Diodes

Simple two-terminal electronic devices.

Made of semiconducting materials: silicon, gallium arsenide, indium phosphide, gallium nitride, etc. (EE 332 stuff.)

Semiconductors are interesting because their electrical properties can be varied over many order of magnitude: resistivity as high as 10^7 Ω-m (almost an insulator) or as low as 10^{-6} Ω-m (almost a conductor).

Also, semiconductors can be made in two different "varieties": either *n-type* in which current is carried by electrons (as usual) or *p-type* which current is carried by positive charges called holes.

A diode consists of a p-type layer of semiconductor joined to a n-type layer, and so is also known as a *p-n junction*. Current flowing across this junction exhibits a very asymmetric, non-linear i-v characteristic.

The non-linearity will force us to change the way we analyze circuits.

Diode applications

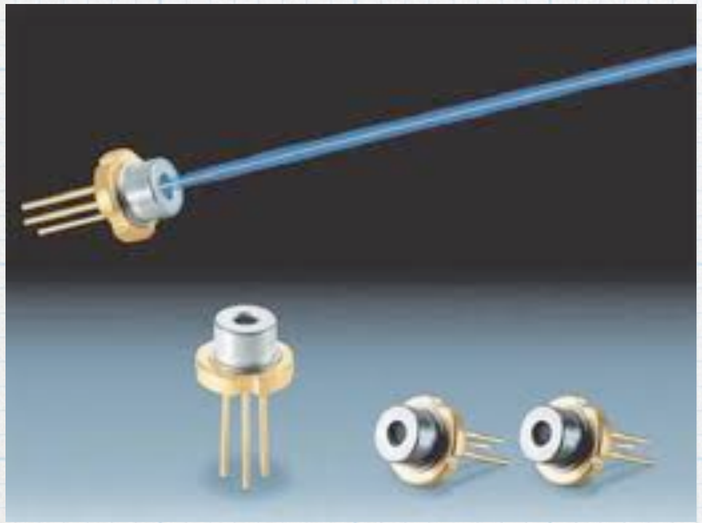
- Rectification – cutting off the top half or bottom half of a voltage signal.
- Voltage regulation – providing a steady voltage reference in a circuit.
- light-emitting diodes – for indicators
- light-emitting diodes – for illumination
- lasers - DVD players, fiber-optic communication, surgery
- photodetectors – sense presence of light, especially low levels or fast pulses
- photovoltaics (solar cells) – “green” electrical power generation
- building block for transistors

rectifying diode
(switching or
small-signal)

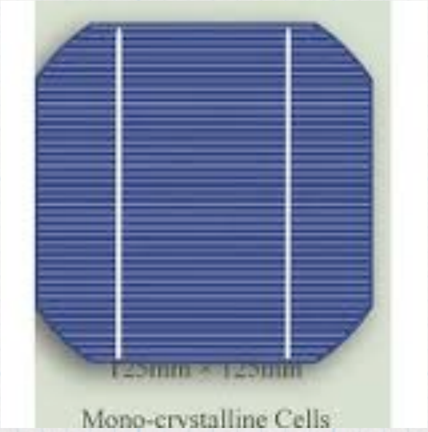
made of silicon

LEDs – various materials (not silicon).
Different material = different colors.

