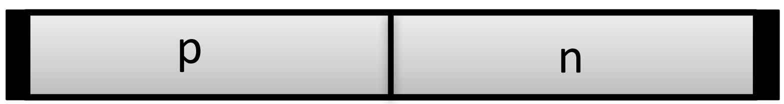
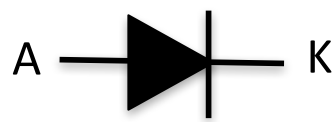
Chapter 5

Electronics I - Diode Circuits





Fall 2017

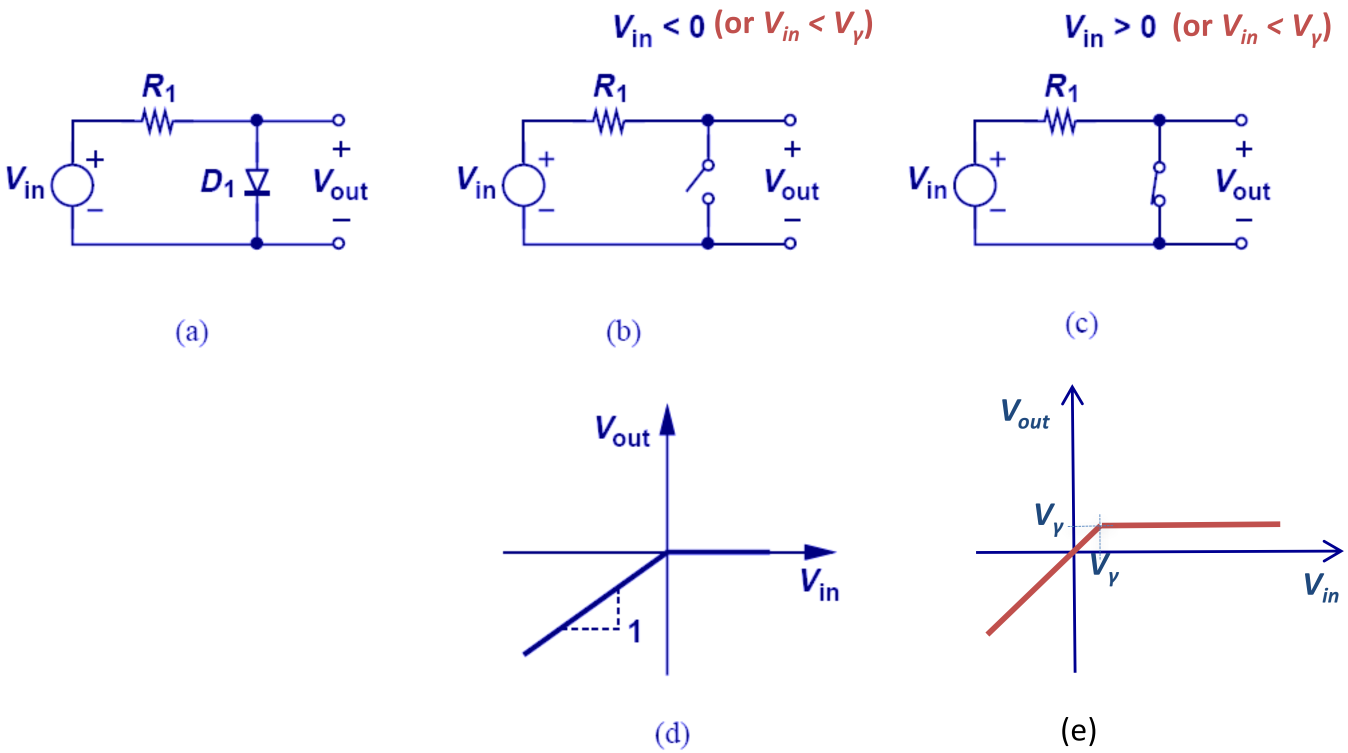
Diode Circuits

- Applications:
  - Rectifiers
  - Limiting Circuits (a.k.a. clippers)
  - Detectors
  - Level Shifters (a.k.a. clampers)
  - Regulators
  - Voltage doublers
  - Switches

Warm-up examples

__Example #1:__ diode and resistor in series

source: Razavi



Side note:

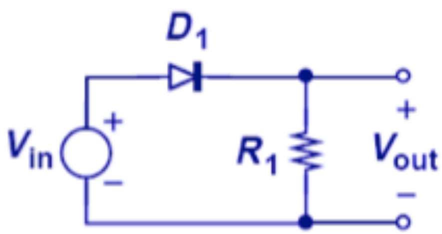
1. When the diode is forward biased the current though the diode is $\approx V_{in}/R$: we cannot make make V_{in} get so large that $V_{in}/R > I_{F,peak}$ otherwise the diode "melts"
2. When the diode is reverse biased the voltage across the diode is $\approx$–Vin: we cannot make Vin get so small that $|-V_{in}| > V_{R,peak}$ otherwise the diode "breaks" $V_{R,peak}$ is a.k.a. PIV (Peak Inverse Voltage)

The input/output characteristics with **ideal** and constant-voltage models yields two different break points. Applying an inappropriate diode's model can be misleading !

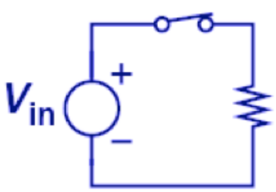
Warm-up examples

<u>Example #2:</u> diode and resistor in series (half-wave rectifier)

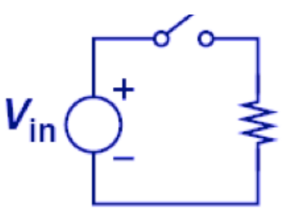
source: Razavi

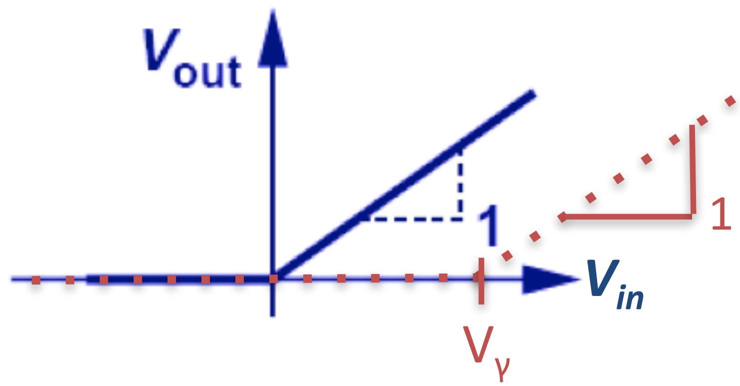


$V_{in} > 0$ (or $V_{in} > V_\gamma$)



$V_{in} < 0$ (or $V_{in} < V_\gamma$)

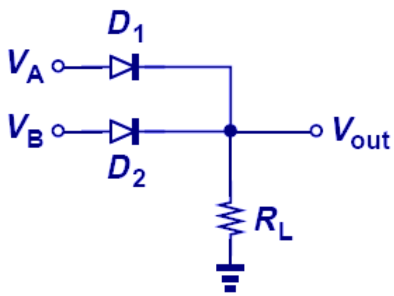




Warm-up examples

Example #3: diode implementation of OR gate

source: Razavi



VA (V)	VB (V)	Vout (V)	D1	D2
0	0	0	OFF	OFF
0	5	≈5	OFF	ON
5	0	≈5	ON	OFF
5	5	≈5	ON	ON

Let's try a few cases:

$V_A = 5V \ and \ V_B = 4V$

Let's guess D_1 is ON $\Rightarrow V_{out}(A-side) = V_A - V_\gamma = 4.3V$

Let's guess D_2 is ON $\Rightarrow V_{out}(B-side) = V_B - V_\gamma = 3.7V \Rightarrow BAD \ GUESS$!!

V_{out}(A-side) must be the same as V_{out}(B-side) otherwise we violate KVL !! $\Rightarrow$ D_2 is OFF

$V_A = 3V \ and \ V_B = 0V$

Let's guess D_1 is ON $\Rightarrow V_{out} = V_A - V_\gamma = 2.3V$

Let's guess D_2 is OFF

$V_A = 0.6V \ and \ V_B = 0V$

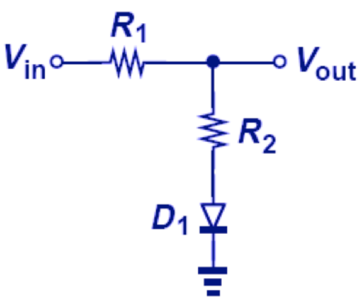
$$\left.\begin{array}{l}\text{Let's guess } D_1 \text{ is } OFF \\ \text{Let's guess } D_2 \text{ is } OFF\end{array}\right] \Rightarrow V_{out} = 0V$$

CONSISTENCY METHOD:
It is sometime difficult to correctly predict the region of operation of each diode by inspection. In such cases, we may simply make an "educated" guess proceed with the analysis, and eventually determine if the final result agrees or conflicts with the original guess.

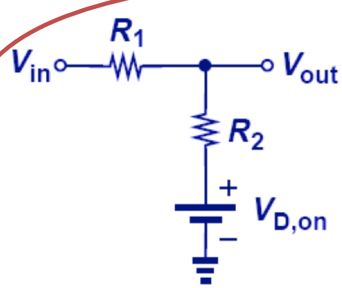
Warm-up examples

Example #4:

source: Razavi



When the diode is ON we can model the circuit as follow:



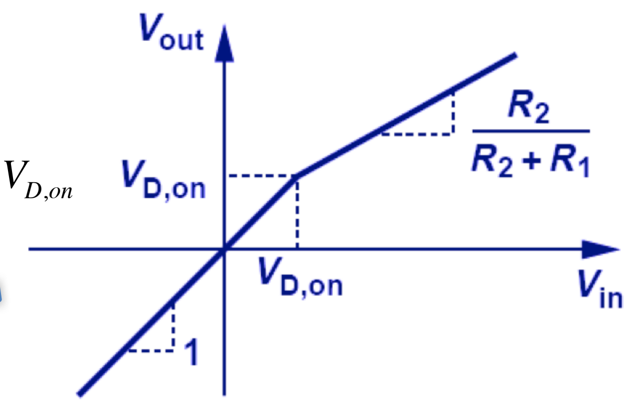
From the model of the circuit is easy to see that if $V_{in} < V_{D,on}$ we cannot have current flowing through the diode => the diode must be OFF $\rightarrow V_{out} = V_{in}$

slope

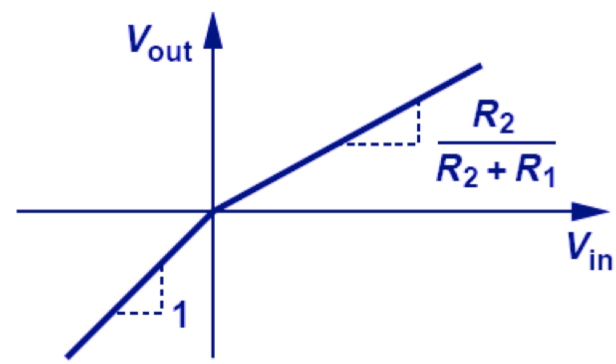
$$V_{out} = \frac{V_{in} - V_{D,on}}{R_1 + R_2} R_2 + V_{D,on} = \frac{R_2}{R_1 + R_2} V_{in} + V_{D,on} \frac{R_1}{R_1 + R_2}$$

$$@V_{in} = V_{D,on} \Rightarrow V_{out} = V_{D,on}$$

$$@V_{in} = V_{D,on} \Rightarrow V_{out} = V_{D,on}$$



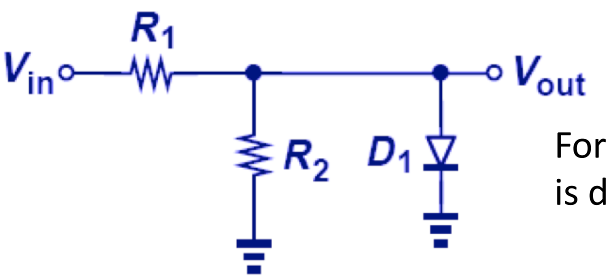
If we prefer to use the ideal diode model all we have to do is to assume $V_{D,on}$=0 rather than $V_{D,on}$=0.7V. We do not need a lot of deep thinking to get the associated I/O characteristic



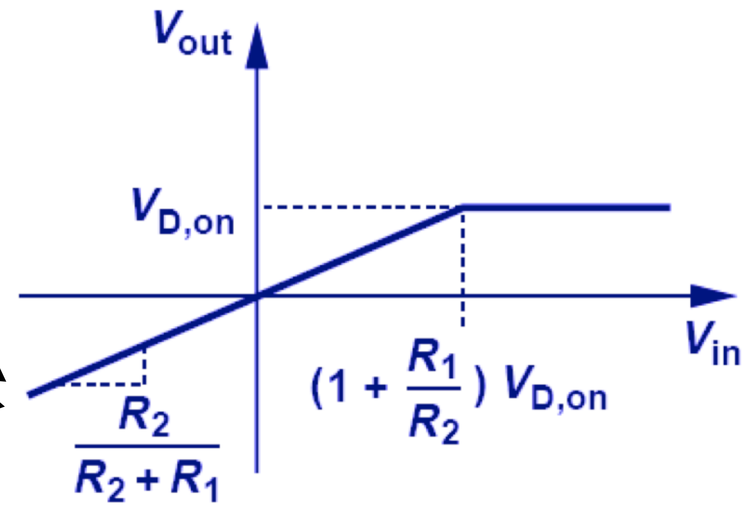
Warm-up examples

Example #5:

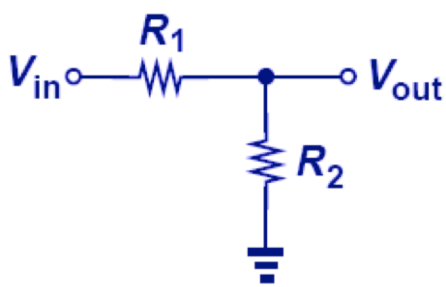
source: Razavi



For $V_{in} < 0$ the diode is definitely OFF



When the diode is OFF we can model the circuit as a resistive divider:



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

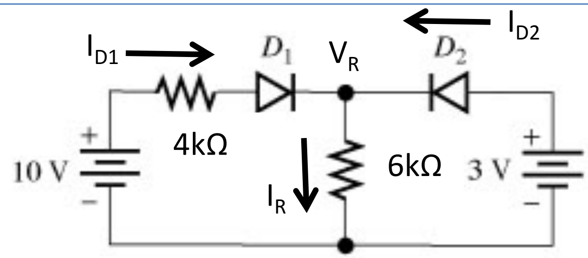
When the diode goes ON => $V_{out} = V_{D,on}$ =>

=> so the turn on point is $V_{D,on} = \frac{R_2}{R_1 + R_2} V_{in} \Rightarrow V_{in} = V_{D,on} \frac{R_1 + R_2}{R_2}$

Warm-up examples

Example #6:

source: Hambley



1. Let's assume both diodes are ON

$$V_R = 3V \rightarrow I_R = 3/6k = 0.5mA$$

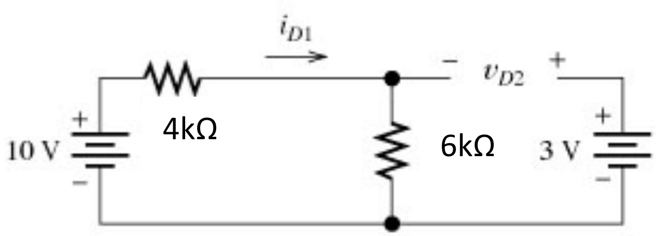
$$I_{D1} = \frac{10-3}{4k} = 1.75mA$$

$$KCL:$$

$$I_{D1} + I_{D2} = I_R \rightarrow I_{D2} = I_R - I_{D1} = -1.25mA$$

The result is not consistent: current cannot flow from K to A

2. D_1 is ON and D_2 is OFF



$$I_{D1} = I_R = \frac{10}{4k+6k} = 1mA$$

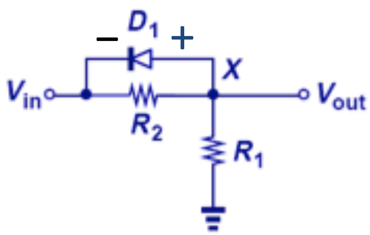
$$V_R = I_R \times R = 1m \times 6k = 6V$$

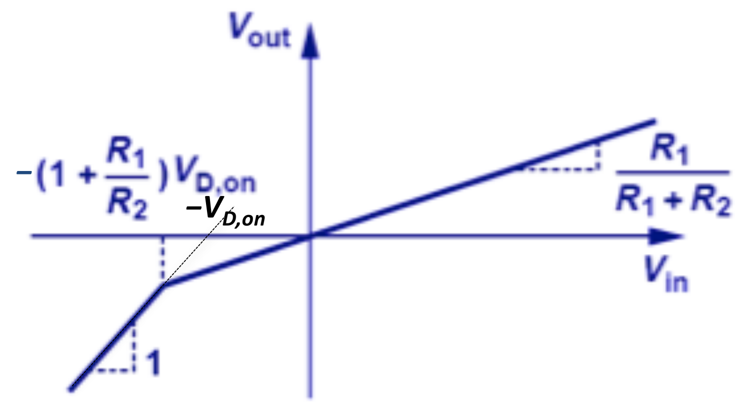
$$V_{D2} = 3V - 6V = -3V$$

Warm-up examples

Example #7:

source: Razavi





For $V_{in} < 0$ the diode is definitely ON.
When the diode is ON:

$V_{out} = V_{in} + V_{D,on}$ (straight line with slope 1 and crossing x axis at $-V_{D,on}$)

When the diode is OFF, the circuit can be modeled as a voltage divider:

$V_{out} = \frac{R_1}{R_1 + R_2} V_{in}$ (straight line passing through the origin and with slope R1/(R1+R2))

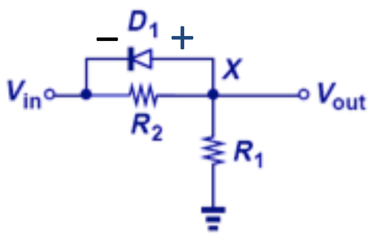
The break point between ON and OFF is when $V_{out} = V_{in} + V_{D,on}$

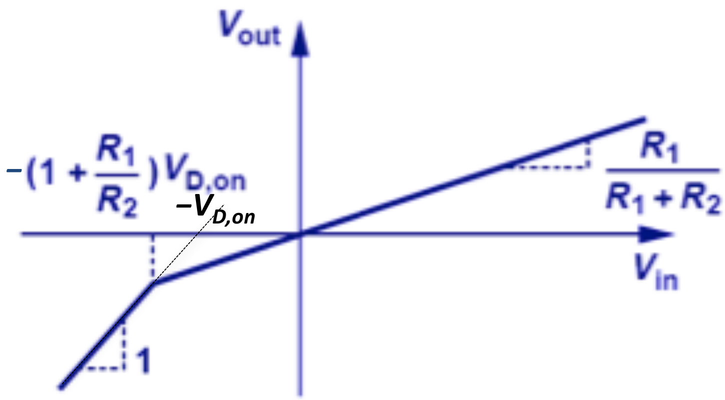
$$V_{in} + V_{D,on} = \frac{R_2}{R_1 + R_2} V_{in} \Rightarrow V_{D,on} = -\frac{R_2}{R_1 + R_2} V_{in} \Rightarrow V_{in} = -V_{D,on} \frac{R_1 + R_2}{R_2}$$

Warm-up examples

Example #8:

source: Razavi





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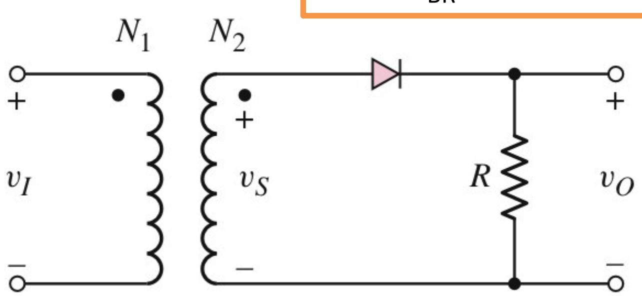
Half-wave rectifiers

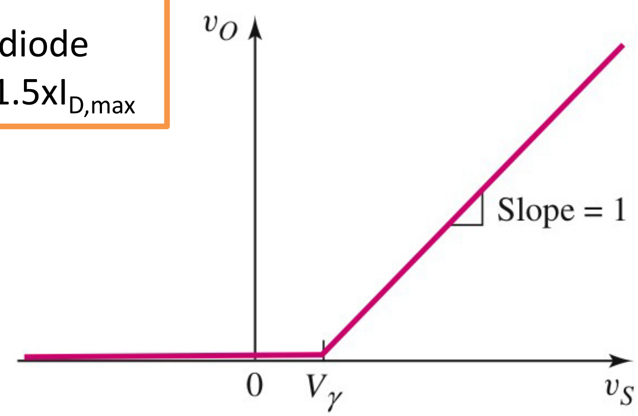
Rule of thumb
it is good practice to select a diode with $V_{BR} \geq 1.5 \times PIV$ and $I_{F,max} \geq 1.5 x I_{D,max}$

source: Neamen



$$\frac{v_I}{v_S} = \frac{N_1}{N_2}$$

(a)



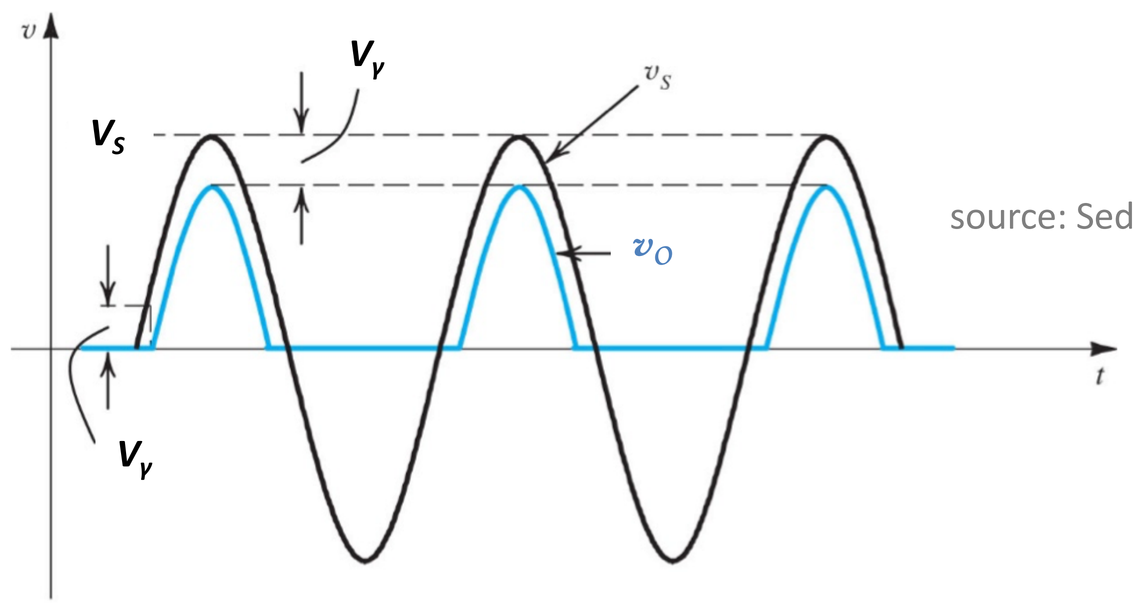
(b)

When the diode is ON the max current flowing through the diode is:

$$I_{D,\max} = \frac{V_S - V_\gamma}{R} \cong \frac{V_S}{R}$$

When the diode is OFF the PIV across the diode is:

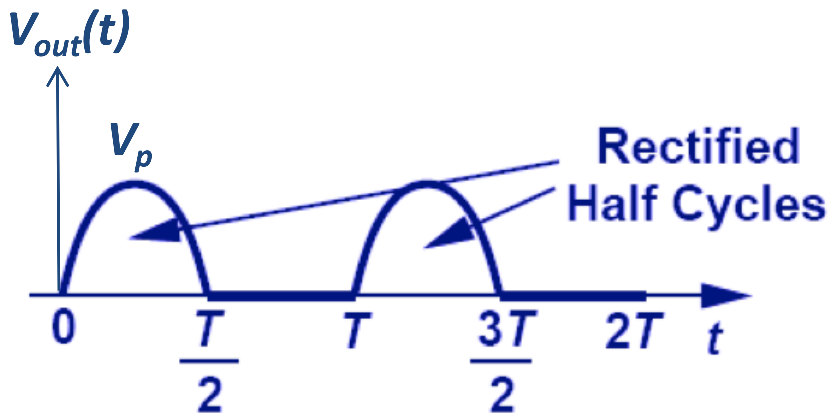
$$PIV = V_S$$



source: Sedra & Smith

Half wave rectifier as a signal strength indicator

source: Razavi



$$V_{out}(t) = \begin{cases} V_p \sin \omega t & \text{for } 0 \leq t \leq T/2 \\ 0 & \text{for } T/2 \leq t \leq T \end{cases}$$

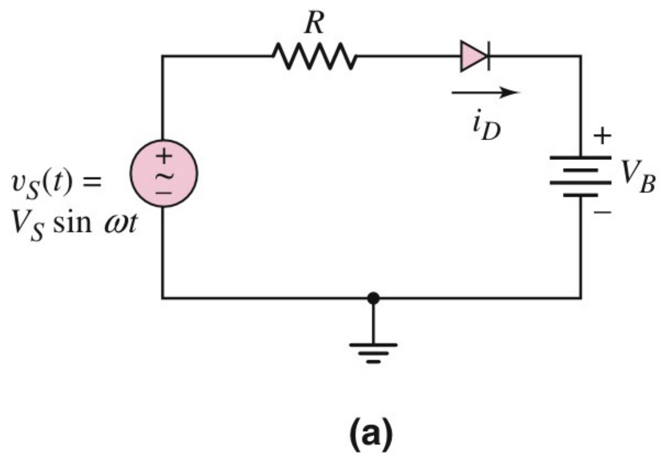
$$V_{out,avg} = \frac{1}{T}\int_0^T V_{out}(t)\,dt = \frac{1}{T}\int_0^{T/2} V_p \sin \omega t\,dt = \frac{1}{T}\frac{V_p}{\omega}\left[-\cos \omega t\right]_0^{T/2} = \frac{V_p}{\pi}$$

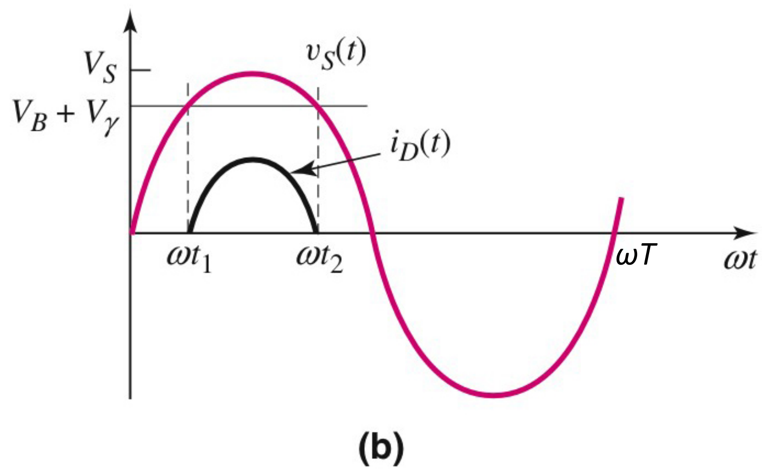
$$V_{out,rms} = \frac{V_P}{2\sqrt{2}}$$

Half wave rectifier as a battery charger

source: Neamen

$$V_S > V_{B,nominal} + V_\gamma$$

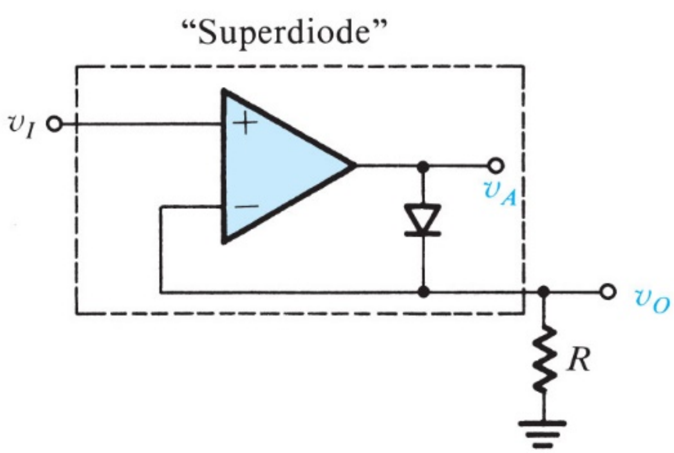




- if $V_B < V_{B,nominal}$ the battery get recharged (diode is ON from t1 to t2)
- otherwise the battery is left alone (the diode is OFF all period T)

Precision half-wave rectifier

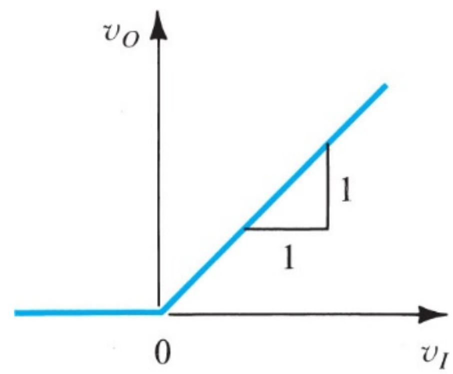
source: Sedra & Smith



(a)

$$PIV = -V_{SS}$$

$$I_{F,\max} = \frac{V_{O,\max}}{R_L} = \frac{V_{I,\max}}{R_L}$$



(b)

- If $v_I > 0$ the diode is ON.
  With the diode ON the circuit becomes a follower.

