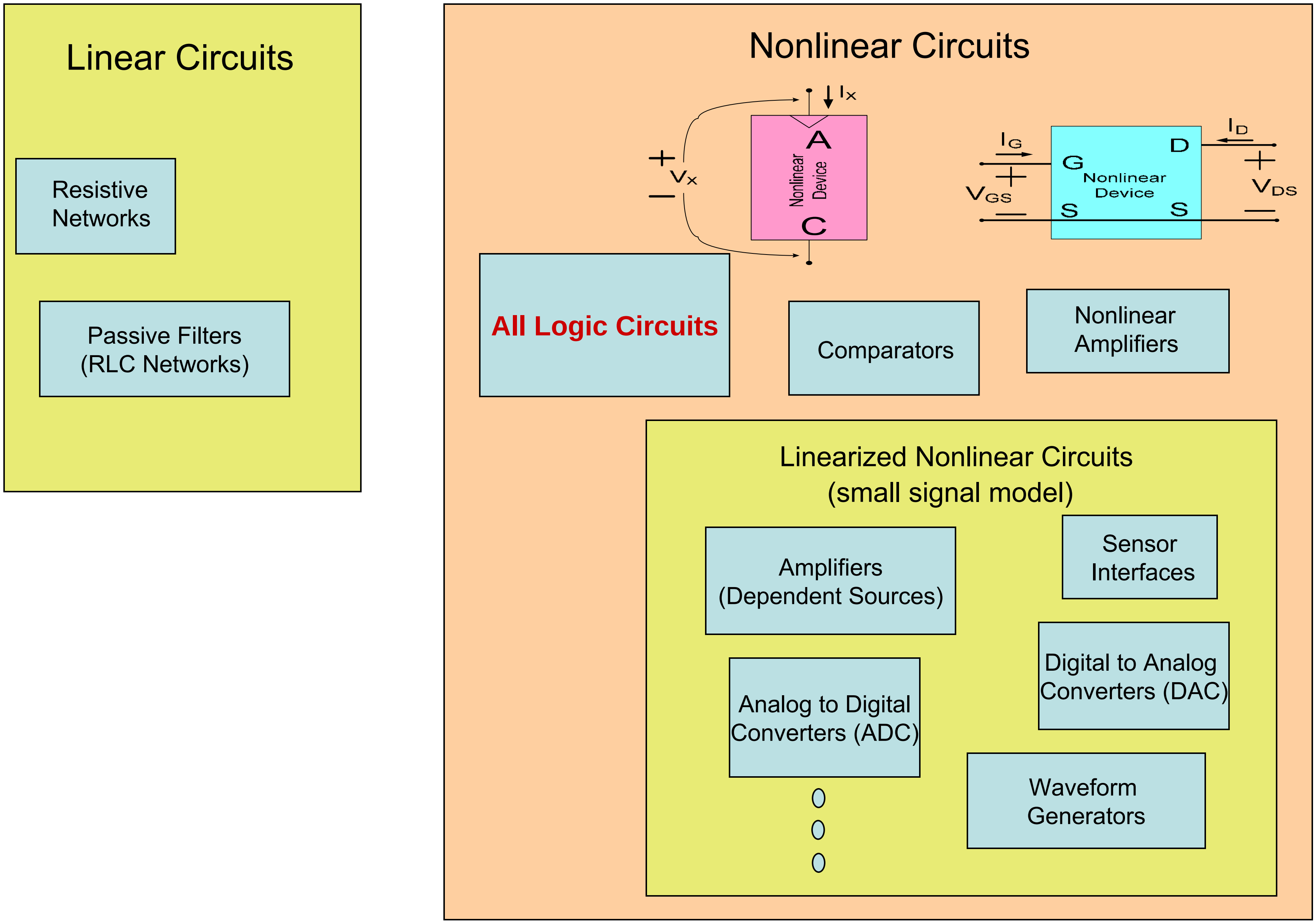


The Electronics World as We See It Until Now

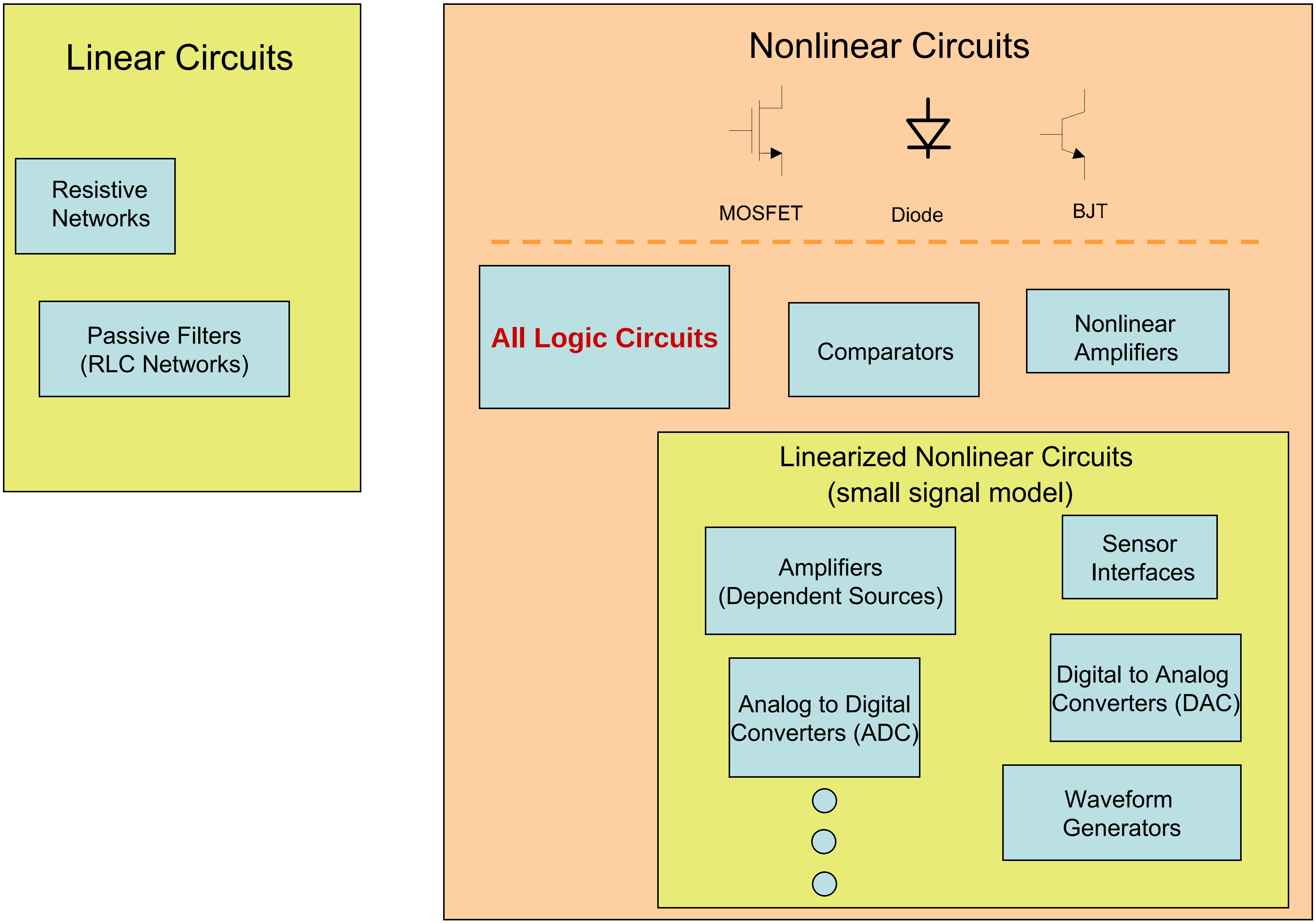
Perception:

- Most of the Electronics World Is Linear
- A few Useful Nonlinear Applications
- Nonlinear Analysis is Hard