laser

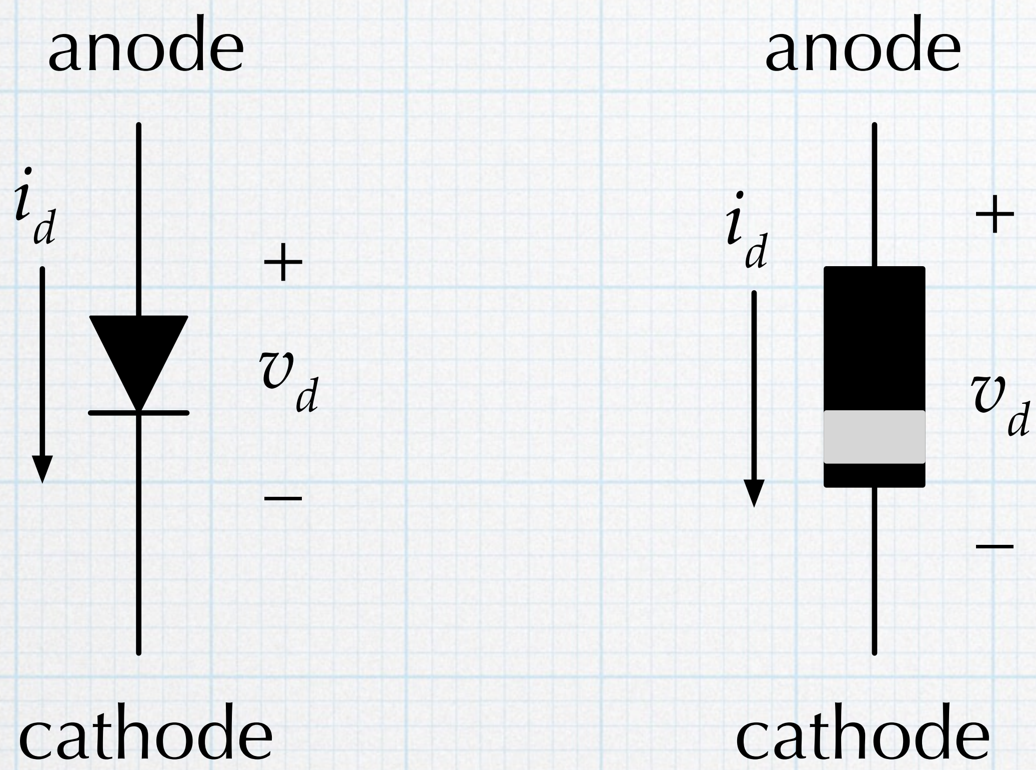


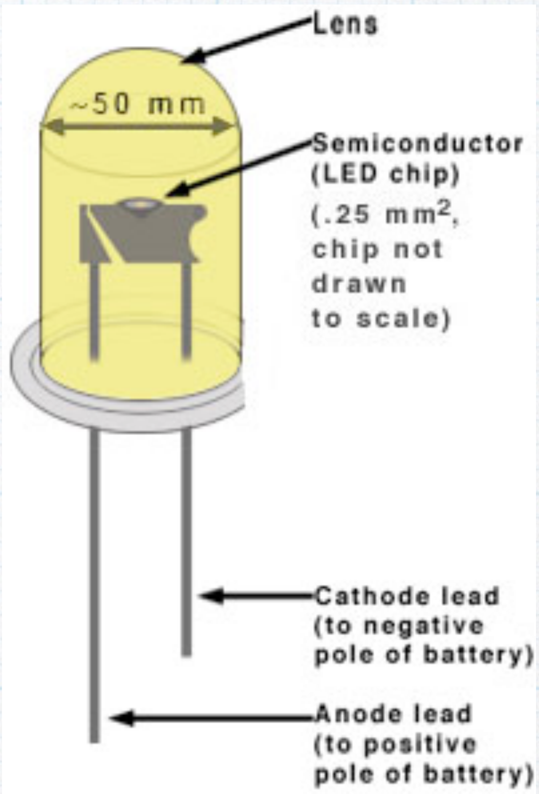
LED lighting – usually gallium nitride
(UV light) that excites a phosphor.



solar cell

Diode



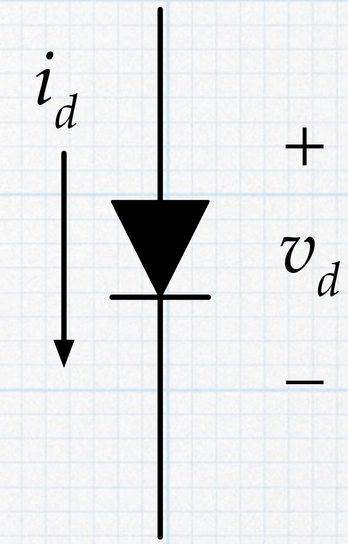


think “funnel” – it flows in one direction

diode i-v characteristic

ideal diode equation

$$i_D = I_S \left[\exp\left(\frac{v_D}{kT/q}\right) - 1\right]$$



Extremely non-linear. Will cause lots of problems in analyzing, but offers many opportunities for applications.

I_S is a parameter of the diode, known as *saturation current* or *scale current*. Different for every diode. (Like R for a resistor.)
Typical: $I_S \approx 10^{-14}$ A.

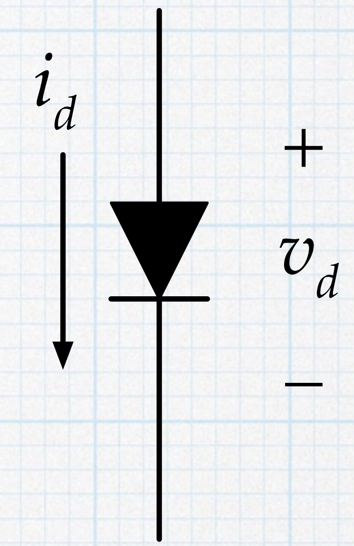
kT is the thermal energy. k (Boltzmann's constant = $1.38\text{x}10^{-23}$ J/K), T = temperature in kelvin (K).

q is the charge on one electron; kT/q is the thermal voltage.

At 300K (= 27°C, approximately room temperature), kT/q = 25.8 mV.

diode: forward and reverse conduction

$$i_D = I_S \left[\exp\left(\frac{v_D}{{}^{kT}/_{q}} \right) - 1 \right]$$



If v_D is positive, $v_D >> kT/q$.