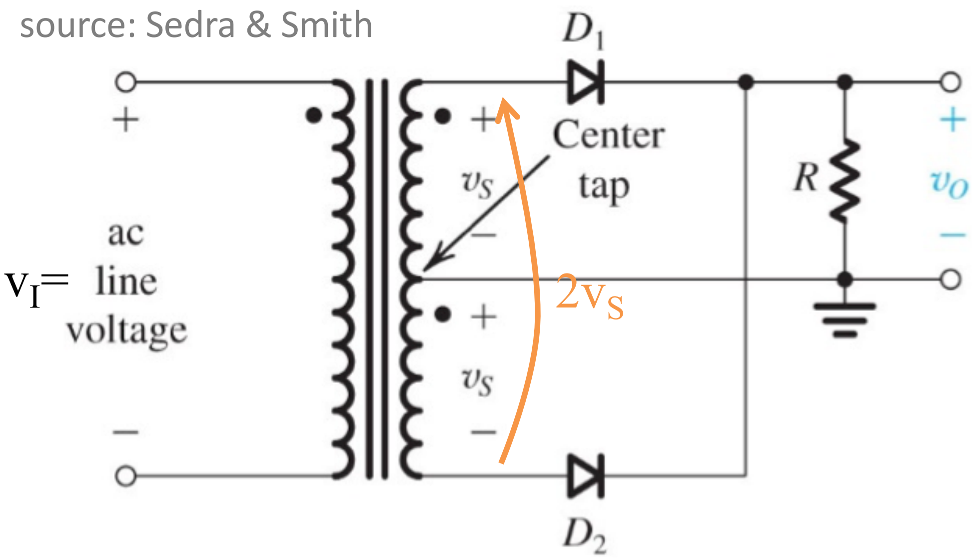
- If $v_I < 0$ the diode is OFF
  with the diode OFF the load is at ground

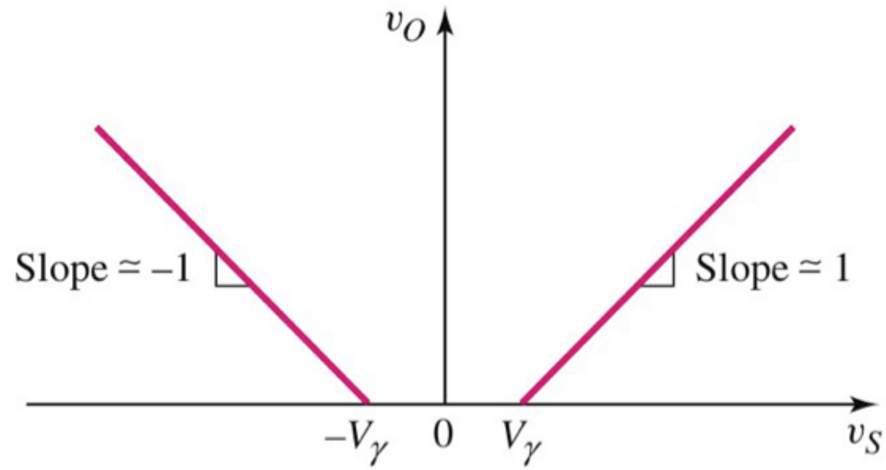
The transfer function is almost ideal: it doesn't suffer from having one or two diode drops

- For the o.a. to start to operate and turn-on the diode, v_I has to exceed only a negligibly small voltage equal to V_γ/A_d

Full-wave rectifiers

source: Sedra & Smith

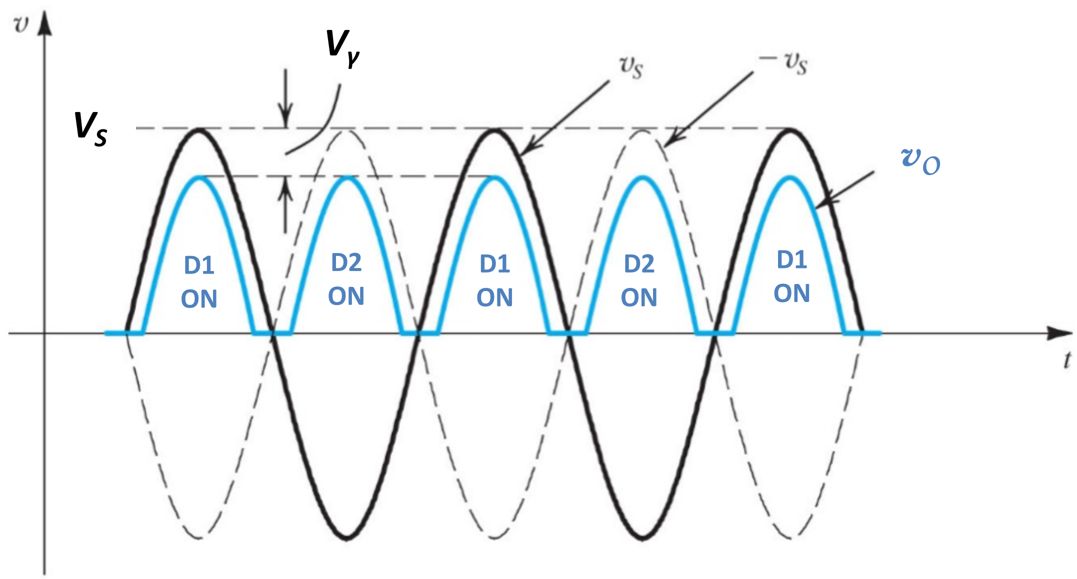




source: Neamen

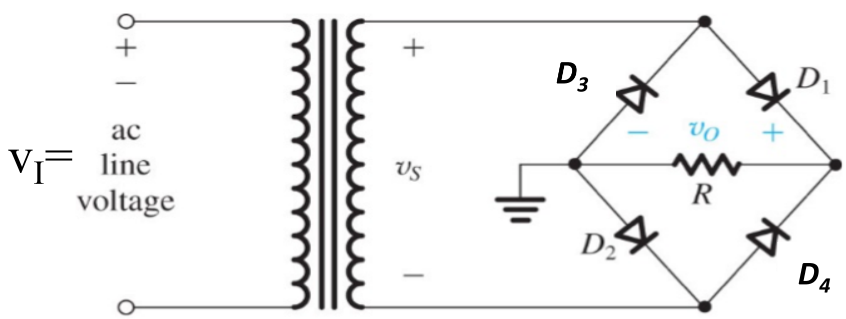
$$I_{D,\max} = \frac{V_s - V_\gamma}{R} \cong \frac{V_S}{R}$$

$$PIV = V_s - V_\gamma - (-V_S) = 2V_S - V_\gamma$$



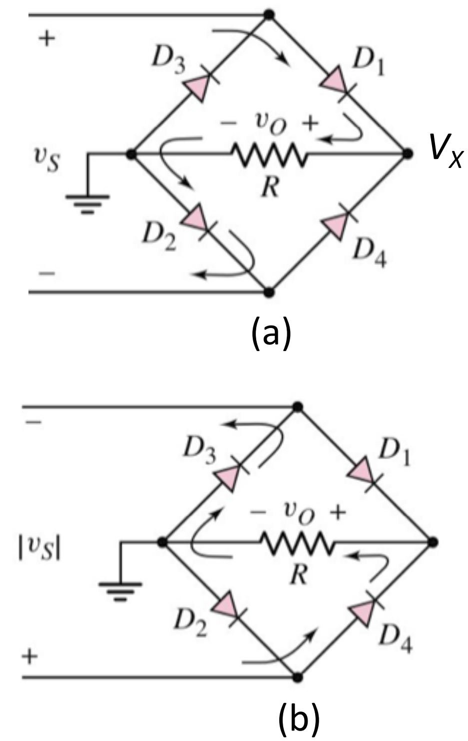
Diode-bridge full wave rectifier

a.k.a. *Grätz bridge*

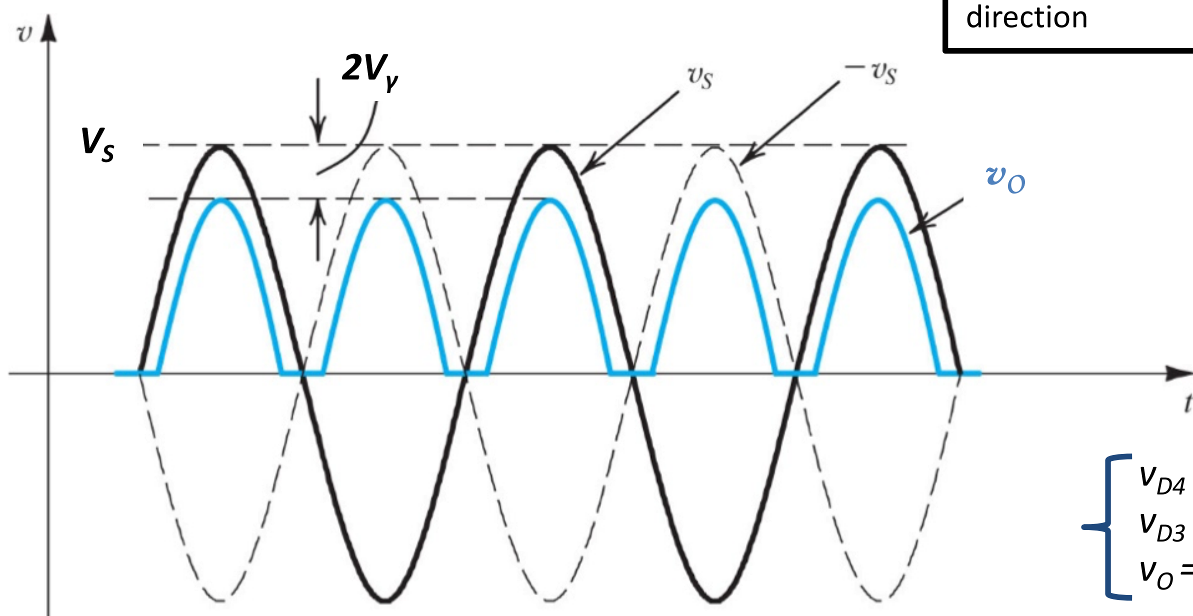


(a) when v_S is positive, D_1 and D_2 are turned ON
(b) when v_S is negative, D_3 and D_4 are turned ON

In either case current flows through R in the same direction



source: Neamen



source: Sedra & Smith

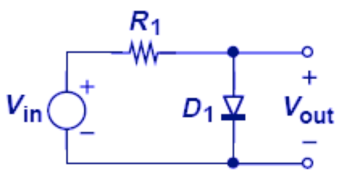
$$\begin{cases} v_{D4} = v_s - v_{D1} \\ v_{D3} = v_{D1} + v_O \\ v_O = v_s - 2V_\gamma \end{cases}$$

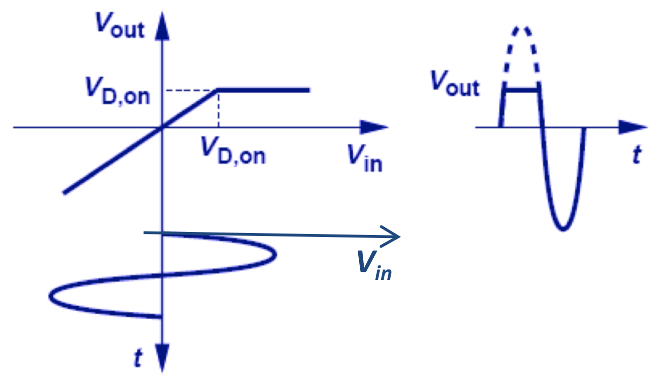
$$I_{D,\max} = \frac{V_s - 2V_\gamma}{R} \cong \frac{V_S}{R}$$

$$PIV = V_S - V_\gamma$$

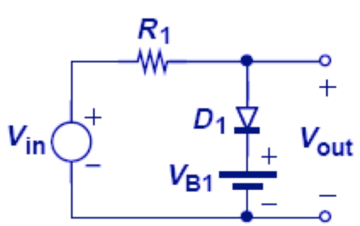
Clippers (a.k.a. Limiters)

- The idea behind clippers is quite simple. We have already built one in the past

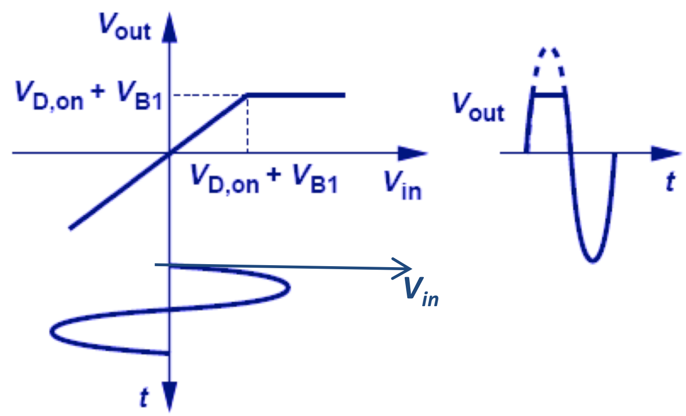




- All we have to do to shift the clipping threshold to a different value is to add a battery

