Chapter 3 Diode Circuits

- 3.1 Ideal Diode
- 3.2 PN Junction as a Diode
- 3.3 Applications of Diodes

Diodes as Circuit Elements		Applications
• Ideal Diode • Circuit Characteristics • Actual Diode	⇨	• Regulators • Rectifiers • Limiting and Clamping Circuits

Diode's Application: Cell Phone Charger

- An important application of diode is *chargers*. 充電器
- Diode acts as the black box (after transformer) that passes only the positive half of the stepped-down sinusoid.

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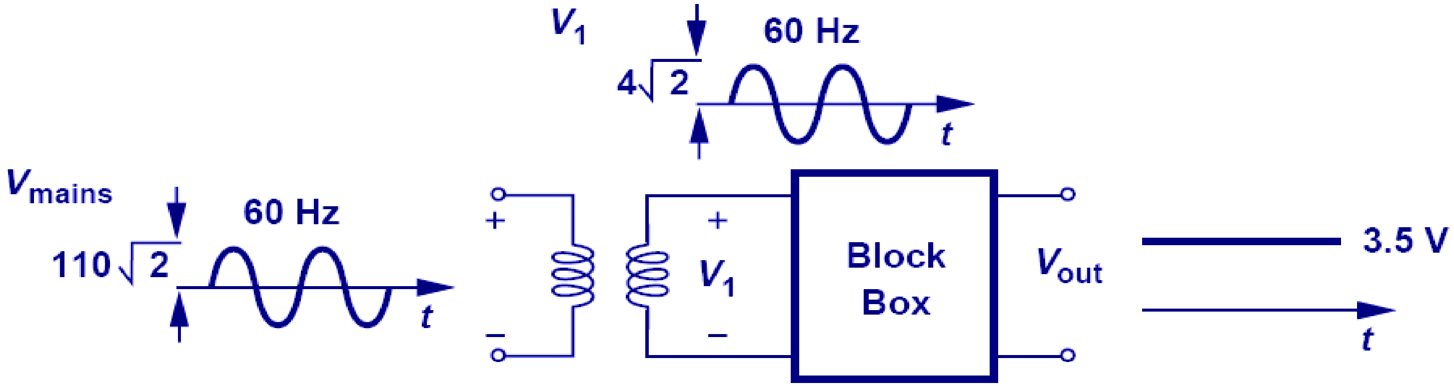

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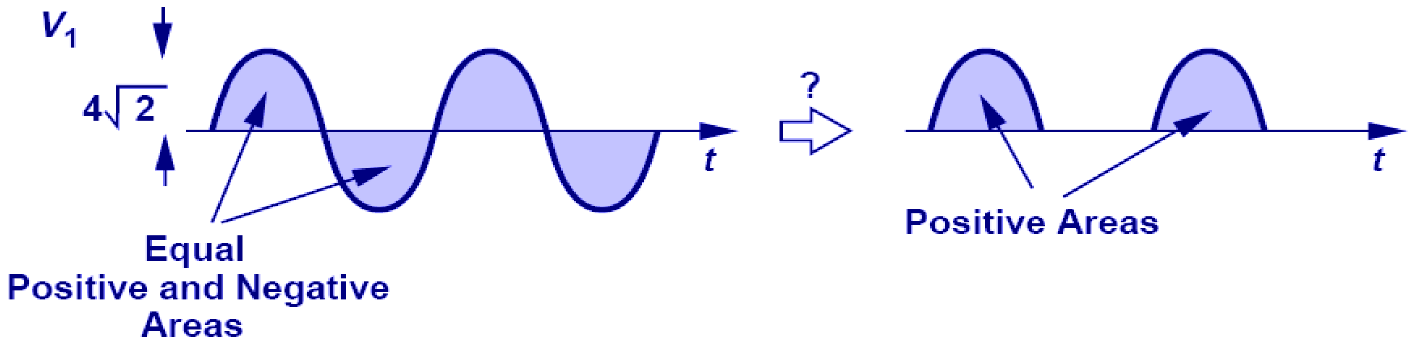

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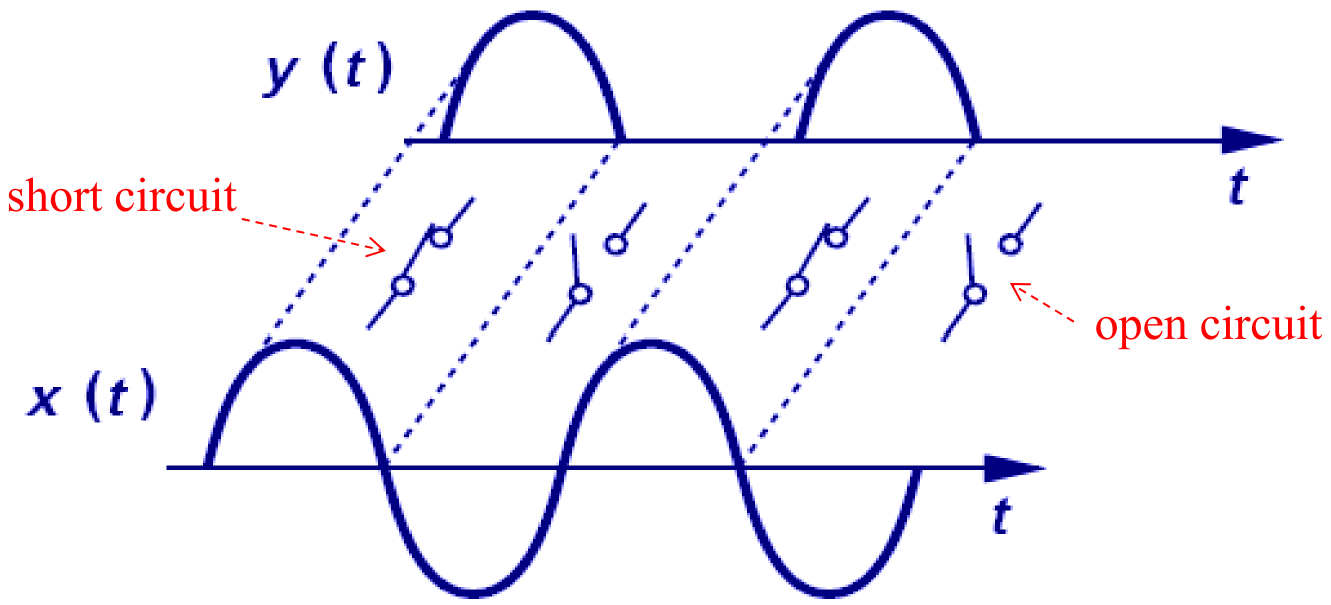
Diode's Action in The Black Box (Ideal Diode)

- The diode behaves as a short circuit during the positive half cycle (voltage across it tends to exceed zero), and an open circuit during the negative half cycle (voltage across it is less than zero).



Ideal Diode

- In an ideal diode, if the voltage across it tends to exceed zero, current flows.
- It is analogous to a water pipe that allows water to flow in only one direction.
- The corresponding terminals are called the "***anode***" and the "***cathode***," respectively.

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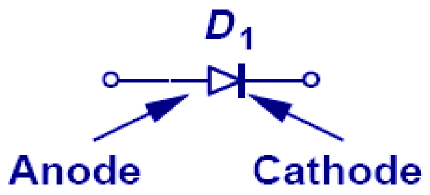

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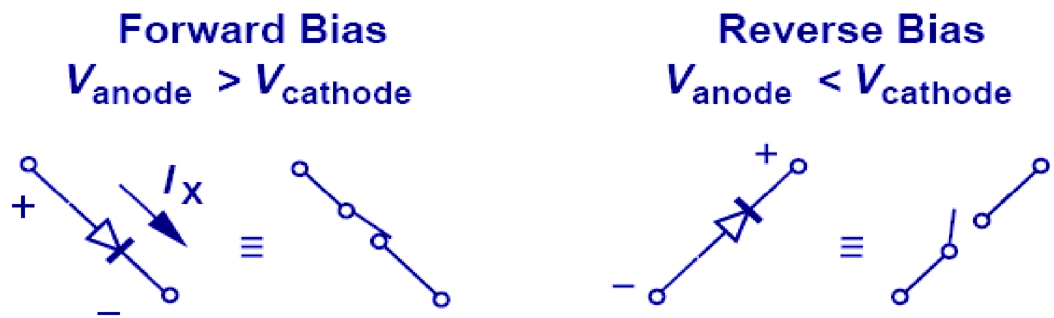

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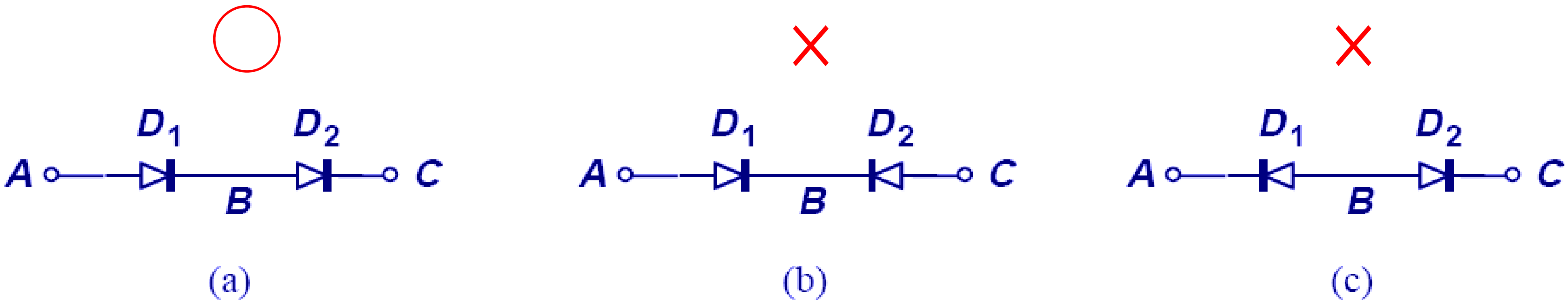
(c)

Diodes in Series

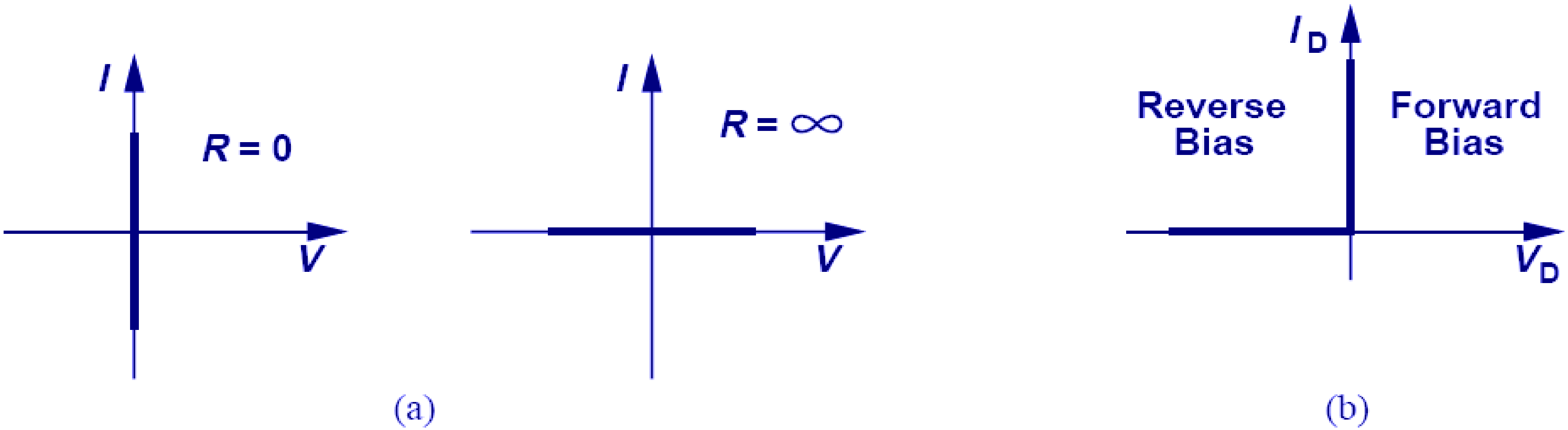
- The diode must turn "**on**" if $V_{anode} > V_{cathode}$ and "**off**" if $V_{anode} < V_{cathode}$.
- Defining $V_{anode} - V_{cathode} = V_D$, we say the diode is "*forward-biased*" if V_D tends to exceed zero and "*reverse-biased*" if $V_D < 0$.



- Diodes cannot be connected in series randomly.
- For the circuits above, only (a) can conduct current from A to C.

IV Characteristics of an Ideal Diode

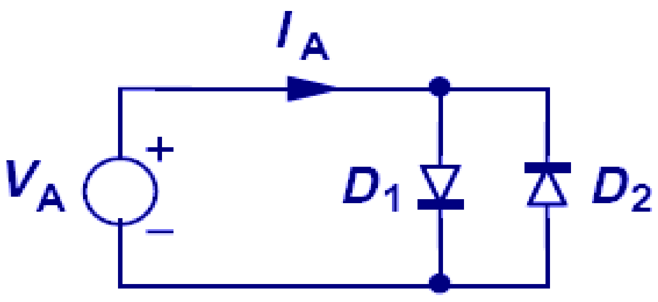
short: $R = 0 \Rightarrow I = \frac{V}{R} = \infty$ open: $R = \infty \Rightarrow I = \frac{V}{R} = 0$



- If the voltage across anode and cathode is greater than zero, the resistance of an ideal diode is zero and current becomes infinite.
- However, if the voltage is less than zero, the resistance becomes infinite and current is zero.

Anti-Parallel Ideal Diodes

- If two diodes are connected in anti-parallel, it acts as a short for all voltages.
- If $V_A > 0$, D_1 is on and D_2 is off, yielding $I_A = \infty$. If $V_A < 0$, D_1 is off, but D_2 is on, again leading to $I_A = \infty$.



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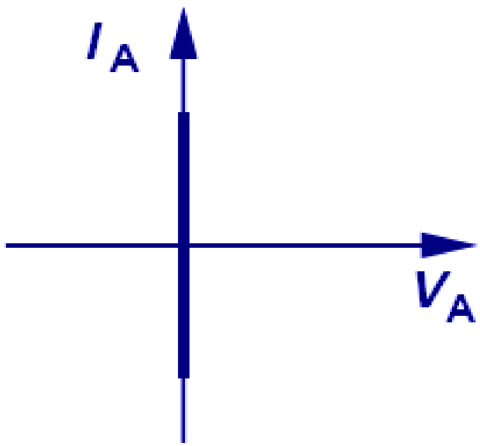

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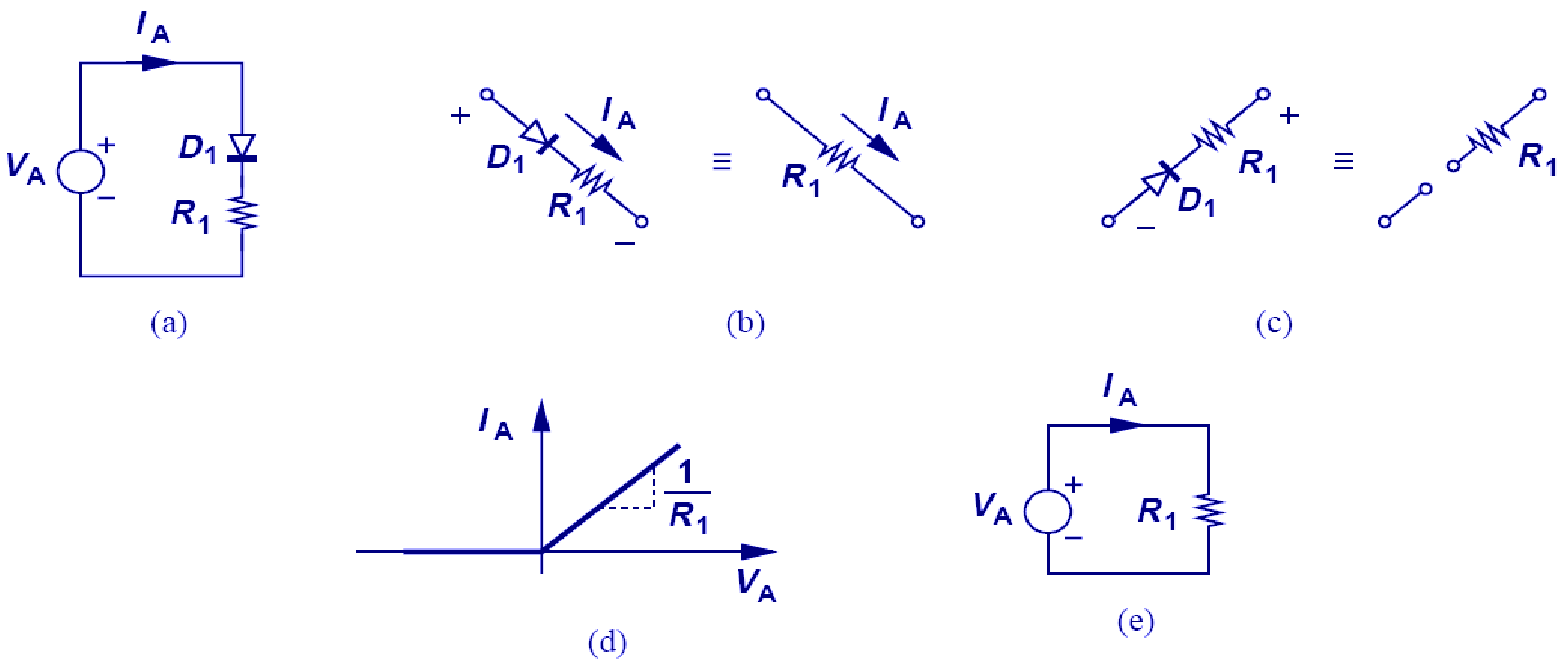
Diode-Resistor Combination

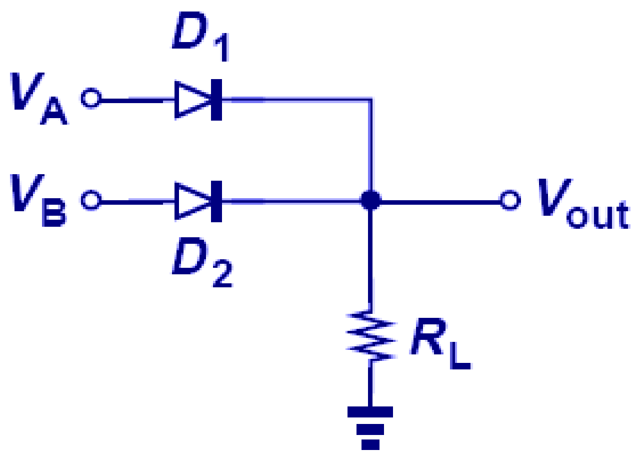
Example 3.4: Plot the I/V characteristic for the diode-resistor combination.

- The IV characteristic of this diode-resistor combination is zero for negative voltages and Ohm's law for positive voltages.



Diode Implementation of OR Gate

Example 3.6: V_A and V_B can assume a value of either zero or 3 V. Determine the response observed at the output, V_{out}.



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

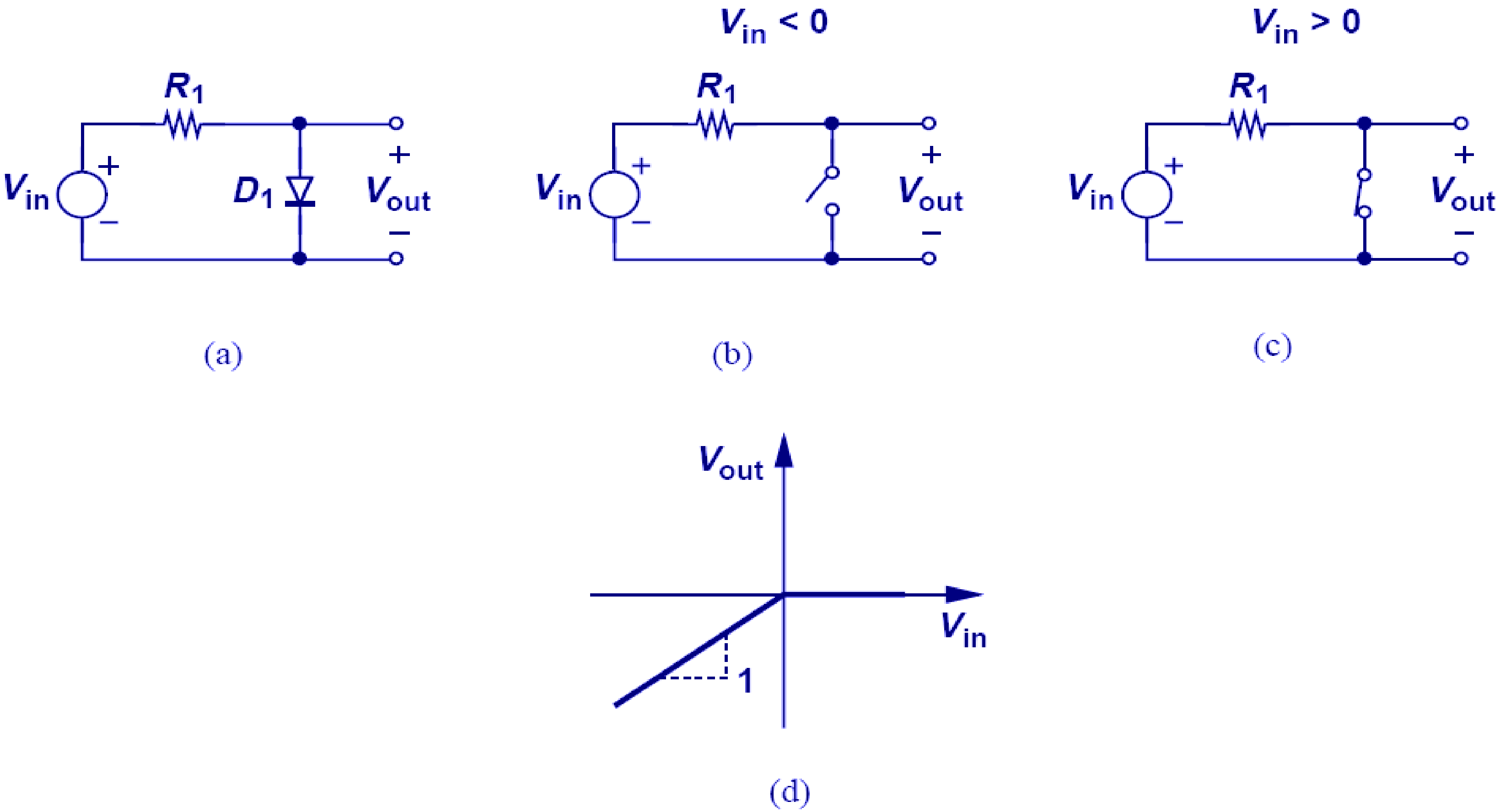
If $V_A = 3$V, and $V_B = 0$, then we surmise that D_1 is forward-biased and D_2 reverse-biased. Thus, $V_{out} = V_A = 3$V. If uncertain, we can assume both D_1 and D_2 are forward-biased, immediately facing a conflict: enforces a voltage of 3 V at the output whereas D_2 shorts V_{out} to $V_B = 0$. This assumption is therefore incorrect.

The symmetry of the circuit with respect to V_A and V_B suggests that $V_{out} = V_B = 3$V if $V_A = 0$ and $V_B = 3$V. The circuit operates as a logical OR gate and was in fact used in early digital computers.

We have introduced NOT and OR gates. How about AND gates?

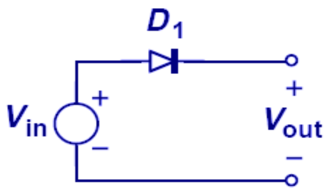
Input/Output Characteristics

- The input/output characteristics of a circuit is constructed by varying the input across an allowable range and plotting the resulting output.
- 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 $V_{out} = 0$.



Diode's Application: Rectifier 整流器

- A *rectifier* is a device that passes positive-half cycle of a sinusoid and blocks the negative half-cycle or vice versa. 前一頁即是相反動作的電路
- When V_{in} > 0, diode shorts, so $V_{out} = V_{in}$; however, when V_{in} < 0, diode opens, no current flows thru R_1, $V_{out} = I_{R1}R_1 = 0$.



