Outline of Section 3 - Diodes

- Two terminal devices
- Diode models
- Exponential model
- Constant voltage drop model
- Reverse breakdown
- *Applications*
- Small-signal model
- PN junctions

Rectification

- Essential building block of AC to DC conversion
- Makes AC input unipolar at output
- Imposes average DC value on output

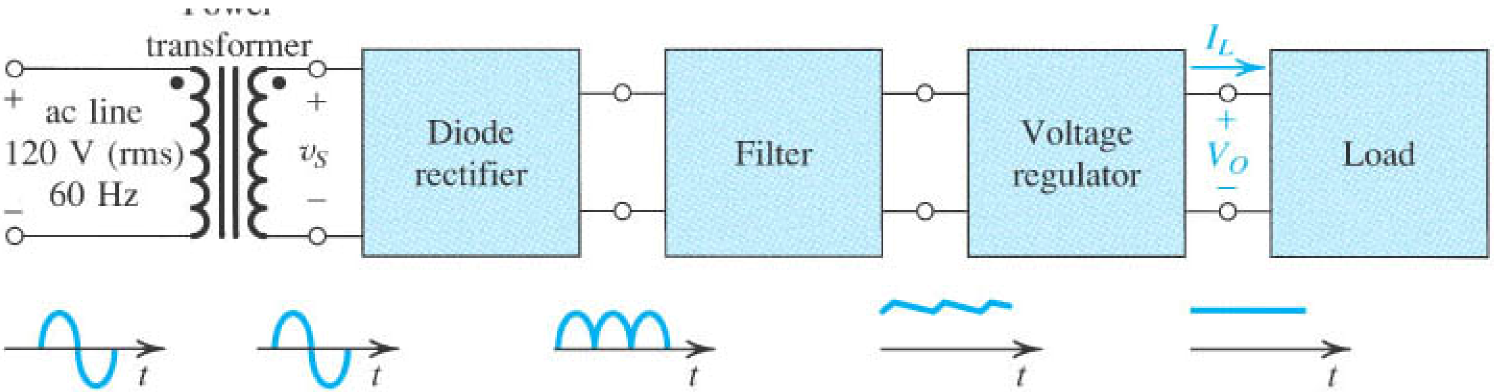
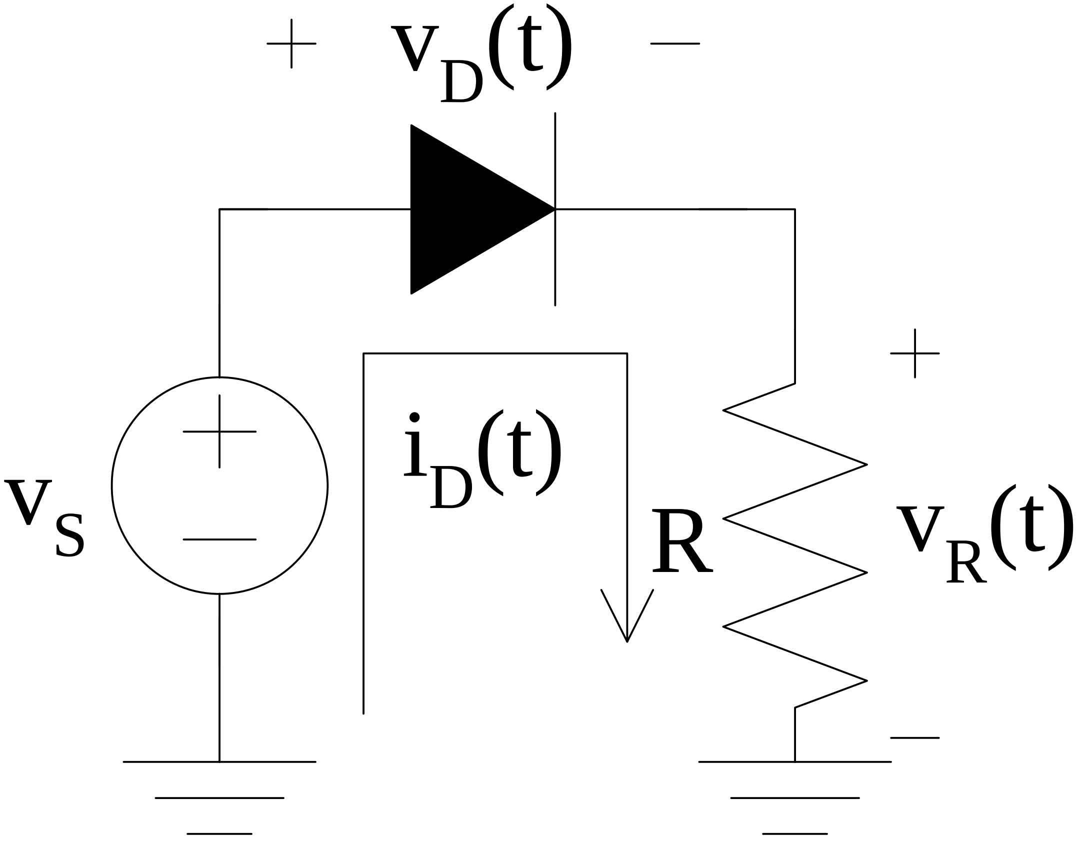


Figure 3.24 Block diagram of a dc power supply.

Rectification – Operation



Let $v_S(t)$ be a sine wave

$$v_S(t) = V_{DC} + V_p \sin(\omega t)$$

For positive v_S:

$i_D = 0$ for $v_S <= 0.7V$

When diode conducts:

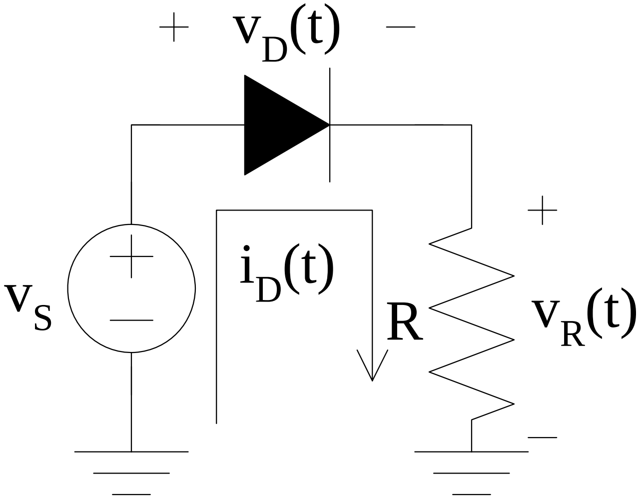
$$v_R(t) = v_S(t) - 0.7$$

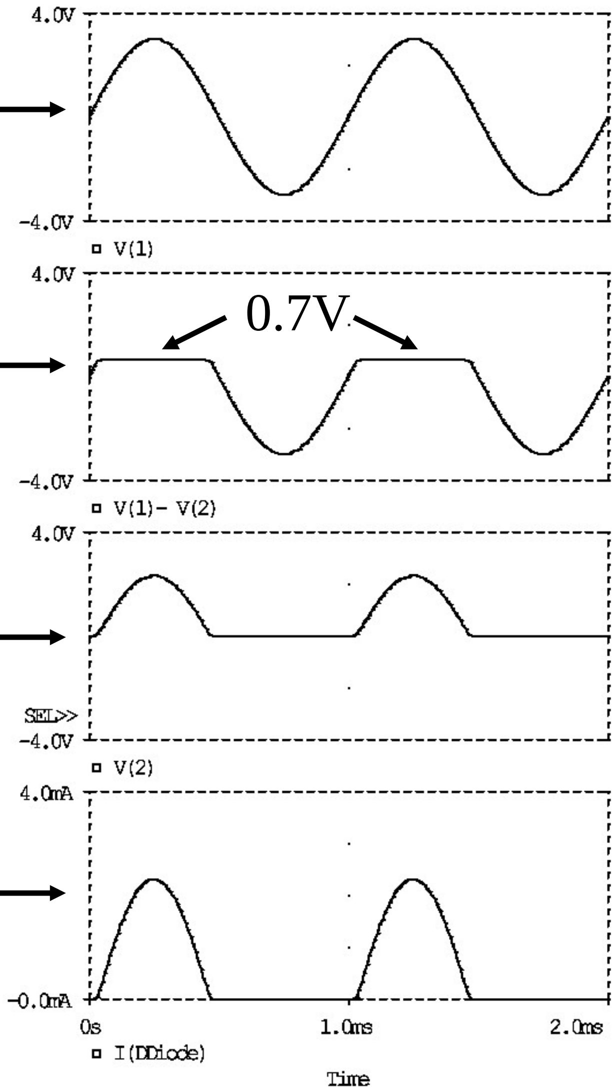
For negative v_S:

