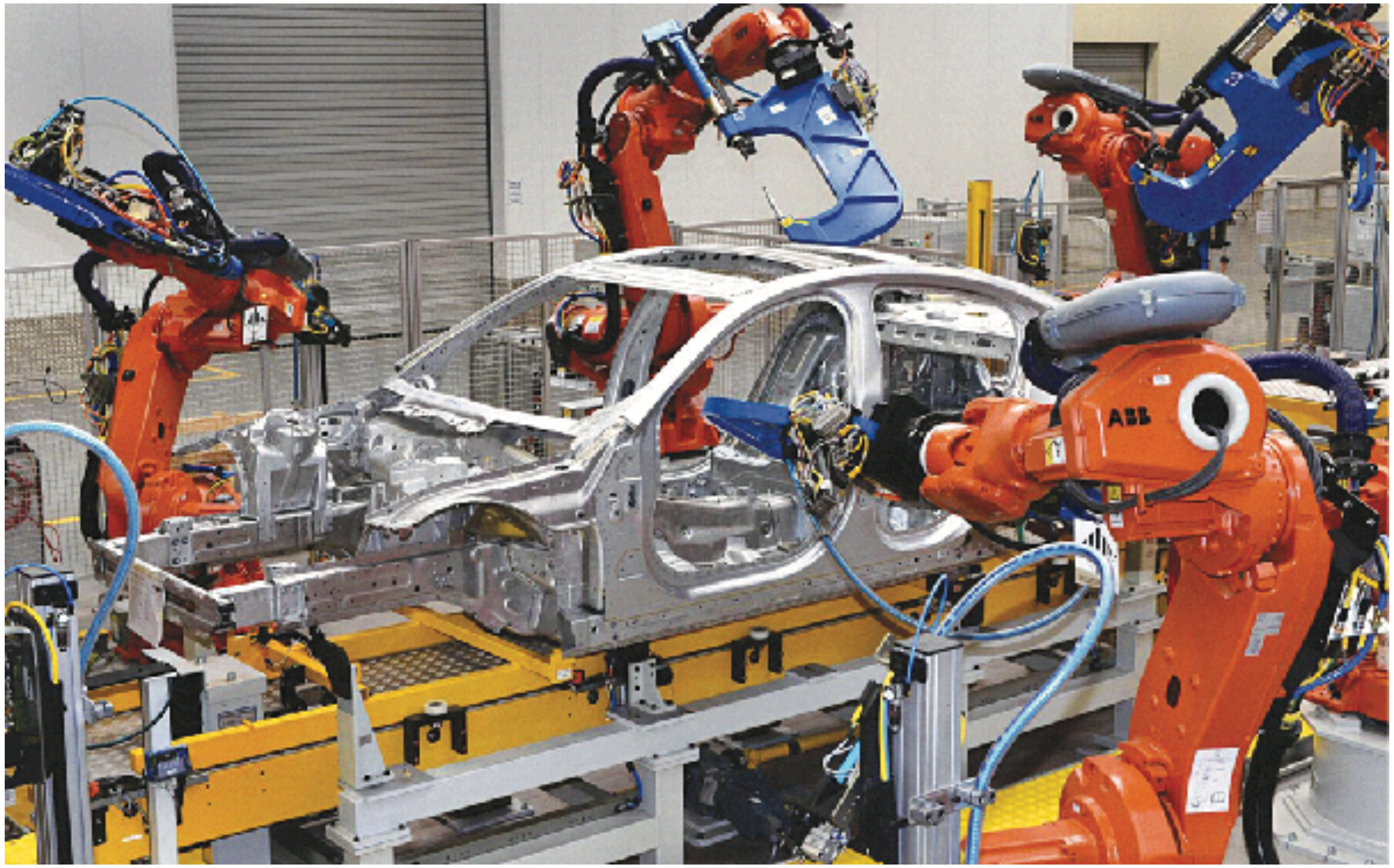
Electronics



Dr. Lana Damaj

Chapter 2: Diode circuits and models

Chapter 1: Summary

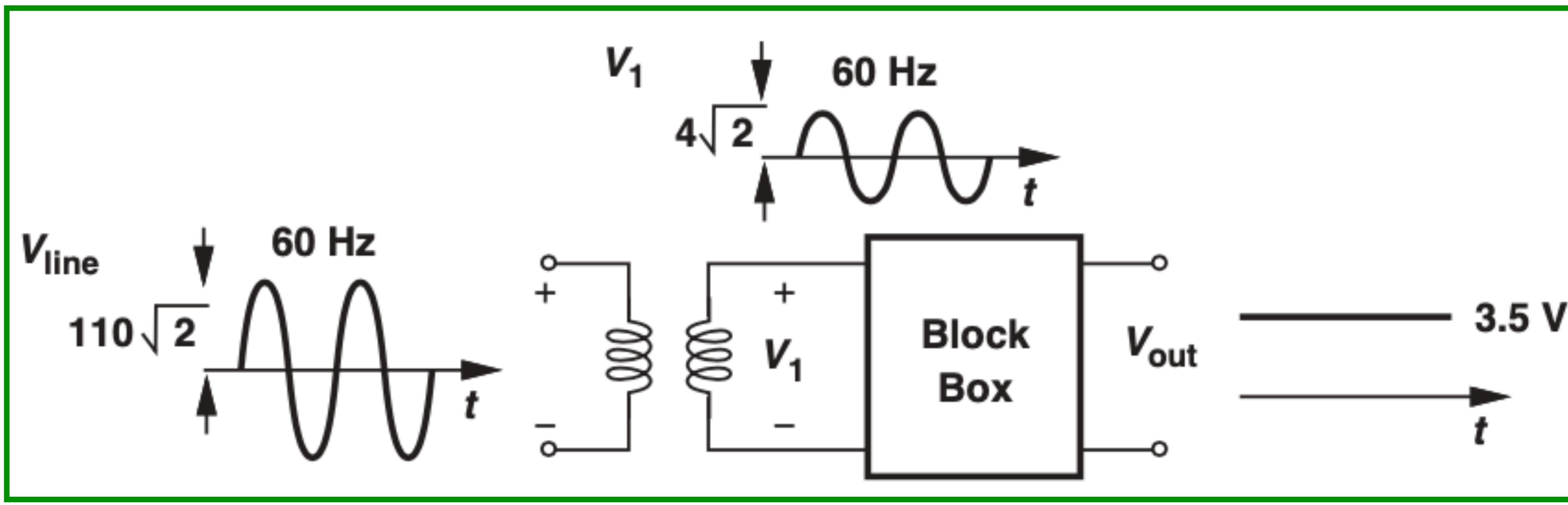
- The bandgap energy is the minimum energy required to dislodge an electron from its covalent bond.
- To increase the number of free carriers, semiconductors are "doped" with certain impurities.
- For doped or undoped semiconductors $np = n_i^2$.
- Charge carriers move in semiconductors via two mechanisms: drift and diffusion.
- Drift current density: $J_{tot} = q(\mu_n n + \mu_p p)E$.
- Diffusion current density: $J_{tot} = q(D_n dn/dx - D_p dp/dx)$.
- A *pn* junction is a piece of semiconductor that receives *n*-type doping in one section and *p*-type doping in an adjacent section.
- The *pn* junction can be considered in three modes: equilibrium, reverse bias, and forward bias.
- Under forward bias, the junction carries a current that is an exponential function of the applied voltage: $I_{tot} = I_s(exp\frac{V_F}{V_T} - 1)$
- Constant- voltage model

Chapter 2: Diode circuits and models

- Ideal diode
- Constant voltage model
- Rectifier:
  - Half-wave rectifier
  - Full-wave rectifier

Diode application

- Diodes are used in the automotive industry to rectify (turn AC into DC) the electrical signal.



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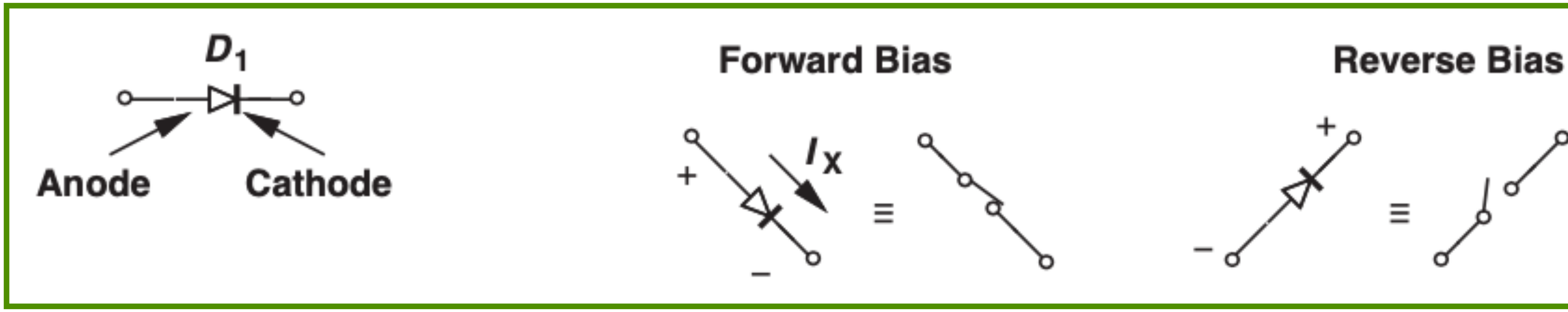
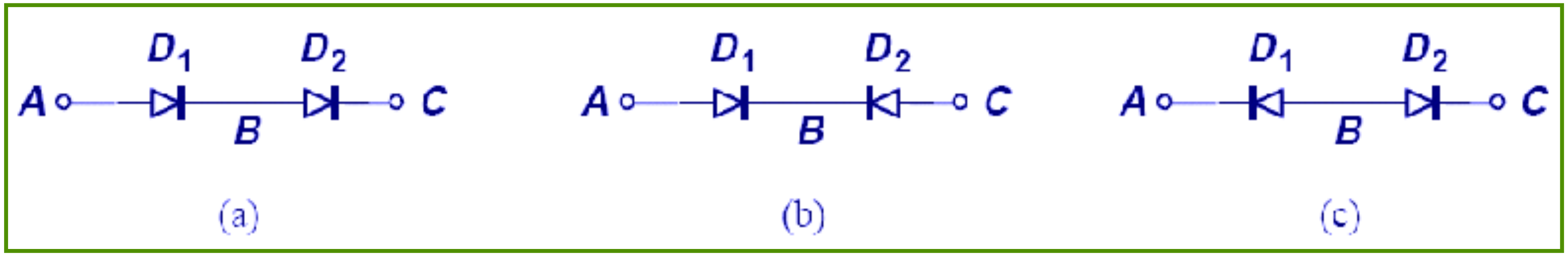
Ideal Diode



- The diode must turn "on" if $V_{anode} > V_{cathode}$ and "off" if $V_{anode} < V_{cathode}$
- Defining $V_{anode} - V_{cathode} = V_D$,
- we say the diode is "forward-biased" if V_D tends to exceed zero
- "reverse biased" if $V_D < 0$

Ideal Diode

- Example 1: As with other two-terminal devices, diodes can be placed in series (or in parallel). Determine which one of the configurations in Fig. below can conduct current.



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Ideal Diode

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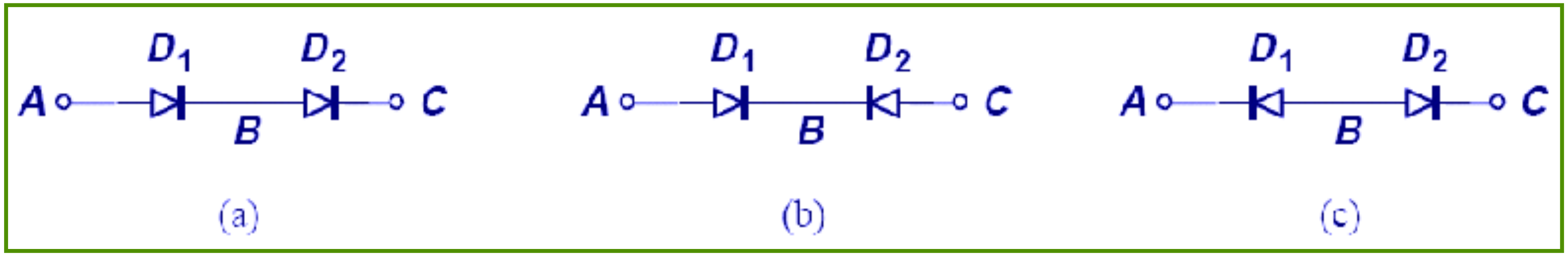
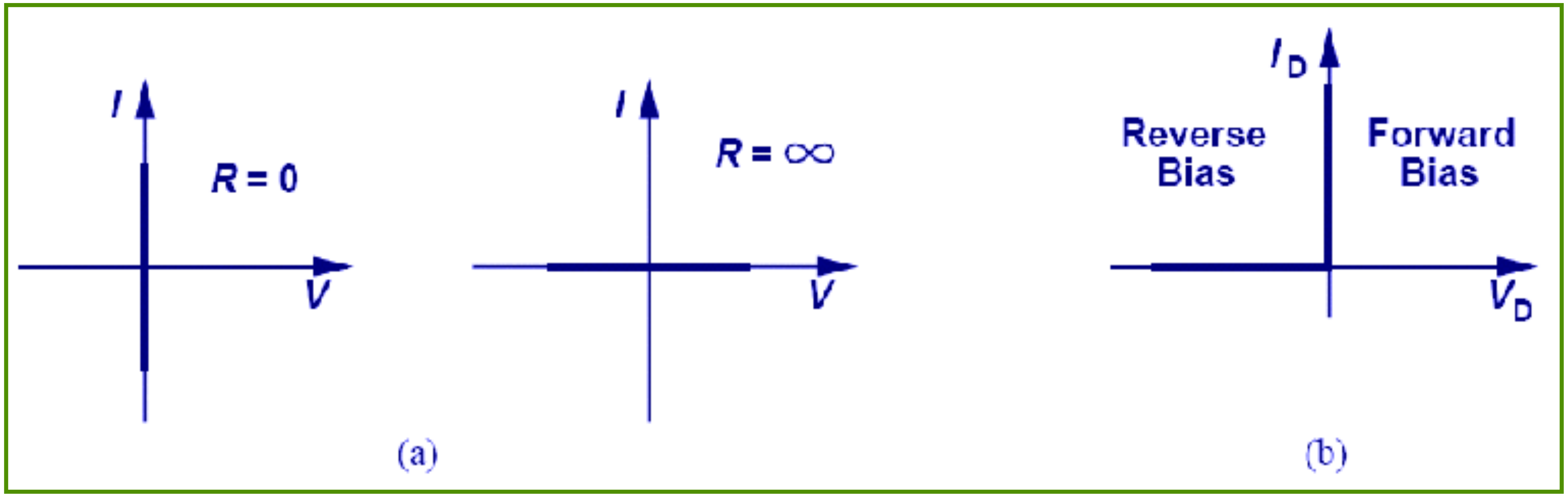