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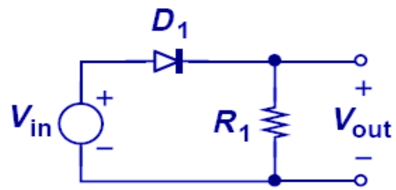

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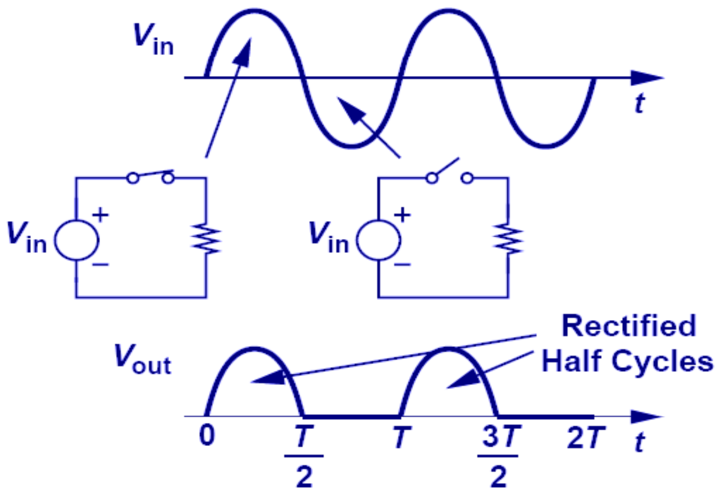

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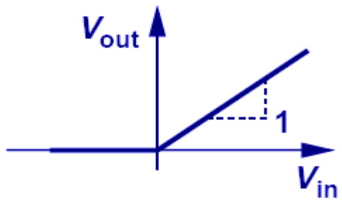


(d)

Signal Strength Indicator 信號強度指示器

- Suppose $V_{in} = V_p \sin\omega t$, where $\omega = 2\pi/T$ denotes the frequency in radians per second and T the period. Then, in the first cycle after $t = 0$, we have

$$V_{out} = V_p \sin \omega t \qquad \text{for } 0 \le t \le \frac{T}{2}$$

$$= 0 \qquad \text{for } \frac{T}{2} \le t \le T$$

- To compute the average, we obtain the area under V_{out} and normalize the result to the period:

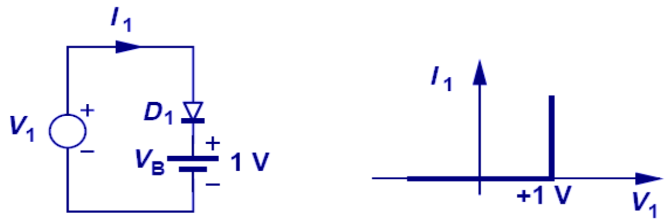
$$V_{out,avg} = \frac{1}{T}\int_0^T V_{out}(t)dt = \frac{1}{T}\int_0^{T/2} V_p \sin \omega t dt$$

$$= \frac{1}{T}\frac{V_p}{\omega}\left[-\cos \omega t\right]_0^{T/2} = \frac{V_p}{\pi}$$

- $V_{out,avg}$ is proportional to V_p, the input signal's amplitude, and can be used as a signal strength indicator for the input.

Diode's application: Limiter 限壓器

- The purpose of a *limiter* is to force the output to remain below certain value.
- In (a), the addition of a 1 V battery forces the diode to turn on after V_1 > 1 V.



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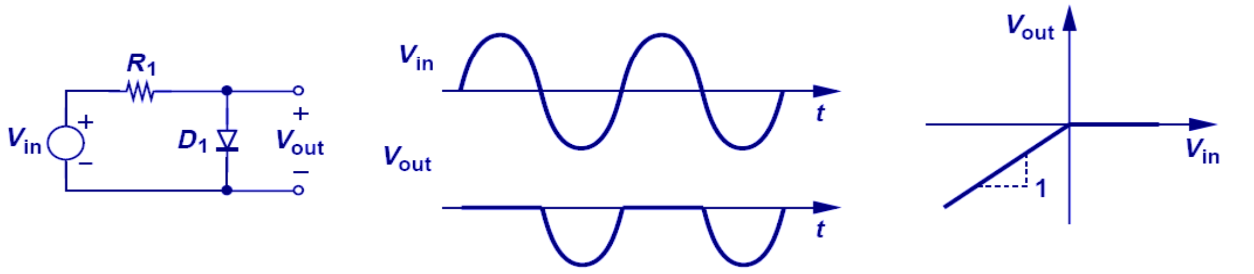

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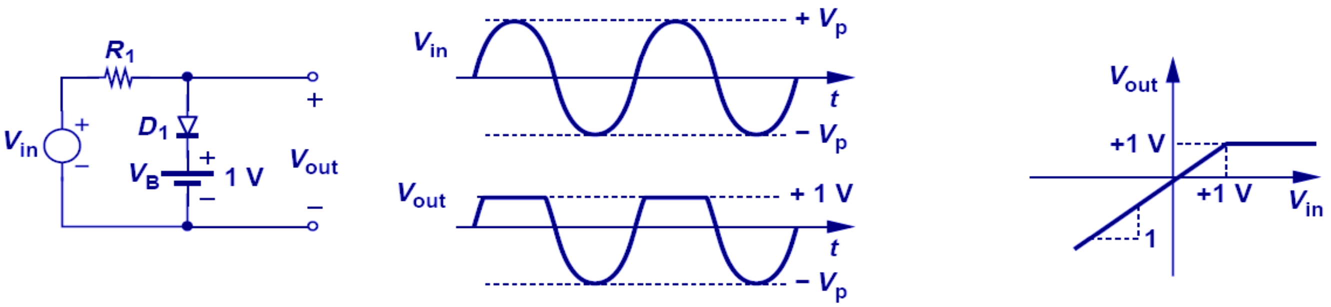

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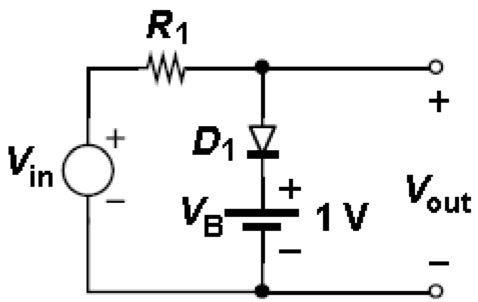
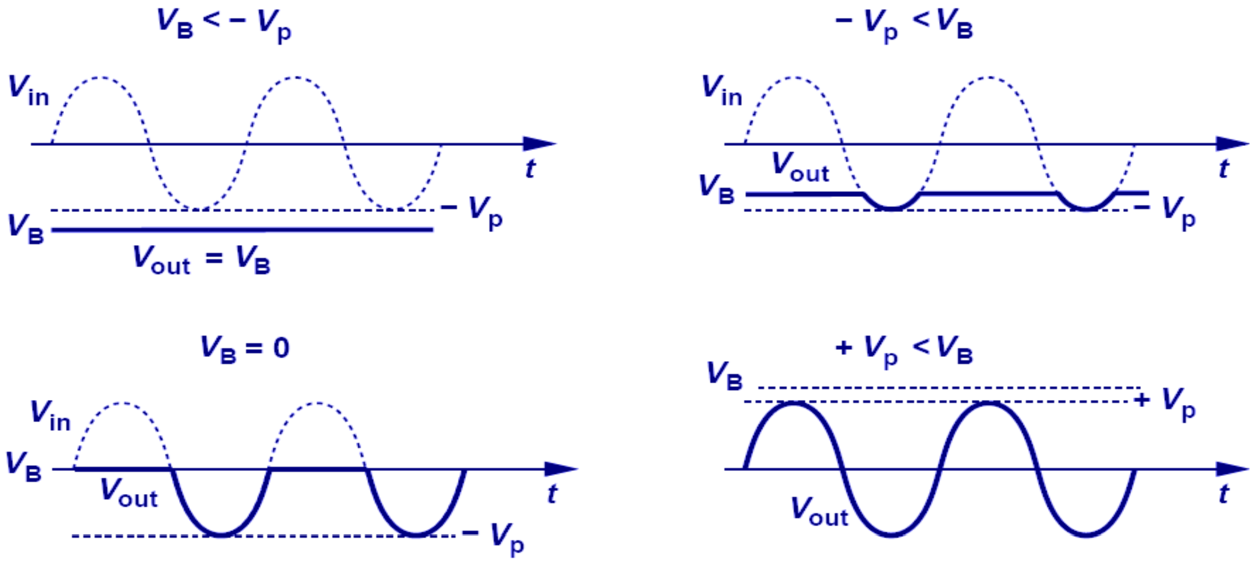
Limiter: When Battery Varies (Example 3.10)

Sketch the time average of V_{out} for a sinusoidal input as the battery voltage, V_B, varies from -∞ to ∞.





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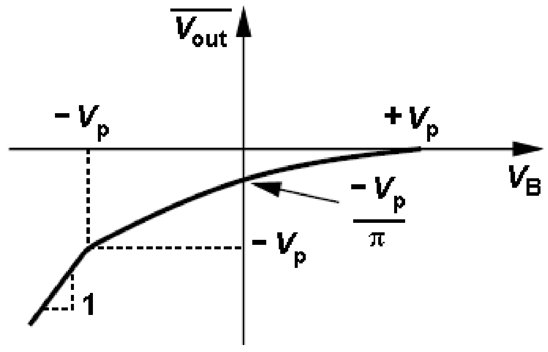
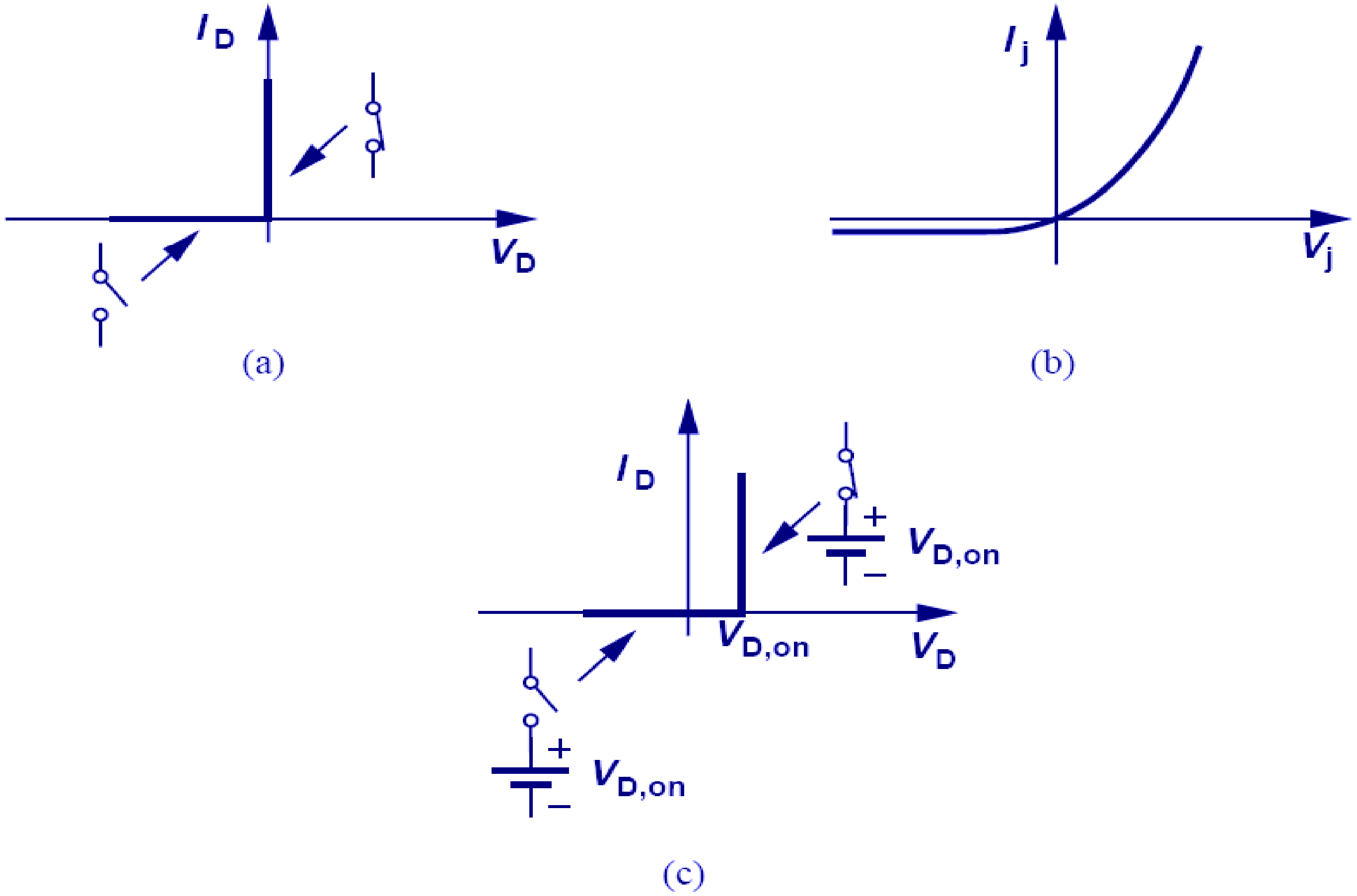


(b)

- Rectification fails if V_B is greater than the input amplitude.
- Passes only negative cycles to the output, producing a negative average.

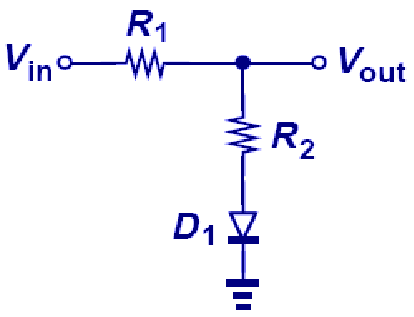
Different Models for Diode

- So far we have studied the ideal model of diode.
- However, there are still (b) the exponential and (c) constant voltage models.

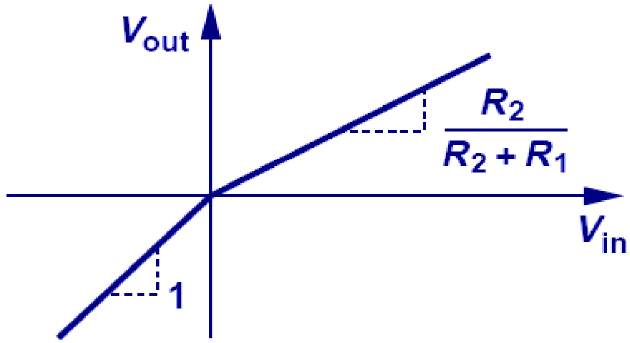


Example 3.12

Plot the input/output characteristic of the circuit in Figure (a) using (a) the ideal model and (b) the constant-voltage model.



(a)



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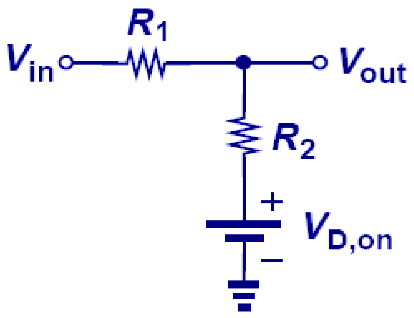

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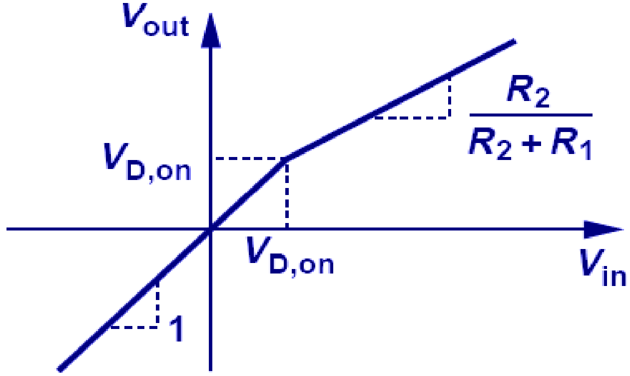


(d)

(a) We begin with V_{in} = -∞, recognizing that D_1 is reverse biased. In fact, for $V_{in} < 0$, the diode remains off and no current flows through the circuit. Thus, the voltage drop across R_1 is zero and $V_{out} = V_{in}$.

As V_{in} exceeds zero, D_1 turns on, operating as a short and reducing the circuit to a voltage divider. That is,

$$V_{out} = \frac{R_2}{R_1 + R_2} V_{in} \text{for} V_{in} > 0.$$

Figure (b) plots the overall characteristic, revealing a slope equal to unity for $V_{in} < 0$ and $R_2/(R_1+R_2)$ for $V_{in} > 0$. In other words, the circuit operates as a voltage divider once the diode turns on and loads the output node with R_2.

(b) In this case, D_1 is reverse biased for $V_{in} < V_{D,on}$, yielding $V_{out} = V_{in}$. As V_{in} exceeds $V_{D,on}$, D_1 turns on, operating as a constant voltage source with a value $V_{D,on}$. Reducing the circuit to that in Fig. (c), we apply Kirchoff's current law to the output node:

$$\frac{V_{in} - V_{out}}{R_1} = \frac{V_{out} - V_{D,on}}{R_2}.$$

It follows that

$$V_{out} = \frac{\frac{R_2}{R_1} V_{in} + V_{D,on}}{1 + \frac{R_2}{R_1}}.$$

As expected, $V_{out} = V_{D,on}$ if $V_{in} = V_{D,on}$. Figure (d) plots the resulting characteristic, displaying the same shape as that in Fig. (b) but with a shift in the break point.

Example 3.13

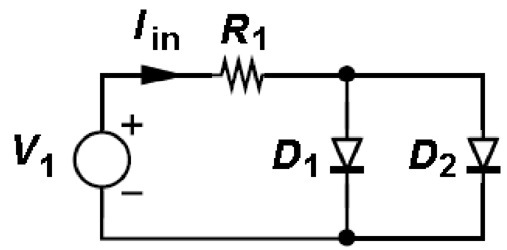
In the circuit, D_1 and D_2 have different cross section areas but are otherwise identical. Determine the current flowing through each diode.

Solution

In this case, we must resort to the exponential equation because the ideal and constant-voltage models do not include the device area. We have $I_{in} = I_{D1} + I_{D2}$.

We also equate the voltages across D_1 and D_2:

$$V_T \ln \frac{I_{D1}}{I_{S1}} = V_T \ln \frac{I_{D2}}{I_{S2}};$$



that is,

$$\frac{I_{D1}}{I_{S1}} = \frac{I_{D2}}{I_{S2}}.$$

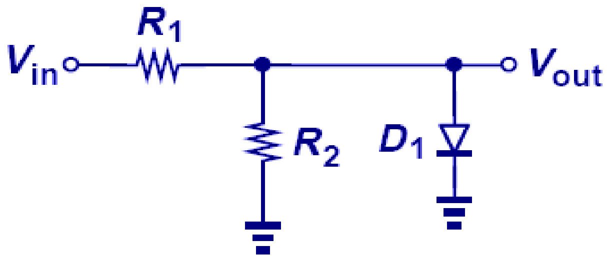
Solving the above equations together yields

$$I_{D1} = \frac{I_{in}}{1 + \dfrac{I_{S2}}{I_{S1}}} \qquad I_{D2} = \frac{I_{in}}{1 + \dfrac{I_{S1}}{I_{S2}}}.$$

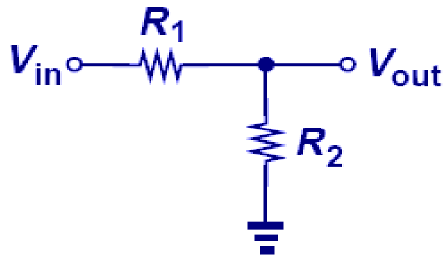
As expected, $I_{D1} = I_{D2} = I_{in}/2$ if $I_{S1} = I_{S2}$.

Example 3.14

Using the constant-voltage model, plot the input/output characteristics of the circuit in Fig. (a). Note that a diode about to turn on carries *zero* current but sustains $V_{D,on}$.



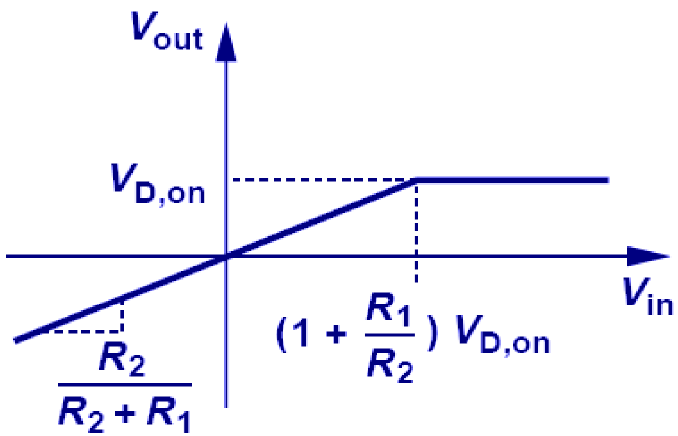
(a)



(b)

if $V_{in} = -\infty$

$$v_{out} = \frac{R_2}{R_1 + R_2} V_{in}.$$



(c)

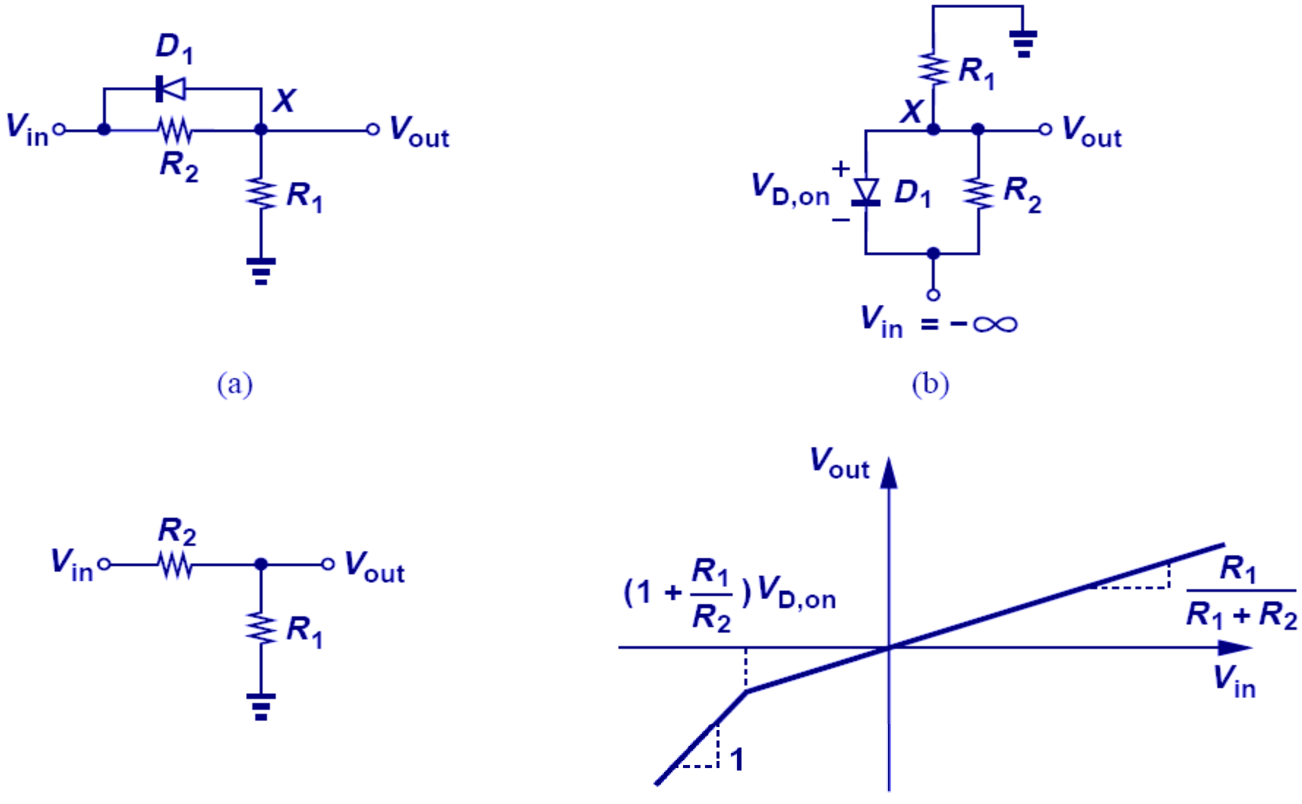
At the point D_1 turns on

$$\frac{R_2}{R_1 + R_2} V_{in} = V_{D,on},$$

and hence

$$V_{in} = \left(1 + \frac{R_1}{R_2}\right) V_{D,on}.$$

Example 3.15



(c) (d)