$i_D = 0$, $v_R = 0$,

$v_D(t) = v_S(t)$

Half-Wave Rectifier





Signal source →

Voltage drop across diode with CVDM →

Voltage across resistor →

- rectified signal
- v_S minus diode drop

Circuit current flow →

Fullwave Rectifier

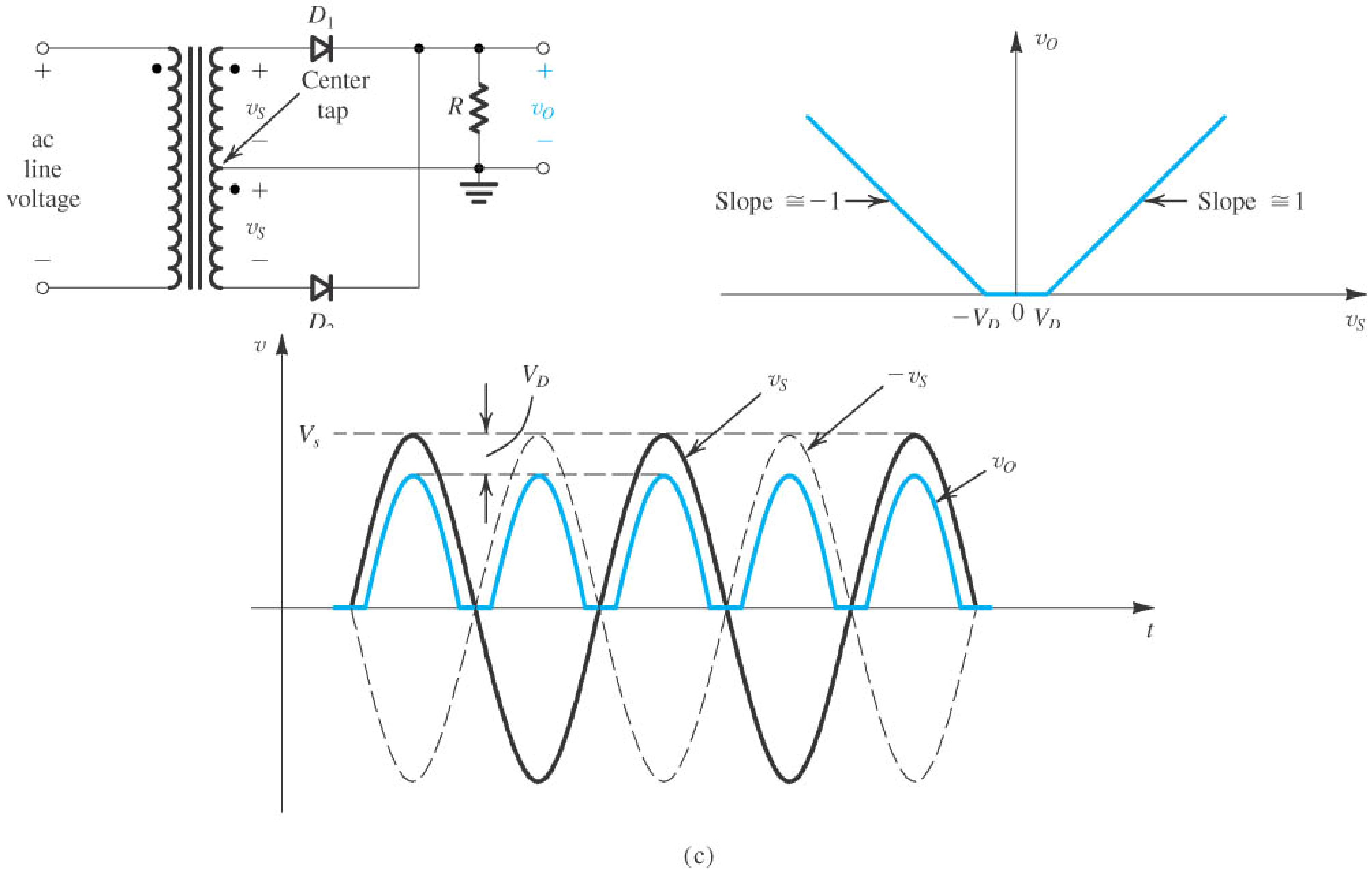
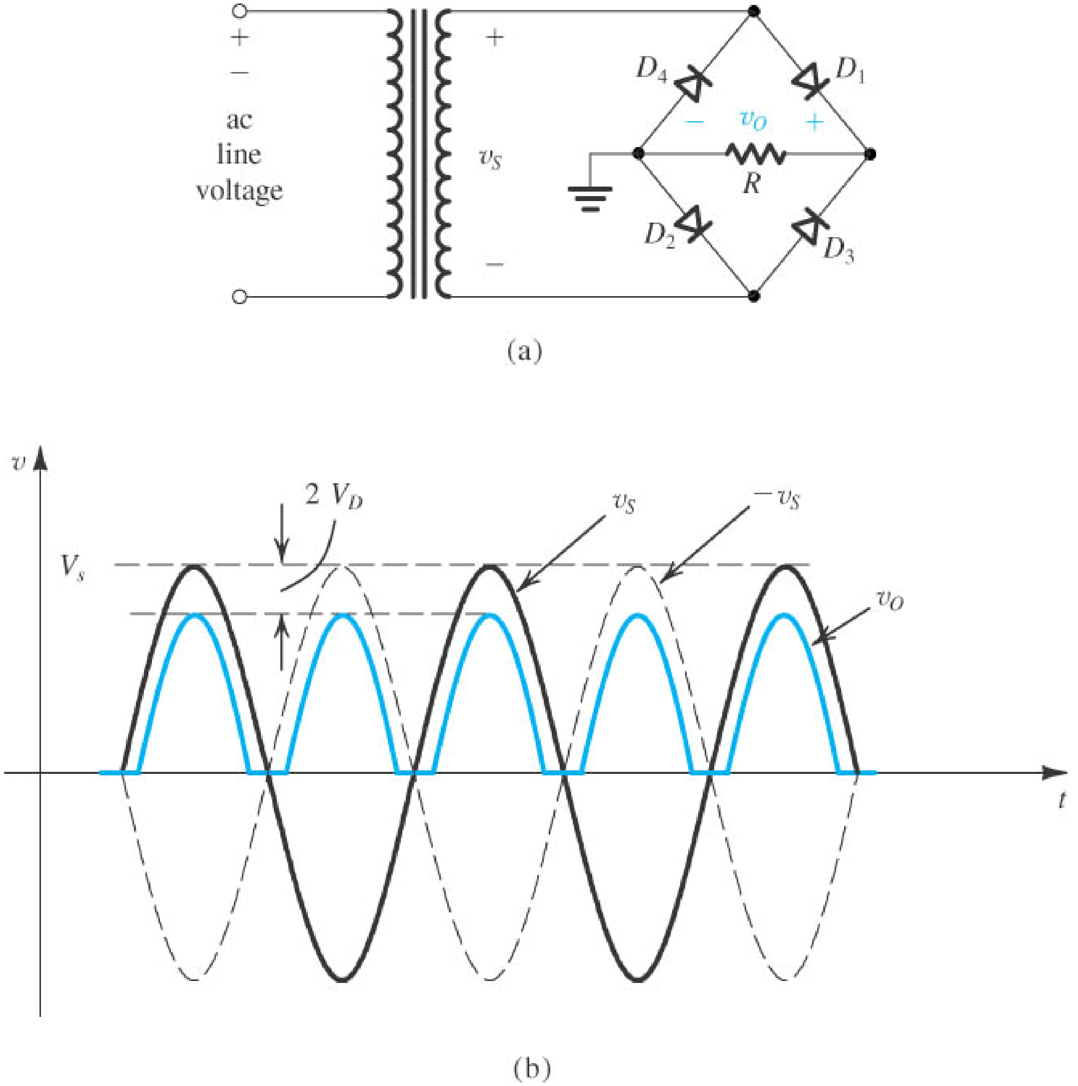


Figure 3.26 Full-wave rectifier utilizing a transformer with a center-tapped secondary winding: **(a)** circuit; **(b)** transfer characteristic assuming a constant-voltage-drop model for the diodes; **(c)** input and output waveforms.

Bridge Rectifier



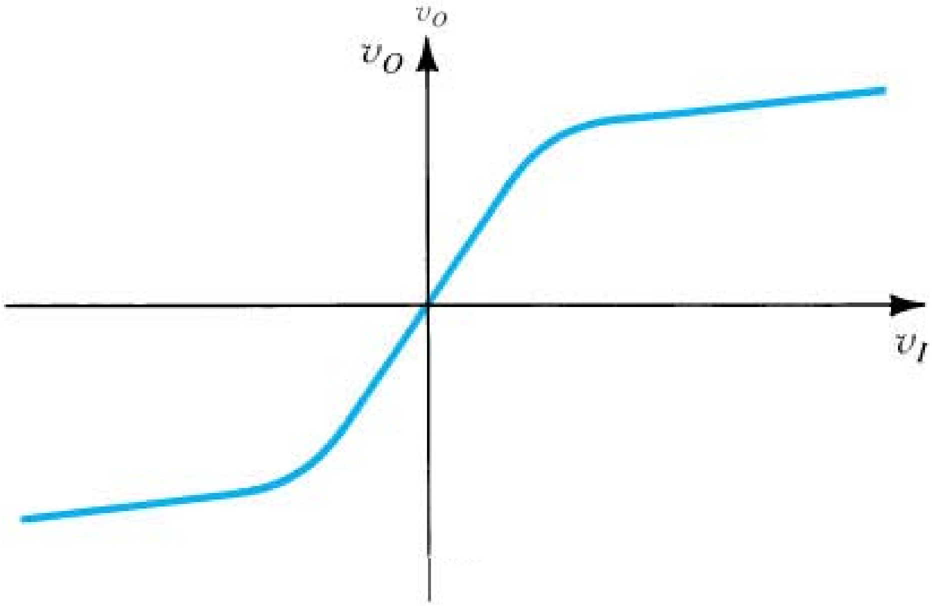
(a)

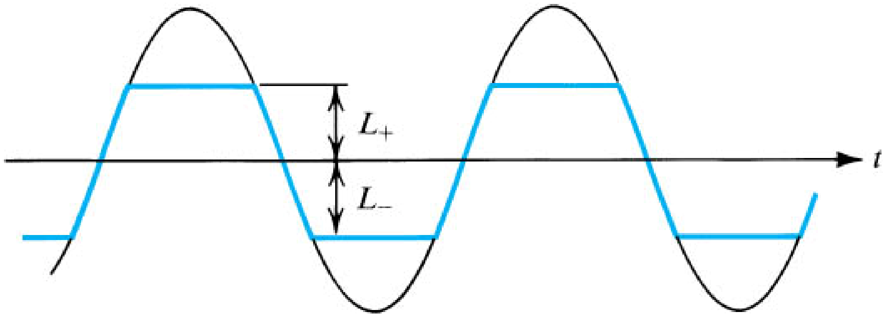
(b)

Figure 3.27 The bridge rectifier: **(a)** circuit; **(b)** input and output waveforms.

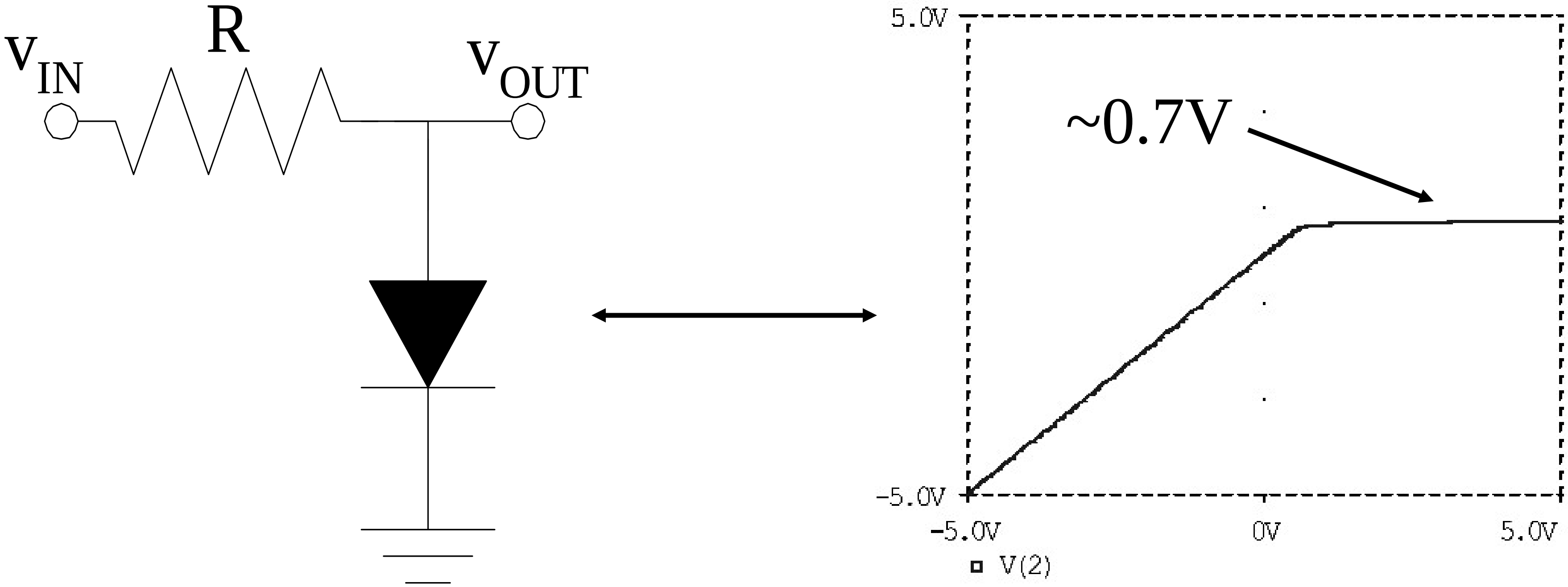
Limiting Circuits – Purpose

- Limiting circuits prevent output signals from exceeding and/or going below certain voltages
- Used for over and undershoot protection at the inputs of logic gates
- Used to perform waveform-shaping functions