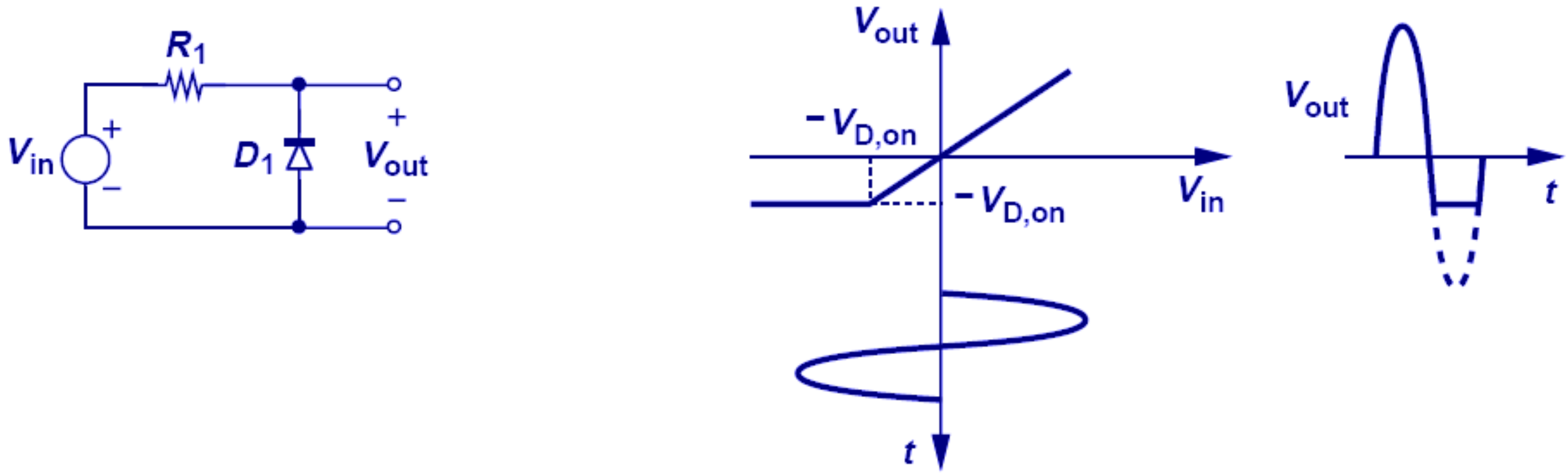


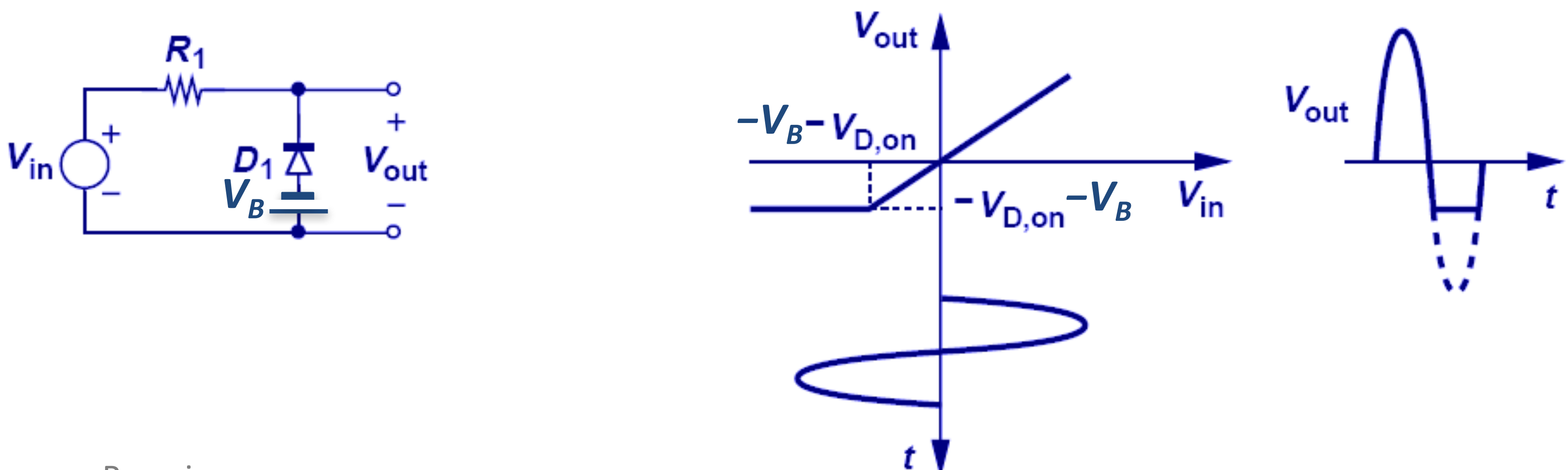
Positive-cycle limiting circuit



source: Razavi

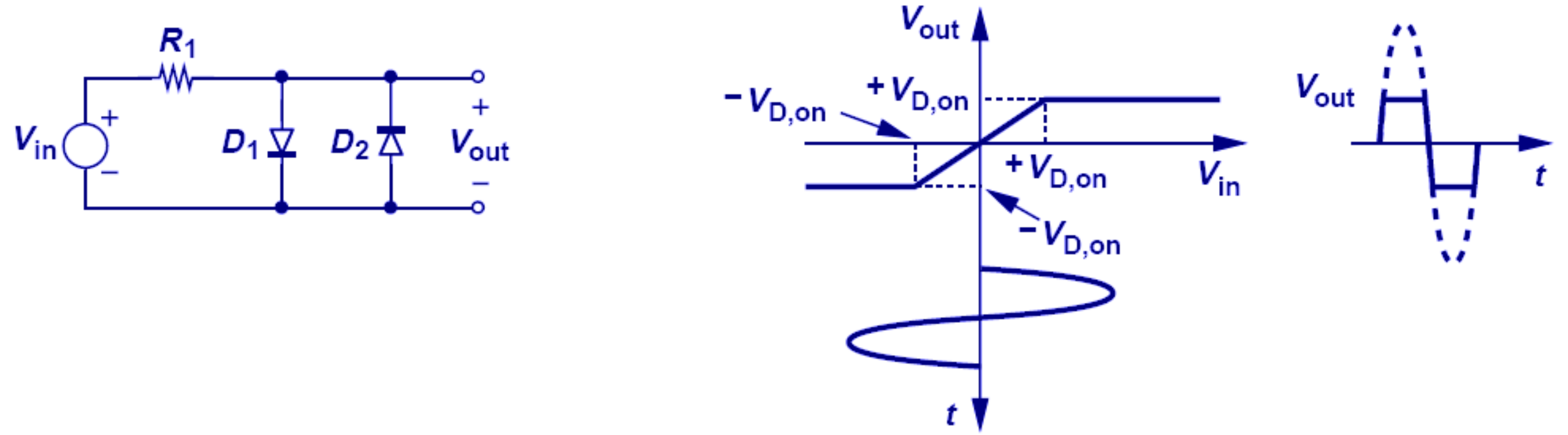
Negative-cycle clipping

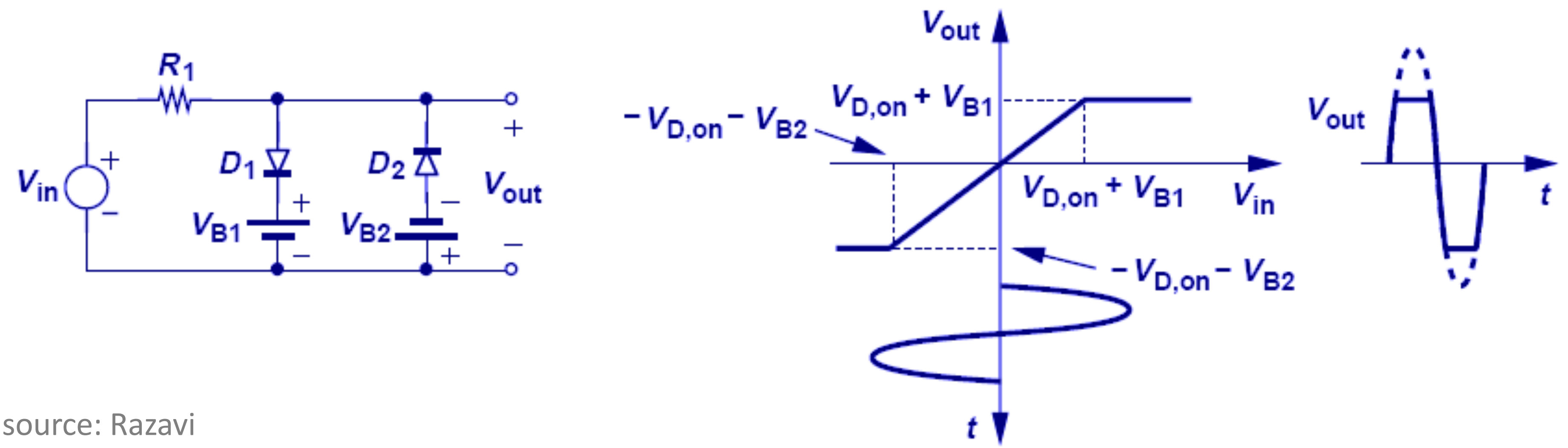




source: Razavi

Positive and negative cycle clipping



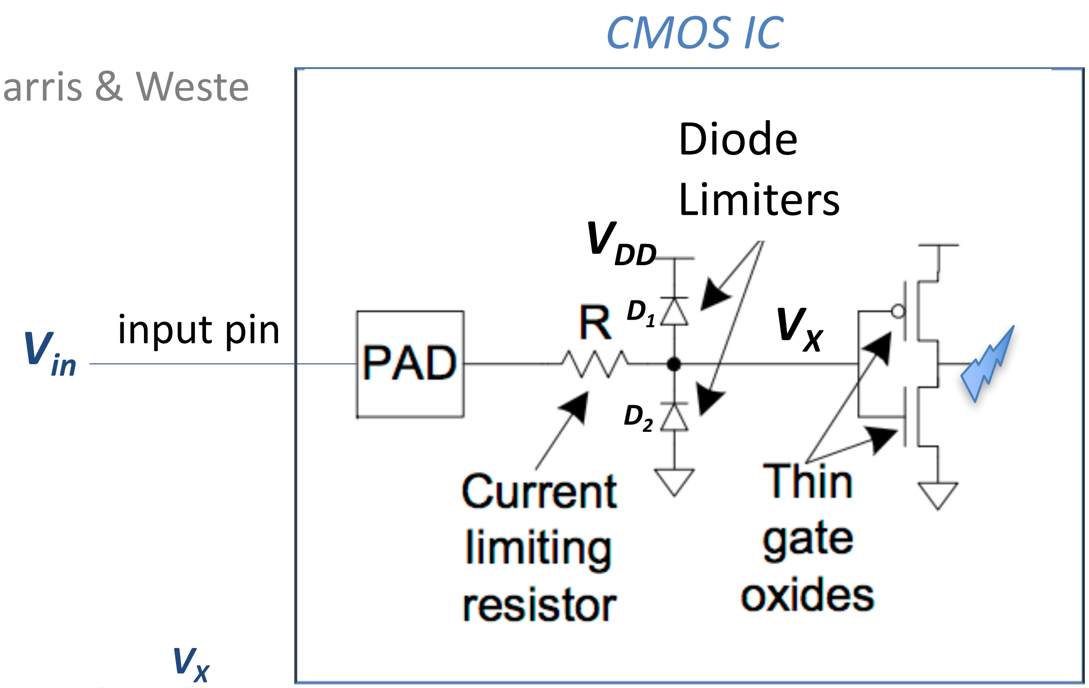


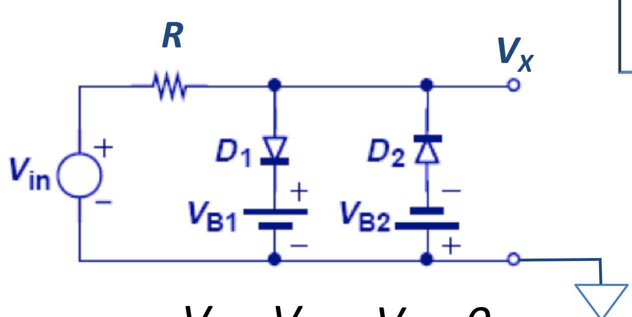
source: Razavi

A very common clipper's application

- Protection circuitry: keep the signals below certain thresholds

source: Harris & Weste

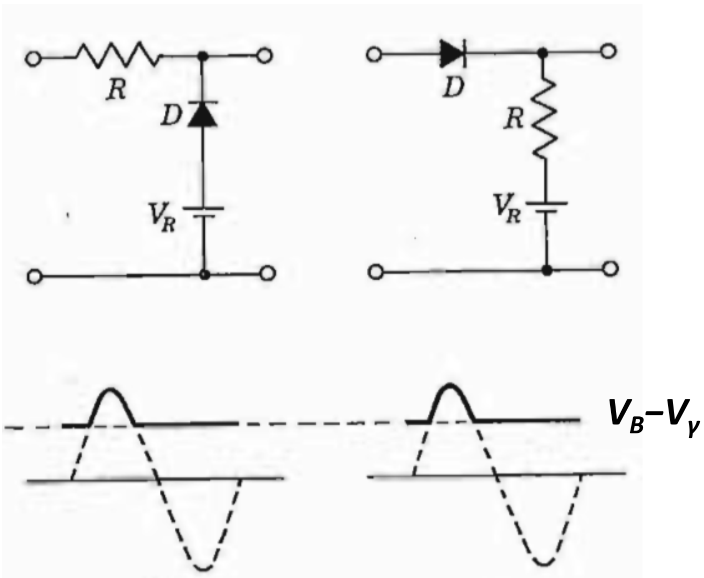


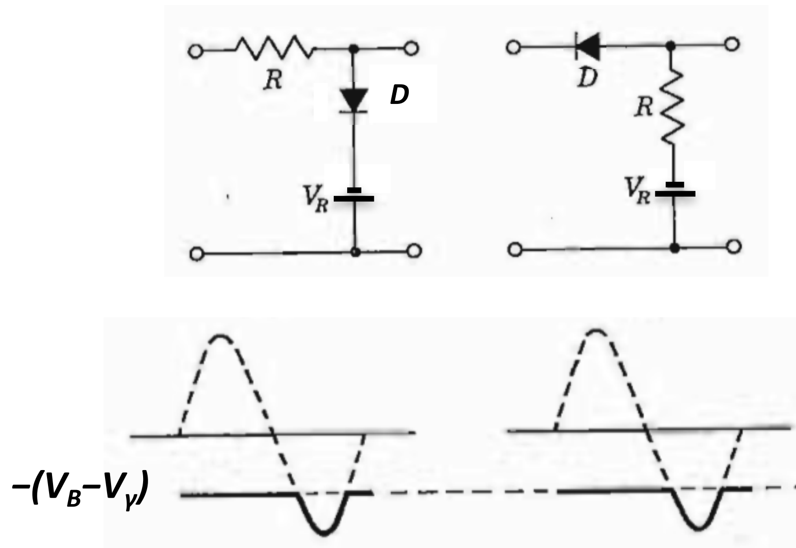


$V_{B1}=V_{DD}$ $V_{B2}=0$

source: Razavi

“Unconventional” clippers



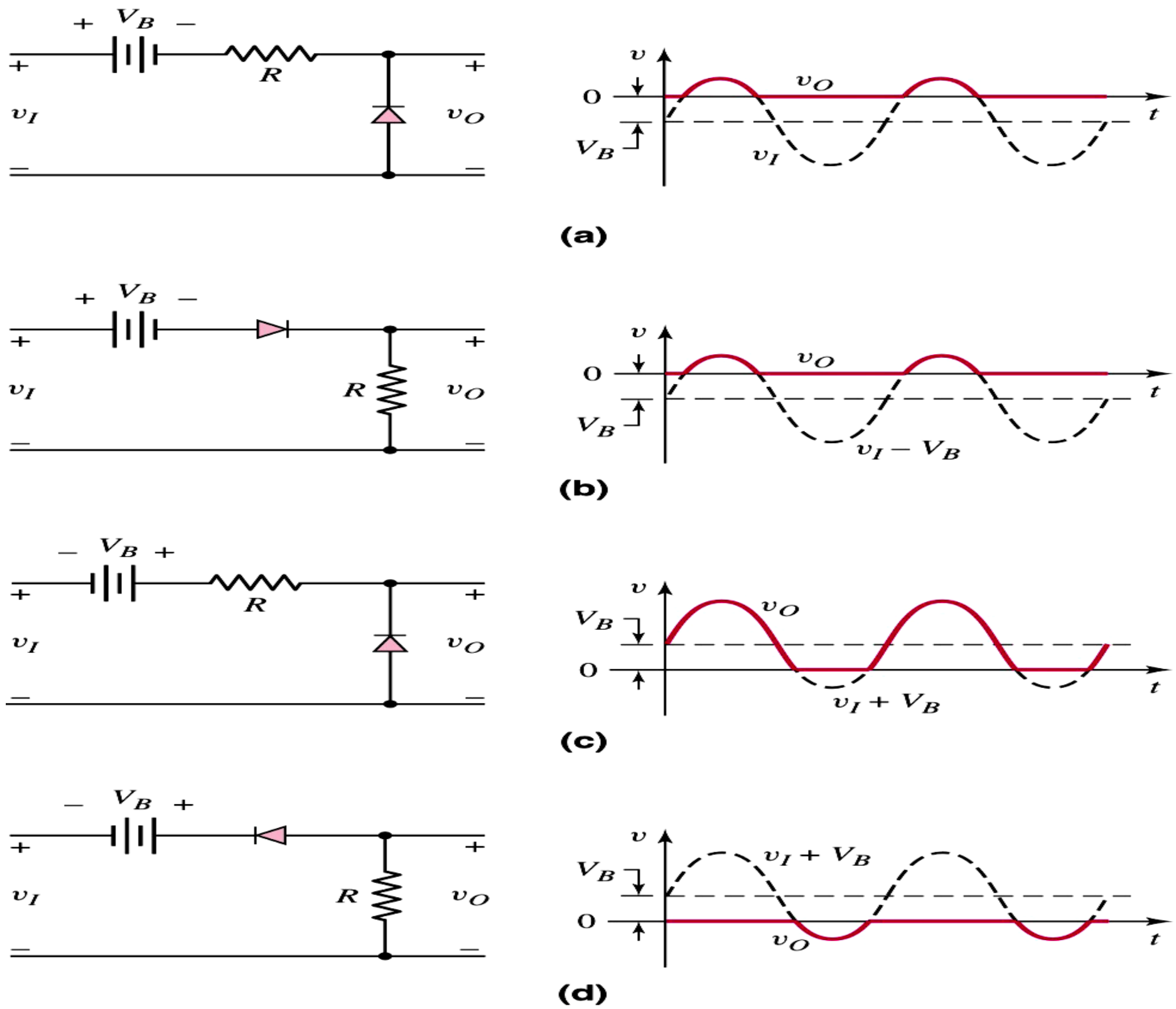


source: Millman

Clippers with the battery in series

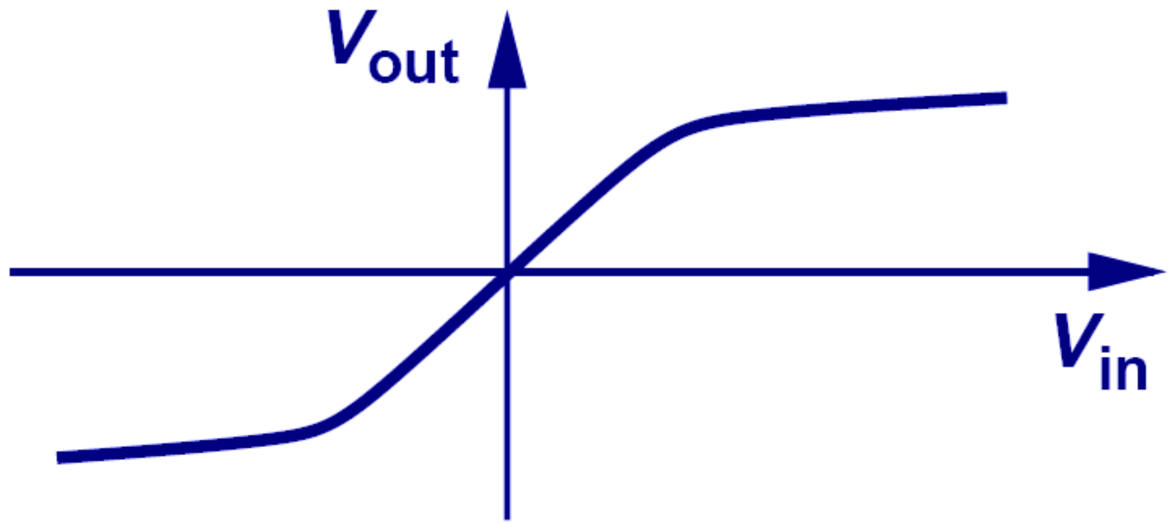
Assuming ideal diode model

source: Neamen



Non-idealities in limiting circuits

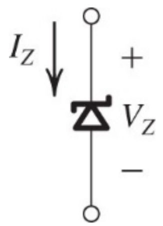
source: Razavi



The clipping region is not exactly flat since as Vin increases, the currents through diodes change, and so does the voltage drop.

Zener diode

source: Sedra & Smith

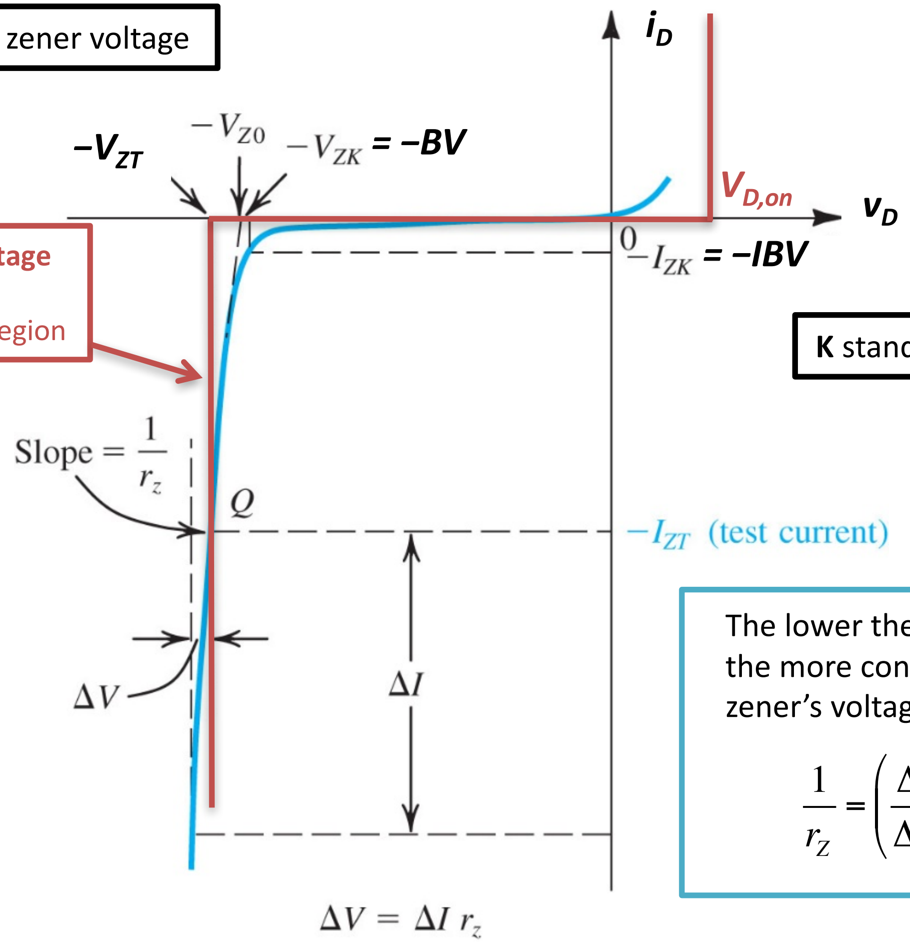


Zener diode symbol

V_{ZT} = zener voltage

constant voltage
I-V model of
breakdown region

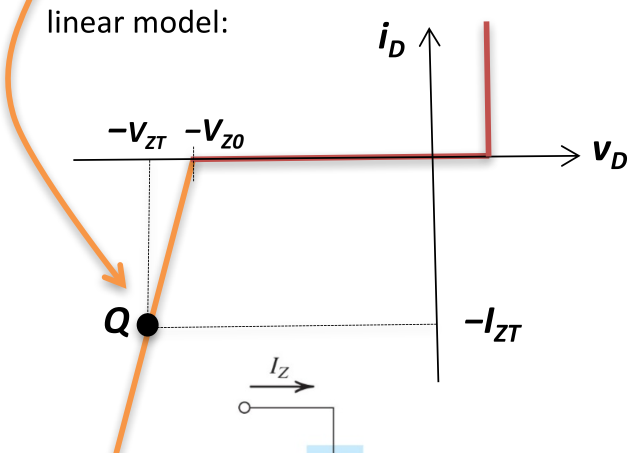
K stands for knee

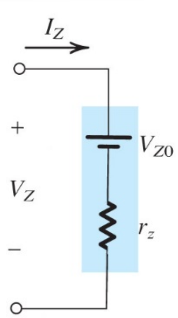


The lower the value of r_Z the more constant the zener's voltage remain

$$\frac{1}{r_Z} = \left(\frac{\Delta I_Z}{\Delta V_Z}\right)\bigg|_{@Q}$$

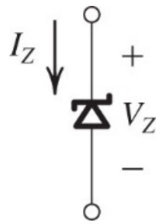
Often is convenient to model the breakdown region with a piece-wise linear model:





The model is valid for $I_Z > I_{ZK}$ and $V_Z > V_{Z0}$:

$$V_Z = V_{Z0} + r_Z \times I_Z$$



Zener diode

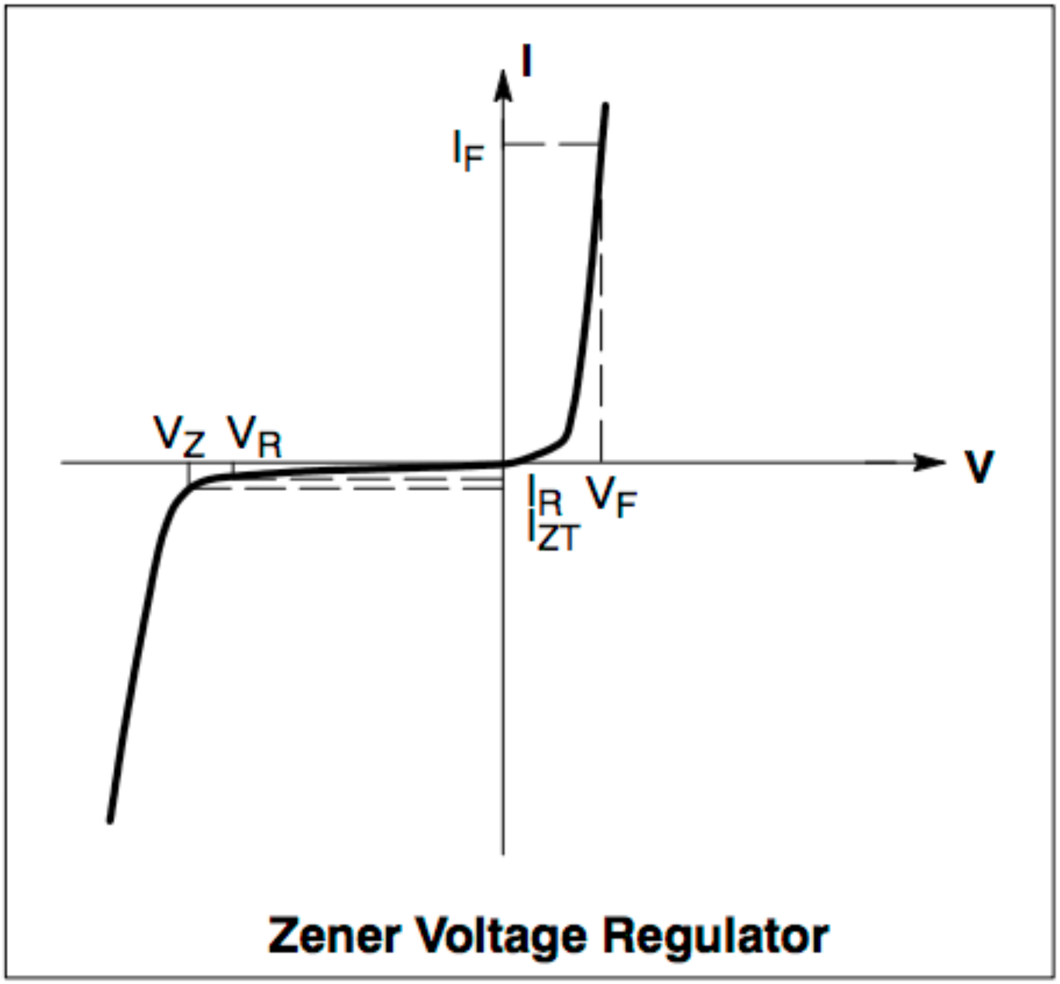
- A zener diode is a diode specifically manufactured to be be used in breakdown region. The zener's I-V curve in breakdown region is very steep (more than usual)
- Diode breakdown is normally not destructive, provided the power dissipated in the diode is limited to a safe level
- The fact that the diode I/V characteristic in breakdown is almost a vertical line (just like a battery) enables it to be used in voltage regulation (more to come soon !)
- There are two mechanism causing the behavior we have in breakdown region (… despite the mechanism the end result is the same)
  - ***Avalanche***: occurs when the minority carriers swept by the electric field in depletion region have enough kinetic energy to be able to break covalent bonds in atoms with which they collide
  - ***Zener***: occurs when the electric field in the depletion region increases to the point that it can tear out a bound electron from its covalent bond

Zener diode: data sheet example

On Semiconductor:
Zener Voltage Regulator with $V_{Z,nom}$=2.4V

ELECTRICAL CHARACTERISTICS
(T_A = 25°C unless otherwise noted,
V_F = 0.9 V Max. @ I_F = 10 mA for all types)

Symbol	Parameter
V_Z	Reverse Zener Voltage @ I_{ZT}
I_{ZT}	Reverse Current
Z_{ZT}	Maximum Zener Impedance @ I_{ZT}
I_{ZK}	Reverse Current
Z_{ZK}	Maximum Zener Impedance @ I_{ZK}
I_R	Reverse Leakage Current @ V_R
V_R	Reverse Voltage
I_F	Forward Current
V_F	Forward Voltage @ I_F
ΘV_Z	Maximum Temperature Coefficient of V_Z
C	Max. Capacitance @V_R = 0 and f = 1 MHz



Zener diode: data sheet example

ELECTRICAL CHARACTERISTICS (V_F = 0.9 Max @ I_F = 10 mA for all types)

ΘV_Z

Device*	Device Marking	Test Current Izt mA	Zener Voltage VZ		Z_{ZK} I_Z = 0.5 mA Ω Max	Z_{ZT} I_Z = IZT @ 10% Mod Ω Max	Max IR @ VR		d_{VZ}/dt (mV/k) @ I_{ZT1} = 5 mA		C pF Max @ V_R = 0 f = 1 MHz
			Min	Max			μA	V	Min	Max	
MM3Z2V4ST1G	T2	5.0	2.29	2.51	1000	100	50	1.0	−3.5	0	450

$V_{Z,nom}$= 2.4V

The impedance of a reference diode is normally specified at the test current (I_{ZT}). It is determined by measuring the ac voltage drop across the device when a 60 Hz ac current with an rms value equal to 10% of the dc zener current is superimposed on the zener current (I_{ZT}).

Zener diode: data sheet example

MAXIMUM RATINGS

Rating	Symbol	Max	Unit
Total Device Dissipation FR−4 Board, (Note 1) @ T_A = 25°C Derate above 25°C	P_D	 300 2.4	 mW mW/°C
Thermal Resistance from Junction−to−Ambient	$R_{\theta JA}$	416	°C/W
Junction and Storage Temperature Range	T_J, T_{stg}	−65 to +150	°C

Stresses exceeding those listed in the Maximum Ratings table may damage the device. If any of these limits are exceeded, device functionality should not be assumed, damage may occur and reliability may be affected.

1. FR−4 printed circuit board, single−sided copper, mounting pad 1 cm^2.

If the current exceed a certain limit the power dissipated $P_D = V_D \times I_D$ rises the junction temperature too much (> 150 °C in our case) and the device may get damaged

$$T_J = T_A + P_D \times R_{\Theta JA}$$

A device may get damaged also in the case the junction temperature becomes too small (< −65 °C in our case)

The max power rating of the diode ($P_{D,max}$ = 300 mW) goes down of 2.4 mW/°C for temperatures above 25°C

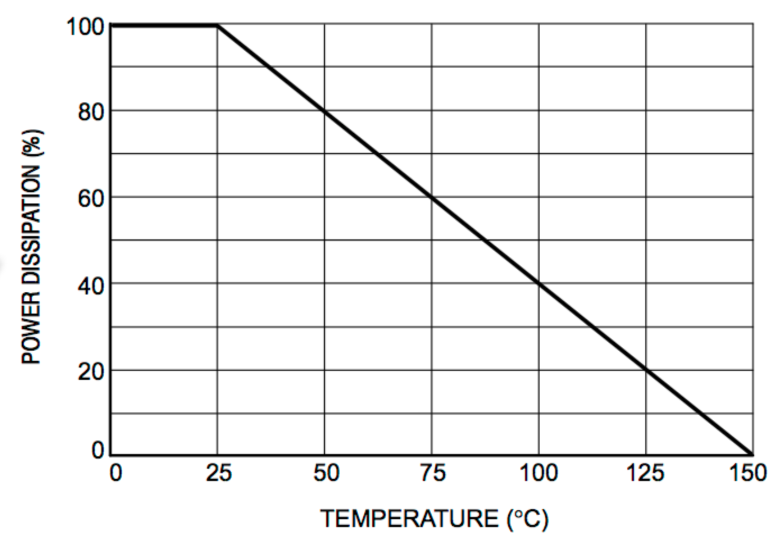
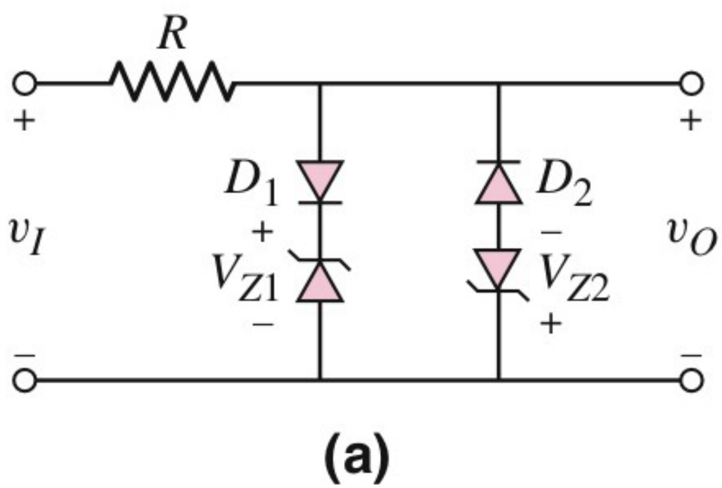


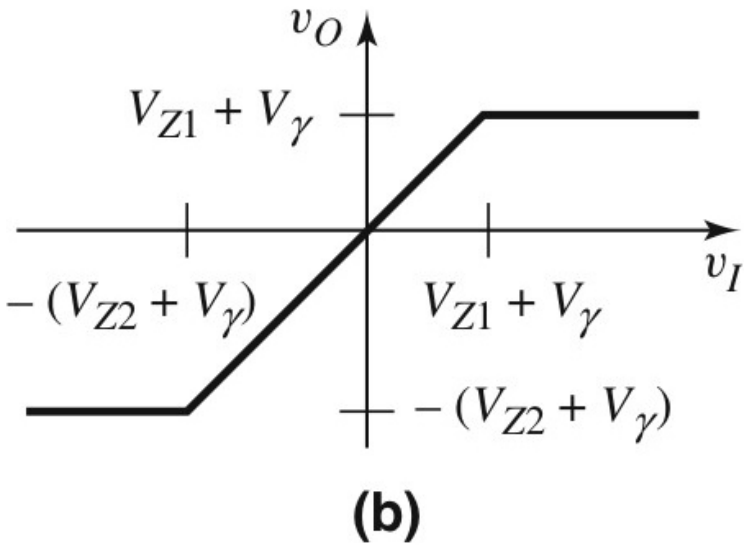
Figure 1. Steady State Power Derating

Clipping with Zener diodes

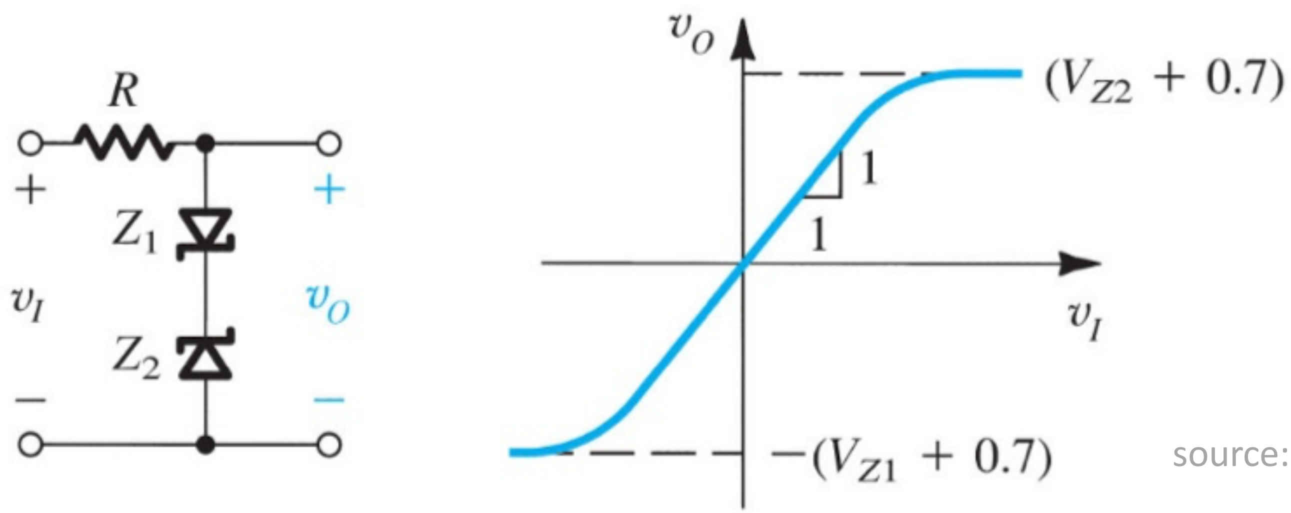
__Basic idea:__
Replacing batteries with Zener diodes

source: Neamen





More clipping with Zener diodes

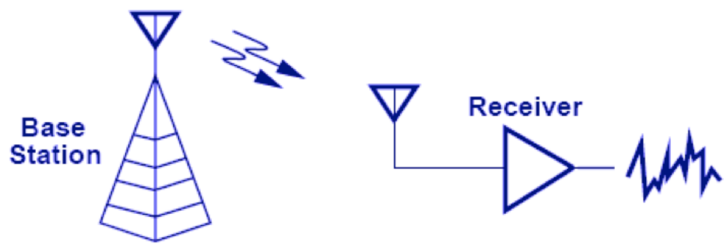


source: Sedra & Smith

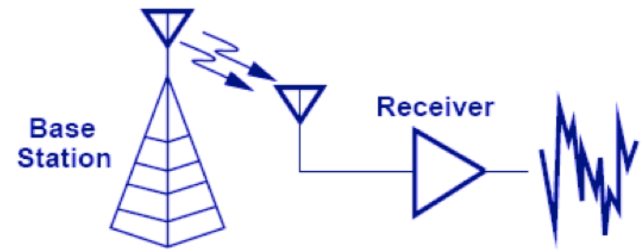
- For large positive v_I the diode D_{Z1} is forward biased and D_{Z2} is biased in zener region ($v_I > V_{Z2} + 0.7$)
- For large negative v_I the diode D_{Z1} is biased in zener region and D_{Z2} is forward biased ($v_I < -V_{Z1} - 0.7$)
- In the range $-(V_{Z1}+0.7) < v_I < V_{Z2}+0.7$ one of the diodes is in forward region and the other one in reverse region (therefore $v_O = v_I$)