The Real Electronics World



The Real Electronics World

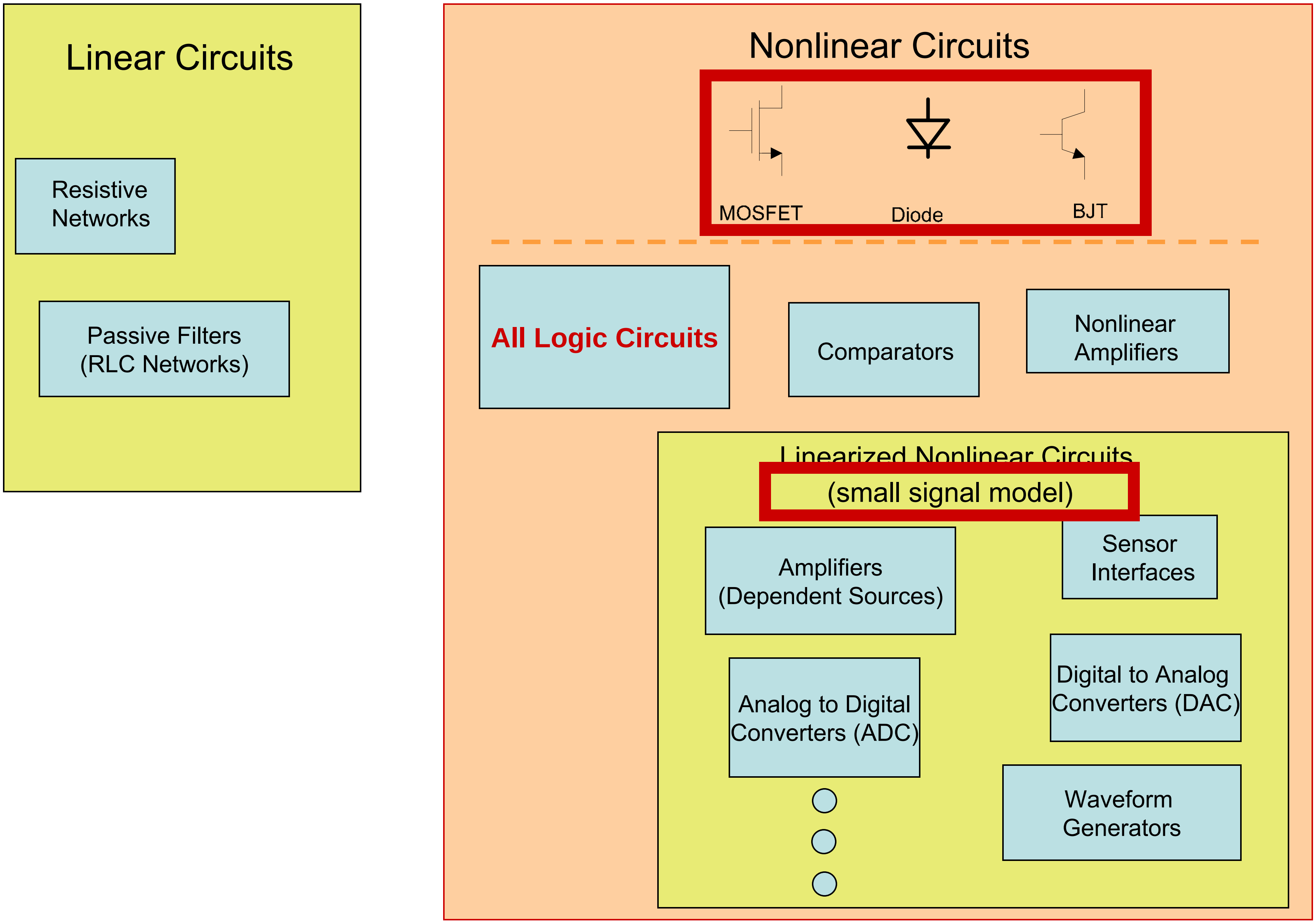


The Real Electronics World

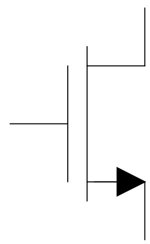
Perception:
- Most of the Electronics World Is Linear
- A few Useful Nonlinear Applications
- Nonlinear Analysis is Hard

Reality:
- **Most Electronic Circuits are Nonlinear**
- **Many combine nonlinear devices to make nearly linear circuits**
- **Nonlinear Analysis is Different**
  - **Sometimes Easier than Linear Analysis**
  - **Sometimes Harder than Linear Analysis**
  - **But mostly just different**

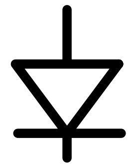
The Real Electronics World



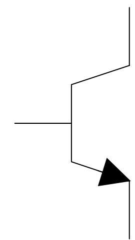
Basic Nonlinear Devices



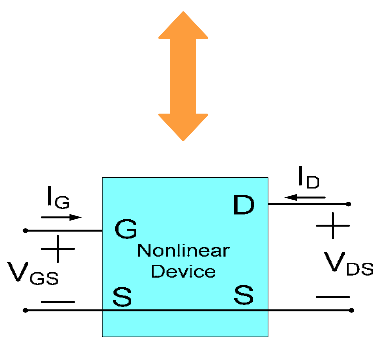
MOSFET

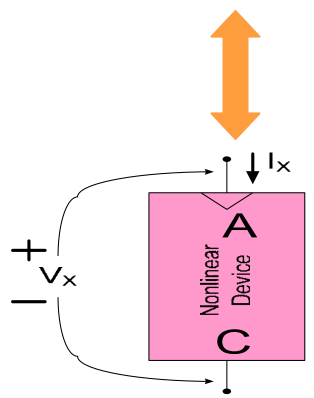


Diode



BJT





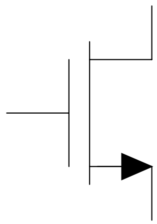
$$I_G = 0$$

$$I_D = \begin{cases} 0 & V_{GS} < 1V \\ 10^{-4}\left(V_{GS} - 1 - \frac{V_{DS}}{2}\right) V_{DS} & V_{GS} > 1V,\ \ V_{DS} < V_{GS} - 1V \\ \frac{10^{-4}}{2}(V_{GS} - 1)^2 & V_{GS} > 1V,\ \ V_{DS} > V_{GS} - 1V \end{cases}$$

$$I_D = 0 \quad \text{if} \quad V_D \le 0$$

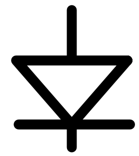
$$V_D = 0 \quad \text{if} \quad I_D > 0$$

Basic Nonlinear Devices



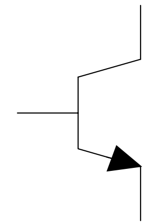
MOSFET

- Proposed in approx 1930
- Manufactured in approx 1970
- Dominant device in digital ICs today
- Widely used for analog ICs
- Device upon which semiconductor industry today is based



Diode

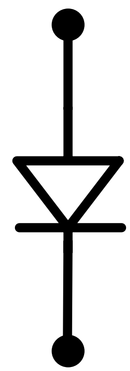
- Proposed and manufactured in approx 1940
- Physics understood approx 1948
- Widely used in power applications
- Some use in signal processing and instrumentation
- Available in most semiconductor processes without additional cost but often not optimized

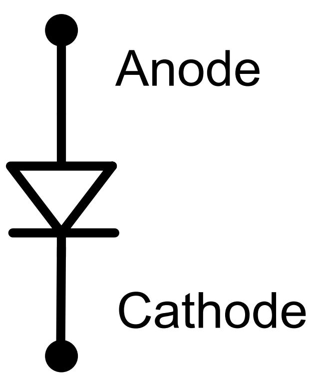


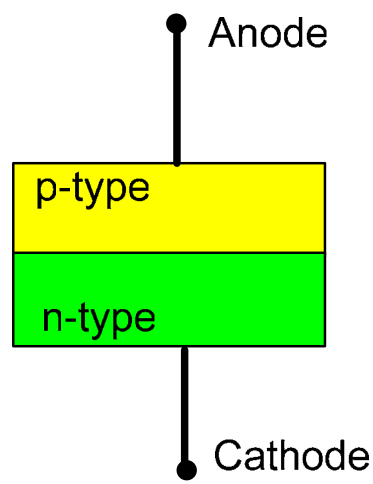
BJT

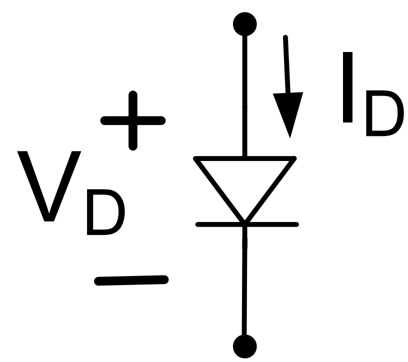
- Invented in 1948 and manufactured almost immediately thereafter
- Dominant device in semiconductor industry till mid 70s
- Preferred in many linear ICs
- Offers some speed benefits over MOSFET
- Good BJTs available in some niche processes