- Solution:
  - In Fig.(a), the anodes of D_1 and D_2 point to the same direction, allowing the flow of current from *A* to *B* to *C* but not in the reverse direction.
  - In Fig.(b), D_1 stops current flow from *B* to *A*, and D_2, from *B* to *C*. Thus, no current can flow in either direction.
  - By the same token, the topology of Fig. (c) behaves as an open for any voltage.

Ideal Diode: I/V Characteristics

- Since an ideal diode behaves as a short or an open, we first construct the I/V characteristics for two special cases of Ohm's law:

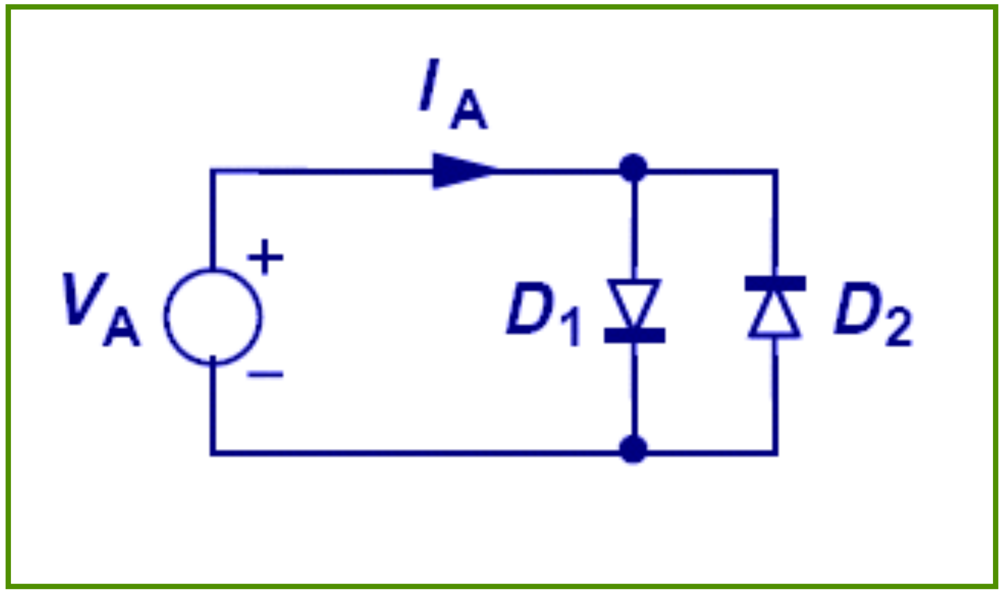
$$R = 0 \Rightarrow I = \frac{V}{R} = \infty$$
$$R = \infty \Rightarrow I = \frac{V}{R} = 0.$$



- This characteristic indicates that as V_D exceeds zero by a very small amount, then the diode turns on and conducts infinite current if the circuit surrounding the diode can provide such a current.

Ideal Diode: I/V Characteristics

- Example 2: Plot the I/V characteristic for the “antiparallel” diodes shown in Fig. below



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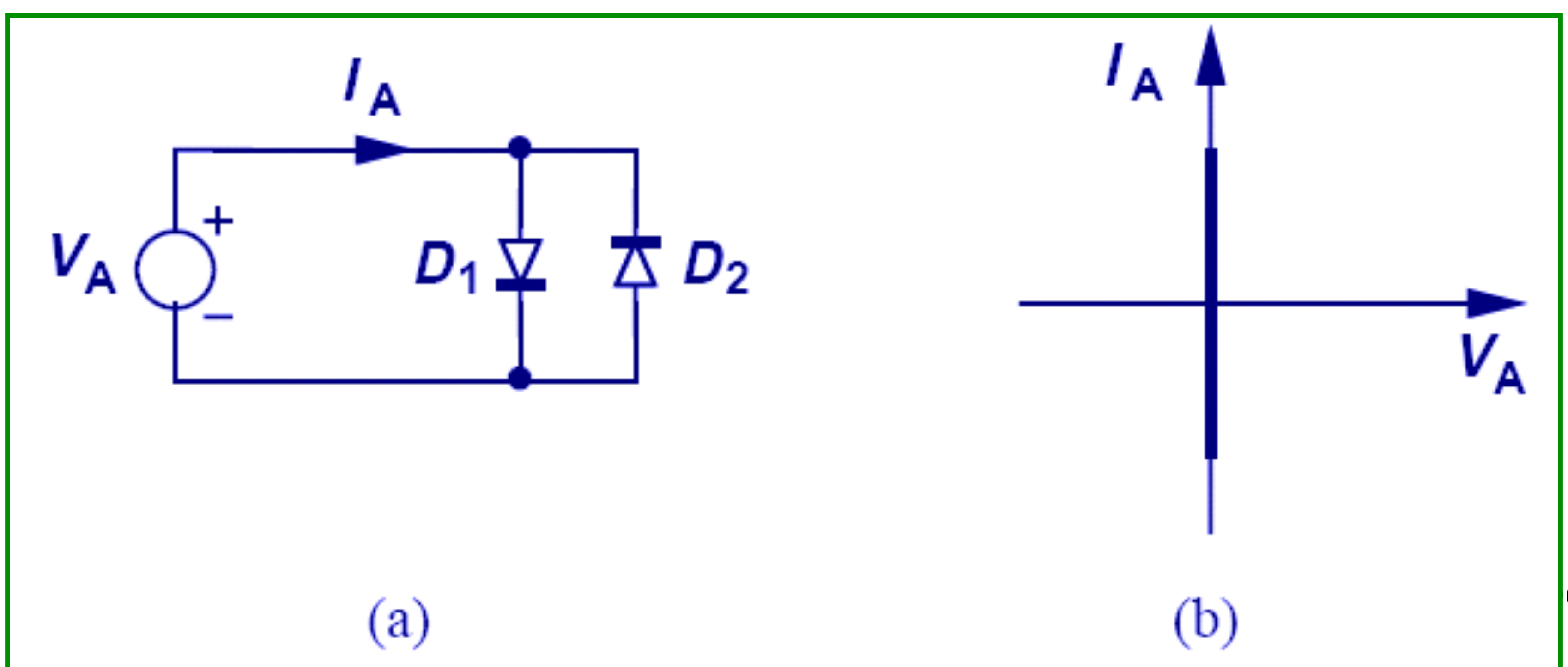
Ideal Diode: I/V Characteristics

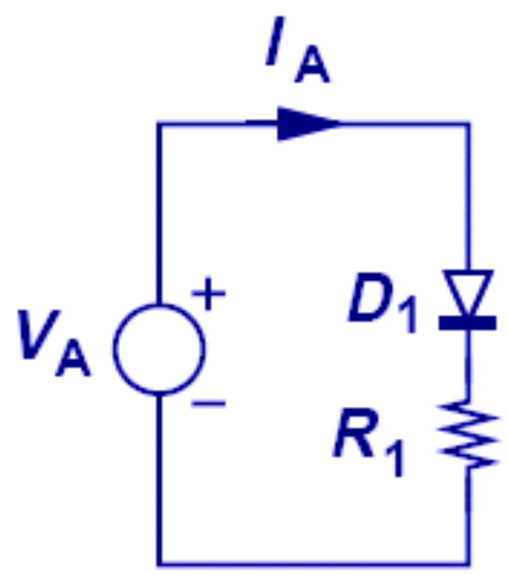
- Example 2: Plot the I/V characteristic for the "antiparallel" diodes shown in Fig. below

- Solution:
- if $V_A>0$ D_1 is forward bias D_2 is reversed bias $\Longleftrightarrow D_1$ equivalent to short circuit
- if $V_A<0$ D_2 is forward bias D_1 is reversed bias $\Longleftrightarrow$ D_2 equivalent to short circuit
- The antiparallel combination therefore acts as a short for all voltages



Ideal Diode: I/V Characteristics

- Example 3: Plot the I/V characteristic for the diode-resistor combination shown in Fig. below



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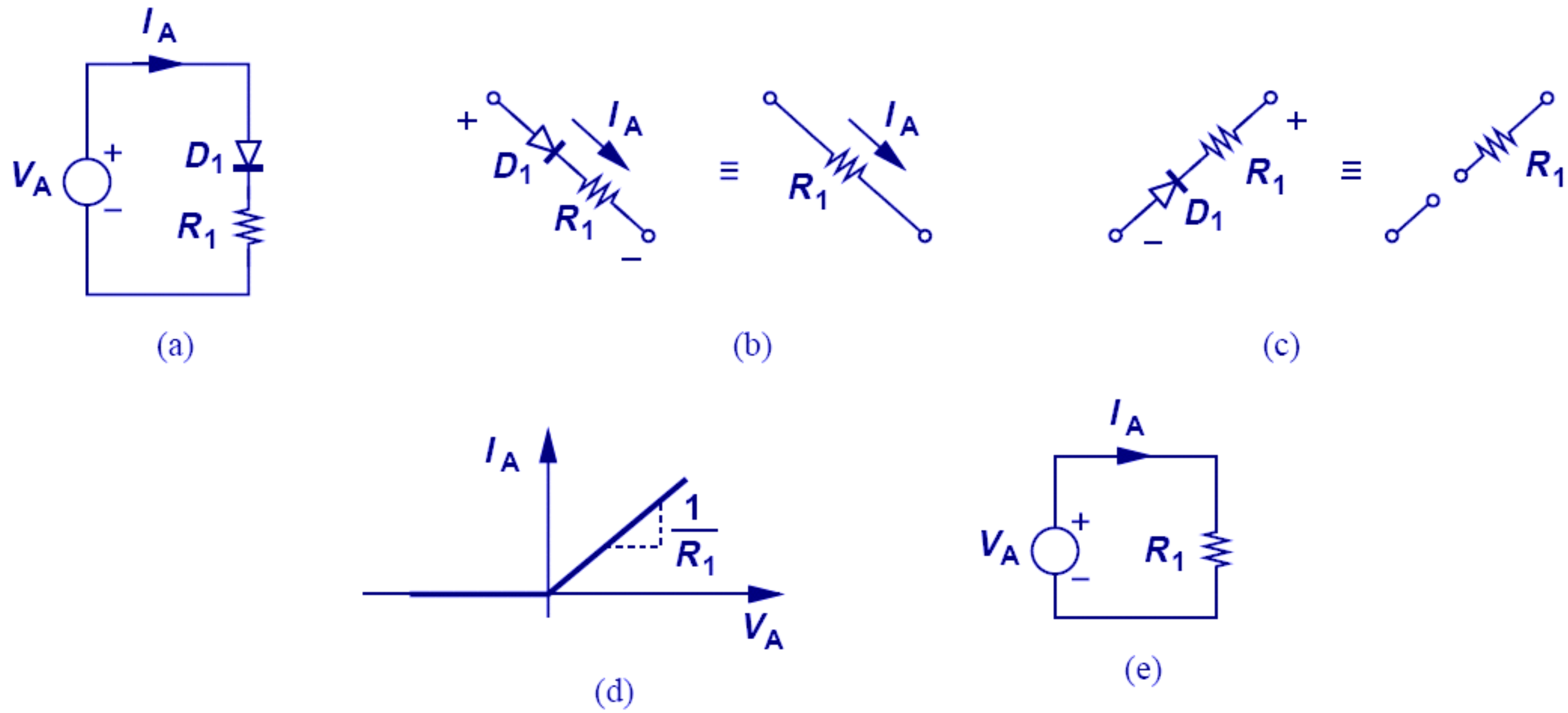
Ideal Diode: I/V Characteristics