$$i_D \approx I_S \exp\left(\frac{v_D}{{}^{kT}/_{q}} \right)$$

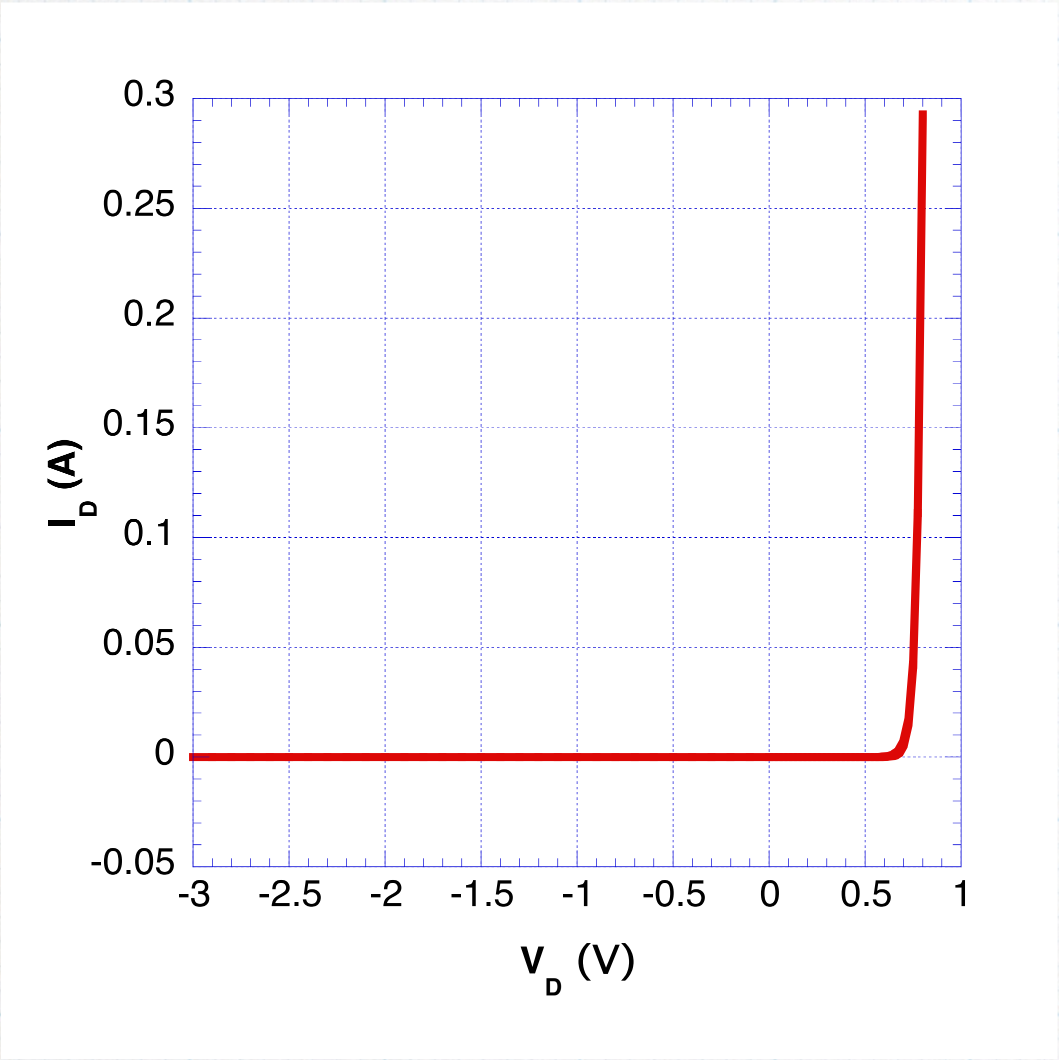
Lots of current can flow. Increases rapidly as v_D increases. Forward *bias* or forward conduction.

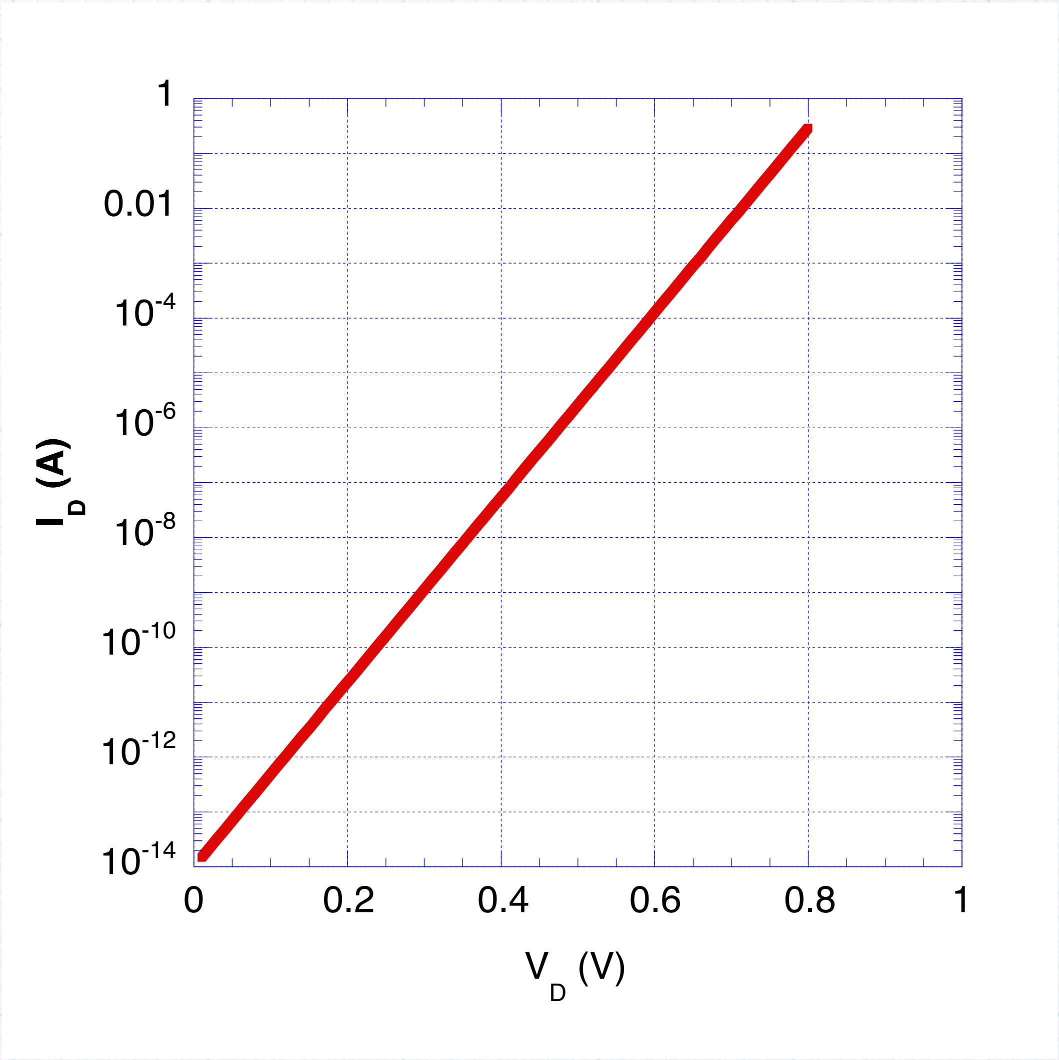
If v_D is negative.