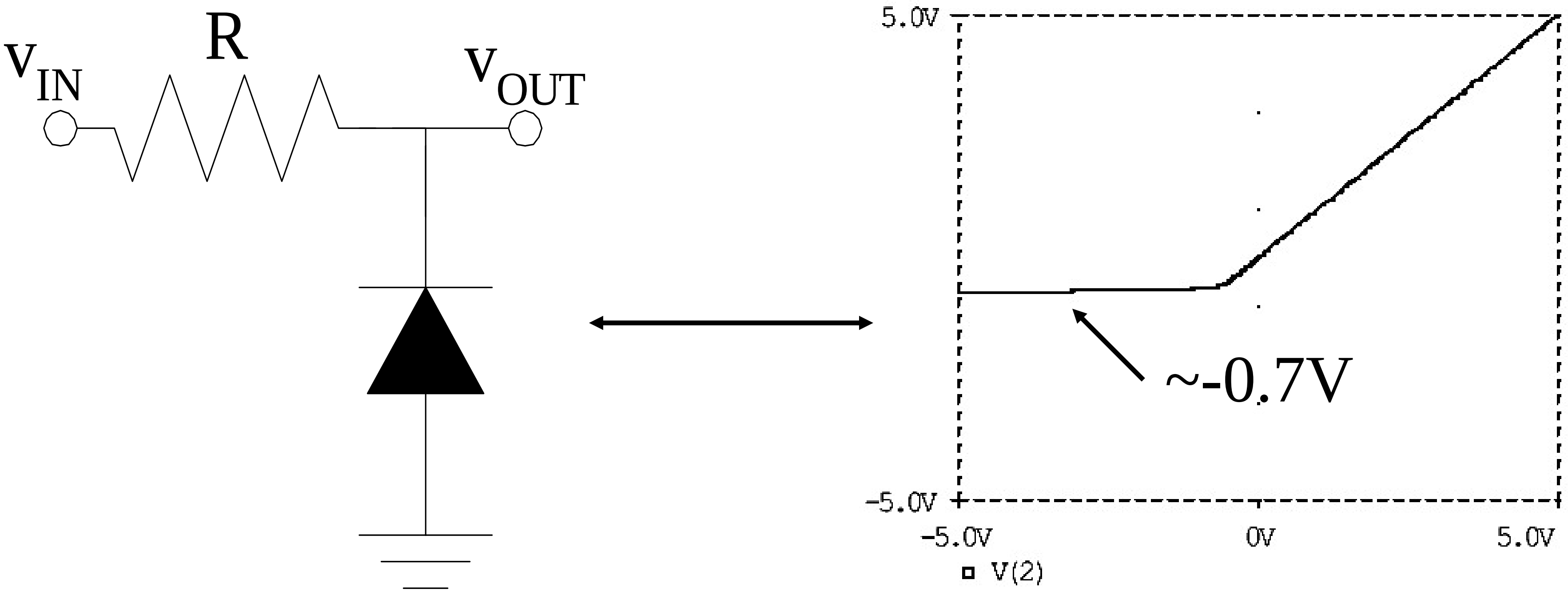


Overshoot Limiter



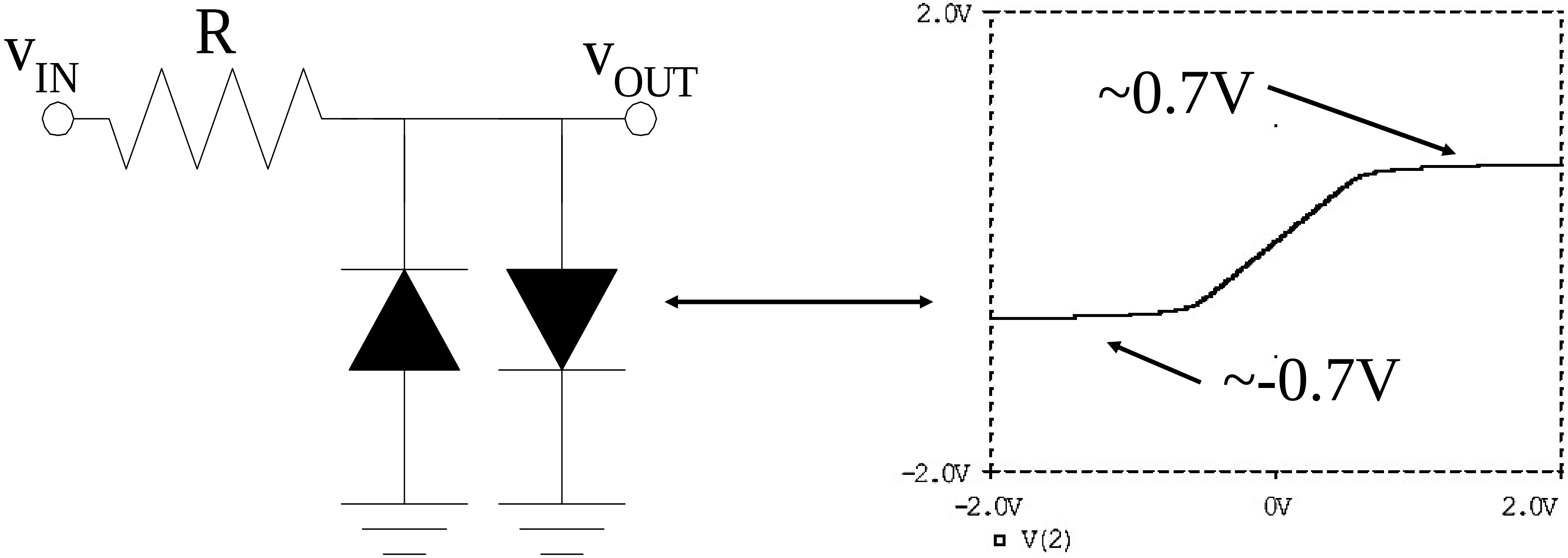
- If V_{IN} gets too large, diode conducts and clamps V_{OUT} to approximately a diode drop above ground
- Slope of transition region = 1 because no load attached thus no current drawn through resistor

Undershoot Limiter



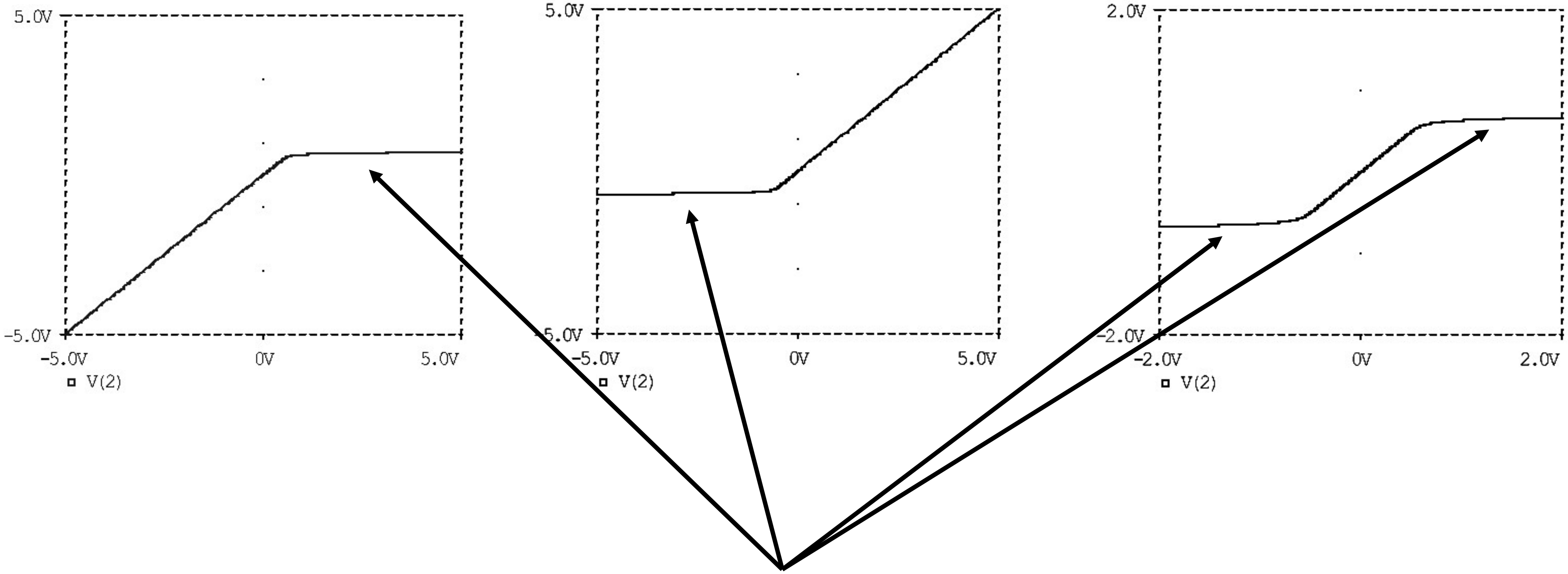
- If V_{IN} gets too negative, diode conducts and clamps V_{OUT} to approximately a diode drop below ground

Double Limiter



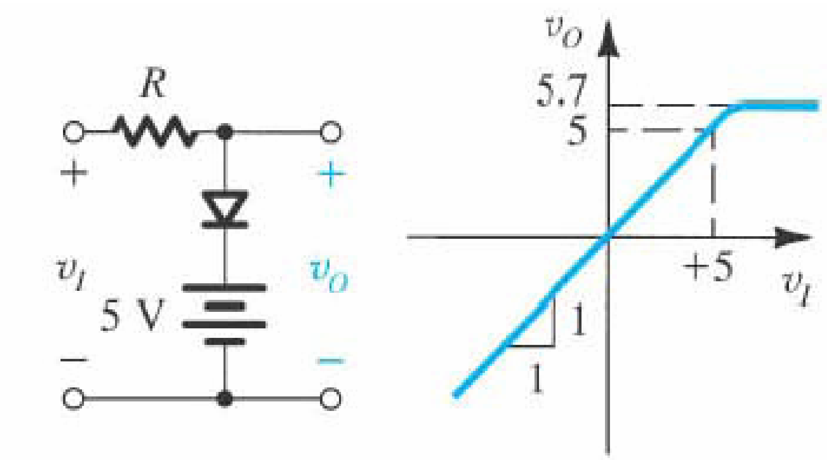
- If V_{IN} gets too positive or negative, a diode conducts to clamp V_{OUT} to approximately a diode drop above or below ground

