Fundamentals of Electronics
Week 5

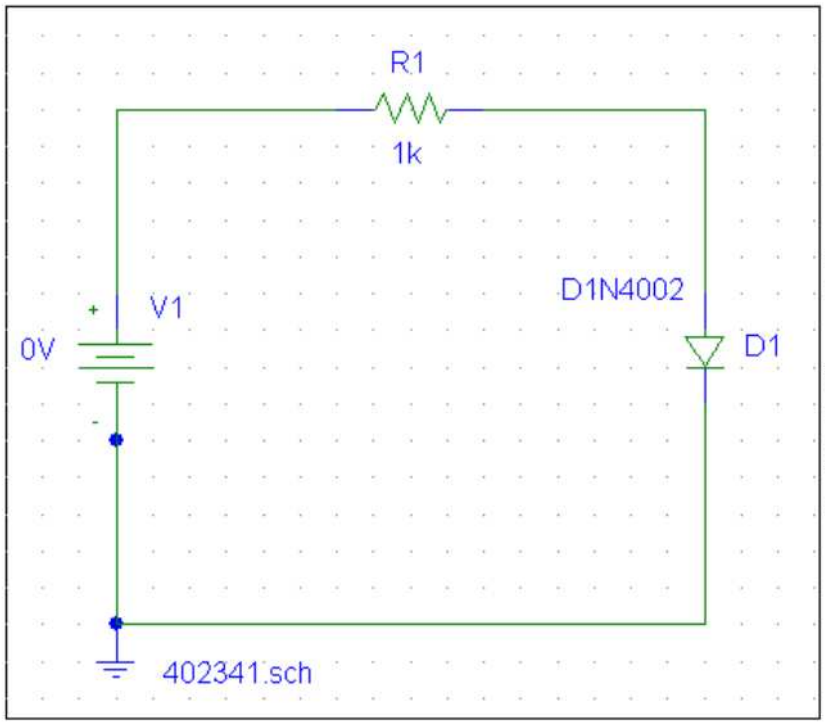
Charles A. DiMarzio
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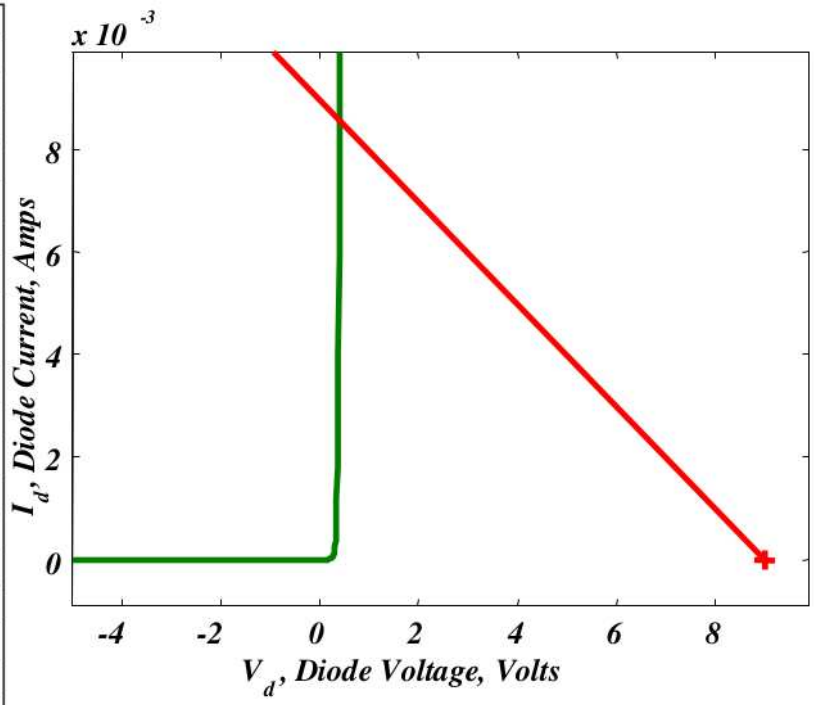
Sep 2024

Agenda

- Solving the Transcendental Equation
  - Iterative Methods
  - Piecewise Linear Approximation
  - Taylor Series
- Examples
  - Regulators
  - AC to DC Power Supplies
    Rectification, Filtering, Regulation
  - Full–Wave Rectifier
  - Limiters
  - Diode Logic
  - Photodiode Circuits

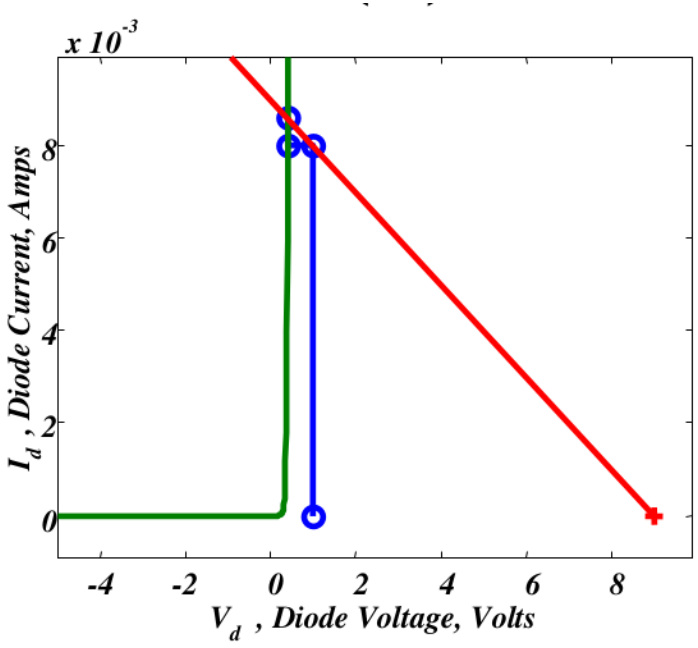
Circuit with Diode





Iteration Methods (1)

Sometimes you eat the bear...

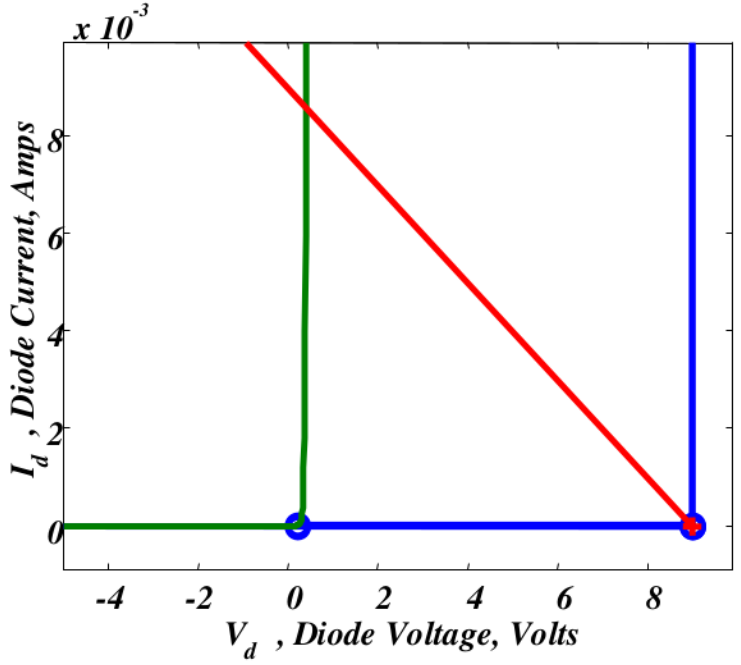



```
vd(1)=1;
id(1)=0;
for n=2:2:10
   vd(n)=vd(n-1);
   id(n)=(vsource-vd(n))/r;
   id(n+1)=id(n);
   vd(n+1)=log(id(n+1)/is-1)*vt;
end;
```

Iteration Methods (2)

....and
Sometimes the bear eats you

```
vd(1)=.2;
id(1)=0;
for n=2:2:10
   vd(n)=vd(n-1);
   id(n)=is*(exp(vd(n)/vt)-1);
   id(n+1)=id(n);
   vd(n+1)=vsource-id(n+1)*r;
end;
```



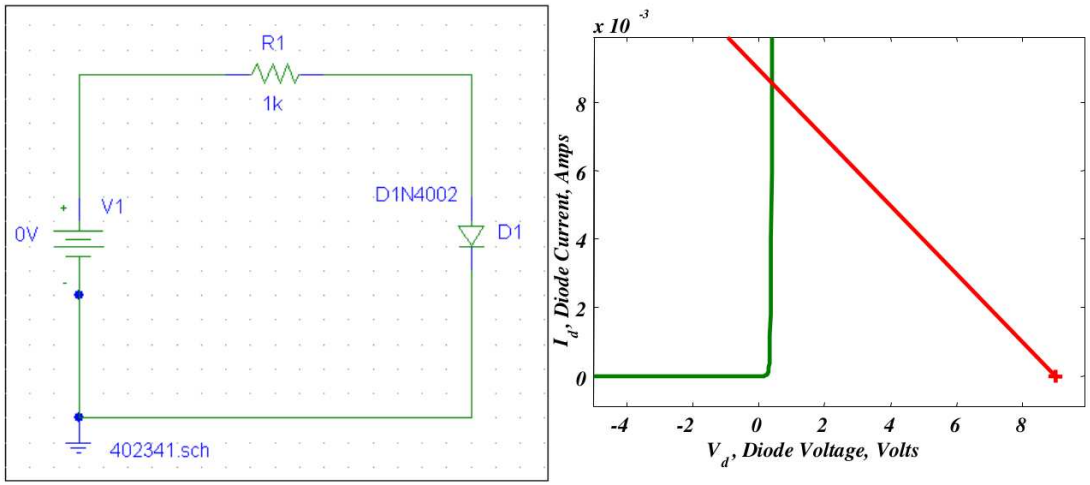
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Piecewise Linear Models

- All Linear Equations
  - Each one is simple to solve. . .
  - But there can be a lot of them.
- Solutions for each line piece
  - Solve the linear equation
  - Check the inequalities
- Pick the solution that works

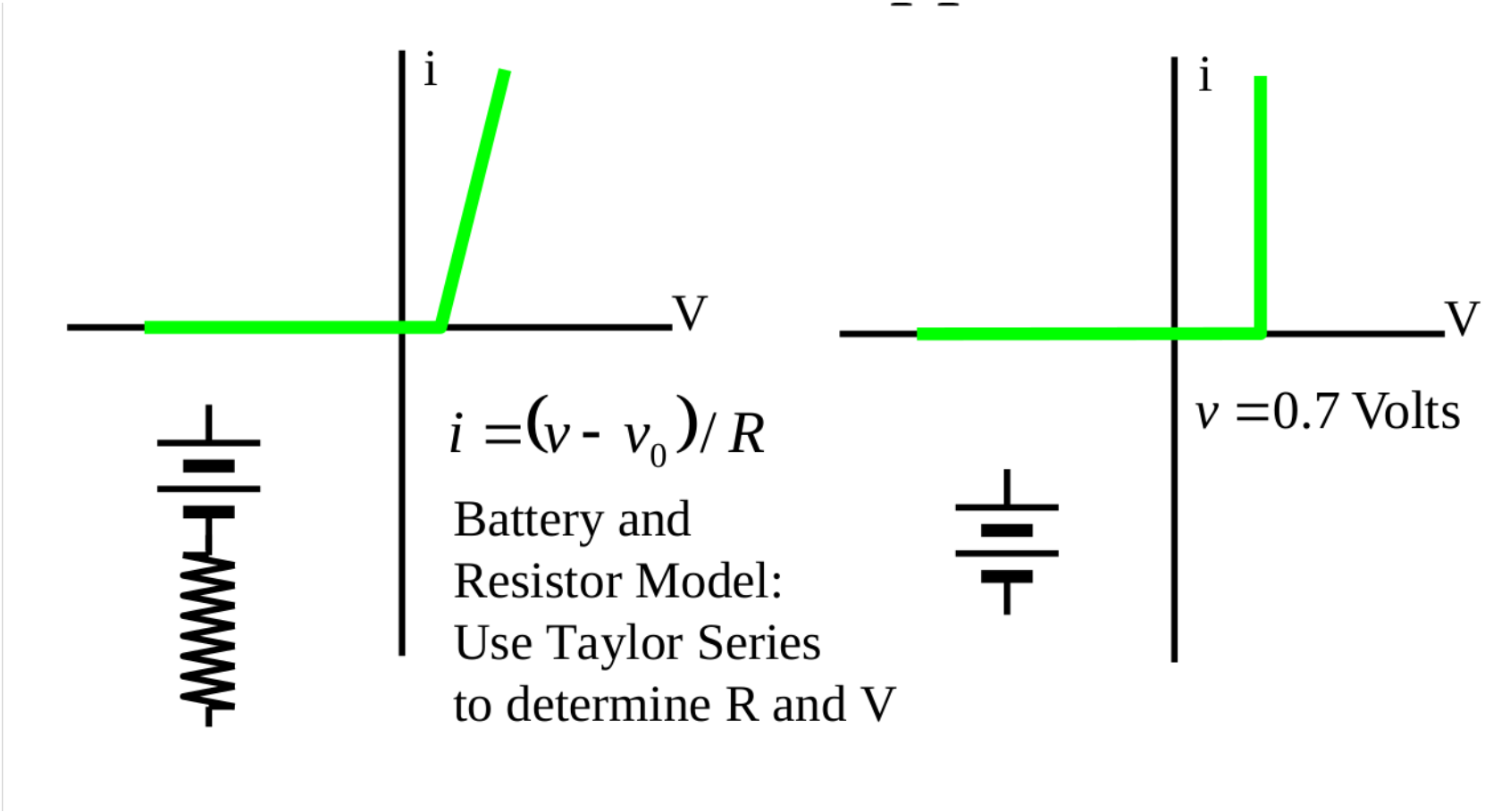
Ideal Diode



- Reverse segment (open circuit): $i = 0,\ v < 0$

- Forward segment (short circuit): $v = 0,\ i > 0$

Two More Piecewise Linear Approximations

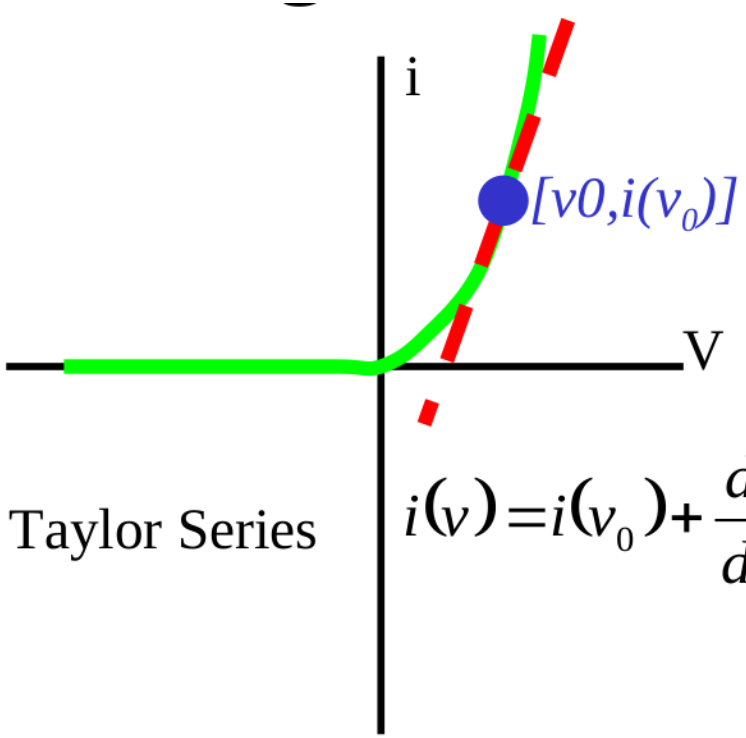


More Complicated Forward Segments

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Large and Small Signal Models



Diode Equation

$$I = I_s\left(e^{V/V_T} - 1\right)$$

Taylor Series

$$i(v) = i(v_0) + \left.\frac{di}{dv}\right|_{v=v_0}(v - v_0) + \left.\frac{d^2 i}{dv^2}\right|_{v=v_0}(v - v_0)^2 + \cdots$$

$$i(v) = I_s\left(e^{v_0/V_T} - 1\right) + \frac{I_s}{V_T}e^{v_0/V_T}(v - v_0) + I_s\left(\frac{e^{v_0/V_T}}{V_T}\right)^2(v - v_0)^2 + \cdots$$