$$i_D \approx -I_S$$

A very small trickle of current flows, almost zero. Independent of the voltage. Reverse bias or reverse conduction.

The asymmetry between forward and reverse conduction is the basis for rectification – current can flow only one way (essentially). (Again, think funnel.)





Diode *i*-*v*

$I_S = 10^{-14}$ A

$T = 300$ K

Same diode

Forward voltage only

semi-log plot

diodes in circuit

The non-linear behavior has some significant effects.

Basic notions are still valid: KCL and KCL, energy and power

Some techniques are invalid with non-linear elements: superposition, Thevenin.

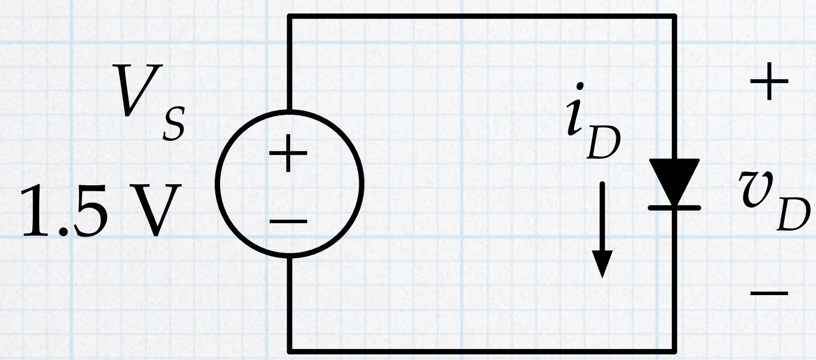
Node-voltage and mesh-current techniques are still applicable, but the result is a set of non-linear equations, which are difficult to solve.

With non-linear elements, we will rely on:

- Approximating the device behavior with linear elements. This requires some guessing and then checking of the results. Of course, it is only approximate.
- SPICE

diodes in circuits

Important: When working with diodes, don't EVER apply a forward voltage directly across the diode. The result is usually a dead diode.



$I_S = 10^{-14}$ A

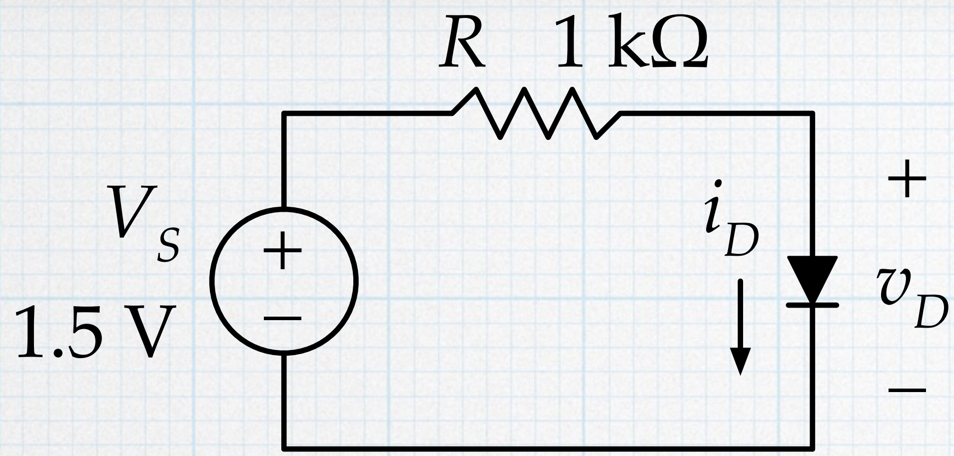
room temp: kT/q = 25.8 mV.

$$v_D = V_S$$

$$i_D \approx I_S \exp\left(\frac{v_D}{{}^{kT}/_{q}}\right)$$

$$= \left(10^{-14}\text{A}\right)\exp\left(\frac{1.5\text{V}}{0.0258\text{V}}\right) = 1.8 \times 10^{+12}\text{A}$$

This is absolutely absurd. Of course, what really happens is that the diode would burn up (due to instant heating) when the current hits 1 A or so. There must always be a current-limiting resistor in series.



