
ECE 320: Electronics I

ECE 111: Intro to ECE

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Please visit [Bison Academy](#) for corresponding
lecture notes, homework sets, and solutions

Electrical and Computer Engineering

Why I like electrical and computer engineering:

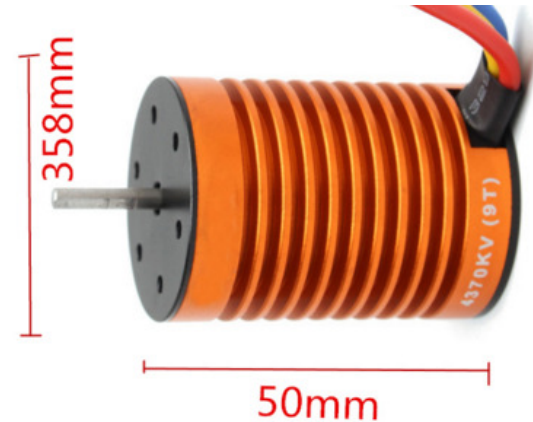
- As long as technology advances, we've got jobs
- You're never going to be stuck doing the same job day after day, year after year
- As long as technology advances, anything I design today can be improved tomorrow.

Example #1: Motors

1990 Technology
1000W DC Servo Motor
40 lbs, \$5000, 18" x 6" dia



2022 Technologyebay
900W Brushless7 Motor
9oz, \$35 (including controller)



1990 Motors (DC) vs. 2022 Motors (AC)

- How Motors Work
- <https://www.animations.physics.unsw.edu.au/jw/electricmotors.html>

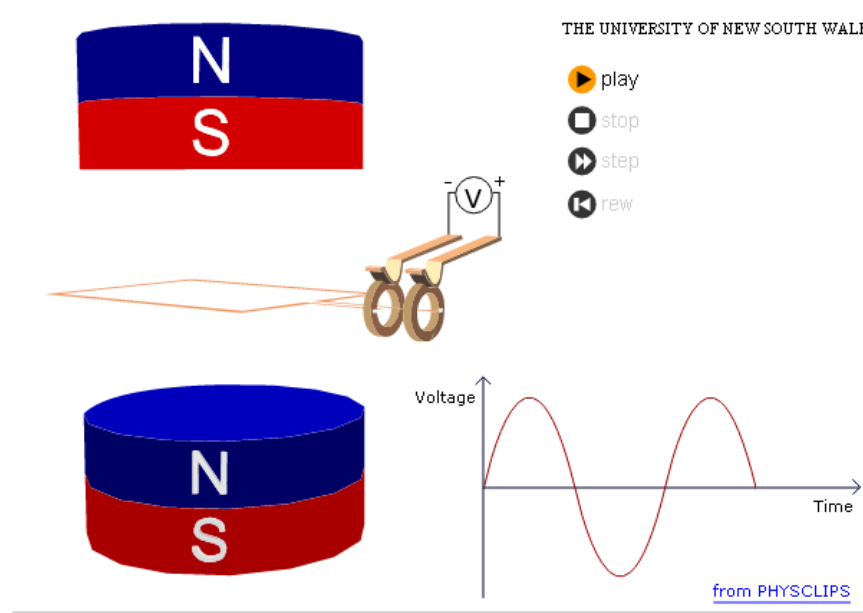


Electric motors and generators

An alternator

If we want AC, we don't need rectification, so we don't need split rings. (This is good news, because the split rings cause sparks, ozone, radio interference and extra wear. If you want DC, it is often better to use an alternator and rectify with diodes.)

In the next animation, the two brushes contact two continuous rings, so the two external terminals are always connected to the same ends of the coil. The result is the unrectified, sinusoidal emf given by $NBA\omega \sin \omega t$, which is shown in the next animation.



3-Phase AC Synchronous Motors

- Think Tesla motors or quadcopter motors

Much harder to drive

- Input is a 3-phase AC sine wave
- Frequency is speed
- Lead angle is torque

If you can figure it out

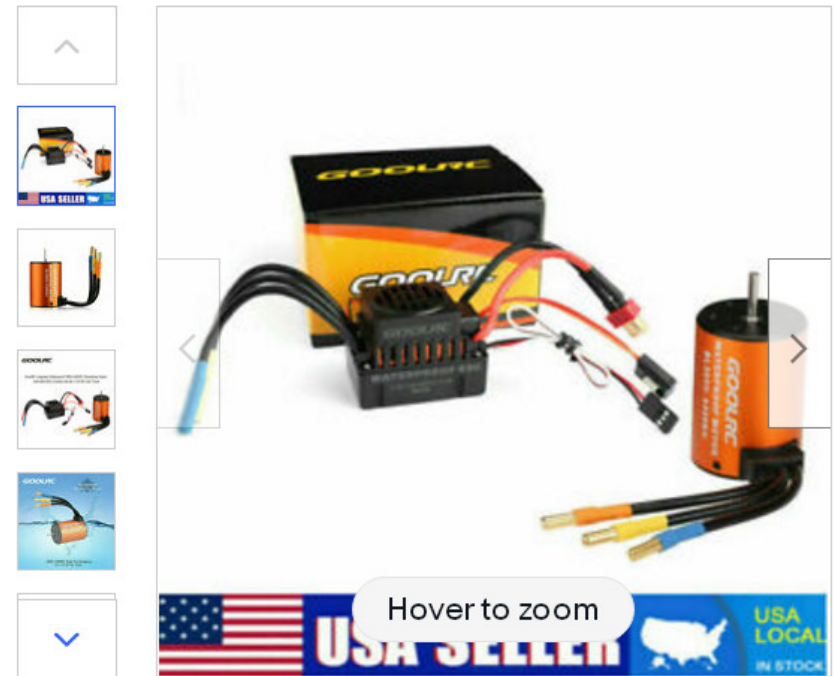
- Size & weight are reduced
- Efficiency is increased
- You open up a wide range of applications (1hp in a 9oz package)



Shop by category ▾

🔍 Search for any

US 3650 4300KV Waterproof Brushless Motor w/ ESC Combo Set for 1:10 RC Car Truck



To make an AC motor work...