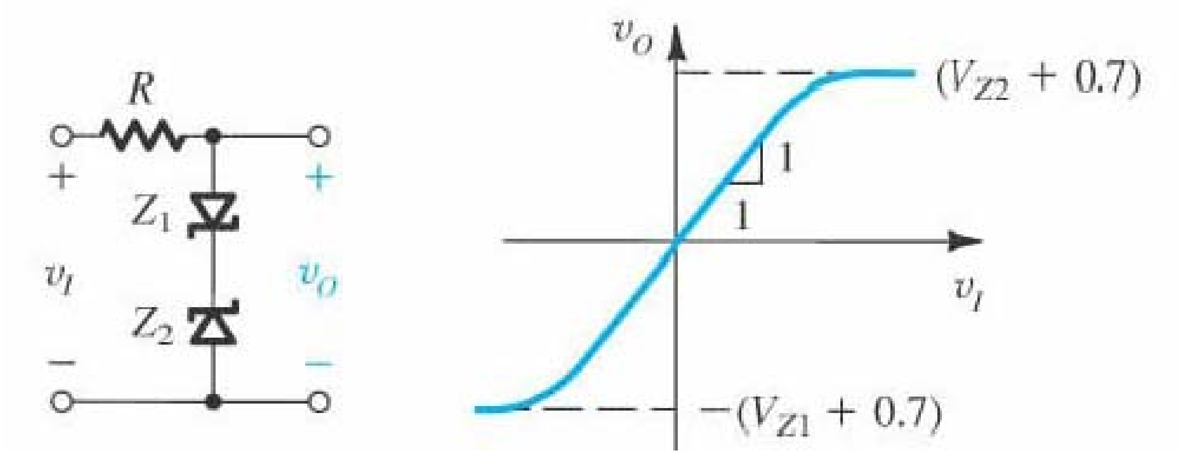
VTCs



- “Flat” portions of VTC’s have small but finite slope due to ‘on-resistance’ of diode
- Slope of transition regions = 1 because no load attached thus no current drawn through resistor

Other Limiting Circuits



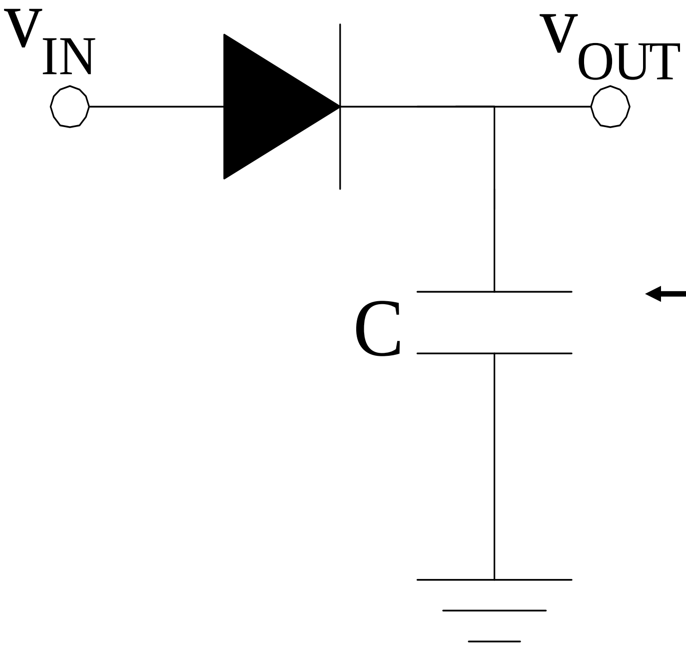


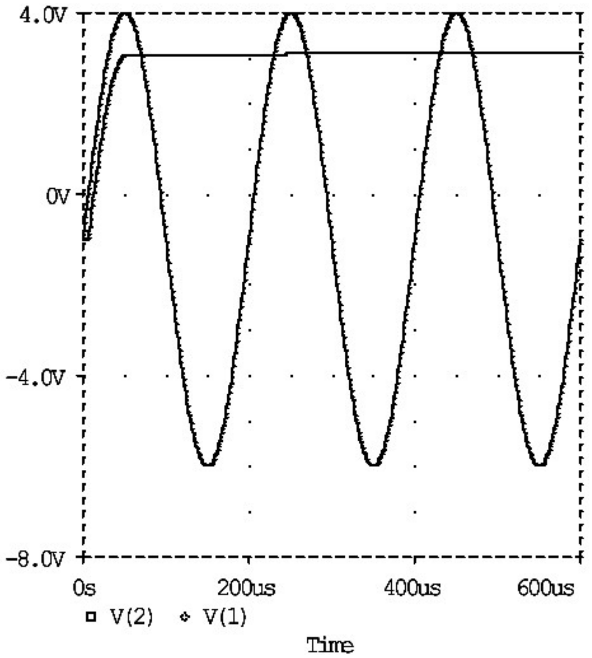
Double-anode Zener

Clamping Circuits – Purpose

- Detect peak signal levels
- Remove DC offsets or restore DC
- Voltage doubling (double peak-clamping)
- Construct AC to DC converters
- Receive amplitude modulated signals (e.g. radio)

Peak Detection





– This circuit is also known as a rectifier with a filter capacitor

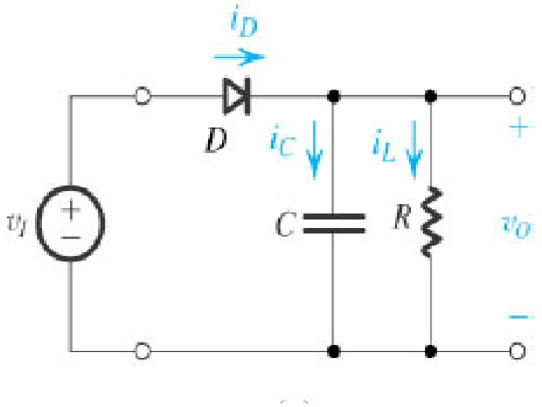
Operation:

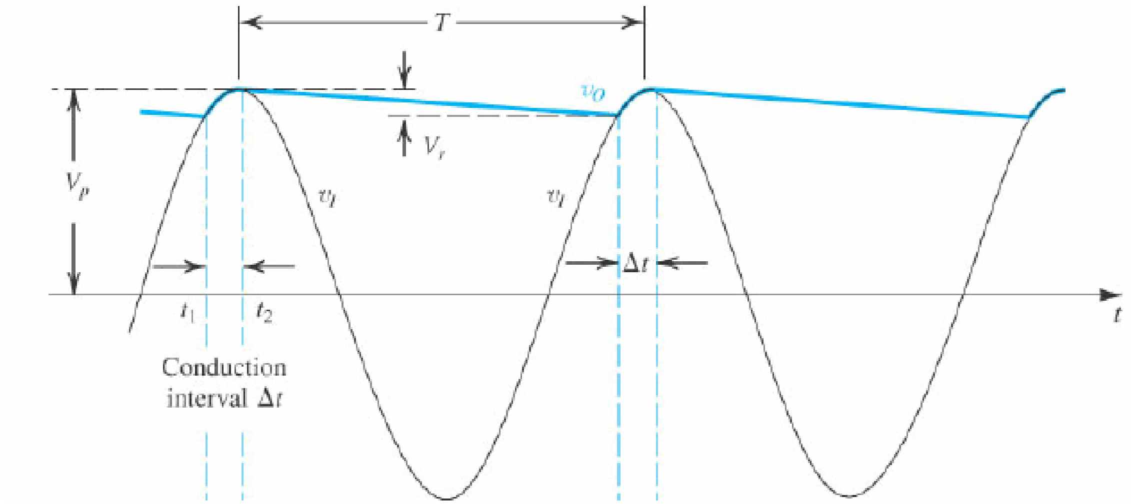
– charge is injected into capacitor whenever diode conducts

– circuit detects signal peak minus a diode drop

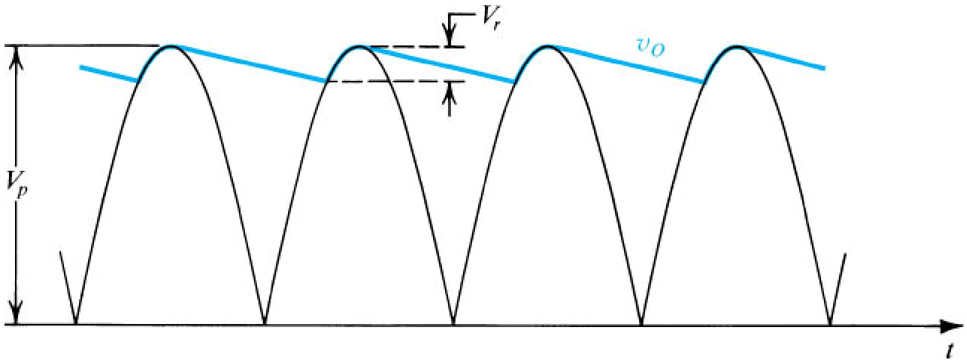
– current loss during reverse-bias neglected