$I_S = 10^{-14}$ A

room temp: $kT/q = 25.8$ mV.

$$i_D = I_S\left[\exp\left(\frac{v_D}{{}^{kT}/_{q}}\right) - 1\right] \qquad v_D = \frac{kT}{q}\ln\left(\frac{i_D}{I_S} + 1\right)$$

$$V_S = v_R + v_D$$

$$V_S = i_D R + \frac{kT}{q}\ln\left(\frac{i_D}{I_S} + 1\right)$$

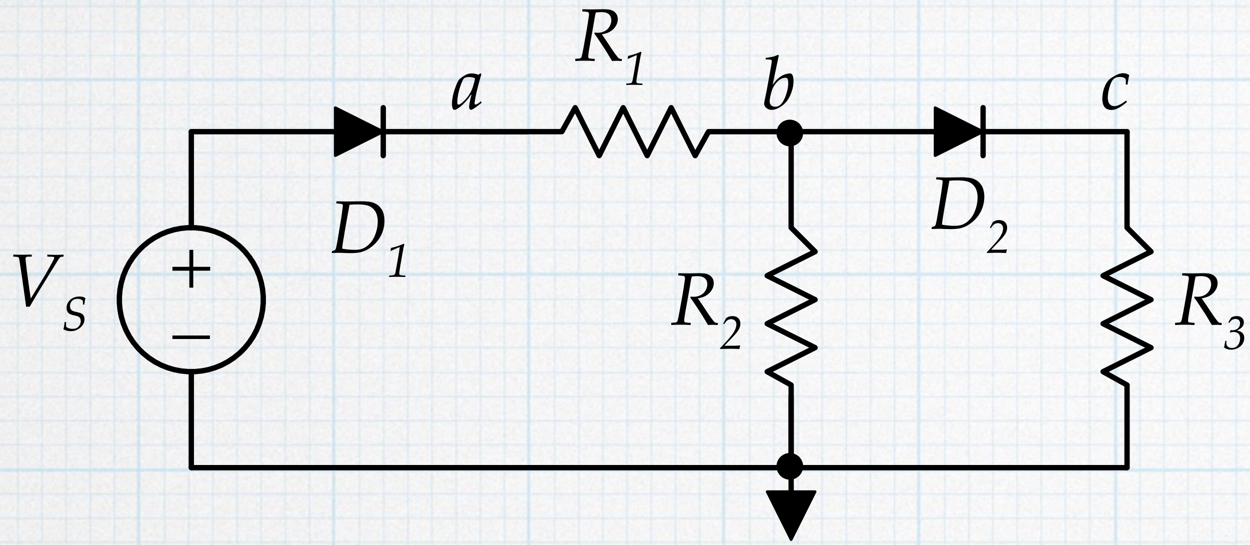
??? Can't be solved in closed form. Transcendental equation. Must use iteration. (Trial-and-error.)

$$i_D = \frac{V_S}{R} - \frac{{}^{kT}/_{q}}{R}\ln\left(\frac{i_D}{I_S} + 1\right) = 1.5\text{mA} - (0.0258\text{mA})\ln\left(\frac{i_D}{10^{-11}\text{mA}} + 1\right)$$

1st guess	1.00 mA
	0.846526 mA
	0.850825 mA
	0.850694 mA
	0.850698 mA

$i_D = 0.851$ mA

$v_D = 0.649$ V



$$i_{D1} = \frac{v_a - v_b}{R_1}$$

$$v_{D1} = V_S - v_a$$

$$\frac{v_a - v_b}{R_1} = \frac{v_b}{R_2} + i_{D2}$$

$$v_{D2} = v_b - v_c$$

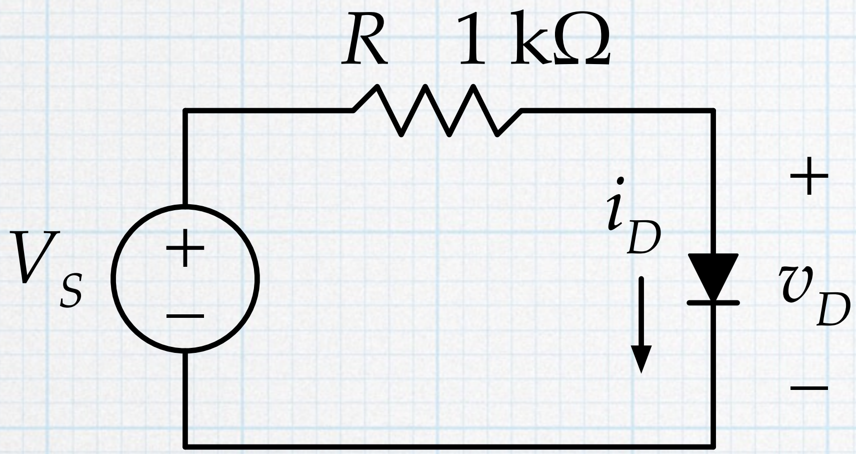
$$i_{D2} = \frac{v_c}{R_3}$$

$$I_{S1}\left[\exp\left(\frac{V_S - v_a}{{}^{kT}/_{q}}\right) + 1\right] = \frac{v_a - v_b}{R_1}$$

$$\frac{v_a - v_b}{R_1} = \frac{v_b}{R_2} + I_{S2}\left[\exp\left(\frac{v_b - v_c}{{}^{kT}/_{q}}\right) + 1\right]$$

$$I_{S2}\left[\exp\left(\frac{v_b - v_c}{{}^{kT}/_{q}}\right) + 1\right] = \frac{v_c}{R_3}$$

3 non-linear equations in 3 unknowns
Good luck with that!!



$$i_D = \frac{V_S}{R} - \frac{{}^{kT}\!/_{q}}{R} \ln\left(\frac{i_D}{I_S} + 1\right)$$

When the diode is reverse-biased ($V_S < 0$, so $v_D < 0$), the diode behaves essentially like an open circuit, $i_D \approx 0$.