The Diode



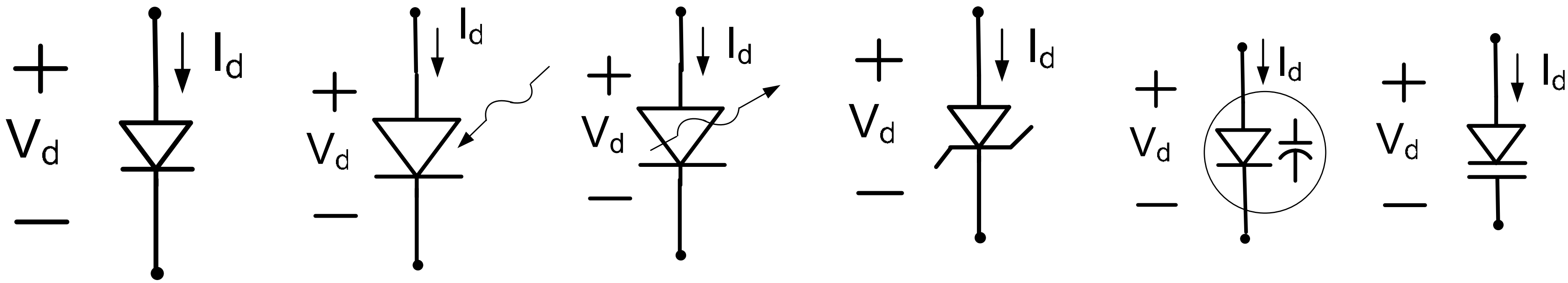






Types of Diodes

pn junction diodes



Signal or Rectifier

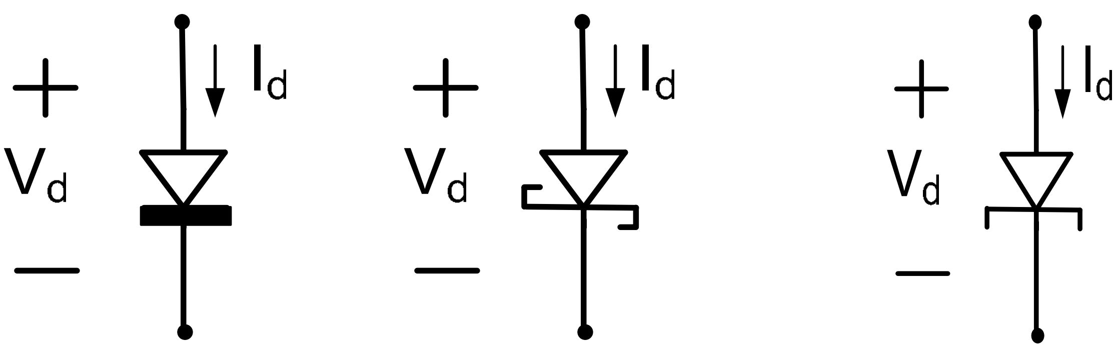
Pin or Photo

Light Emitting LED Laser Diode

Zener

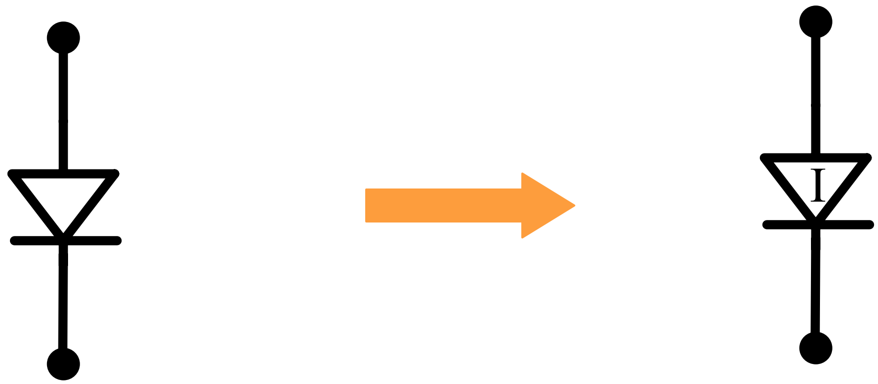
Varactor or Varicap

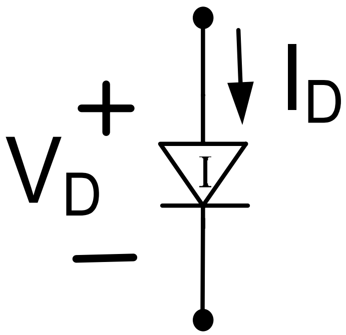
Metal-semiconductor junction diodes

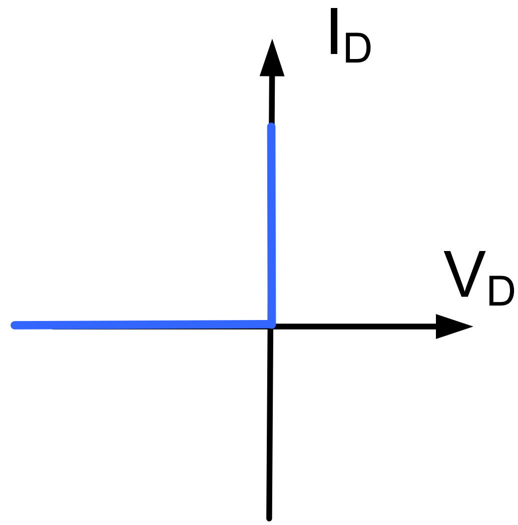


Schottky Barrier

The Ideal Diode



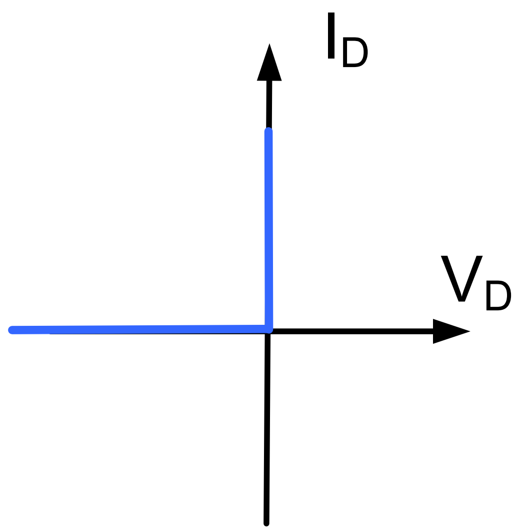




$$I_D = 0 \quad \text{if} \quad V_D \leq 0$$

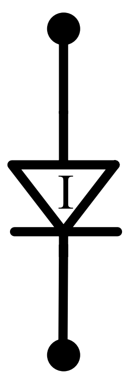
$$V_D = 0 \quad \text{if} \quad I_D > 0$$

The Ideal Diode

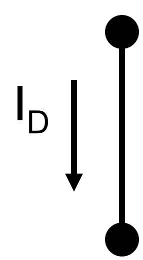


$$I_D = 0 \quad \text{if} \quad V_D \le 0$$ "OFF"

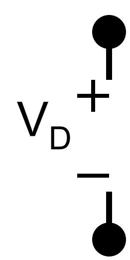
$$V_D = 0 \quad \text{if} \quad I_D > 0$$ "ON"



"ON"

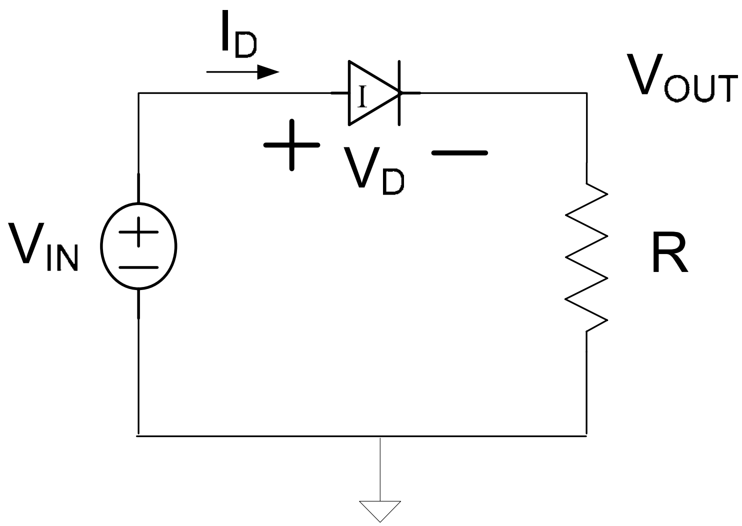


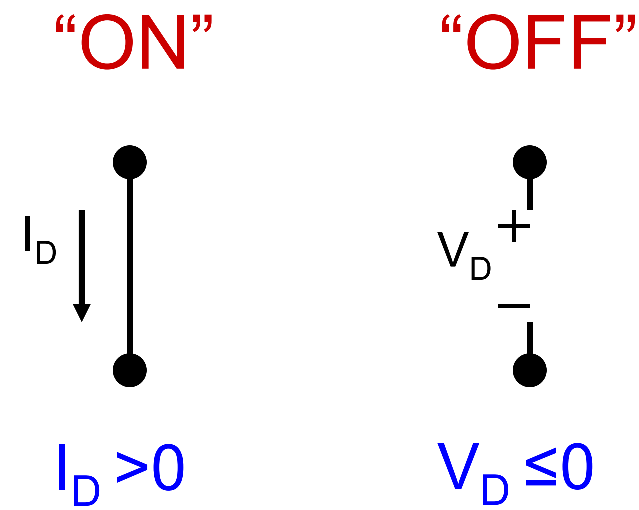
"OFF"



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

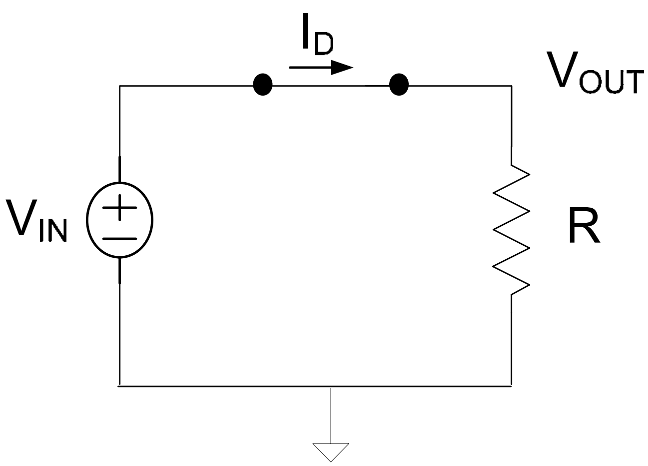
Consider a simple diode circuit





Analysis:

Case 1 Guess Diode in "ON"



solution:

$V_{OUT} = V_{IN}$

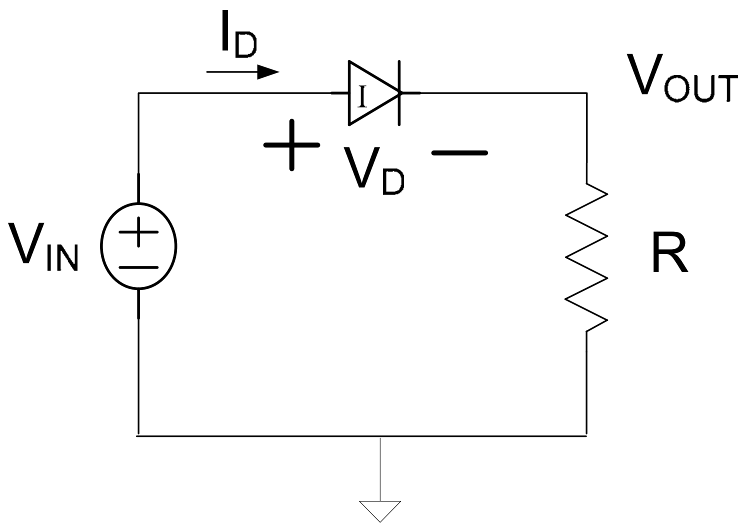
valid for:

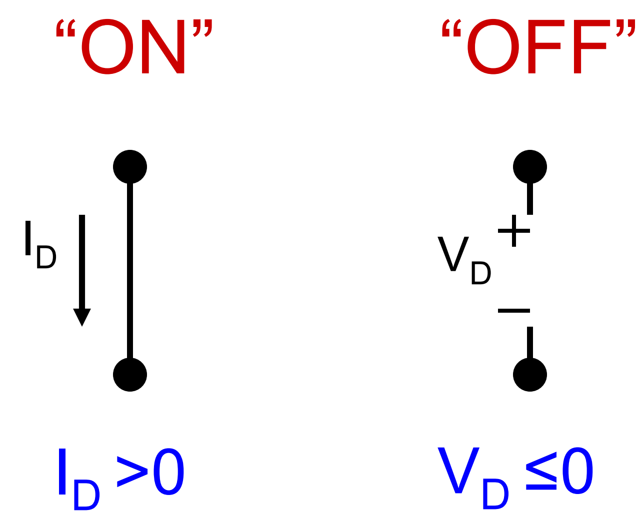
$I_D > 0$

$I_D = \frac{V_{OUT}}{R}$ Always express in terms of V_{IN} $I_D = \frac{V_{IN}}{R}$

$V_{IN} > 0$

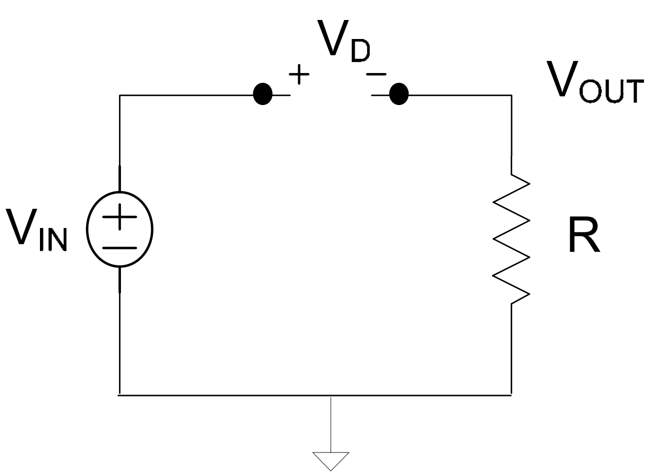
Consider a simple diode circuit





Analysis:

Case 2 Guess Diode is "OFF"



solution:

$V_{OUT} = 0$

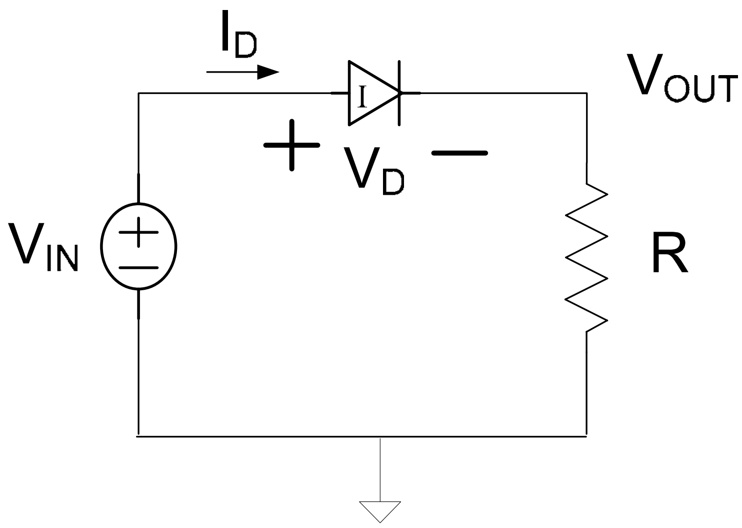
valid for:

$V_D \leq 0$

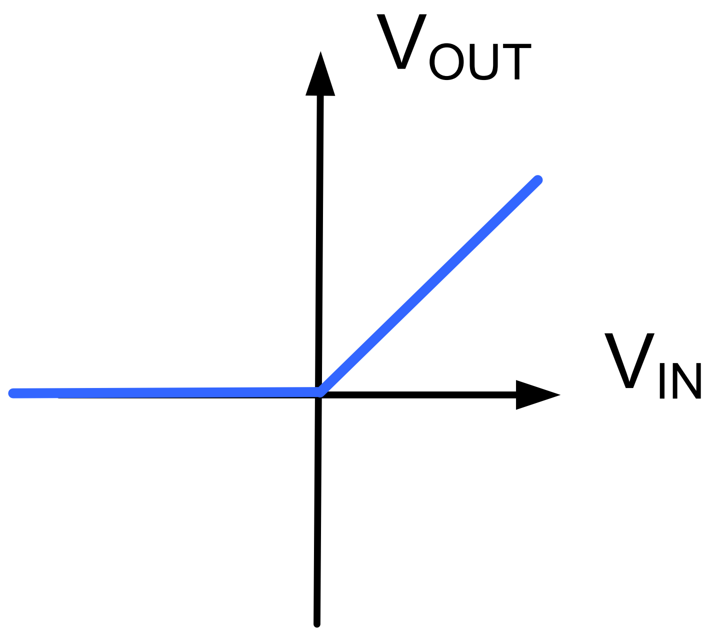
$V_D = V_{IN} - V_{OUT} = V_{IN} \leq 0$