If $V_{in} = -\infty$, D_1 turns on

$$V_{out} = V_{in} + V_{D,on}.$$

$$I_{R2} = \frac{V_{D,on}}{R_2}$$

$$I_{R1} = \frac{0 - V_X}{R_1} = \frac{-(V_{in} + V_{D,on})}{R_1}.$$

D_1 turns off when $I_{R1} = I_{R2}$

$$\frac{V_{D,on}}{R_2} = -\frac{V_{in} + V_{D,on}}{R_1}$$

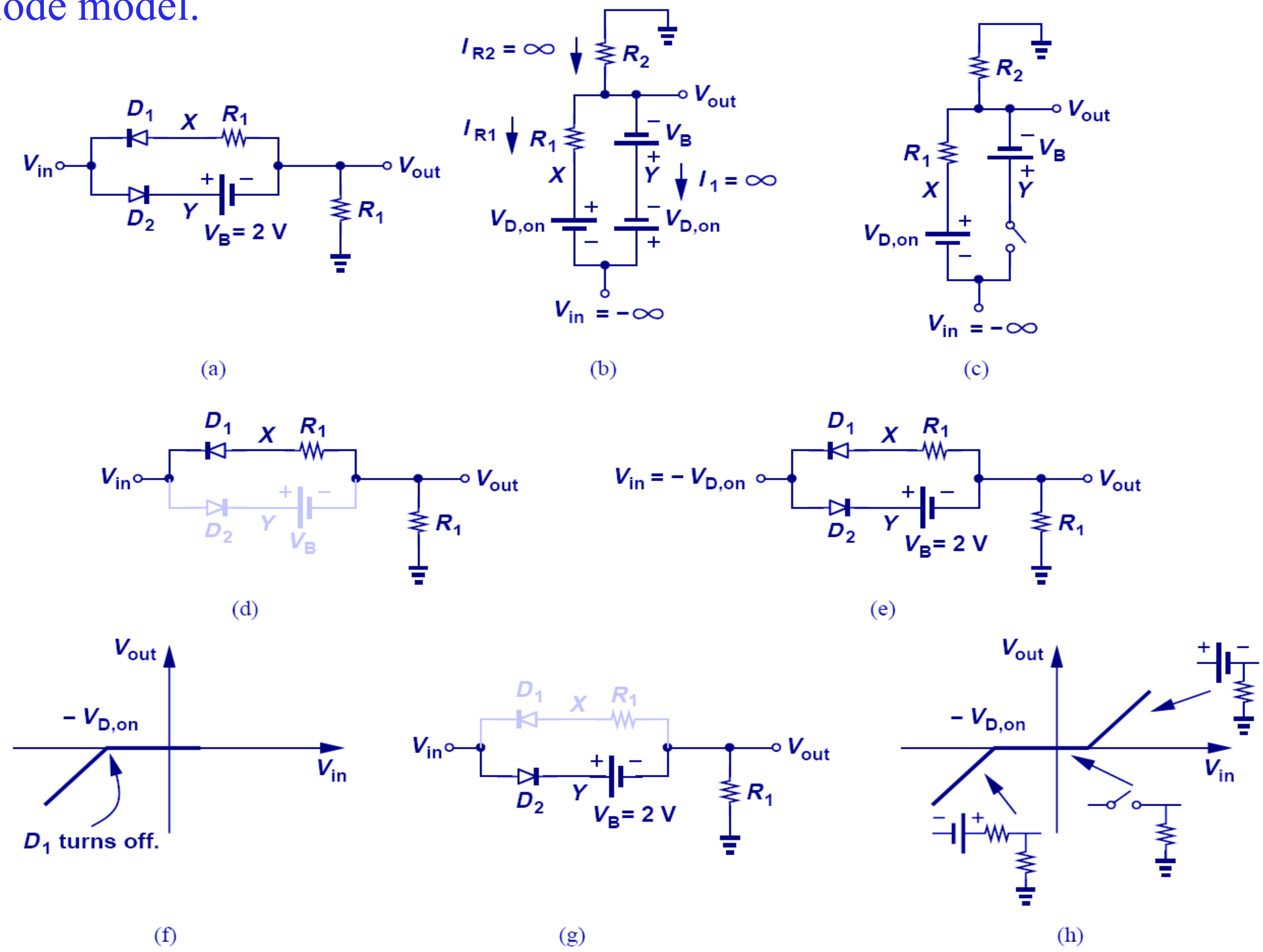
$$V_{in} = -(1 + \frac{R_1}{R_2})V_{D,on}.$$

$$V_{out} = \frac{R_1}{R_1 + R_2} V_{in}.$$

- In this example, since V_{in} is connected to the cathode, the diode conducts when V_{in} is very negative.
- The break point where the slope changes is when the current across R_1 is equal to the current across R_2.

Example 3.16

Plot the input/output characteristic of the circuit shown in Fig. (a) using the constant-voltage diode model.

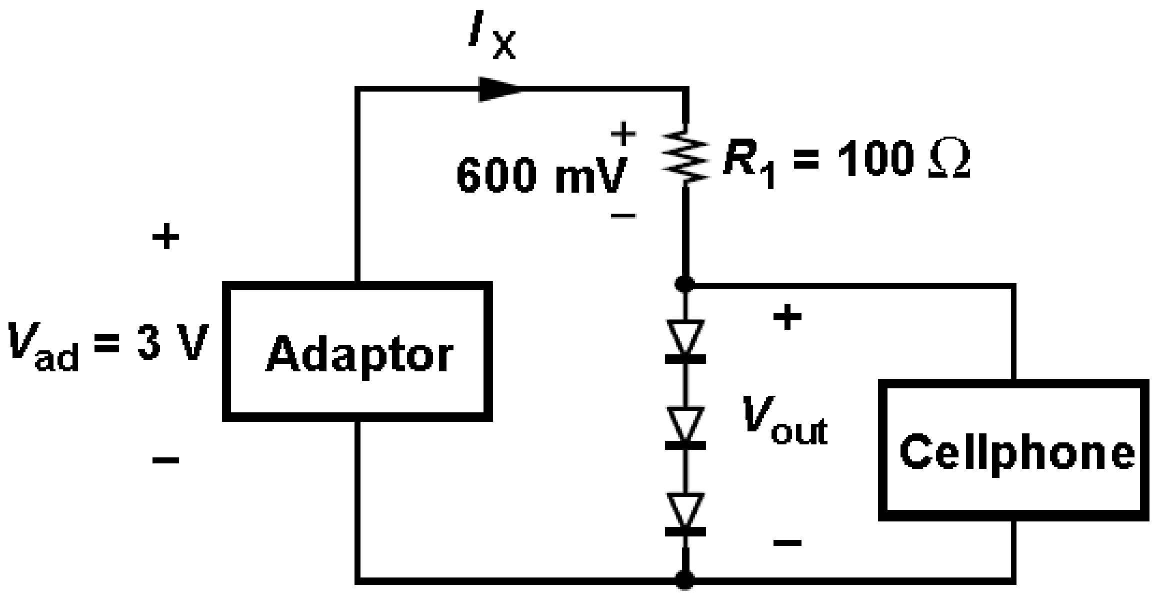


Cell Phone Adapter (Example 3.17)

- $V_{out} = 3\ V_{D,on}$ is used to charge cell phones.
- However, if I_x changes, iterative method is often needed to obtain a solution, thus motivating a simpler technique.

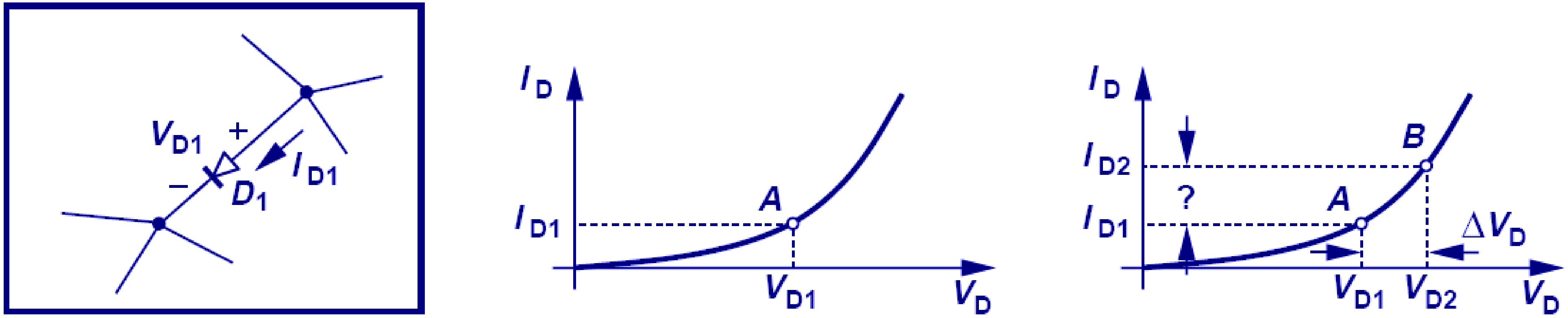
$$V_{out} = 3V_D \approx 2.4V$$

$$= 3V_T \ln \frac{I_X}{I_s}$$



Small-Signal Analysis 小訊號分析

- Small-signal analysis is performed around a ***bias point*** by perturbing the voltage by a small amount and observing the resulting linear current perturbation. 偏壓點



(a) (b) (c)

$$e^{\frac{\Delta V}{V_T}} \approx 1 + \frac{\Delta V}{V_T}$$

$$I_{D2} = I_S \exp\frac{V_{D1} + \Delta V}{V_T} = I_S \exp\frac{V_{D1}}{V_T} \exp\frac{\Delta V}{V_T}.$$

If $\triangle V << V_T$, then $\exp(\triangle V/V_T) \approx 1 + \triangle V/V_T$

$$\Rightarrow \quad \Delta I_D = \frac{\Delta V}{V_T} I_{D1}$$

$$I_{D2} = I_S \exp\frac{V_{D1}}{V_T} + \frac{\Delta V}{V_T} I_S \exp\frac{V_{D1}}{V_T} = I_{D1} + \frac{\Delta V}{V_T} I_{D1}.$$

Small-Signal Analysis in Detail

- If two points on the IV curve of a diode are close enough, the trajectory connecting the first to the second point is like a line, with the slope being the proportionality factor between change in voltage and change in current.
- Point *A* is called the "***bias***" point or the "***operating***" point. Also called the "***quiescent***" point.

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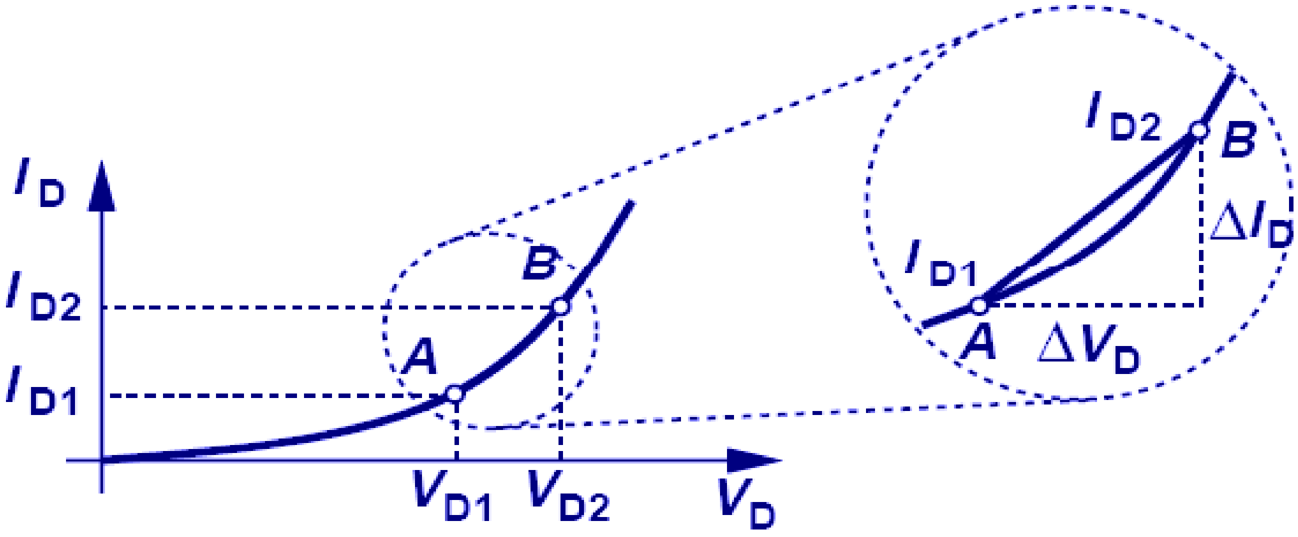


$$\frac{\Delta I_D}{\Delta V_D} = \frac{dI_D}{dV_D}\Big|_{VD=VD1}$$

$$= \frac{I_s}{V_T}\exp\frac{I_{D1}}{V_T}$$

$$= \frac{I_{D1}}{V_T}$$

Example 3.18

A diode is biased at a current of 1 mA. (a) Determine the current change if V_D changes by 1 mV. (b) Determine the voltage change if I_D changes by 10%.

Solution

(a) We have

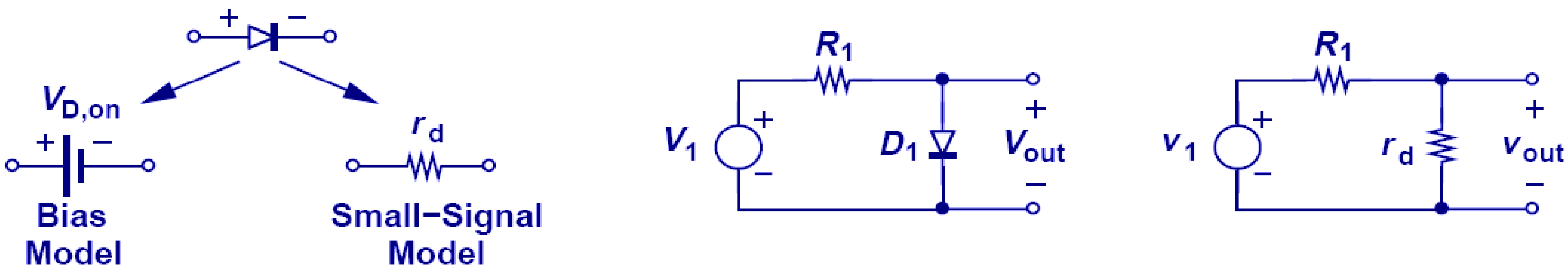
$$\Delta I_D = \frac{I_D}{V_T}\Delta V_D \quad = 38.4\mu\text{A}.$$

(b) Using the same equation yields

$$\Delta V_D = \frac{V_T}{I_D}\Delta I_D \quad = \left(\frac{26\text{mV}}{1\text{mA}}\right)\times(0.1\text{mA}) = 2.6\text{mV}.$$

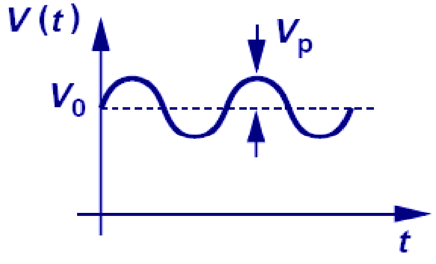
Small-Signal Incremental Resistance

- Since there's a linear relationship between the small signal current and voltage of a diode, the diode can be viewed as a linear resistor when only small changes are of interest.
- We define the "***small-signal resistance***" of the diode as: $r_d = \frac{V_T}{I_D}$
- Also called the "incremental" resistance to emphasize its validity for small changes.
- In the above example, I_D = 1 mA -> r_d = 26 Ω .

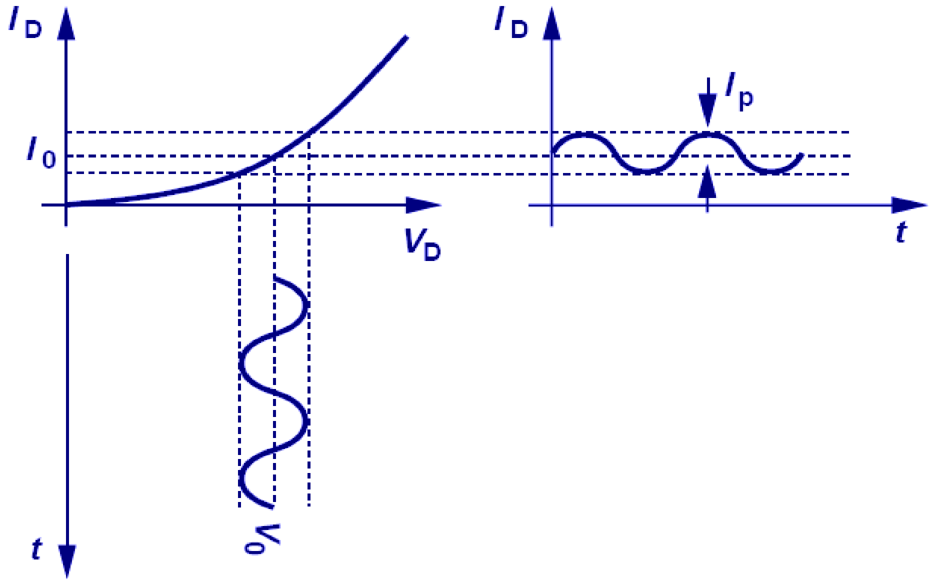


(a) (b) (c)

Small Sinusoidal Analysis (Example 3.19)



(a)



(b)

$$V(t) = V_0 + V_p \cos \omega t$$

$$I_D(t) = I_0 + I_p \cos \omega t = I_s \exp \frac{V_0}{V_T} + \frac{V_T}{I_0} V_p \cos \omega t$$

$$I_0 = I_S \exp \frac{V_0}{V_T},$$

$$I_p = V_p / r_d = \frac{I_0}{V_T} V_p, \quad r_d = \frac{V_T}{I_0}.$$

- If a sinusoidal voltage with small amplitude is applied, the resulting current is also a small sinusoid around a DC value.

Cause and Effect (Example 3.20)

In previous derivation, we assumed a small change in V_D and obtained the resulting change in I_D. Beginning with $V_D = V_T \ln(I_D/I_S)$, investigate the reverse case, i.e., I_D changes by a small amount and we wish to compute the change in V_D.

Solution

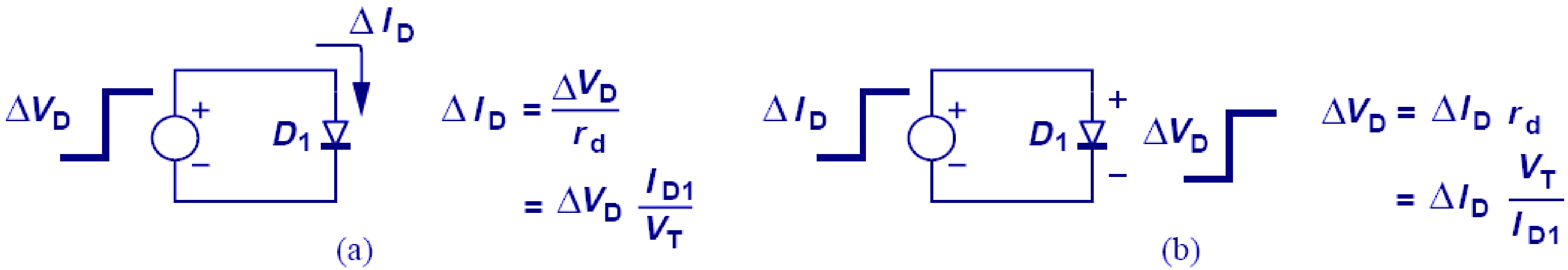
Denoting the change in V_D by ΔV_D, we have

$$V_{D1} + \Delta V_D = V_T \ln \frac{I_{D1} + \Delta I_D}{I_S} = V_T \ln\left[\frac{I_{D1}}{I_S}\left(1 + \frac{\Delta I_D}{I_{D1}}\right)\right] = V_T \ln \frac{I_{D1}}{I_S} + V_T \ln\left(1 + \frac{\Delta I_D}{I_{D1}}\right).$$

For small-signal operation, we assume $\Delta I_D << I_{D1}$ and note that $\ln(1+\epsilon) \approx \epsilon$ if $\epsilon \ll 1$. Thus,

$$\Delta V_D = V_T \cdot \frac{\Delta I_D}{I_{D1}},$$

Figure below illustrates the two cases, distinguishing between the cause and the effect.



(a) voltage is the cause and current is the effect; (b) the other way around.

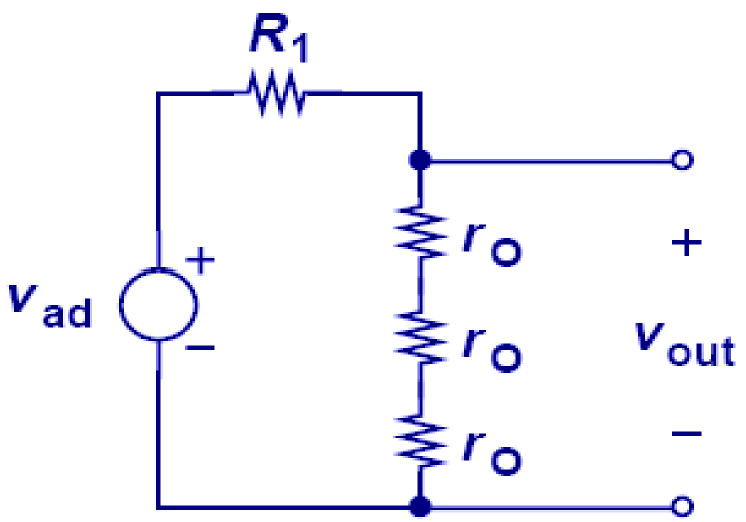
Example 3.17 Revisited (Example 3.21)

- With our understanding of small-signal analysis, we can revisit our cell phone charger example and easily solve it with just algebra instead of iterations.

Since each diode carries $I_{D1} = 6$ mA with an adaptor voltage of 3 V and $V_{D1} = 800$ mV, we can construct the small-signal model shown below, where $v_{ad} = 100$ mV and $r_d = 26\text{mV}/6\text{mA} = 4.33\Omega$. We can thus write:

$$v_{out} = \frac{3r_d}{R_1 + 3r_d} v_{ad}$$

$$= 11.5mV$$



That is, a 100-mV change in V_{ad} yields an 11.5-mV change in V_{out}. In Example 3.17, solution of nonlinear diode equations predicted an 11-mV change in V_{out}. The small-signal analysis therefore offers reasonable accuracy while requiring much less computational effort.

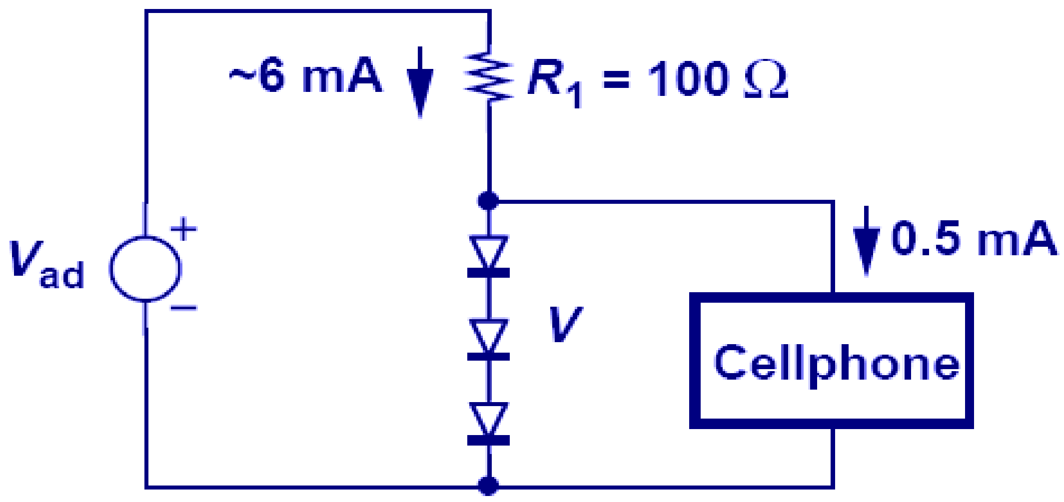
Simple is Beautiful (Example 3.22)

In Examples 3.17 and 3.21, the current drawn by the cellphone is neglected. Now suppose, the load pulls a current of 0.5 mA and determine the change in V_{out}.