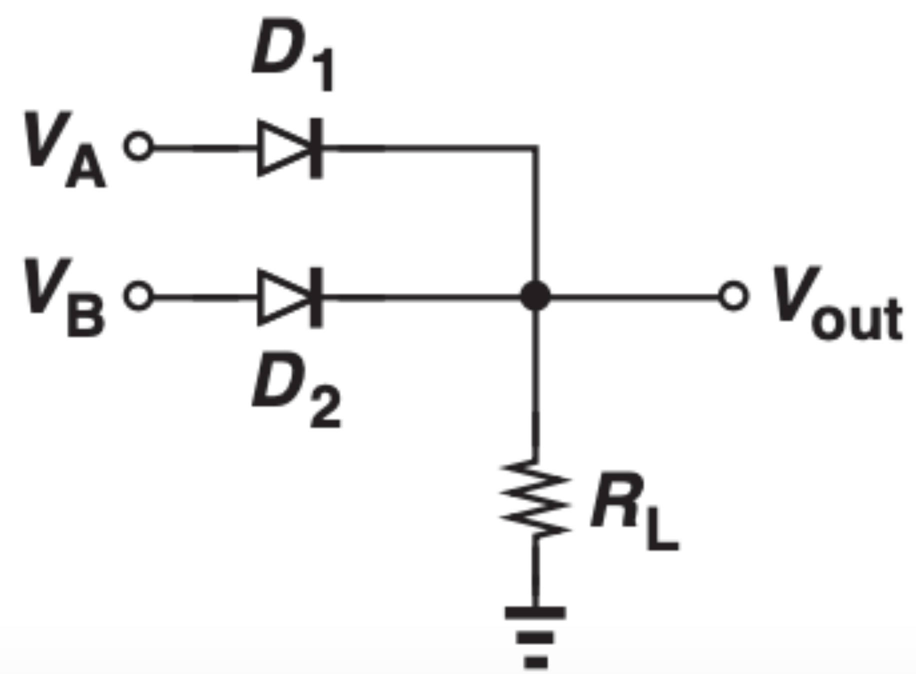
- Example 3: Plot the I/V characteristic for for the diode-resistor combination shown in Fig. below



- Solution:
- $if\, V_A \rightarrow -\infty$ Diode reversed biased $\Rightarrow I_A = 0$
- $if\, V_A \rightarrow +\infty$ Diode forward biased $\Rightarrow I_A = \dfrac{V_A}{R_1}$
- intersection of $I_A = 0$ and $I_A = \dfrac{V_A}{R_1} \Rightarrow V_A = 0$

Ideal Diode: I/V Characteristics

- Example 4: In the circuit of Fig. below, each input can assume a value of either zero or +3 V. Determine the response observed at the output.



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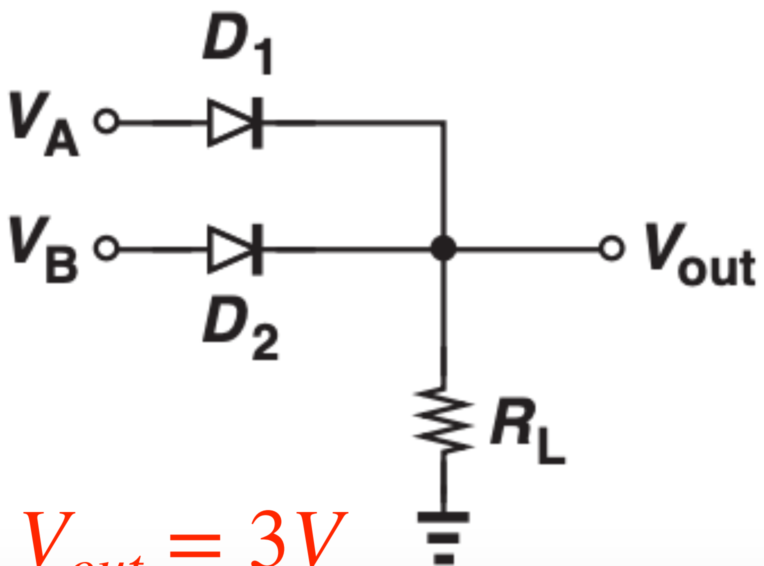
Ideal Diode: I/V Characteristics

- Example 4: In the circuit of Fig. below, each input can assume a value of either zero or +3 V. Determine the response observed at the output.



- Solution:
- If $V_A = 3V$ and $V_B = 0 \Rightarrow D_1$ is on and D_2 is off $\Rightarrow V_{out} = 3V$
- If $V_B = 3V$ and $V_A = 0 \Rightarrow D_2$ is on and D_1 is off $\Rightarrow V_{out} = 3V$

V_A	V_B	V_{out}
0	0	0
0	3	3
3	0	3
3	3	3

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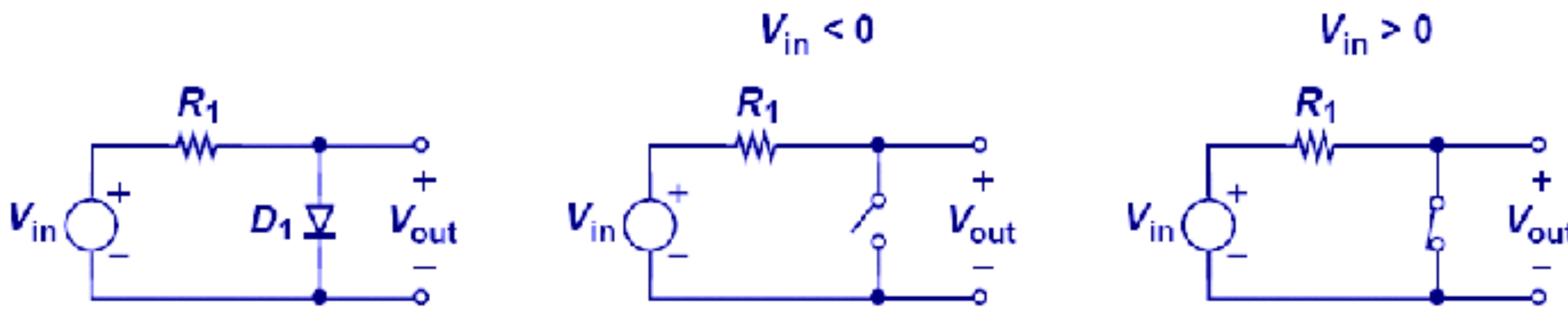
Input/Output Characteristics

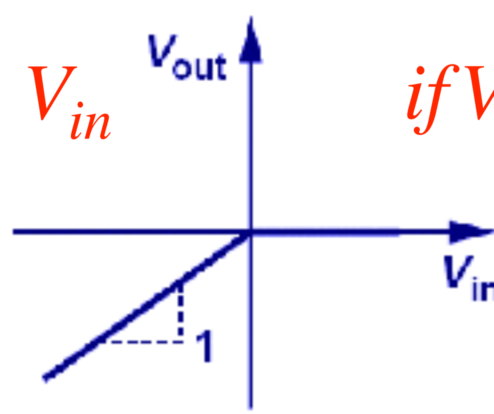
- Electronic Circuits process input and generate output.
- In the circuit below:
  - When V_{in} is less than zero, the diode opens, so $V_{out} = V_{in}$.
  - When V_{in} is greater than zero, the diode shorts, so $V_{out} = 0$.



(a) (b) (c)

$if\, V_A \rightarrow -\infty$ Diode off $\Rightarrow V_{out} = V_{in}$

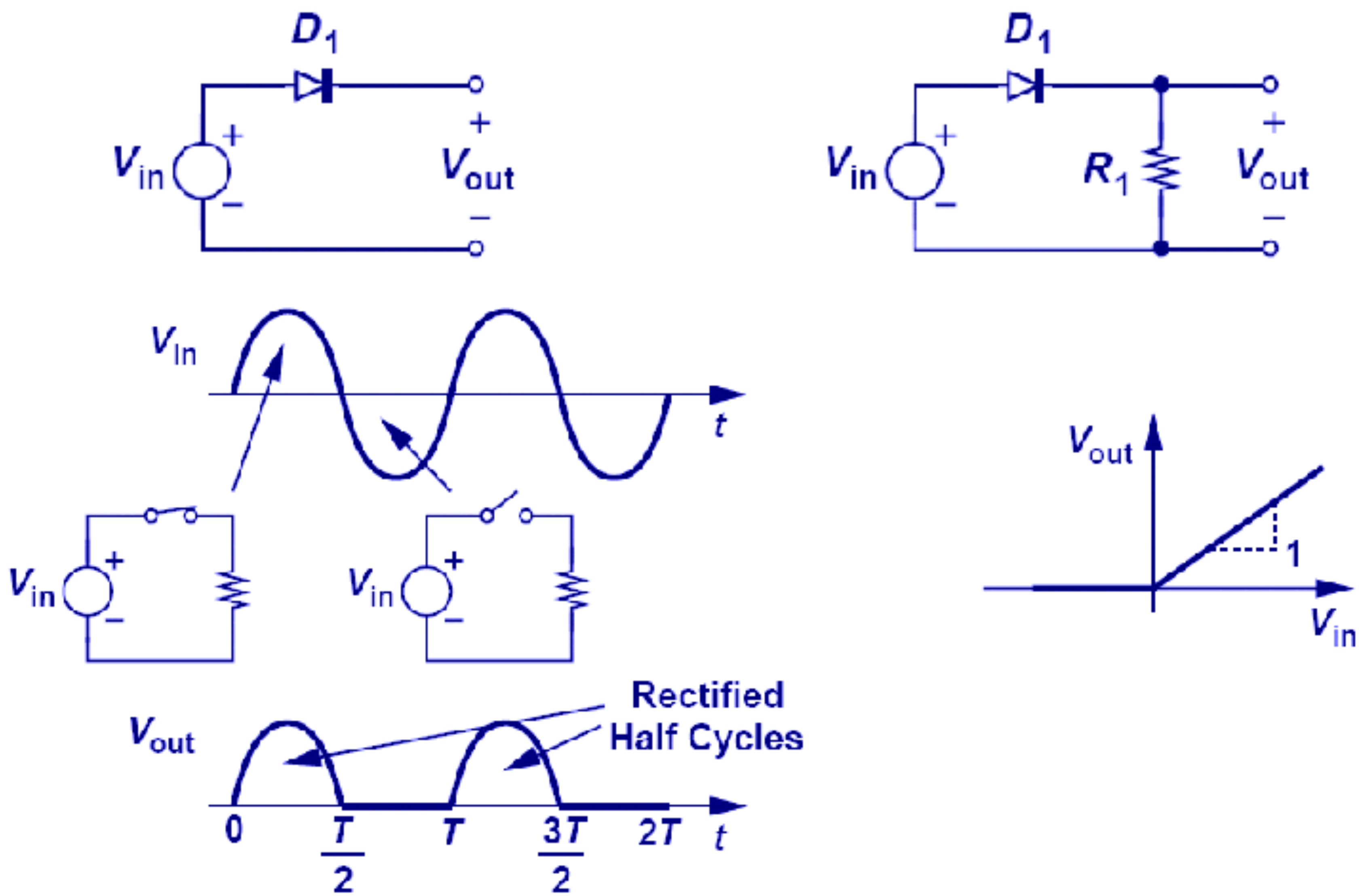
$if\, V_A \rightarrow +\infty$ Diode on $\Rightarrow V_{out} = 0$



(d)

Diode's application: rectifier

- Diode response to a sinusoidal input
- A rectifier is a device that passes positive-half cycle of a sinusoid and blocks the negative half-cycle or vice versa.
- When V_{in} is greater than 0, diode shorts, so $V_{out} = V_{in}$; however, when V_{in} is less than 0, diode opens, no current flows thru R_1, $V_{out} = I_{R1}R_1 = 0$.