DC to AC converter

- Acceleration
- Battery (DC) to Motor (AC)
- ECE 320 Electronics I
- ECE 437 Power Electronics
- ECE 438 Electric Drives

AC to DC

- Braking
- Motor (AC) to Battery (DC)
- ECE 320 Electronics I
- ECE 437 Power Electronics
- ECE 438 Electric Drives

The heart of all of this is electronics



Example #2: Lighting

As long as technology advances, we've got jobs

1970: Incandescent Light Bulb

- 2% efficient
- 30% of the nation's energy went to lighting

2022: LED Light Bulb

- Electronic device (diode)
- 36% efficient
- 80% efficient is possible in theory
- 5% of the nation's energy goes to lighting



Problem with LED Lighting

- Problem: Convert 60Hz AC to DC

Current Solution:

- Use electronics to pass current briefly

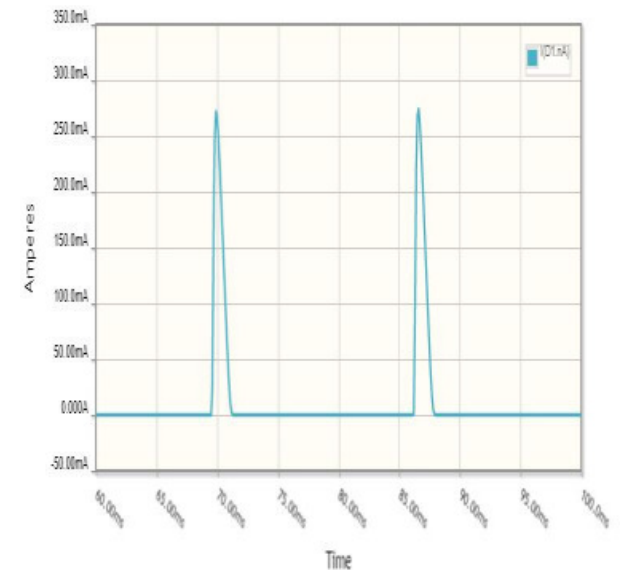
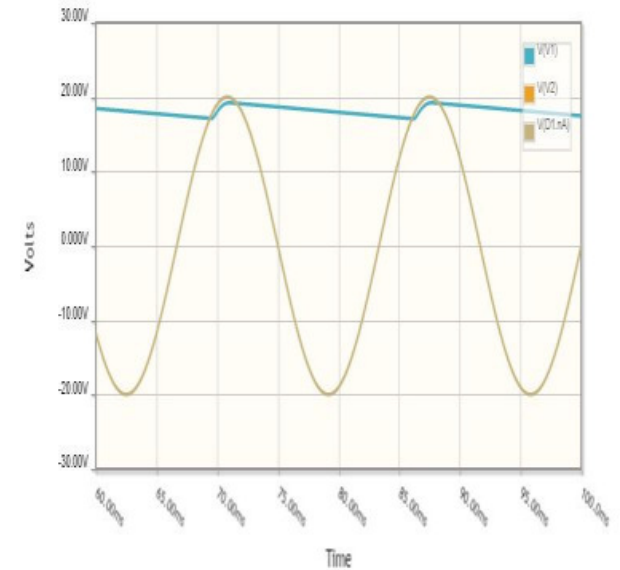
Problem

- This results in current spikes
- This creates losses in transformers
- It can also burn out neutral lines

How do you make

- The AC current a nice clean sine wave,
- The DC current a nice clean constant
- At 90-95% efficiency with electronics?

Whoever figures this out will make billions



Electronics I

Analysis of circuits with semiconductor elements

- Thermistors temperature sensitive resistor
- Diodes valve: allow current to flow in only one direction
- Transistors diode + current amplifier
- SCR voltage controlled valve
- Mosfet voltage controlled resistor

Solution of circuits with nonlinear elements

- Solve N equations for N unknowns with nonlinear elements

Semiconductors

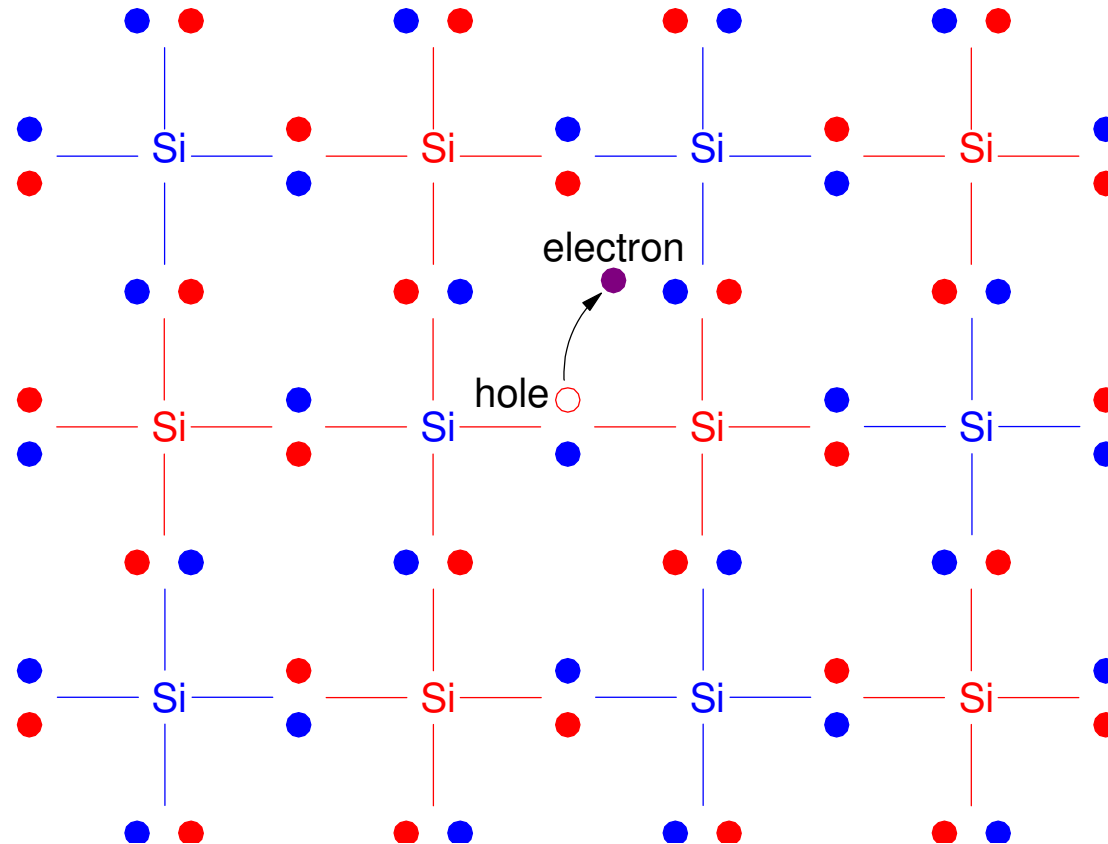
Si, Ge: Column IVA of the periodic table