When the diode is forward-biased ($V_S > 0$, so $v_D > 0$), the diode voltage is roughly constant at 0.6 V - 0.7 V.

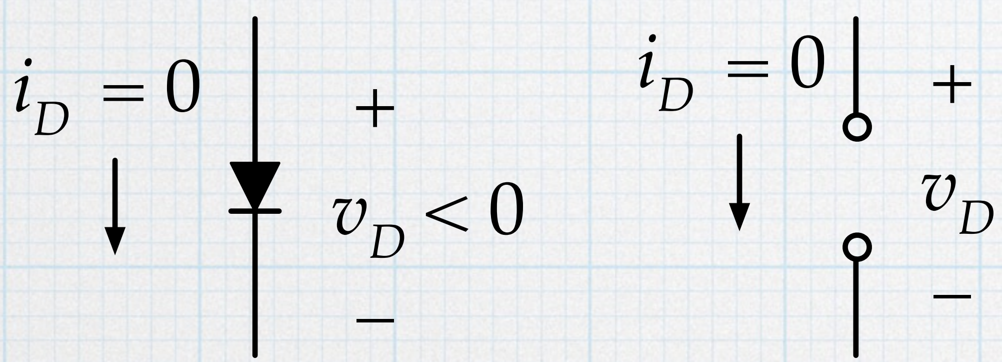
V_S (V)	v_D (V)	i_D (mA)
-10	-10 V	≈ 0
-8	- 8V	≈ 0
-6	-6 V	≈ 0
-4	-4 V	≈ 0
-2	-2 V	≈ 0
0	0	0
1	0.628	0.372
2	0.661	1.339
3	0.6752	2.3248
4	0.6844	3.3156
5	0.6911	4.3088
6	0.6965	5.3035
7	0.701	6.299
8	0.7047	7.2953
9	0.708	8.292
10	0.711	9.289

piecewise diode model

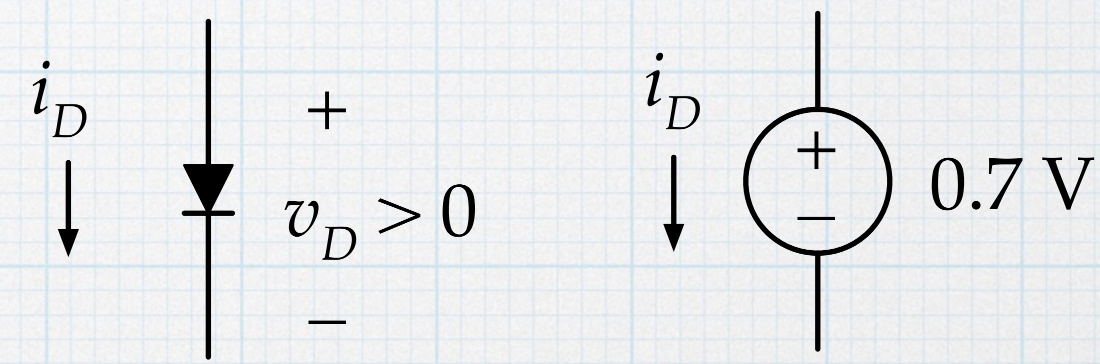
The results of the previous slide suggest the following approximate model.

- When the diode is reverse-biased, we can treat it as if it is an open-circuit
- When the diode is forward-biased, we treat it like an ideal source with a value of 0.7 V.

Reverse ($v_D < 0$)



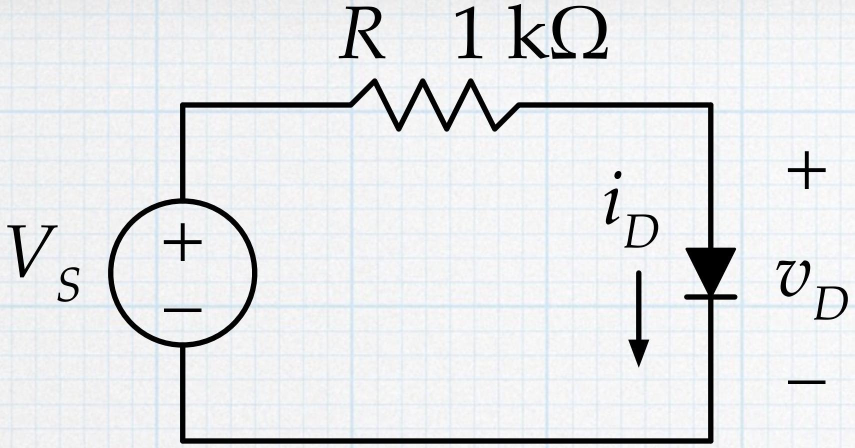
Forward ($v_D > 0$)