Solution

Since the current flowing through the diodes decreases by 0.5 mA and since this change is much less than the bias current (6 mA), we write the change in the output voltage as:

$$\begin{aligned}\Delta V_{out} &= \Delta I_D \cdot (3r_d) \\ &= (-0.5mA)(3 \times 4.33\Omega) \\ &= -6.5mV\end{aligned}$$



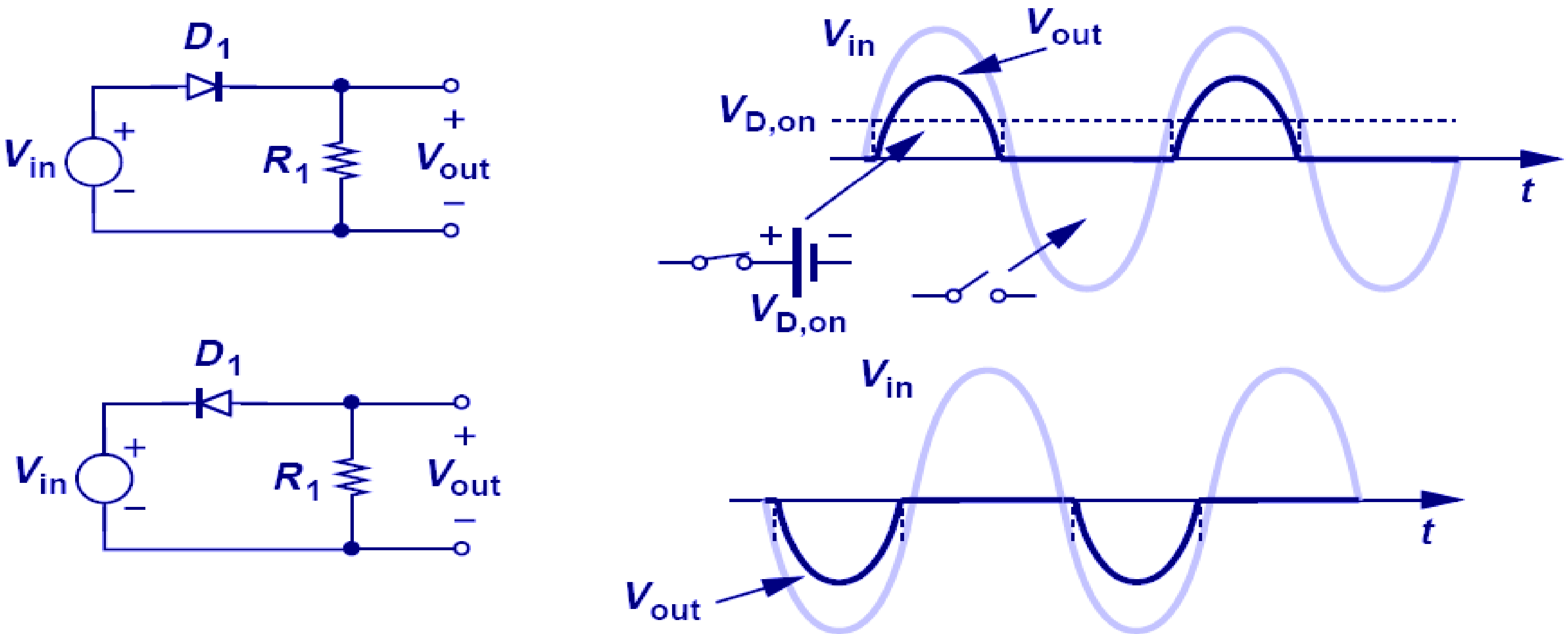
Half-Wave Rectifier 半波整流器

- A very common application of diodes is half-wave rectification, where either the positive or negative half of the input is blocked.
- But, how do we generate a *constant* output?

no longer assume diode is ideal, but use a constant-voltage model.

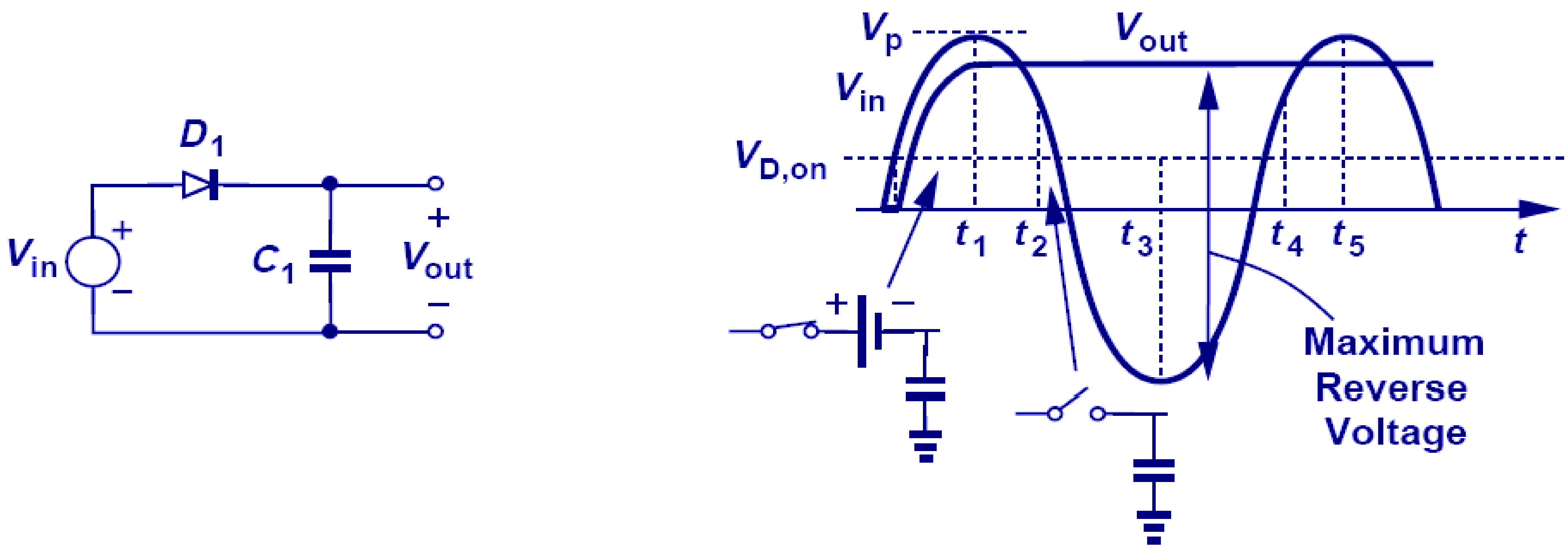
for $V_{in} > V_{D,on}$, D_1 turns on and $V_{out} = V_{in} - V_{D,on}$

for $V_{in} < V_{D,on}$, D_1 turns off and $V_{out} = 0$



Diode-Capacitor Circuit: Constant Voltage Model

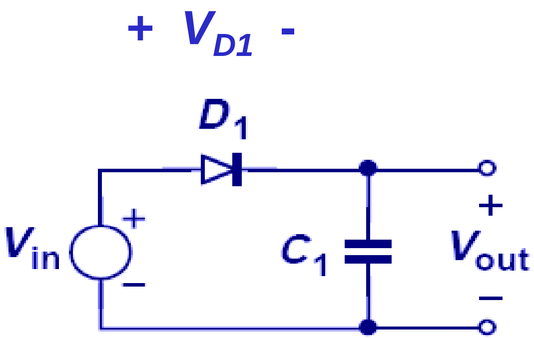
- If the resistor in half-wave rectifier is replaced by a capacitor, a fixed voltage output of (V_p - $V_{D,on}$) is obtained since the capacitor (assumed ideal) has no path to discharge.
- At t_3, V_{in} = -V_p, applying a maximum reverse bias of (2V_p - $V_{D,on}$) across the diode. Hence, diodes used in rectifiers must withstand a reverse voltage of approximately 2V_p with no breakdown.

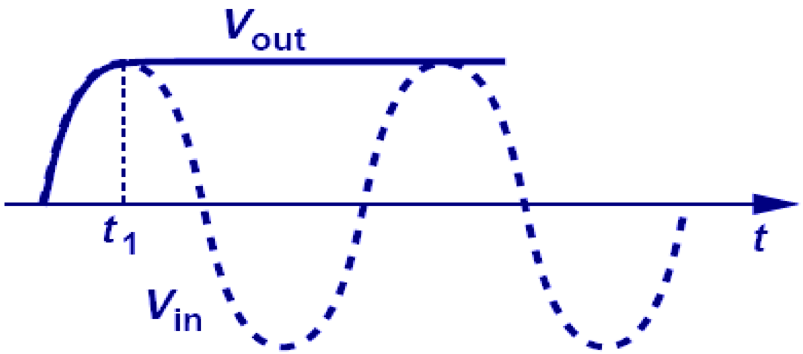


(a) (b)

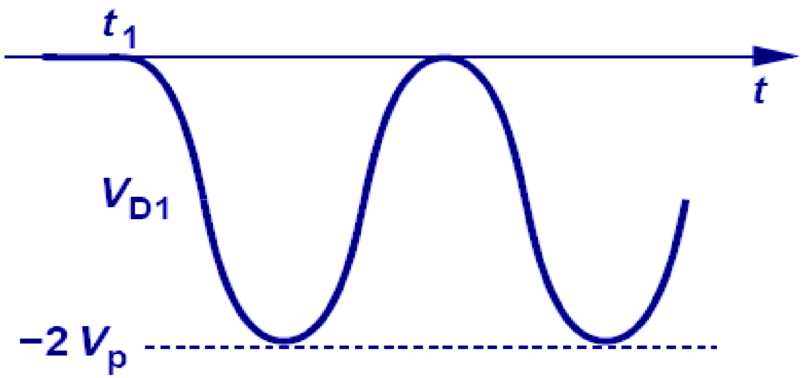
Diode-Capacitor Circuit: Ideal Model (Example 3.24)

- Note that in Fig. (b) the voltage across the diode, V_{D1}, is just like $V_{in,}$ only shifted down.





(a)



(b)

Example 3.25

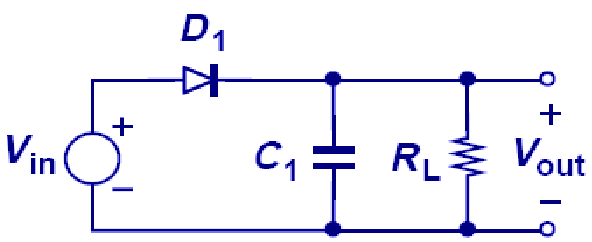
A laptop computer consumes an average power of 25 W with a supply voltage of 3.3 V. Determine the average current drawn from the batteries or the adapter.

Solution

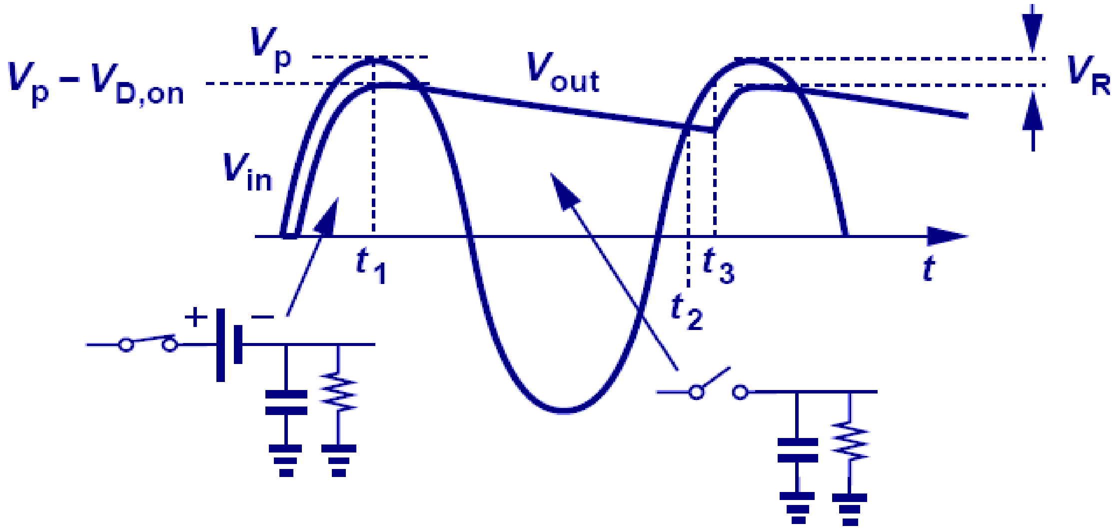
Since $P = V \times I$, we have $I = 25\text{W}/3.3\text{V} \approx 7.58$ A. If the laptop is modeled by a resistor, R_L, then $R_L = V/I = 0.436\Omega$.

Diode-Capacitor With Load Resistor

- As suggested by the Example 3.25, the ***load*** can be represented by a simple resistor in some cases. 負載
- A path is available for capacitor to discharge. Therefore, V_{out} will not be constant and a ***ripple*** exists. 漣波
- V_{out} behaves as before until t_1; as V_{in} begins to fall after t_1, so does V_{out} because R_L provides a discharge path for C_1.
- C_1 must be large that the current drawn by R_L does not reduce V_{out} significantly.



(a)



(b)

Behavior for Different Capacitor Values

- The resulting variation in V_{out} is called the "***ripple***." Also, C_1 is called the "***smoothing***" or "***filter***" capacitor. For large C_1, V_{out} has small ripple.

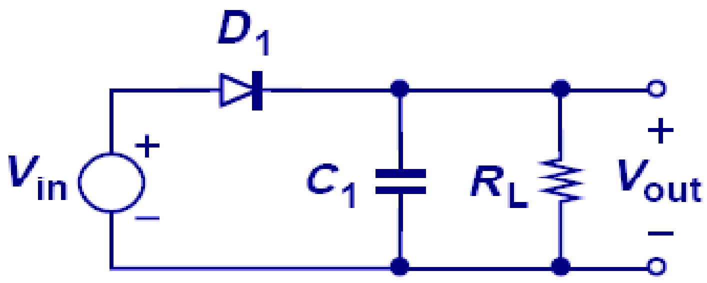
濾波

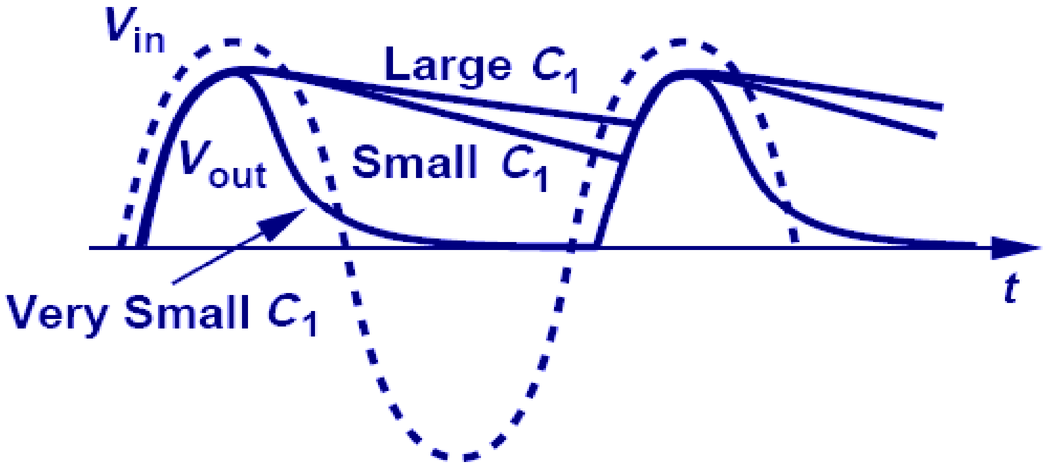
Example 3.26

Sketch the output waveform as C_1 varies from very large values to very small values.

Solution

If C_1 is very large, the current drawn by R_L when D_1 is off creates only a small change in V_{out}. Conversely, if C_1 is very small, the circuit approaches the previous figure, exhibiting large variations in V_{out}. Figure below illustrates several cases.





Peak to Peak Amplitude of Ripple

- The ***peak-to-peak*** (***p2p***) ripple amplitude, V_R, is the decaying part of the exponential. 峰到峰值
- P2p ripple voltage becomes a problem if it goes above 5 to 10% of the output voltage.
- If the maximum current drawn by the load is known, the value of C_1 is chosen large enough to yield an acceptable ripple.
- Since $V_{out} = V_p - V_{D,on}$ at t_1, the discharge of C_1 through R_L is expressed as:

$$V_{out}(t) = (V_p - V_{D,on})\exp\frac{-t}{R_L C_1} \quad 0 \le t \le t_3,$$

- To ensure a small ripple, $R_L C_1$ must be much greater than t_3-t_1; thus, noting that exp(-ϵ) ≈ 1 - ϵ for ϵ « 1,

$$V_{out}(t) \approx (V_p - V_{D,on})\left(1 - \frac{t}{R_L C_1}\right) \approx (V_p - V_{D,on}) - \frac{V_p - V_{D,on}}{R_L} \cdot \frac{t}{C_1}.$$

- The first term on the right hand side represents the initial condition across C_1 and the second term, a falling ramp—as if a constant current equal to (V_p - $V_{D,on}$)/R_L discharges C_1.

- The p2p amplitude of the ripple is equal to the amount of discharge at t_3.
- Since t_4 - t_1 is equal to the input period, T_{in}, we write $t_4 - t_1 = T_{in} - \Delta T$, where ΔT (= $t_4 - t_3$) denotes the time during which D_1 is on. Thus,

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

- 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

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

where $f_{in} = T_{in}^{-1}$

- If the load current, I_L, is known, we can write

$$V_R = \frac{I_L}{C_1 f_{in}}.$$

Example 3.27

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 the laptop computer of Example 3.25. Determine the minimum value of the filter capacitor that maintains the ripple below 0.1 V. Assume $V_{D,on}$ = 0.8 V.

Solution

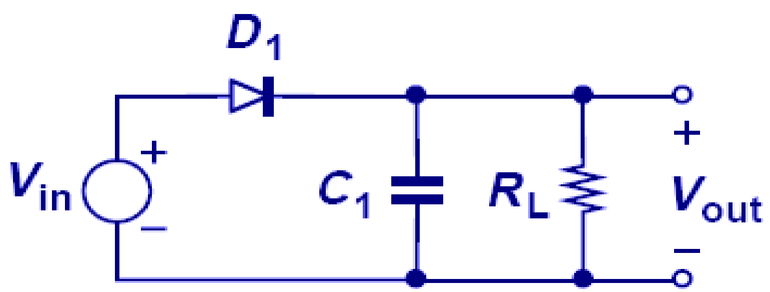
We have V_p = 4.5 V, R_L = 0.436Ω, and T_{in} = 16.7 ms. Thus,

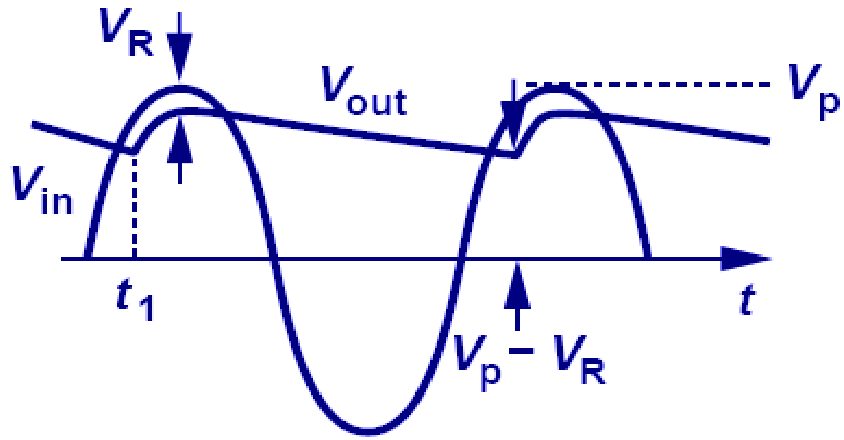
$$C_1 = \frac{V_p - V_{D,on}}{V_R} \cdot \frac{T_{in}}{R_L} = 1.417\text{F}.$$

This is a very large value. The designer must trade the ripple amplitude with the size, weight, and cost of the capacitor. In fact, limitations on size, weight, and cost of the adaptor may dictate a much greater ripple, e.g., 0.5 V, thereby demanding that the circuit following the rectifier tolerate such a large, periodic variation.

Maximum Diode Current

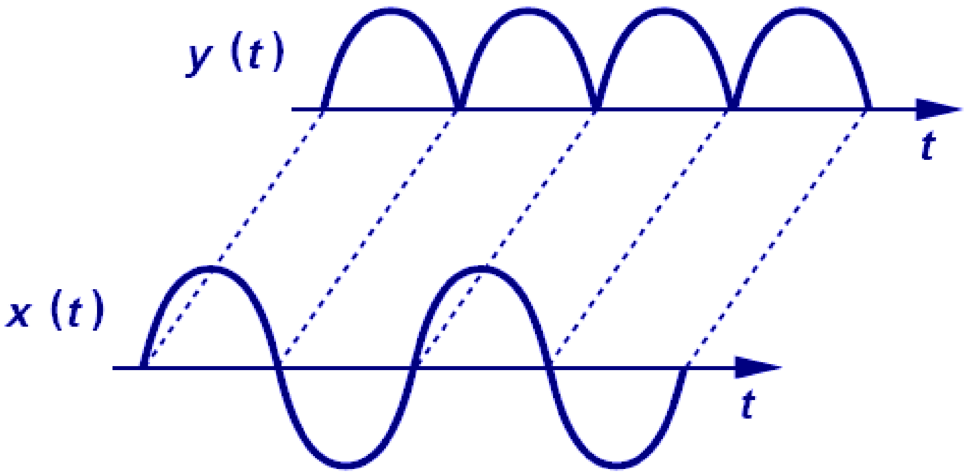
- The diode has its maximum current at t_1, since that's when the slope of V_{out} is the greatest.
- This current has to be carefully controlled so it does not damage the device.
- The current in forward bias consists of two components:
  - (1) the transient current drawn by C_1, $C_1 dV_{out}/dt$, and
  - (2) the current supplied to R_L, approximately equal to $(V_p - V_{D,on})/R_L$.
- The peak diode current occurs at the point D_1 turns on because the slope of the output waveform is maximum.
- Check textbook for the derivation $I_p \approx C_1\omega_{in}V_p\sqrt{\frac{2V_R}{V_p}} + \frac{V_p}{R_L} \approx \frac{V_p}{R_L}(R_L C_1 \omega_{in}\sqrt{\frac{2V_R}{V_p}} + 1)$



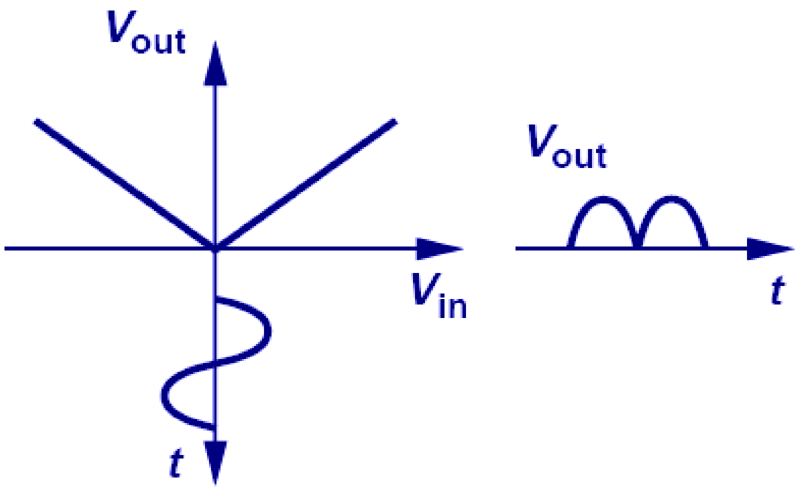


Full-Wave Rectifier 全波整流器

- 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.