Periodic Table of the Elements

1 1IA 11A	2 IIA 2A											13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A	
1 H Hydrogen 1.0079													5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.00674	8 O Oxygen 15.9994	9 F Fluorine 18.998403	10 Ne Neon 20.1797
3 Li Lithium 6.941	4 Be Beryllium 9.01218												13 Al Aluminum 26.981539	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948
11 Na Sodium 22.989769	12 Mg Magnesium 24.305	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 9	10 VIII 10	11 IB 1B	12 IIB 2B	13 Al Aluminum 26.981539	14 Si Silicon 28.0855	15 P Phosphorus 30.973762	16 S Sulfur 32.066	17 Cl Chlorine 35.4527	18 Ar Argon 39.948	
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.95591	22 Ti Titanium 47.88	23 V Vanadium 50.9415	24 Cr Chromium 51.9961	25 Mn Manganese 54.938	26 Fe Iron 55.847	27 Co Cobalt 58.9332	28 Ni Nickel 58.6934	29 Cu Copper 63.546	30 Zn Zinc 65.39	31 Ga Gallium 69.723	32 Ge Germanium 72.64	33 As Arsenic 74.92159	34 Se Selenium 78.96	35 Br Bromine 79.904	36 Kr Krypton 83.80	
37 Rb Rubidium 85.4678	38 Sr Strontium 87.62	39 Y Yttrium 88.90585	40 Zr Zirconium 91.224	41 Nb Niobium 92.90638	42 Mo Molybdenum 95.94	43 Tc Technetium 98.9072	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.9055	46 Pd Palladium 106.42	47 Ag Silver 107.8682	48 Cd Cadmium 112.411	49 In Indium 114.818	50 Sn Tin 118.71	51 Sb Antimony 121.760	52 Te Tellurium 127.6	53 I Iodine 126.90447	54 Xe Xenon 131.29	
55 Cs Cesium 132.90543	56 Ba Barium 137.327	57-71	72 Hf Hafnium 178.49	73 Ta Tantalum 180.9479	74 W Tungsten 183.85	75 Re Rhenium 186.207	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.9665	80 Hg Mercury 200.59	81 Tl Thallium 204.3833	82 Pb Lead 207.2	83 Bi Bismuth 208.98037	84 Po Polonium (209.9824)	85 At Astatine 209.9871	86 Rn Radon 222.0176	
87 Fr Francium 223.0192	88 Ra Radium 226.0254	89-103	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Seaborgium (266)	107 Bh Bohrium (264)	108 Hs Hassium (269)	109 Mt Meitnerium (268)	110 Ds Darmstadtium (269)	111 Rg Roentgenium (272)	112 Cn Copernicium (277)	113 Uut Ununtrium unknown	114 Fl Flerovium (289)	115 Uup Ununpentium unknown	116 Lv Livermorium (294)	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown	

Holes and Electrons

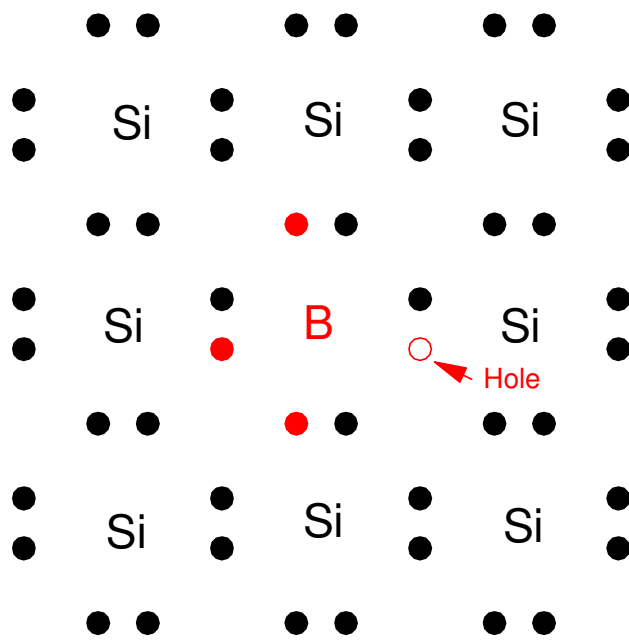
Semiconductors have two types of charge carriers: holes and electrons



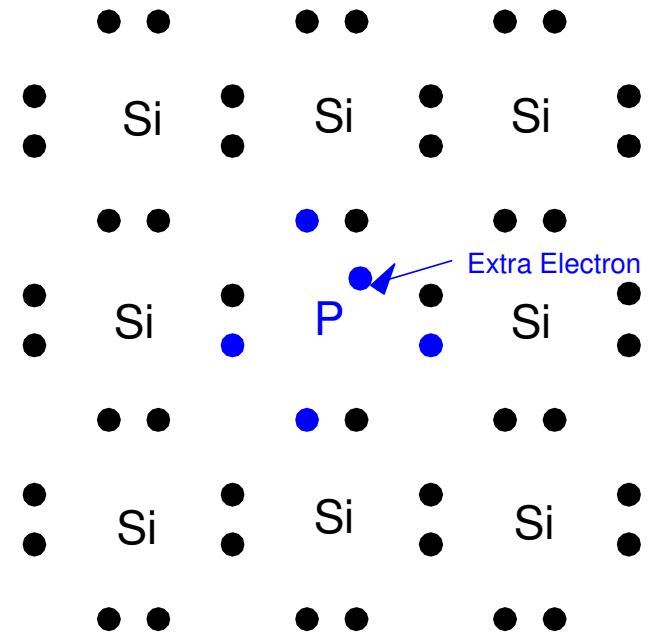
Doping

By doping, you can control what type of carriers exist in the semiconductor

- Dope with Boron: Almost all of the charge carriers are holes (p-type)
- Dope with Phosphorus: Almost all of the charge carriers are electrons (n-type)



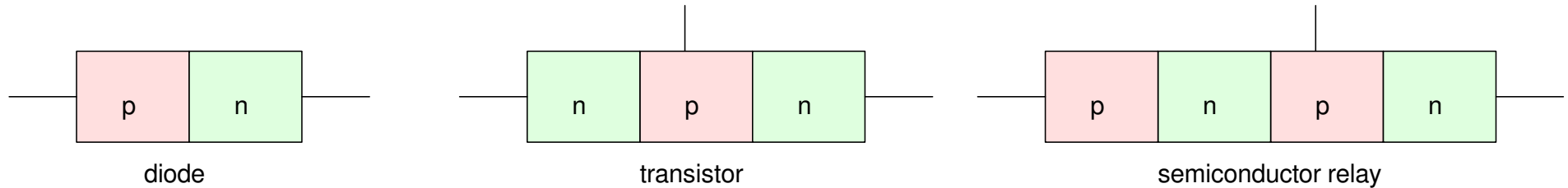
p-type silicon



n-type silicon

Semiconductor Devices

- np: diode (valve)
- npn, pnp: transistor (current amplifier)
- pnpn: semiconductor relay (voltage controlled valve)
- npn + gate: MOSFET (voltage controlled resistor)