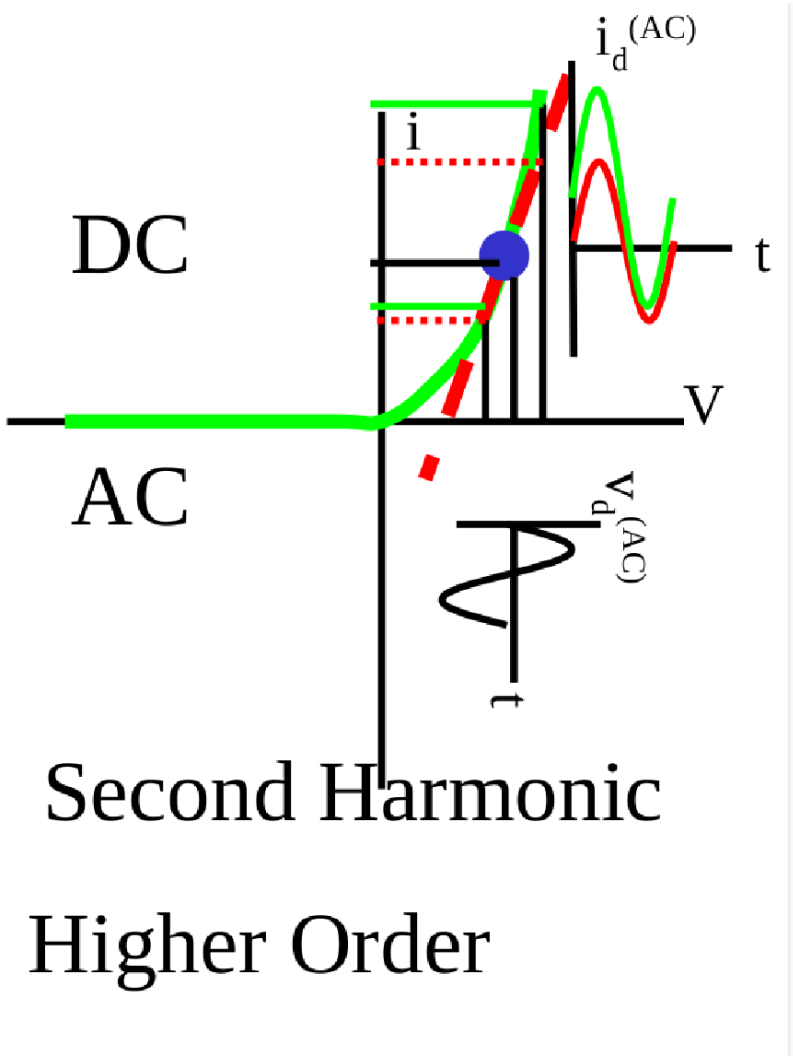
Small Signal Model

$$i(v) = I_s\left(e^{v_0/V_T} - 1\right)$$

$$+ \frac{I_s}{V_T} e^{v_0/V_T}\left(v - v_0\right)$$

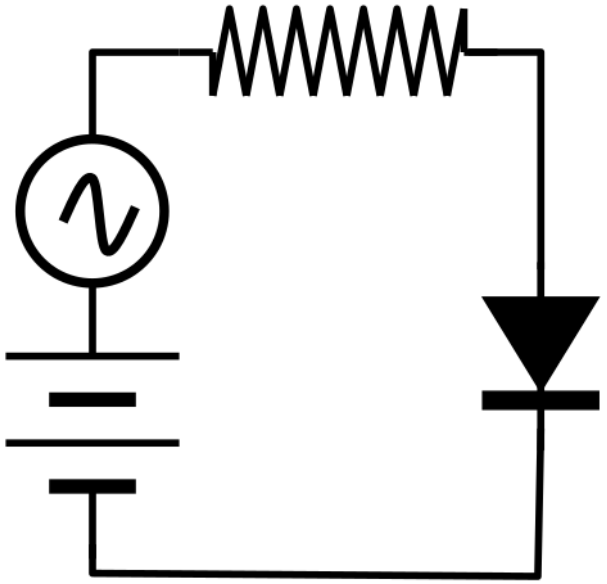
$$+ I_s\left(\frac{e^{v_0/V_T}}{V_T}\right)^2 \left(v - v_0\right)^2$$

$$+ \cdots$$

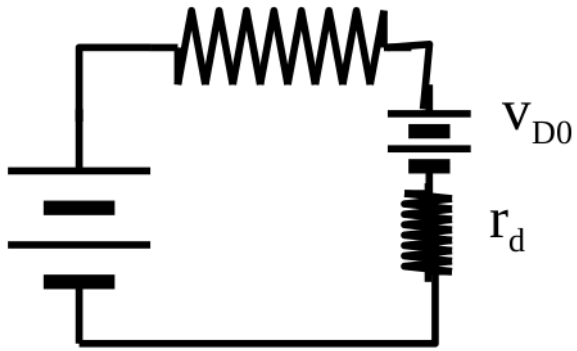


Separating the Models

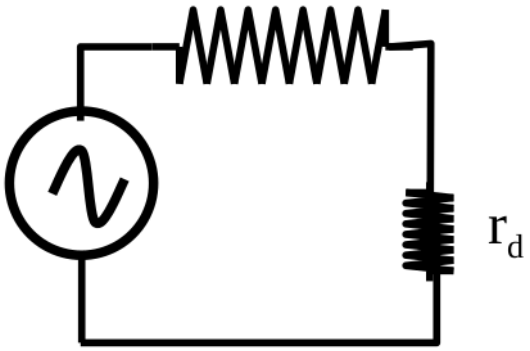
Complete Circuit



DC Model



AC Model



DC and AC Models

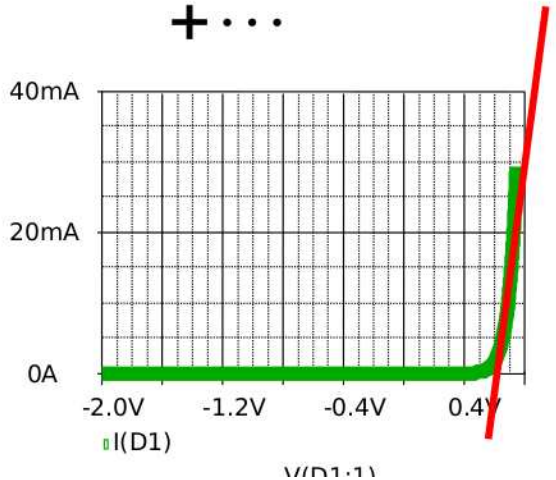
$$i(v) = I_s\left(e^{v_0/V_T} - 1\right) \longrightarrow i_D = I_D^{(DC)}$$

$$+\frac{I_s}{V_T}e^{v_0/V_T}(v - v_0) \longrightarrow +\frac{I_s}{V_T}e^{V_D^{(DC)}/V_T}v_d^{(AC)}$$

$$+I_s\left(\frac{e^{v_0/V_T}}{V_T}\right)^2(v - v_0)^2$$

$$+\cdots$$

$$+\cdots$$



Model Approximation

- DC Model Approximation

$$I_D^{(DC)} = I_s\left(e^{V_D^{(DC)}/V_T} - 1\right) \qquad I_D^{(DC)} \approx I_s e^{V_D^{(DC)}/V_T}$$

- AC Model Approximation

$$id_D^{(AC)} + \frac{I_s}{V_T} e^{V_D^{(DC)}/V_T} v_d^{(AC)} \qquad i_d^{(AC)} + \frac{I_D^{(DC)}}{V_T} v_d^{(AC)}$$

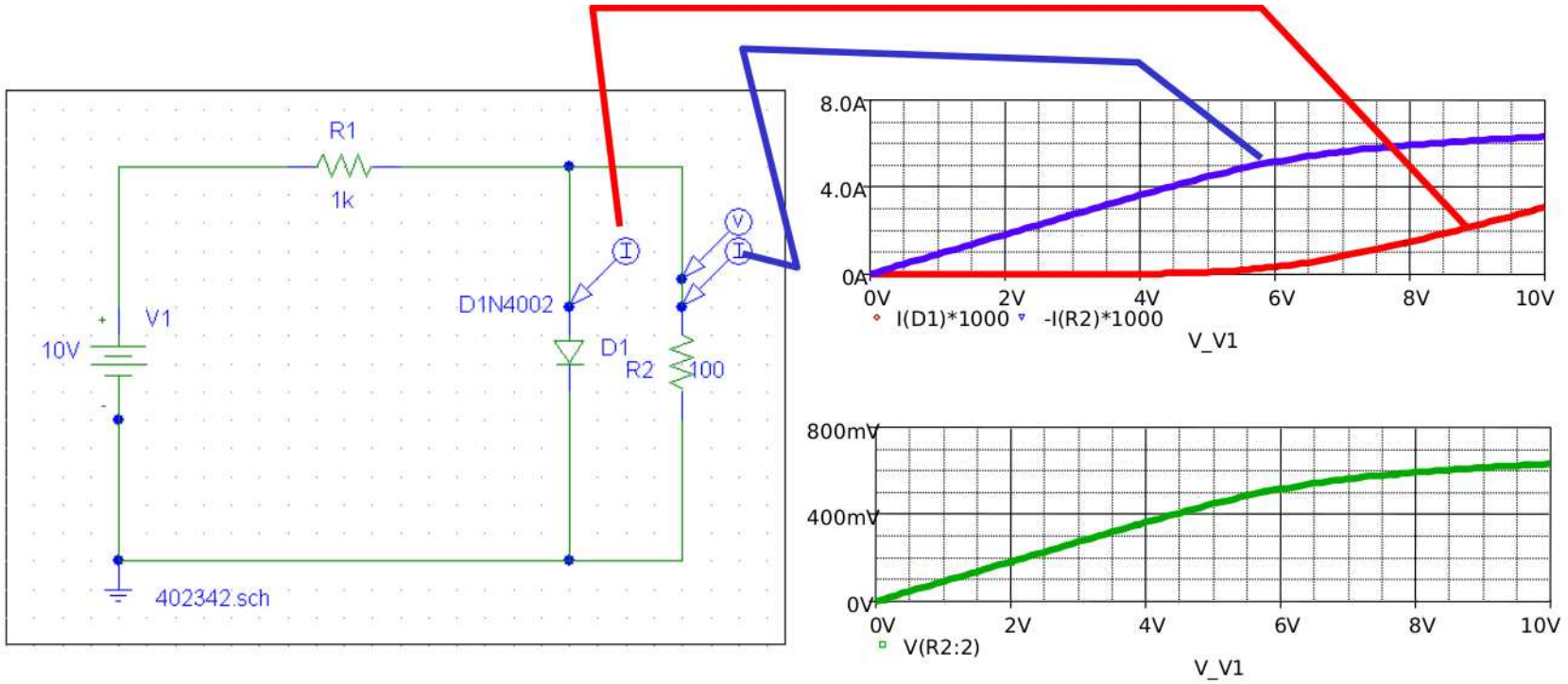
- Equivalent Resistor

$$R_{eq} \approx \frac{V_T}{I_D^{(DC)}} \approx \frac{25\text{mV}}{\text{few mA}}$$

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Forward–Drop Regulator (1)



What Happens if I change the value of R2?

Diode Parameters in Regulator

**** Diode MODEL PARAMETERS

D1N4002

IS	14.110000E-09
N	1.984
ISR	100.000000E-12
IKF	94.81
BV	100.1
IBV	10
RS	.03389
TT	4.761000E-06
CJO	51.170000E-12
VJ	.3905
M	.2762