Another application of clippers: soft limiters

source: Razavi

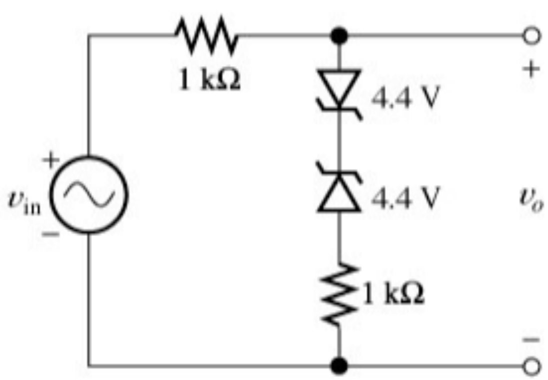


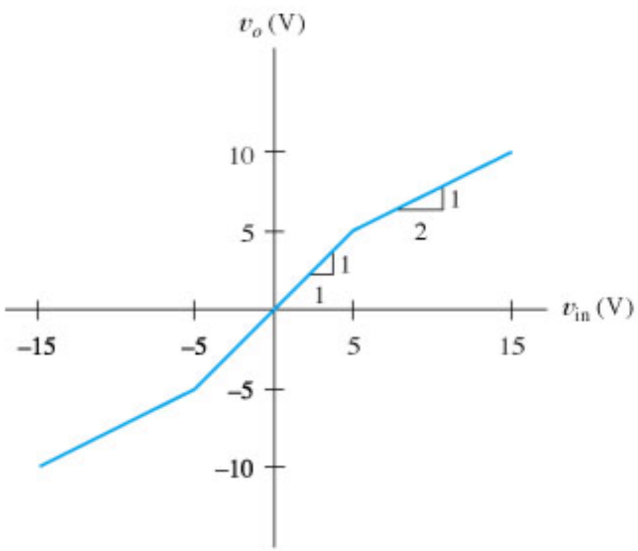
cell phone far from base station



cell phone near a base station

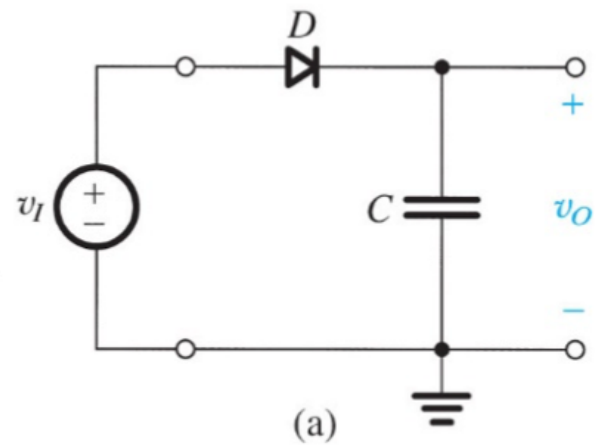
source: Hambley



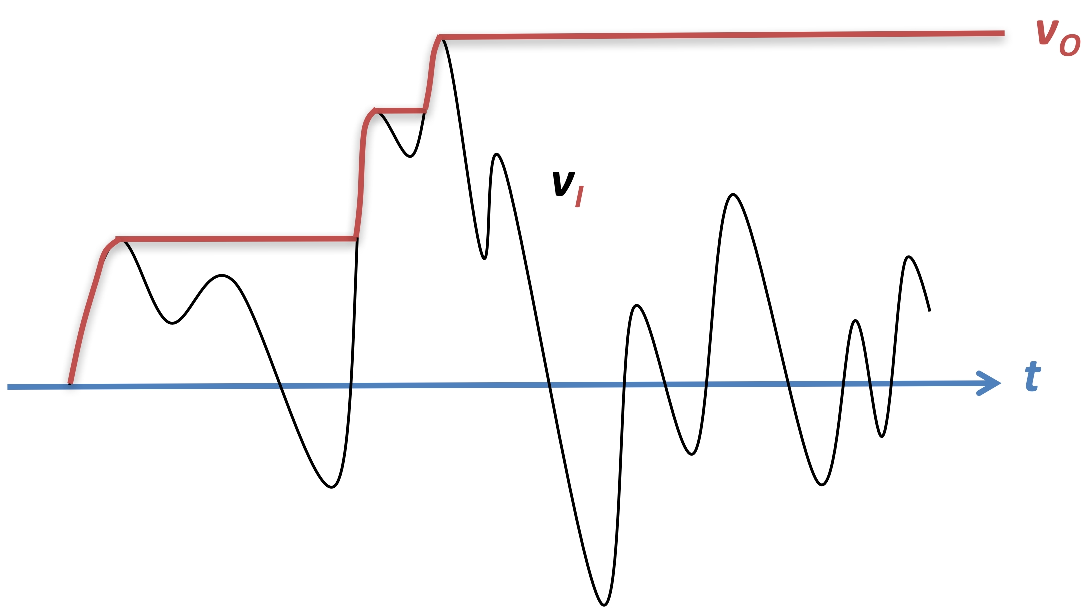


Detectors

Peak Detector

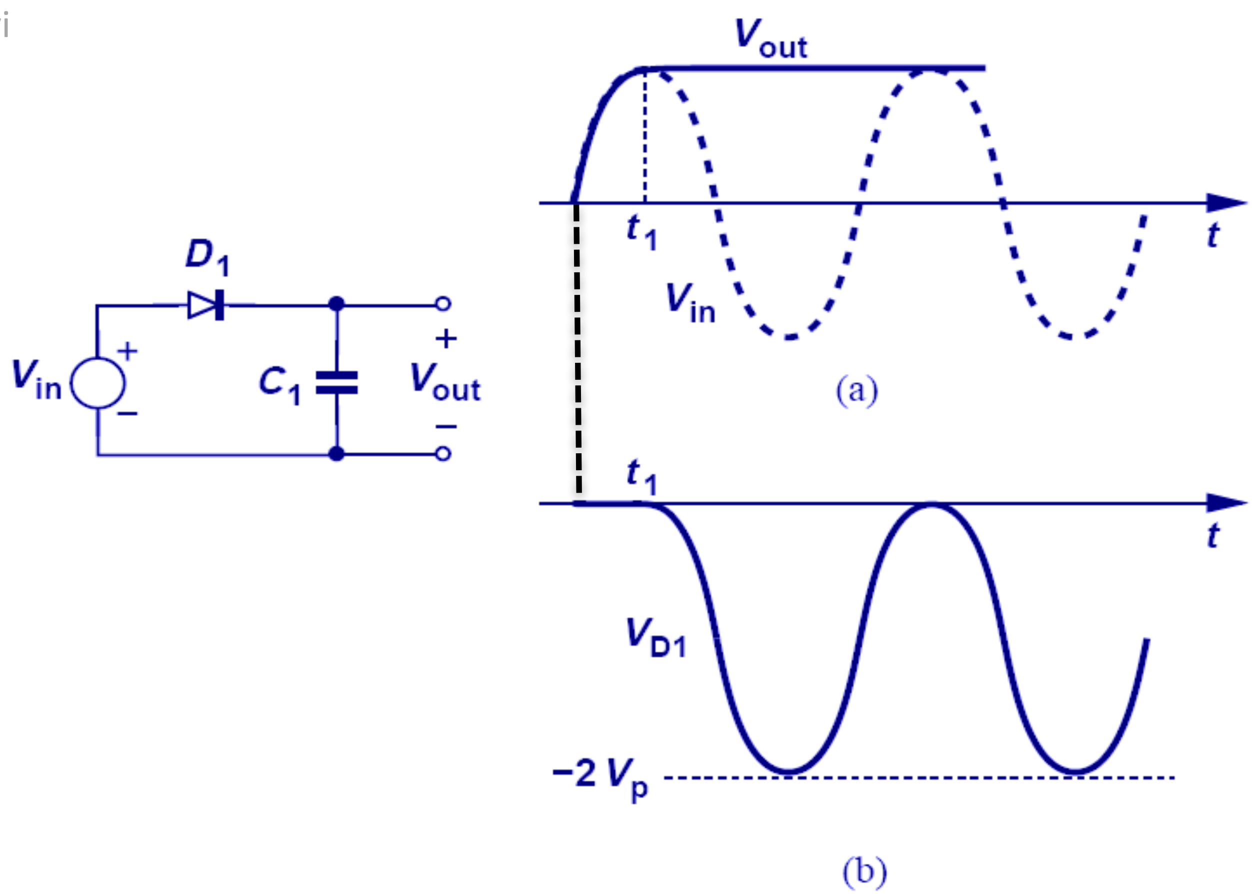


source: Sedra & Smith



Dissecting the peak detector a little more

source: Razavi

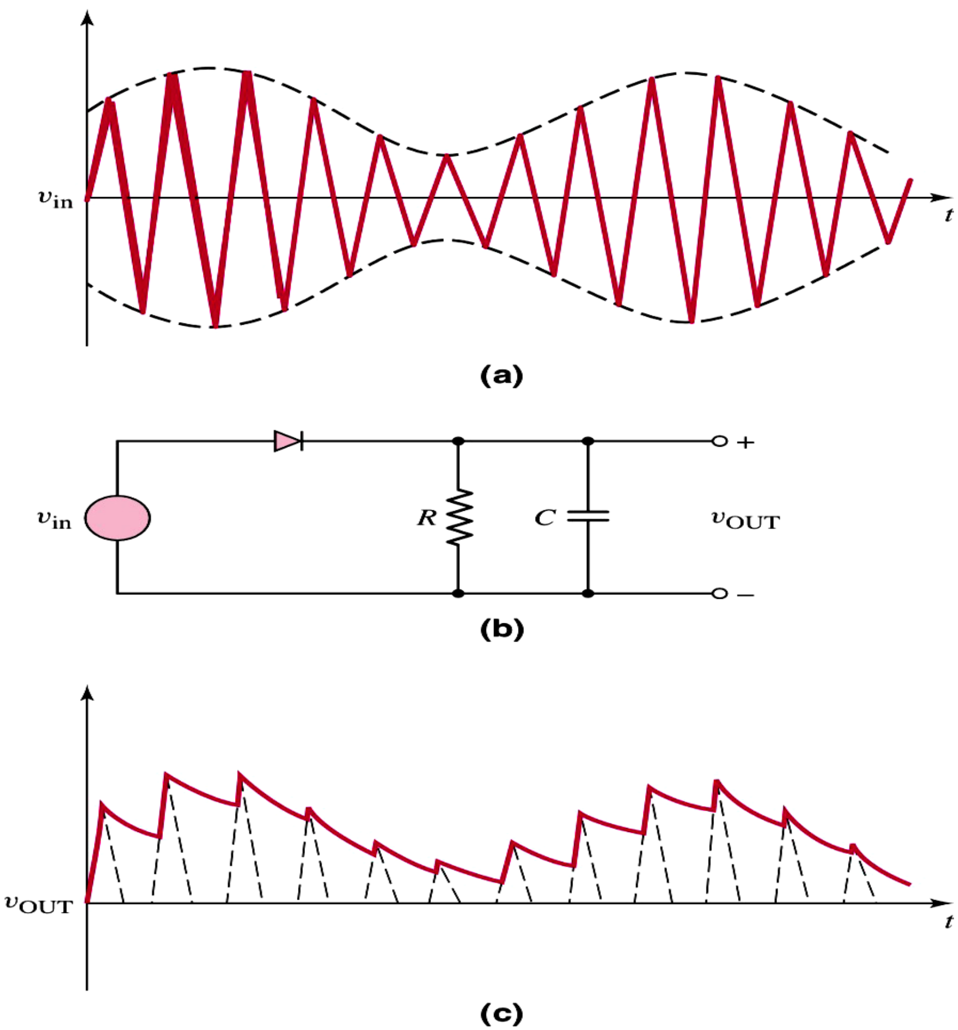


__Note:__ the voltage across the diode (***V_{D1}***) is just like Vin, only shifted down

Detectors: AM demodulator

AM Demodulator

source: Neamen



Modulated input signal

Detector circuit

RC >> T_C

period carrier

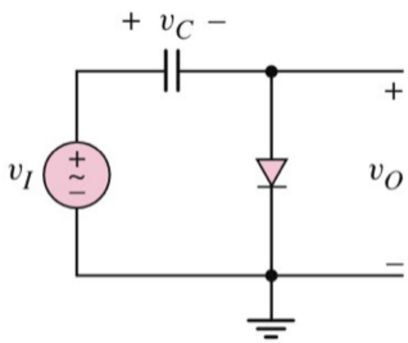
Demodulated output signal

Clampers (a.k.a. level shifters)

- Clampers shift the entire signal applied at the input by a DC level.
- In steady state, the output signal is an exact replica of the input waveform, but the output signal is shifted by a DC value
- Common application:
  - Suppose there is a stage (e.g. an amplifier) that does not operate properly with the DC level provided at its input, the issue can be solved by putting a level shifter in front of the stage

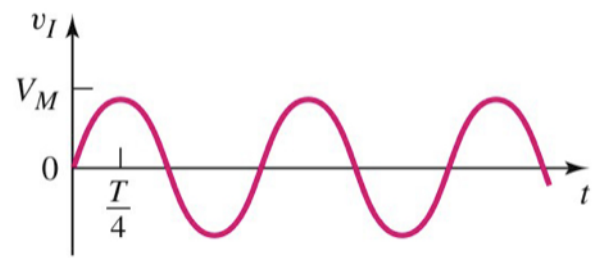
Positive Peaks Clamper

source: Neamen



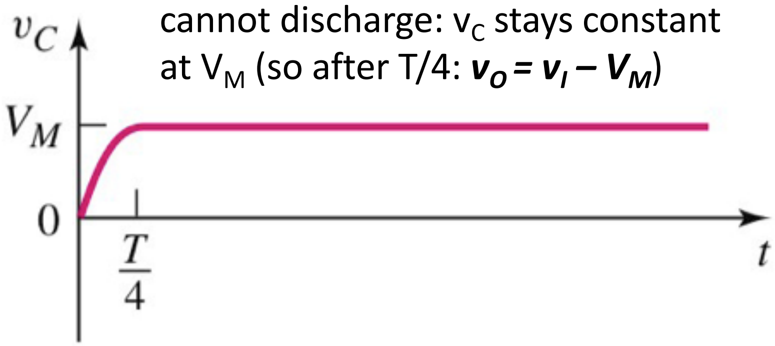
$$v_O = v_I - v_C$$

Assuming $r_f \cong 0\ \Omega$ and $V_\gamma = 0$ V

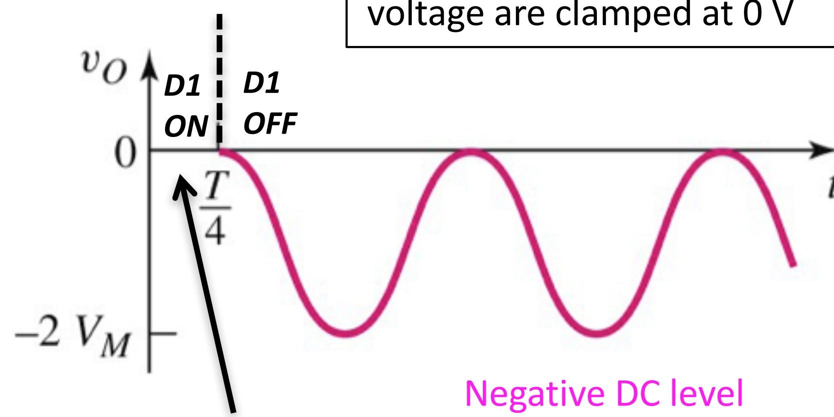


This is the “same” circuit of the peak detector, but now we take the output across the diode!

When the diode goes OFF there is no path to ground so the capacitor cannot discharge: v_C stays constant at V_M (so after T/4: $\boldsymbol{v_O = v_I - V_M}$)



The positive peaks of the output voltage are clamped at 0 V

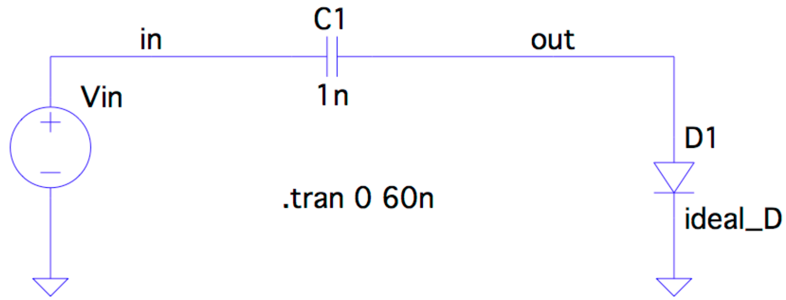


Negative DC level

C gets charged (at T/4 $v_C \approx V_M$)

Level shifter with peak at $-2V_M$

Positive peaks clamper

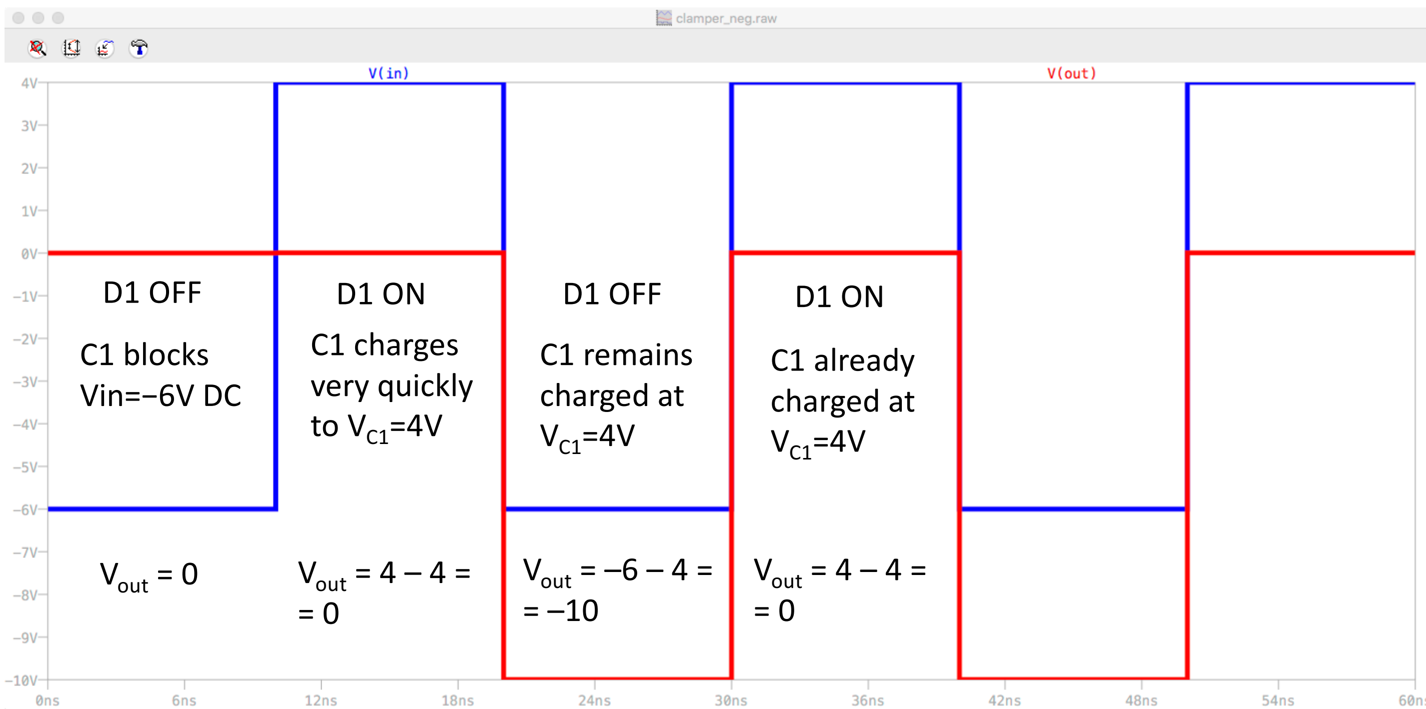



```
.model ideal_D D
+ IS=10f
+ n = 0.01
+ IBV = 0.1n
* by default BV = inf
```

The positive peaks of the output voltage are clamped at 0 V

Negative DC Level Shifter

PWL(0 -6 9.999n -6 10n 4 19.999n 4 20n -6 29.999n -6 30n 4 39.999n 4 40n -6 49.999n -6 50n 4)

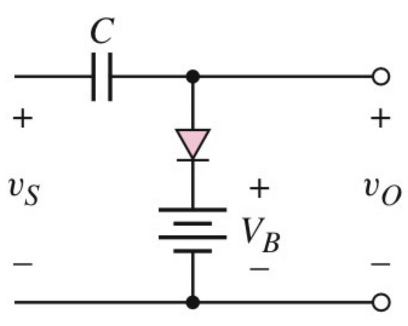


$$V_{out} = V_{in} - V_{C1}$$

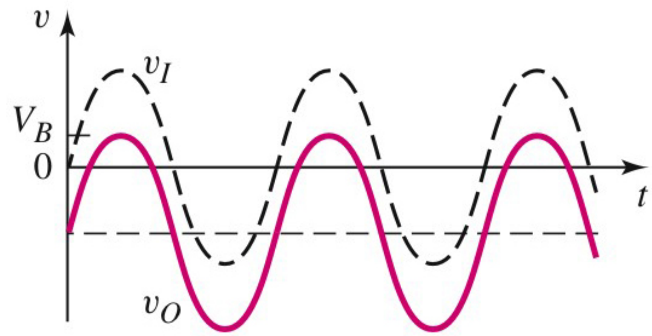
Positive peaks clamper with Battery

source: Neamen

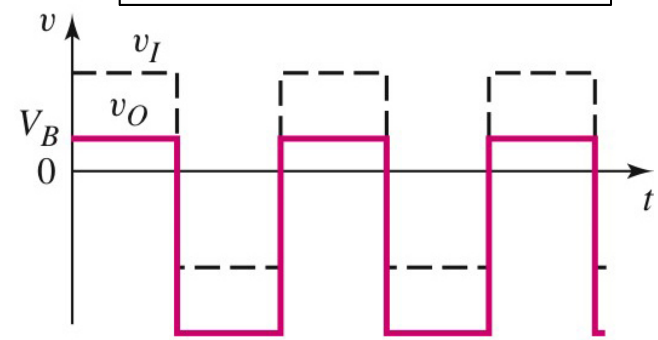
The positive peaks of the output voltage are clamped at V_B



(a)



(b)

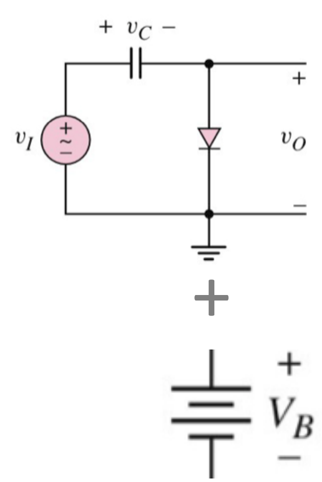


(c)

steady state (it takes T/4 to reach it)

steady state (it takes T to reach it)

Superposition of



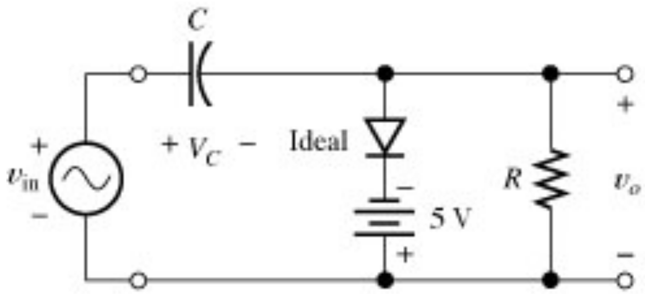
Positive peaks clamper with battery

- If we take the circuit we just analyzed, and reverse the polarity of the battery we clamp the positive peaks of the signal to a negative voltage value.

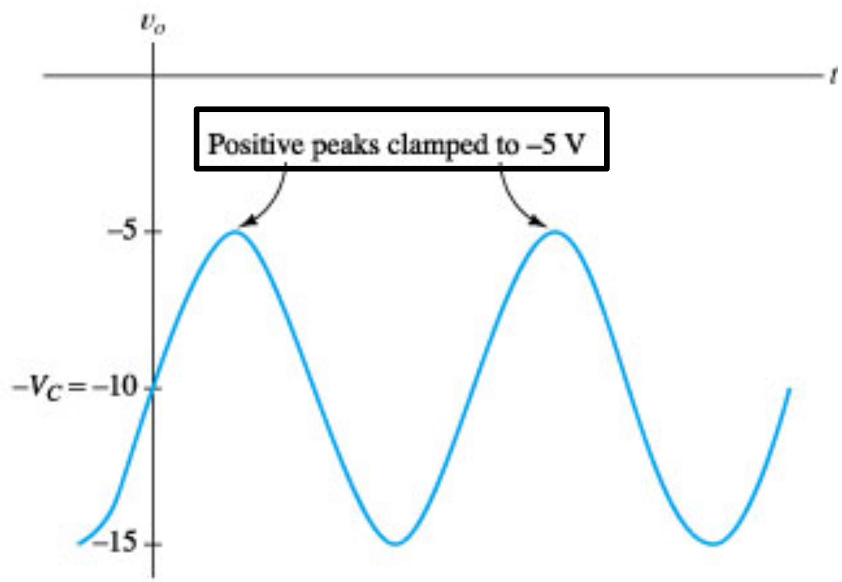
- This is no surprise: we still clamp the positive peaks to V_B (but now V_B happens to be negative)

source: Hambley

NOTE:
when v_{in} is at +5V the diode is ON and the cap is charged to V_C=10V



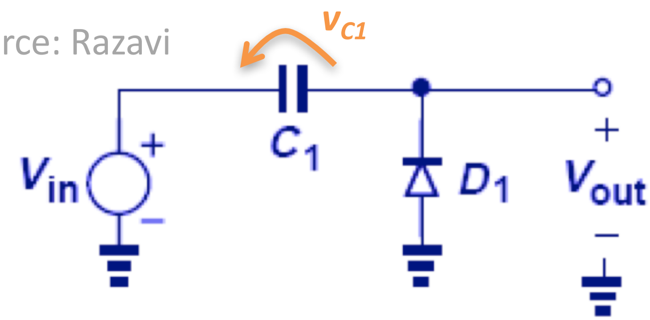
(a) Circuit diagram



(b) Output waveform for $v_{in} = 5 \sin(\omega t)$

Negative peaks clamper

source: Razavi



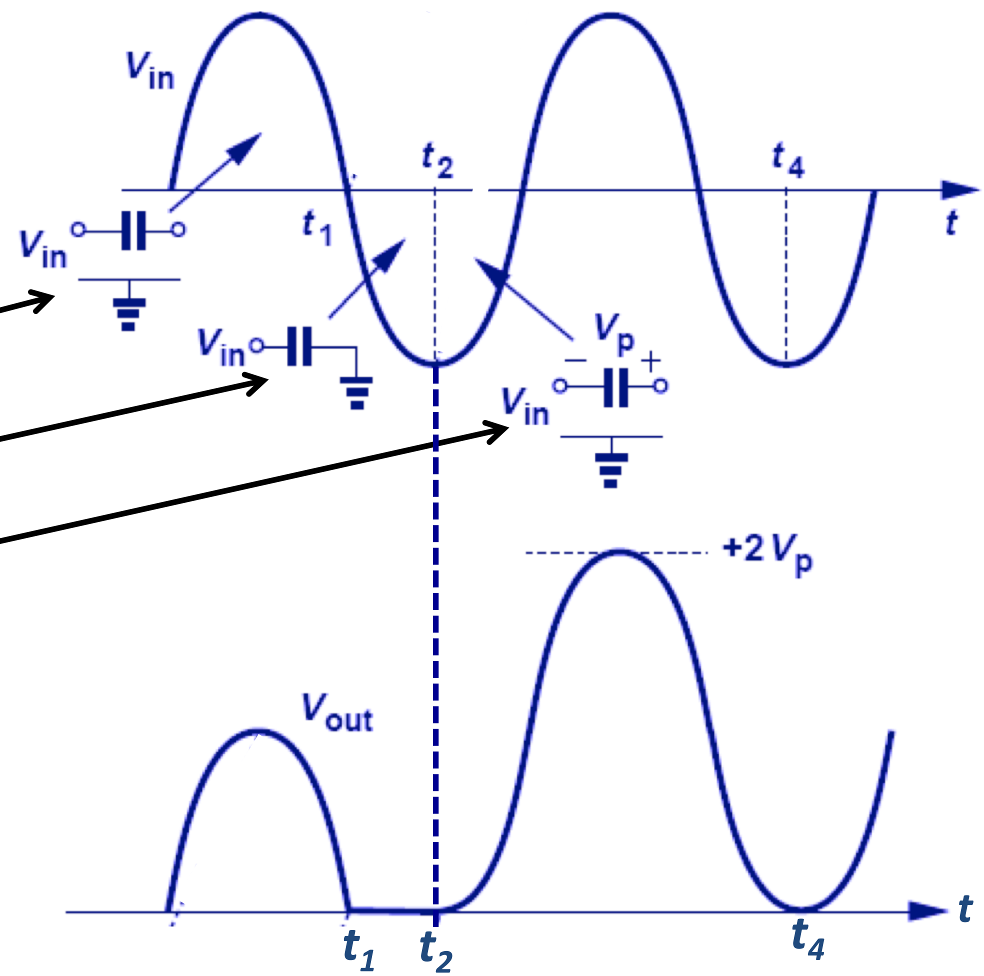
initially the cap is uncharged: $v_{C1}(0)=0$