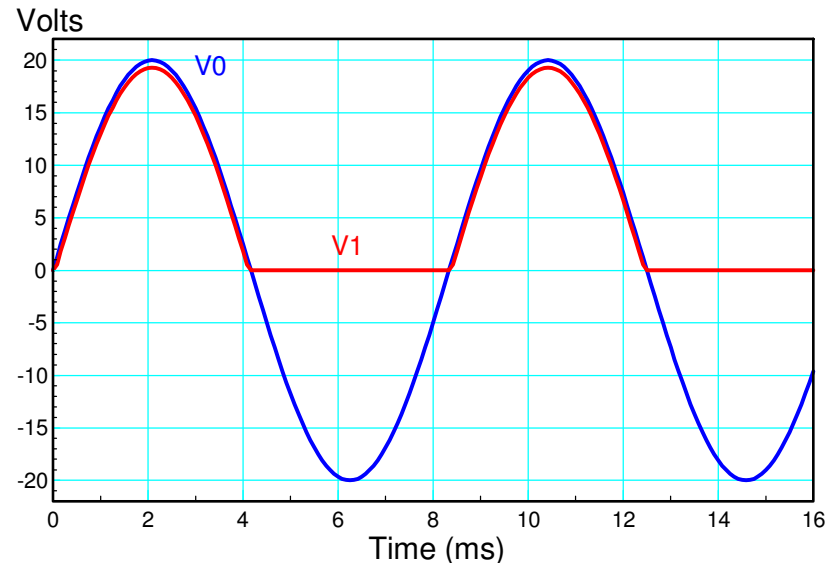
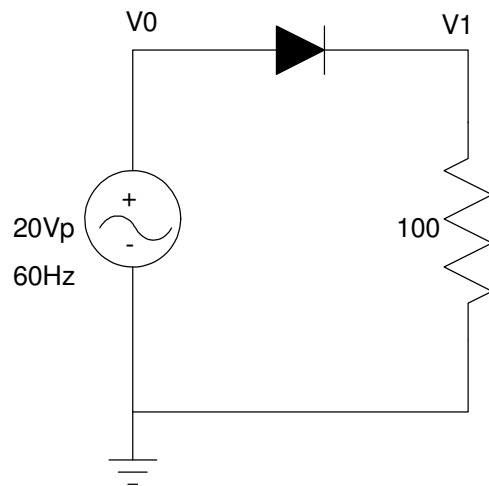
semiconductor relay

Diodes

- A pn junction makes a diode

Diodes are valves

- They only allow current to flow one way
- They allow you to find the maximum or minimum of a set of voltges
- With diodes, you can convert AC to DC



Diodes

With diodes, you can convert current to light

- Light Emitting Diodes
- *Much* more efficient than incandescent lights

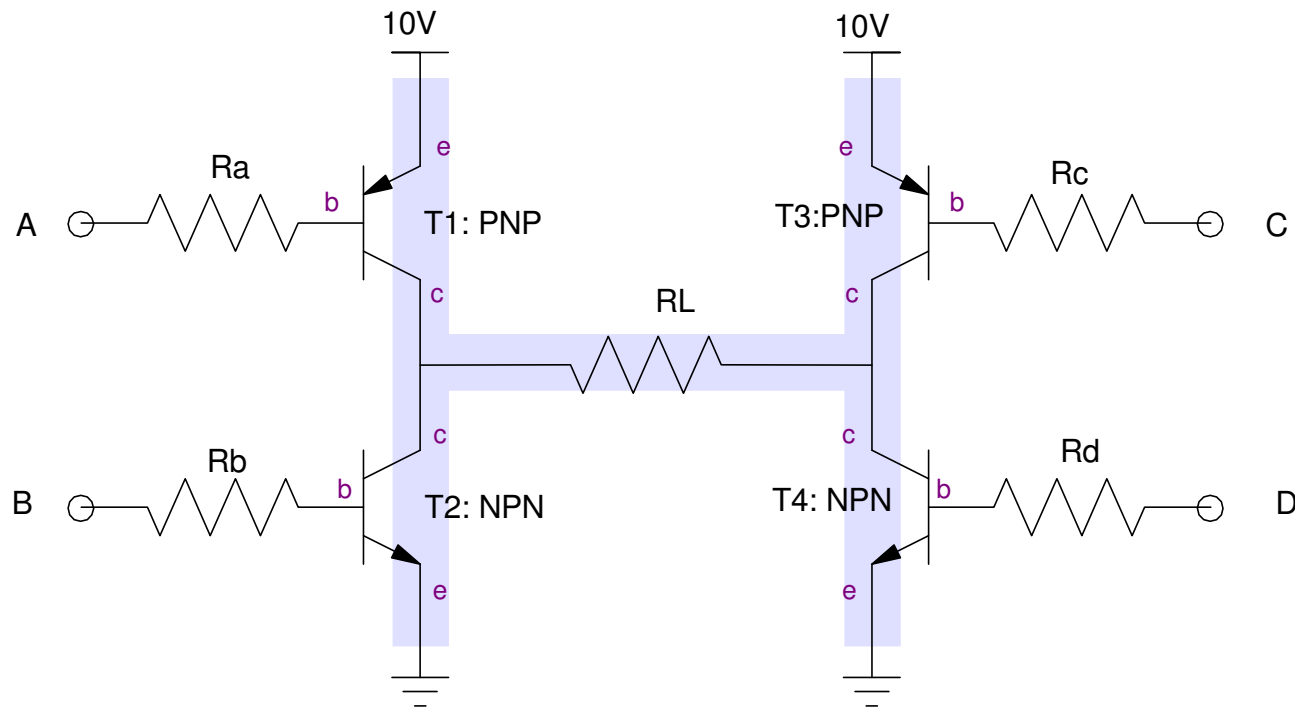
	W, Lumens	Price		Lm / W	eff
		new	@ 1000 hr		
Incandescent (c. 2000)	60W, 300 Lm	-	-	5.27	2.1%
Incandescent: GE 66247	43W, 620 Lm	\$1.36	\$1.38	14.4	5.7%
Halogen: Phillips 60W	43W, 750 Lm	\$1.46	\$1.48	17.4	6.9%
CFL: Philips 823031 CFL	13W, 860Lm	\$3.50	\$0.36	66.2	26.4%
LED: Sylvania 74765	8.5W, 800 Lm	\$0.83	\$0.075	94.1	37.5%
Street Lights:					
Mercury: GE 175W Street	175W / 7850 Lm	\$11.29		36	14%
Sodium: BulBrite	70W / 6000 Lm	\$8.95		86	34%
100W LED	100W / 9000 Lm	\$8.29		90	36%
LED Light (theory)				201	80%
Ideal Black Body	-	-		251	100%

Transistors

- npn or pnp

Transistors act as electronic switches

- Allow a small device (microprocessor) turn on and off a motor, power LED, etc
- Allow a small device to drive a motor forwards and backwards (H-bridge)
- Heart of a DC to AC converter (used for driving AC synchronous motors)



Transistors (cont'd)

Transistors also act as current amplifiers

- Allow you to amplify an analog signal (push-pull amplifier)
- Heart of a stereo
- Covered in ECE 321 Electronics 2

Note that transistors dump voltage (meaning they will get hot when used as an amplifier). The four transistors at the top are likewise connected to a heat-sink.