**** OPERATING POINT INFORMATION

TEMPERATURE = 27.000 DEG C

****

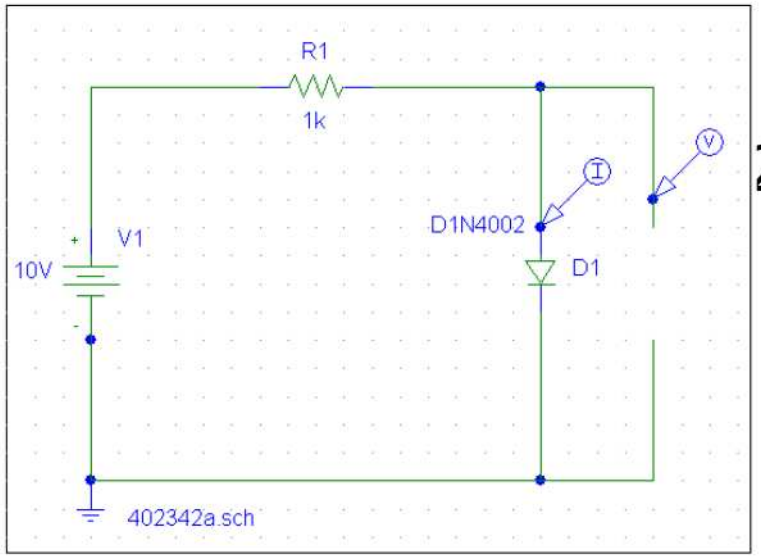
**** DIODES

NAME	D_D1
MODEL	D1N4002
ID	3.07E-03
VD	6.30E-01
REQ	1.67E+01
CAP	2.85E-07

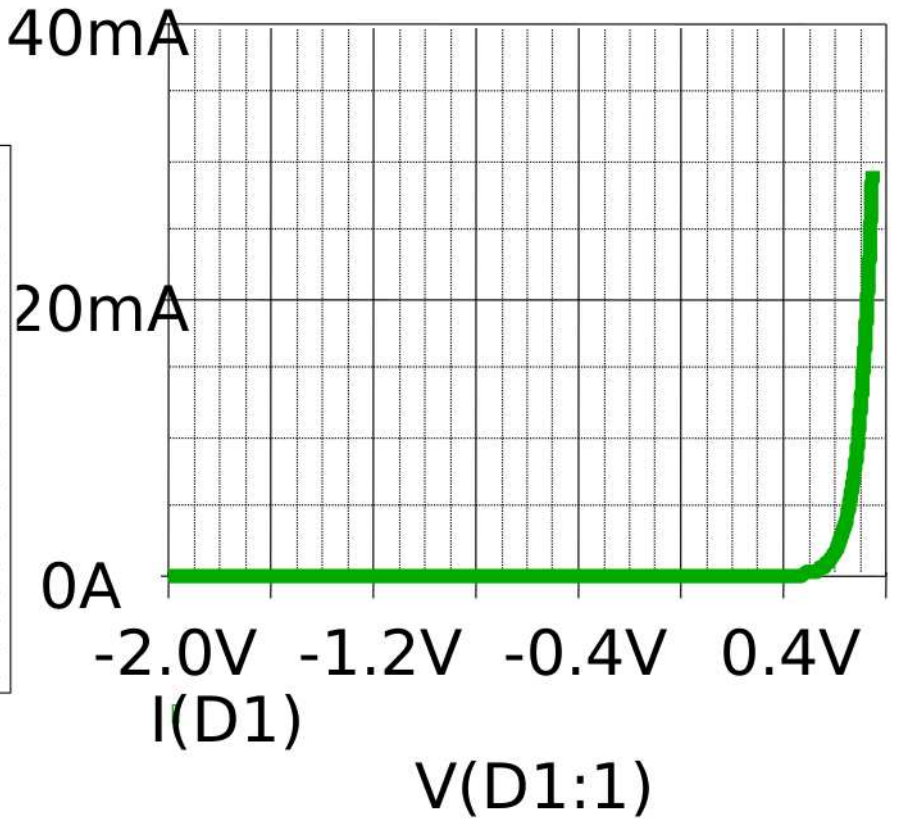


Regulator Diode Curves

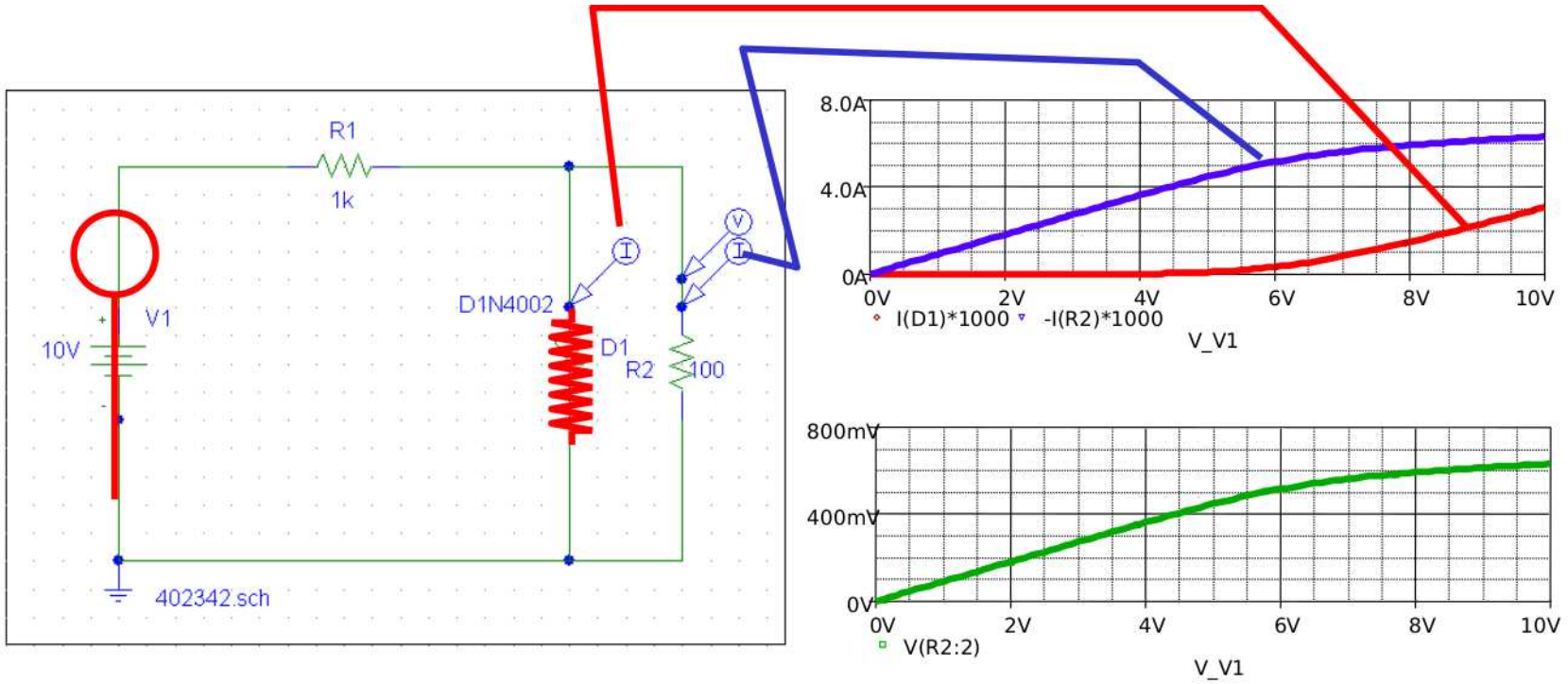
Circuit for Generating Characteristic Curves



Sweep V1 –2:0.1:30 Volts

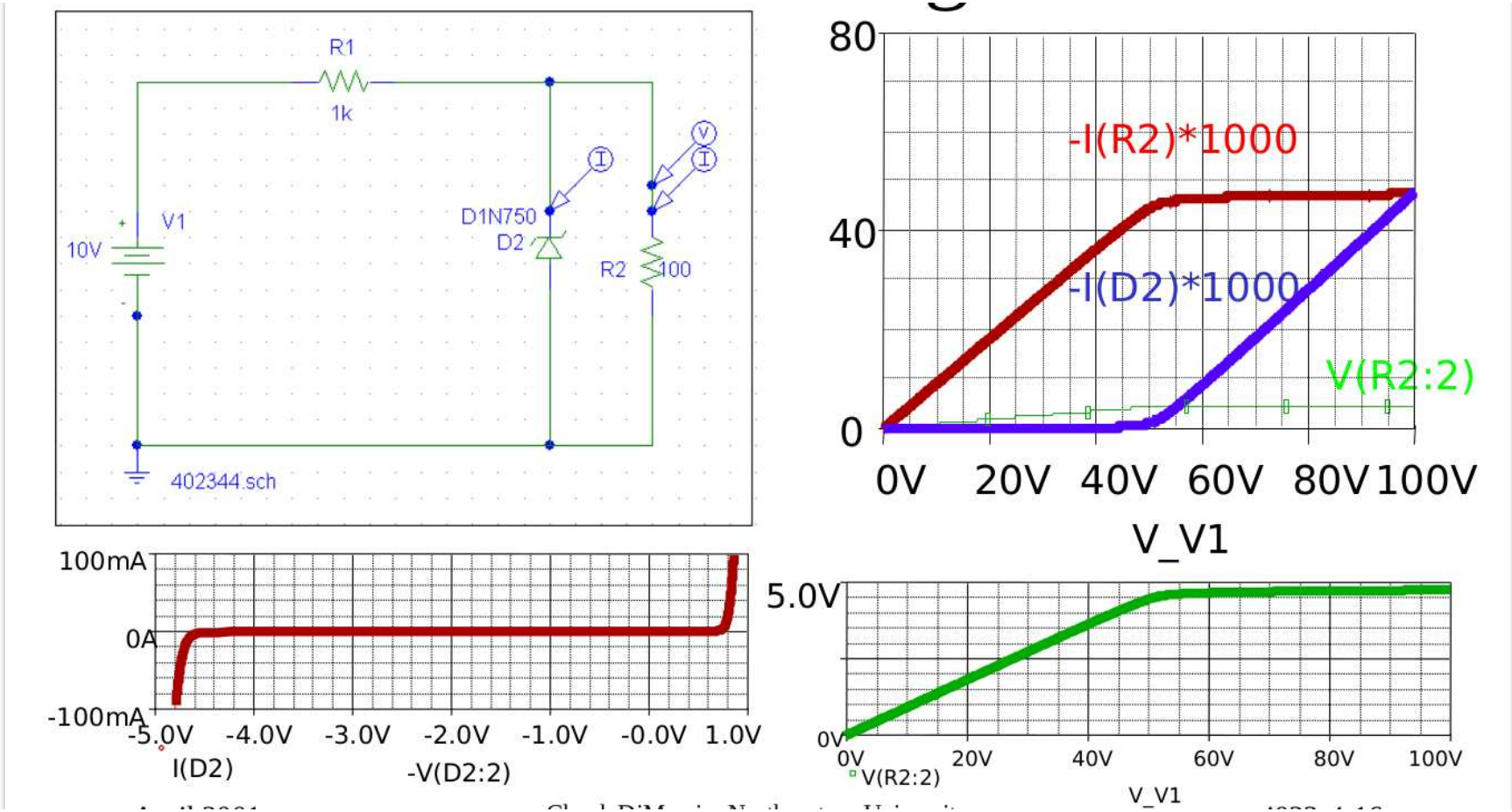


Regulator AC Model

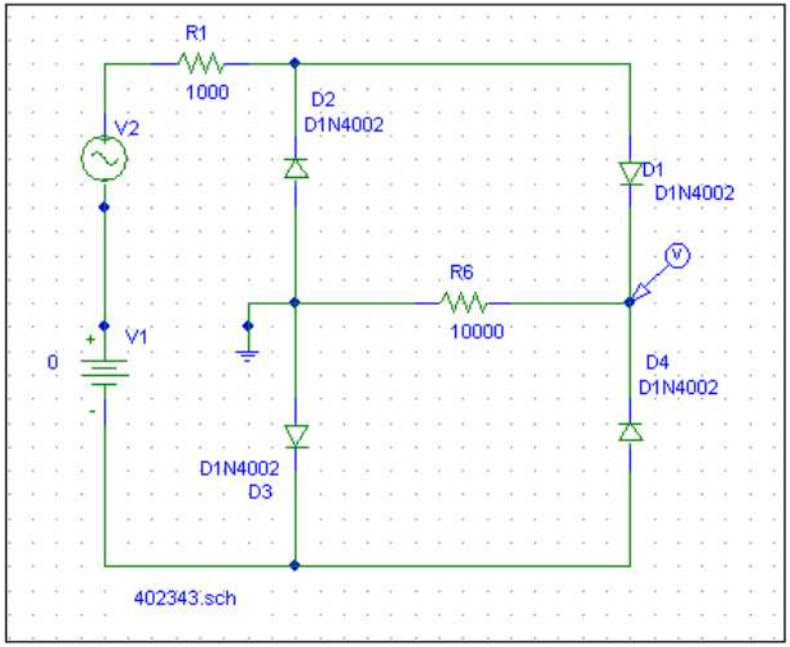


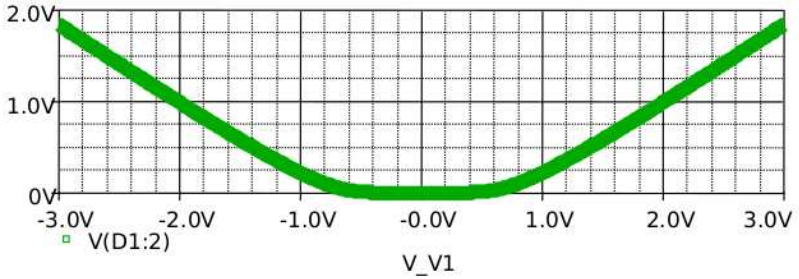
What Happens if I change the value of R2?

Zener–Diode Regulator



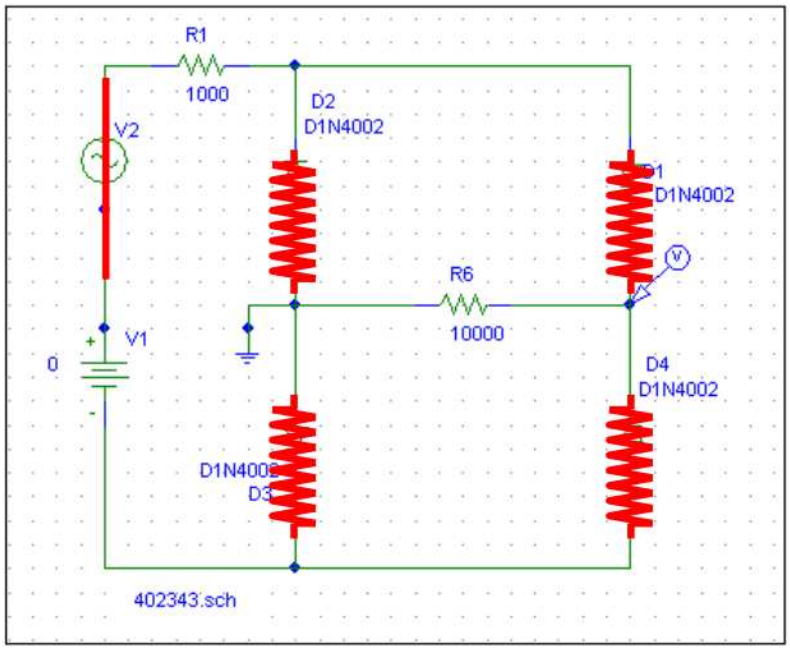
Digression: A Mixer





$$i_D = 0 + \frac{I_s}{V_T} v_d^{(AC)} + \frac{I_s}{V_T^2} \left(v_d^{(AC)}\right)^2 + \cdots$$

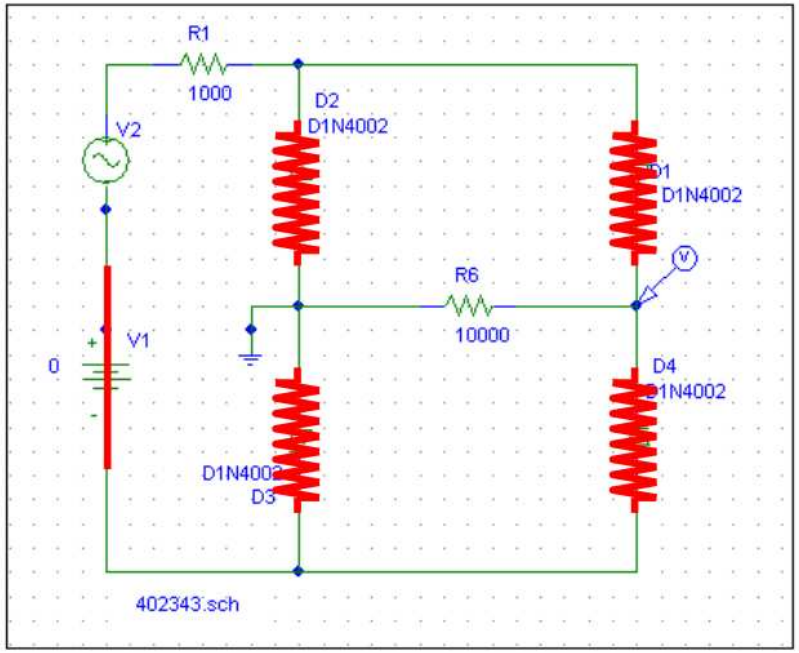
Mixer DC Model



$$i_D = 0 + \frac{I_s}{V_T} v_d^{(AC)} + \frac{I_s}{V_T^2} \left(v_d^{(AC)}\right)^2 + \cdots$$

$$V^{(DC)} = 0$$

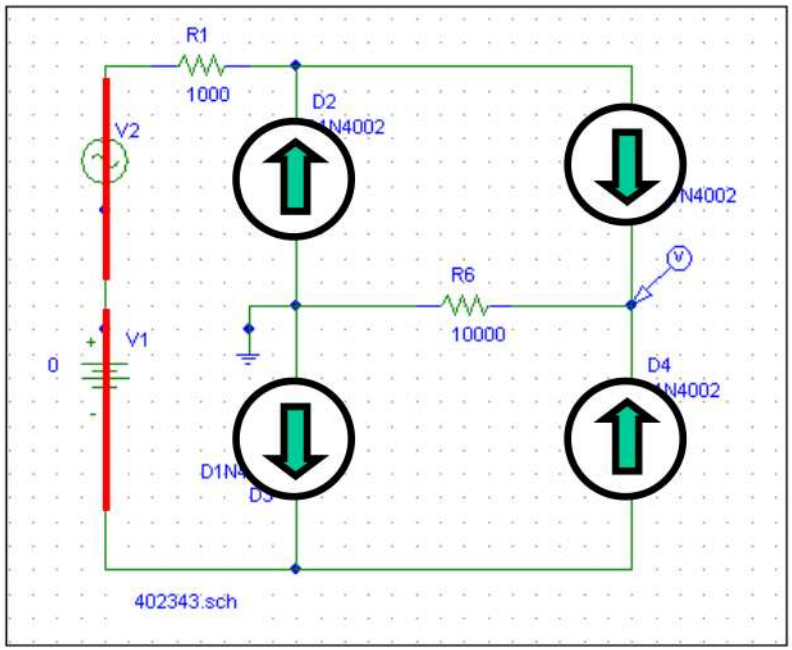
MIxer AC Model

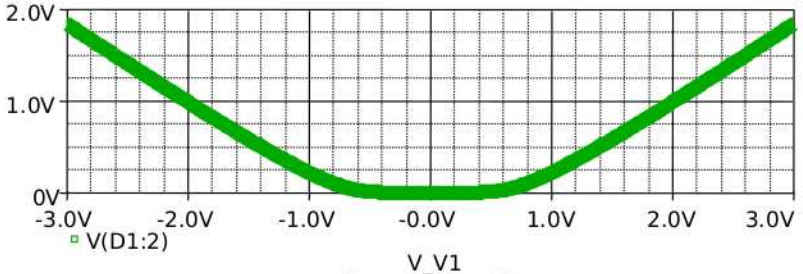


$$i_D = 0 + \frac{I_s}{V_T} v_d^{(AC)} + \frac{I_s}{V_T^2} \left(v_d^{(AC)}\right)^2 + \cdots$$