$$v_{out} = v_{in} - v_{C1} = v_{in}$$

The diode turns ON and the cap. charges to $-V_P$

The diode turns OFF for good:

$$v_{out} = v_{in} - (-V_P) = v_{in}$$

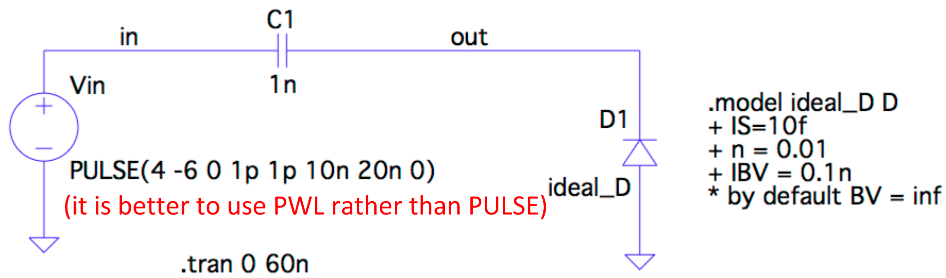


The negative peaks of the output voltage are clamped at 0 V

Positive DC level

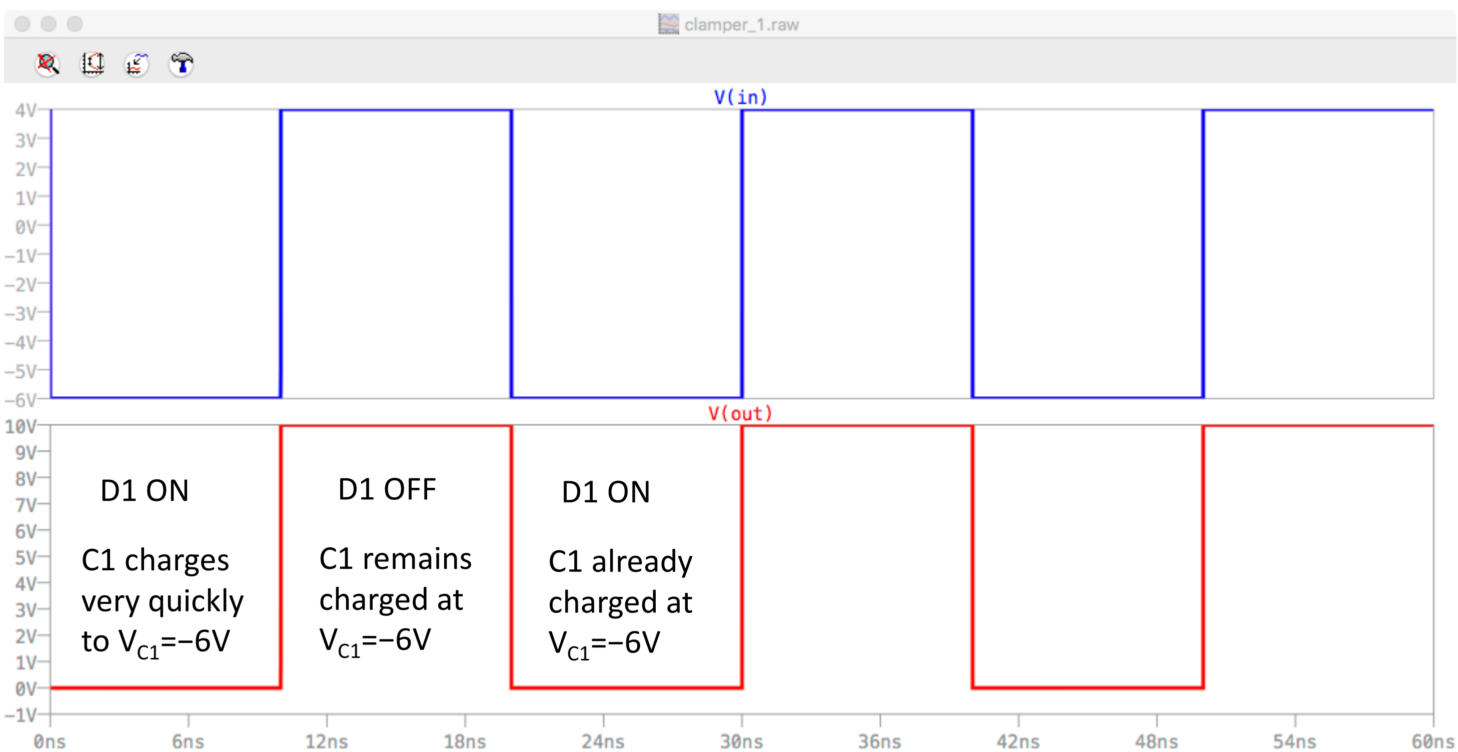
Level shifter with peak at $+2V_P$

Negative peaks clamper



Positive DC Level Shifter

The negative peaks of the output voltage are clamped at 0 V



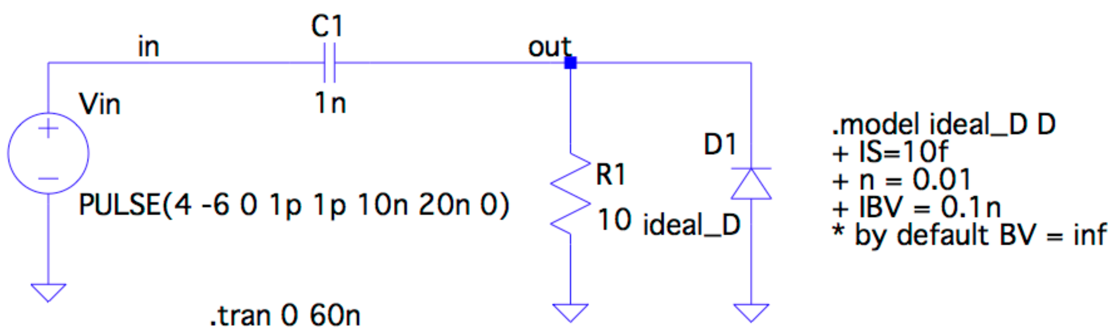
$$V_{out} = V_{in} - V_{C1}$$

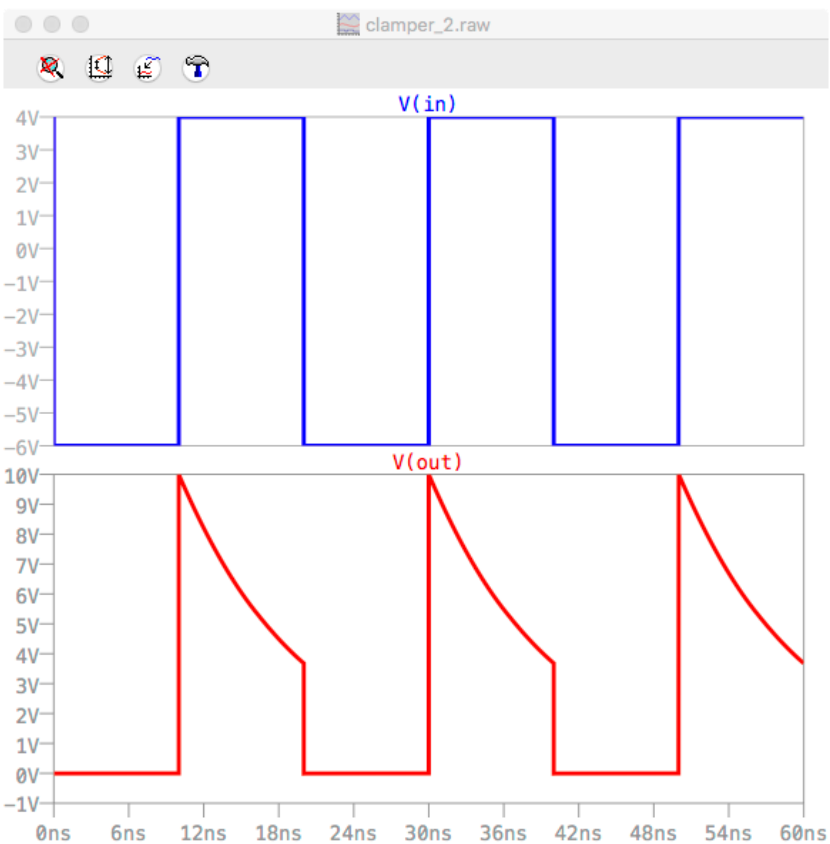
V_{out} =−6 − (−6)= = 0

V_{out}= 4 − (−6)= =10

V_{out} =−6 − (−6)= = 0

Positive DC level shifter: effect of load





- In practice the clamper will be driving a load.

⇩

- we need to make sure that $R_1C_1 >> T/2$, otherwise when D_1 is OFF the cap. C_1 loses too much charge on the load

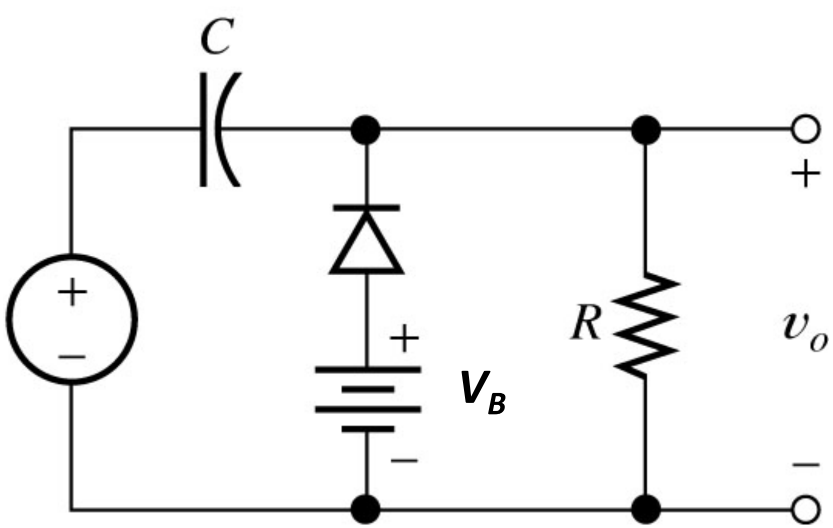
Example showing the effect of having R_1C_1 too small ($R_1C_1 = T/2$)

Negative peaks clamper with battery

- Example: This circuit clamps the negative peaks of an AC signal to +6V

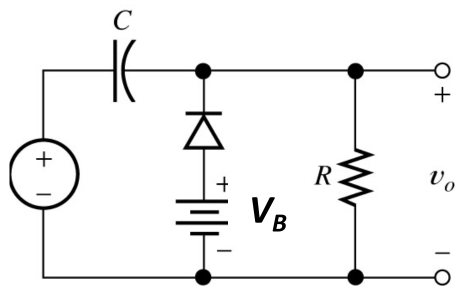
source: Hambley

$v_{in} = V_P \sin \omega t$



$V_B = 6$ **if we assume:** $V_\gamma \approx 0V$
or
$V_B = 6.7$ **if we assume:** $V_\gamma \approx 0.7V$

Negative peaks clamper with battery



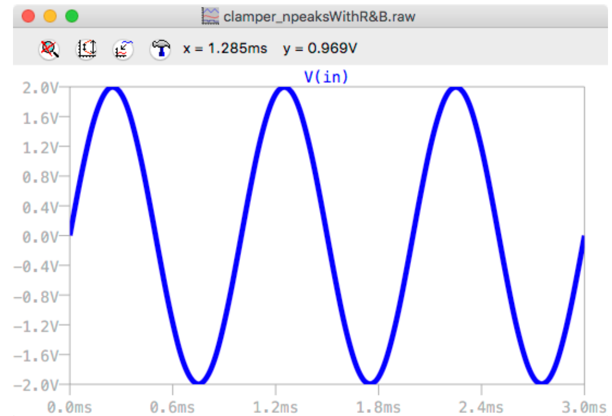
$v_{in} = V_P \sin \omega t$

$V_B = 6V$

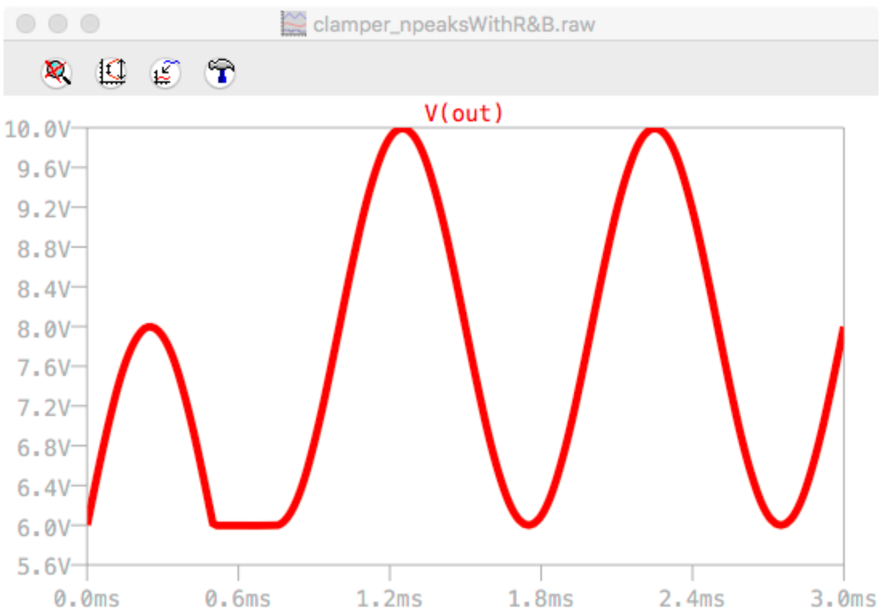
$V_B = -1V$

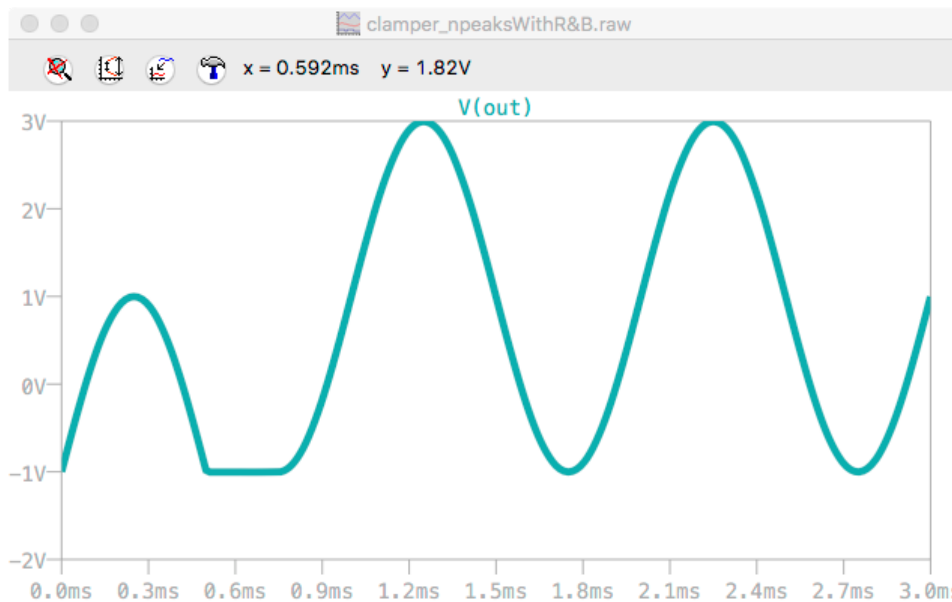
ideal diode

$V_\gamma \approx 0V$



$V_p = 2V, f_{in} = 1KHz$

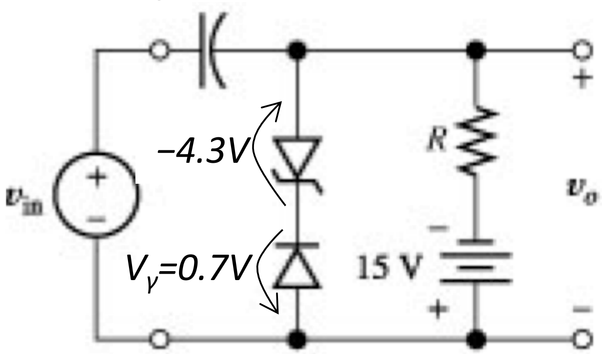




What about replacing batteries with Zeners ?

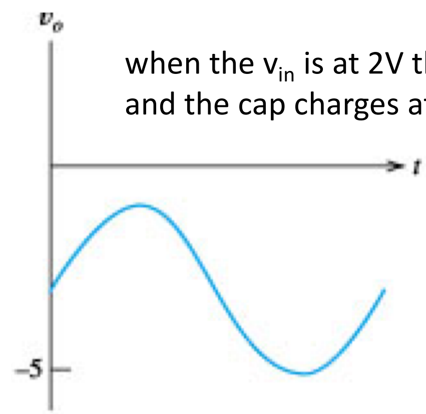
- It kind of works, but we need to keep in mind that (differently from what happened with the limiters) here the zener must work in zener region at all time. So it must be biased in zener region at all time !!

source: Hambley



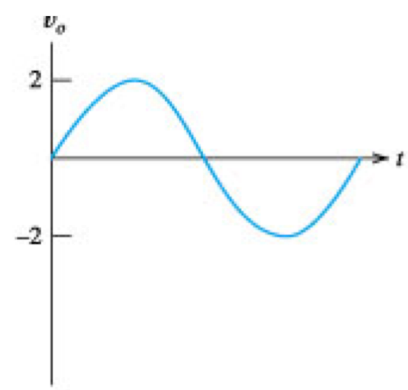
Circuit that clamps the negative peaks to −5V

when the v_{in} is at 2V the diode is ON and the cap charges at 2−5=−3V



(b) Output for $v_{in} = 2\sin(\omega t)$

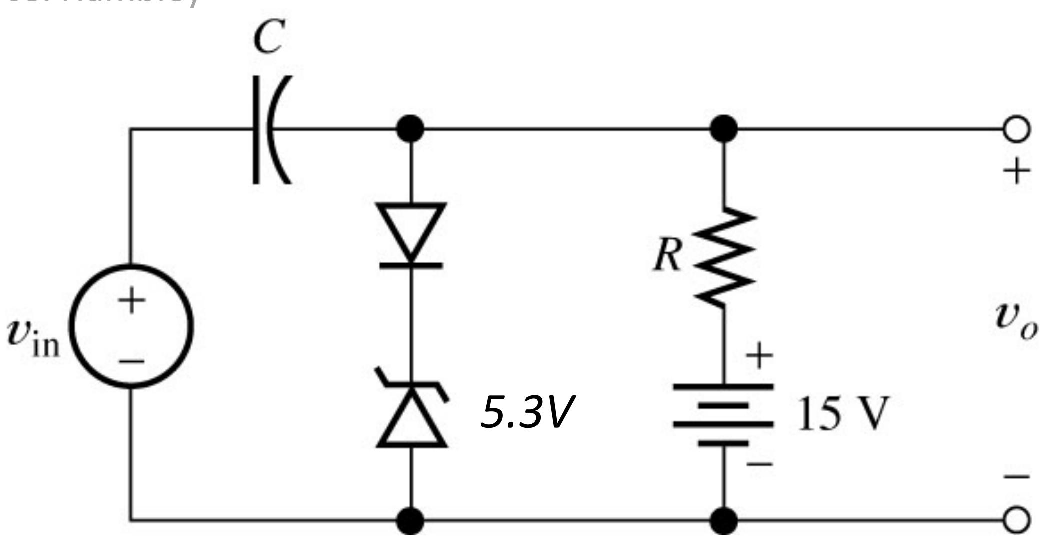
If we take off the −15V bias voltage and return R directly to ground the diode never turns ON and the circuit doesn't work



Replacing batteries with Zeners

- Example of circuit for clamping positive peaks

source: Hambley



Circuit that clamps the positive peaks to +6V

Example: another clamper

source: Millman

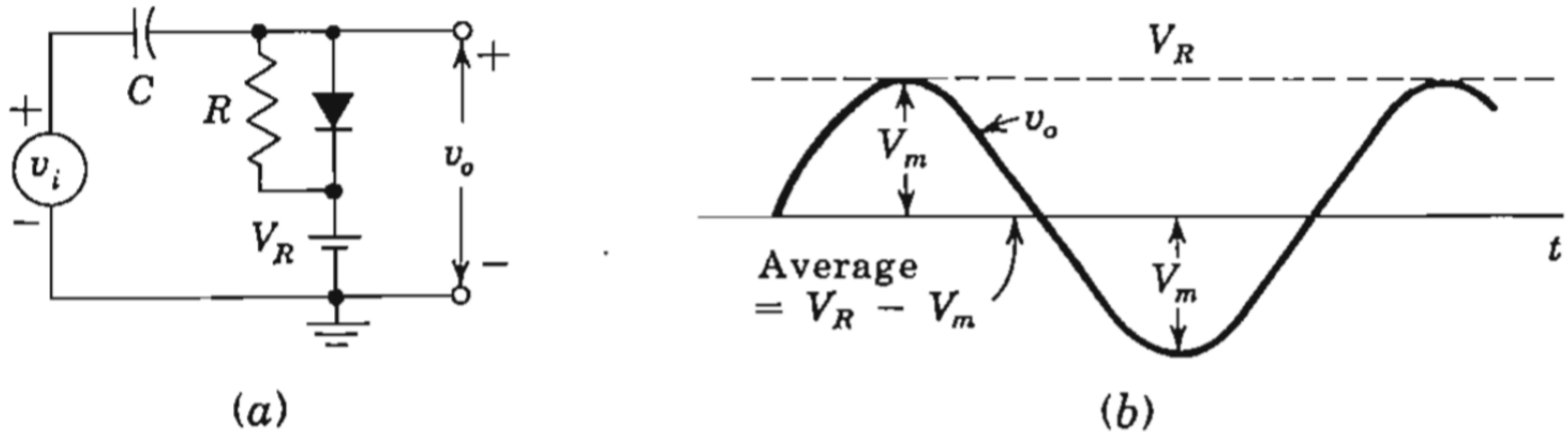


Fig. 4-28 (a) A circuit which clamps to the voltage V_R. (b) The output voltage v_o for a sinusoidal input v_i.

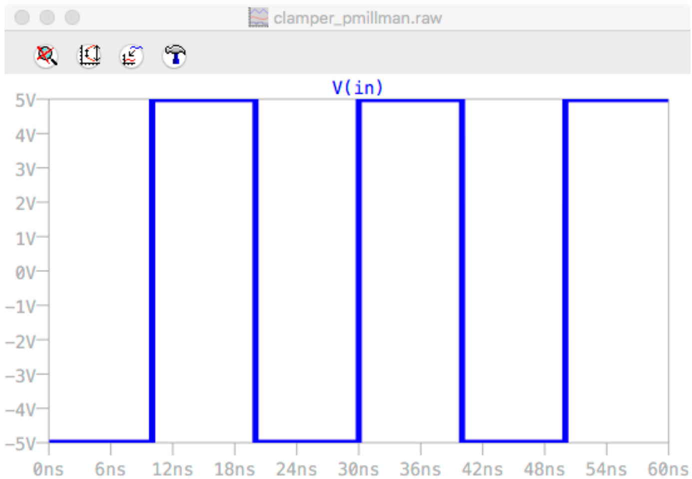
In steady state the cap is charged to $V_m - V_R$

Example: another clamper

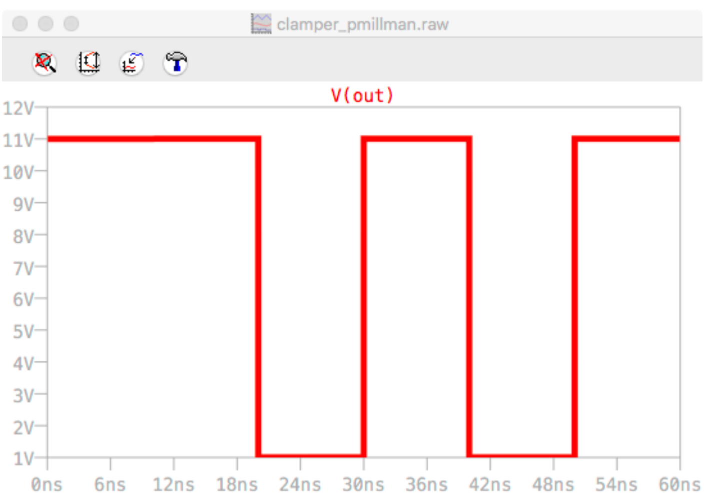
Circuit's elements:

C=1nF
R=100KΩ
Ideal diode

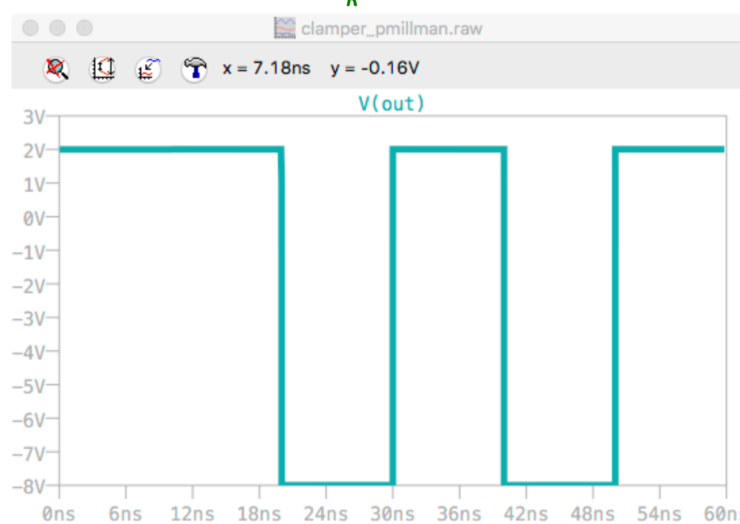
f_{in}=1/20ns



V_R=11V



V_R=2V

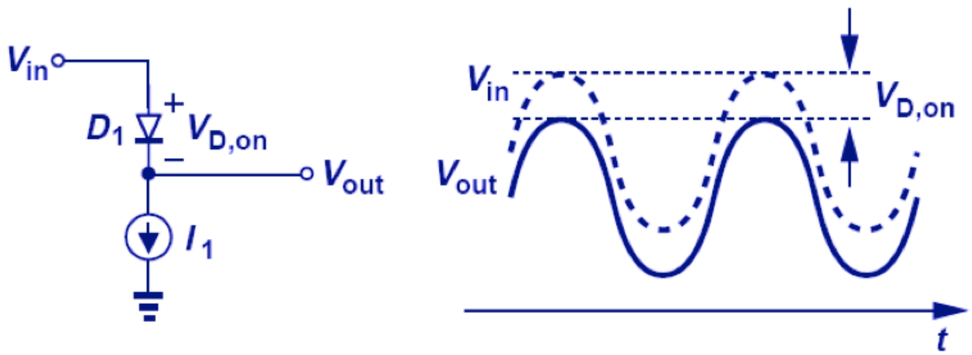


Alternative ways of clamping

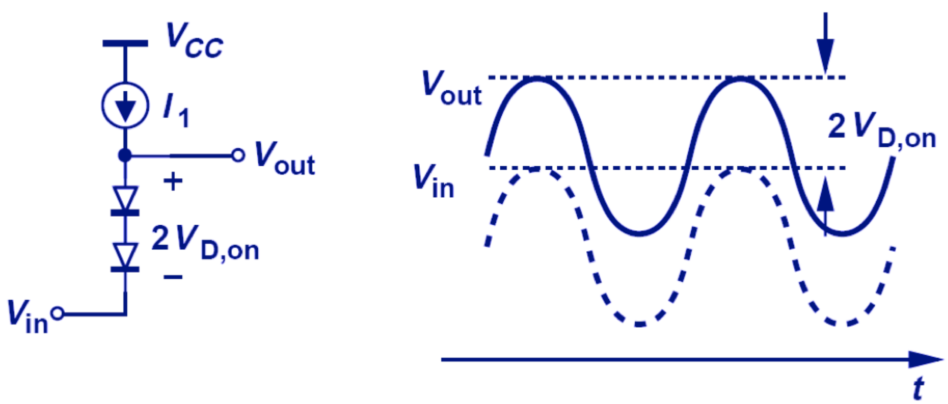
- Inside CMOS ICs DC level shifting is usually achieved using current sources (i.e. MOS transistors) and cascade of diodes (or diode connected MOS transistors)