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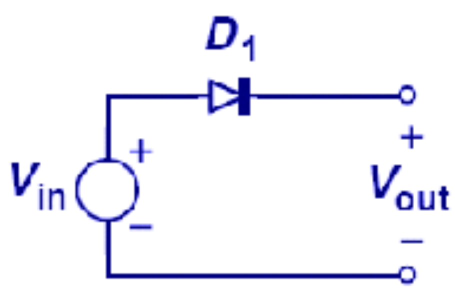
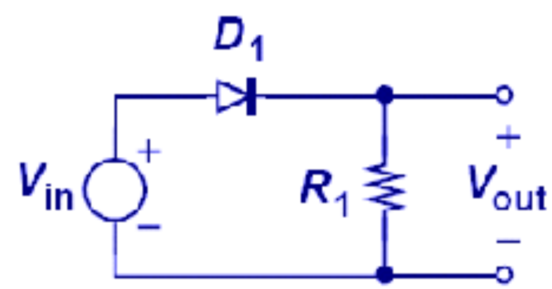
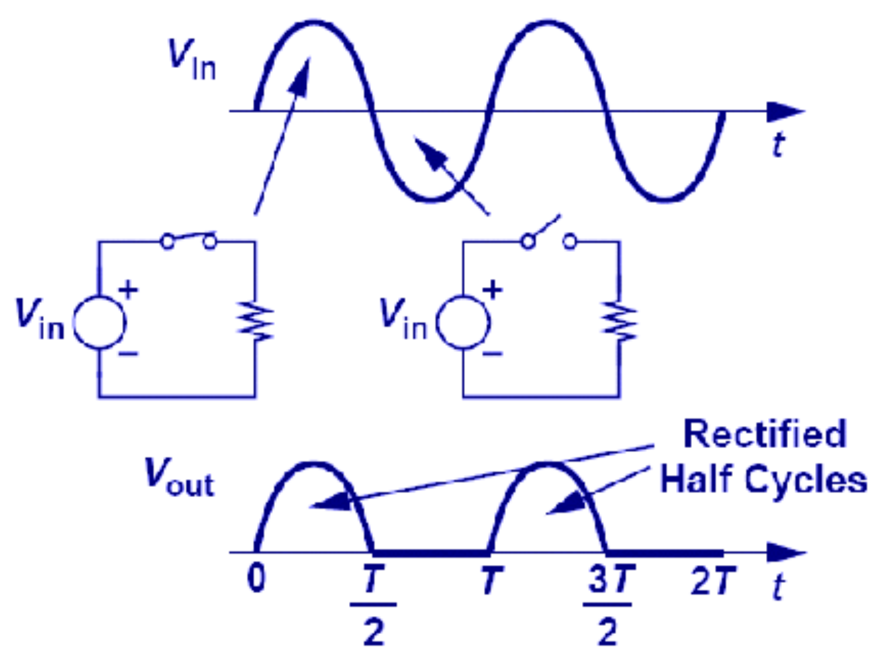
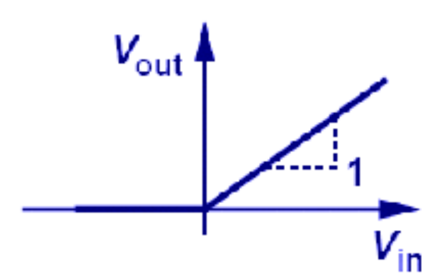
Diode's application: rectifier

- $V_{in} = V_p sin\omega t$
- $v_{out} = \begin{cases} V_p sin\omega t & \text{if } 0 < t < \frac{T}{2} \\ 0 & \text{if } \frac{T}{2} < t < T \end{cases}$
- $v_{out,avg} = \frac{1}{T}\int_0^T v_{out}dt = \frac{1}{T}\int_0^{\frac{T}{2}} V_p sin\omega t dt = \frac{V_p}{\omega T}[-cos(\omega t)]_0^{\frac{T}{2}} = \frac{V_p}{\pi}$



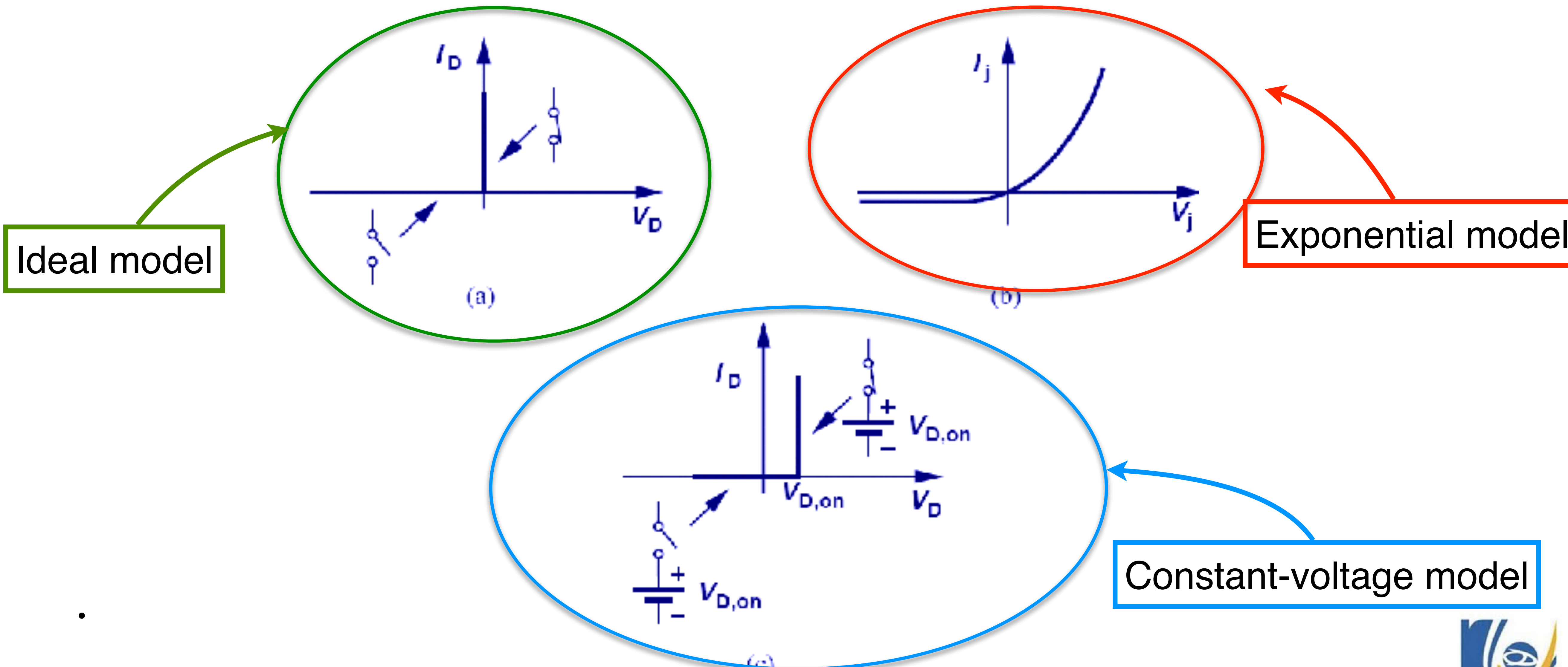


- 



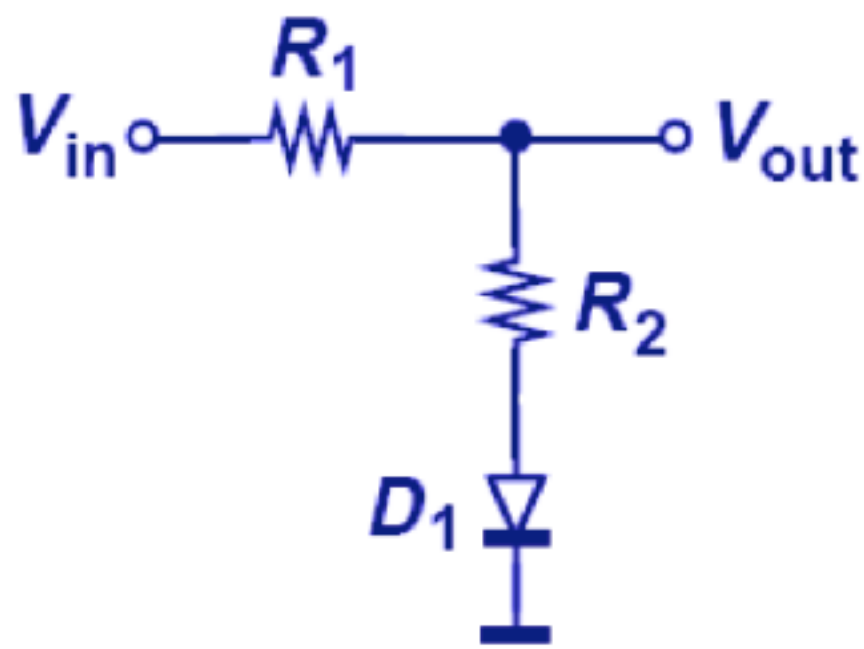
pn JUNCTION AS A DIODE

- The operation of the ideal diode is somewhat reminiscent of the current conduction in *pn* junctions.
- However, there are still the exponential and constant voltage models.
- In this course we will not consider exponential model. Some algorithm will be used instead.



In/Out Characteristics with Ideal and Constant-Voltage Models

- Example 5: In the circuit of Fig. below, sketch the in/out characteristics using ideal model and constant-voltage model.



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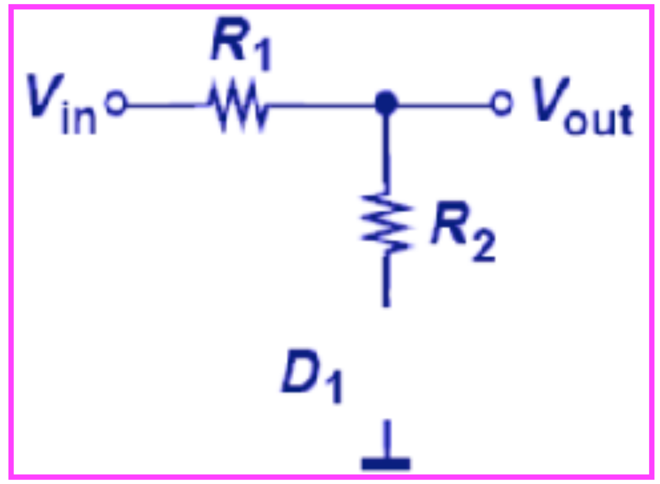
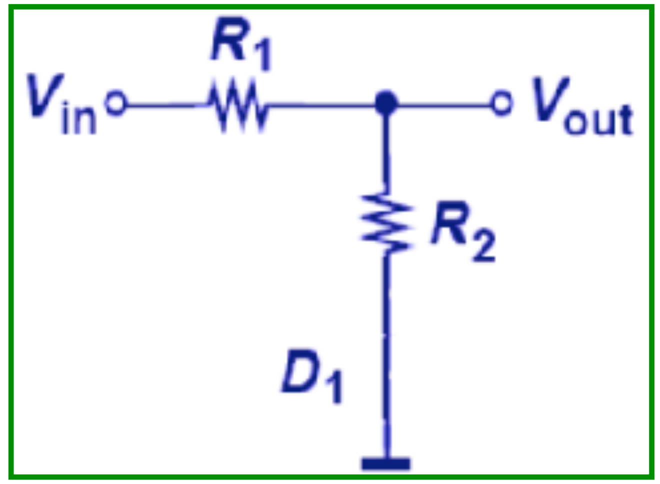
In/Out Characteristics with Ideal and Constant-Voltage Models

- Example 5: In the circuit of Fig. below, sketch the in/out characteristics using ideal model and constant-voltage model.
- Solution:
- Using ideal model:

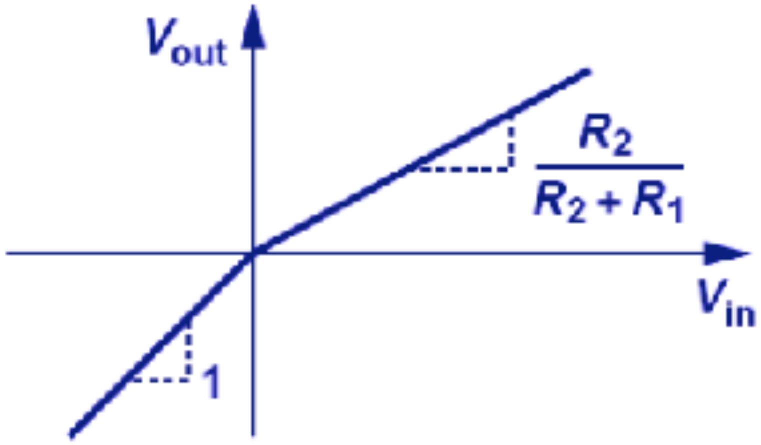
- We start with $V_{in} \rightarrow -\infty \Rightarrow D_1$ off $\Rightarrow V_{out} = V_{in}$



- $V_{in} \rightarrow \infty \Rightarrow D_1$ on $\Rightarrow V_{out} = \dfrac{R_2}{R_1 + R_2} V_{in}$



- intersection of $V_{out} = V_{in}$ and $V_{out} = \dfrac{R_2}{R_1 + R_2} V_{in}$ @ $V_{in} = 0$



In/Out Characteristics with Ideal and Constant-Voltage Models

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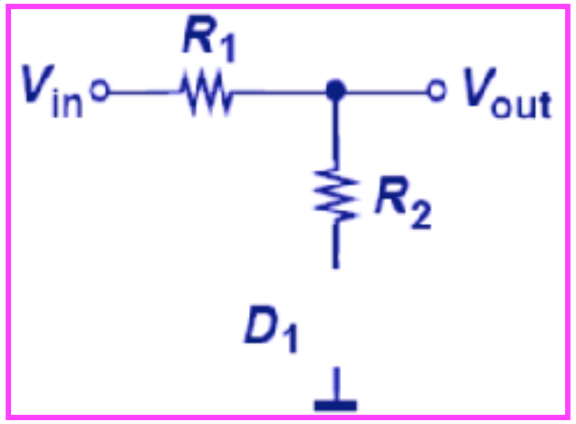
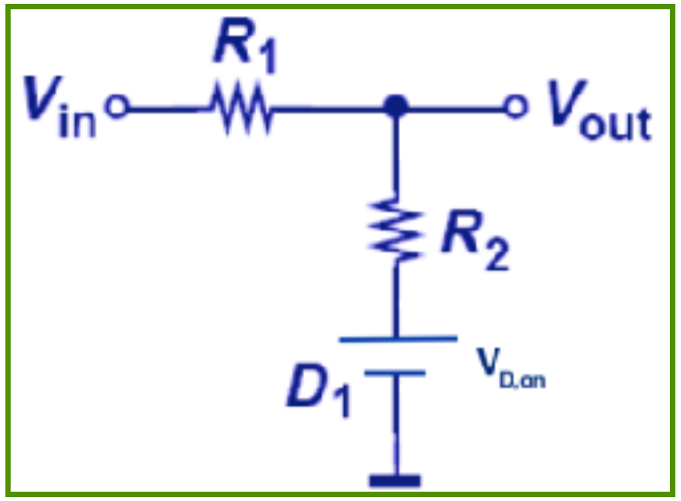