Same AC Current in All Diodes
so $v^{(AC)}=0$

Mixer 2nd–Order Model





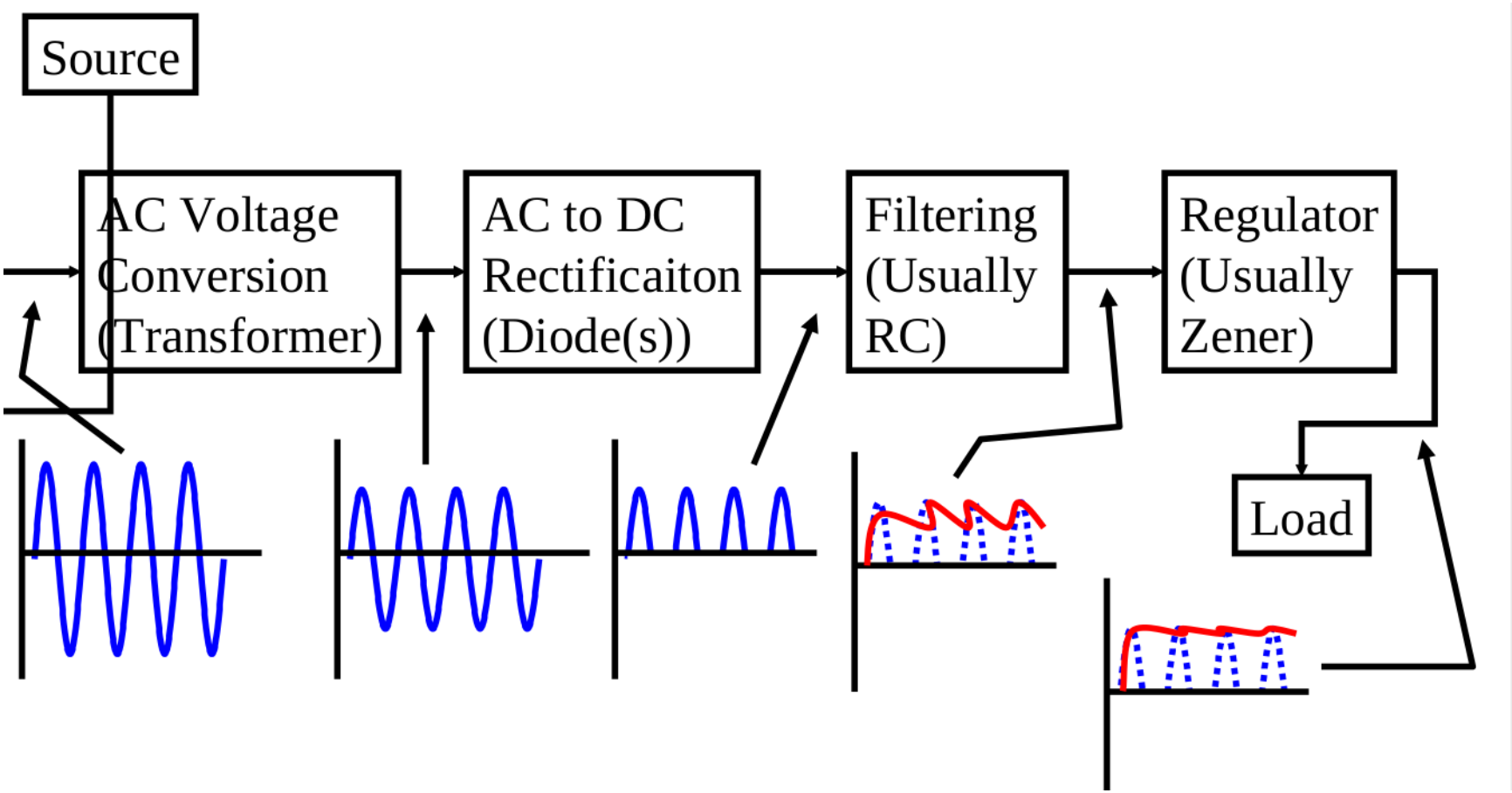
$$i_D = 0 + \frac{I_s}{V_T} v_d^{(AC)} + \frac{I_s}{V_T^2} \left(v_d^{(AC)}\right)^2 + \cdots$$

$$2\frac{I_s}{V_T^2}\left(\frac{v_{source}^{(AC)}}{2}\right)^2 R \approx \frac{14\text{nA}}{(25\text{mV})^2}(3\text{V})^2 10\text{k}\Omega \approx 1\text{V} \quad \text{(Close)}$$

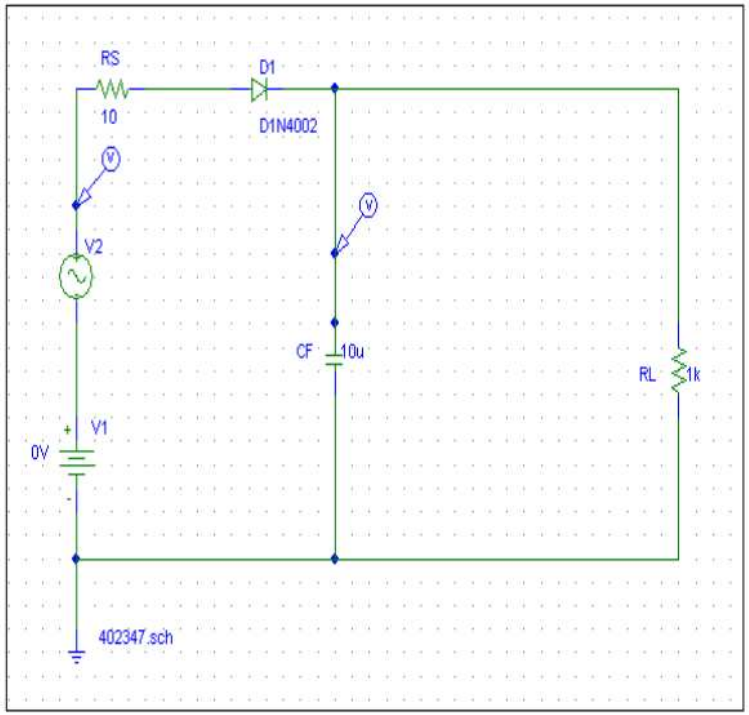
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Block Diagram of Power Supply



Analyzing a Power Supply

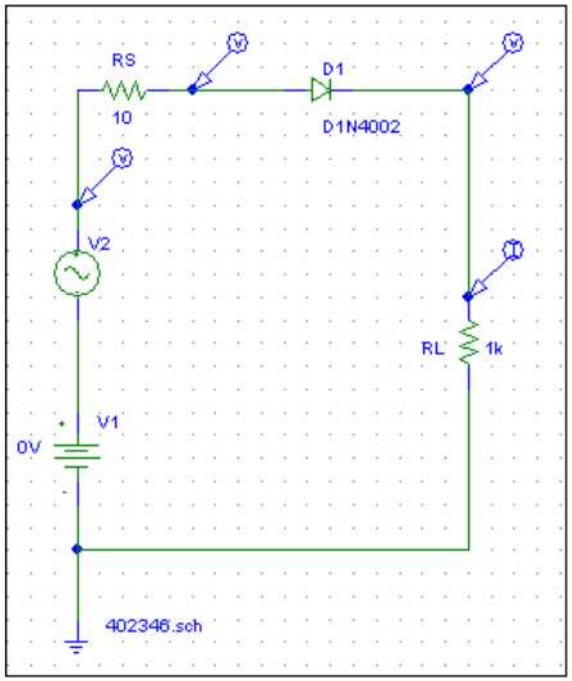


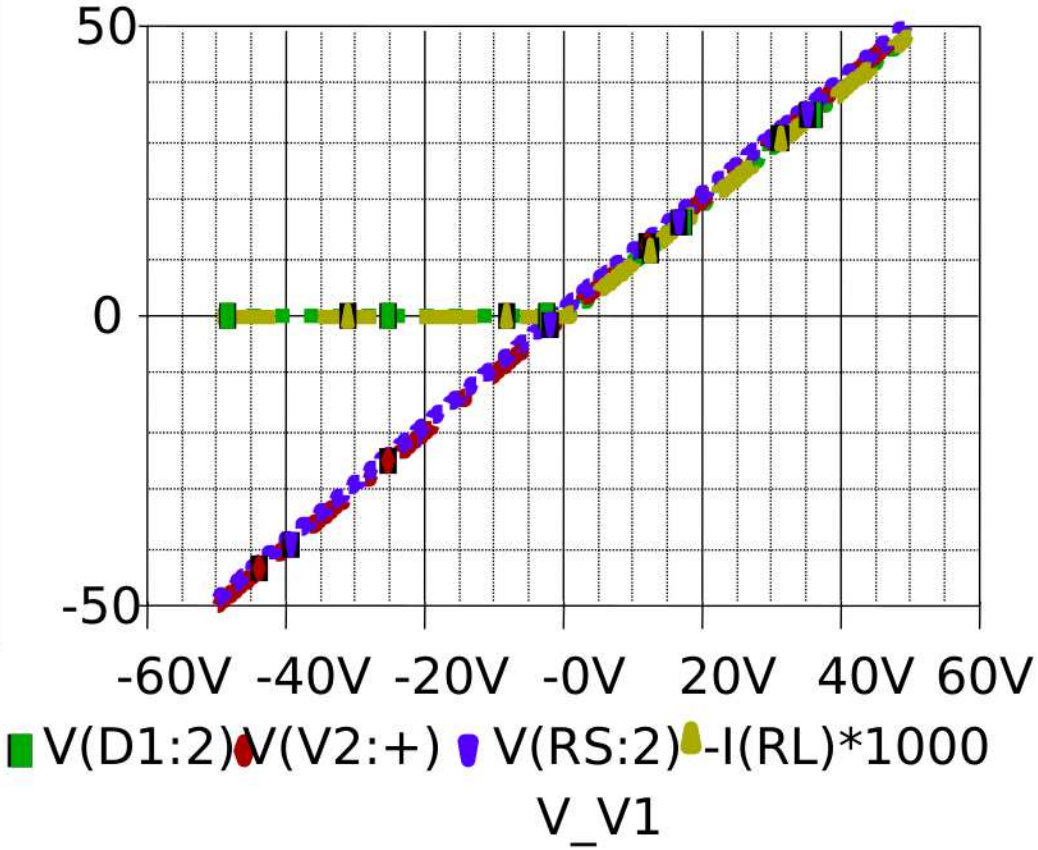
$$i = \frac{dQ}{dt} + v_L / R_L = C_F \frac{dV}{dt} + v_L / R_L$$

$$v_L = v_S - iR_S - v_D$$

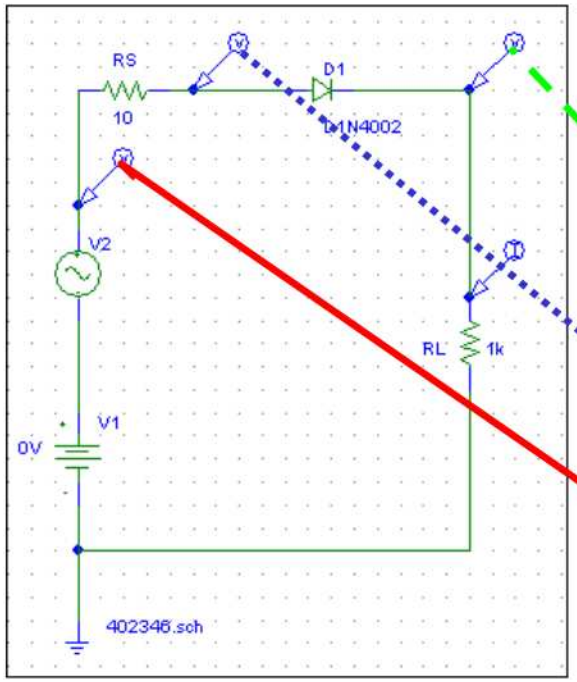
$$i = I_s \left(e^{v_D / V_T} - 1 \right)$$