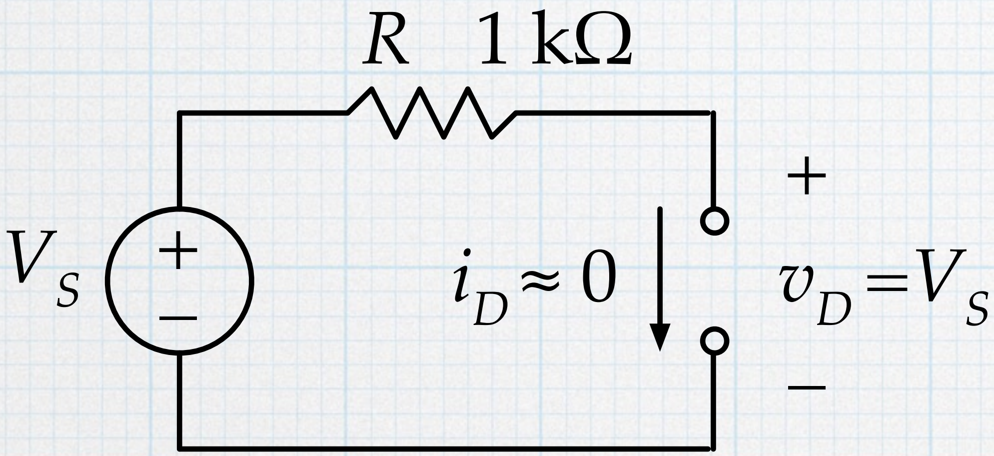
To use the models.

- Guess forward or reverse
- Insert the corresponding model
- Solve for voltage/current using model
- Check the result: for reverse, $v_D < 0$, for forward, i_D flows in correct direction

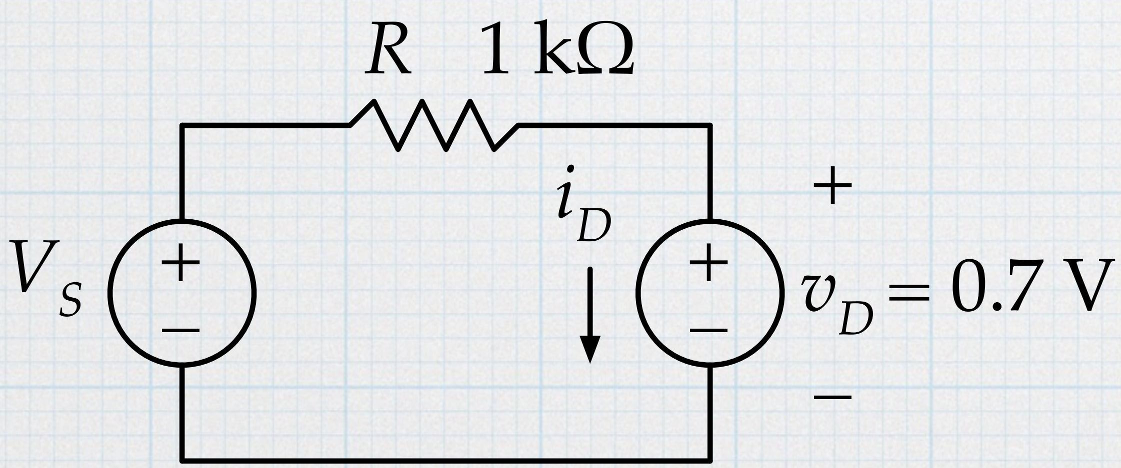
Note that the diode is NOT a voltage source. It does not provide power to the circuit. It simply behaves as if it were a small voltage source or battery that is absorbing power.



Reverse ($v_D < 0$ when $V_S < 0$)



Forward ($v_D > 0$ when $V_S > 0$)