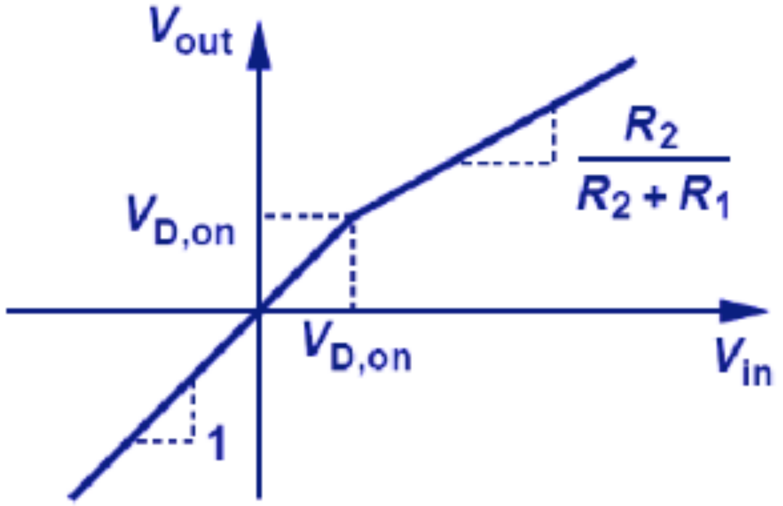
- Solution:
- Using constant-voltage model:

- We start with $V_{in} \to -\infty \Rightarrow\ D_1$ off $\Rightarrow V_{out} = V_{in}$
- D_1 stay off if $V_{in} < V_{D,on}$

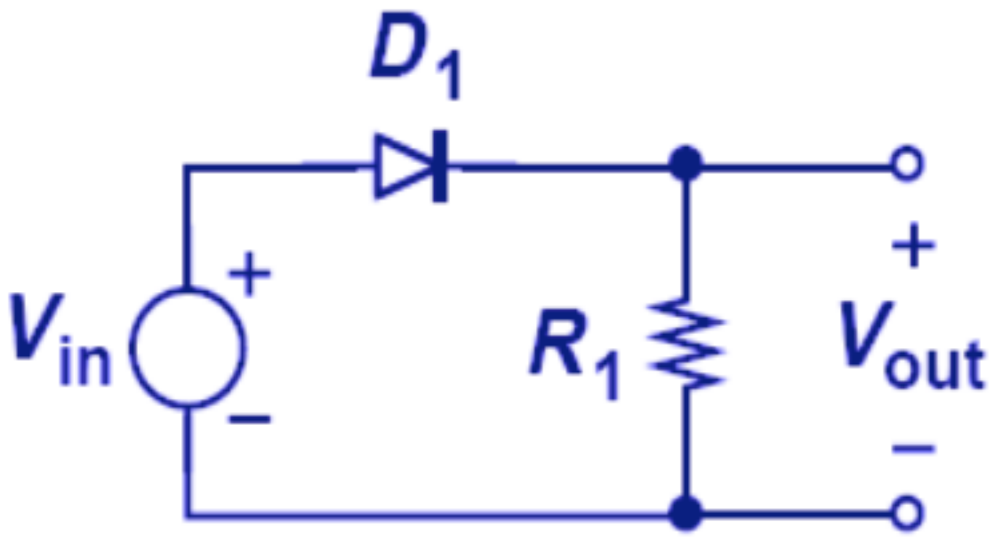


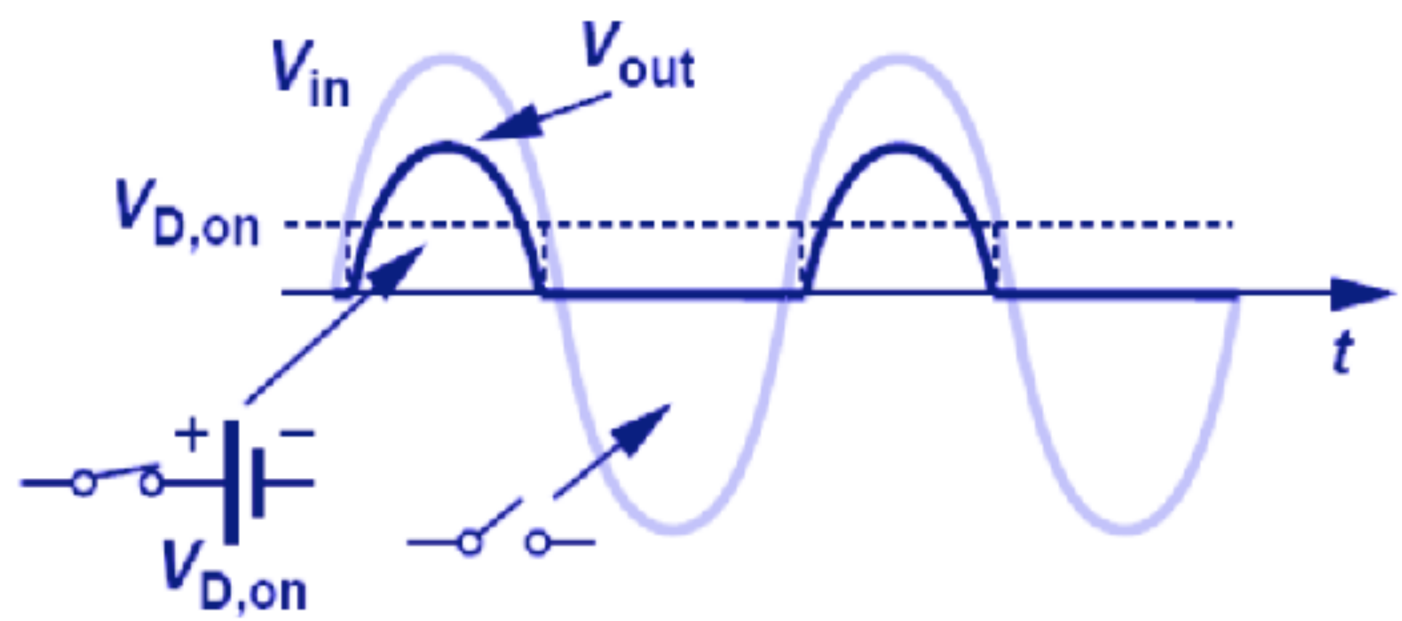
- $V_{in} \to \infty \Rightarrow\ D_1$ on $\Rightarrow V_{out} = ??$
- $\dfrac{V_{in} - V_{out}}{R_1} = \dfrac{V_{out} - V_{D,on}}{R_2} \Rightarrow V_{out} = \dfrac{R_2}{R_1 + R_2} V_{in} + \dfrac{R_1}{R_1 + R_2} V_{D,on}$

- intersection of $V_{out} = V_{in}$ and $V_{out} = \dfrac{R_2}{R_1 + R_2} V_{in} + \dfrac{R_1}{R_1 + R_2} V_{D,on}$ @ $V_{in} = V_{D,on}$



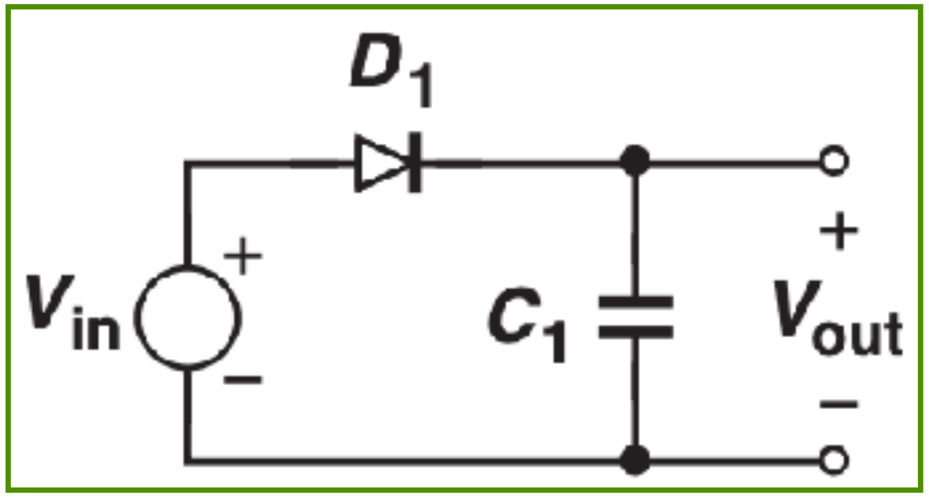
Applications of Diode: Half-wave rectifier

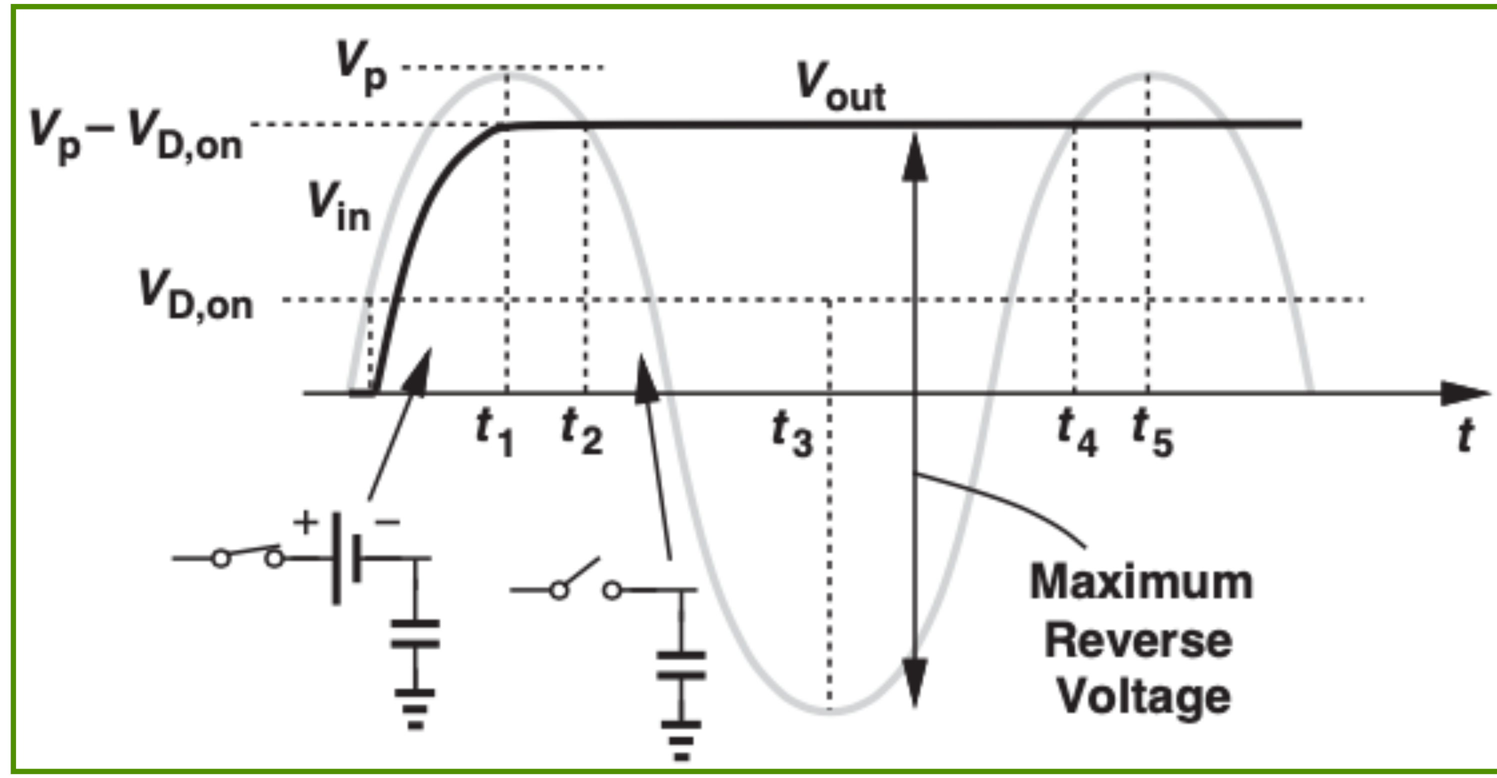




- We no longer assume D_1 is ideal, but use a constant-voltage model.
- For $V_{in} < V_{D,on}$, D_1 is off and $V_{out} = 0$
- For $V_{in} > V_{D,on}$, D_1 is on and $V_{out} = V_{in} - V_{D,on}$
- Half-wave rectification, where either the positive or negative half of the input is blocked.
- But the output is not constant. Unlike a battery, the rectifier generates an output that *varies* considerably with time and cannot supply constant power.