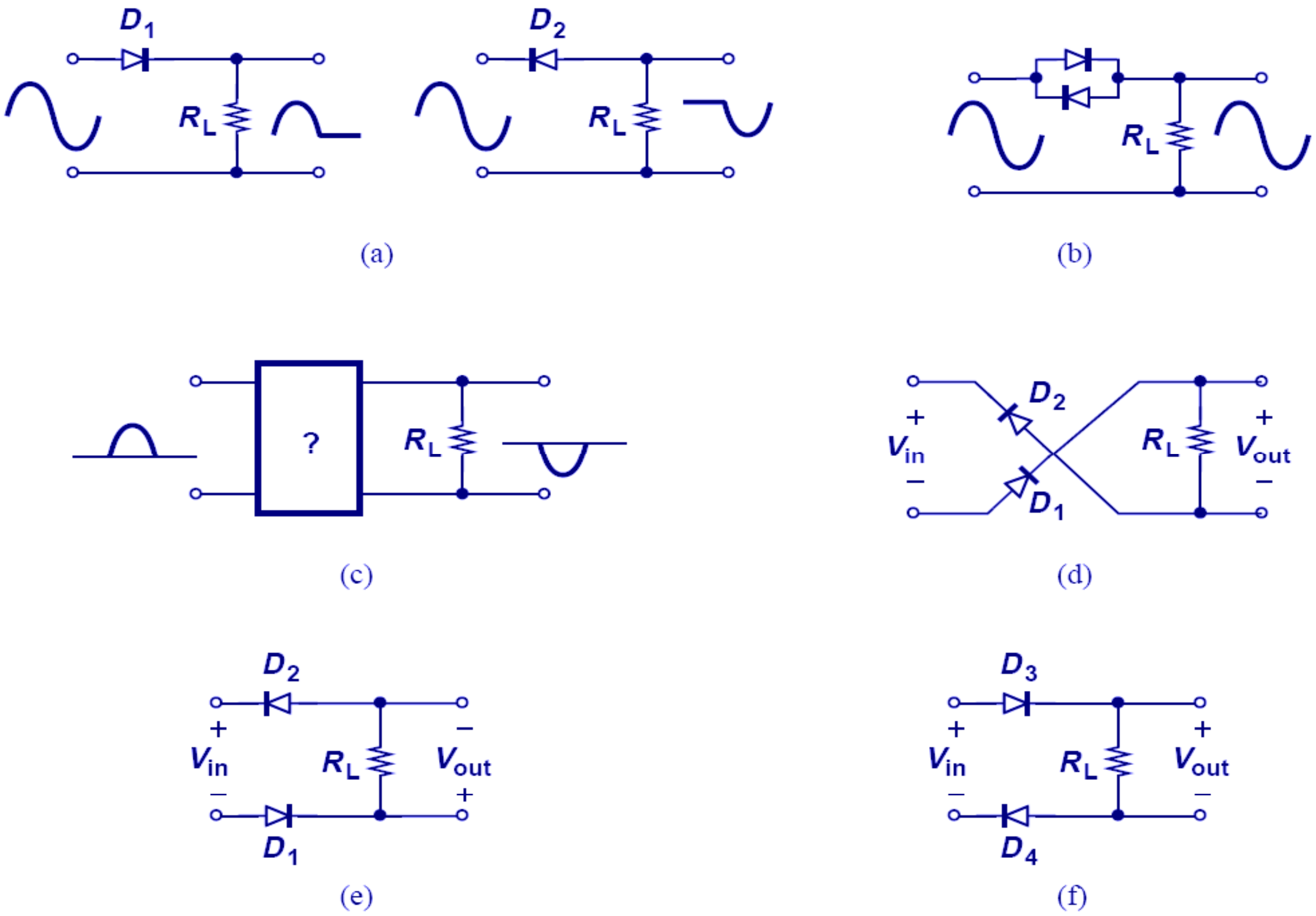
(a)



(b)

The Evolution of Full-Wave Rectifier

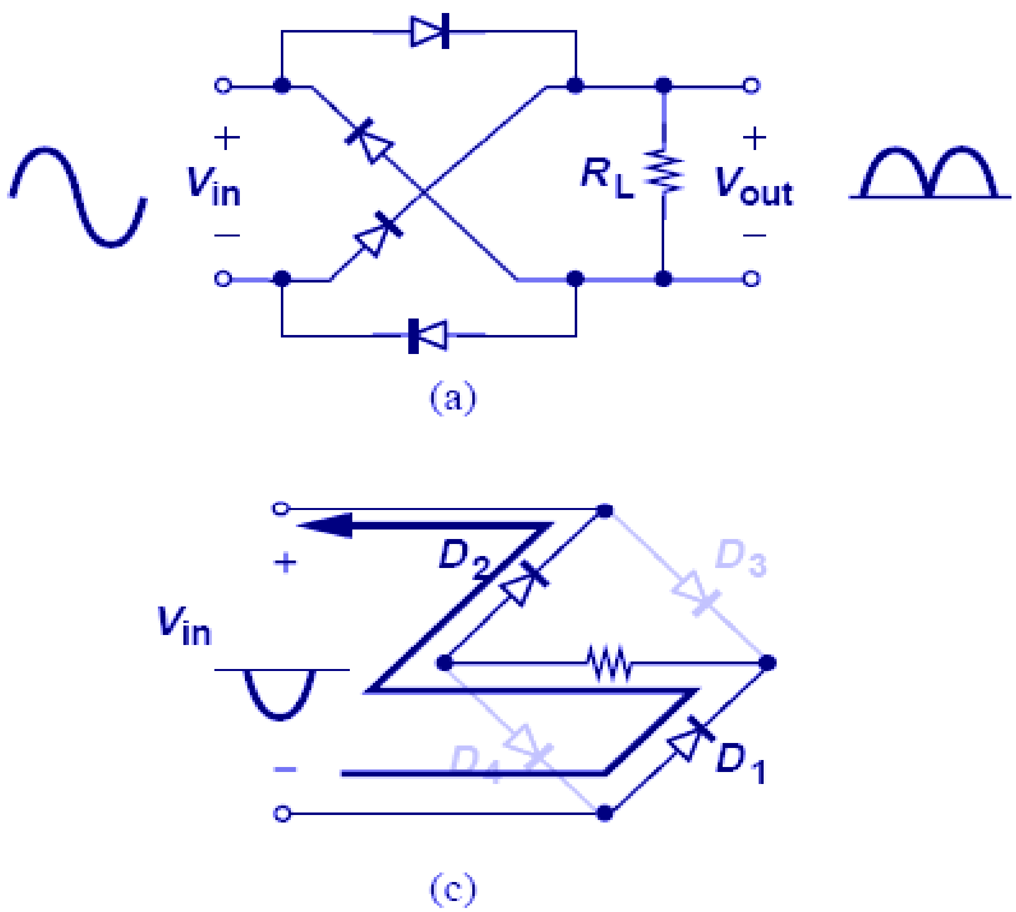
- (a) two half-wave rectifiers for positive and negative cycles; (b) error trial, no rectification; (c) and (d) inverted rectification
- (e) and (f) rectification for the positive and negative half cycles of the input.



(a) (b) (c) (d) (e) (f)

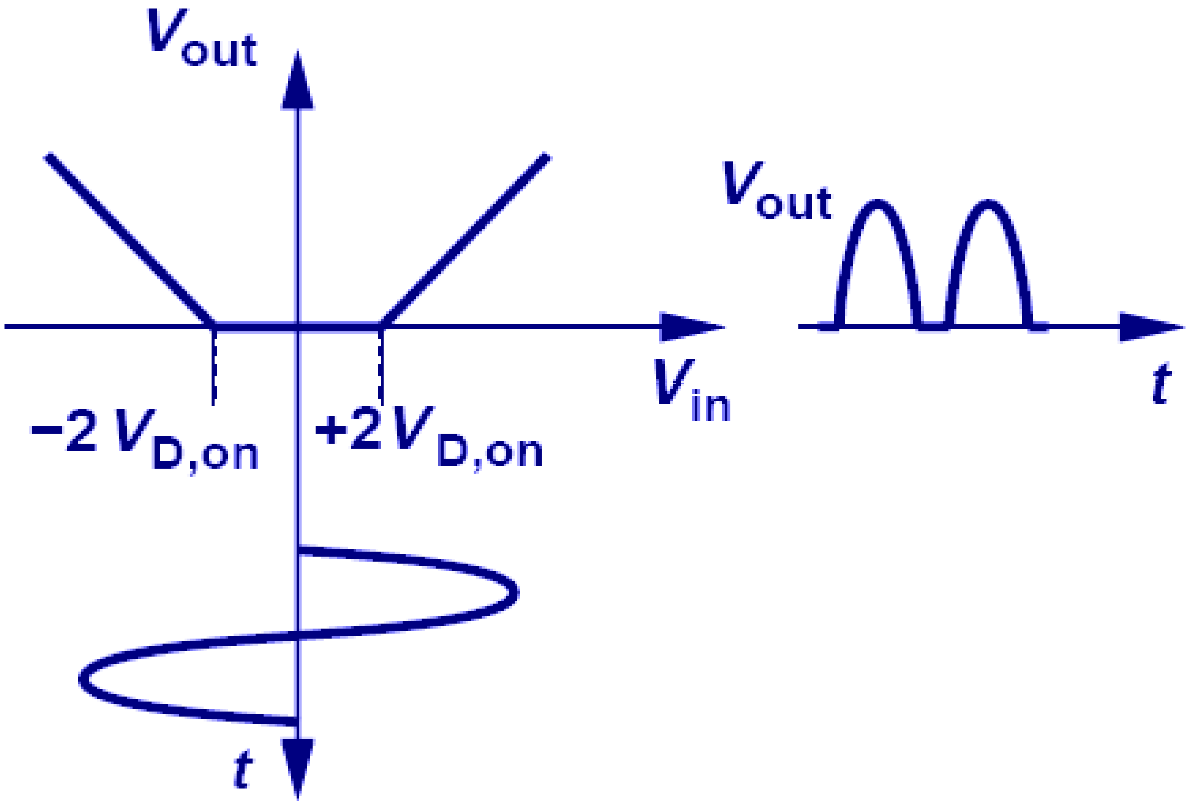
Full-Wave Rectifier: Bridge Rectifier 橋式整流器

- Combine (e) and (f) of previous slides to a full-wave rectifier, where D_1 and D_2 pass/invert the negative half cycle and D_3 and D_4 pass the positive half cycle.



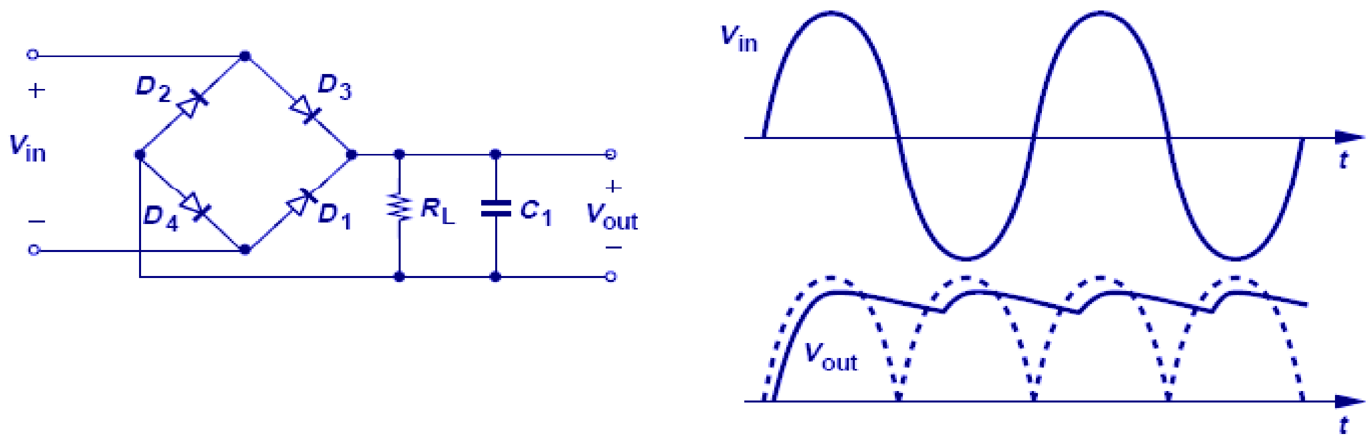
Input/Output Characteristics of a Full-Wave Rectifier (Constant-Voltage Model)

- The dead-zone around V_{in} arises because V_{in} must exceed 2 $V_{D,ON}$ to turn on the bridge.
- A drop of $2V_{D,on}$ on V_{out}.

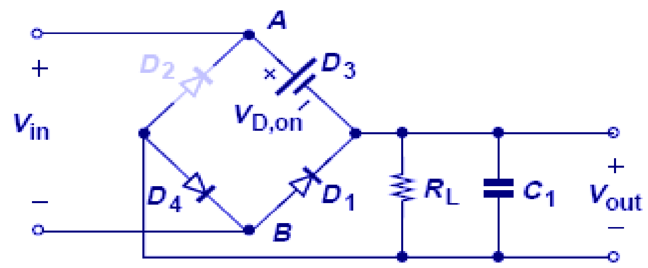


Complete Full-Wave Rectifier

- Since C_1 only gets half of the period to discharge, ripple voltage is decreased by a factor of 2.
- Also (b) shows that each diode is subjected to approximately one V_p reverse bias drop (versus $2V_p$ in half-wave rectifier).



(a)



(b)

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

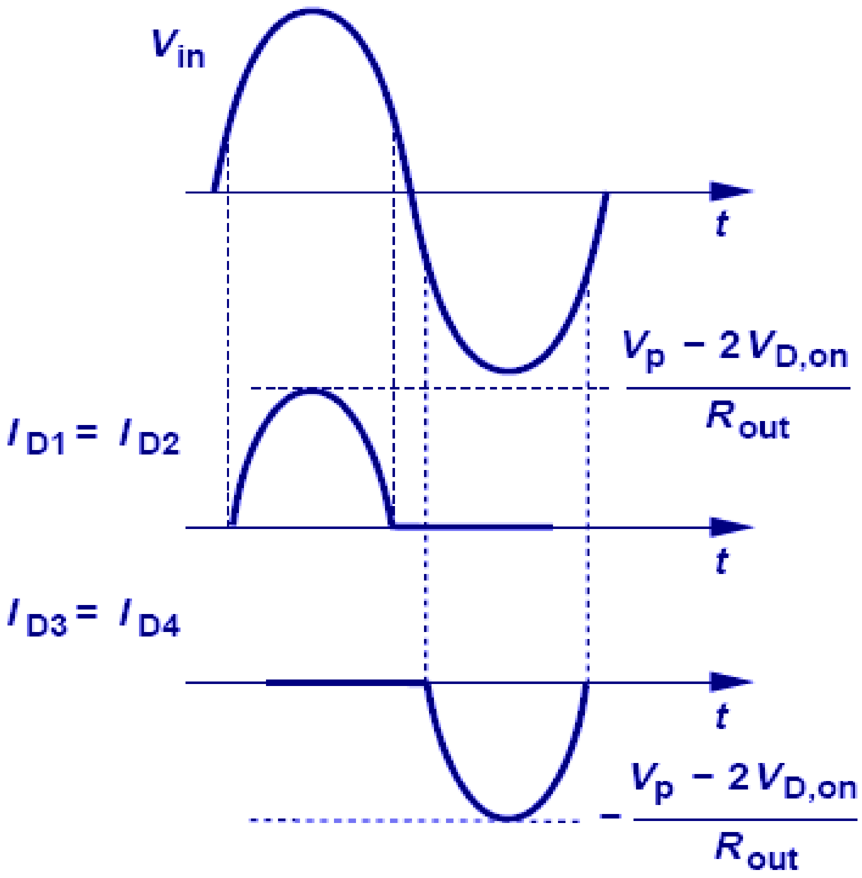
Diode Current in the Full-Wave Rectifier

Example 3.30

Plot the currents carried by each diode in a bridge rectifier as a function of time for a sinusoidal input. Assume no smoothing capacitor is connected to the output.

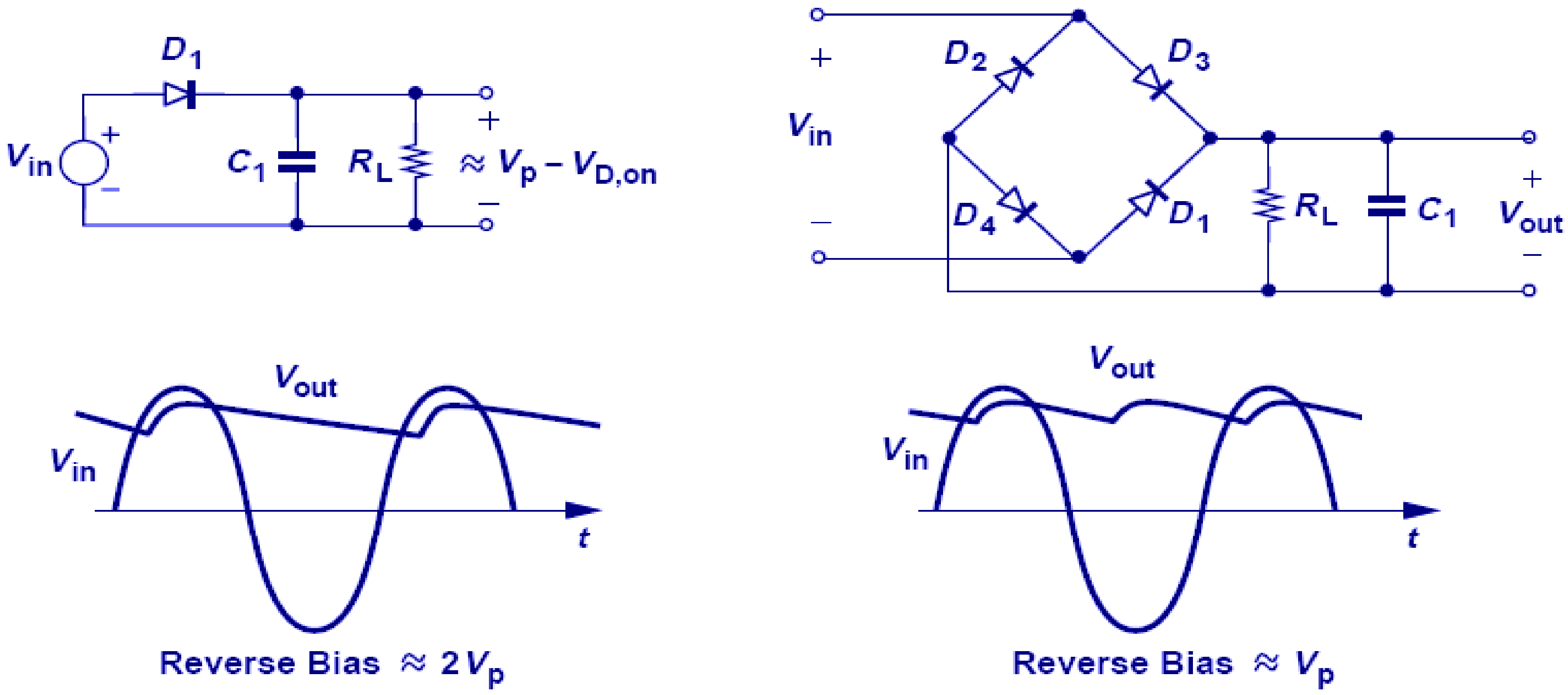
Solution

From Figs. 3.38(c) and (d), we have $V_{out} = -V_{in} + 2V_{D,on}$ for $V_{in} < -2V_{D,on}$ and $V_{out} = V_{in} - 2V_{D,on}$ for $V_{in} > +2V_{D,on}$. In each half cycle, two of the diodes carry a current equal to V_{out}/R_L and the other two remain off. Thus, the diode currents appear as shown in the Figure.



Summary of Half and Full-Wave Rectifiers

➢ While using two more diodes, full-wave rectifiers exhibit a lower ripple and require only half the diode breakdown voltage, more suited to adapter and charger applications.



(a) (b)

Example 3.31

Design a full-wave rectifier to deliver an average power of 2 W to a cellphone with a voltage of 3.6 V and a ripple of 0.2 V.

Solution

We begin with the required input swing. Since the output voltage is approximately equal to V_p - $2V_{D,on}$, we have

$$V_{in,p} = 3.6\text{V} + 2V_{D,on} \approx 5.2\text{V}.$$

Thus, the transformer preceding the rectifier must step the line voltage (110 or 220 V_{rms}) down to a peak value of 5.2 V.

Next, we determine the minimum value of the smoothing capacitor that ensures VR ≤ 0.2 V. For a full-wave rectifier,

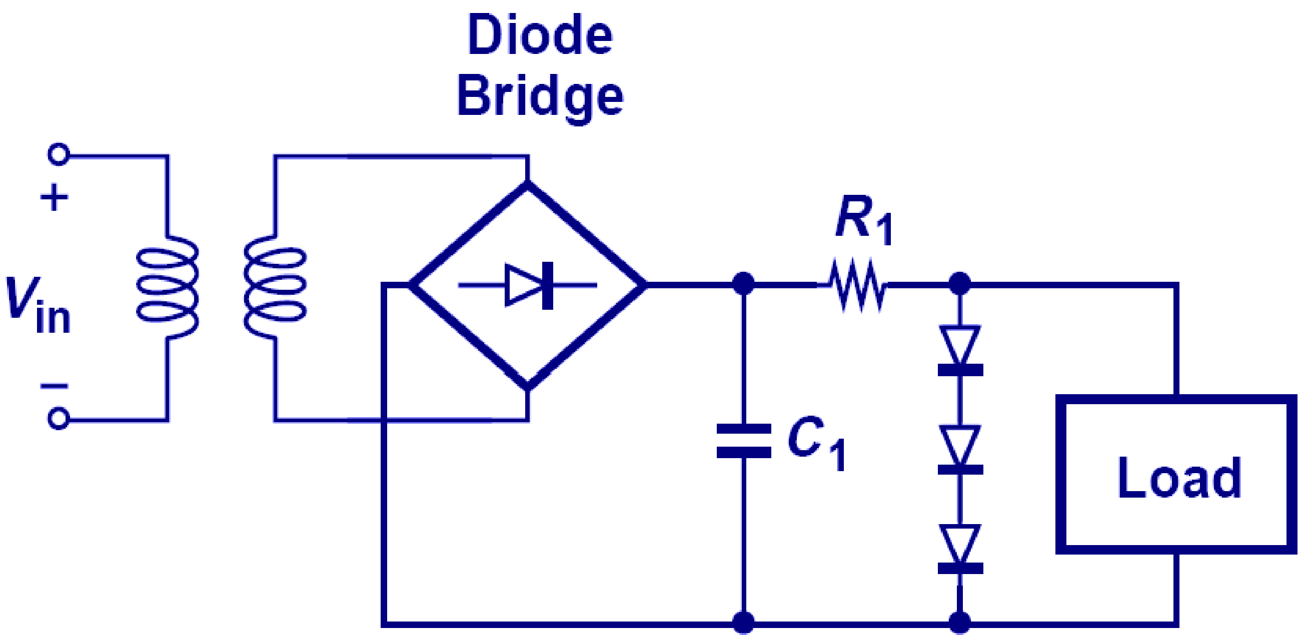
$$V_R = \frac{I_L}{2C_1 f_{in}} = \frac{2\text{W}}{3.6\text{V}} \cdot \frac{1}{2C_1 f_{in}}.$$

For VR = 0.2 V and f_{in} = 60 Hz, C_1 = 23000 μF.

The diodes must withstand a reverse bias voltage of 5.2 V.

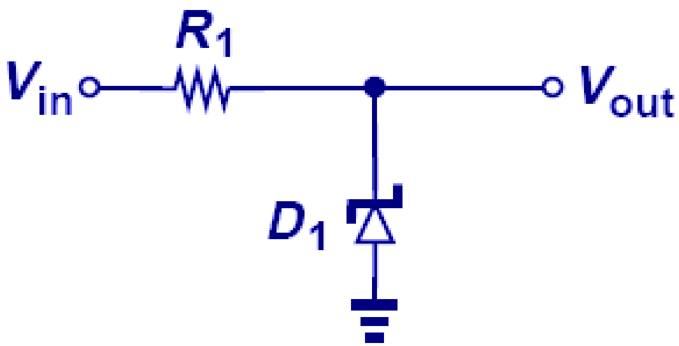
Voltage Regulator 穩壓器

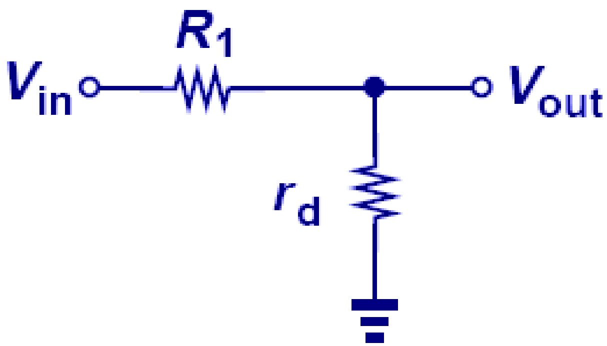
- The ripple created by the rectifier can be unacceptable to sensitive load; therefore, a regulator is required to obtain a very stable output.
- Three diodes operate as a primitive regulator.
- The regulator needs to regulate the variation of the line voltage, "***line regulation***" defined as $\Delta V_{out}/\Delta V_{in}$; and regulate the variation of the load current, "***load regulation*** " defined as $\Delta V_{out}/\Delta I_L$.



Voltage Regulation With Zener Diode

- Voltage regulation can be accomplished with Zener diode operating in reverse breakdown.
- Since D_1 exhibits a small-signal resistance, r_d (1-10Ω), large change in the input will not be reflected at the output.
- The Zener regulator has poor stability if the load current varies significantly.