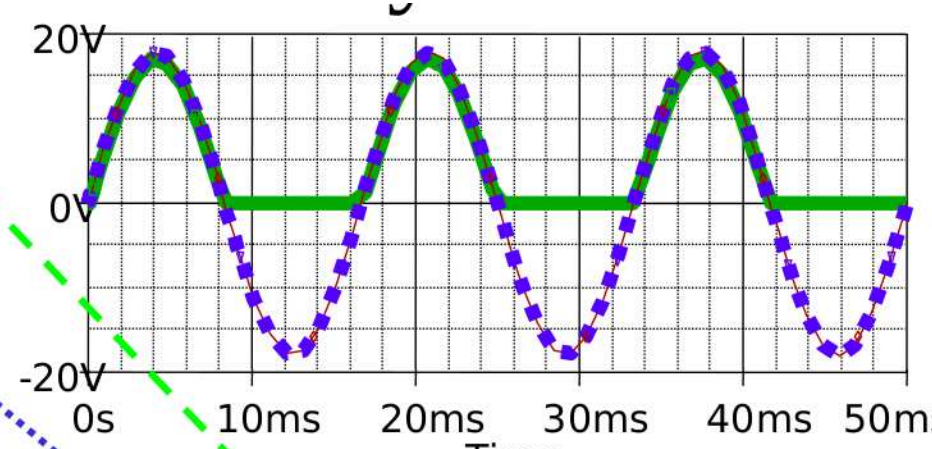
Basic Rectifier

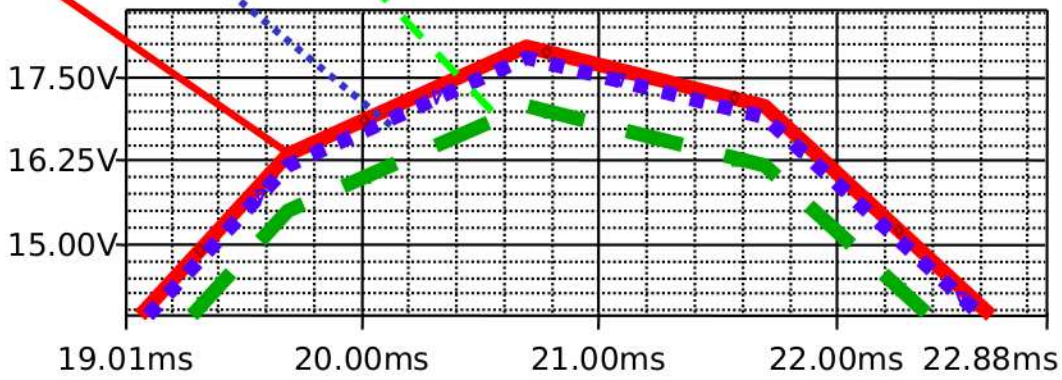




Transient Analysis

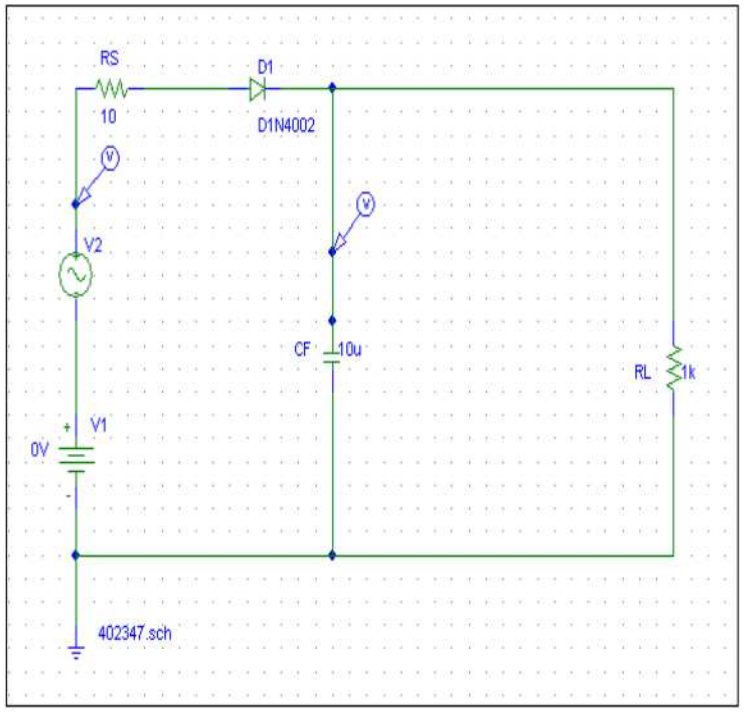


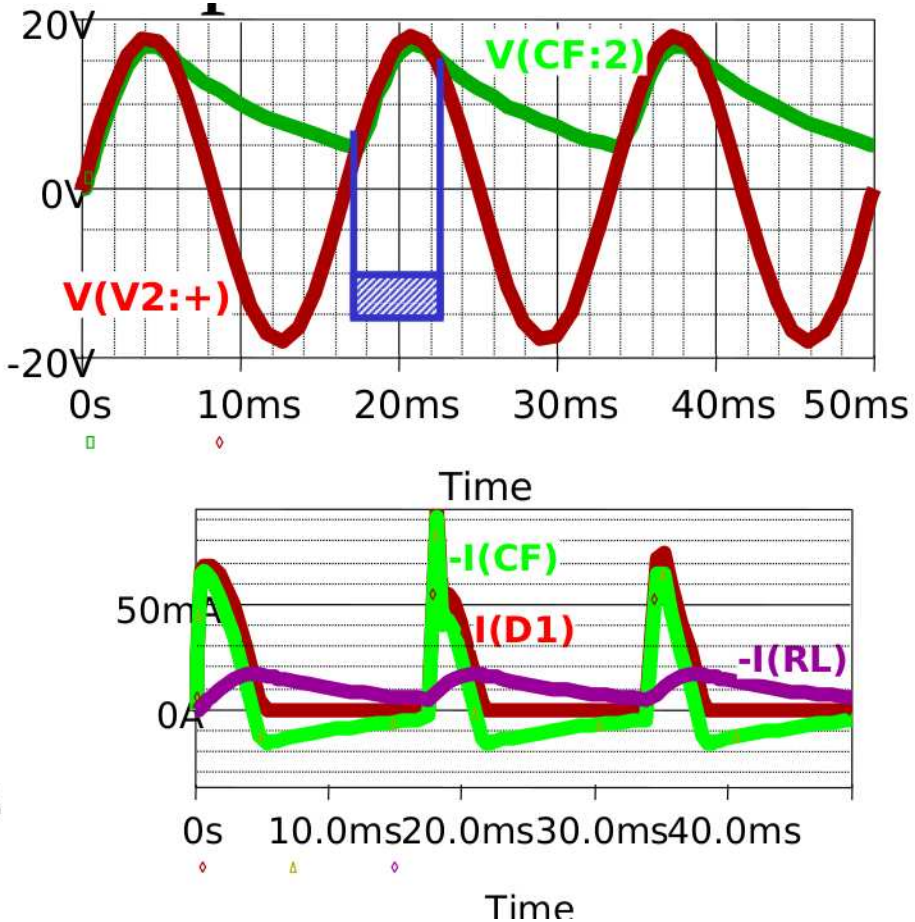




Note Drop Across Diode (about 0.7 V)

The Filter Capacitor





Charging Time Approaches Zero. Current Becomes Large

Capacitor Time Constants

Charging

$$\tau \approx (R_s + R_D)C$$

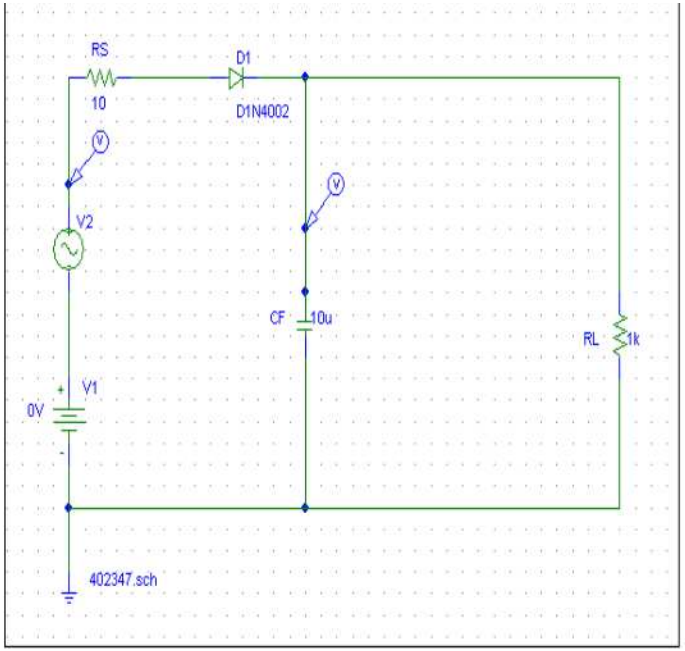
Discharging

$$\tau \approx R_L C$$

Ripple

$$\Delta V \approx V_S\left(1 - e^{t/R_L C}\right)$$

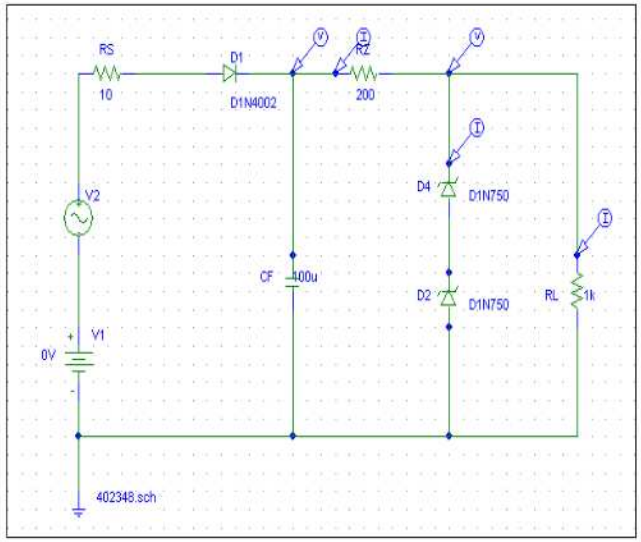
$$\approx V_S\left(1 - e^{1/R_L Cf}\right) \approx \frac{V_S}{R_L Cf}$$

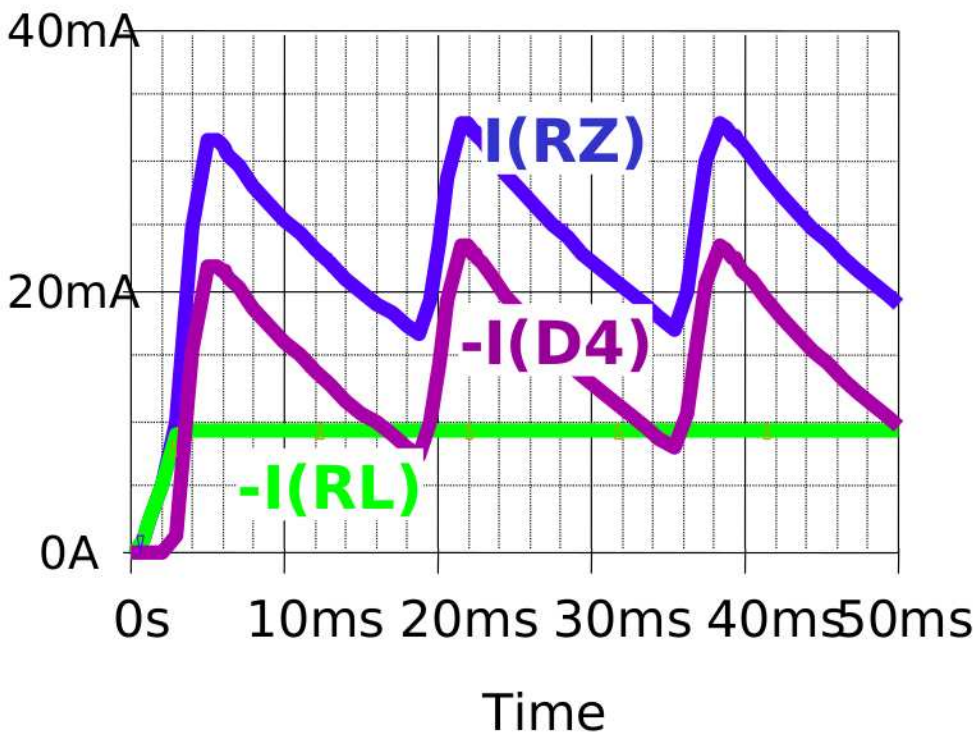


Fractional Ripple

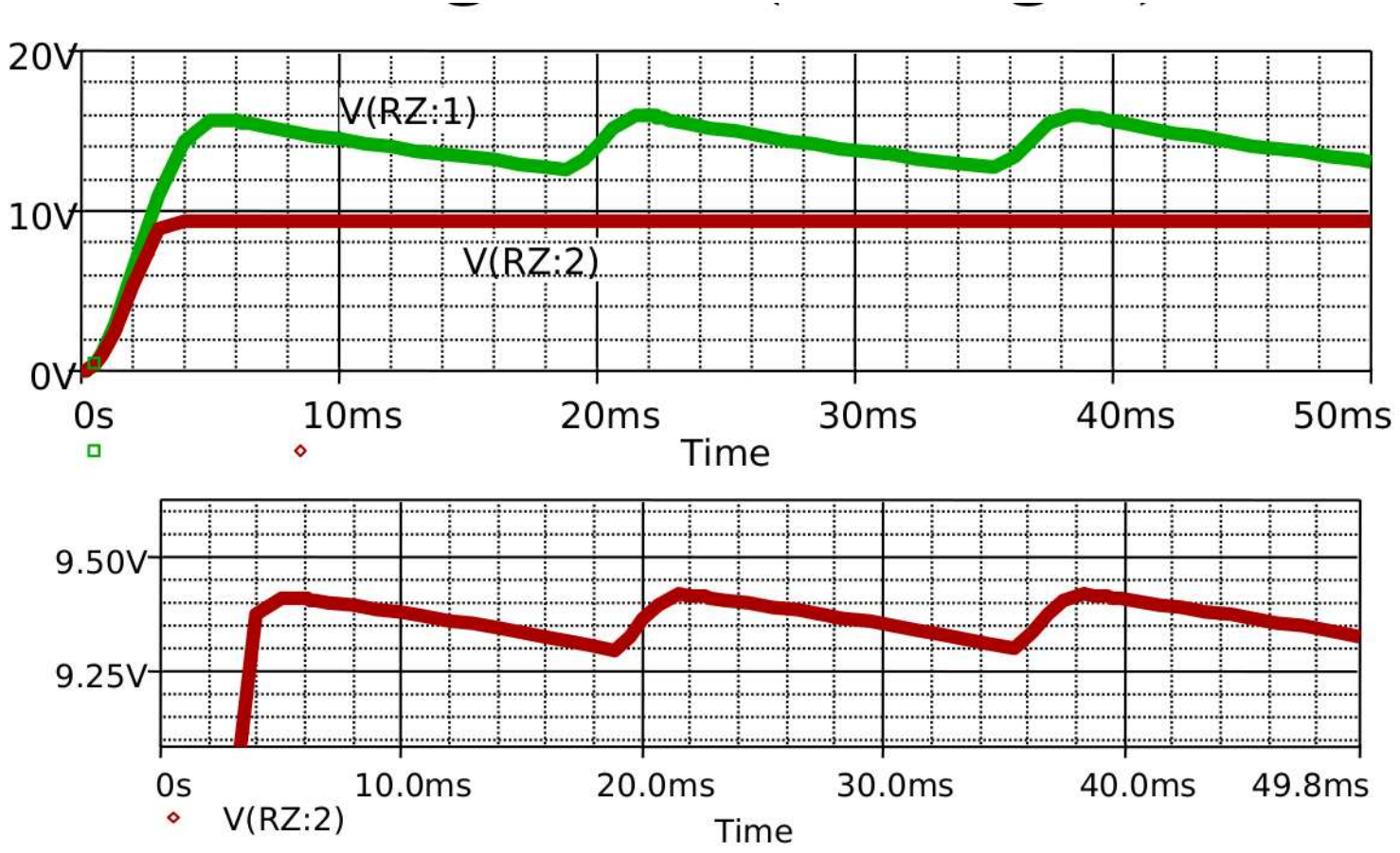
$$\frac{\Delta V}{V_L^{(DC)}} \approx \frac{1}{R_L Cf}$$