Assumption:
the current pulled by the next stage is negligible (or at least constant), so that the current through the diode establish a drop of $V_{D,on}$ across the diode

source: Razavi



shift down circuit

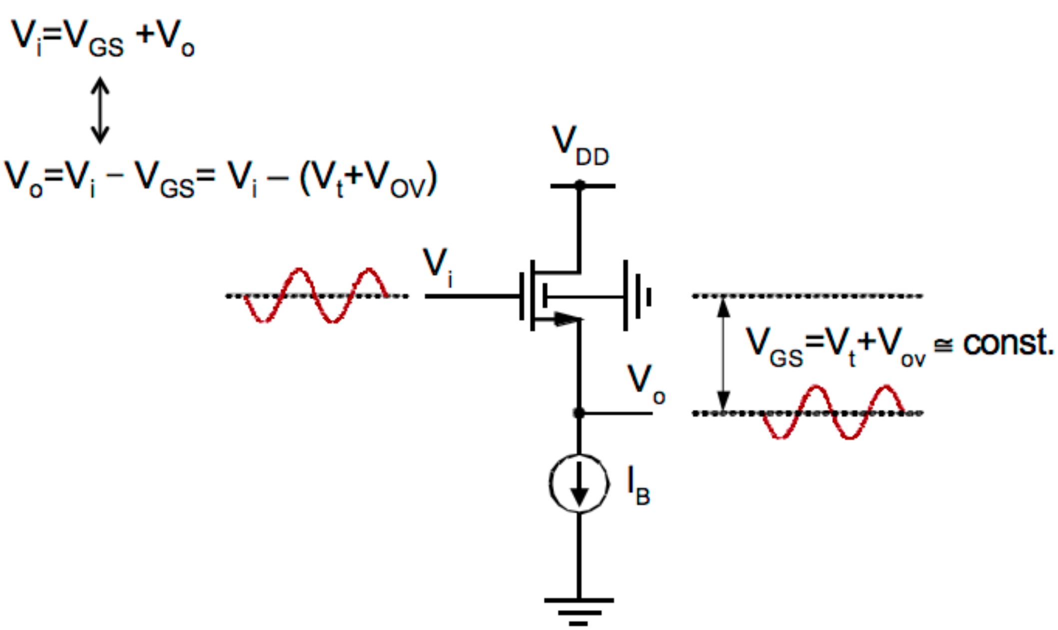


shift up circuit

Alternative ways of clamping

- Inside CMOS ICs, another common way of a achieving DC level shifting is by using a Common Drain stage

source: B. Murmann & R. Dutton



- Output quiescent point is roughly $V_t + V_{ov}$ lower than input quiescent point
- Adjusting the W/L ratio allows to “tune” Vov (= the desired shifting level)

Application: DC Power supply

- Let's take a look at how to build a DC power supply (AC-DC power converter)

source: Sedra & Smith

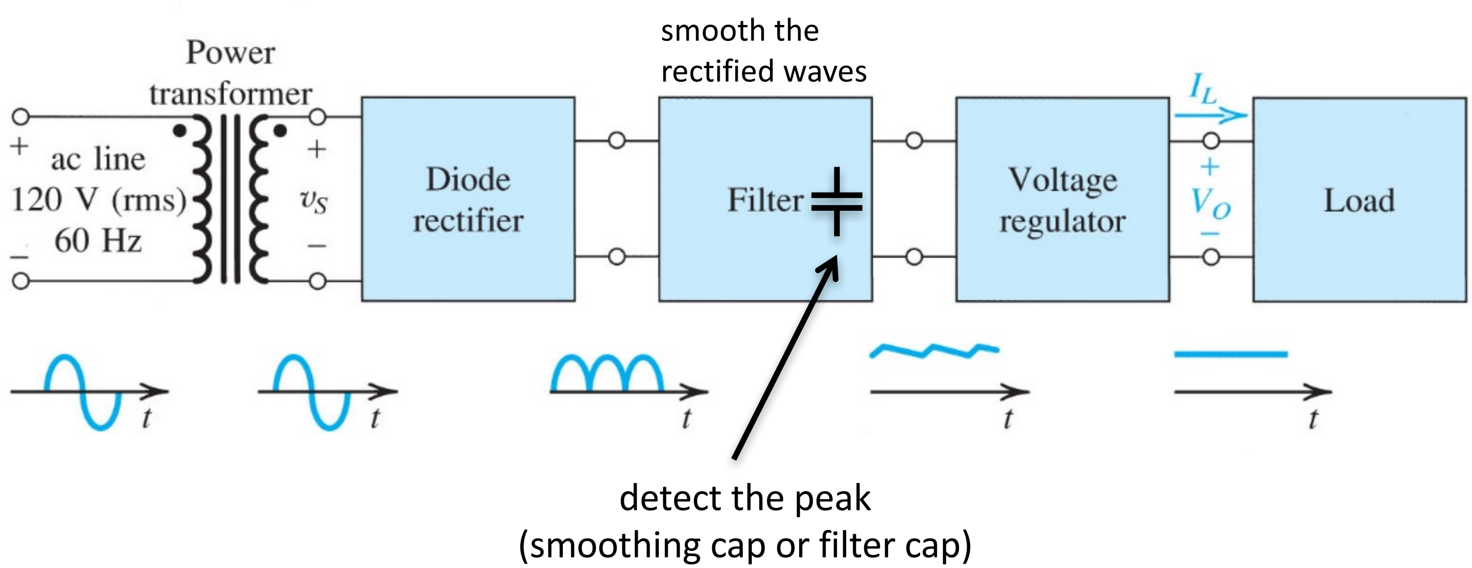
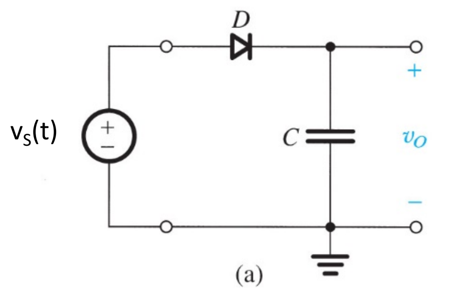


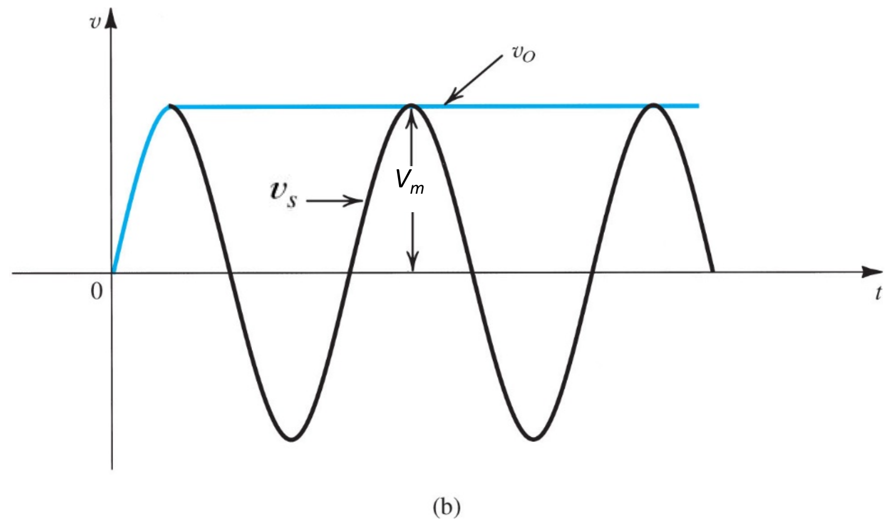
Figure 4.22 Block diagram of a dc power supply.

Rectifier + Filter Capacitor + Load

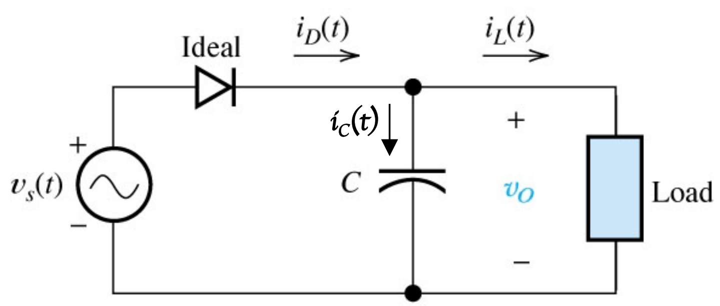
The following circuit (peak rectifier or peak detector) provides a DC voltage equal to the peak of the input sine wave



source: Sedra & Smith



So at a first glance it would seem a reasonable solution to use it as a DC power supply to drive a load.



However, once we connect the load if we look at the circuit a little harder we realize it presents some issues

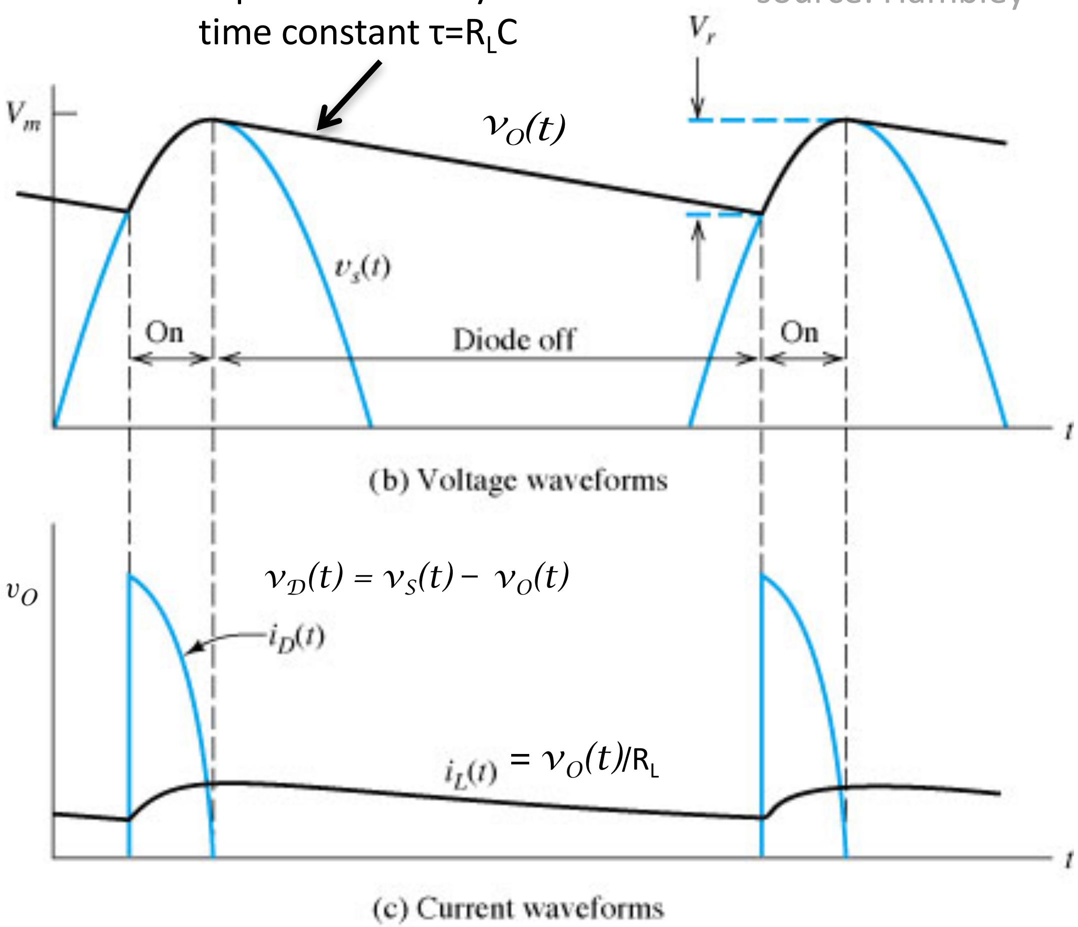
source: Hambley

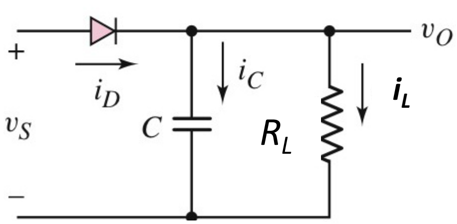
Rectifier + Filter Capacitor + Load

exponential decay with time constant τ=$R_L C$

source: Hambley

The voltage across the load is not constant. There is a ripple. A ripple more than 5% – 10% of V_m (or $V_m - V_\gamma$ with the constant voltage model) is a problem!





source: Neamen

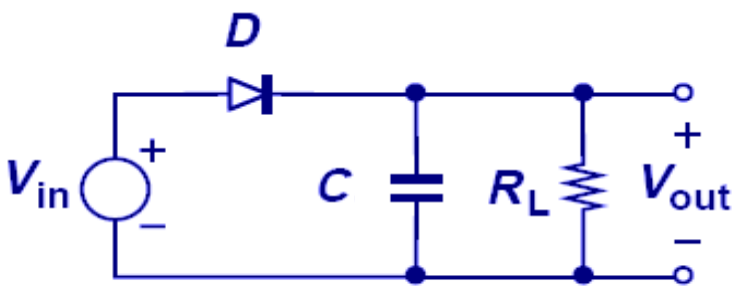
We have two design decisions:

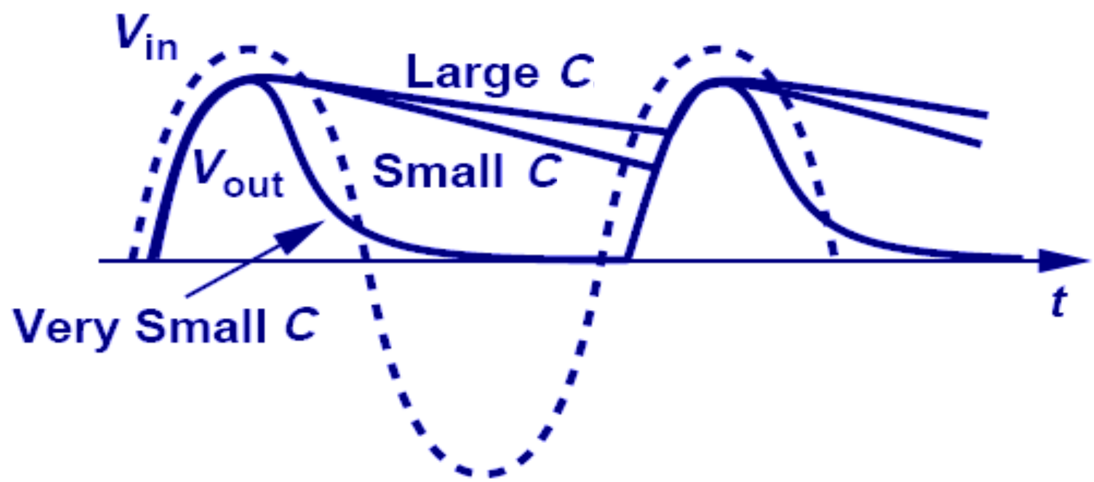
- pick C (how much ripple we want to tolerate)
- pick D (how much current the diode must withstand in forward region, and what is the PIV in reverse region)

Waveforms for half-rectifier with smoothing capacitor

Ripple for different capacitor values

source: Razavi



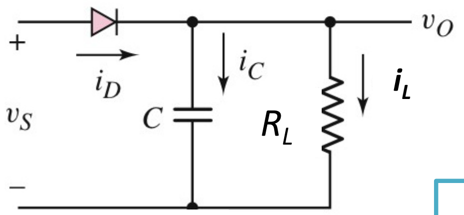


$V_D = V_{in} - V_{out}$

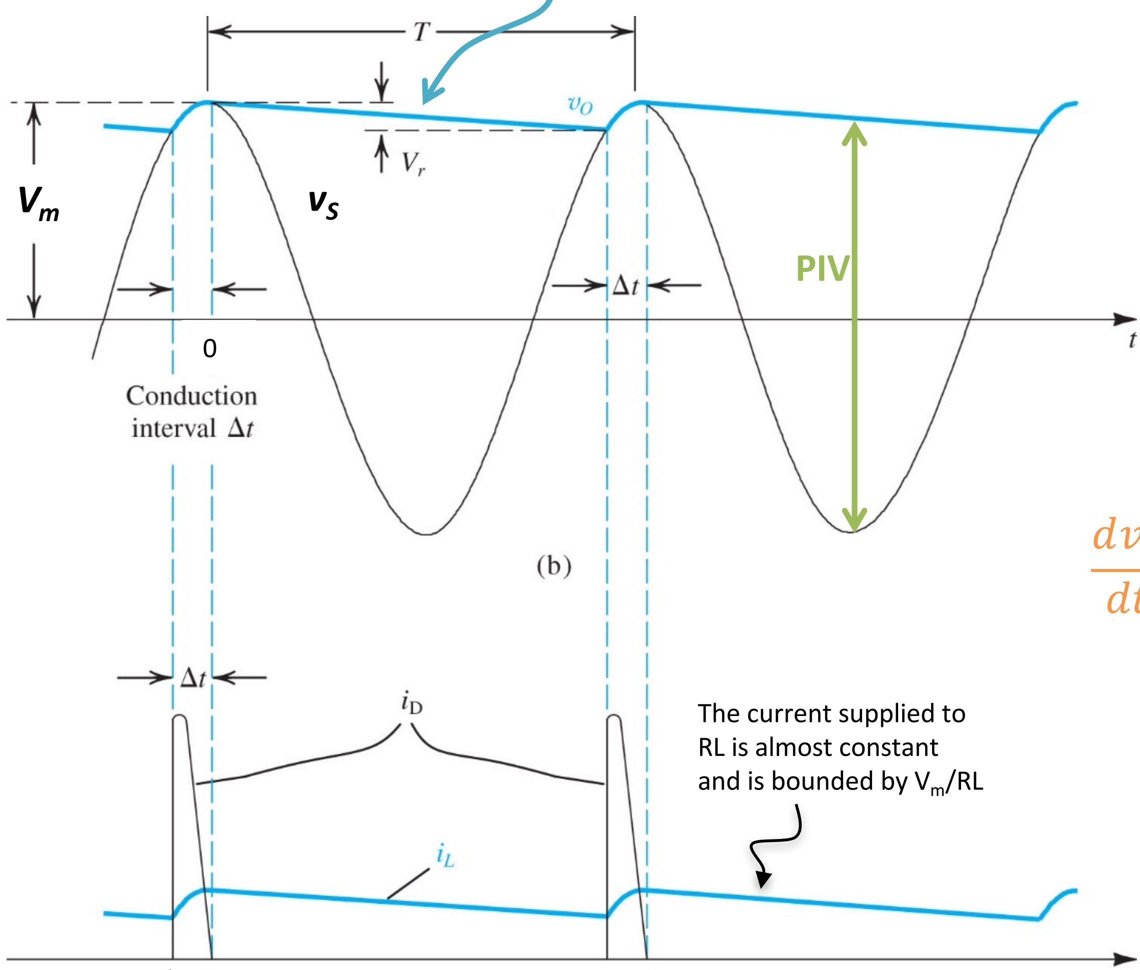
$PIV \approx 2 \times V_M$

- The amplitude of the ripple is given by the decaying exponential
- For V_{out} to have small ripple we need large C

Ripple and $I_{D,max}$



when diode is OFF $v_O = V_m e^{-\frac{t}{R_L C}}$



The current supplied to RL is almost constant and is bounded by V_m/RL

The diode's current is max at the beginning of the conduction interval and it goes down as the diode tends to turns off

This is also when the current through the cap. is max (this is because the slope of Vout is max)

Assuming $R_L C >> T$:

$$\frac{V_m}{R_L C} \cong \frac{V_R}{T} \Rightarrow V_R \cong \frac{V_m}{R_L} \times \frac{T}{C}$$

slope of exponential decay at t=0

slope by using simple geometry

$$\left.\frac{dv_0}{dt}\right|_{t=0} = \left.\frac{d\left[V_m e^{-t/(R_L C)}\right]}{dt}\right|_{t=0}$$

$$I_{D,\max} = \underbrace{C \left.\frac{dV_{out}}{dt}\right|_{t=-\Delta t}}_{= I_{C,max}} + \frac{V_m}{R_L}$$

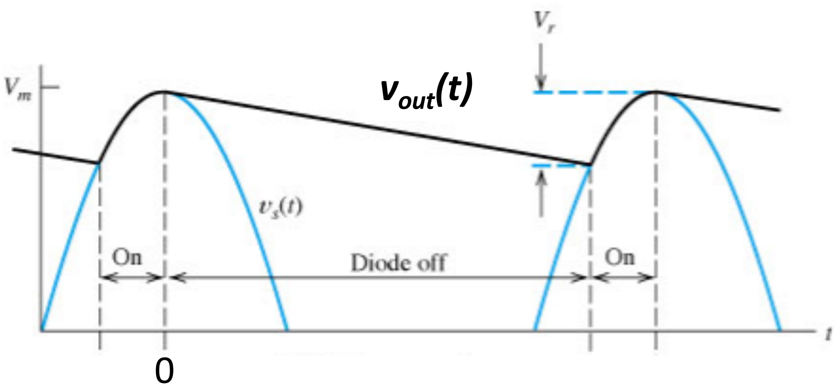
We need to find $I_{C,max}$!

Ripple and $I_{D,max}$

$$I_{C,\max} = C\frac{dV_{out}}{dt}\bigg|_{t=-\Delta t} = C\frac{d}{dt}(V_m\cos\omega t)\bigg|_{t=-\Delta t} = CV_m\omega[-\sin(-\omega\Delta t)] = CV_m\omega\sin\omega\Delta t$$

The diode conducts current only a small portion of the period ($\Delta t/T << 1$) therefore $\omega\Delta t$ is a small angle and $\sin(\omega\Delta t) \approx \omega\Delta t$

$$I_{C,\max} \approx \omega C V_m(\omega\Delta t)$$



Looking at the "geometry" of V_{out} we see that:

$$V_m\cos(-\omega\Delta t) = V_m\cos\omega\Delta t = V_m - V_r \Rightarrow \cos\omega\Delta t = 1 - \frac{V_r}{V_m}$$

Taylor for small angles

$$\cos\omega\Delta t \approx 1 - \frac{1}{2}(\omega\Delta t)^2$$

$$1 - \frac{1}{2}(\omega\Delta t)^2 \cong 1 - \frac{V_r}{V_m} \Rightarrow \boxed{\omega\Delta t \approx \sqrt{\frac{2V_r}{V_m}}}$$

Finally

$$\boxed{I_{C,\max}} \approx \omega C V_m(\omega\Delta t) \approx \boxed{\frac{2\pi}{T}CV_m\sqrt{\frac{2V_r}{V_m}}}$$

$$\boxed{\frac{\Delta t}{T} \approx \frac{1}{2\pi}\sqrt{\frac{2V_r}{V_m}}}$$

← % of time the diode is ON

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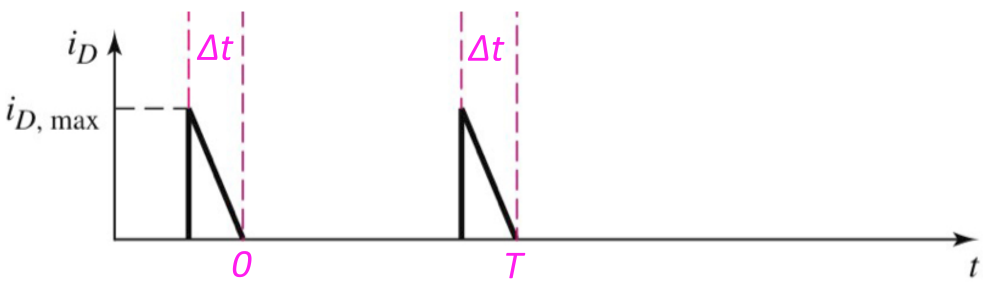
Ripple and $I_{D,max}$

$$I_{D,\max} = \frac{2\pi}{T} C V_m \sqrt{\frac{2V_r}{V_m}} + \frac{V_m}{R_L} = \frac{V_m}{R_L}\left(1 + 2\pi \frac{CR_L}{T}\sqrt{\frac{2V_r}{V_m}}\right) \approx \frac{V_m}{R_L}\left(1 + 2\pi\sqrt{\frac{2V_m}{V_r}}\right)$$

$$\frac{V_m}{R_L C} \cong \frac{V_r}{T} \leftarrow \text{slope of exponential decay at t=0}$$

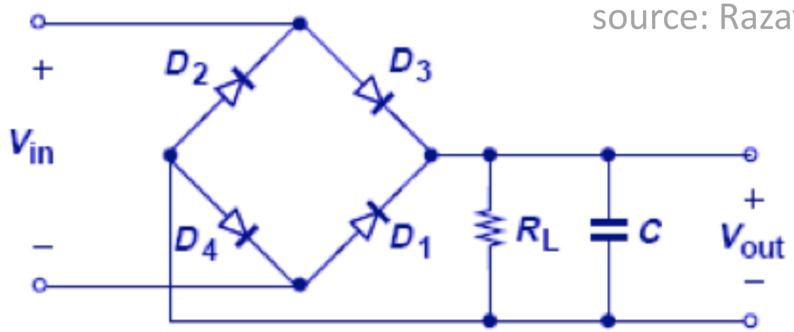


$$I_{D,avg} \approx \frac{1}{T} \times \underbrace{\frac{V_m}{R_L}\left(1 + 2\pi\sqrt{\frac{2V_m}{V_r}}\right) \times \frac{\Delta t}{2}}_{\text{area triangle}} = \frac{1}{2} \times \frac{V_m}{R_L} \times \frac{\Delta t}{T}\left(1 + 2\pi\sqrt{\frac{2V_m}{V_r}}\right) \cong \frac{V_m}{R_L} \times \left(\frac{1}{4\pi}\sqrt{\frac{2V_r}{V_m}} + 1\right)$$

$$\frac{\Delta t}{T} \approx \frac{1}{2\pi}\sqrt{\frac{2V_r}{V_m}}$$

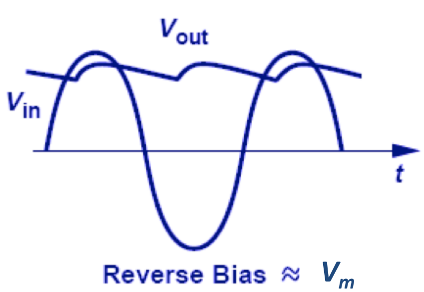
Can we further reduce the ripple ?