$V_{IN} \leq 0$

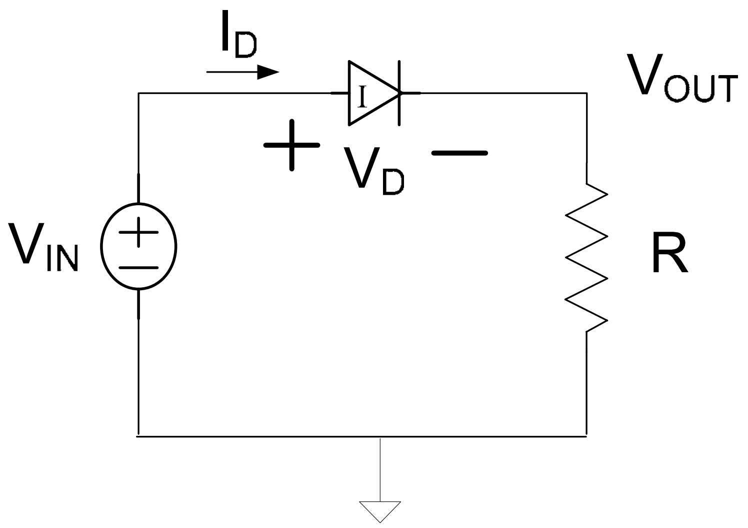
Consider a simple diode circuit

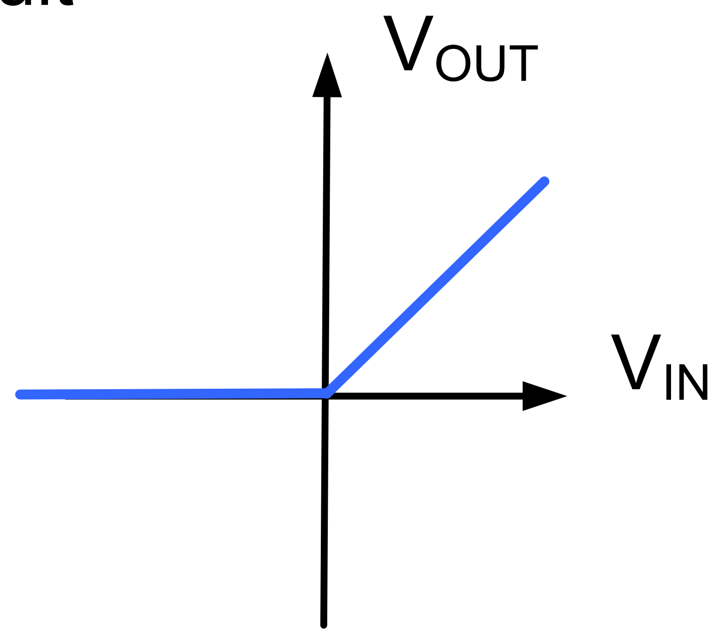


$$V_{OUT} = \begin{cases} V_{IN} & V_{IN} > 0 \\ 0 & V_{IN} \leq 0 \end{cases}$$

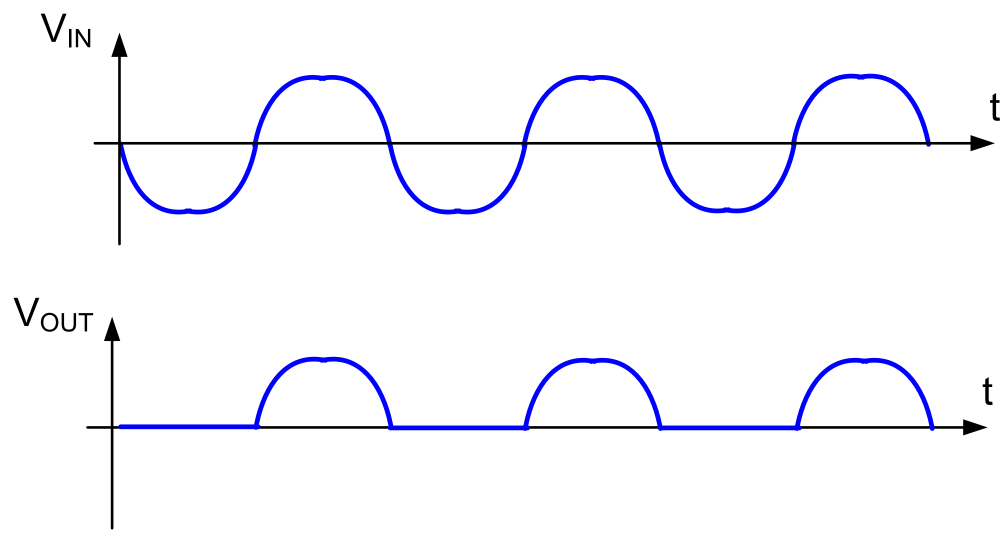


Consider a simple diode circuit





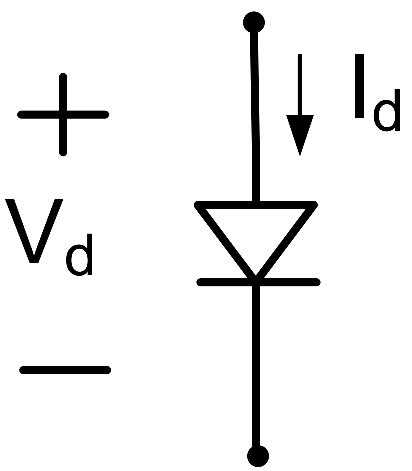
If $V_{IN}=V_M \sin\omega t$

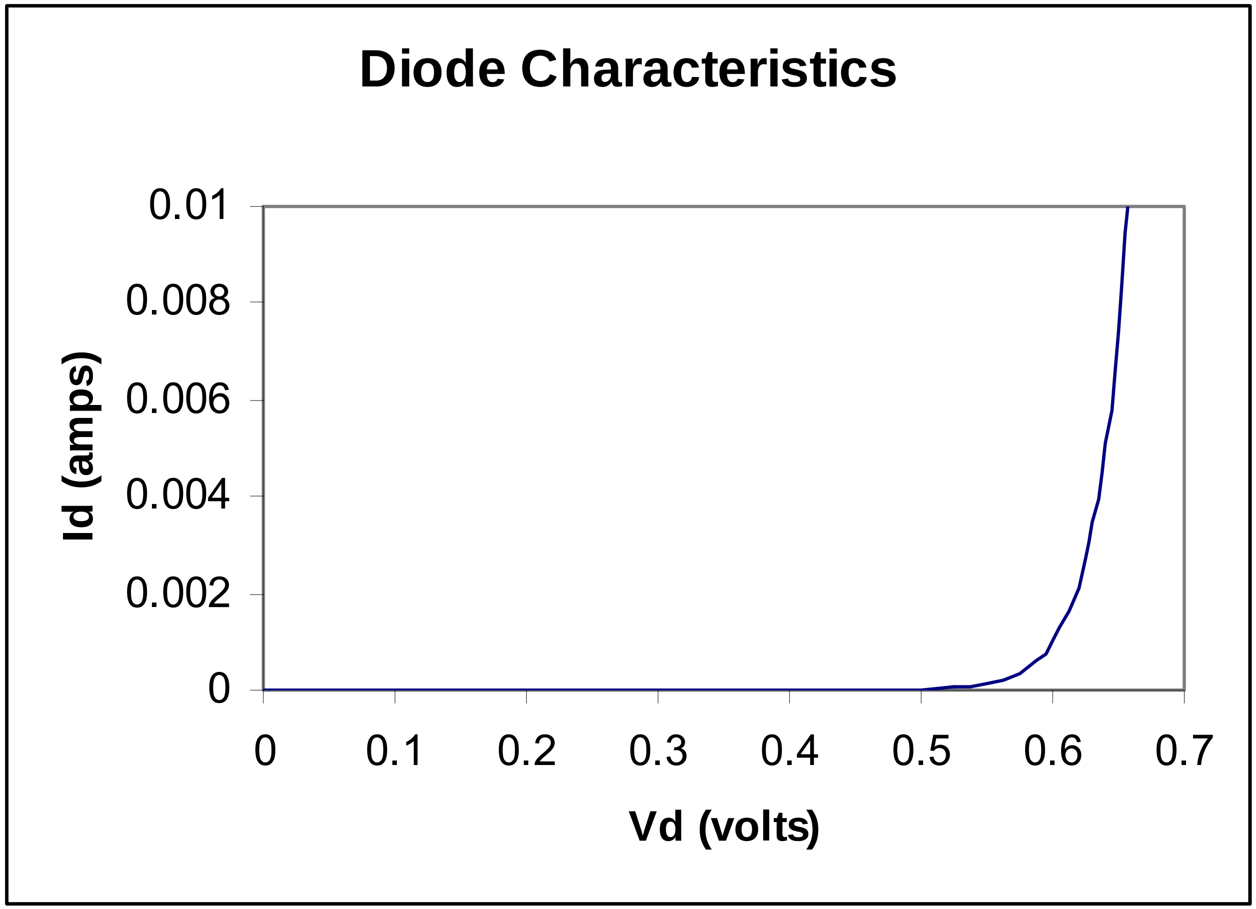


Serves as a rectifier – very useful function !

I-V characteristics of pn junction

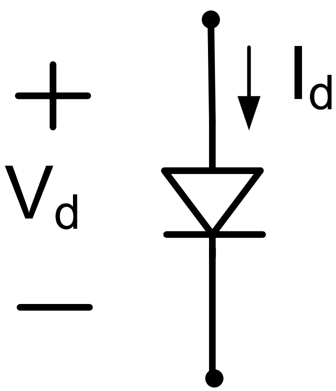
(signal or rectifier diode)

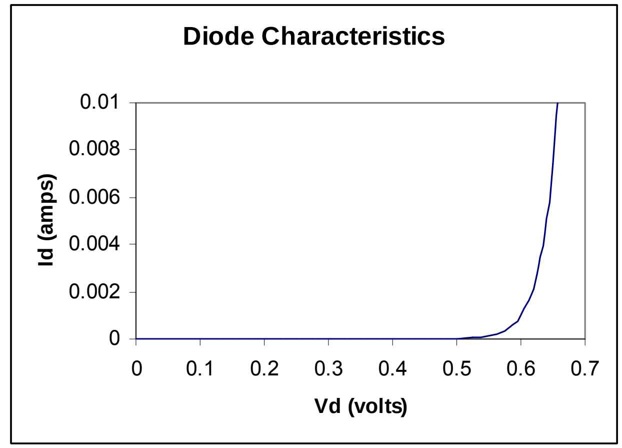




I-V characteristics of pn junction

(signal or rectifier diode)





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

I_S is a constant (typically 10fA < I_S 100fA)

$V_t = kT/q$ k Boltzman's Constant, q charge of electron, T temp in K

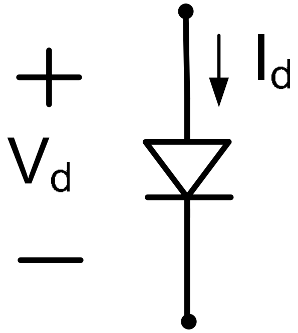
k/q=8.63E-5 V/ °K

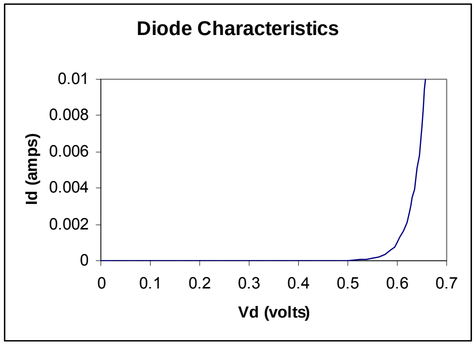
At room temperature, V_t is approximately 25mV

I_D highly temperature dependent (widely used in temp sensors!)

I-V characteristics of pn junction

(signal or rectifier diode)





Termed Diode Equation

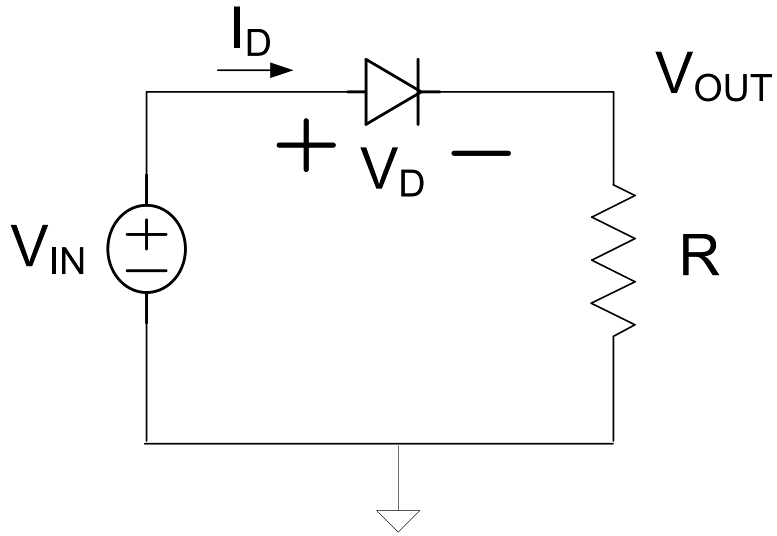
$$I_D = I_S \left(e^{\frac{V_d}{V_t}} - 1 \right)$$

Under reverse bias, $I_D \cong -I_S$

Under forward bias, $I_D = I_S e^{\frac{V_d}{V_t}}$

Diode Equation or forward bias simplification is unwieldy to work with analytically

Consider again the basic rectifier circuit



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

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

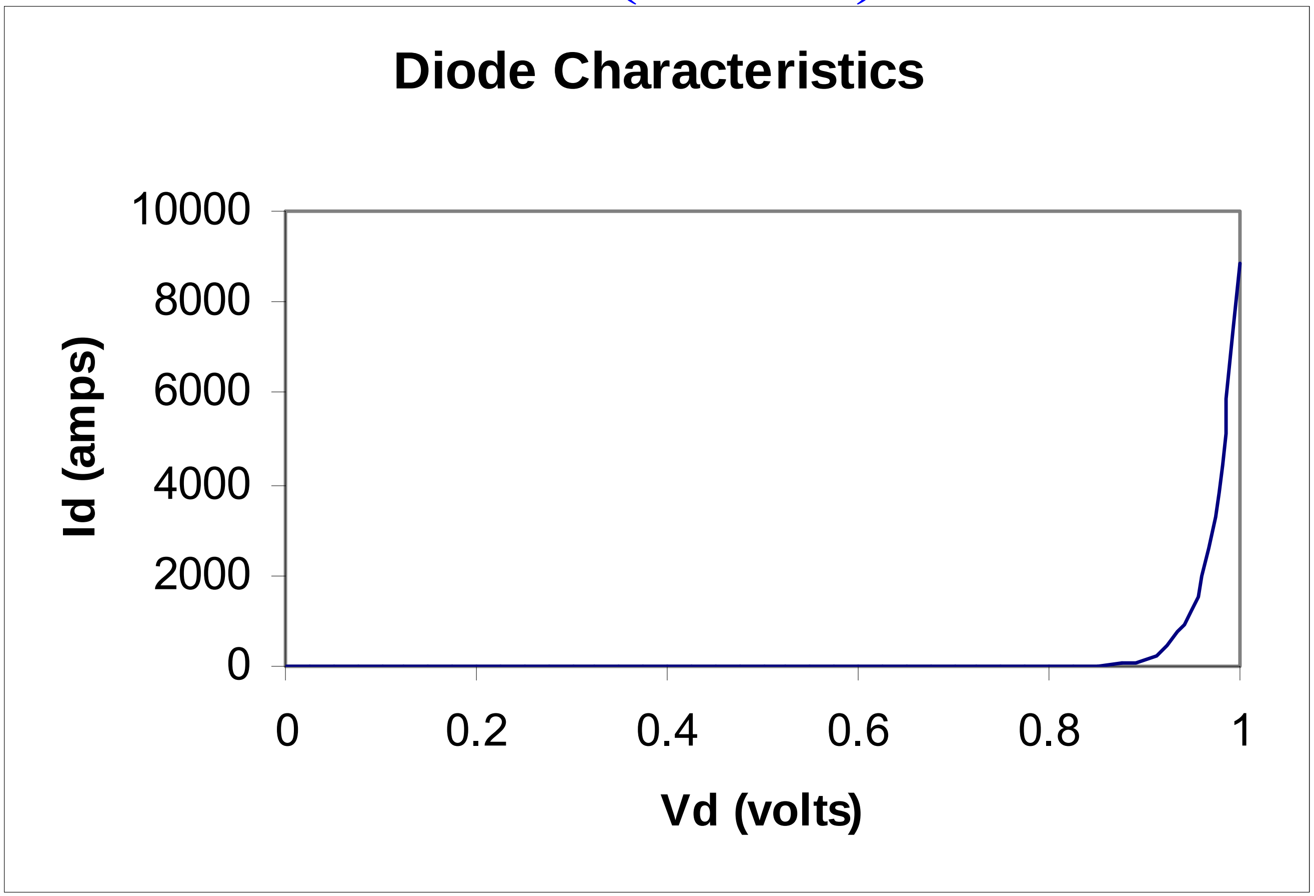
Even the simplest diode circuit does not have a closed-form solution when diode equation is used to model the diode !!