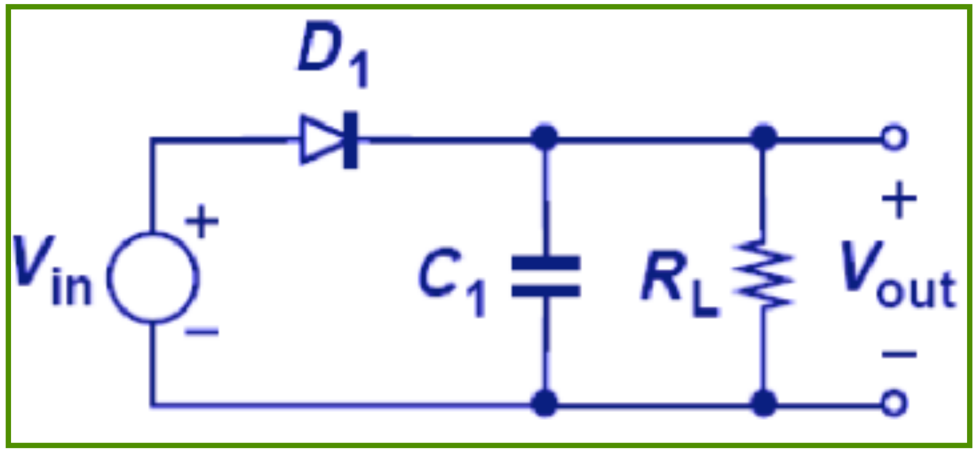
Applications of Diode: Half-wave rectifier

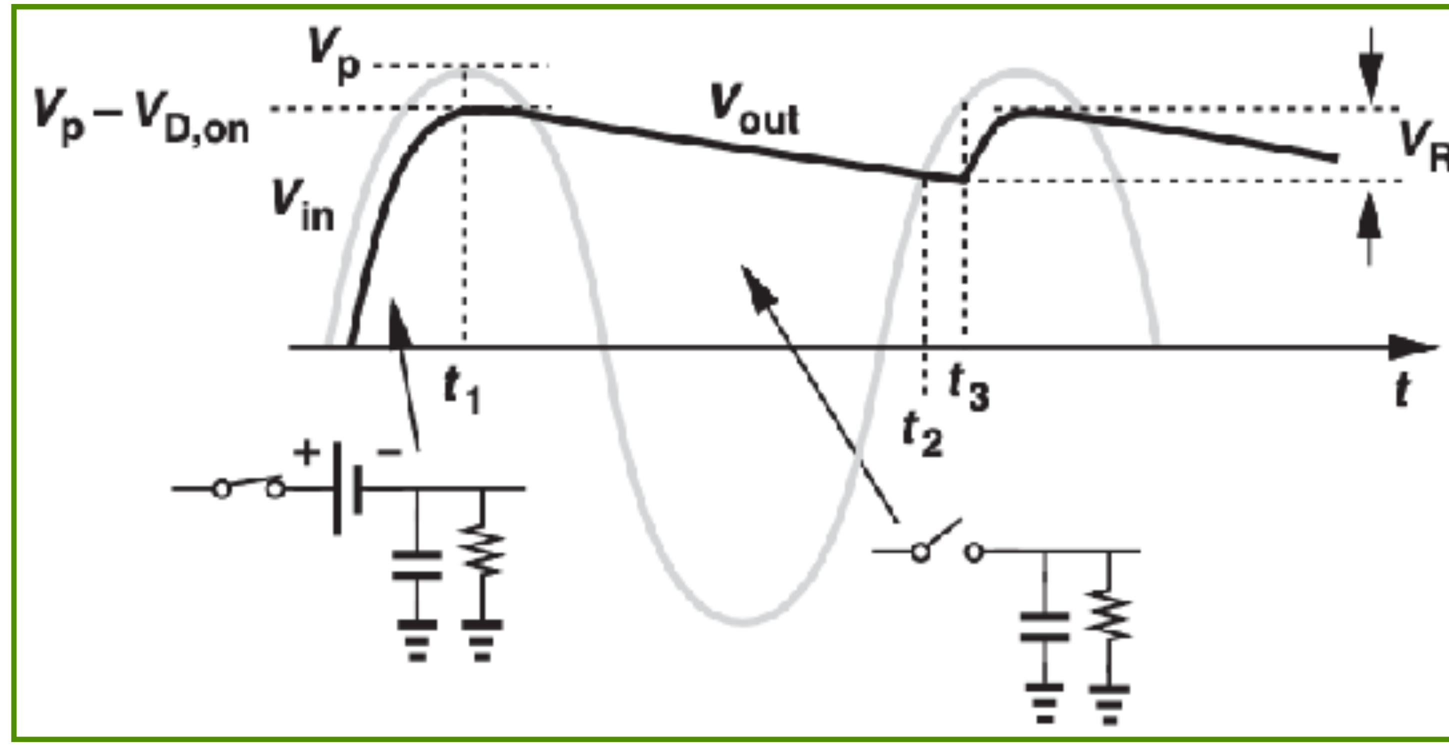




- Fortunately, a simple modification solves the problem. The resistor is replaced with a capacitor.
- At $t = t_1$, we have $V_{in} = V_p$ and $V_{out} = V_p - V_{D,on}$. As V_{in} begins to fall, V_{out} must remain *constant*. This is because if V_{out} were to fall, then C_1 would need to be *discharged* by a current flowing from its top plate through the cathode of D_1, which is impossible.
- The diode therefore turns off after t_1. At $t = t_2$, $V_{in} = V_p - V_{D,on} = V_{out}$,
- the diode sustains a zero voltage difference. At $t > t_2$, $V_{in} < V_{out}$ and the diode experiences a negative voltage.
- V_{out} remains equal to $V_p - V_{D,on}$ indefinitely.
- Fixed voltage output is obtained since the capacitor **(assumed ideal)** has no path to discharge.

Applications of Diode: Half-wave rectifier





- We recognize that V_{out} behaves as before until $t = t_1$, still exhibiting a value of $V_{in} - V_{D,on} = V_p - V_{D,on}$ if the diode voltage is assumed relatively constant.
- However, as V_{in} begins to fall after $t = t_1$, so does V_{out} because R_L provides a discharge path for C_1.
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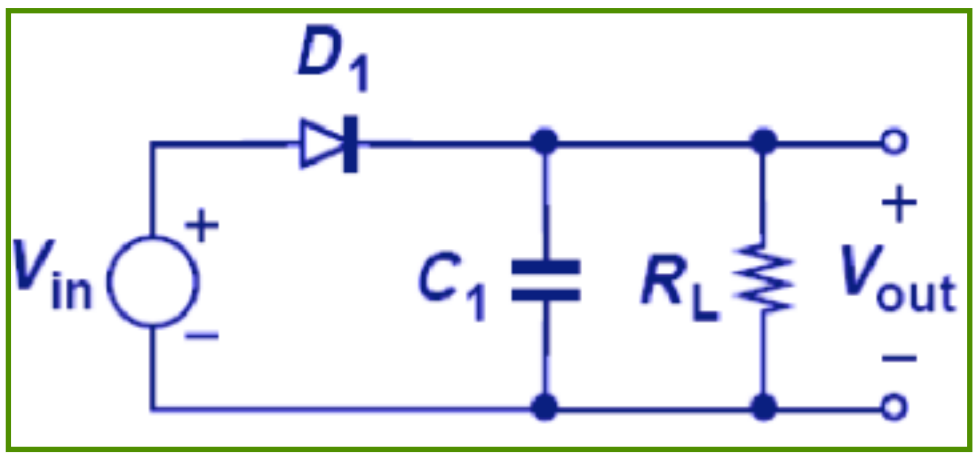
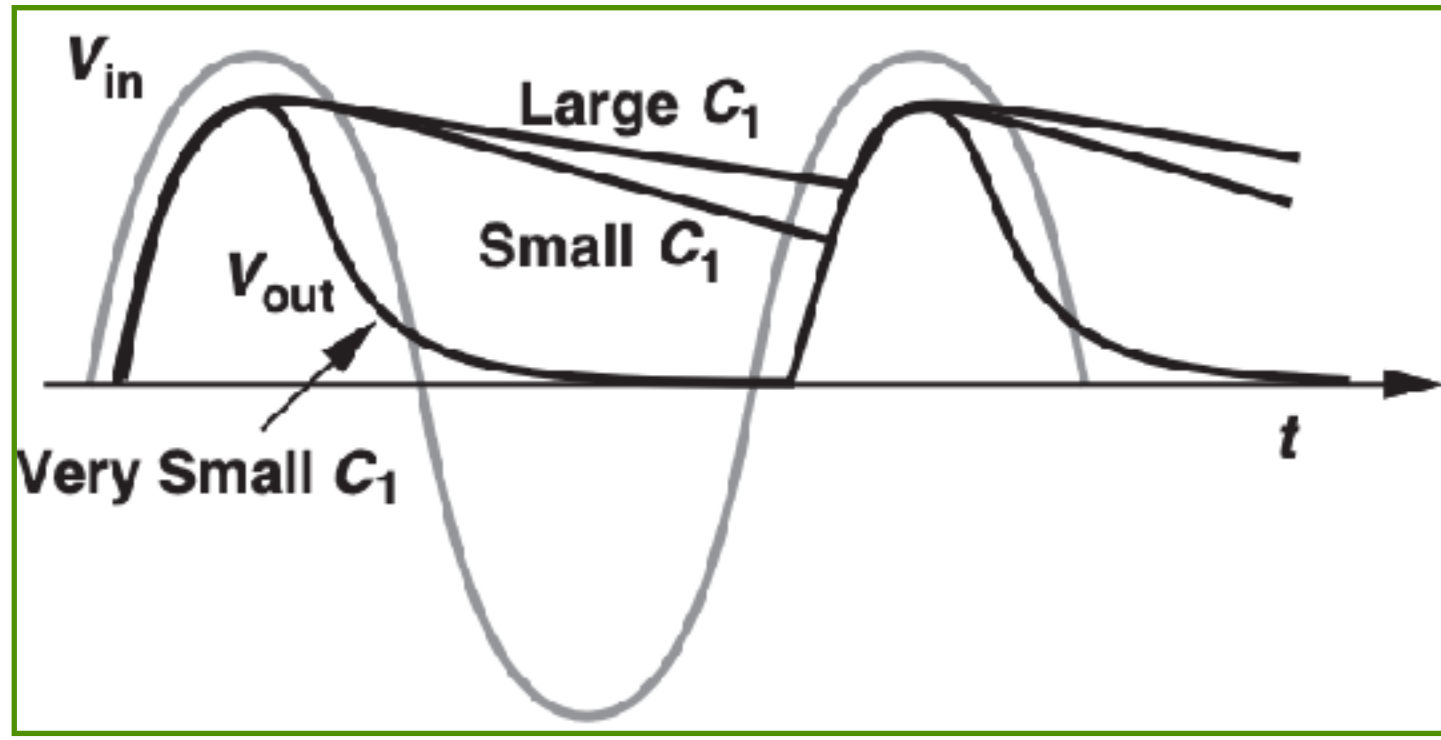
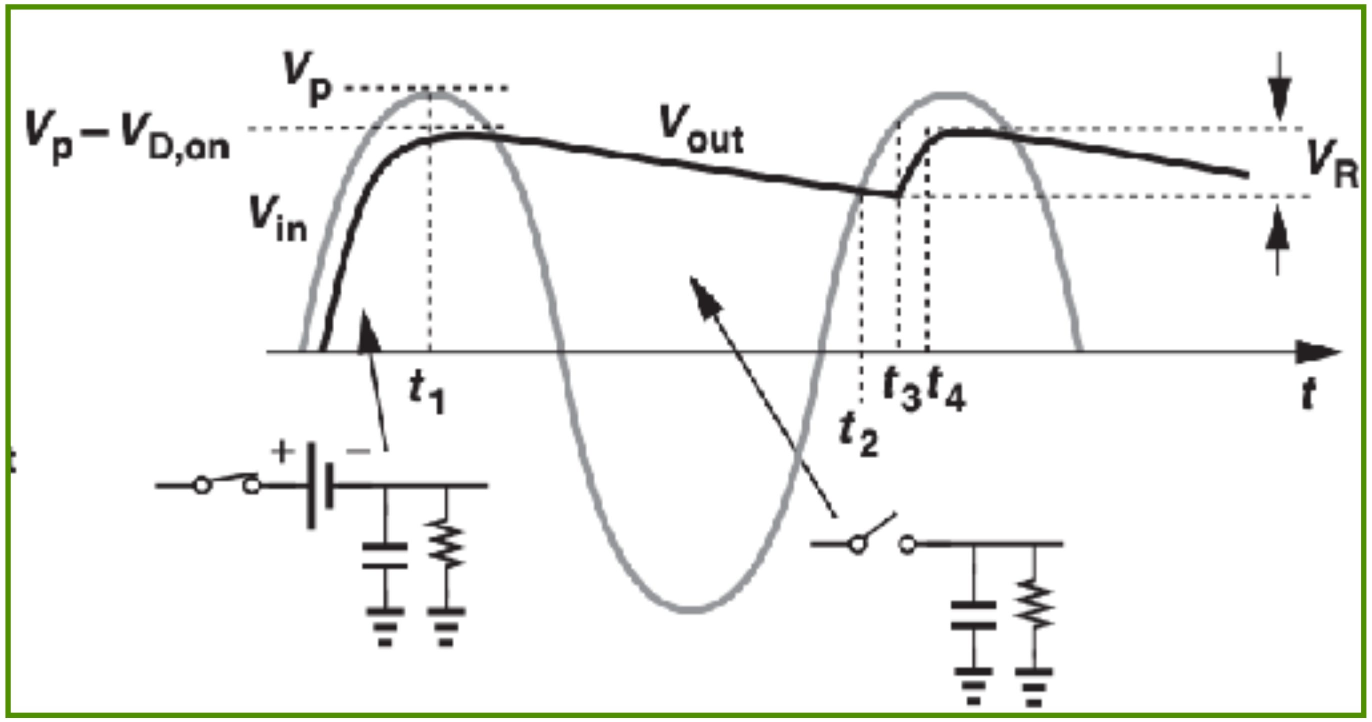
Applications of Diode: Half-wave rectifier





- Behavior for Different Capacitor Values: For large C_1, V_{out} has small ripple.