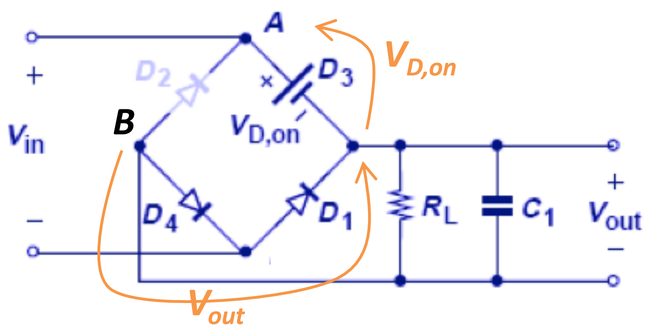
- Yes it is. Instead of using a simple diode rectifier we can use a bridge



source: Razavi

- Since C discharges only for ½ period, the ripple voltage is decreased by a factor of 2
- Also each diode is approximately subjected to only one V_m reverse bias drop (versus the $2V_m$ we had with the half-wave rectifier).





$$V_{AB} = V_{D,on} + V_{out}$$

Bridge Rectifier + Filter Capacitor + Load

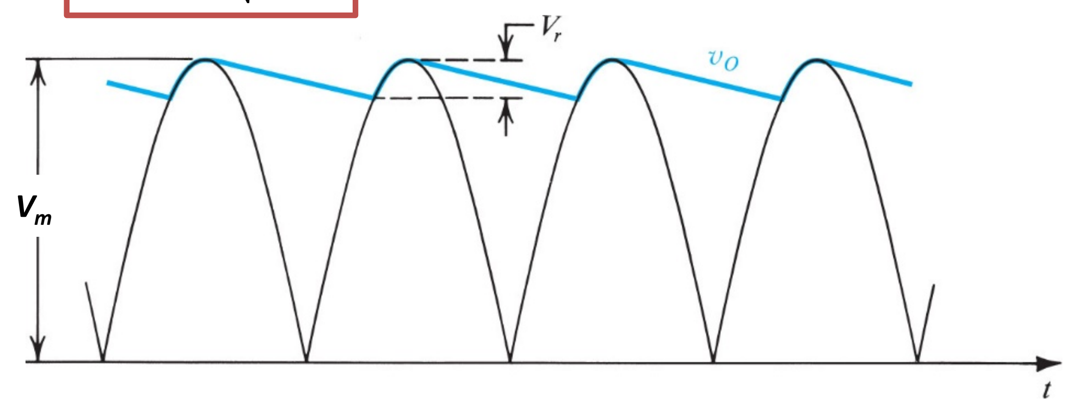
$$\frac{V_m}{R_L C} \cong \frac{V_r}{T/2} \Rightarrow V_r \cong \frac{1}{2} \times \frac{V_m}{R_L} \times \frac{T}{C}$$

slope of exponential decay at t=0

T replaced by T/2

% of time the diode is ON

$$\frac{\Delta t}{T} \simeq \frac{1}{\pi}\sqrt{\frac{2V_r}{V_m}}$$



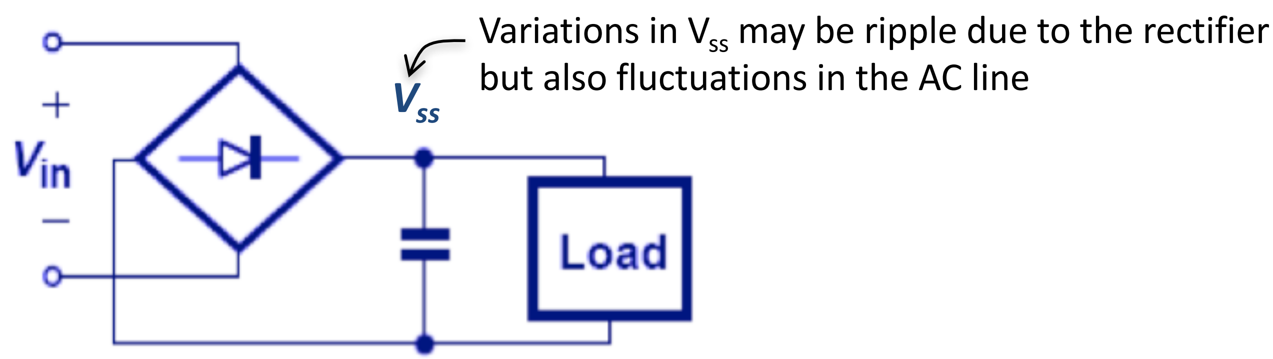
source: Sedra and Smith

$$I_{D,\max} \cong \frac{V_m}{R_L} \times \left(1 + \pi\sqrt{\frac{2V_m}{V_r}}\right)$$

$$I_{D,avg} \approx \frac{V_m}{R_L} \times \left(\frac{1}{\pi}\sqrt{\frac{V_r}{2V_m}} + 1\right)$$

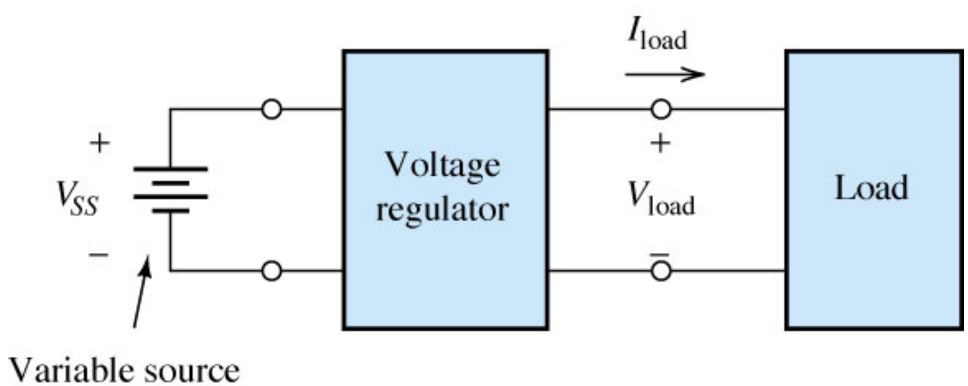
Voltage Regulator

source: Razavi



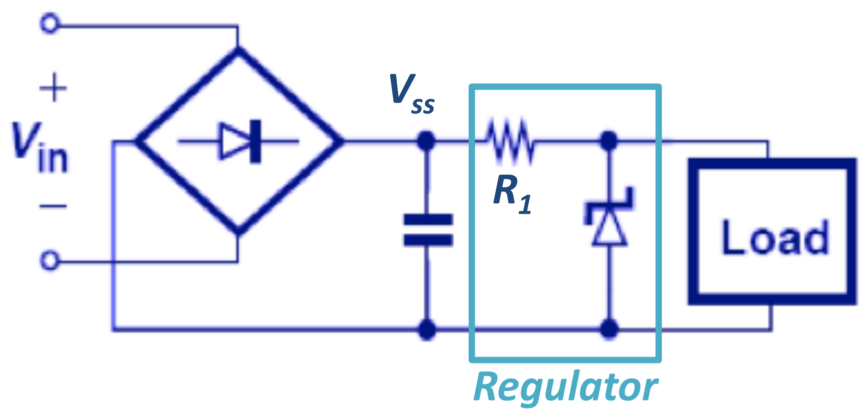
- The ripple created by the rectifier can be unacceptable to sensitive loads. Therefore, a regulator is required to obtain a more stable output.

source: Hambley

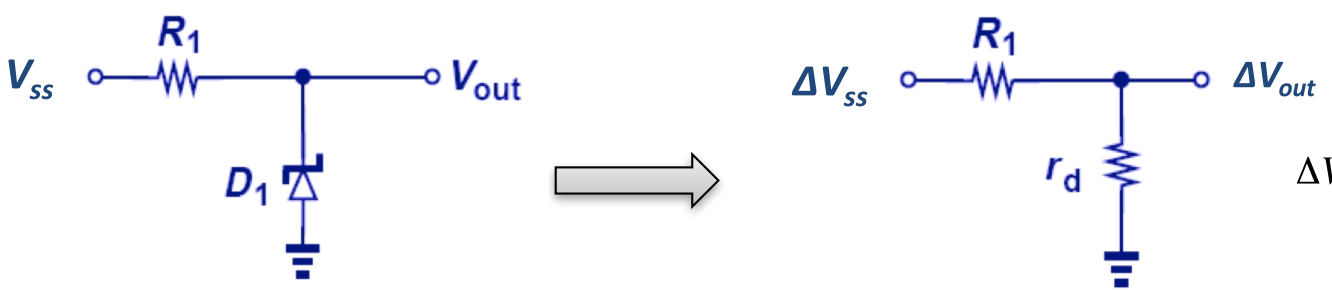


Voltage Regulator

source: Razavi



- As long as $r_d << R_1$, the use of a Zener diode provides a relatively constant output despite input variations



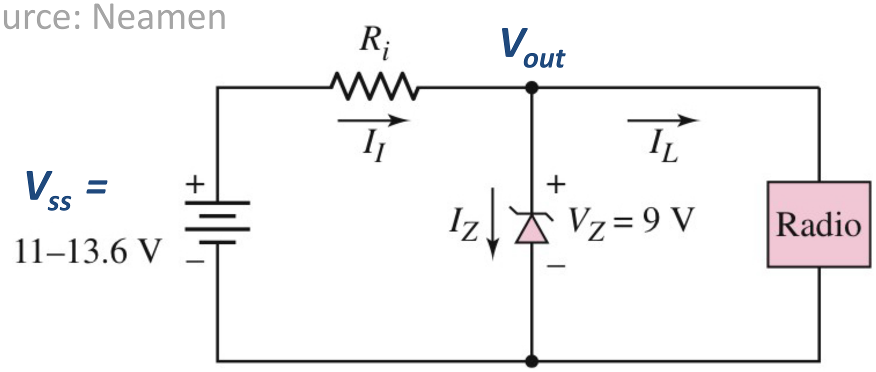
$$\Delta V_{out} = \frac{r_d}{r_d + R_1} \Delta V_{ss}$$

<u>*Example:*</u> r_d=5Ω, R_1=1K
changes in V_{ss} are attenuated by about 200 times at the output

Voltage Regulation with Zener Diode

- *Example*
  Design a voltage regulator to power a car radio at V_{out}=9V from an automobile battery whose voltage may vary between 11V and 13.6V.
  The current in the radio will vary between 0 (off) to 100 mA (full volume).

source: Neamen

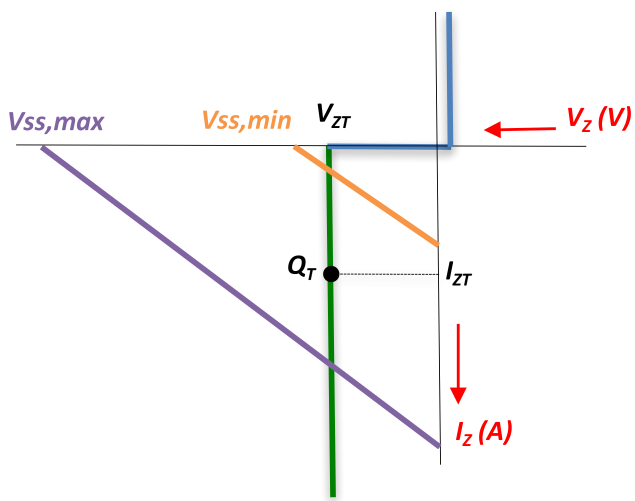


$V_{ss,nom}$=12V, $V_{SS,middle}$=12.3V

Initially, we need to find out the proper input resistance R_i.

- The resistance R_i limits the current through the zener diode and drops the "excess" voltage between V_{ss} and the nominal voltage we want on the load $V_{out,nom} = V_{Z,T} = V_{Z,nom}$ (in other words it sets the diode operating point Q_T)

Voltage Regulation with Zener Diode



Initially, assume ideal diode:

$$R_i = \frac{V_{SS,nom} - V_{Z,nom}}{I_{Z,nom} + I_{L,nom}}$$

$$I_{L,nom} = \frac{V_{Z,nom}}{R_{L,nom}}$$

More thoroughly, for the circuit to work properly, the diode must remain in zener region and the power dissipation of the diode must not exceed its rated value (P_D). In other words:

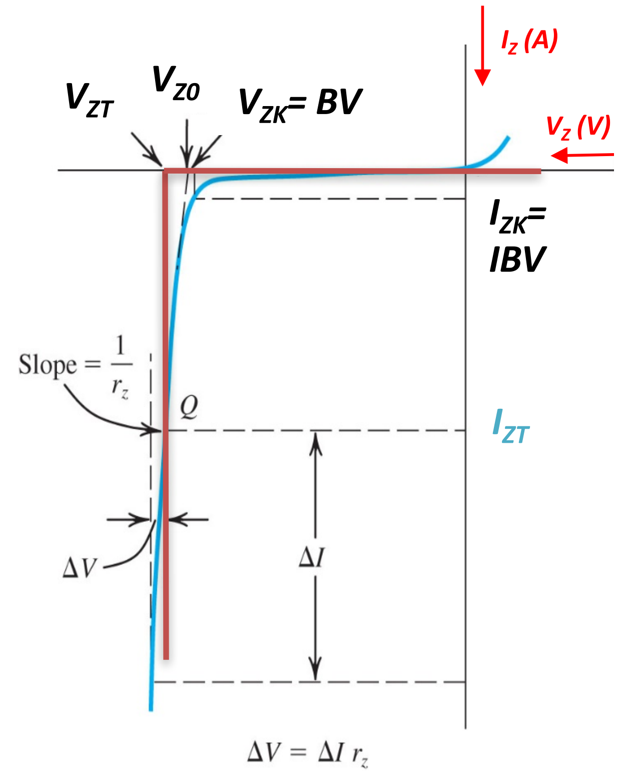
- The current in the diode is a minimum $I_{Z,min}$ when the load current is a maximum $I_{L,max}$, and the source voltage is a minimum $V_{ss,min}$
- The current in the diode is a maximum $I_{Z,max}$, when the load current is a minimum $I_{L,min}$ and the source voltage is a maximum $V_{ss,max}$

Therefore we can impose the two following constraints: $R_i = \frac{V_{SS,\min} - V_{Z,nom}}{I_{Z,\min} + I_{L,\max}}$ and $R_i = \frac{V_{SS,\max} - V_{Z,nom}}{I_{Z,\max} + I_{L,\min}}$

Voltage Regulation with Zener Diode

$$R_i = \frac{V_{SS,\min} - V_{Z,nom}}{I_{Z,\min} + I_{L,\max}} \qquad R_i = \frac{V_{SS,\max} - V_{Z,nom}}{I_{Z,\max} + I_{L,\min}}$$

Reasonably, we can assume that we know the range of input voltage, the range of output load current, and the Zener voltage. Further, it is reasonable to set the minimum zener current to be $I_{Z,min} \approx 0.1 \times I_{Z,max}$
More stringent design requirements may require the minimum zener diode current to be 20 or 30 percent of the maximum value.
The important point in setting $I_{Z,min}$ is to make sure is far enough from the knee !!



By equating the constrains on R_i and setting $I_{Z,min} \approx 0.1 \times I_{Z,max}$ we can write:

$$I_{Z,\max} = \frac{I_{L,\max} \cdot \left(V_{ss,\max} - V_{Z,nom}\right) - I_{L,\min} \cdot \left(V_{ss,\min} - V_{Z,nom}\right)}{V_{ss,\min} - 0.9 \times V_{Z,nom} - 0.1 \times V_{ss,\max}}$$

The maximum power dissipated in the Zener diode is approximately:

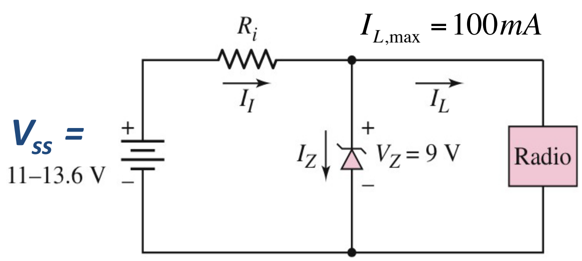
$$P_{Z,\max} \approx I_{Z,\max} \times V_{Z,nom}$$

Therefore: $R_i = \frac{V_{ss,\max} - V_{Z,nom}}{I_{Z,\max} + I_{L,\min}}$ and $I_{Z,\min} = \frac{V_{ss,\min} - V_{Z,nom}}{R_i} - I_{L,\max}$

Voltage Regulation with Zener Diode

… and finally make sure $P_{Z,max} < P_D$ and $I_{Z,min} < I_{ZK}$

Let's now go back to the example and plug in some numbers:



source: Neamen

$$I_{Z,\max} = \frac{I_{L,\max}\cdot\left(V_{ss,\max} - V_{Z,nom}\right) - I_{L,\min}\cdot\left(V_{ss,\min} - V_{Z,nom}\right)}{V_{ss,\min} - 0.9\times V_{Z,nom} - 0.1\times V_{ss,\max}} = \frac{100\cdot(13.6-9)-0}{11-0.9\cdot 9-0.1\cdot 13.6} \cong 300mA$$

$$P_{Z,\max} \approx I_{L,\max}\times V_{Z,nom} = 300mA\times 9V = 2.7W$$

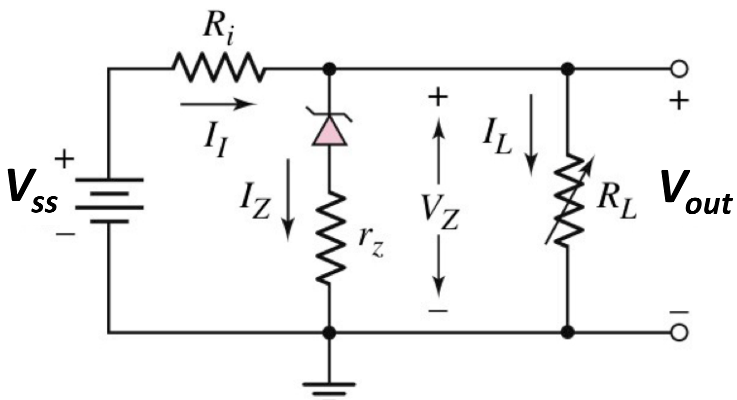
$$R_i = \frac{V_{ss,\max} - V_{Z,nom}}{I_{Z,\max} + I_{L,\min}} = \frac{13.6-9}{300m+0} \cong 15.3\Omega$$

$$I_{Z,min} = 0.1\times I_{Z,max} \cong 30mA$$

$$P_{Ri,\max} = \frac{\left(V_{ss,\max} - V_{Z,nom}\right)^2}{R_i} = \frac{(13.6-9)^2}{15.3} \cong 1.4W$$

Regulator's figures of merit

- In reality the zener is not ideal. It has some non zero resistance, therefore if the source voltage or the load current fluctuates, so does the $V_{out}=V_Z$



source: Neamen

__Source regulation (a.k.a. line regulation)__

It is a measure of how much the output voltage changes as the source voltage change (assuming no-load condition $R_L=\infty$)

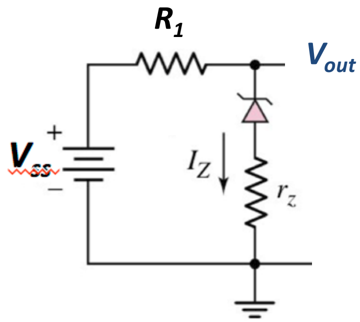
$$\text{source regulation} \equiv \frac{\Delta V_{out}}{\Delta V_{ss}} \times 100\%$$

ability to maintain a constant output voltage level on the output despite changes to the input voltage level

Line regulation example

<u>Example:</u>

Find the line regulation for the previous example, assuming r_Z=2Ω



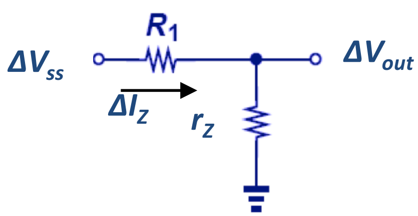
source: Neamen

For V_{ss}=13.6V: $I_Z = \frac{V_{ss} - V_Z}{R_1 + r_Z} = \frac{13.6 - 9}{15.3 + 2} \cong 265.9mA \Rightarrow V_{out} = I_Z \times r_Z + V_Z = 9.532V$

For V_{ss}=11V: $I_Z = \frac{V_{ss} - V_Z}{R_1 + r_Z} = \frac{11 - 9}{15.3 + 2} \cong 115.61mA \Rightarrow V_{out} = I_Z \times r_Z + V_Z = 9.231V$

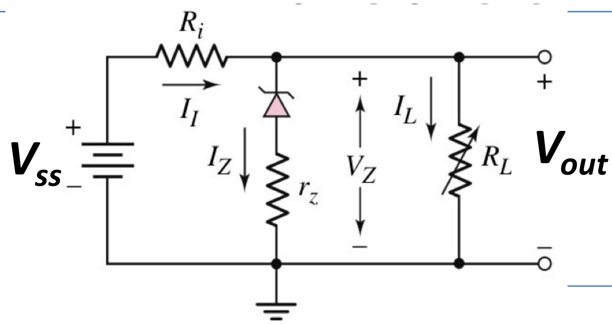
$$\frac{\Delta V_{out}}{\Delta V_{in}} = \frac{9.532 - 9.231}{13.6 - 11} \cong 15.6\%$$

Alternatively by considering just the variations (small signal circuit)



source: Razavi

$$\frac{\Delta V_{out}}{\Delta V_{ss}} = \frac{r_Z}{R_1 + r_Z} = \frac{2}{15.3 + 2} \cong 15.6\%$$



Regulator's figures of merit

Load regulation

It is a measure of the change in output voltage with a change in load current

$$\text{load regulation} \equiv \frac{V_{out,noload} - V_{out,fullload}}{V_{out,fullload}} \times 100\%$$

capability to maintain a constant voltage on the output despite changes in the load (such as a change in resistance value connected across the supply output

where:
- $V_{out,noload}$ is the load voltage for zero load current
- $V_{out,fullload}$ is the load voltage for the maximum rated load current

In practice, there are a couple of other ways of defining load regulation.

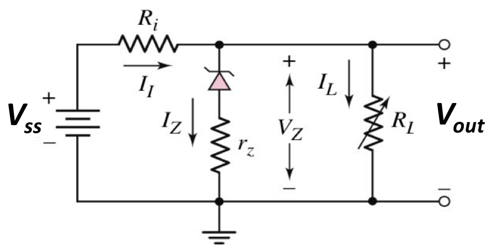
$$\text{load regulation} \equiv \frac{V_{out,noload} - V_{out,fullload}}{V_{out,nomload}} \times 100\%$$

$$\text{load regulation} \equiv \left| \frac{V_{out,noload} - V_{out,fullload}}{I_{L,noload} - I_{L,fullload}} \right| = \left| \frac{\Delta V_{out}}{\Delta I_L} \right| \quad (\Omega)$$

Load regulation example

Example:

Find the load regulation for the usual example. Assume r_Z=2Ω



Note:
When measuring the load regulation the source is assumed constant. Since the full load current is reached for $V_{ss} = V_{ss,max}$ for load regulation computations we must assume $V_{ss} = V_{ss,max}$= const

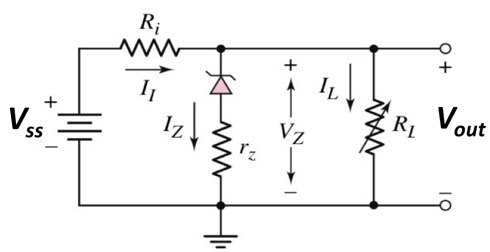
For I_L = 0A: $$I_Z = \frac{V_{ss,\max} - V_Z}{R_1 + r_Z} = \frac{13.6-9}{15.3+2} \cong 265.9mA \Rightarrow V_{out} = I_Z \times r_Z + V_Z = 9.532V$$

For I_L=100mA: $$I_Z = \frac{V_{R1}}{R_1} - I_L = \frac{V_{ss,\max} - (V_Z + r_Z \times I_Z)}{R_1} - I_L$$

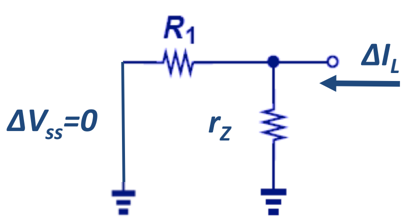
$$\Rightarrow I_Z = \frac{V_{ss,\max} - V_Z - I_L \times R_1}{R_1 + r_Z} = \frac{13.6 - 9 - 100m \times 15.3}{15.3+2} \cong 177.46mA \Rightarrow V_{out} = I_Z \times r_Z + V_Z = 9.355V$$

$$\frac{V_{out,noload} - V_{out,fullload}}{V_{out,fullload}} \times 100\% = \frac{9.532 - 9.355}{9.355} \times 100\% \cong 1.89\%$$

Load regulation example



Alternatively by considering just the variations (small signal circuit)



$$\Delta V_{out} = (R_1 \parallel r_Z)\Delta I_L \Rightarrow \frac{\Delta V_{out}}{\Delta I_L} = (R_1 \parallel r_Z) = 15.3 \parallel 2 \cong 1.77\Omega$$

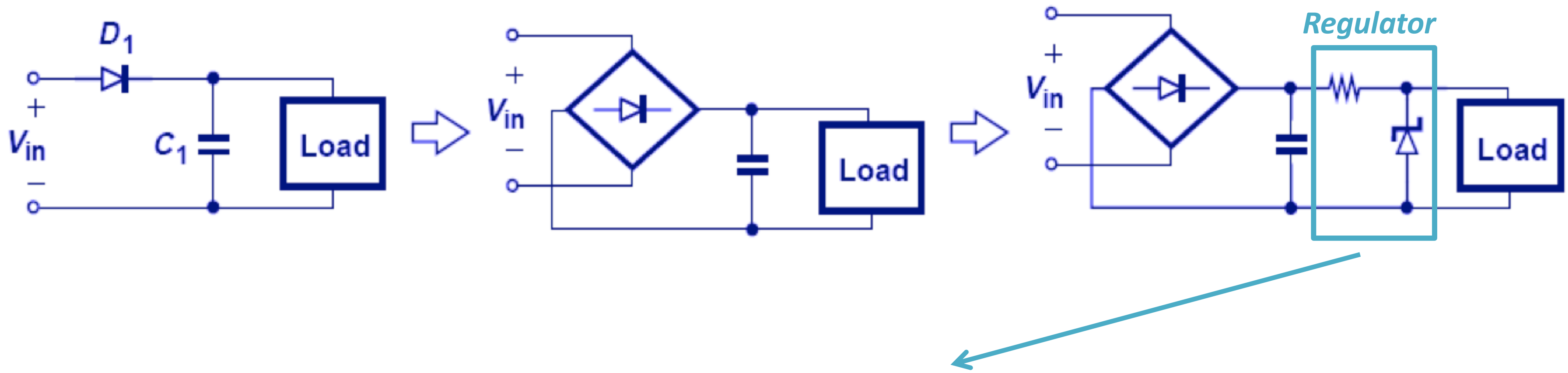
For a ΔI_L of 100 mA we have that $\Delta V_{out} \cong$ 177 mV

(As expected this is the same result we got before ΔV_{out}= 9.532 – 9.355 = 177 mV)