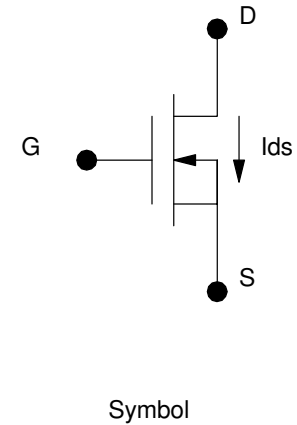
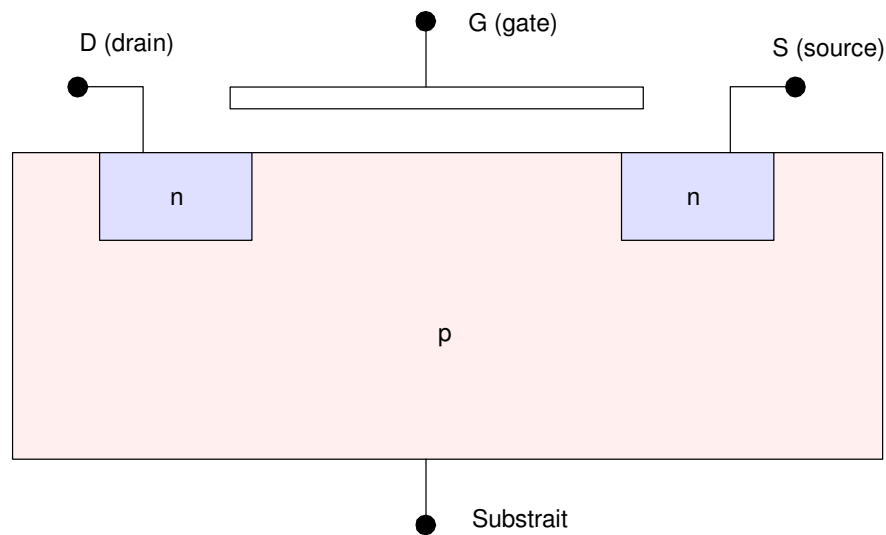


MOSFET

- Voltage controlled resistor

Heart of DC to AC converters

Heart of CMOS logic (building block of computers)

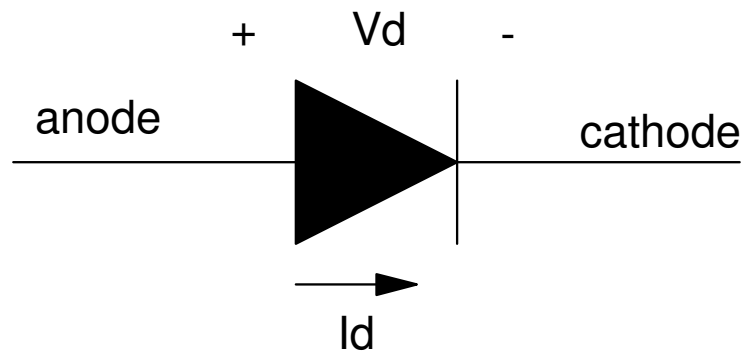


Diode VI Characteristics

A diode is a nonlinear circuit element which acts like a valve:

- The resistance is low when you try to force current to flow from the anode to cathode
- The resistance is high when you try to force current to flow from the cathode to the anode.

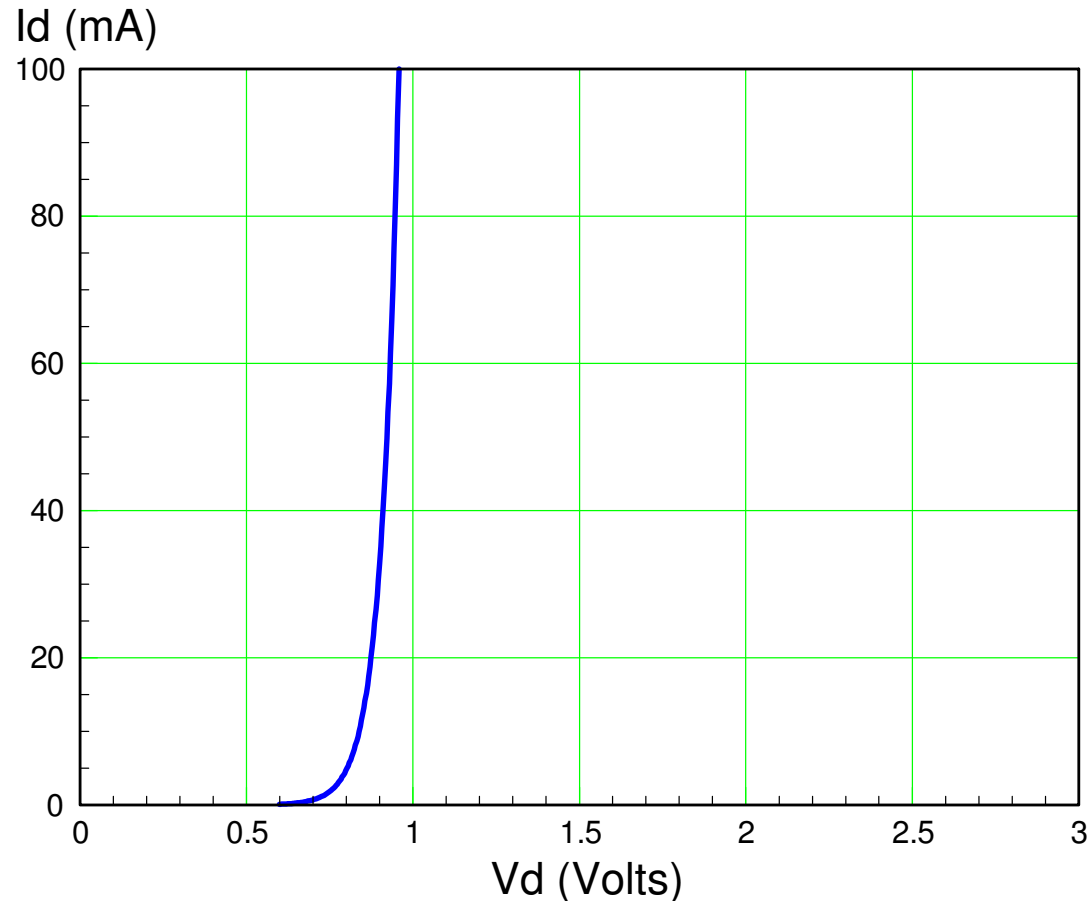
The symbol for a diode acts as a reminder of this: it looks like an arrow which points in the direction current can flow



Symbol for a diode: current only flows from anode to cathode

The VI characteristics for a diode are nonlinear

$$I_d = I_{dss} \left(\exp \left(\frac{V_d}{nV_T} \right) - 1 \right) \qquad V_d = nV_T \ln \left(\frac{I_d}{I_{dss}} + 1 \right)$$



What makes electronics so hard?