Applications of Diode: Half-wave rectifier



- The ripple amplitude is the decaying part of the exponential.
- Ripple voltage becomes a problem if it goes above 5 to 10% of the output voltage.
- Where $\Delta T (= t_4 - t_3)$ denotes the time during which D_1 is on

$$\boxed{V_R = \frac{V_p - V_{D,on}}{R_L} \frac{T_{in} - \Delta T}{C_1}}$$

- Recognizing that if C_1 discharges by a small amount, then the diode turns on for only a brief period, we can assume $\Delta T \ll T_{in}$ and hence

$$\boxed{V_R \approx \frac{V_p - V_{D,on}}{R_L} \cdot \frac{T_{in}}{C_1}}$$

Applications of Diode: Half-wave rectifier

- Example 6: A transformer converts the 110-V, 60-Hz line voltage to a peak-to-peak swing of 9 V. A half-wave rectifier follows the transformer to supply the power to a DC motor. The motor consumes an average power of 25 W with a supply voltage of 3.3 V.
  - a) Determine the average current drawn from the batteries, and the equivalent resistance of the motor.
  - b) Determine the minimum value of the filter capacitor that maintains the ripple below 0.1 V. Assume $V_{D,on} = 0.8$ V.

$$\boxed{V_R \approx \frac{V_p - V_{D,on}}{R_L} \cdot \frac{T_{in}}{C_1}}$$

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Applications of Diode: Half-wave rectifier

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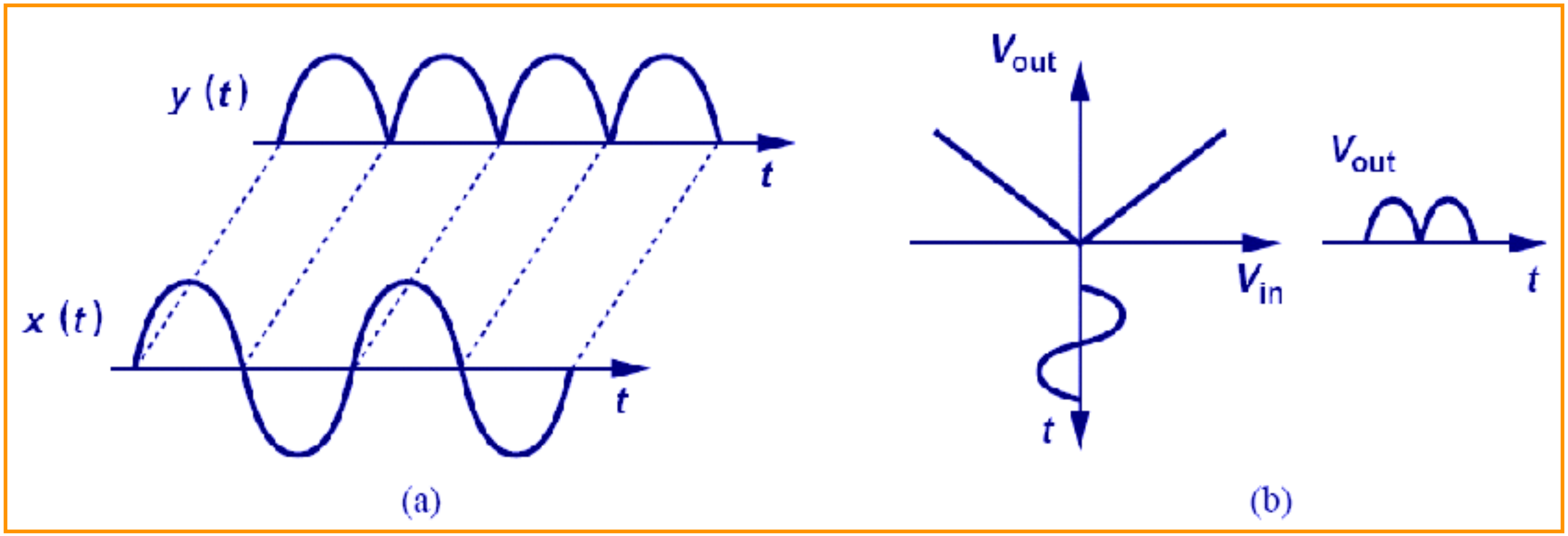
  - a) Determine the average current drawn from the batteries, and the equivalent resistance of the motor.
  - b) Determine the minimum value of the filter capacitor that maintains the ripple below 0.1 V. Assume $V_{D,on} = 0.8$ V.

- Solution:
- a) $P = VI \Rightarrow I = \frac{P}{V} \simeq 7.58A$ and $R_L = \frac{V}{I} = 0.436\Omega$
- b)We have $V_p = \frac{9}{2} = 4.5V,$ and $T_{in} = \frac{1}{f} \simeq 16.7ms$
- $C_1 = \frac{V_p - V_{D,on}}{V_R}\frac{T_{in}}{R_L} \simeq 1.417F$
- Note that this capacitor is very large.

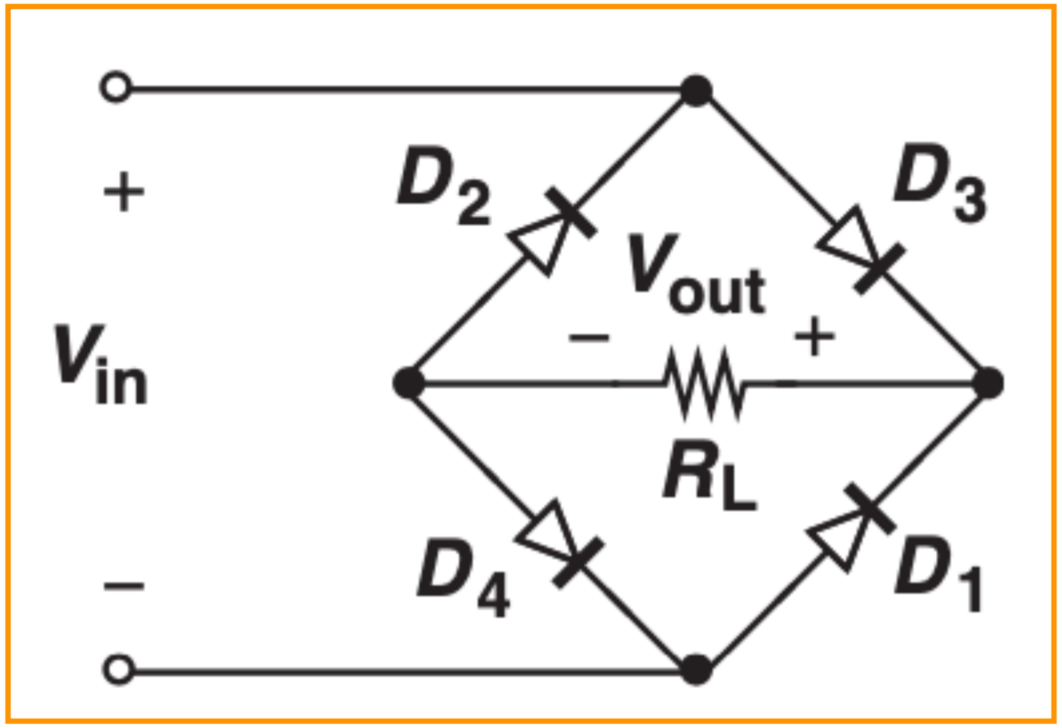
Applications of Diode: Full-Wave Rectifier

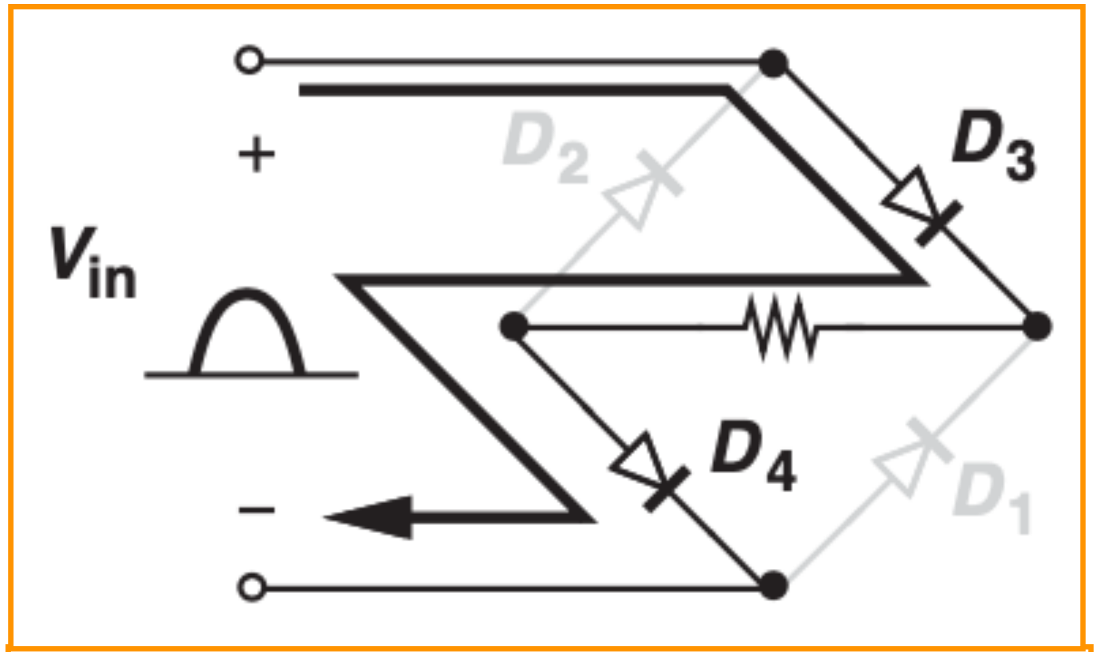
- A full-wave rectifier passes both the negative and positive half cycles of the input, while inverting the negative half of the input.
- As proved later, a full-wave rectifier reduces the ripple by a factor of two.

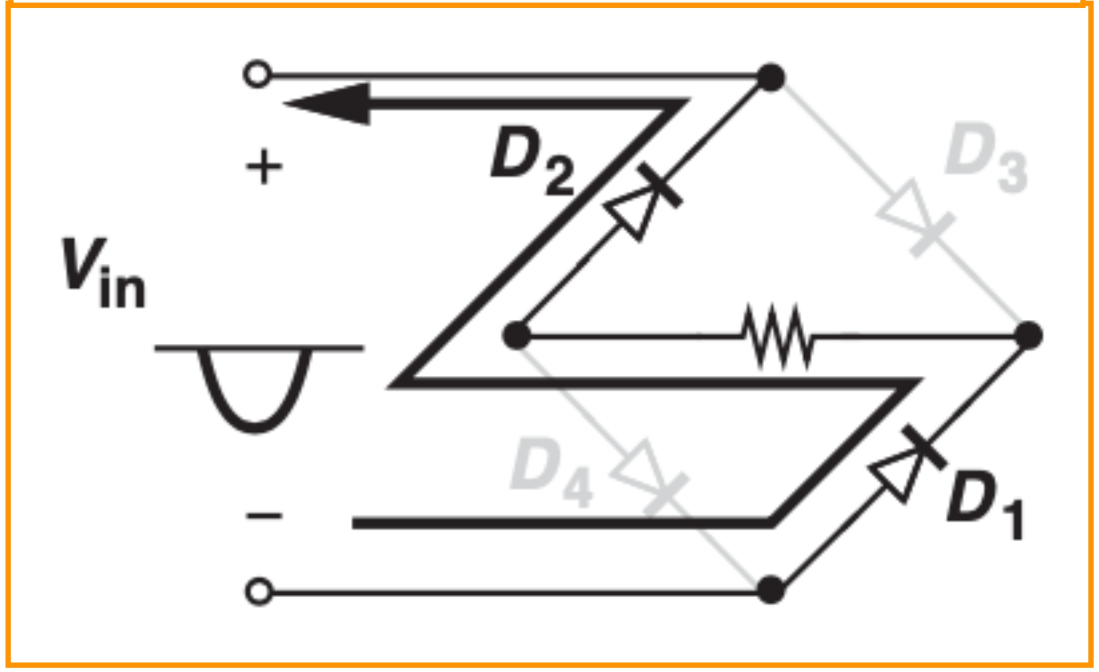


Applications of Diode: Full-Wave Rectifier

- The circuit passes the negative half cycles through D_1 and D_2 with a sign reversal and the positive half cycles through D_3 and D_4 with no sign reversal.