$V_{out,noload}$ $V_{out,fullload}$

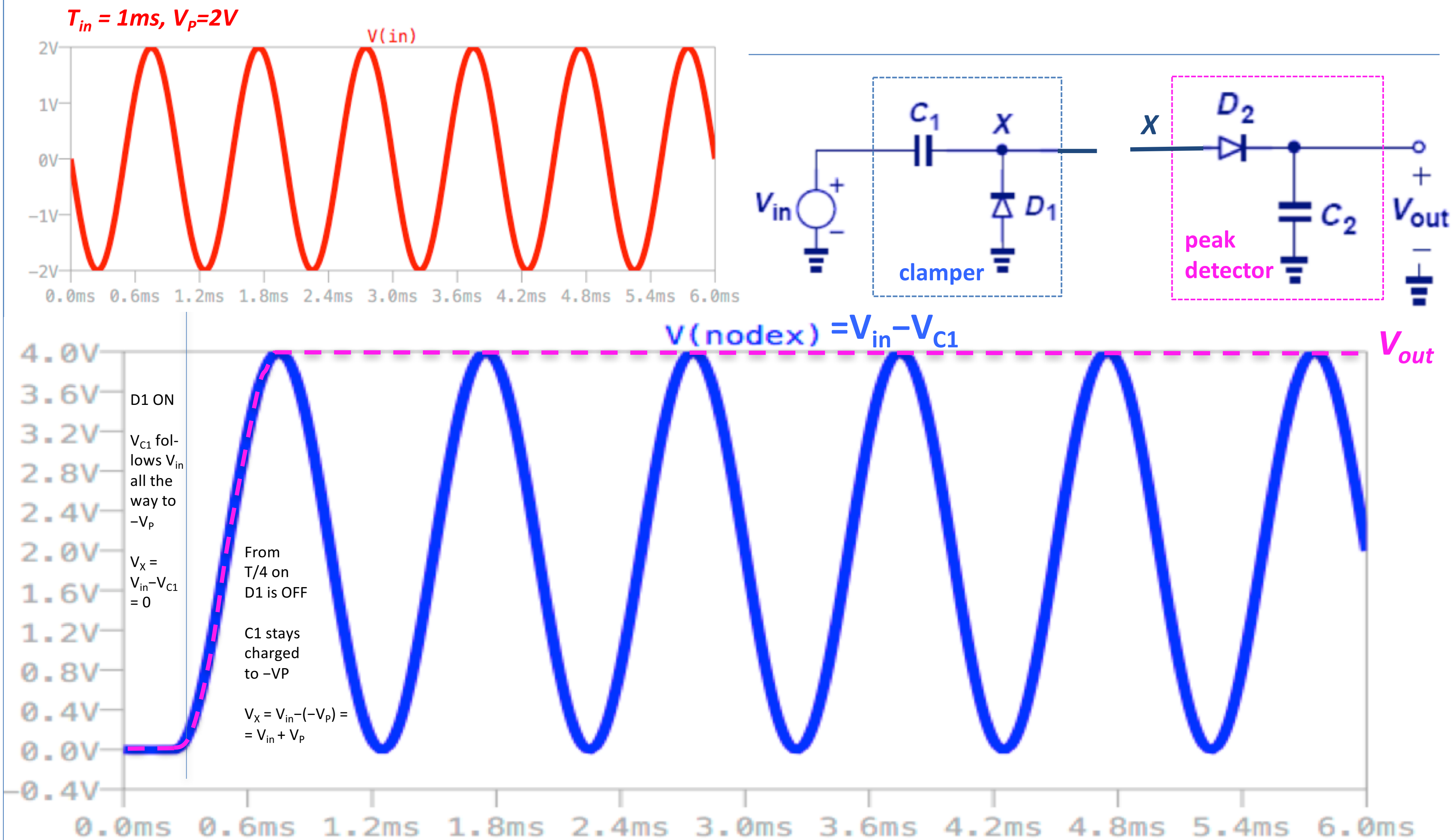
Evolution of an AC-DC converter

source: Razavi



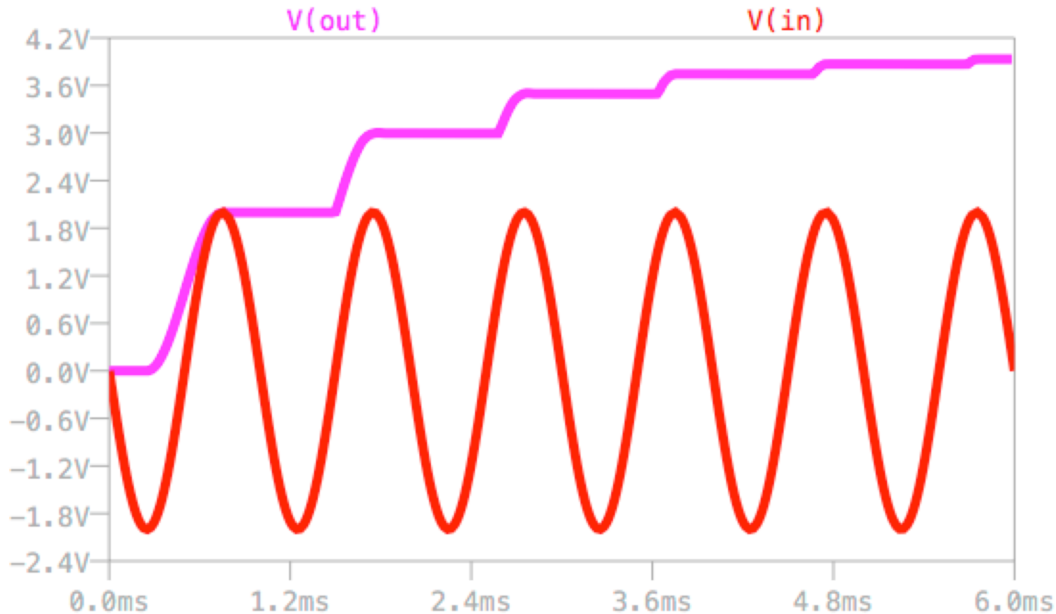
Ideally we want both line regulation and load regulation to be as close as possible to 0%

Voltage doubler

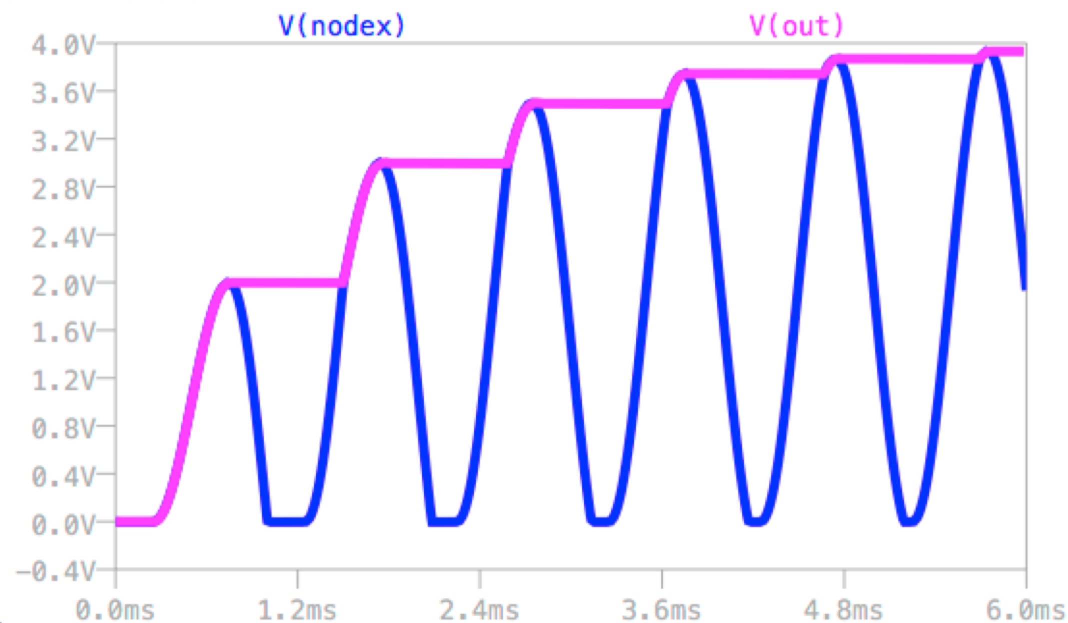


If we take the clamper just designed and attach a peak detector at its output we get a voltage doubler

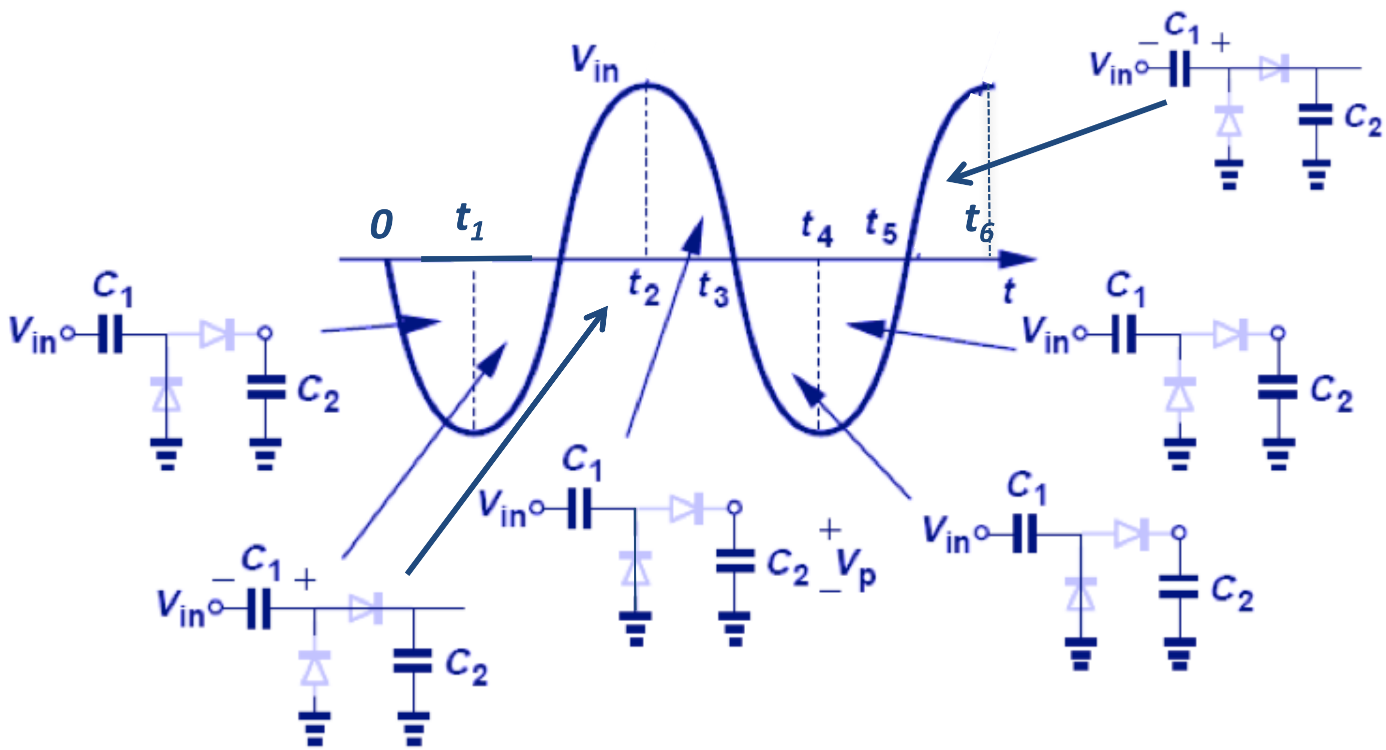
Voltage doubler: detailed analysis



In the reality the charging of C1 and C2 ($V_{C2} = V_{out}$) is not as simple as assumed in the previous slide (slide 52 is a snapshot of the steady state)



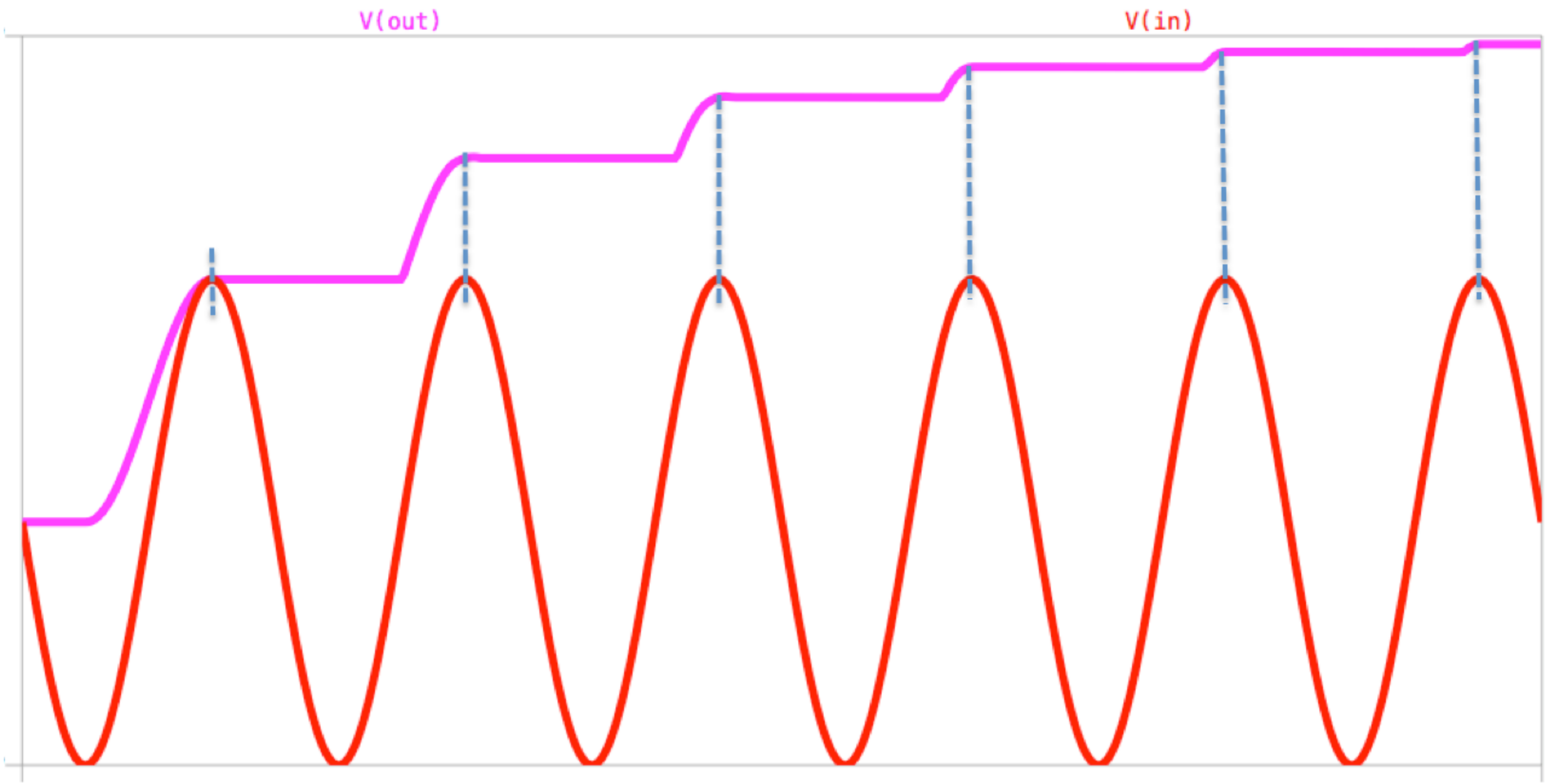
Voltage doubler: detailed analysis



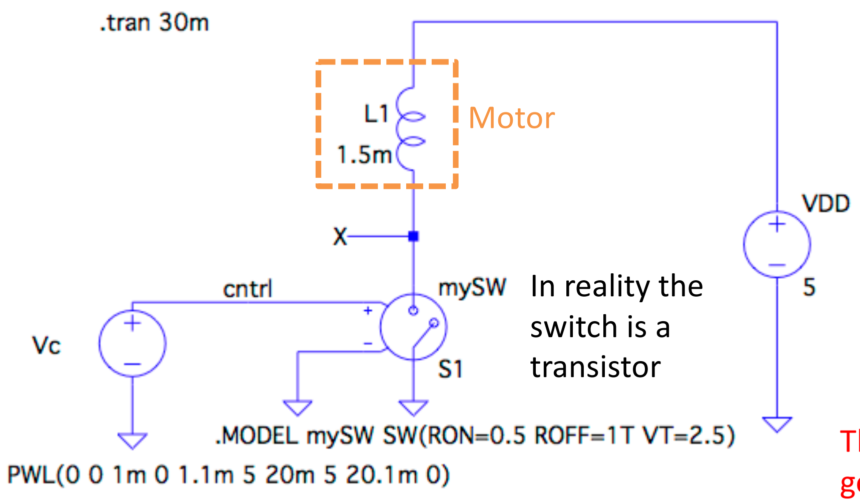
Each input cycle, the output increases by V_p, $V_p/2$, $V_p/4$, etc., eventually settling to $2\,V_p$

$$V_{out} = V_P\left(1+\frac{1}{2}+\frac{1}{4}+\frac{1}{8}+\ldots\right) = V_P\sum_{n=0}^{\infty}\left(\frac{1}{2}\right)^n = V_P\,\frac{1}{1-1/2} = 2V_P$$

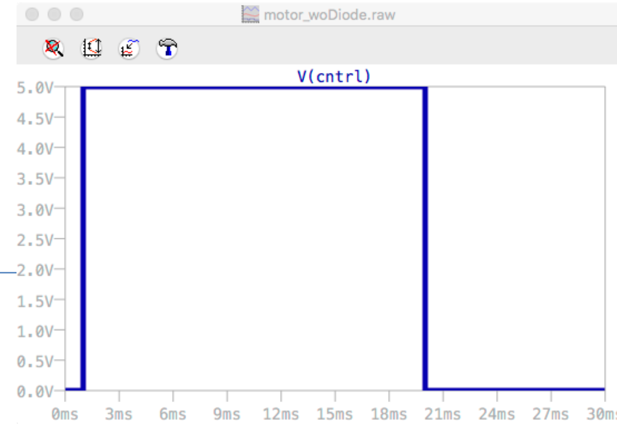
Voltage doubler: detailed analysis

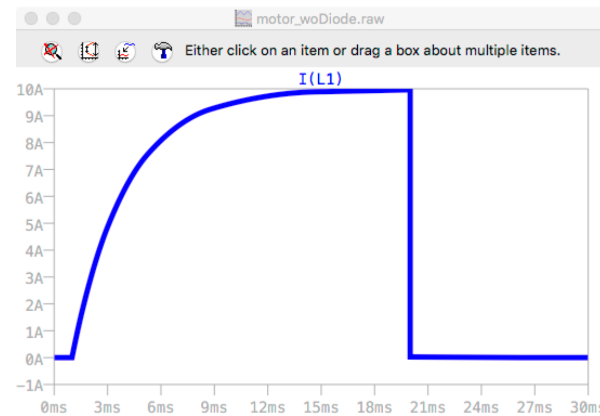


Diodes as Switches

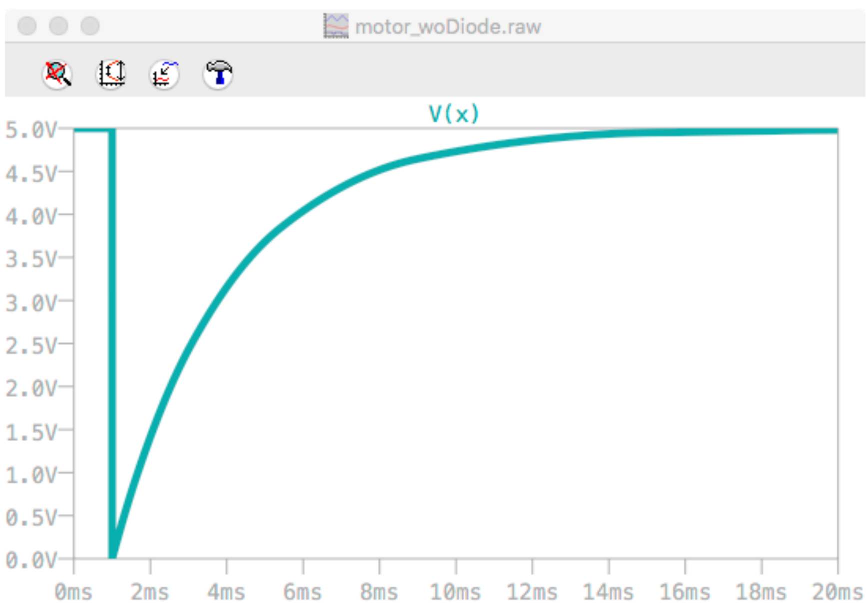


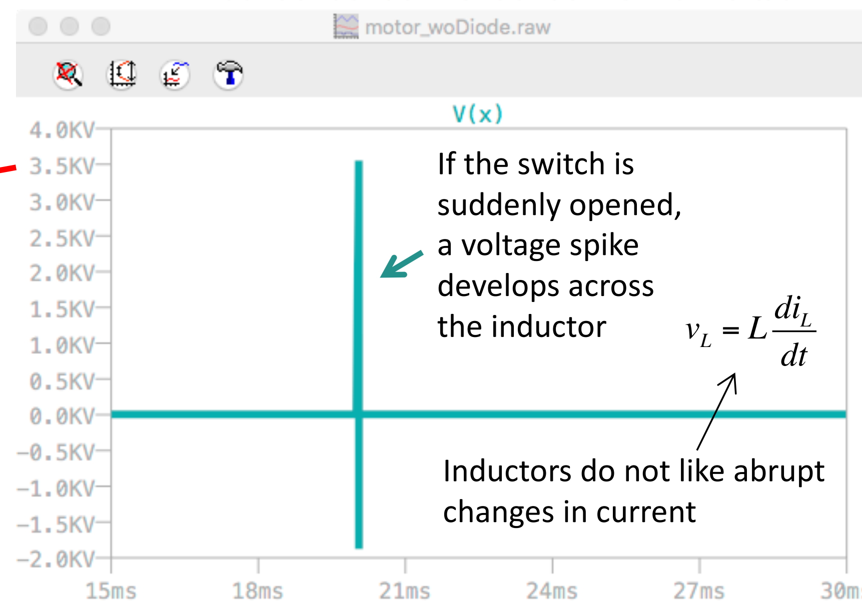
In reality the switch is a transistor





The transistor goes in "smoke"





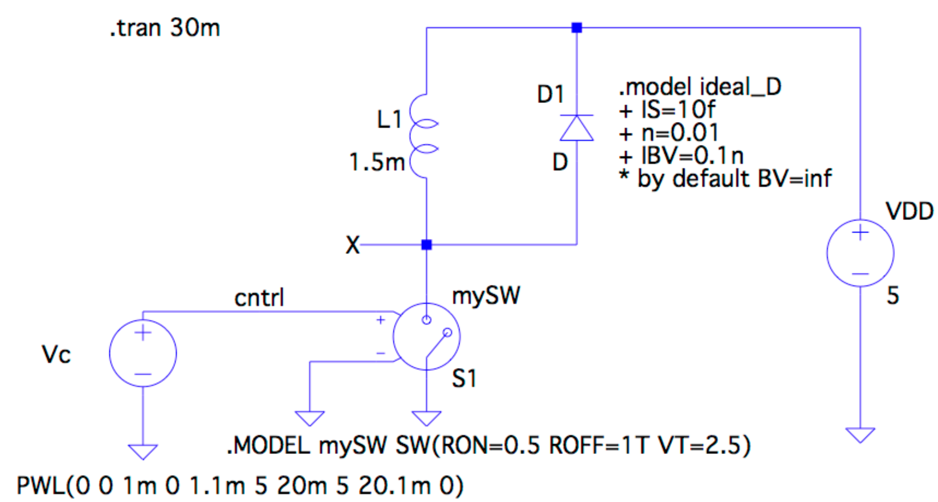
If the switch is suddenly opened, a voltage spike develops across the inductor

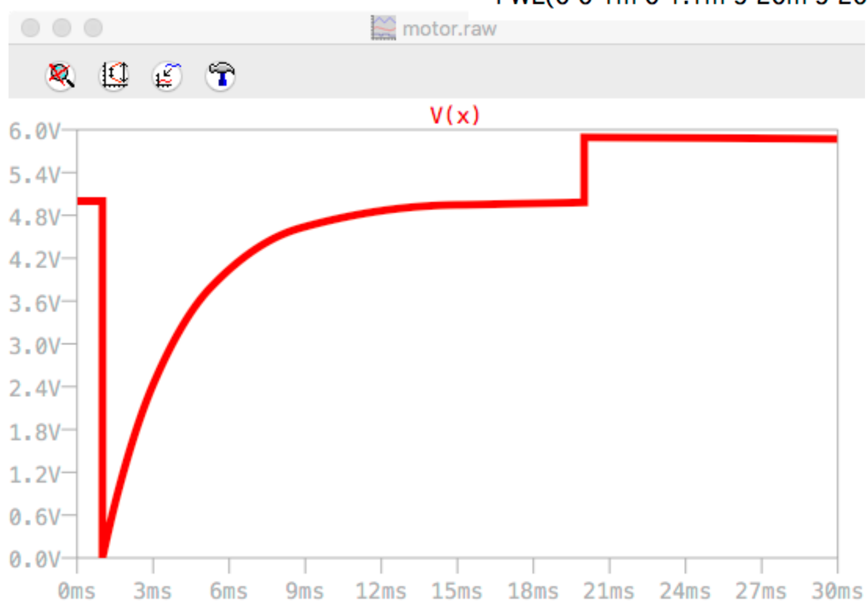
$$v_L = L\frac{di_L}{dt}$$

Inductors do not like abrupt changes in current

Diodes as Switches

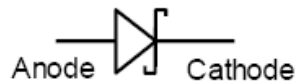
A diode placed across the inductive load, will give the voltage spike a safe path to discharge, looping over-and-over through the inductor and diode until it eventually dies out.





Special Diodes

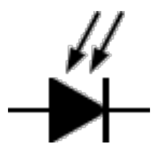
- Schottky-Barrier Diode (SBD)



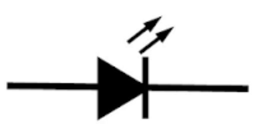
  - SBD are built using a metal-semiconductor junction
  - current is conducted by majority carriers (electrons).
    Thus SBD do not exhibit the minority carrier charge storage effect.
    As a result SBD can be switched from on to off and vice versa much faster
  - The forward voltage drop is lower (0.3V to 0.5V for silicon)

- Varactors

- Photodiodes

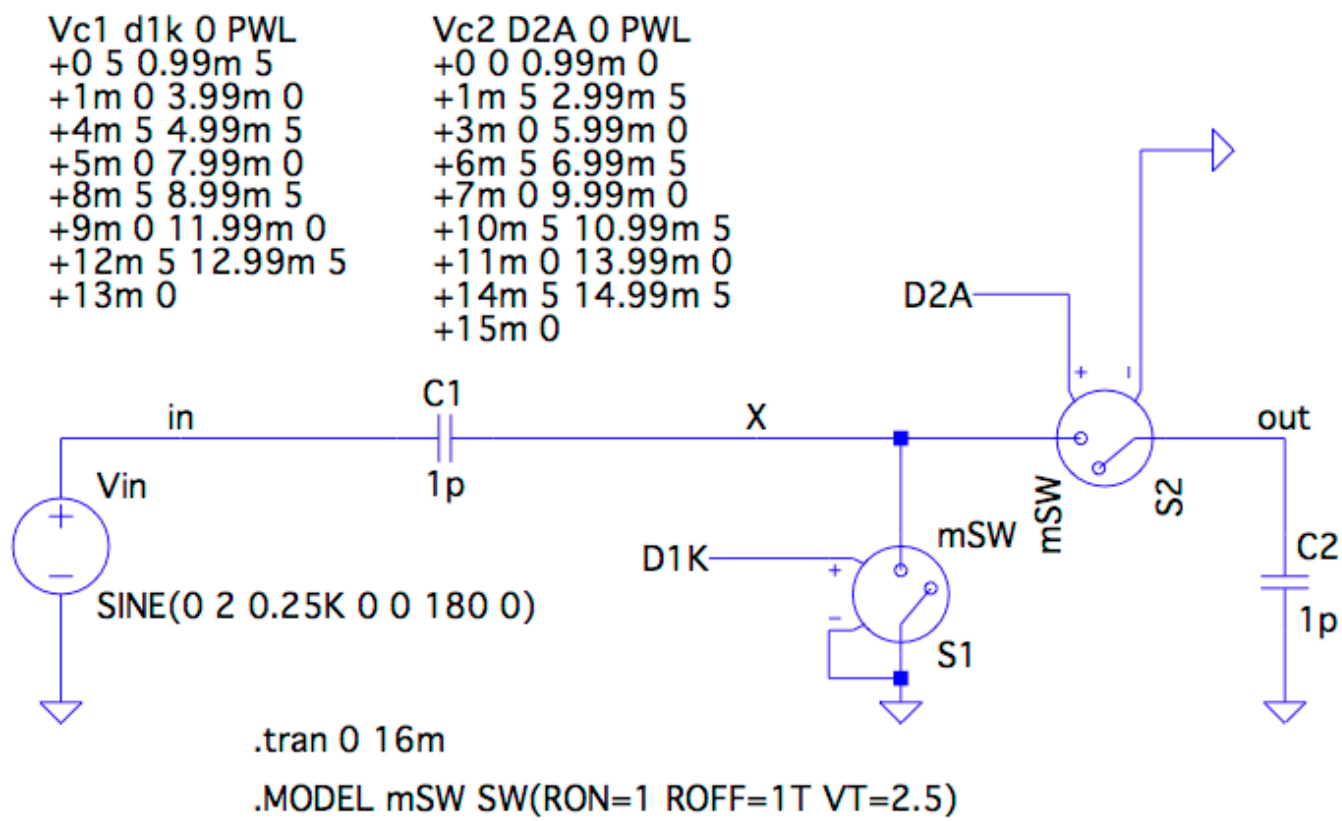


- LEDs



The wavelength of the light emitted, and thus the color, depends on the band gap energy of the materials forming the p-n junction.
(Example. Red LED:
λ_d=630nm, VF=2.1V IF=50mA, luminous Intensity I_V=7500 mcd)

Voltage doubler modeled with switches



Voltage doubler modeled with switches