The Regulator Zener Current





The Regulator Voltages

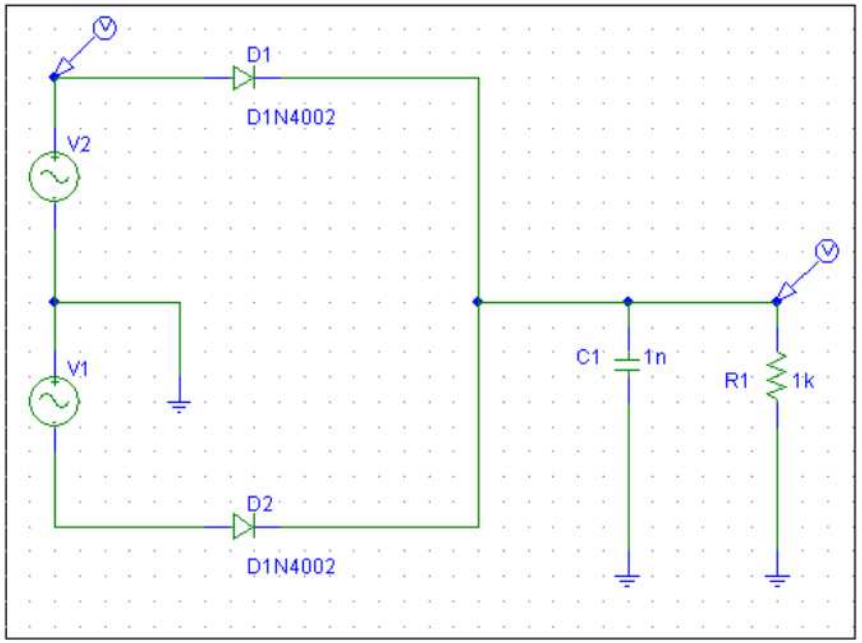


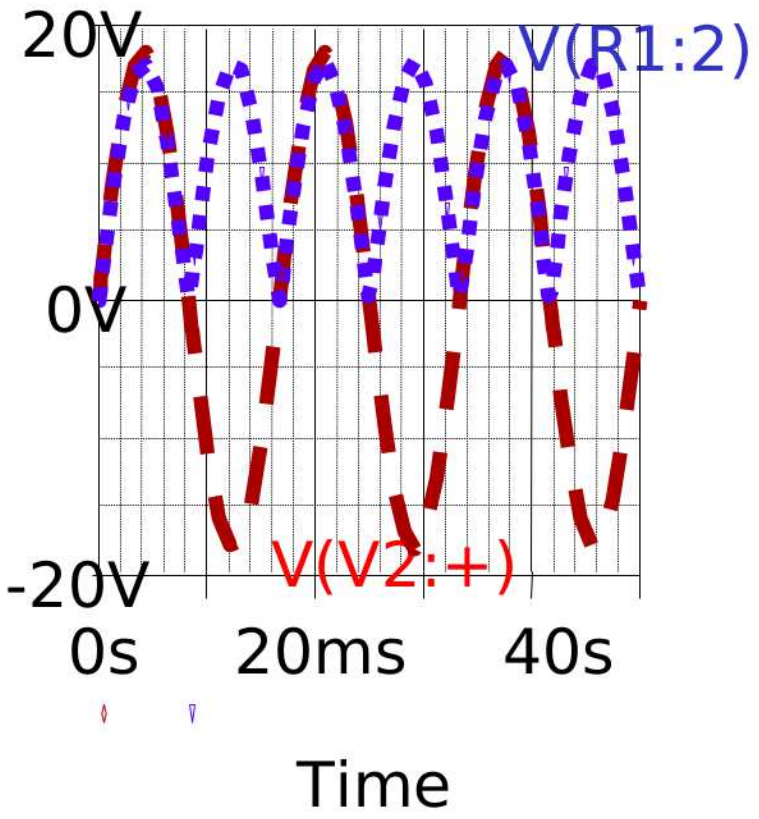
Vertical Zoom on Lower Graph

Agenda

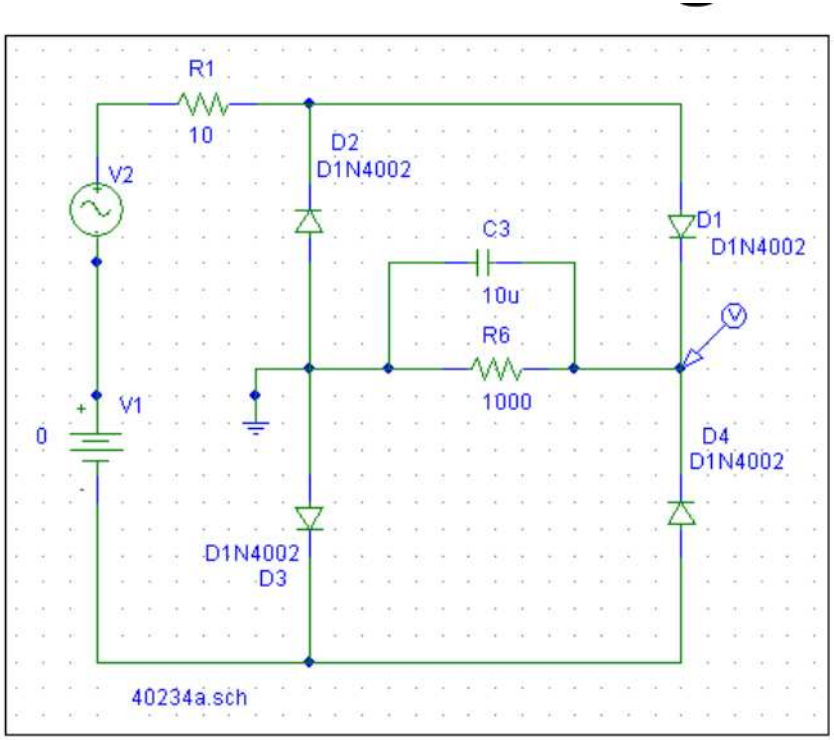
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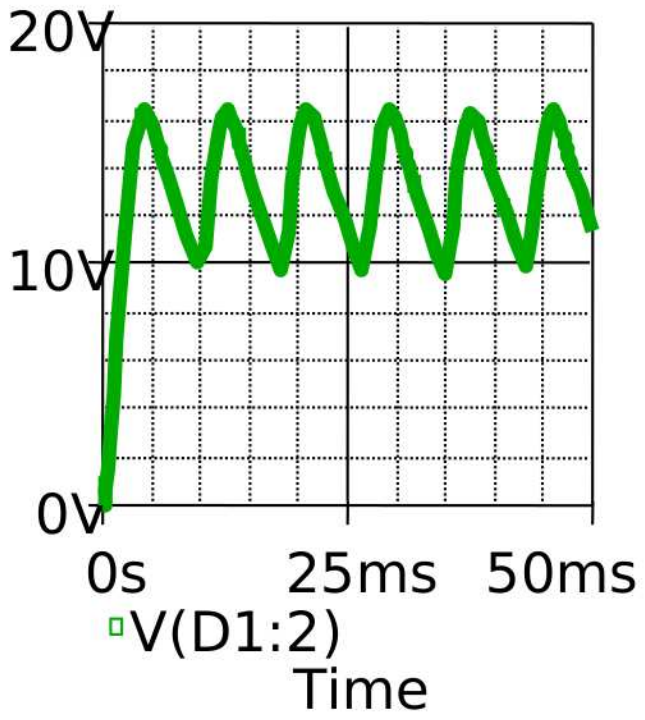
Full–Wave Rectifier





Bridge Rectifier

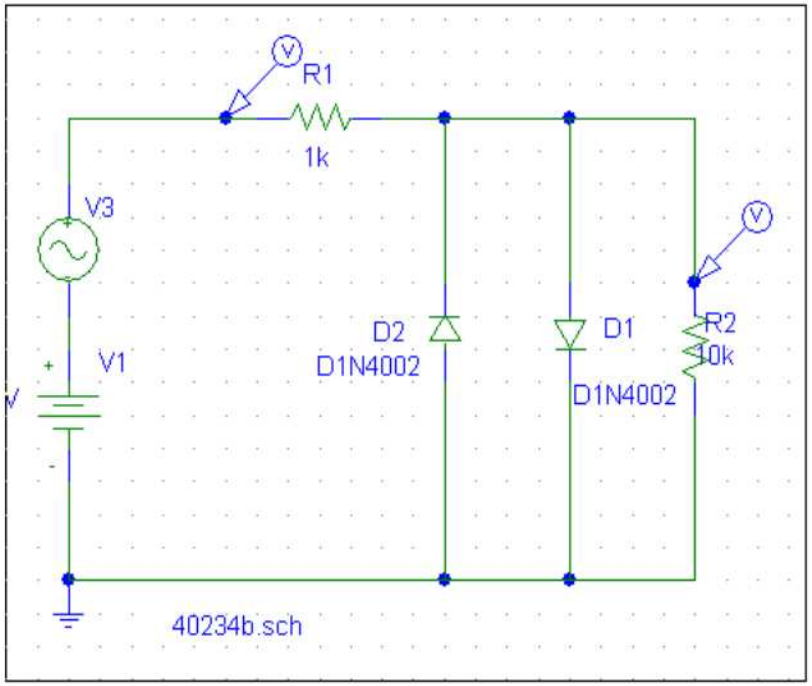


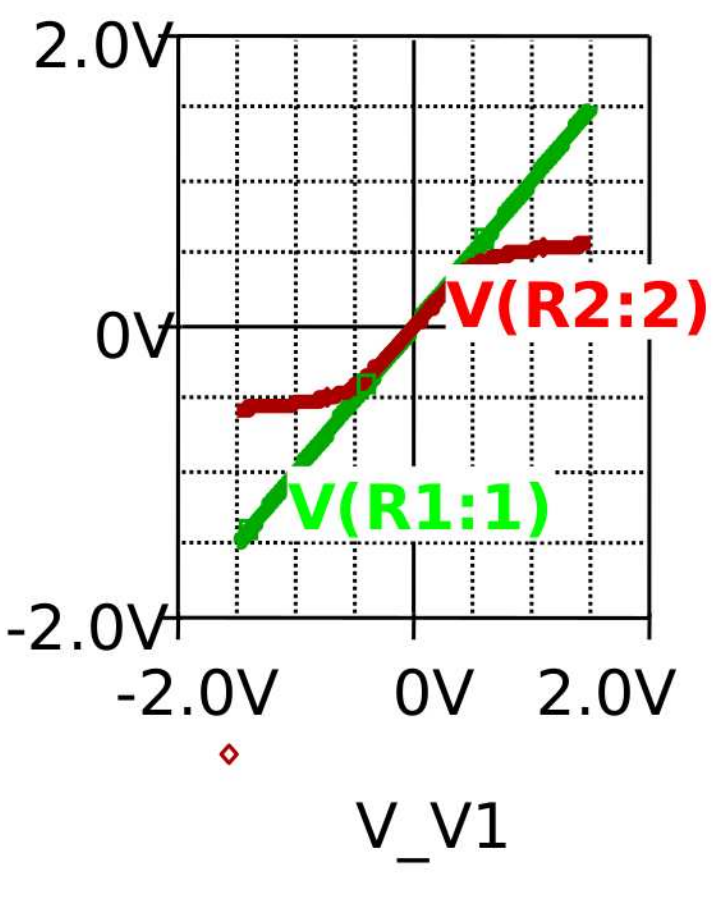


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  - Photodiode Circuits

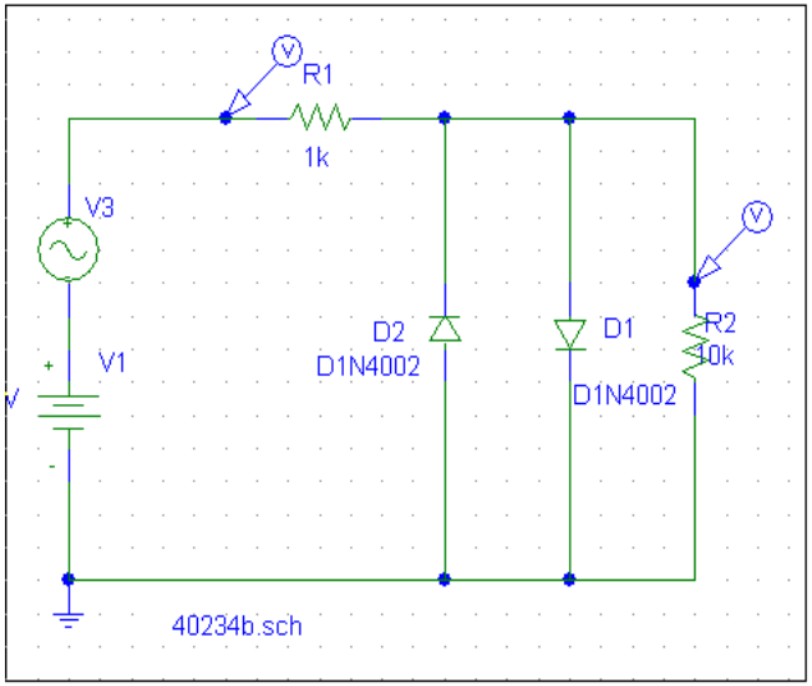
Diodes in Parallel (Reversed)