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

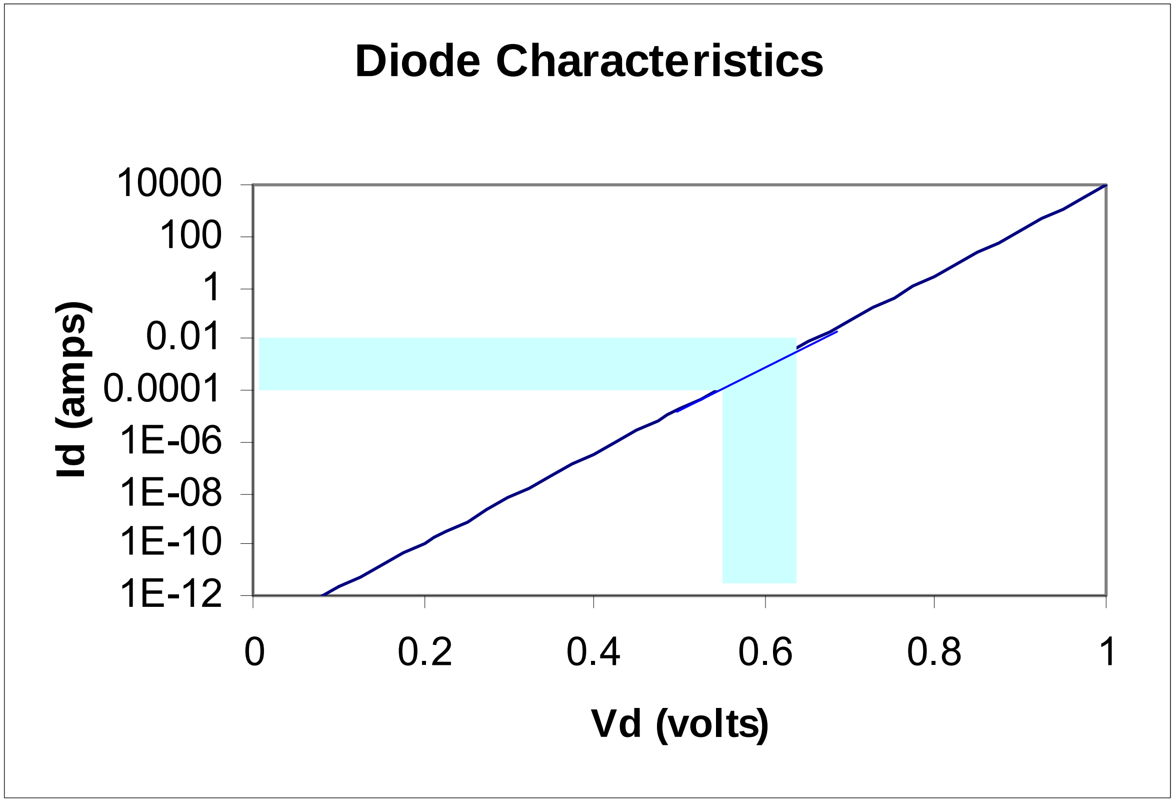
$$I_d = I_S\left(e^{\frac{V_d}{V_t}} - 1\right)$$