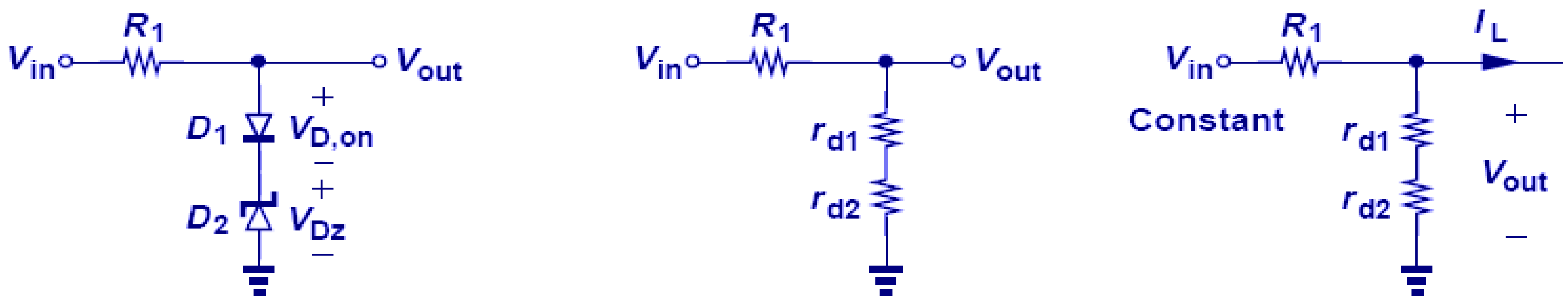
(a)

$$V_{out} = \frac{r_D}{r_D + R_1} V_{in}$$

(b)

Example 3.33

In the circuit of Fig. (a), V_{in} has a nominal value of 5 V, R_1 = 100 Ω, and D_2 has a reverse breakdown of 2.7 V and a small-signal resistance of 5 Ω. Assuming $V_{D,on} \approx 0.8$V for D_1, determine the line and load regulation of the circuit.



(a) (b) (c)

Solution

We first determine the bias current of D_1 and hence its small-signal resistance:

$$I_{D1} = \frac{V_{in} - V_{D,on} - V_{D2}}{R_1} = 15\text{mA}.$$

Thus,

$$r_{D1} = \frac{V_T}{I_{D1}} = 1.73\Omega.$$

Example 3.33 (cnt'd)

From the small-signal model of Fig. (b), we compute the line regulation as

$$\frac{v_{out}}{v_{in}} = \frac{r_{D1} + r_{D2}}{r_{D1} + r_{D2} + R_1} = 0.063.$$

For load regulation, we assume the input is constant and study the effect of load current variations. Using the small-signal circuit shown in Fig. (c) (where $v_{in} = 0$ to represent a constant input), we have

$$\frac{v_{out}}{(r_{D1} + r_{D2}) \| R_1} = -i_L.$$

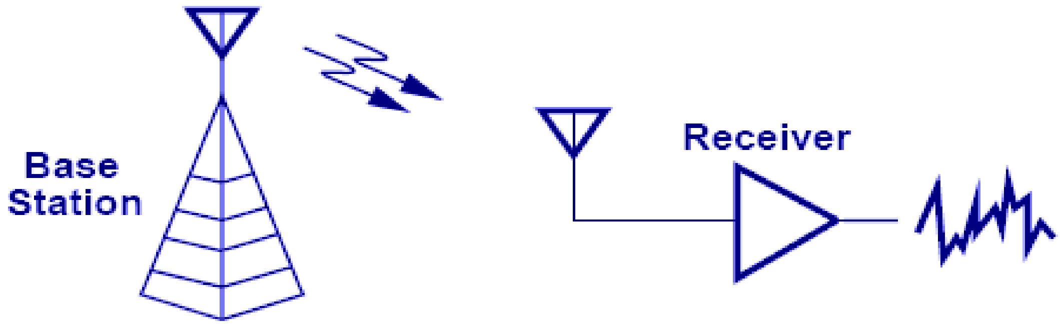
That is,

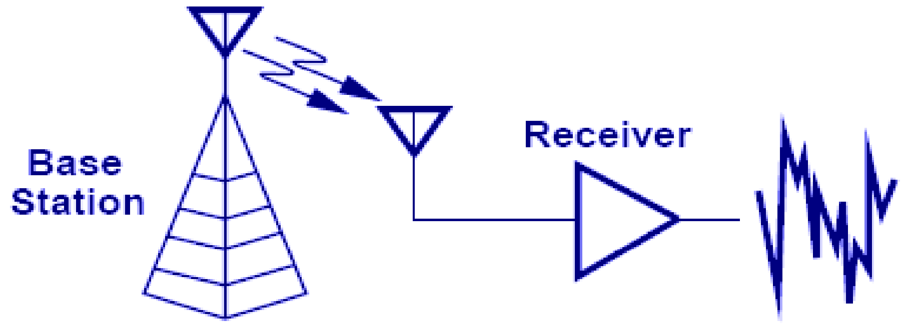
$$\left|\frac{v_{out}}{i_L}\right| = (r_{D1} + r_{D2}) \| R_1 = 6.31\Omega.$$

This value indicates that a 1-mA change in the load current results in a 6.31-mV change in the output voltage.

Limiting Circuits

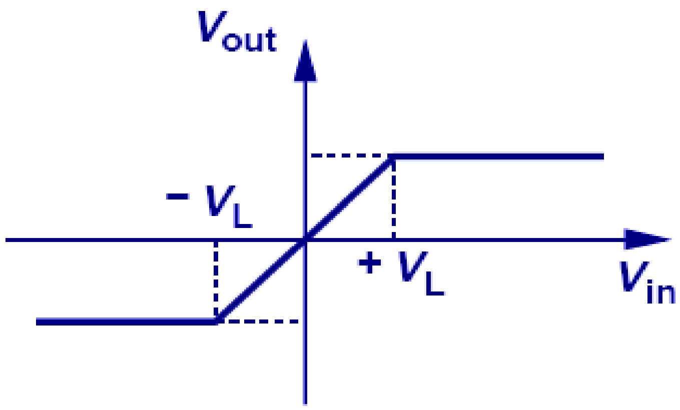
- The motivation of having limiting circuits is to keep the signal below a threshold so it will not ***saturate*** the entire circuitry. 飽和
- When a receiver is close to a base station, signals are large and limiting circuits may be required.



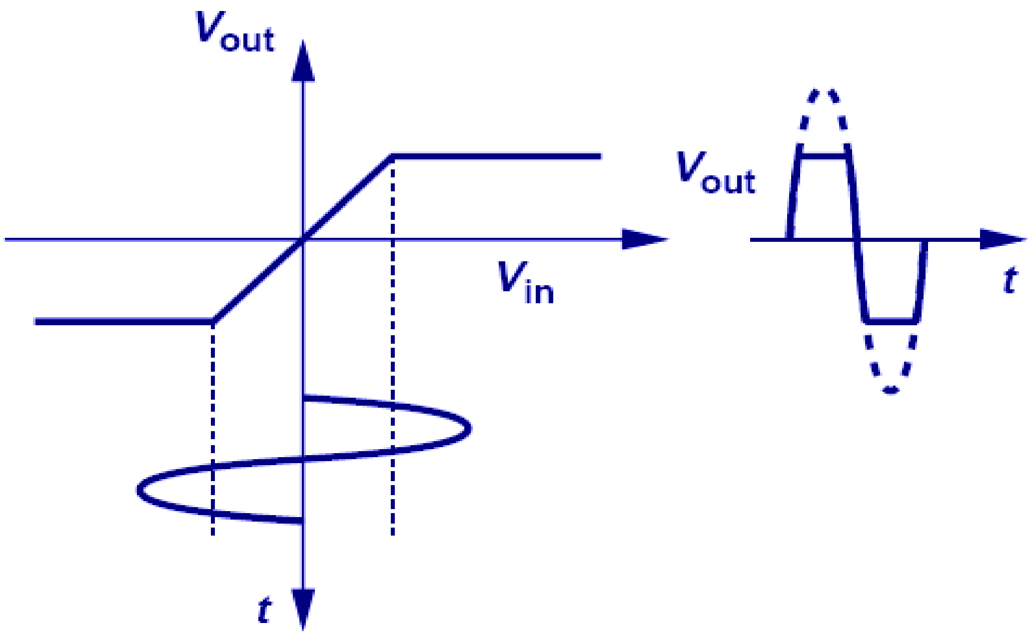


Input/Output Characteristics

- For small input levels, the circuit must simply pass the input to the output.
- As the input level exceeds a "***threshold***" or "*limit*," the output must remain constant. 臨界值
- This behavior must hold for both positive and negative inputs.
- The input signal is ***clipped*** at $\pm V_L$. 剪波器



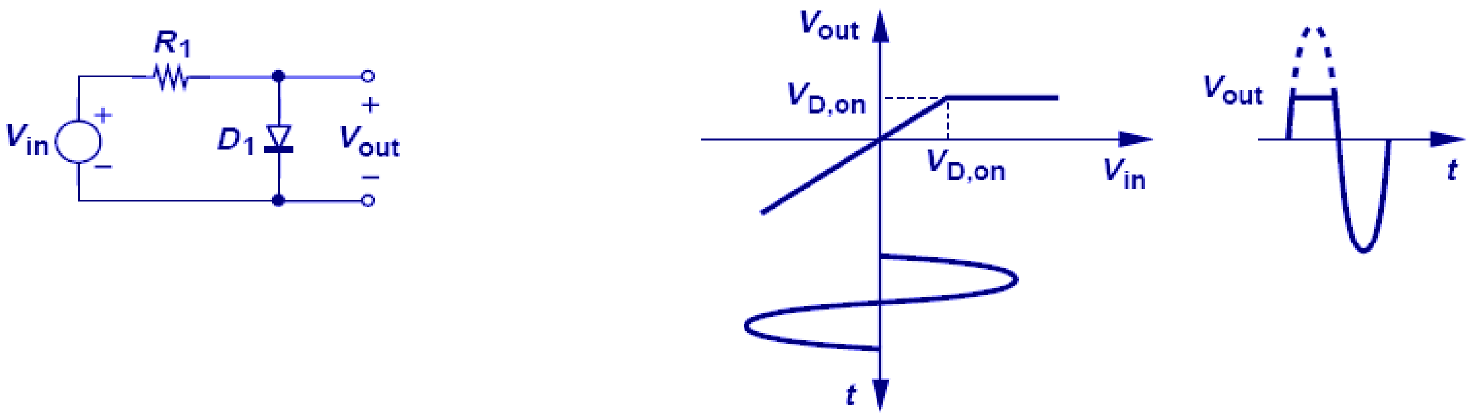
(a)



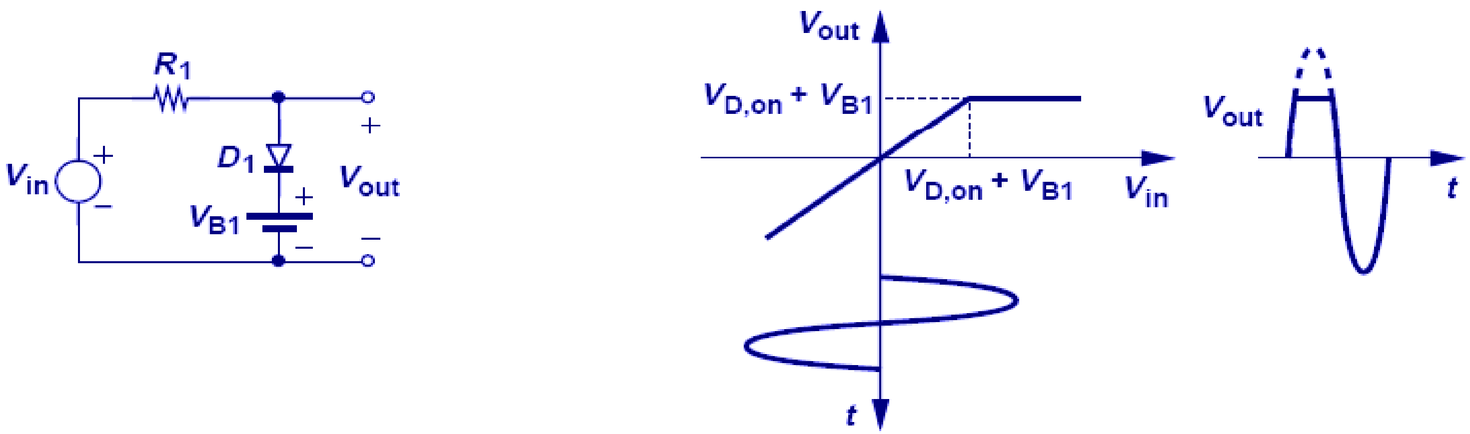
(b)

Limiting Circuit Using a Diode: Positive Cycle Clipping

- As was studied in the past, the combination of resistor-diode creates limiting effect.
- The battery V_{B1} performs a ***level shift***. 移位：準位移動

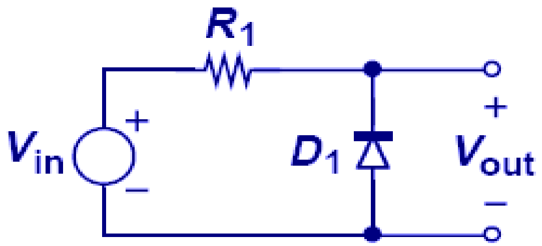


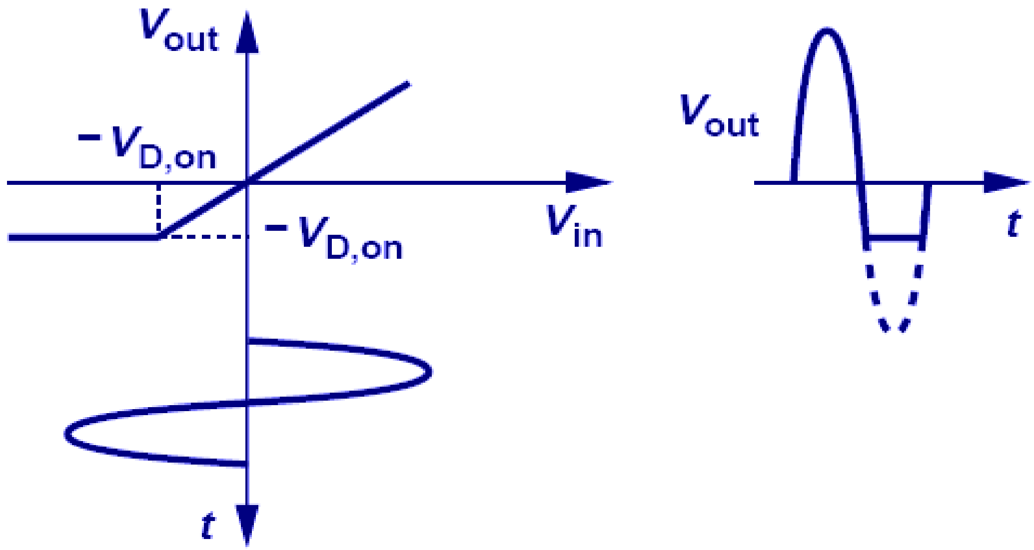
(a)



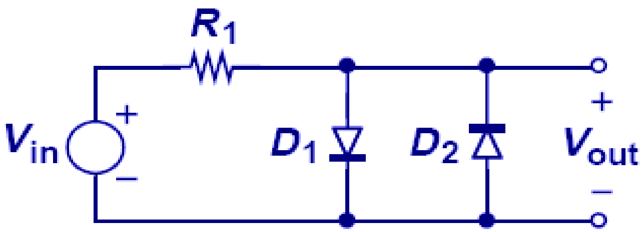
(b)

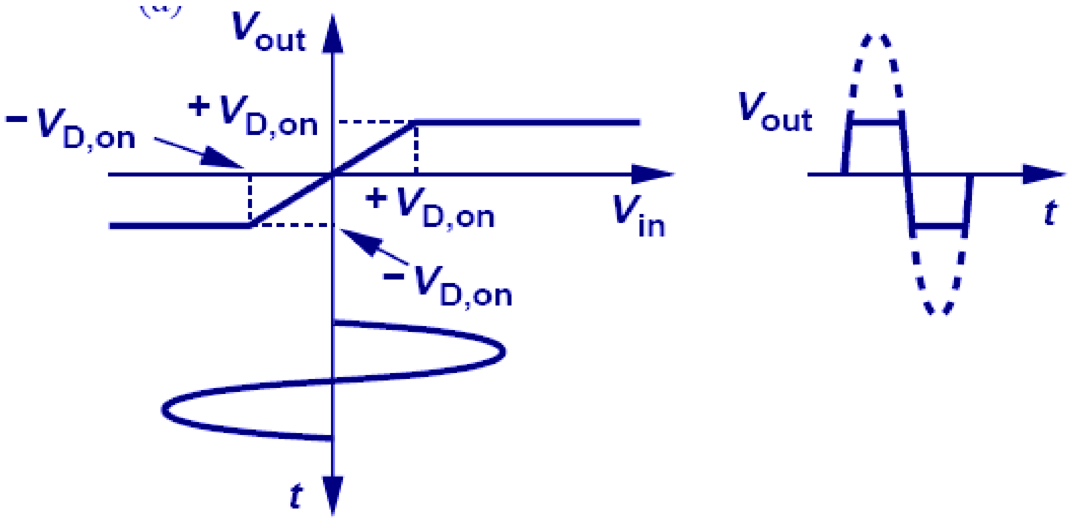
Limiting Circuit Using a Diode: Negative Cycle Clipping





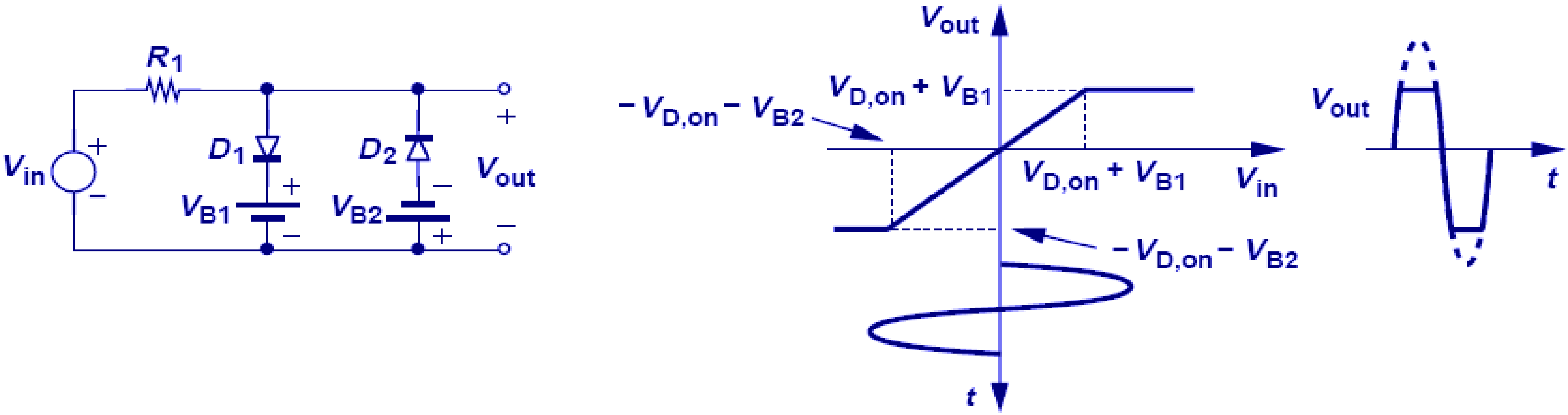
Limiting Circuit Using a Diode: Positive and Negative Cycle Clipping





General Voltage Limiting Circuit

- Two batteries in series with the antiparalle diodes control the limiting voltages.

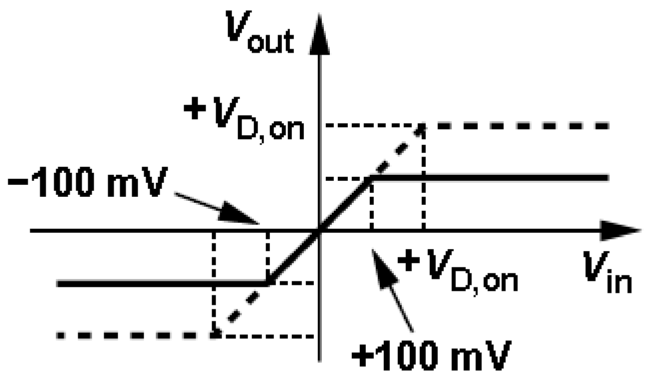


Example 3.34

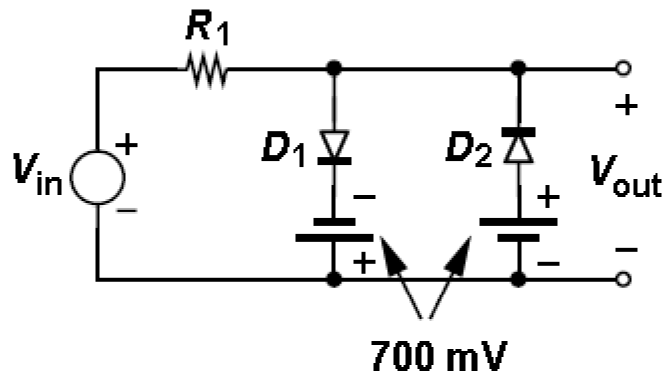
A signal must be limited at ± 100 mV. Assuming $V_{D,on}$ = 800 mV, design the required limiting circuit.

Solution

Figure (a) illustrates how the voltage sources must shift the break points. Since the positive limiting point must shift to the left, the voltage source in series with D_1 must be *negative* and equal to 700 mV. Similarly, the source in series with D_2 must be positive and equal to 700 mV. Figure (b) shows the result.



(a)

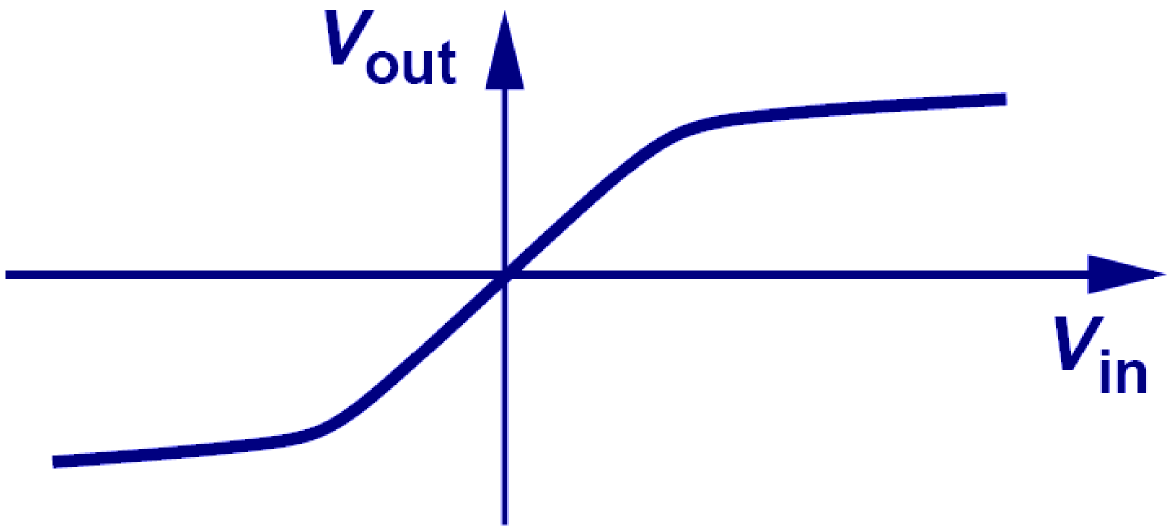


(b)

Non-idealities in Limiting Circuits

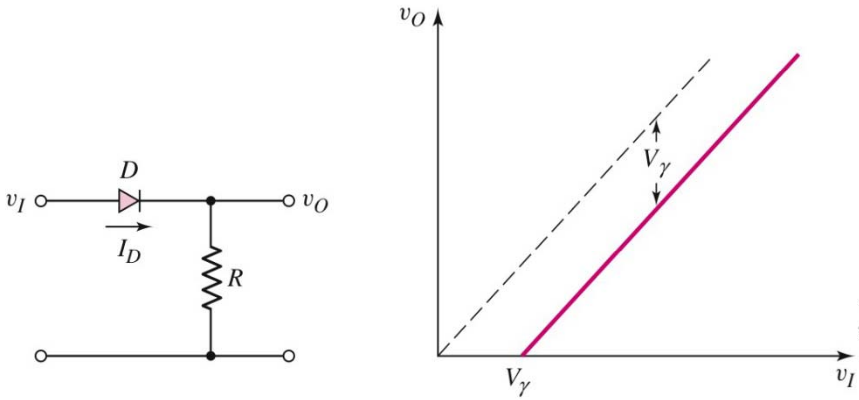
- The clipping region is not exactly flat since as V_{in} increases, the currents through diodes change, and so does the voltage drop.

$$V_D = V_T \ln(I_D/I_S)$$

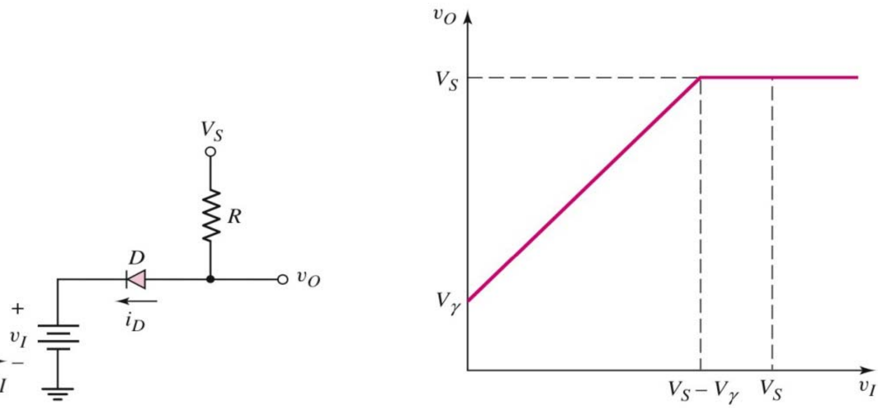


Multiple-diode Circuits

- Example diode circuits
  - Turn-on region and turn-off region.
    - Diode in series with the resistance
    - Diode in series with the resistance and the voltage source.