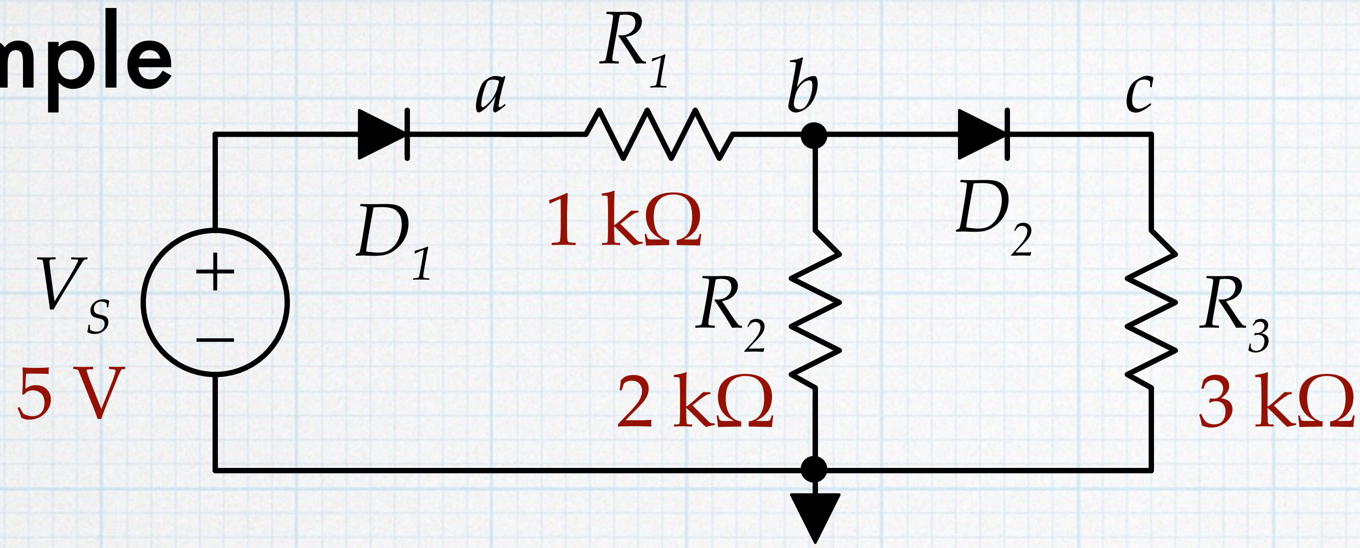


$$i_D = \frac{V_s - v_D}{R} = \frac{V_S - 0.7\text{V}}{R}$$

V_S (V)	v_D (V)	i_D (mA)
-10	-10 V	≈ 0
-8	- 8V	≈ 0
-6	-6 V	≈ 0
-4	-4 V	≈ 0
-2	-2 V	≈ 0
0	0	0
1	0.7	0.3
2	0.7	1.3
3	0.7	2.3
4	0.7	3.3
5	0.7	4.3
6	0.7	5.3
7	0.7	6.3
8	0.7	7.3
9	0.7	8.3
10	0.7	9.3

compare to slide 12 – very similar

Example



Since V_S is positive, we might guess that both diodes are forward-biased.

$v_a = V_S - 0.7\text{ V} = 4.3\text{ V}.$

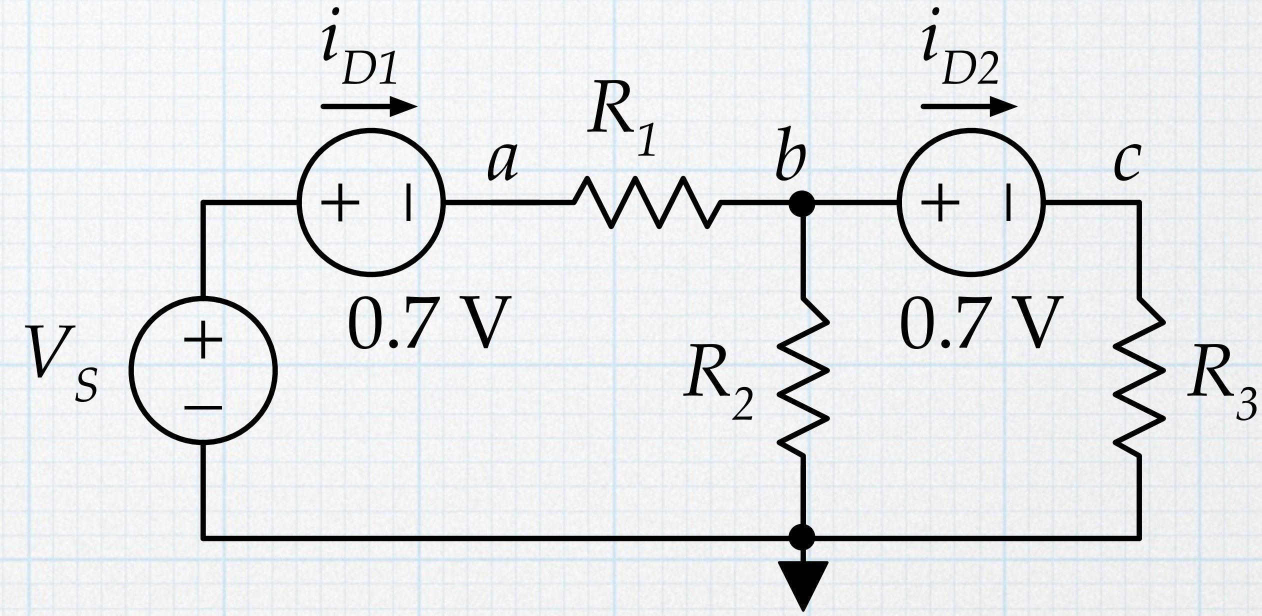
$v_c = v_b - 0.7\text{ V}.$

$$\frac{v_a - v_b}{R_1} = \frac{v_b}{R_2} + i_{D2}$$

$$i_{D2} = \frac{v_c}{R_3} = \frac{v_b - 0.7\text{V}}{R_3}$$

$$\frac{V_S - 0.7\text{V} - v_b}{R_1} = \frac{v_b}{R_2} + \frac{v_b - 0.7\text{V}}{R_3}$$

$v_b = 2.47\text{ V}.$



check:

$$i_{D1} = \frac{v_a - v_b}{R_1} = \frac{V_S - 0.7\text{V} - v_b}{R_1} = 1.83\text{mA}$$

$$i_{D2} = \frac{v_c}{R_3} = \frac{v_b - 0.7\text{V}}{R_3} = 0.591\text{mA}$$

Both currents are positive, consistent with forward conducting diodes. The guesses were correct.