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

Lets study the diode equation a little further

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

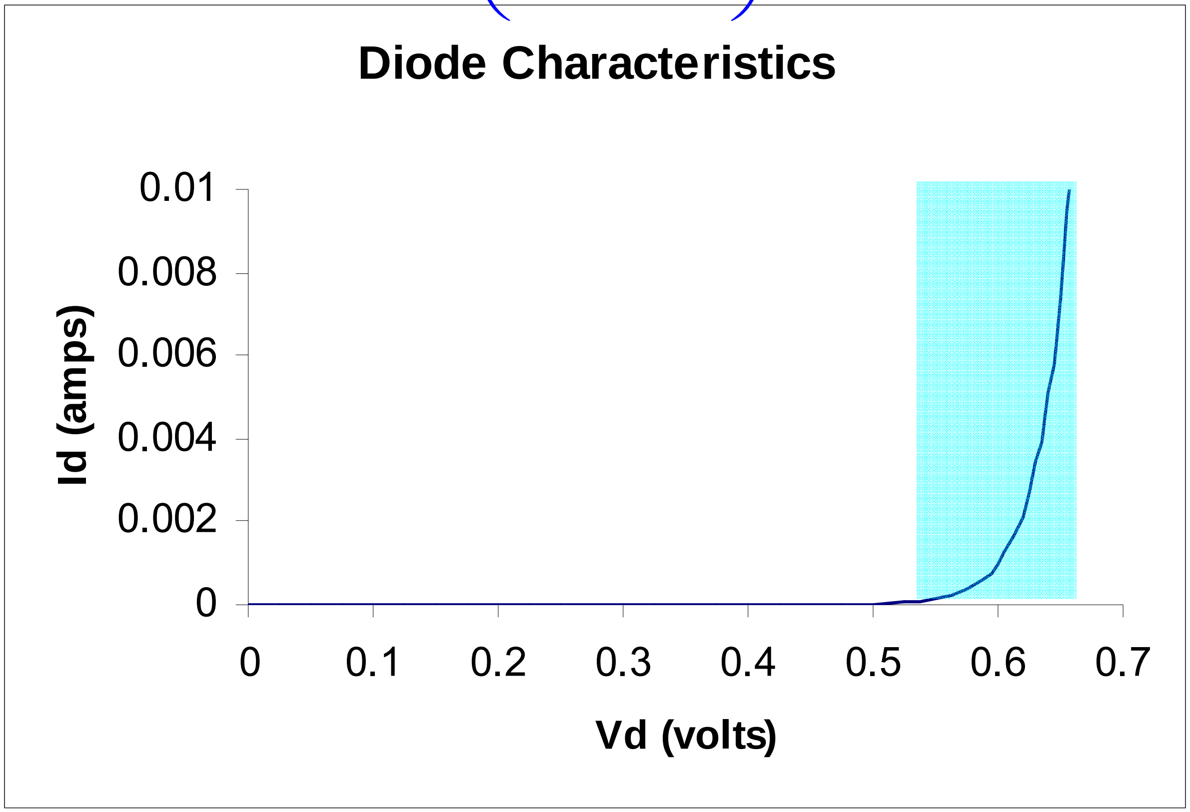


For two decades of current change, Vd is close to 0.6V

This is the most useful current range for many applications

Lets study the diode equation a little further

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

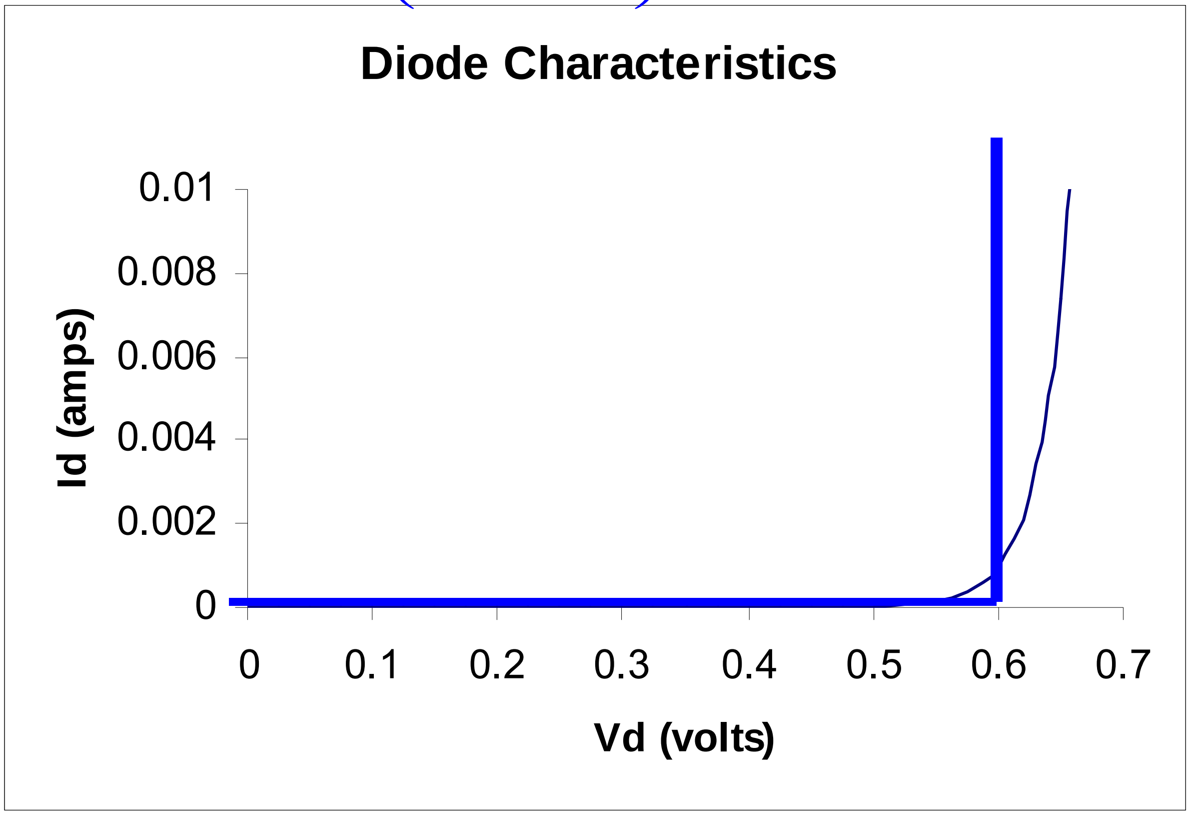


For two decades of current change, Vd is close to 0.6V

This is the most useful current range for many applications

Lets study the diode equation a little further

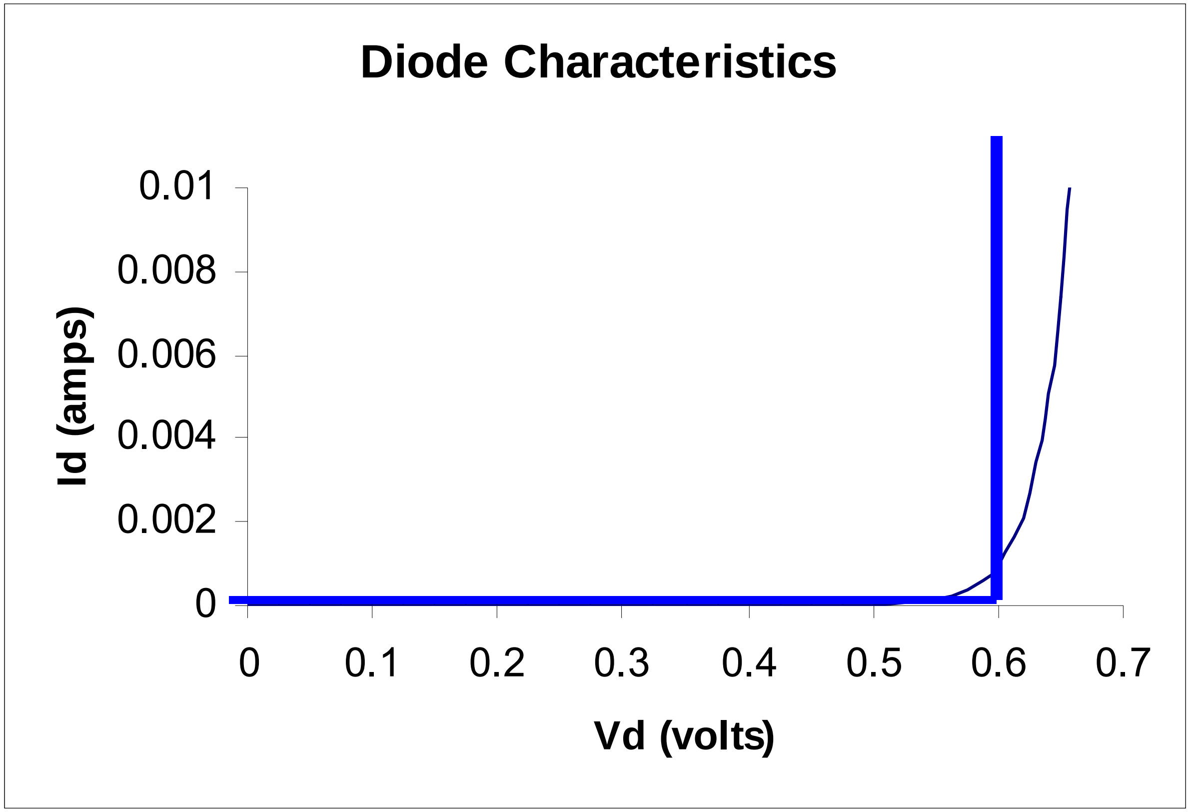
$$I_d = I_S\left(e^{\frac{V_d}{V_t}} - 1\right)$$



Widely Used Piecewise Linear Model

Lets study the diode equation a little further

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



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

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

Lets study the diode equation a little further

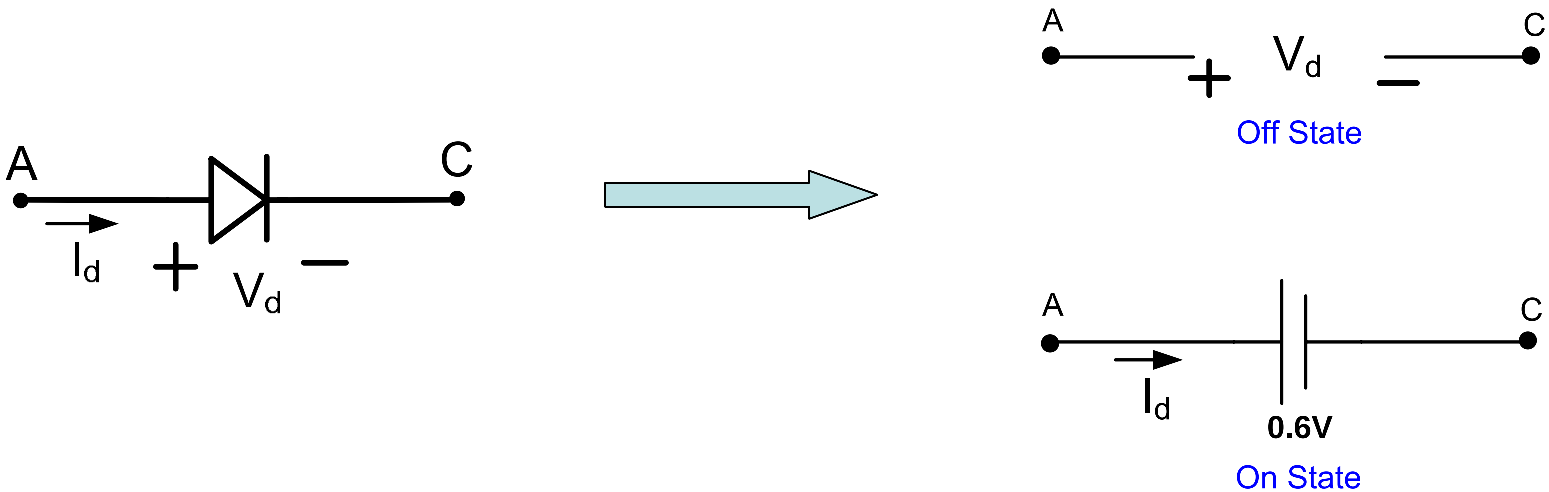
$$I_d = I_S\left(e^{\frac{V_d}{V_t}} - 1\right)$$

Piecewise Linear Model

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

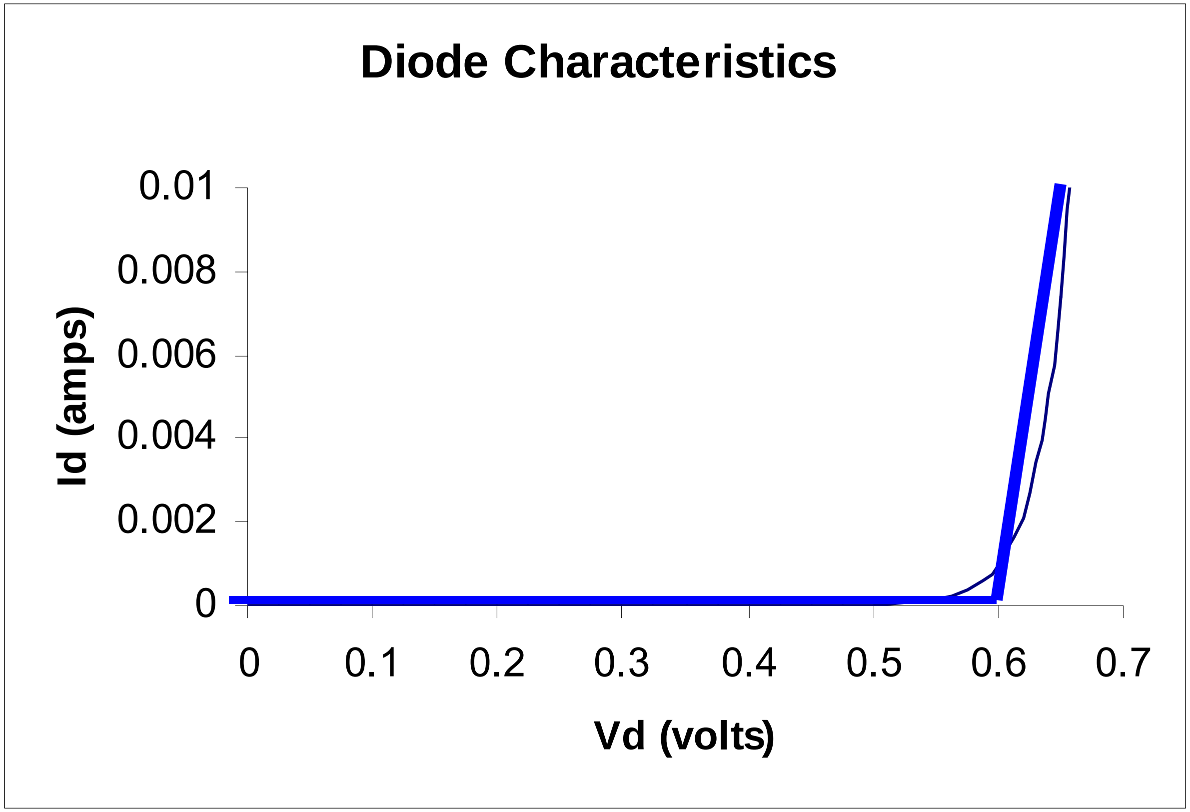
$$V_d = 0.6V \qquad I_d > 0$$

Equivalent Circuit



Lets study the diode equation a little further

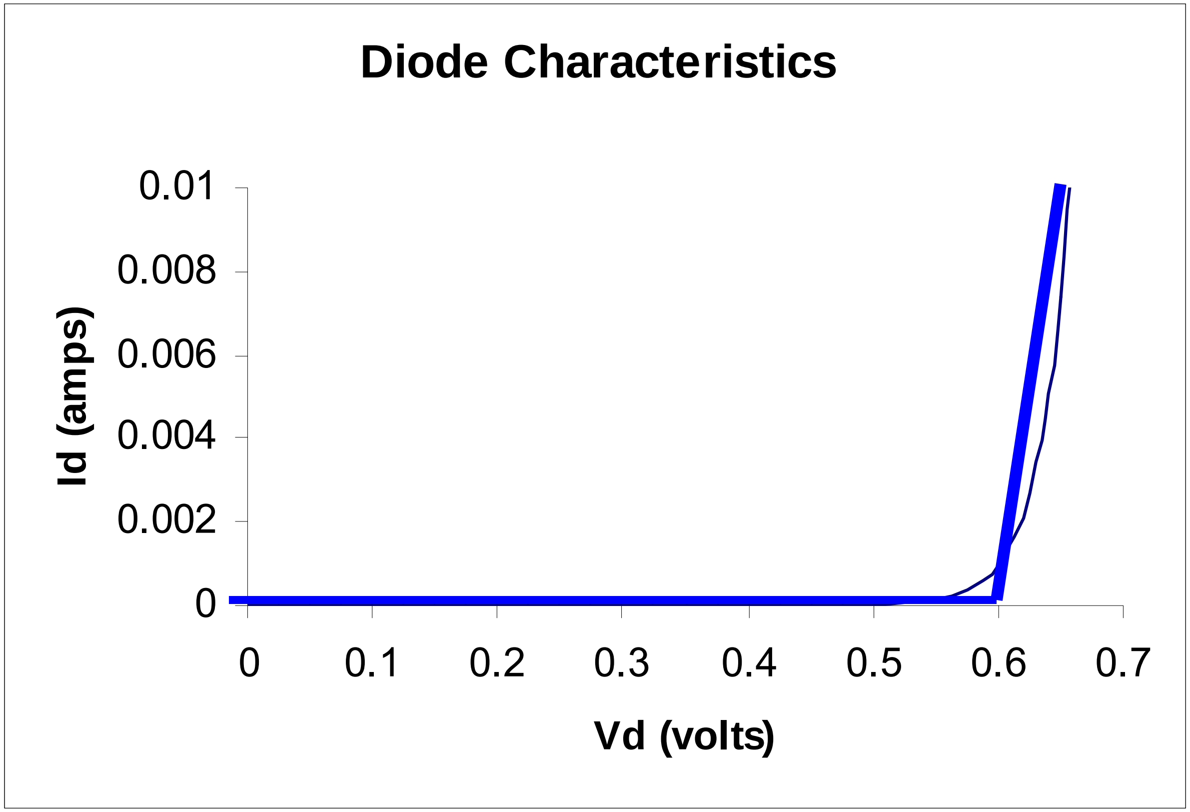
$$I_d = I_S\left(e^{\frac{V_d}{V_t}} - 1\right)$$