In circuits, you deal with linear circuit elements

- Resistors, Capacitors, Inductors
- Linear algebra can be used to solve these problems
- N equations for N unknowns

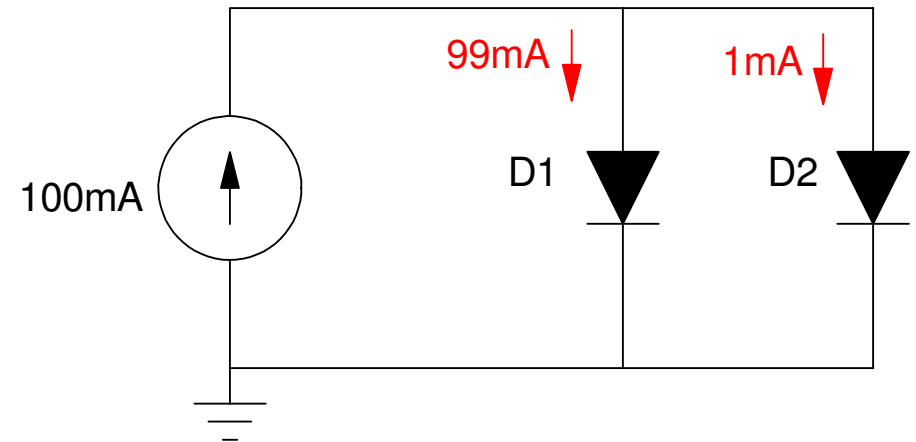
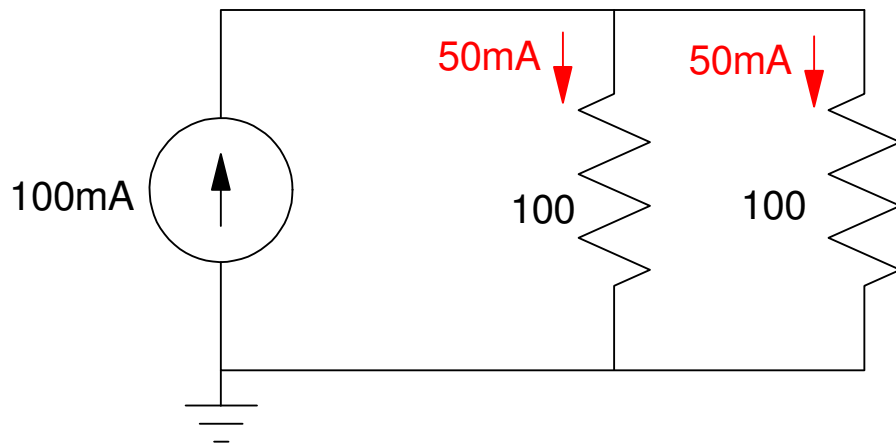
In electronics, you deal with *nonlinear* circuit elements

- Diodes, Transistors, MOSFETs
 - You still have N equations for N unknowns
 - But linear algebra no longer works (the equations are nonlinear)
-

Nonlinear Elements Behave Weird

Example: Resistors vs. Diodes in Parallel

- Two resistors in parallel share the load equally
- Two diodes in parallel do not: one takes the brunt of the current



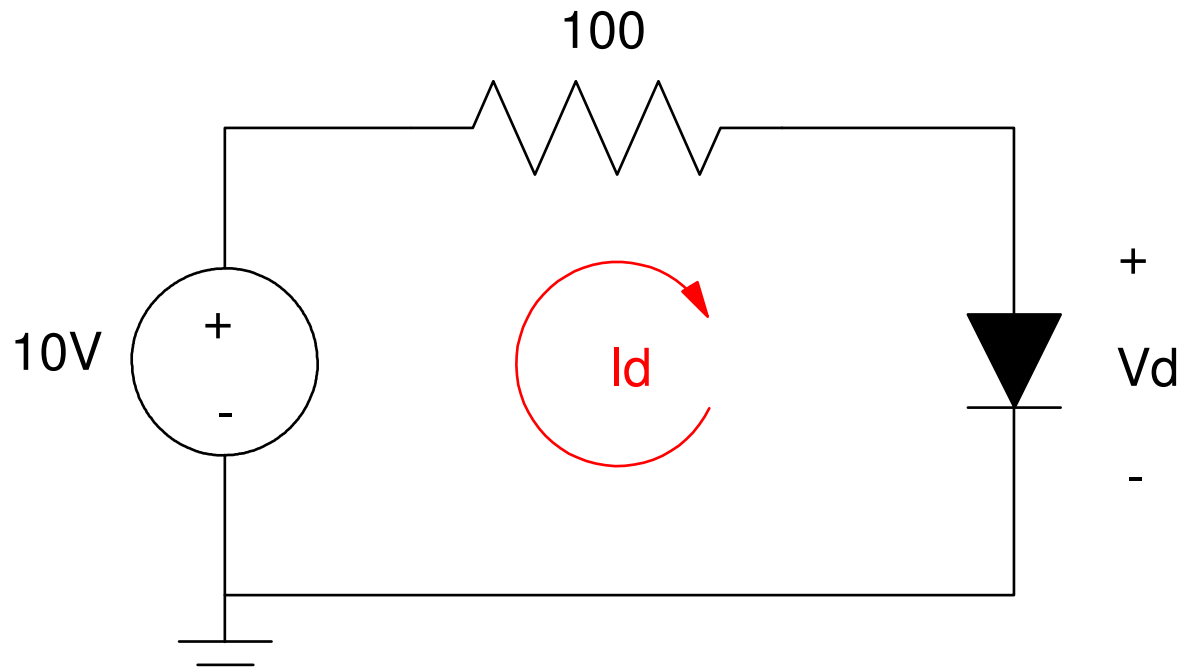
Nonlinear Equations are Hard to Solve

Example: Single diode circuit:

- 2 equations for 2 unknowns:

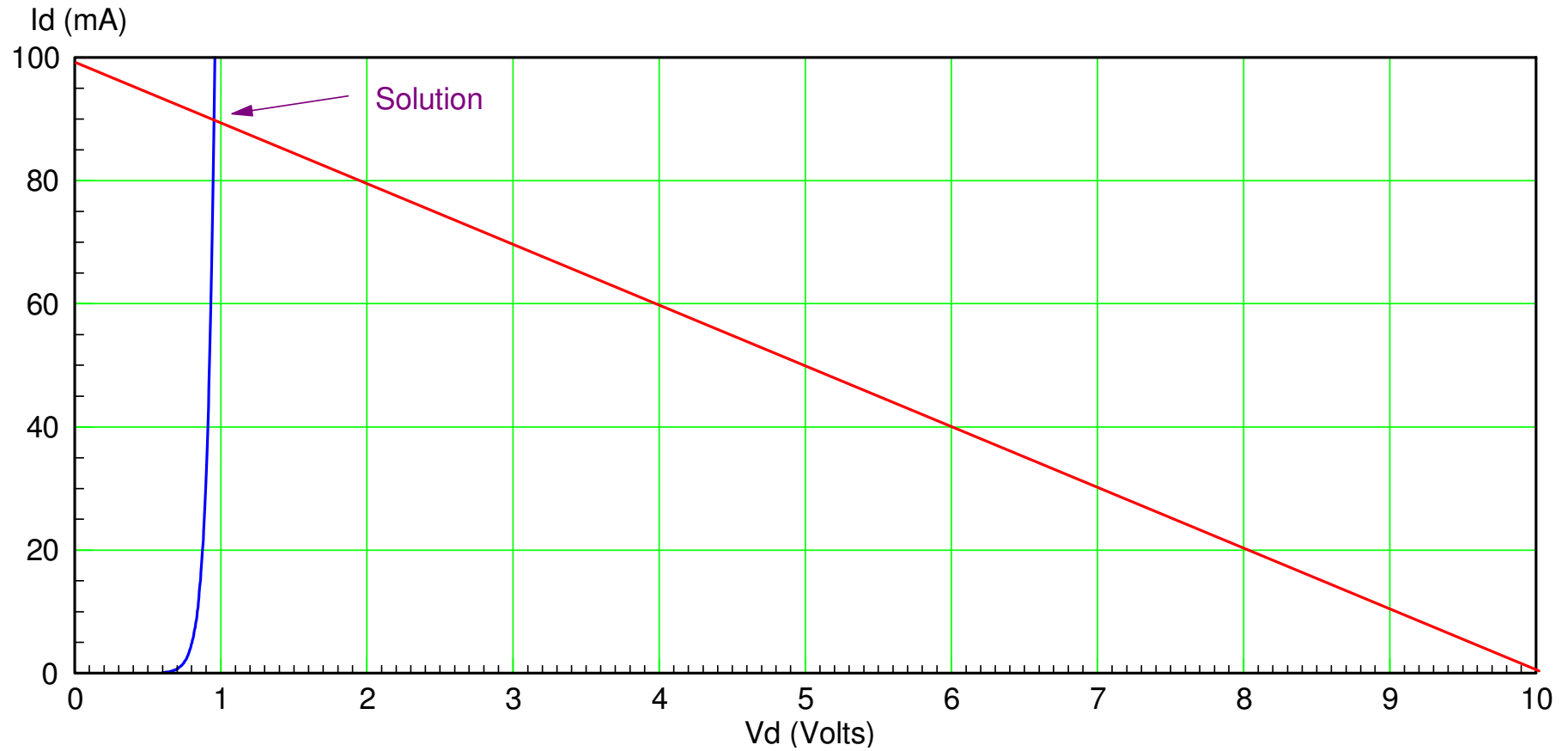
$$V_d = nV_T \ln\left(\frac{I_d}{I_{dss}} + 1\right) = 0.0377 \ln\left(\frac{I_d}{7.69 \cdot 10^{-11}} + 1\right)$$

$$V_d + 100I_d = 10$$



Load Line Analysis:

- Plot I_d vs. V_d for both equations
- The solution is where they intersect



Numerical Solution

- Matlab to the rescue!

Guess Vd

- Compute Id (diode equation)
- Compute the excess current (voltage nodes)
- Minimize the error using *fminsearch()*

```
function [ J ] = Diode1( z )

    Vd = z(1);

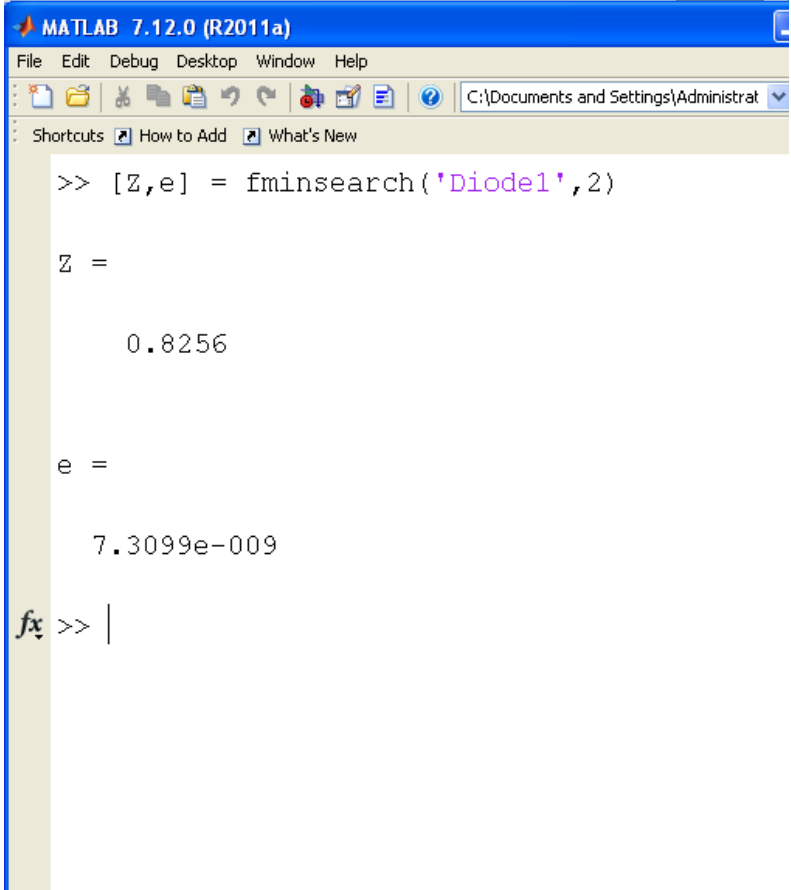
    Idss = 7.69e-11;
    nVt = 0.0377;

    Id = Idss* exp( Vd/nVt - 1 );

    e1 = Id + (Vd - 10)/100;

    J = (e1)^2;

end
```



```
MATLAB 7.12.0 (R2011a)
File Edit Debug Desktop Window Help
C:\Documents and Settings\Administrat
Shortcuts How to Add What's New

>> [Z,e] = fminsearch('Diode1',2)

Z =

    0.8256

e =







    7.3099e-009

fx >> |
```