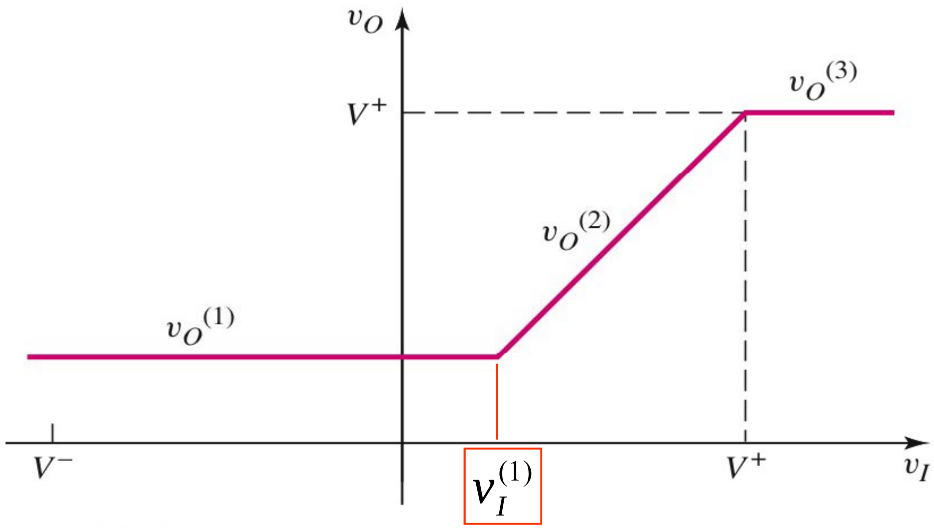
(a) (b)

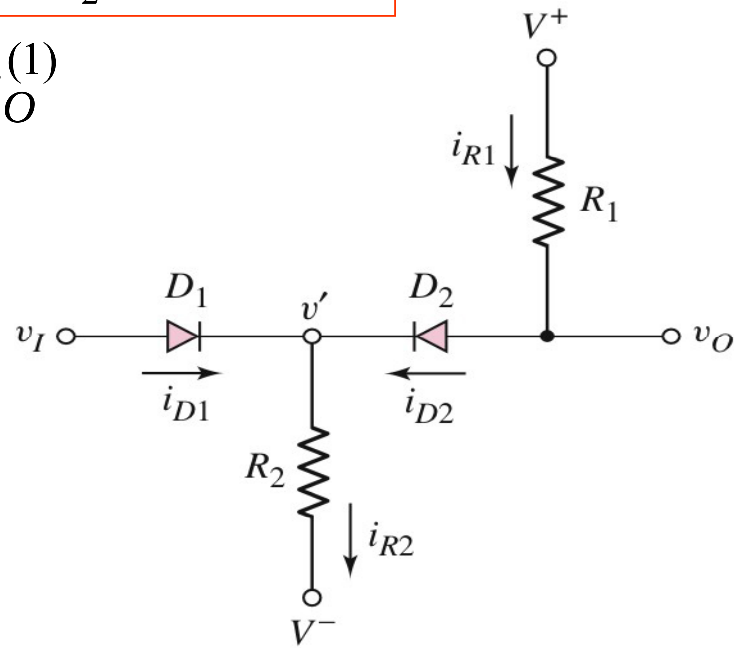


(a) (b)

Two diode circuit

- Assume $V^+ > V^-, \quad V^+ - V^- > V_\gamma$
  - D_2 ON, D_1 OFF, $$v_O = V^- + i_{R_2} R_2 \equiv v_O^{(1)}$$
  - D_1 just ON, $$v_I = V^- + R_2 \bullet \frac{V^+ - V_\gamma - V^-}{R_1 + R_2} + V_\gamma \equiv v_I^{(1)}$$
    - » when $v_I \le v_I^{(1)} \qquad v_O = v_O^{(1)}$





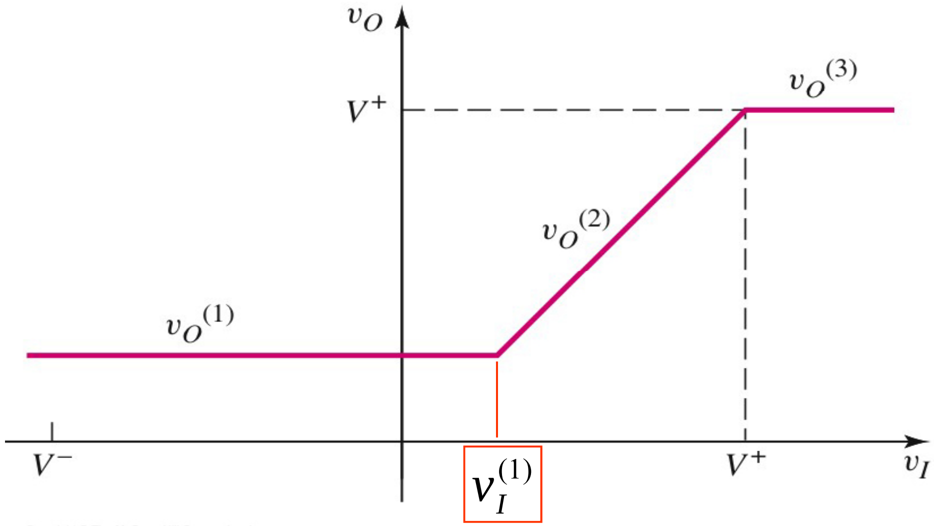
– D_1 ON, D_2 ON $\quad v_O = v_I \equiv v_O^{(2)}$

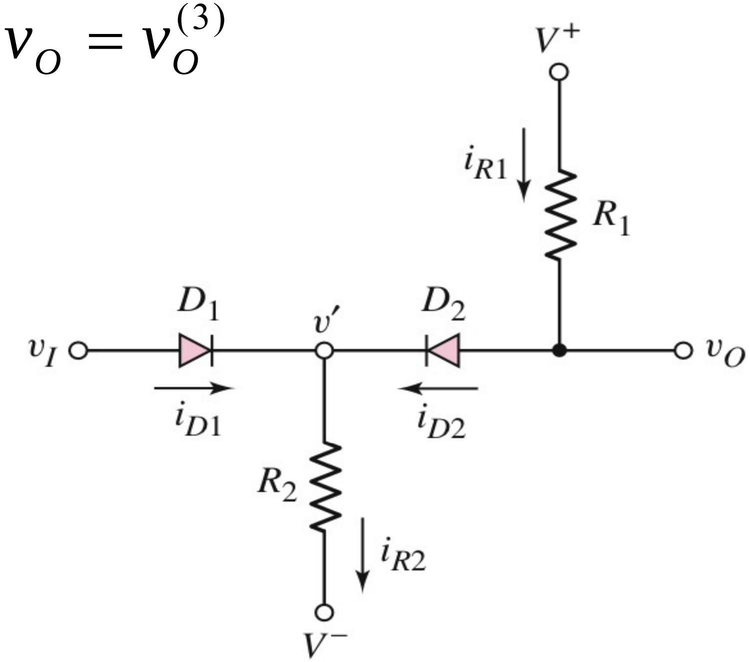
» when $\quad v_I^{(1)} < v_I < v_I^{(2)}$, $\quad v_O \equiv v_O^{(2)}$

– D_2 just OFF, $\quad v_I = v_O = V^+ \equiv v_I^{(2)}$

– D_1 ON, D_2 OFF, $\quad v_O = V^+ \equiv v_O^{(3)}$

» when $\quad v_I \geq v_I^{(2)} \quad v_O = v_O^{(3)}$





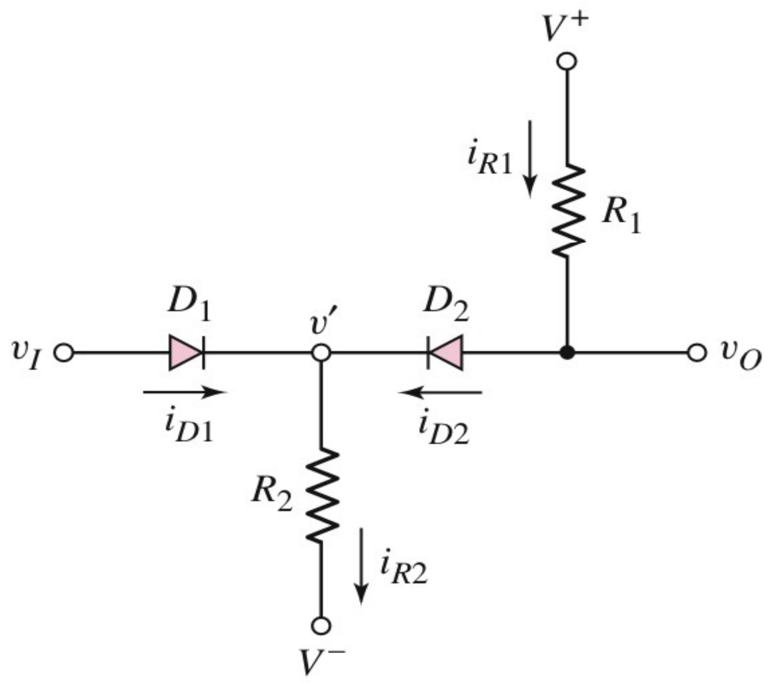
Example

- Assume R_1 = 5kΩ, R_2 = 10kΩ. V_γ = 0.7V, V^+ = +5V, V^- = -5V. Determinate v_O, i_{D1} and i_{D2} for v_I =0 and v_I = 4V.
- **Solution：**
  - 0 V： D_1 off，D_2 on，$i_{D_1} = 0$，

$$i_{D_2} = i_{R_2} = \frac{V^+ - V_\gamma - V^-}{R_1 + R_2} = 0.62$$

$$v_O = V^+ - i_{R_1} R_1 = 1.9$$

$$v' = v_O - V_r = 1.9 - 0.7 = 1.2V$$



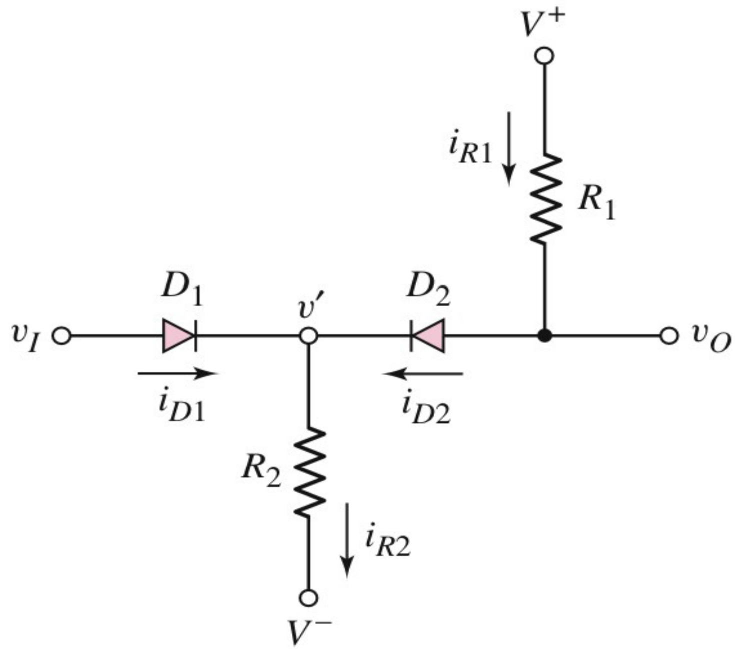
– 4 V：D_1 and D_2 on，then $v_O = v_I = 4$ V

$$i_{D_2} = i_{R_1} = \frac{V^+ - v_O}{R_1} = 0.2$$

$$v' = v_O - V_r = 4 - 0.7 = 3.3V$$

$$i_{R2} = \frac{v' - V^-}{R_2} = \frac{3.3 - (-5)}{10} = 0.83mA$$

$$i_{D_1} = i_{R_2} - i_{D2} = \frac{v_I - V_\gamma - V^-}{R_2} - 0.2 = 0.63$$



Problem-solving Technique: Multiple Diode Circuits

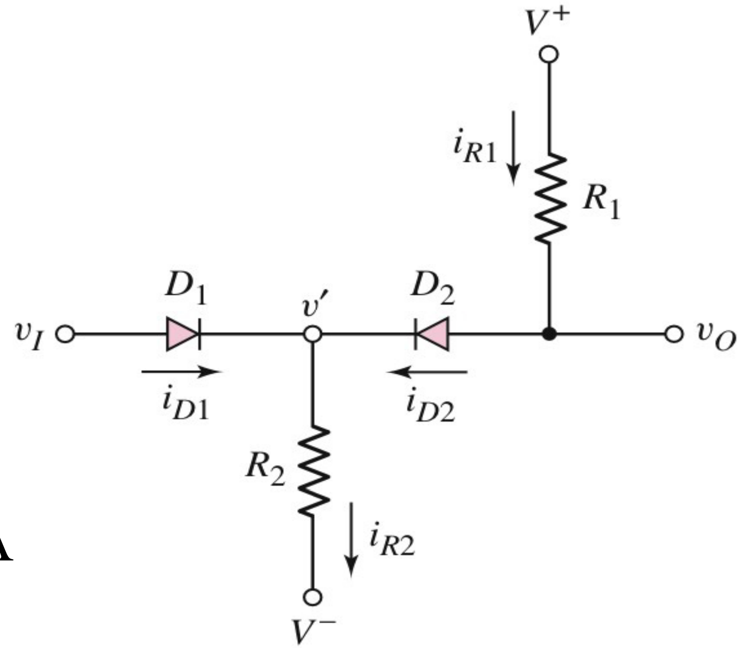
- We must initially **guess** the state of each device, then analyze the circuit to determine if we have a solution consistent with our initial guess.
  - Assume the state of a diode. If a diode is assume to be on, the voltage across the diode is V_γ. If a diode is assume to be off, the current through the diode is zero.
  - Analyze the 'linear' circuit with the assumed diode states.
  - Evaluate the resulting state of each diode.
    - If the initial assumption were that a diode is off and the analysis shows that $I_D = 0$ and $V_D \leq V_\gamma$, then the assumption is correct. If, however, $I_D > 0$ and/or $V_D > V_\gamma$, then the initial assumption is wrong.
    - Similarly, if the initial assumption were that a diode is on and the analysis shows that $I_D \geq 0$ and $V_D = V_\gamma$, then the assumption is correct. If, however, $I_D < 0$ and/or $V_D > V_\gamma$, then the initial assumption is wrong.
  - If any assumption is proven incorrect, a new assumption must be made and a new linear circuit must be analyzed.

Example

- Demonstrate how inconsistencies develop in a solution with incorrect assumptions.
- Solution:
  - Assume initially that both D1 and D2 are conducting. Then *v'* = -0.7V and v_O = 0. Two currents are

$$i_{R1} = i_{D2} = \frac{V^+ - v_O}{R_1} = \frac{5-0}{5} = 1\text{mA}$$

$$i_{R2} = \frac{v' - V^-}{R_2} = \frac{-0.7-(-5)}{10} = 0.43\text{mA}$$



  - Summing the current at v',

$$i_{D1} = i_{R2} - i_{D2} = 0.43 - 1.0 = -0.57\text{mA}$$

  - It is an inconsistent solution.

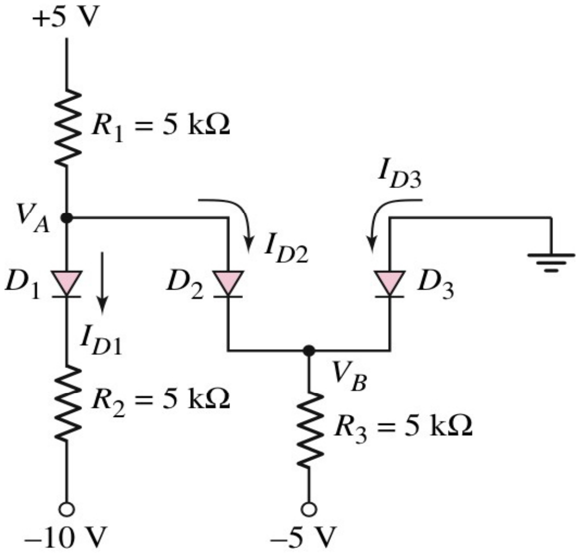
Example

- Determine the I_{D1}, I_{D2} and I_{D3} and V_A and V_B. Let V_γ = 0.7V for each diode.
- Solution：
  - D_1, D_2 and D_3 are on, $V_B = -0.7V \quad V_A = 0V$
  - currents at the node，we find

$$\frac{5 - V_A}{5} = I_{D2} + \frac{(V_A - 0.7) - (-10)}{5}$$

$$V_A = 0V$$

$$\frac{5}{5} = I_{D2} + \frac{9.3}{5} \Rightarrow I_{D2} = -0.86mA$$



  - which is inconsistent with the I_{D2} on

– D_1 and D_3 are on and D_2 is off.

$$I_{D1} = \frac{5-0.7-(-10)}{5+5} = 1.43mA$$

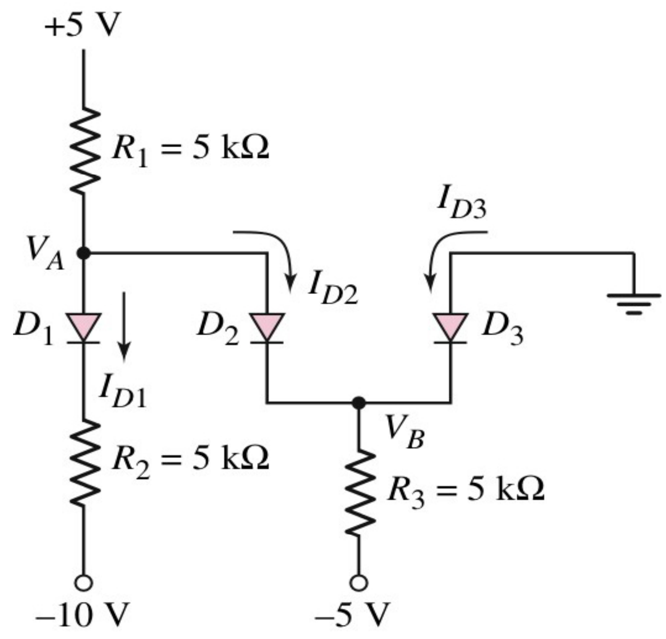
$$I_{D3} = \frac{(0-0.7)-(-5)}{5} = 0.86mA$$

– We find the voltages as

$$V_B = -0.7V$$

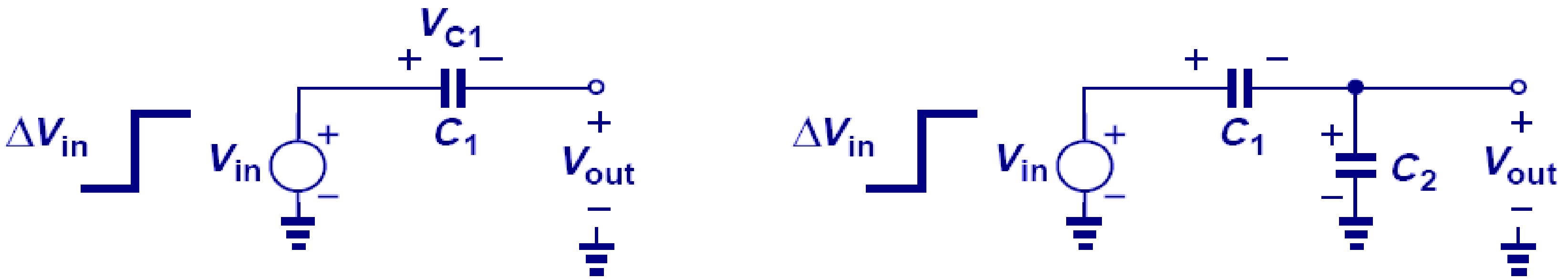
$$V_A = 5-(1.43)(5) = -2.15V$$

$$I_{D2} = 0$$



Capacitive Divider

- Typically a "global" supply voltage, e.g., 3 V, is used in electronic systems. However, some circuits in the system needs a *higher* supply voltage, e.g., 6 V. "***Voltage doublers***" may serve this purpose. 倍壓器
- In Fig. (a), the voltage at C_1 *cannot* change even if V_{in} changes because the right plate of C_1 cannot receive or release charge ($Q = CV$). Since V_{C1} remains constant, an input change ΔV_{in} directly appears at the output.
- In Fig. (b), if V_{in} becomes more positive, the left plate of C_1 receives positive charge from V_{in}, thus requiring that the right plate absorb negative charge of the same magnitude from the top plate of C_2. Having lost negative charge, the top plate of C_2 equivalently holds more positive charge, and hence the bottom plate absorbs negative charge from ground. Thus, Δv_{out} is a *capacitive division* of Δv_{in}.



(a)

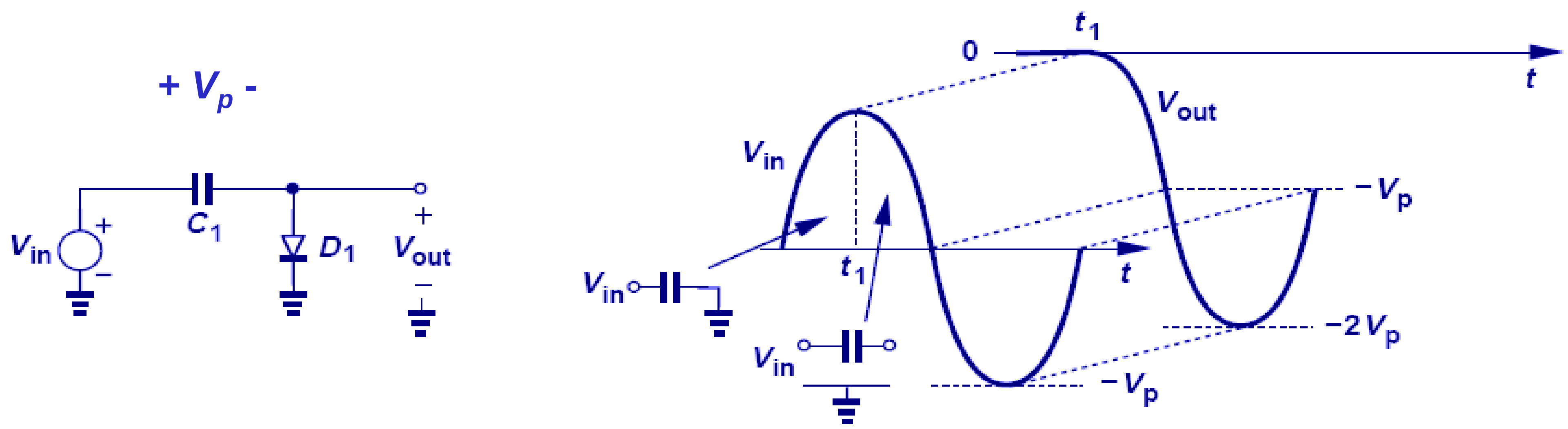
$$\Delta V_{out} = \Delta V_{in}$$

(b)

$$\Delta V_{out} = \frac{C_1}{C_1 + C_2}\Delta V_{in}$$

Waveform Shifter: Peak at $-2V_p$

- As V_{in} increases, D_1 turns on and V_{out} is zero.
- As V_{in} decreases, D_1 turns off, and V_{out} drops with V_{in} from zero.
- The lowest V_{out} can go is $-2V_p$, doubling the voltage.