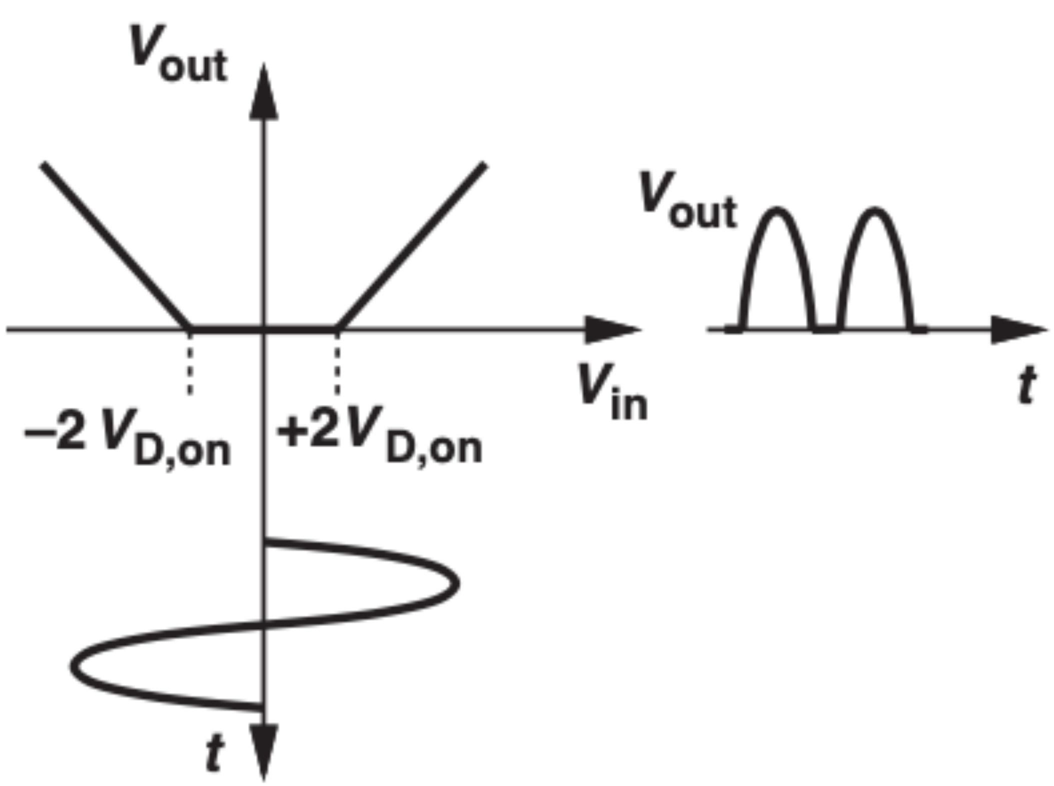






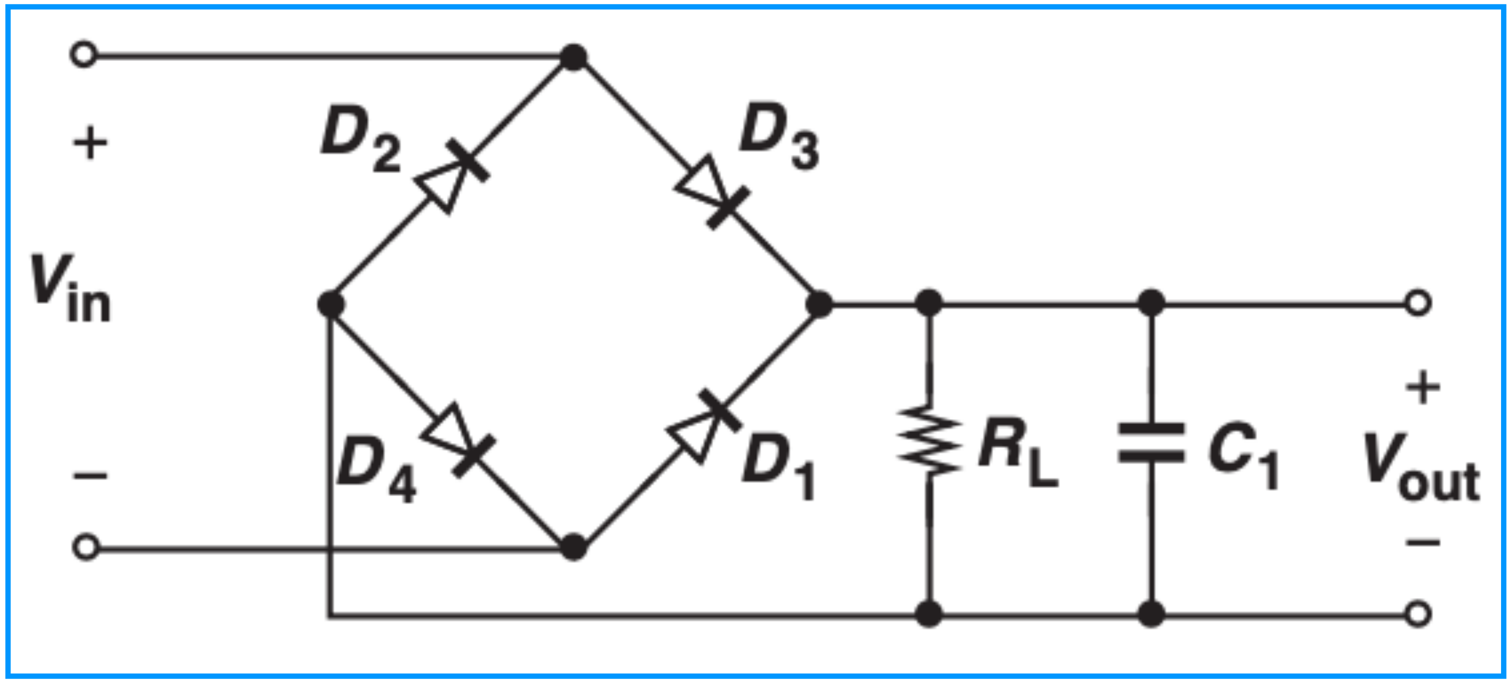
Applications of Diode: Full-Wave Rectifier

- If the diodes are not ideal, $V_{out} = -V_{in} - 2V_{D,on}$ for $V_{in} < 0$.
- By contrast, the half-wave rectifier produces $V_{out} = V_{in} - V_{D,on}$. The drop of $2V_{D,on}$ may pose difficulty if V_p is relatively small and the output voltage must be close to V_p.

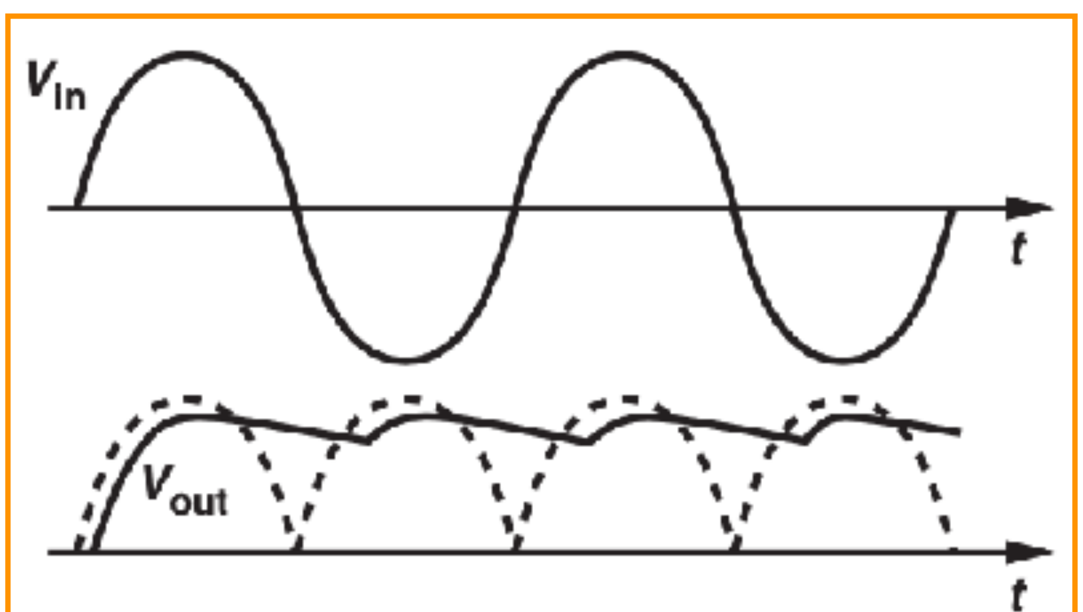


Applications of Diode: Full-Wave Rectifier

- The ripple in full-wave rectifier is approximately equal to half of that in half-wave rectifier. Since C_1 only gets ½ of period to discharge, ripple voltage is decreased by a factor of 2.



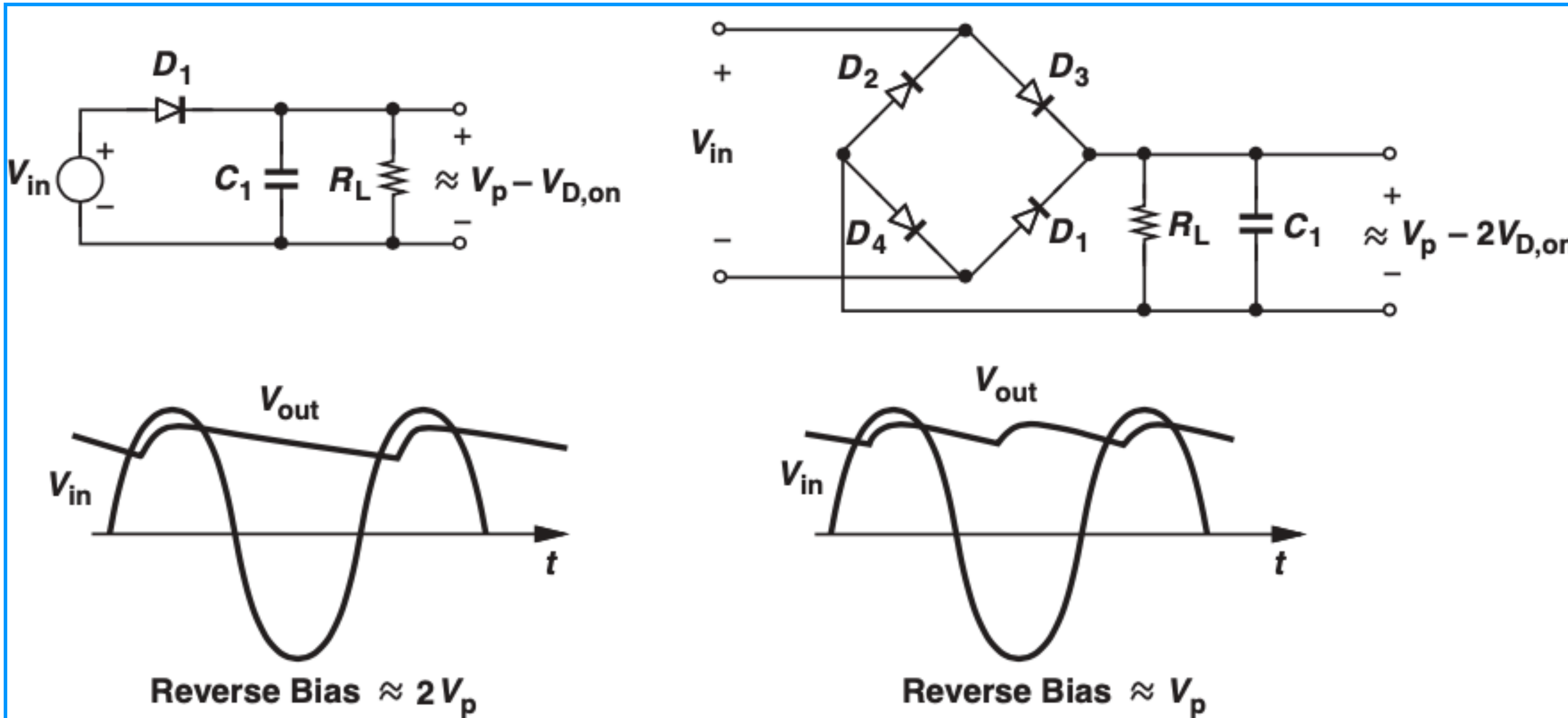
$$V_R \approx \frac{V_p - V_{D,on}}{R_L} \cdot \frac{T_{in}}{C_1}$$



$$V_R \approx \frac{1}{2} \cdot \frac{V_p - 2V_{D,on}}{R_L C_1 f_{in}}$$

Summary of rectifier circuits

- While using two more diodes, full- wave rectifiers exhibit a lower ripple.



Summary

- In addition to the exponential and constant-voltage models, an "ideal" model is sometimes used to analyze diode circuits. The ideal model assumes the diode turns on with a very small forward bias voltage.
- For many electronic circuits, the "input/output characteristics" are studied to understand the response to various input levels, e.g., as the input level goes from –∞ to +∞.
- Half-wave rectifiers pass the positive (negative) half cycles of the input wave- from and block the negative (positive) half cycles. If followed by a capacitor, a rectifier can produce a dc level nearly equal to the peak of the input swing.

$$V_R \approx \frac{V_p - V_{D,on}}{R_L} \cdot \frac{T_{in}}{C_1}$$

- Full-wave rectifiers convert both positive and negative input cycles to the same polarity at the output. If followed by a smoothing capacitor and a load resistor.
-

$$V_R \approx \frac{1}{2} \cdot \frac{V_p - 2V_{D,on}}{R_L C_1 f_{in}}$$