Slightly More Accurate Piecewise Linear Model

Lets study the diode equation a little further

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



$I_d = 0$ $\quad V_d < 0.6V$

$V_d = 0.6V + I_d R_d$ $\quad I_d > 0$

Lets study the diode equation a little further

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

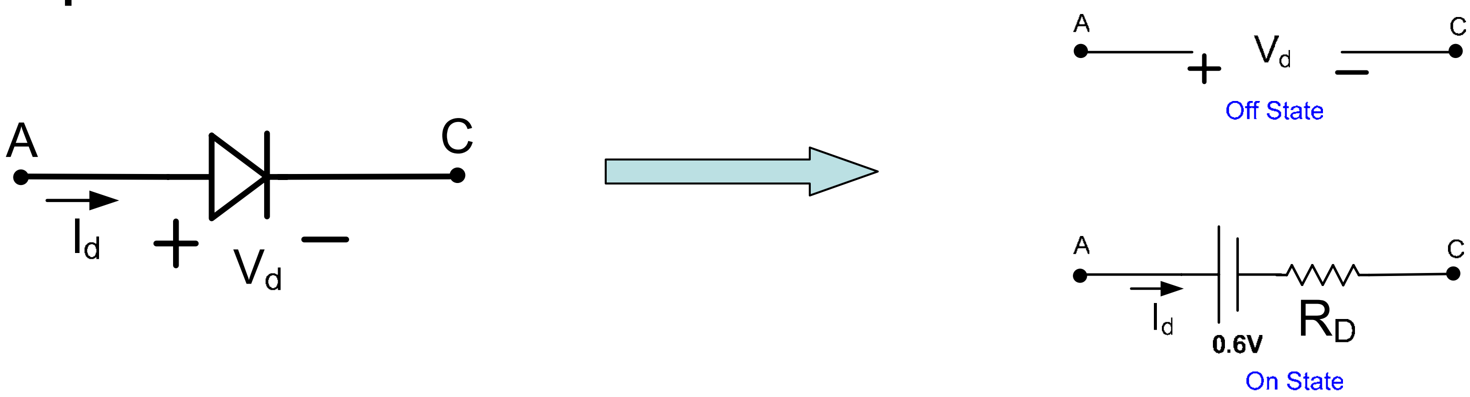
Piecewise Linear Model with Diode Resistance

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

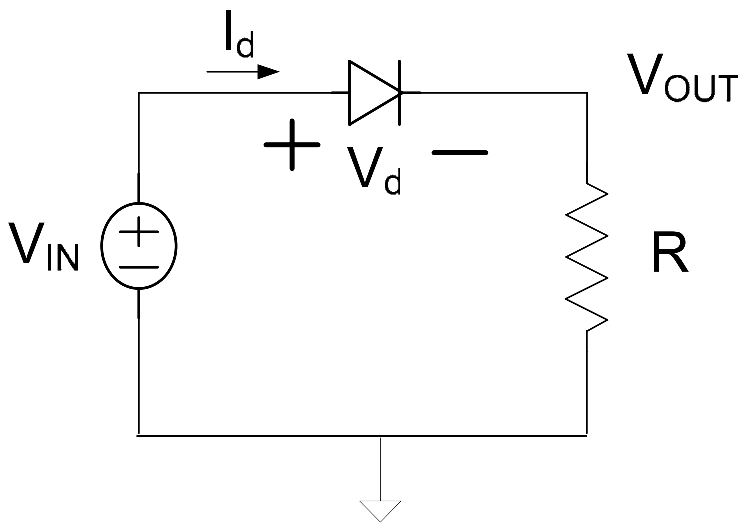
$$V_d = 0.6V + I_d R_D \qquad I_d > 0$$

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

Equivalent Circuit



Consider again the basic rectifier circuit

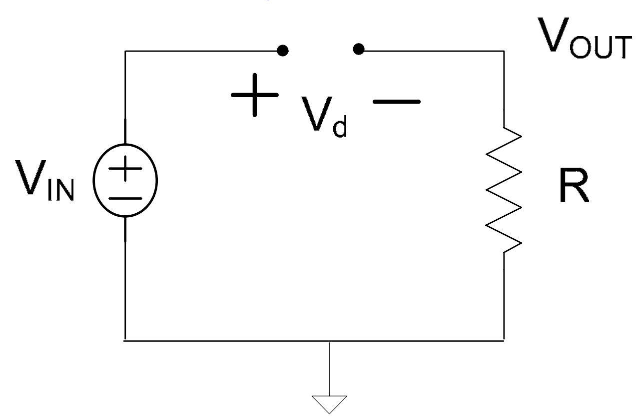


Analyze with piecewise linear model $I_d = 0 \qquad V_d \leq 0.6V$

$V_d = 0.6V \qquad I_d > 0$

Case 1 $\qquad I_d = 0$

$V_{OUT}=0$

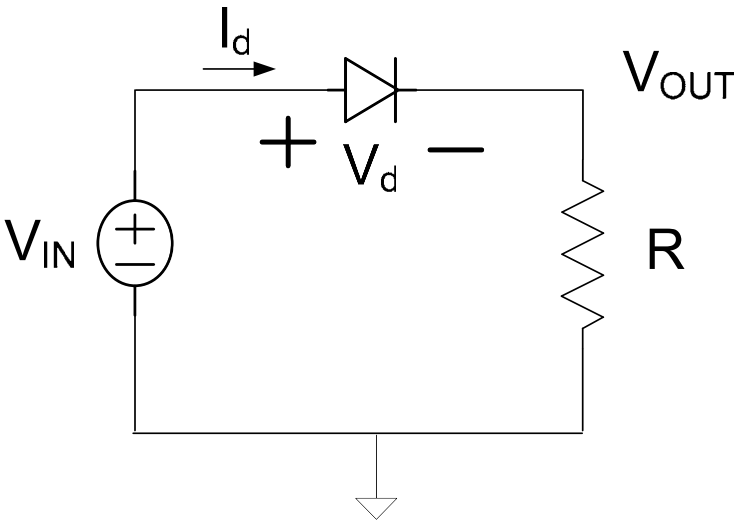


valid for $V_d \leq 0.6V$

but $V_d = V_{IN}$

$\therefore$ valid for $V_{IN} \leq 0.6V$

Consider again the basic rectifier circuit



Analyze with piecewise linear model

$I_d = 0 \qquad V_d < 0.6V$

$V_d = 0.6V \qquad I_d > 0$

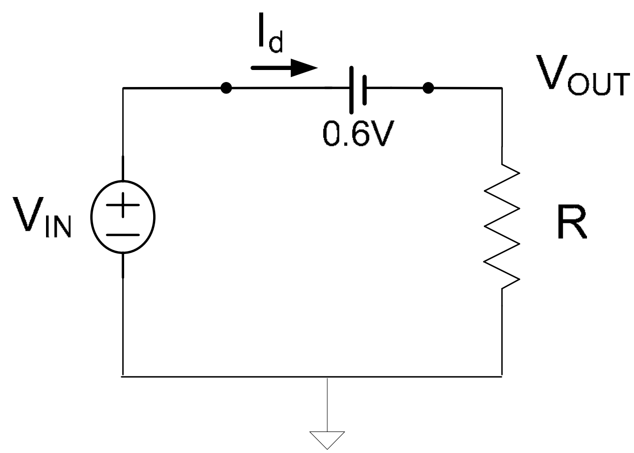
Case 2 $\qquad V_d = 0.6V$

$V_{OUT} = V_{IN} - 0.6V$

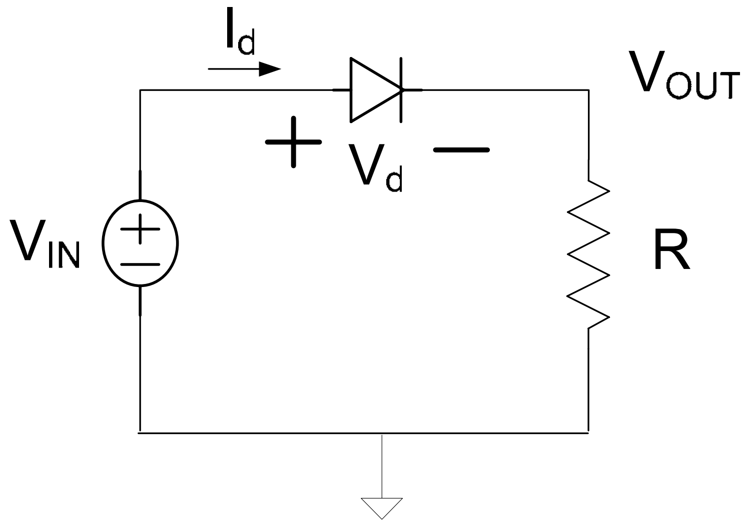
valid for $I_d > 0$

but $\quad I_d = \dfrac{V_{IN} - 0.6V}{R}$

$\therefore$ valid for $V_{IN} > 0.6V$



Consider again the basic rectifier circuit



Analyze with piecewise linear model

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

Solution summary:

$$V_{OUT} = \begin{cases} 0 & V_{IN} \leq 0.6V \\ V_{IN}\text{-}0.6V & V_{IN} > 0.6V \end{cases}$$