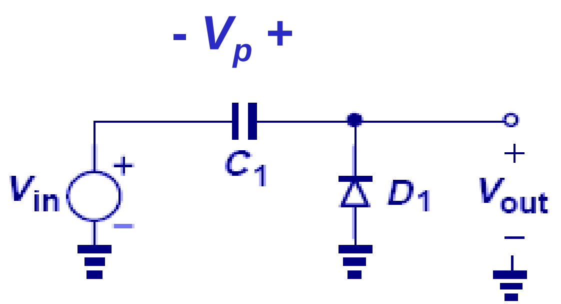


(a) (b)

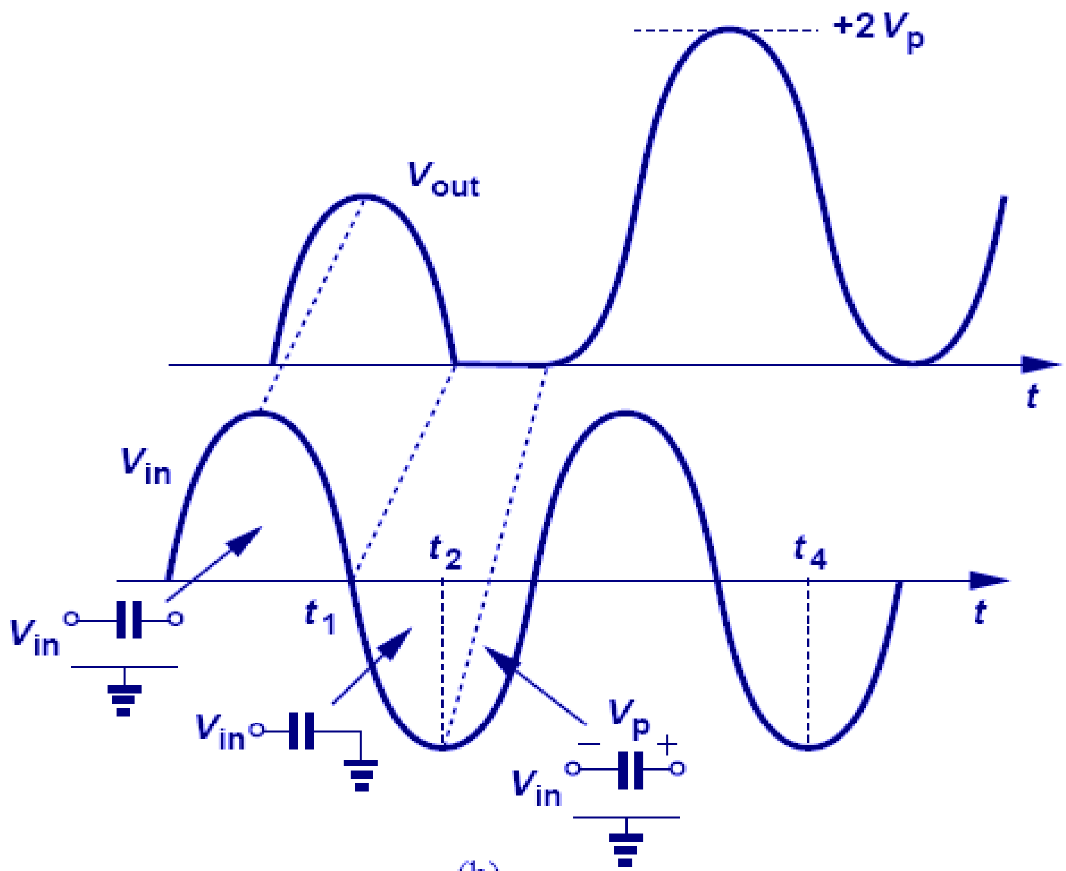
$$V_{out} = -V_p + V_{in}$$

Waveform Shifter: Peak at $2V_p$

- Similarly, when the terminals of the diode are switched, a voltage doubler with peak value at $2V_p$ can be conceived.



(a)



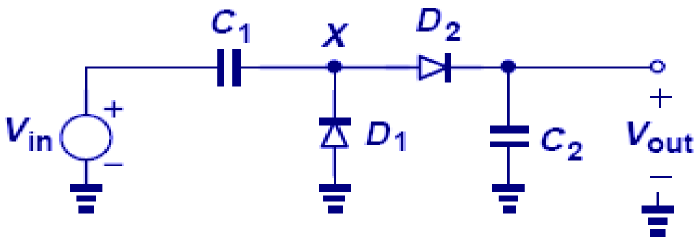
(b)

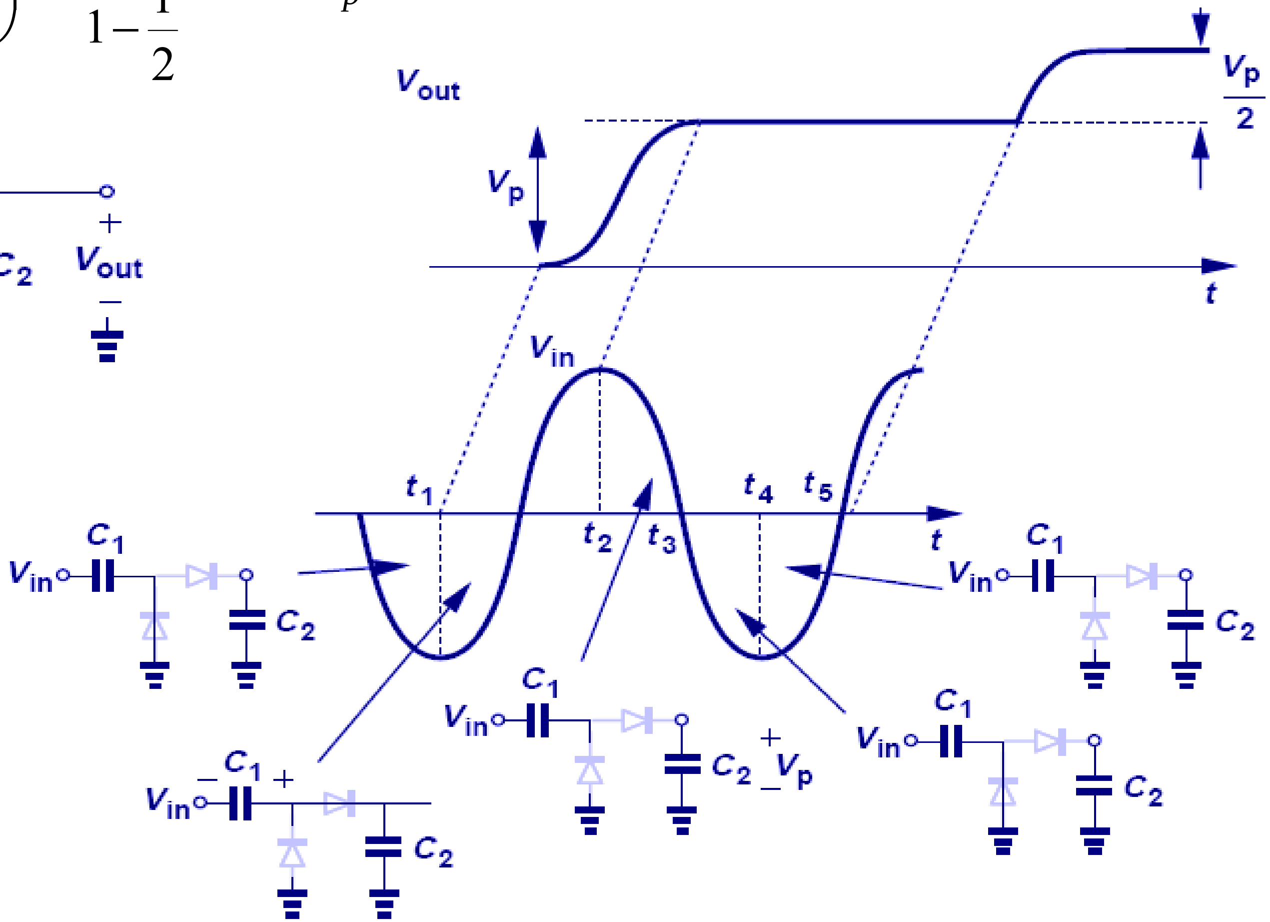
$$V_{out} = V_p + V_{in}$$

Voltage Doubler

- The output increases by V_p, $\frac{1}{2}V_p$, $\frac{1}{4}V_p$, etc in each input cycle, eventually settling to $2V_p$. ($C_1 = C_2$)

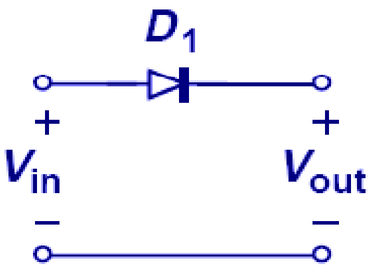
$$V_{out} = V_p\left(1+\frac{1}{2}+\frac{1}{4}+\cdots\right) = \frac{V_p}{1-\frac{1}{2}} = 2V_p .$$



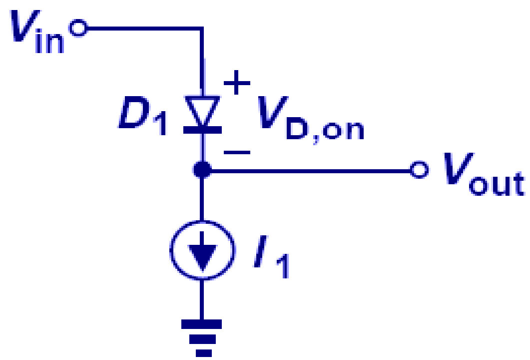


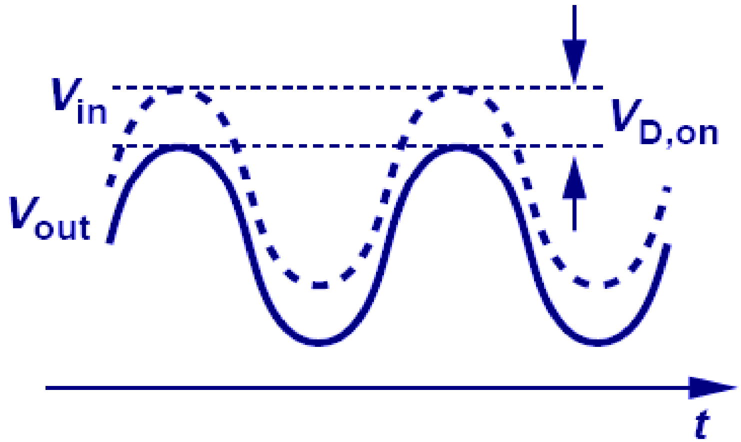
Voltage Shifter

- Shift the average level of a signal up or down because the subsequent stage (e.g., an amplifier) may not operate properly with the present dc level.
- A diode can be viewed as a battery and hence a device capable of shifting the signal level, $V_{D,on}$.



(a)





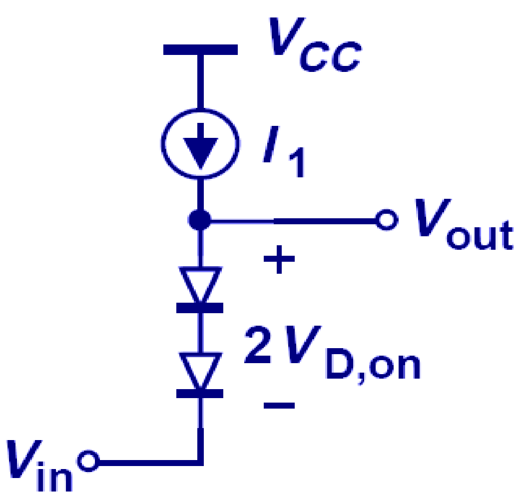
(b)

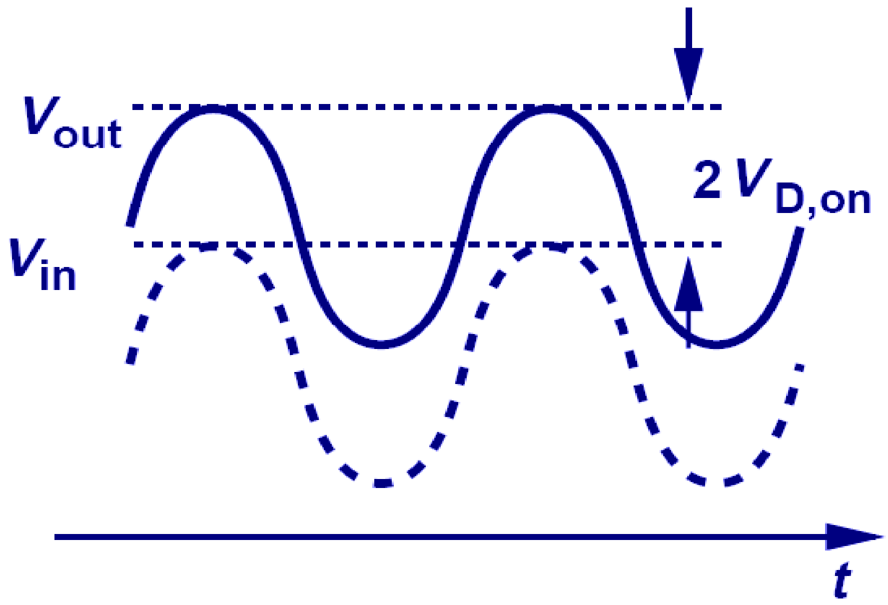
Example 3.37

Design a circuit that shifts up the dc level of a signal by 2 $V_{D,on}$.

Solution

To shift the level *up*, we apply the input to the *cathode*. Also, to obtain a shift of $2V_{D,on}$, we place two diodes in series. Figure below shows the result.

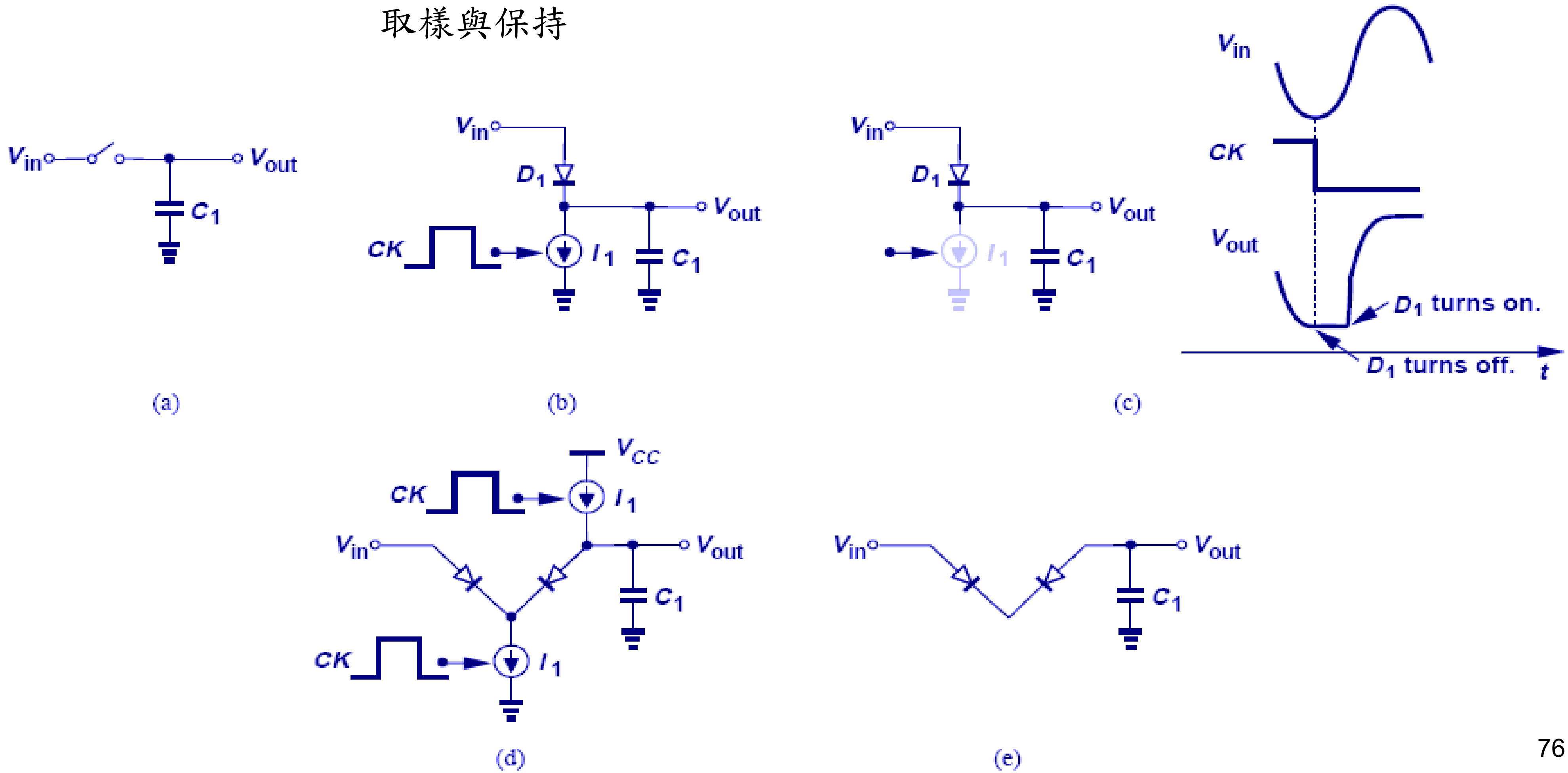




Diode as Electronic Switch

- Diode as a ***switch*** finds application in logic circuits and data converters. 開關
- (a) is a simple ***sample and hold***, can be regarded as *analog memory*
- Diode is a fast switch, but more generally ***MOSFET*** is used as the switch

取樣與保持

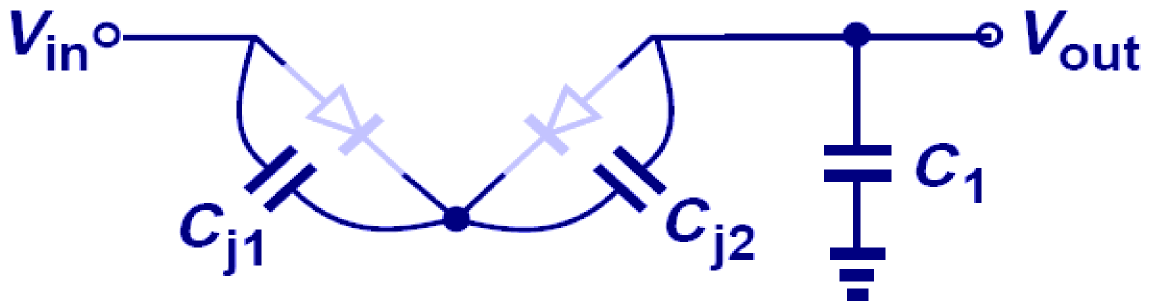


Junction Feedthrough *

- For (e) of the previous slide, a small ***feedthrough*** from input to output via the junction capacitors exists even if the diodes are reverse biased. 穿饋

$$\Delta V_{out} = \frac{C_j/2}{C_j/2 + C_1}\Delta V_{in} \qquad \text{if } C_{j1} = C_{j2} = C_j$$

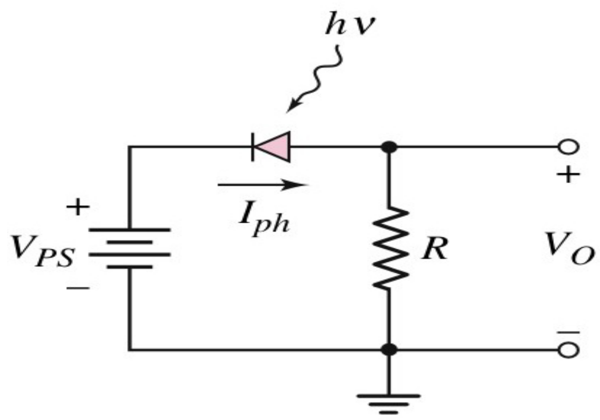
- Therefore, C_1 has to be large enough to minimize this feedthrough.



Photodiode (PD) 光二極體偵測器

- Light → electricity
- The photodiode circuit
  - PD under reverse-biased.
  - No photon intensity

    ➔ only reverse-saturation current.



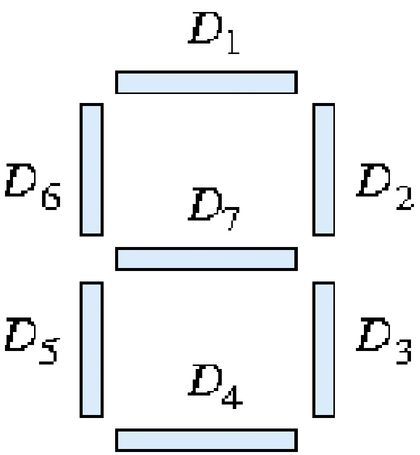
  - Photons striking the diode create excess electrons and holes in the space-charge region.
  - The photocurrent #/cm^2-s (quantum efficiency • electronic charge • photon flux density ($I_{ph} = \eta e \Phi A$) • junction area)
    - The electric field quickly separates these excess carriers and sweeps them out of the space-charge region.
    - Assumed that linear relationship between photocurrent and photon flux.
    - Voltage drop across R must be small. Namely photocurrent and value of R is very small.

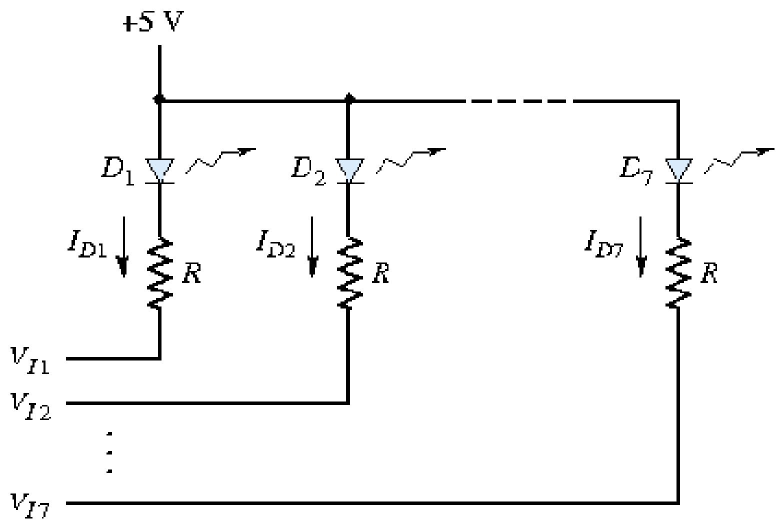
Light Emitting Diode (LED) 發光二極體

- Electricity → light
- Electrons and holes are injected across the space-charge region under forward-biased
  - Became “excess” “minority” carriers and diffused into the neutral n- and p-region.
  - It recombined with majority carriers, and then emitted of a photon.
- Fabricated from compound semiconductor materials (GaAs or GaAsP)
  - These are direct-bandgap semiconductor with higher bandgap than silicon.
  - The forward-bias junction voltage is large than that in silicon-based diode.

Seven-segment Display 七段顯示器

- Numeric readout of digital instrument.
- Common-anode display
  - The anodes of all LEDs are connected to a 5 V source.
  - The input are controlled by logic gates.
  - dark：high input, the diode is turn-off.
  - bright：low input, the diode is turn-on.





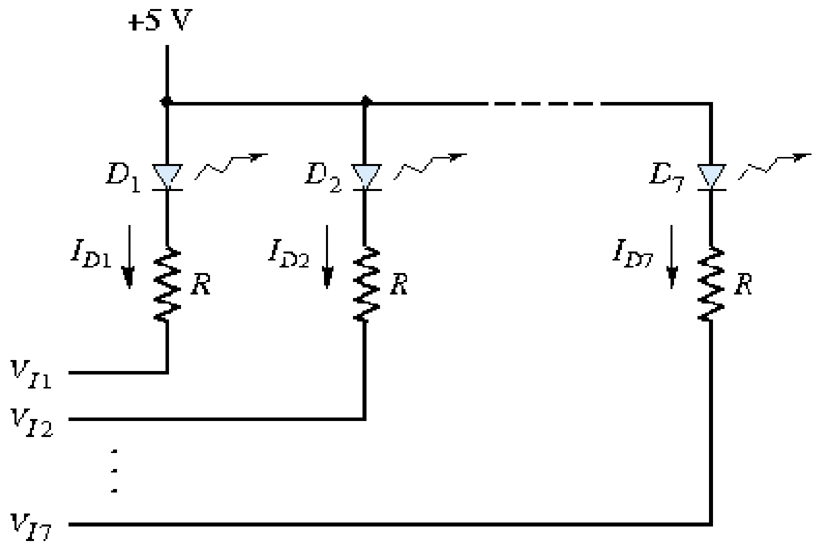
Example

- Assume that a diode current of 10 mA produces the desired light output, and that the the corresponding forward-bias voltage drop is 1.7 V.
- Solution：
  - If $V_I = 0.2V$ in the “low ”state，then the diode current is

$$I = \frac{5 - V_r - V_I}{R}$$

  - The resistance R is then determined as

$$R = \frac{5 - V_r - V_I}{I} = \frac{5 - 1.7 - 0.2}{10} \Rightarrow 310\Omega$$



Optoisolators 光隔離器

- The input and the output are electrical isolation.
- The input signal applied to the LED generates light, which is subsequently detected by the photodiode.
- The photodiode then converts the light back to an electrical signal.
- There is no electrical feedback or interaction between the output and input portions of the circuit.