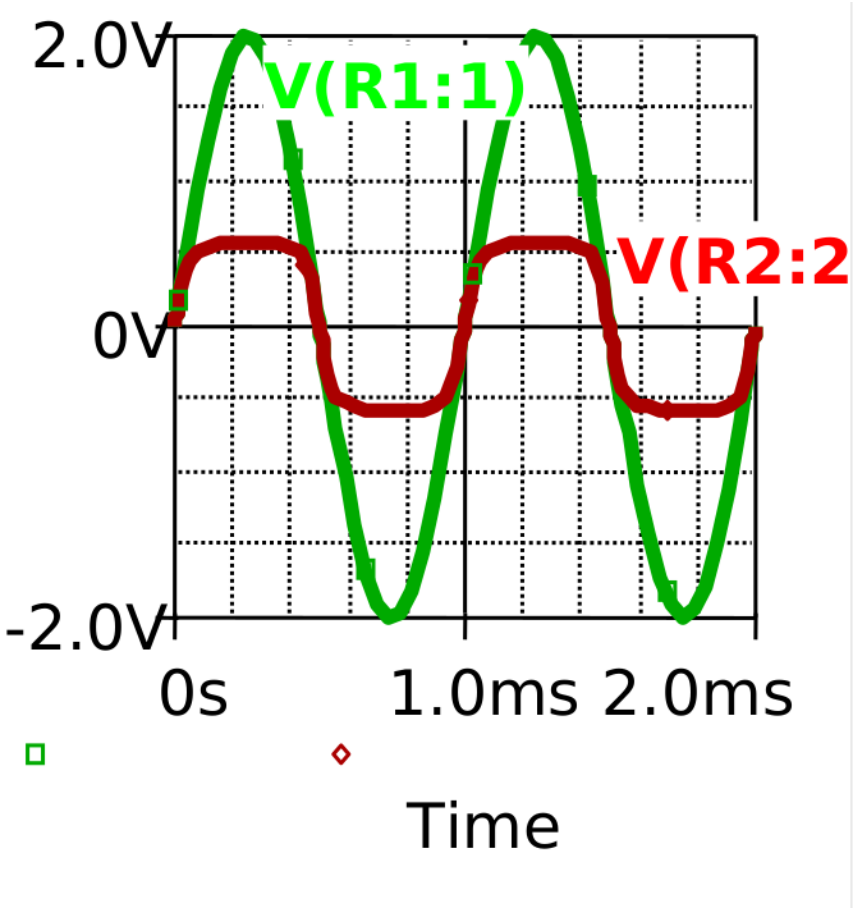




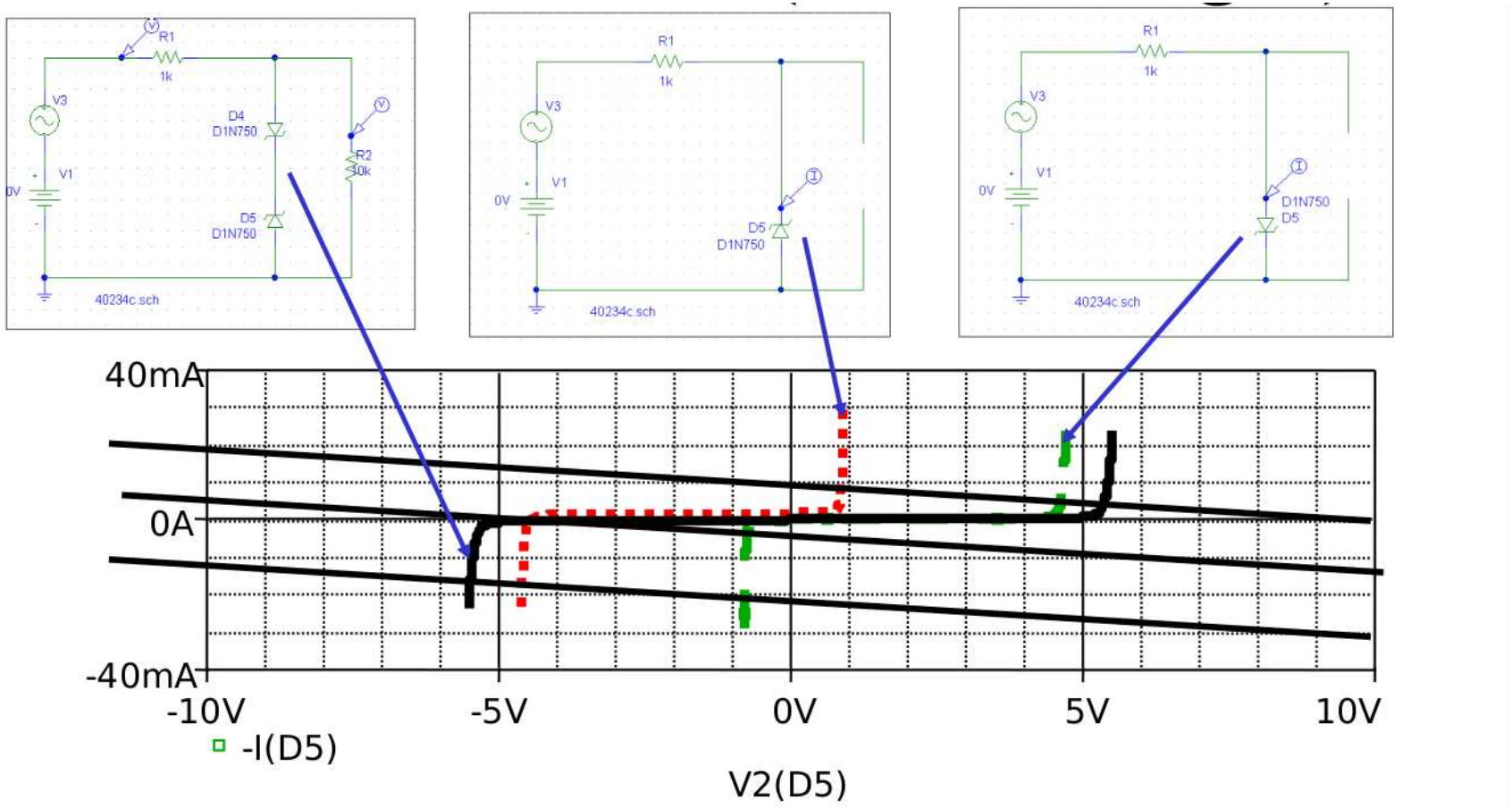
Add Currents

Diode Limiter

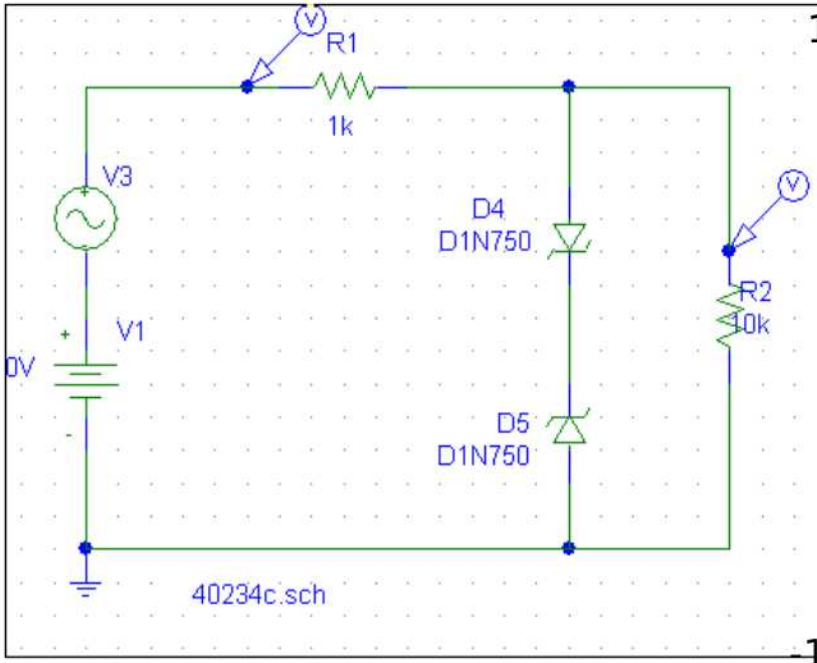


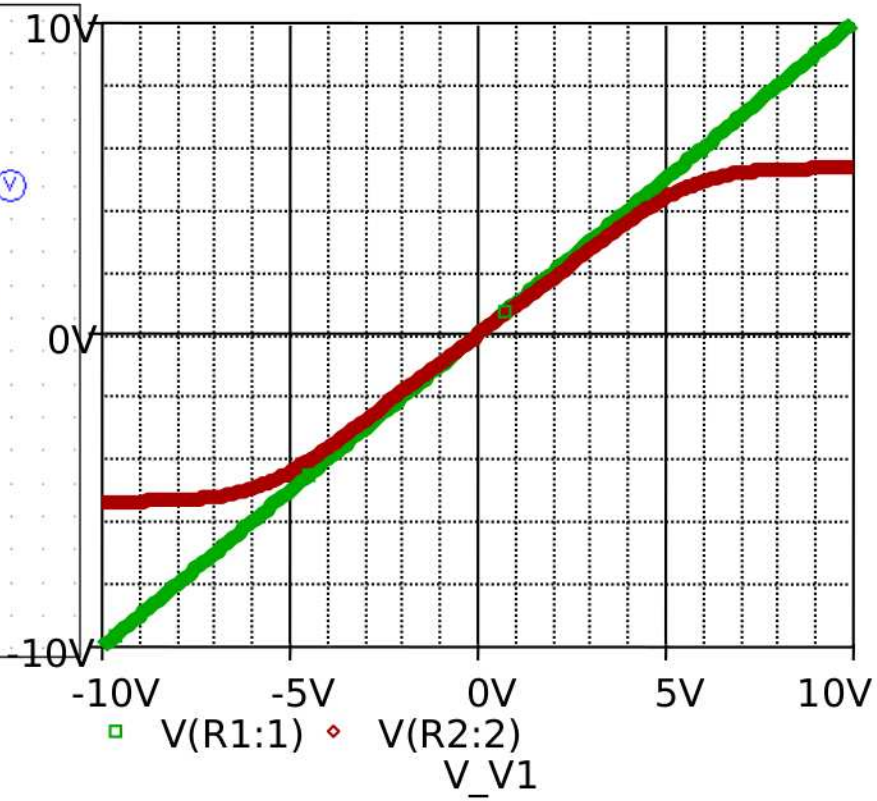


Diodes in Series (Voltages Add)



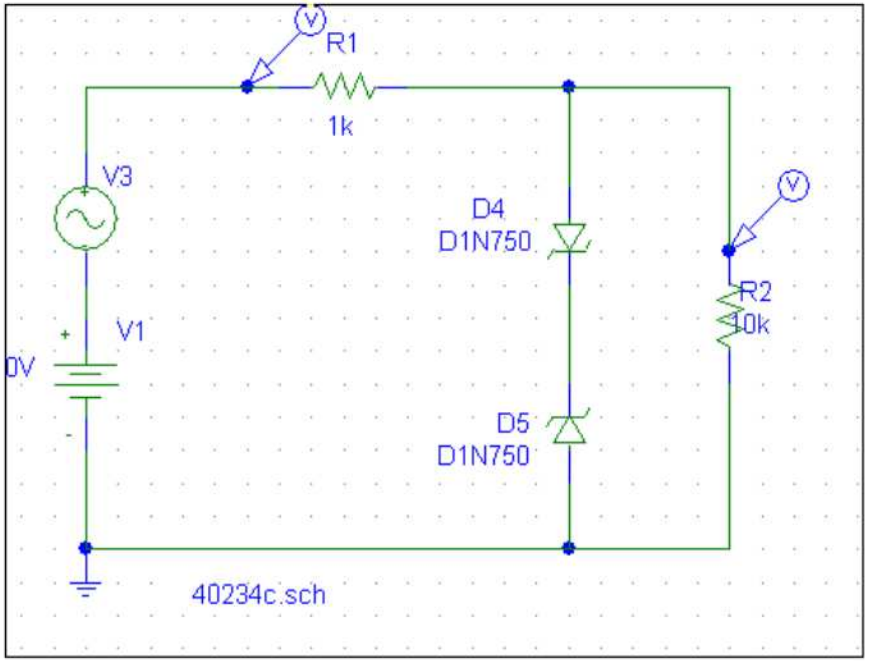
Diodes in Series as a Limiter

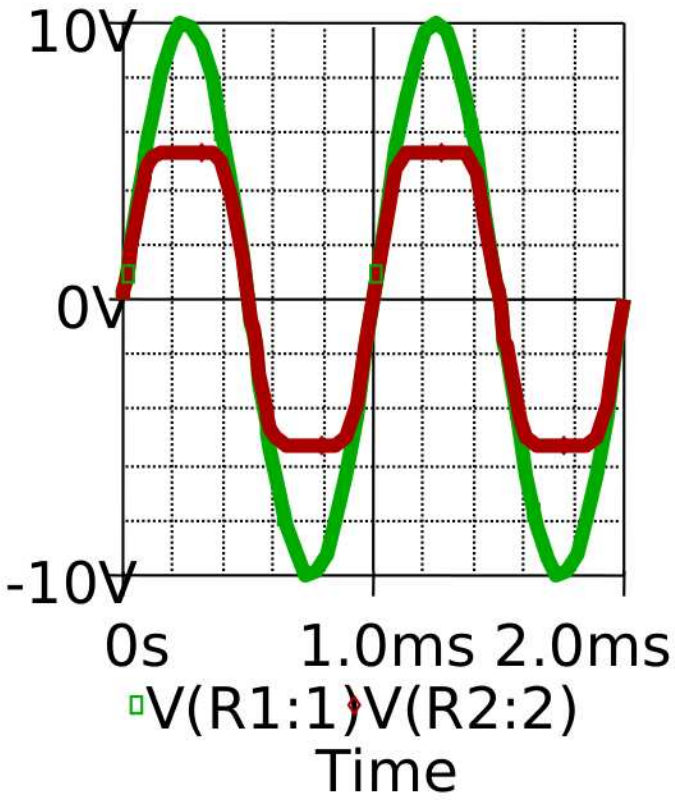




Add Voltages

Zener Diode Limiter

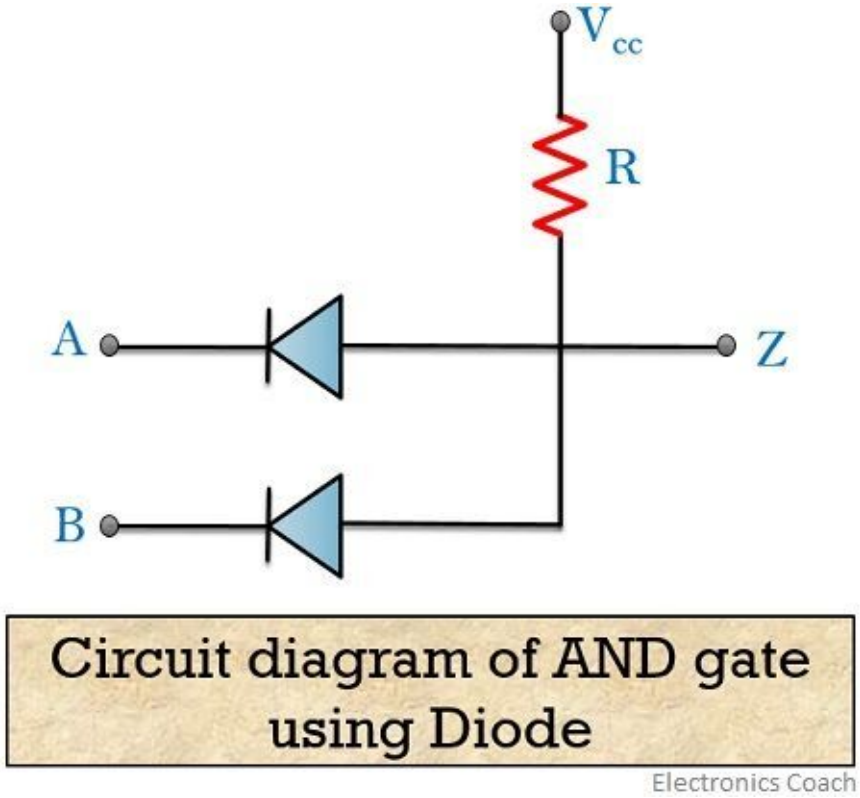


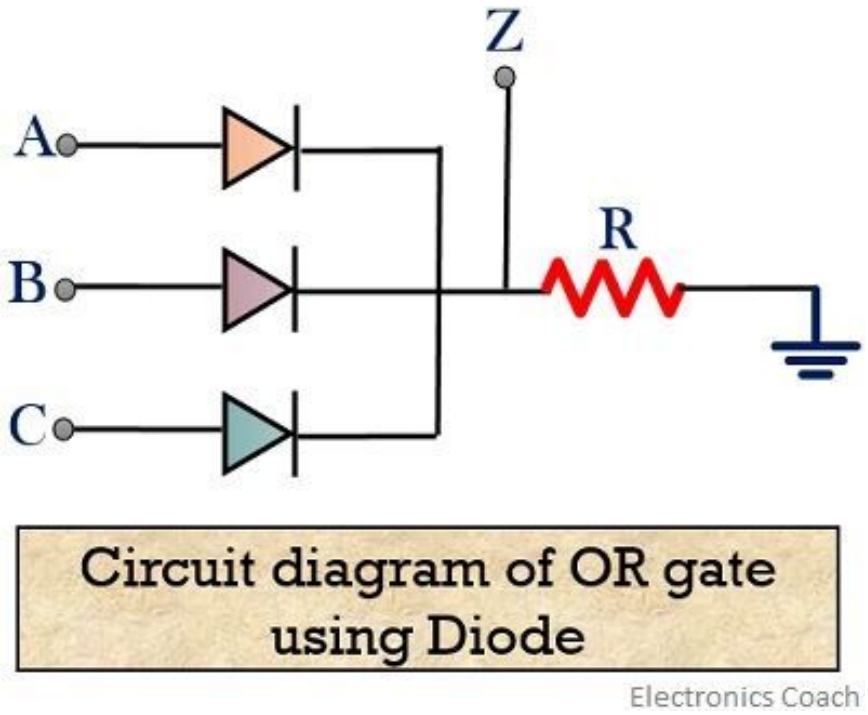


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Diode Logic





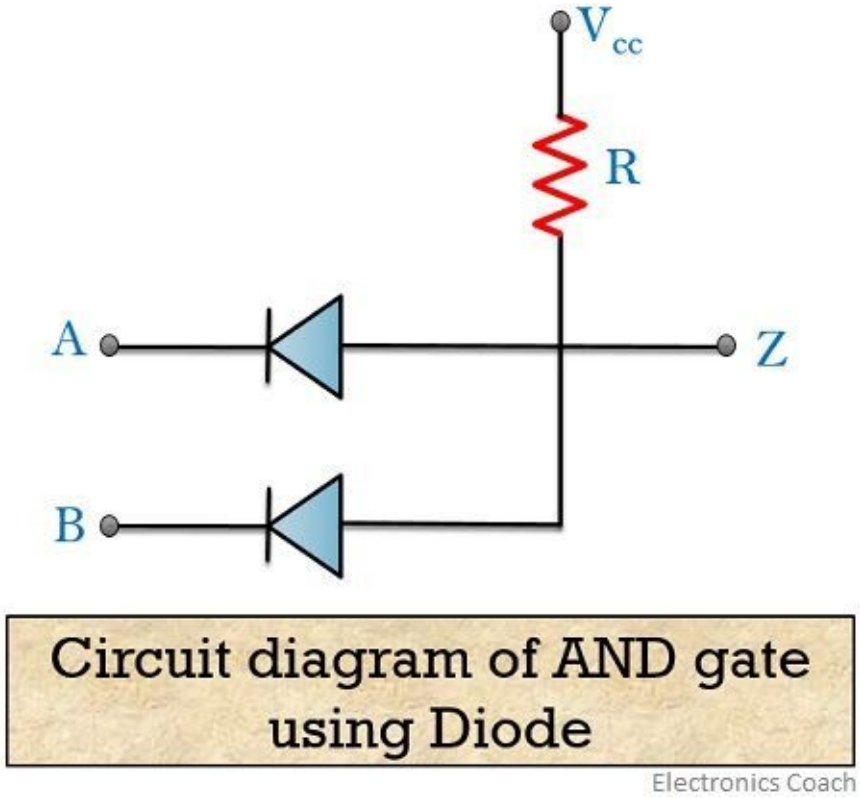
AND

OR

$V_{CC} = 5\text{V}$

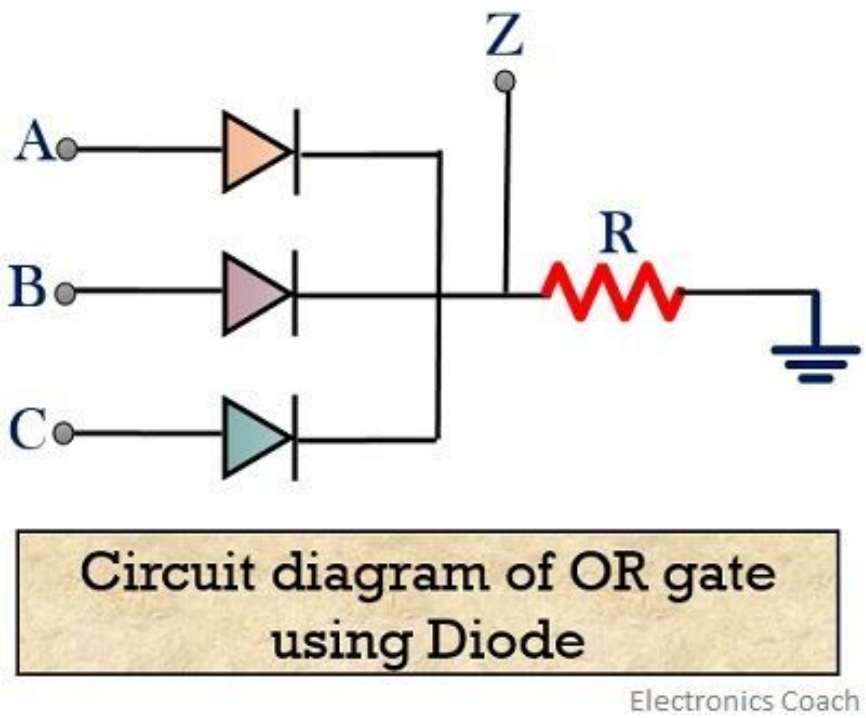
$V_X = 5\text{V or } 0$

Ideal–Diode Logic



AND

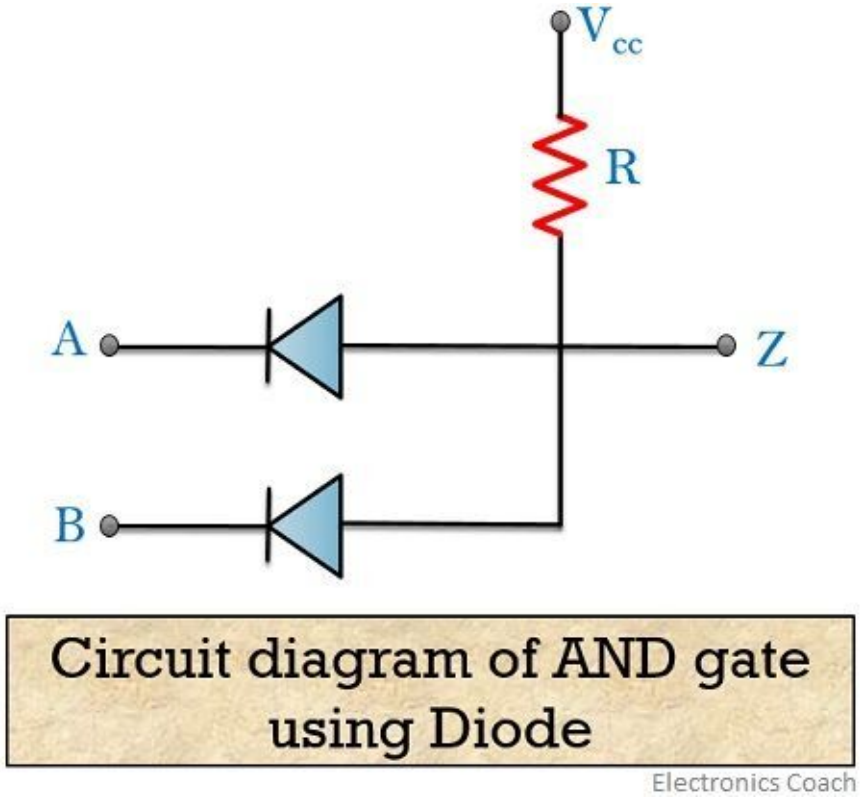
$V_Z = 5$V Only if All Inputs ≥ 5V or both.