Peak Detection



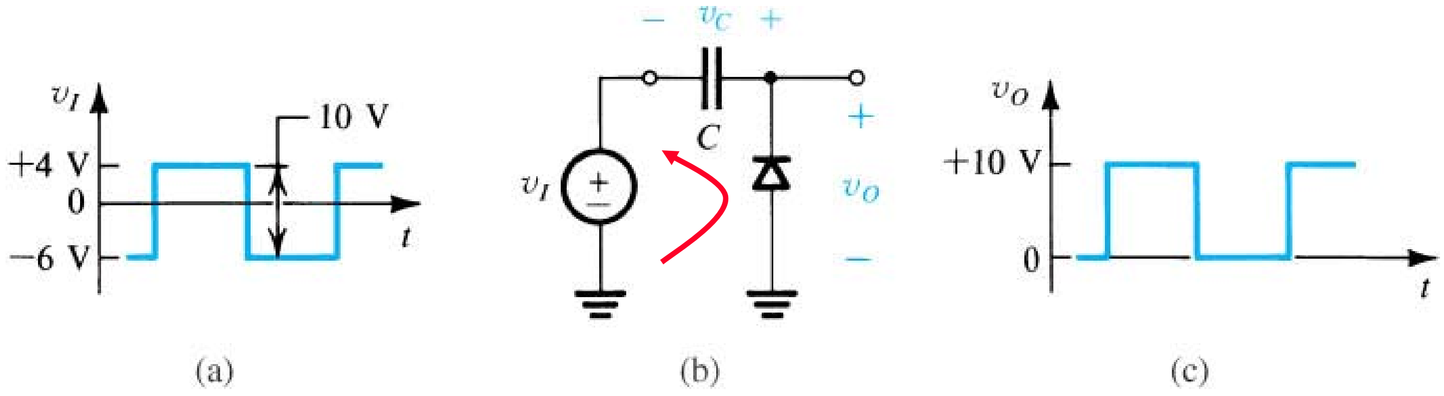


If we have a Fullwave Rectifier before peak detection



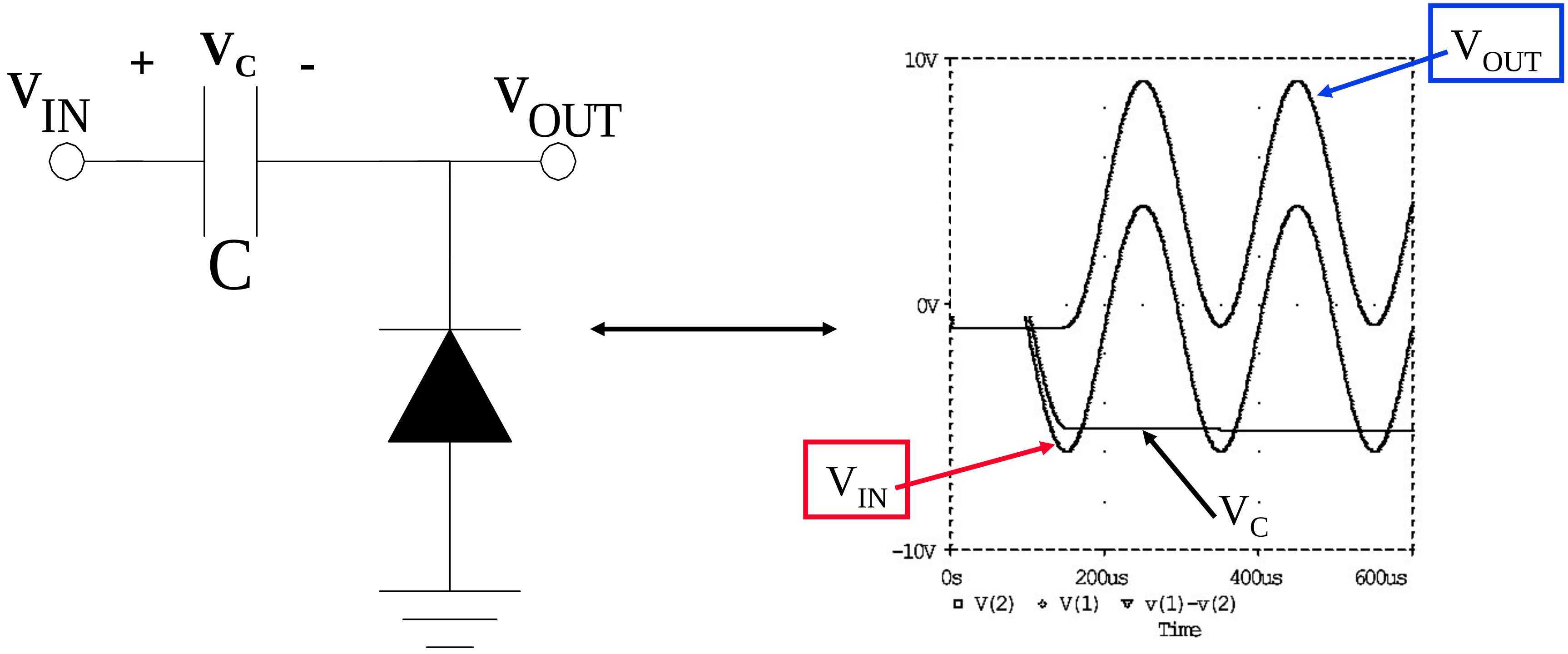
- Basis for **AM demodulators** and **AM receivers**
- You will see more about this (calculations of conduction time, ripple voltage, average and peak currents, etc.) **in EC2 lab**

DC Restorer or Clamped Capacitor



- Operation considering Ideal Model for the diode:
  - At the beginning when v_I = -6V, the diode conducts and the capacitor charges up to 6 V, v_C =6V
  - When v_I = +4V, the voltage drop across the diode is $v_I + v_C = v_O$ =6+4=10V, therefore the diode is off, no current goes through the diode and $v_O = v_I + v_C$
  - This is how a DC shift appears at the output

Another Example with CVDM

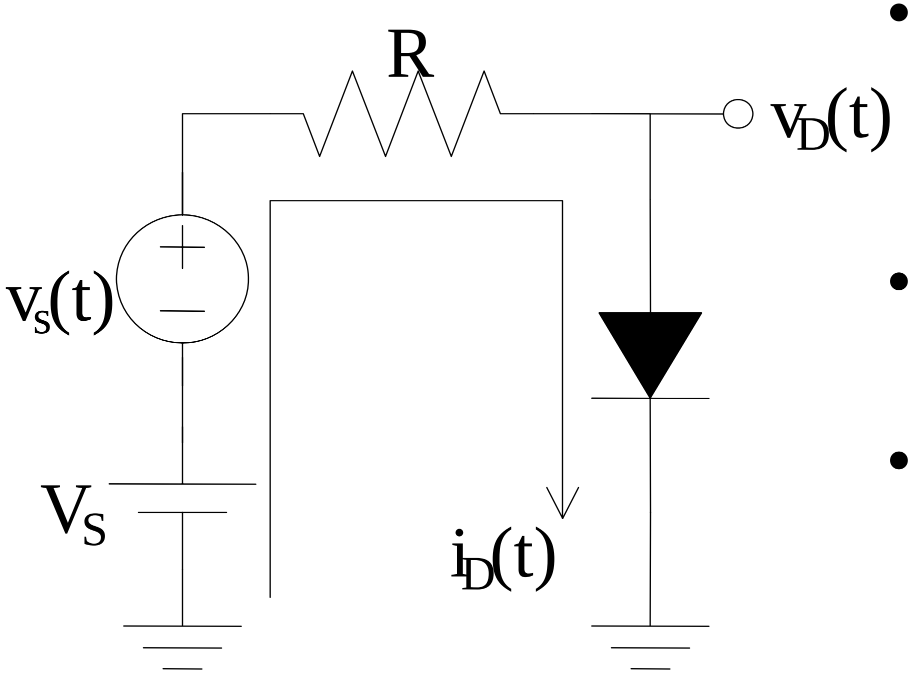


- as V_{IN} falls below -0.7V, capacitor charged by diode
- V_C clamps at a diode drop above the negative input peak
- diode prevents capacitor discharge, removing most of DC offset

Outline of Section 3 - Diodes

- Two terminal devices
- Diode models
- Exponential model
- Constant voltage drop model
- Reverse breakdown
- Applications
  - **Note:** Voltage Doubler and Super Diode applications and calculations of conduction time, ripple voltage, average and peak currents of peak rectifier circuit are not covered
- *<u>Small-signal model</u>*
- PN junctions

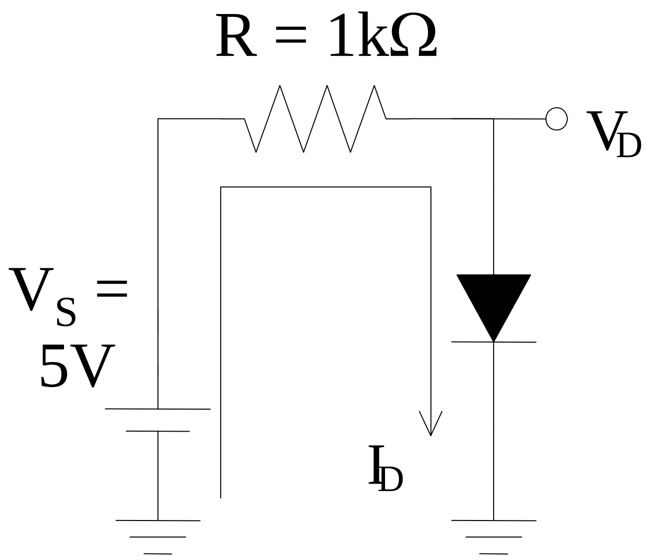
Mixed DC and AC Analysis



- Consider circuit contains DC and AC sources, resistors and diodes
- Linear superposition of the signals applies
- Therefore, we can separate our analysis into two sets:

1. DC analysis
2. AC analysis

DC analysis to determine the Operating Point



1) "Kill" AC sources

2) Perform DC analysis on the remaining DC circuit.

3) Make an assumption about the state of the diodes.

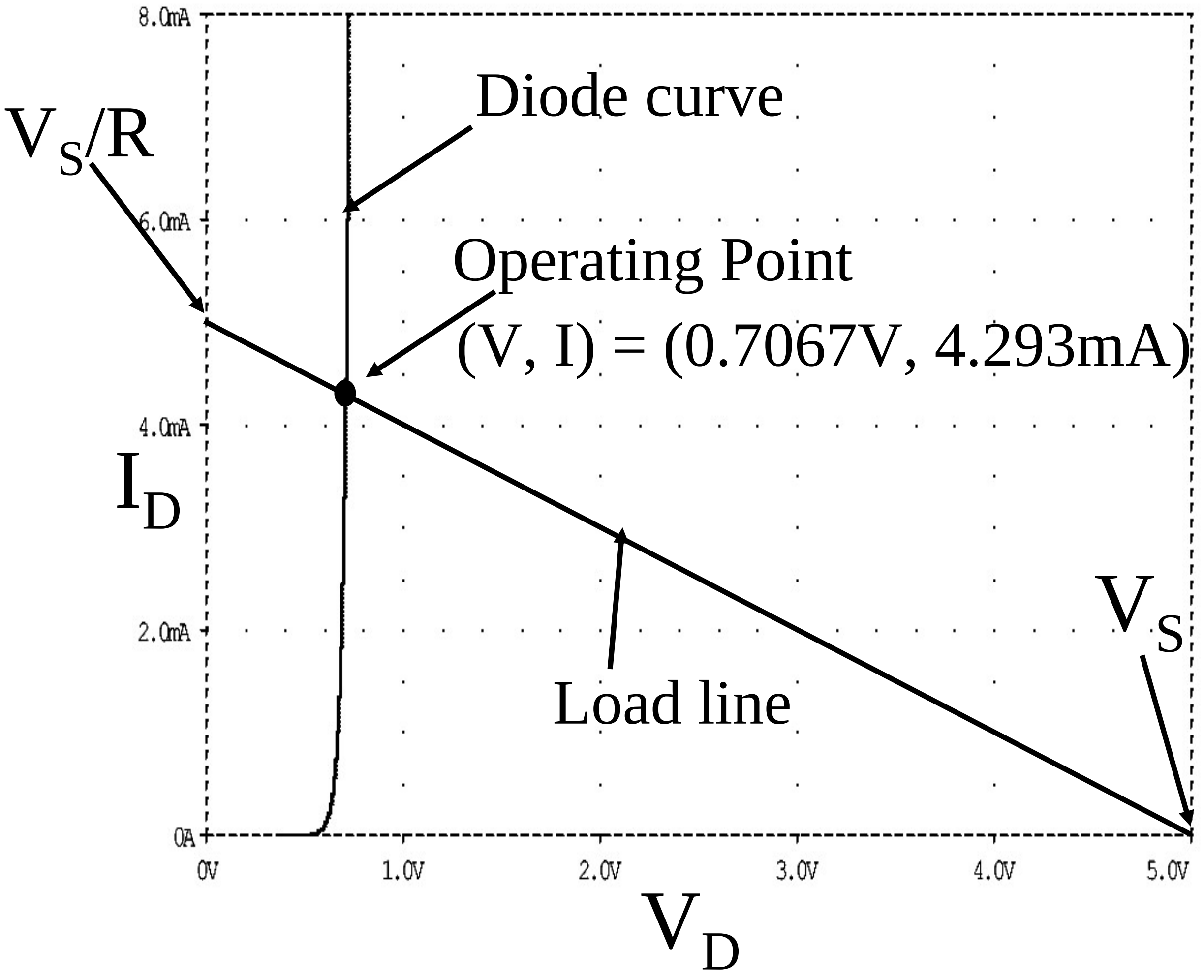
4) Use **Exponential or CVDM** to find the DC voltages and currents.

For example, in this circuit, if exponential model is used. we follow iterative solution or graphical solution:

a) Assume diode is in strong forward bias and governed by: $I_D = I_S e^{V_D/nV_T}$

b) Kirchhoff loop equation: $I_D = \frac{V_S - V_D}{R}$

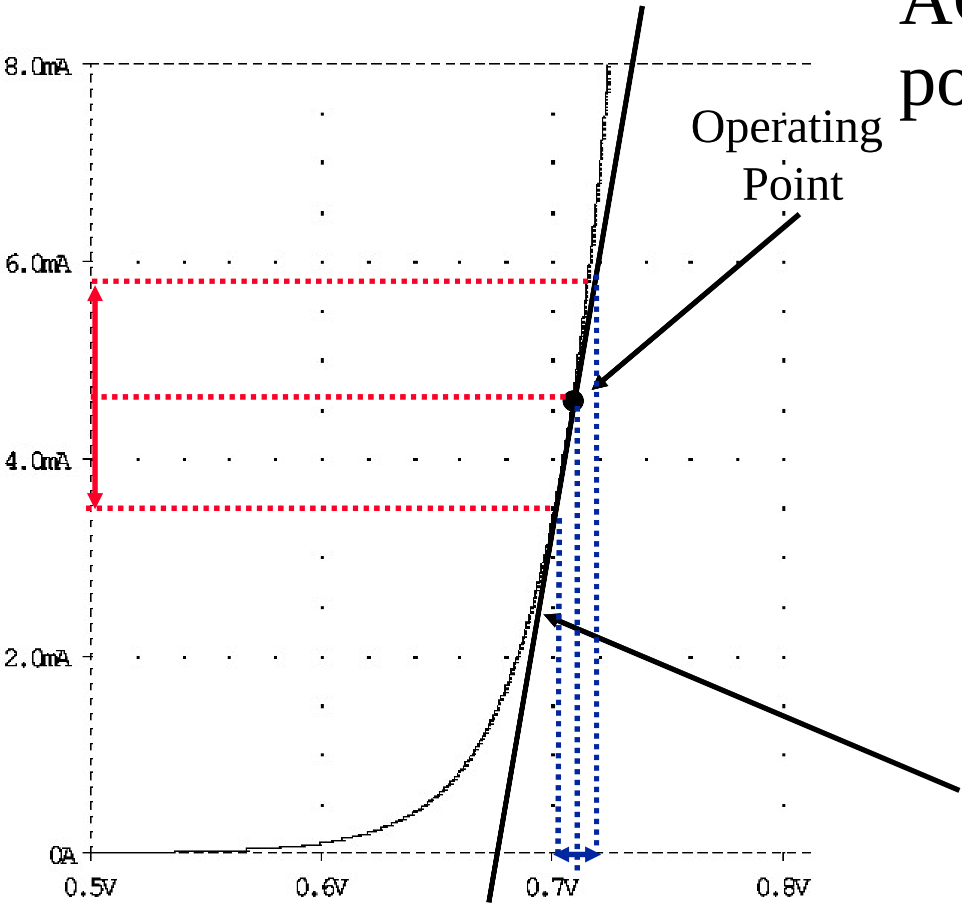
Example: Graphical Analysis



1) Plot two relationships on the i-v plane.

2) The solution is the intersection of the two graphs; operating point

AC Analysis: Diode Small Signal Model



Consider superposition of an AC signal at the DC operating point:

a) A ΔV will result in a ΔI

b) If ΔV is small, the resulting ΔI will be related linearly to ΔV

c) ***Slope*** of I-V curve ***at the operating point*** is defined as ***the diode small signal conductance/resistance***:

$$g_m \equiv \frac{1}{r_d} \equiv \left.\frac{\partial i_D}{\partial v_D}\right|_{OP} \approx \frac{\Delta I}{\Delta V}$$

Derivations to Find Diode's Small-Signal Resistance – r_d

To derive an expression for r_d, we use the exponential model and calculate the derivative at DC operating point:

<u>*Define:*</u> $r_d \equiv \left[\left. \frac{\partial i_D}{\partial v_D} \right|_{OP} \right]^{-1}$

$$i_D = I_S\left[e^{v_D/nV_T} - 1\right]$$

$$\frac{\partial i_D}{\partial v_D} = I_S \exp\left(\frac{v_D}{n \cdot V_T}\right) \cdot \frac{1}{n \cdot V_T}$$

$$I_S \exp\left(\frac{v_D}{n \cdot V_T}\right) = i_D + I_S$$

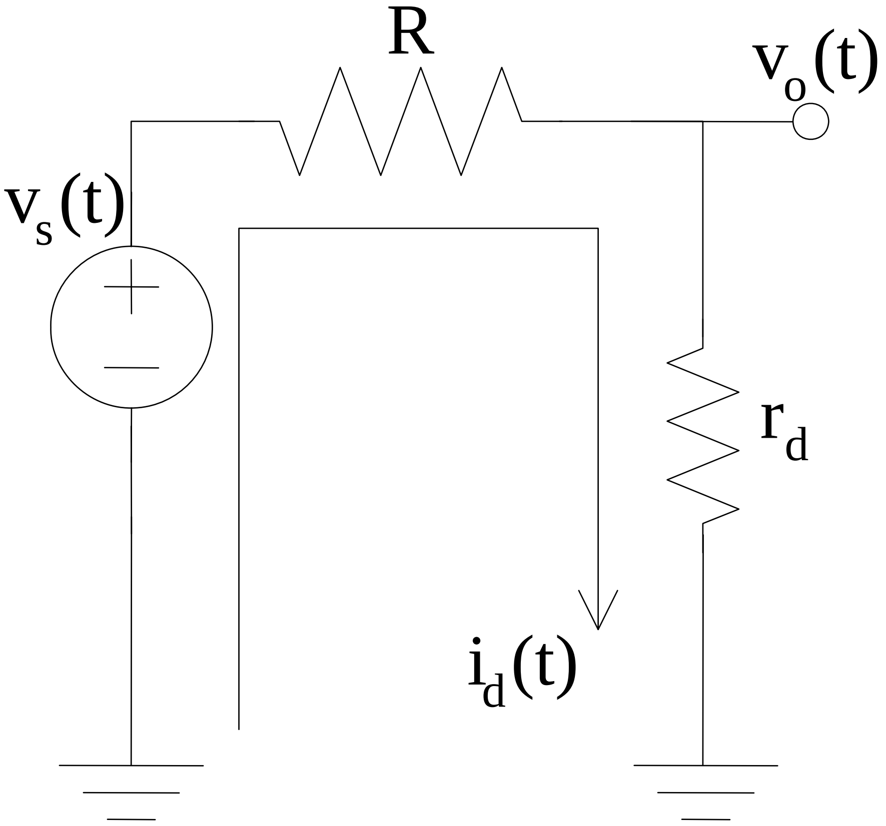
$$\therefore \frac{\partial i_D}{\partial v_D} = \frac{i_D + I_S}{n \cdot V_T} \approx \frac{i_D}{n \cdot V_T}$$

$$\boxed{r_d = \frac{n \cdot V_T}{I_D}}$$

Now plug in the operating point (the DC value of I_D) to find r_d

Complete AC Analysis

- The result of linearization around DC operating point is that **AC signals see the forward biased diode as a resistor: $\mathbf{r_d}$**
- Based on this result, we construct **the small-signal equivalent circuit** as shown
- Perform circuit analysis – in this case it is just a voltage division to find v_o



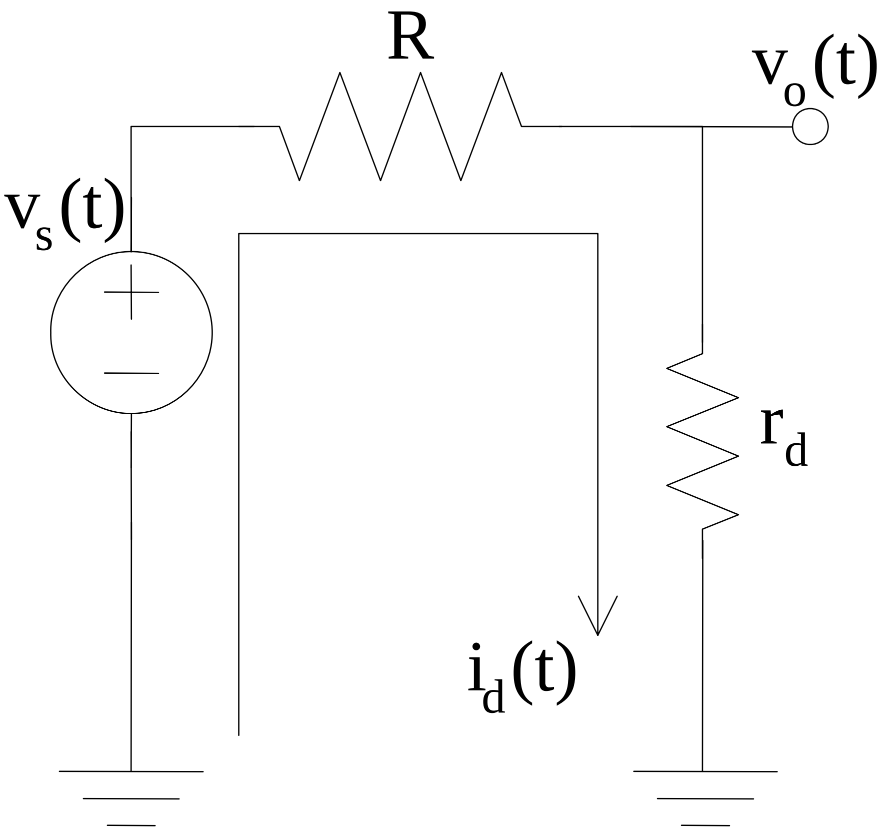
Complete AC Analysis

- Performing circuit analysis by first computing diode small signal resistance based on operating point:

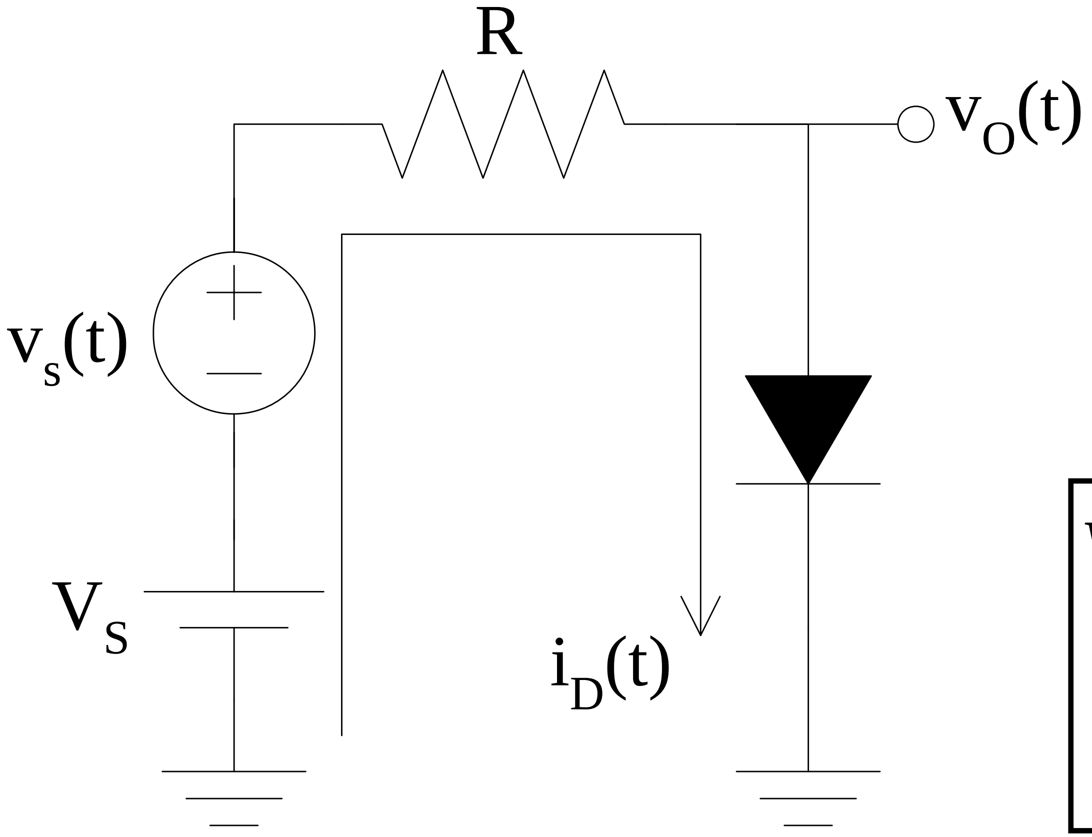
$$r_d = \frac{n \cdot V_T}{I_D} = \frac{(1.1)(25mV)}{4.293mA} = 6.4\Omega$$

- Complete voltage divider circuit analysis:

$$\frac{v_o}{v_s} = \frac{r_d}{r_d + R} = \frac{6.4}{6.4 + 1k} = 6.36 \, {}^{mV}\!/_{V}$$



Final Results- Linear Superposition



Total: $v_O(t) = V_O + v_o(t)$

DC: V_O

AC: $v_s(t) = V_p \sin(\omega t)$

$$\boxed{\begin{aligned} v_O(t) &= V_O + v_o(t) \\ &= 0.7067 + \\ &\quad 0.0063 \cdot V_p \sin(\omega t) \end{aligned}}$$

Small-Signal Analysis Technique Summary

- Tool for analyzing the behavior of circuits that contain nonlinear devices and have *small signal sources*
- Through linearization of the exponential model, we separate DC and AC analysis; linear superposition
- **Analysis procedure:**
  - Turn off AC sources, solve for DC operating point
  - Based on DC operating point parameters, solve for small signal-signal equivalent circuit model parameters
  - Construct small-signal equivalent circuit; short circuit voltage sources and open circuit current sources
  - Solve for AC parameters

Alternative Small-Signal Derivation Method of the text Book

$$i_D \approx I_S \exp\left(\frac{v_D}{n \cdot V_T}\right)$$

$$v_D \Rightarrow V_D + v_d$$

$$i_D \Rightarrow I_D + i_d$$

$$I_D + i_d = I_S \exp\left(\frac{V_D + v_d}{n \cdot V_T}\right) = I_S \exp\left(\frac{V_D}{n \cdot V_T}\right) \exp\left(\frac{v_d}{n \cdot V_T}\right)$$

$$I_D + i_d = I_D \exp\left(\frac{v_d}{n \cdot V_T}\right)$$

Condition for Small-Signal Derivation

$$I_D + i_d = I_D\left[1 + \frac{v_d}{n\cdot V_T} + \frac{\left(\frac{v_d}{n\cdot V_T}\right)^2}{2!} + \ldots\right] \approx I_D\left[1 + \frac{v_d}{n\cdot V_T}\right]$$

$$i_d = v_d \frac{I_D}{n\cdot V_T} \Rightarrow \frac{v_d}{i_d} = \frac{n\cdot V_T}{I_D} = r_d$$

$$\frac{v_d}{n\cdot V_T} << 1$$

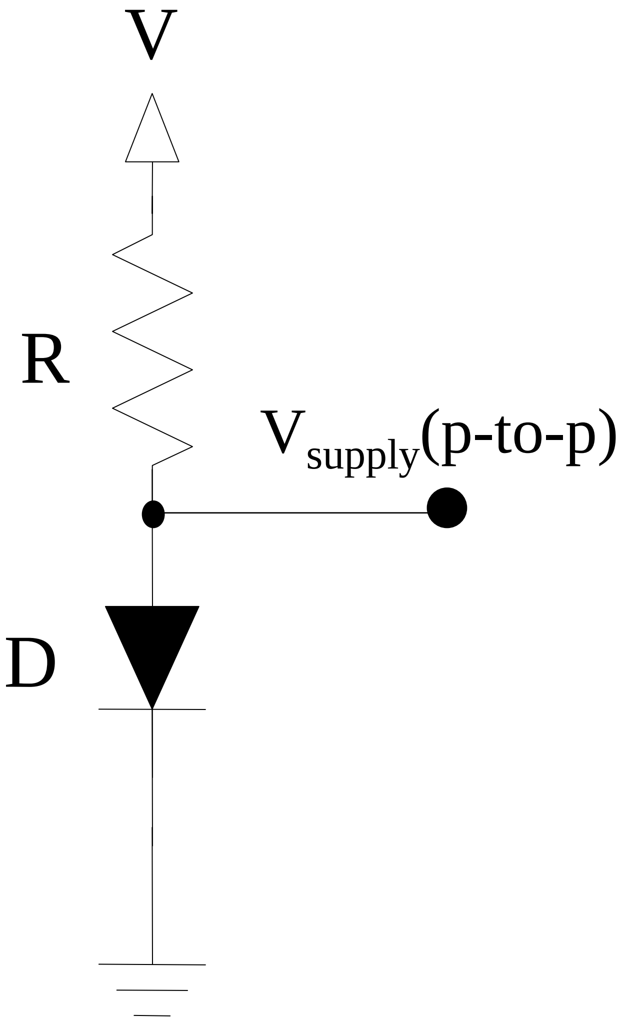
The condition for small signal assumption the applied AC signal:

$v_d << nV_T$

Small Signal Approximation

- Modeling diode as a resistor is an *approximation*
- Typically valid for signal amplitudes of order 10mV or less; this gets stretched to 25mV in some of S&S problems
- Although accurate, load line analysis and iterative analysis are not typically done when performing “hand” calculations of a diode circuit.
- DC voltage assumed to be 0.7V (CVDM) for purposes of determining I_D, and subsequently r_d

Example



1) Power supply: 10V with 60-Hz 1V peak amplitude fluctuation, also known as power supply ripple
2) R=10kΩ
3) Diode: Assume 0.7V drop at 1mA of current and n=2

Find the peak-to-peak signal voltage across the diode due to power supply ripple.

Example (cont')

- Using DC information given, can compute I_D, the DC diode current:

$$I_D = \frac{10 - 0.7}{10k\Omega} = 0.93mA$$

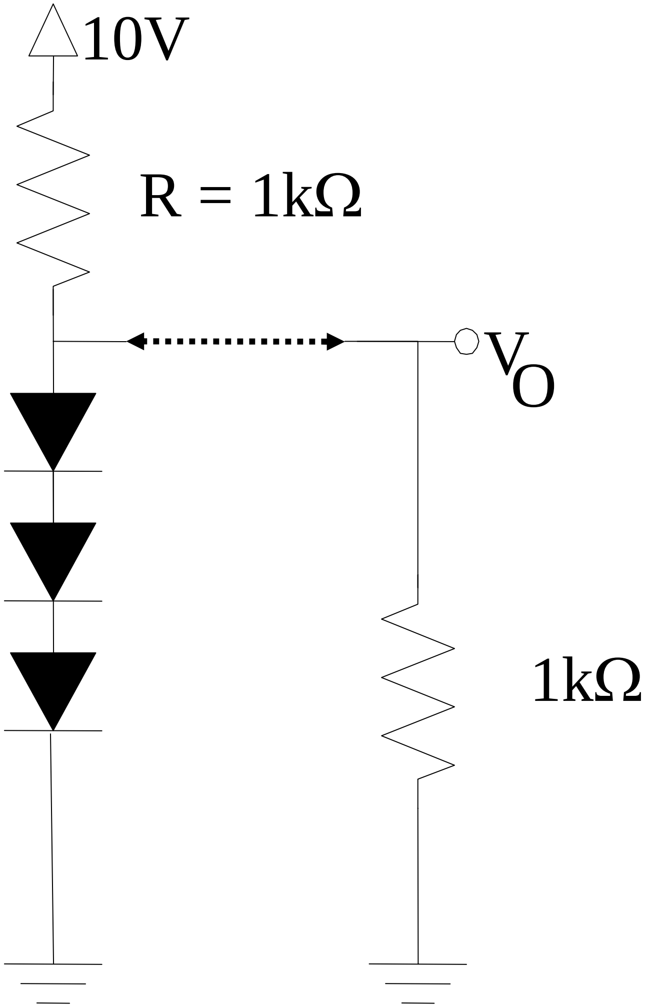
- Using this value for I_D, can compute diode small signal resistance:

$$r_d = \frac{n \cdot V_T}{I_D} = \frac{(2)(25mV)}{0.93mA} = 53.8\Omega$$

- Peak-to-peak signal voltage across diode found using voltage divider circuit analysis:

$$v_d(peak - to - peak) = 2V \frac{r_d}{R_D + r_d} = 2V \frac{53.8}{10k\Omega + 53.8} = 10.7mV$$

Example

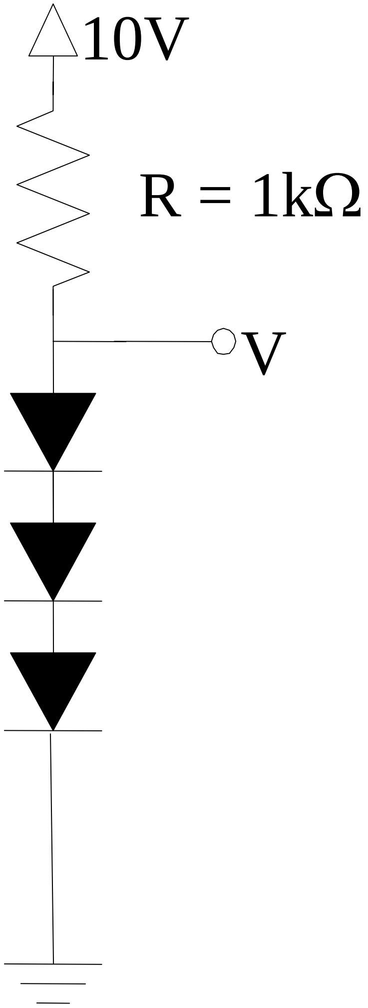


Consider circuit with 3 diodes in series with a resistor and power supply.