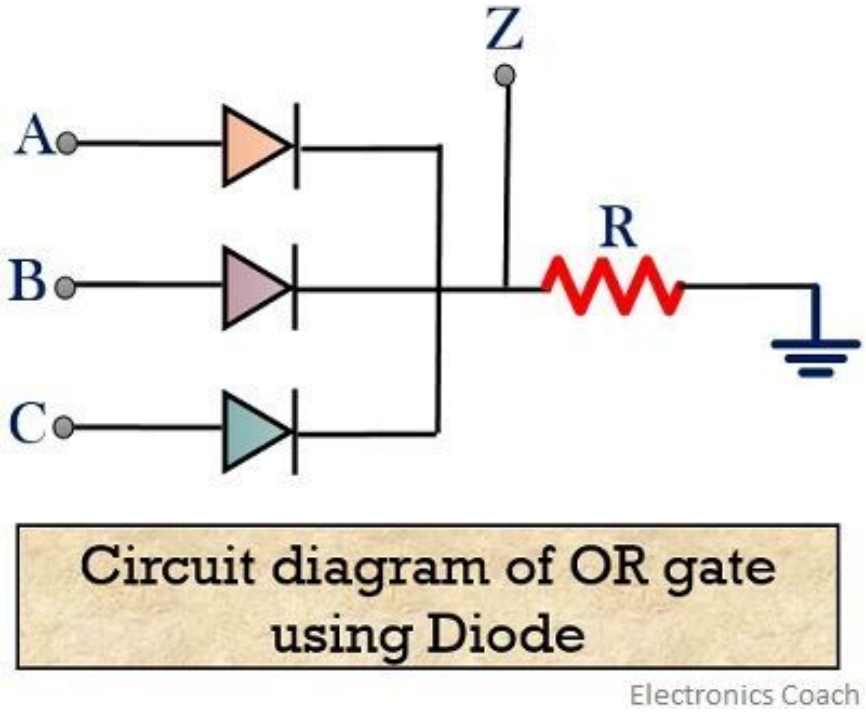


OR

$V_Z = 5$V if Any Inputs ≥ 5V or both. $V_Z = 0.7$V if inputs $= 0$.

Diode Logic: Better Model





AND

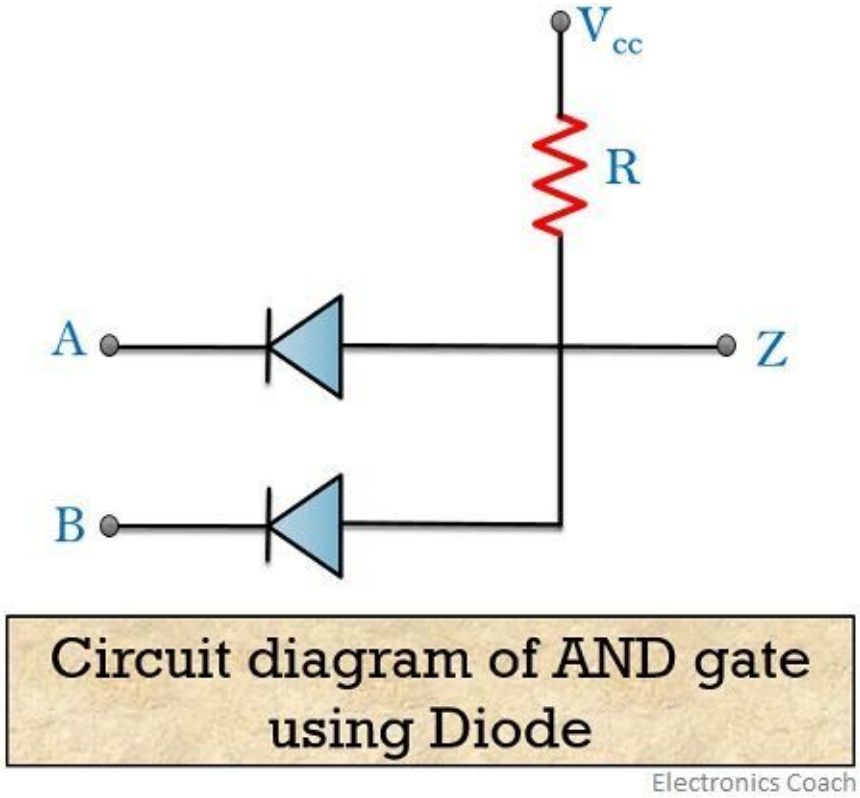
V_Z = 5V if All Inputs $>$ 4.3V.

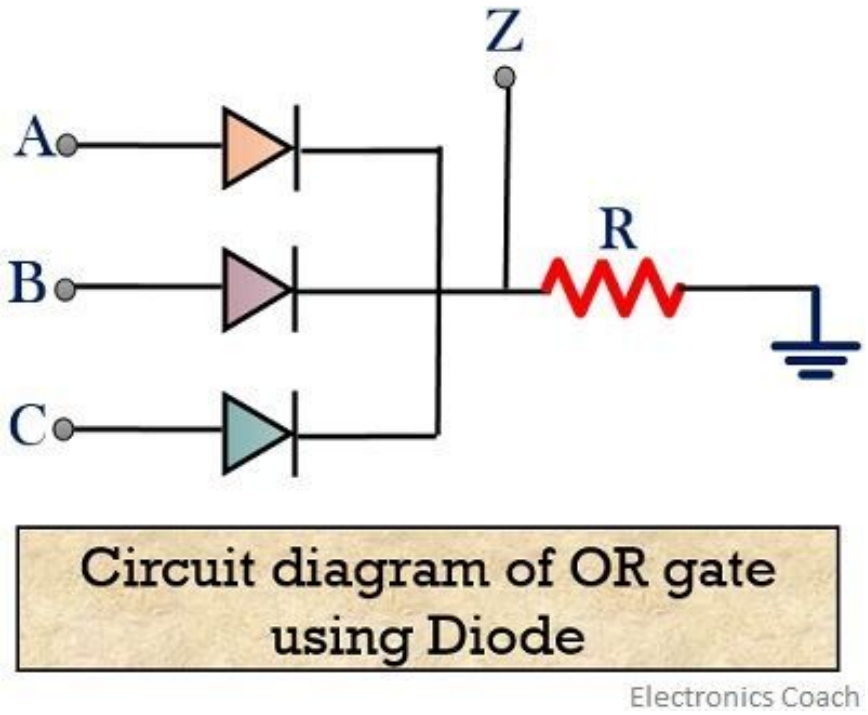
V_Z = 0.7V if inputs = 0.

OR

V_Z = 4.3V if Any Inputs = 5V.

Diode Logic





AND OR

Cascade OR gates. Connect Z of first to A of second, *etc.*

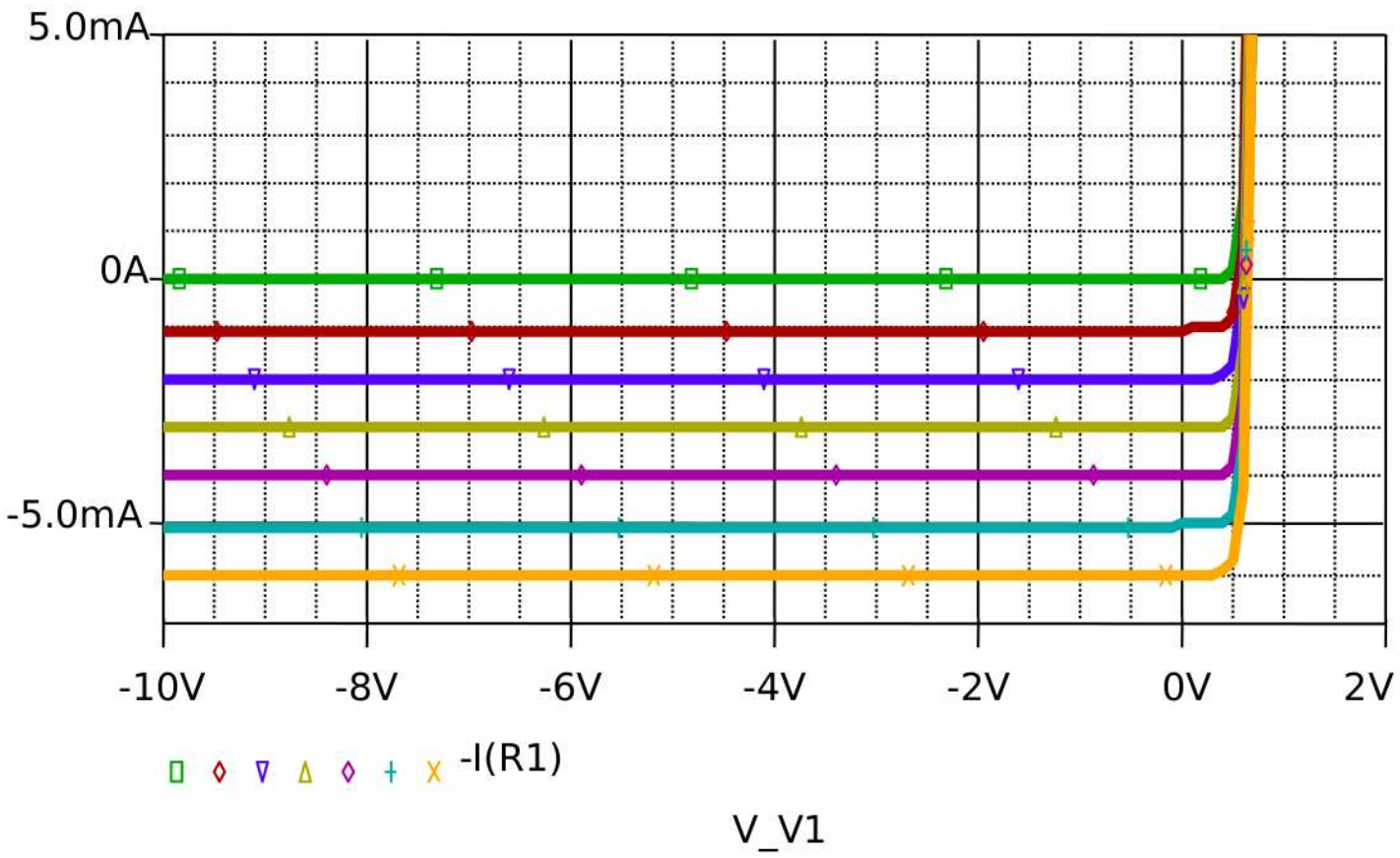
(On your own, try other combinations)

What are your thoughts about Diode Logic?

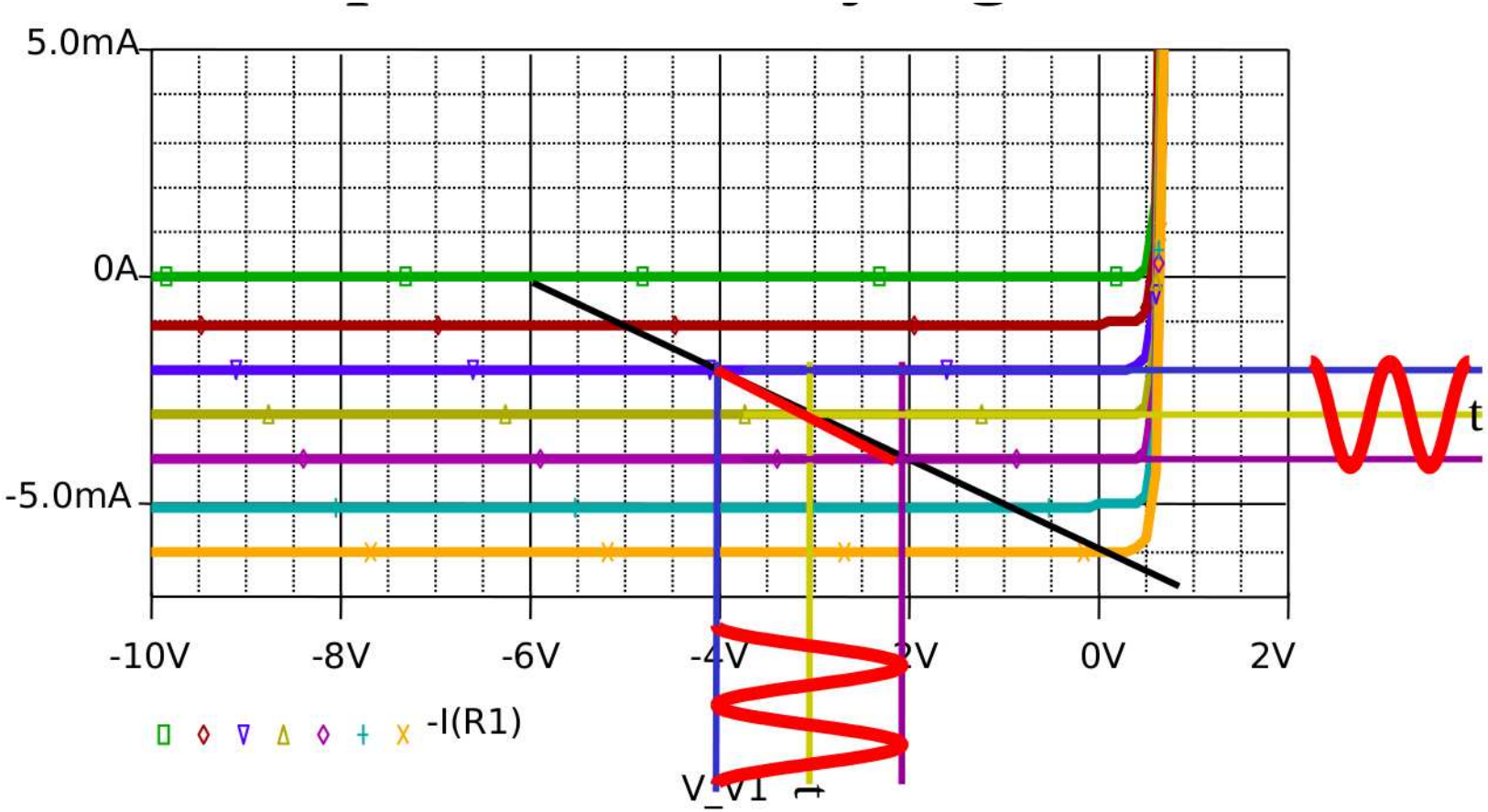
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Photodiode I–V Curves



Response to Varying Power



Photovoltaic Mode