Calculate the percentage change in the voltage across the diodes caused by connecting a 1kΩ resistor.

All diodes have n=2 and can assume CVD model for DC analysis.

Compute Diode Small Signal Resistance



- Start assuming resistor not attached; V_O = 2.1V (3x0.7V).
- Nominal current through string

$$I = \frac{10 - 2.1}{1k\Omega} = 7.9mA$$

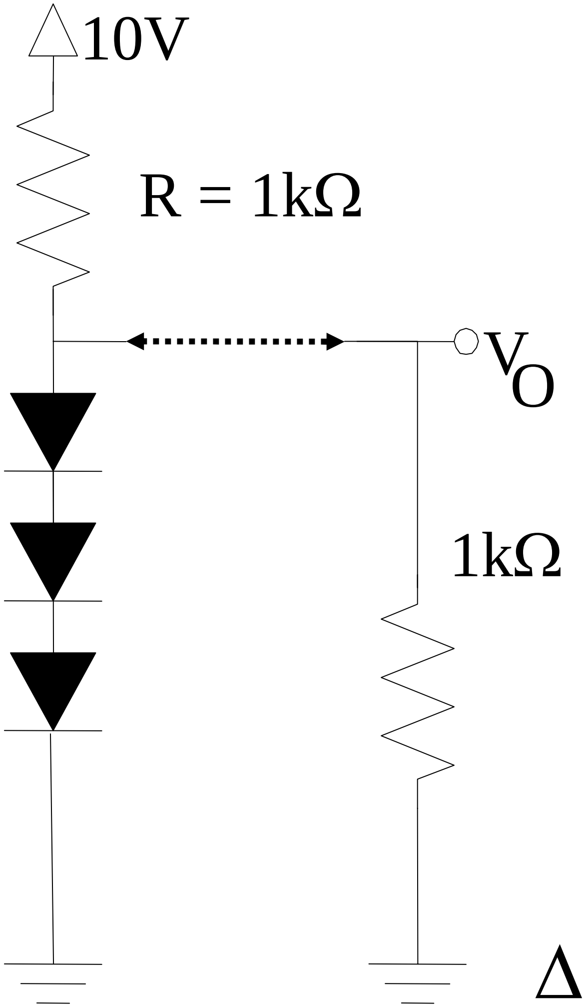
- Diode small signal resistance

$$r_D = \frac{2 \times 0 \cdot 25mV}{7.9mA} = 6.3\Omega$$

- Total resistance

$$r = 3r_d = 18.9\Omega$$

Compute Impact of Attaching Load



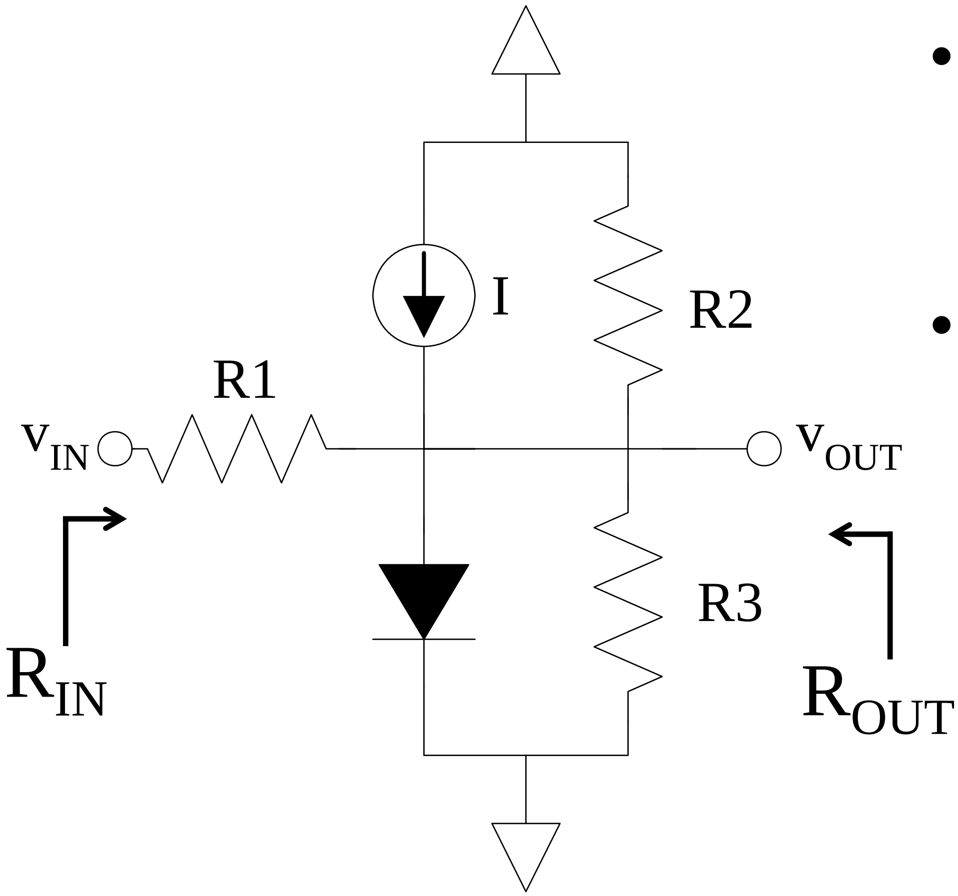
- Hook up load resistor and estimate how much current will be drawn by the load; since DC voltage drop across 3 diodes is 2.1 V, can assume

$$I_{load} \approx \frac{2.1V}{1k\Omega} = 2.1mA$$

- Result is a reduction in diode current of ~ 2.1 mA; can use this to calculate reduction in v_o:

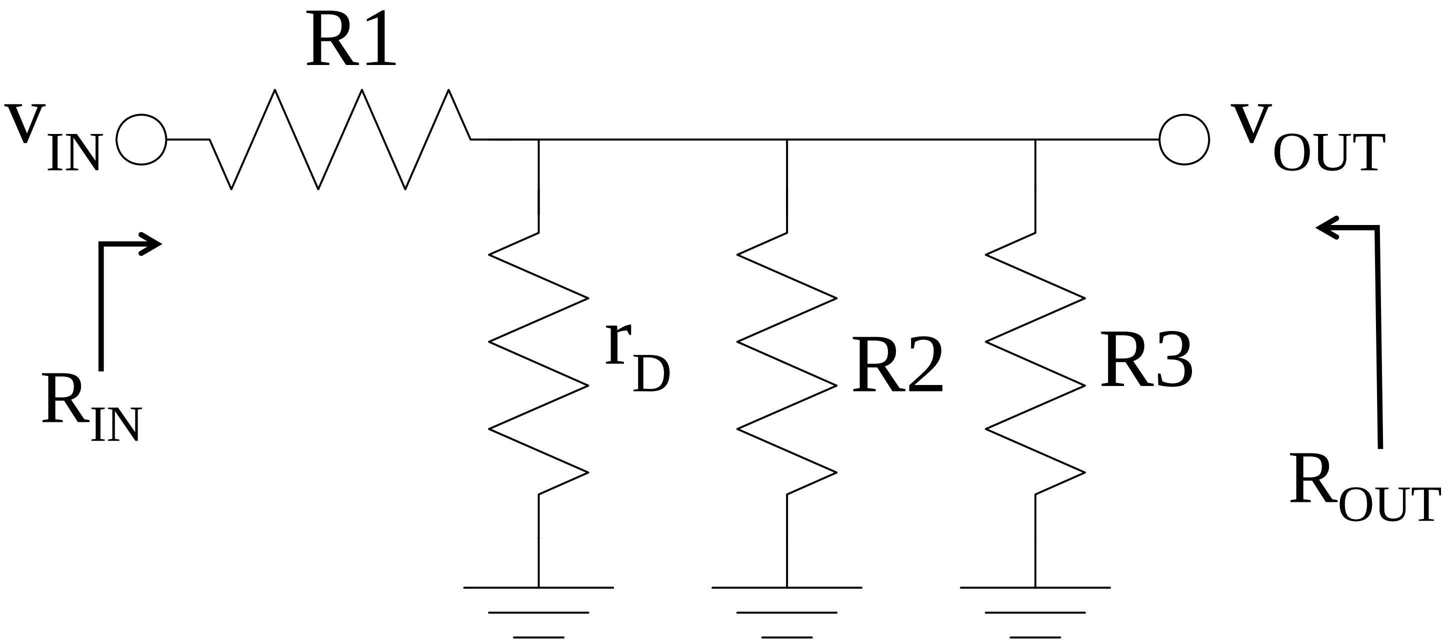
$$\Delta v_O = -2.1 \times r = -2.1 \times 18.9 = -39.7mV$$

Input/Output Signal Resistance



- Consider following circuit with DC voltage and current sources
- Compute R_{IN} & R_{OUT} the small signal resistance seen at the input and output, respectively

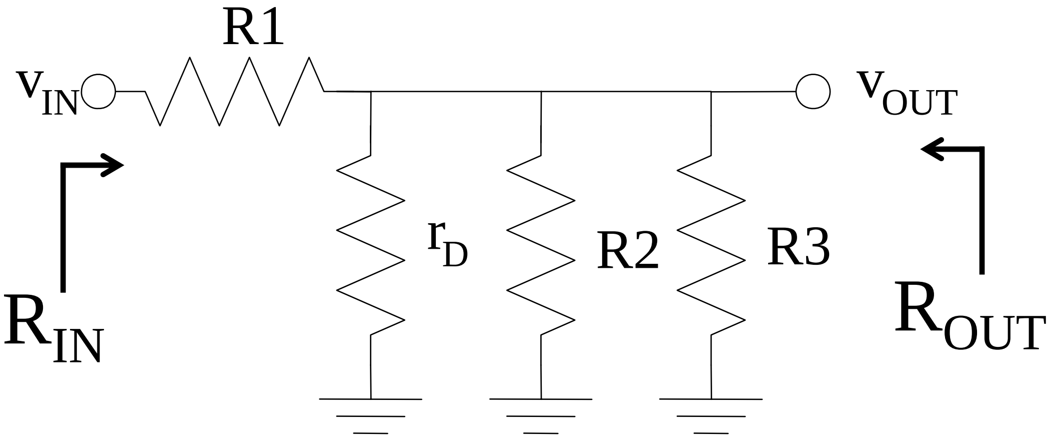
Draw Small Signal Equivalent Circuit



Note: **In AC/small signal analysis batteries (DC Supply voltages) are short circuited and current sources are open circuited**

Compute Input/Output Signal Resistance

- Find R_{IN} by inspection
- For R_{OUT}, use method #2 (discussed in the introduction to amplifiers slides)
- Ground v_{IN} in the small-signal circuit
- Now, find R_{OUT} by inspection:



$$\boxed{R_{IN} = R_1 + r_D \| R_2 \| R_3}$$

$$\boxed{R_{OUT} = R_1 \| r_D \| R_2 \| R_3}$$