CircuitLab Solution

- Matlab: $V_d = 0.8256\text{V}$

▼ DC

V(V0)	10.00 V		
V(V1)	782.7 mV		
I(D1.nA)	92.17 mA		

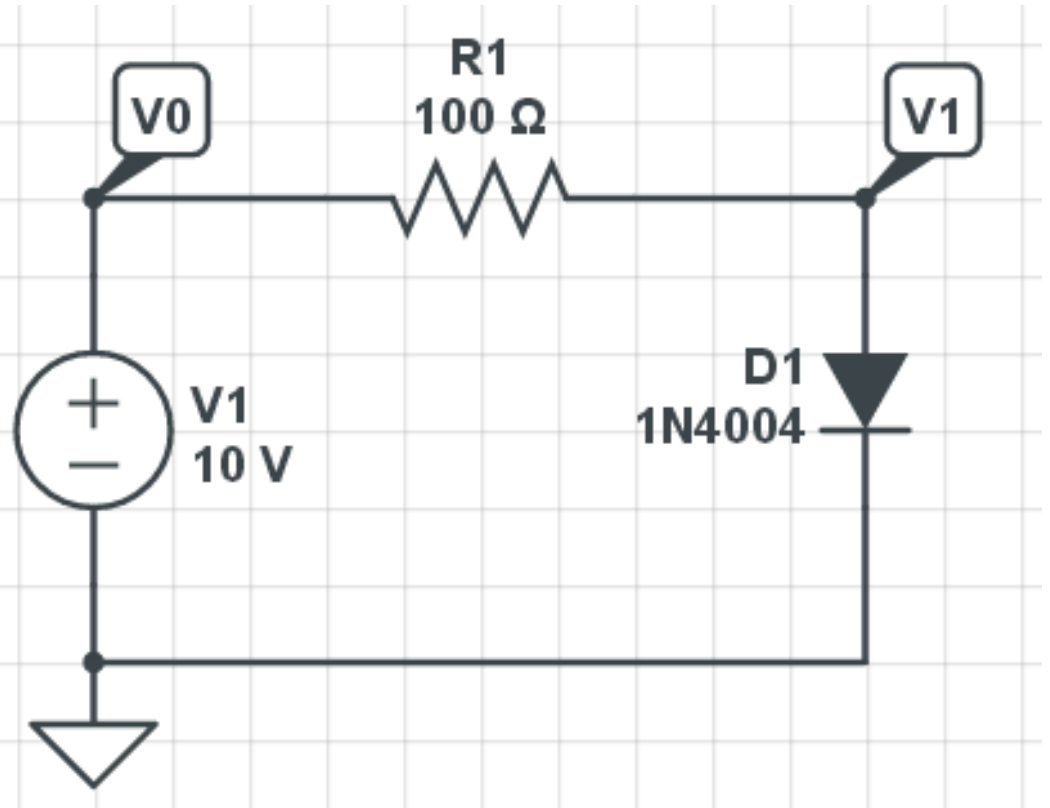
[+ Add Expression](#)

 Export Results...

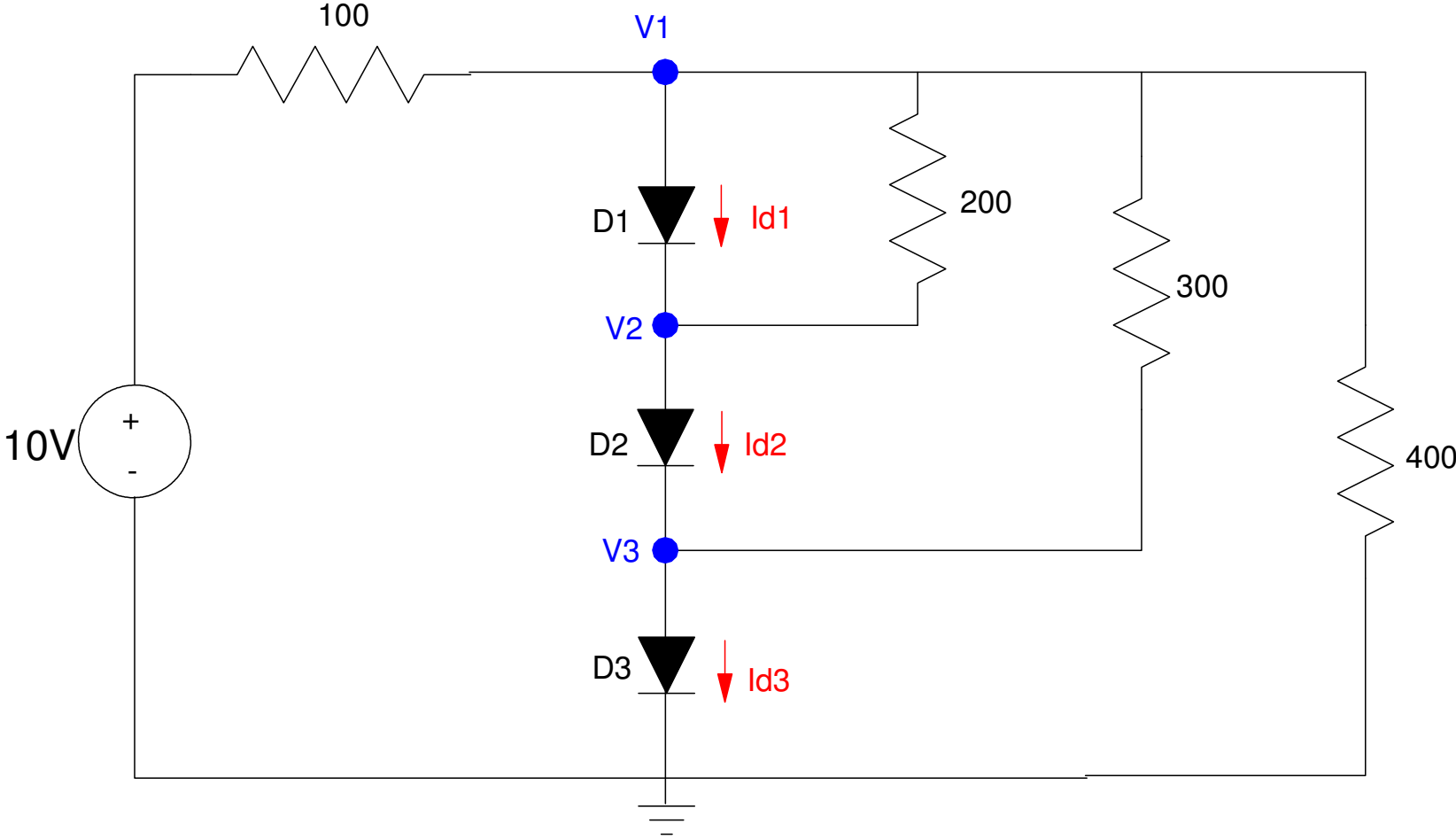
[Run DC Solver](#)

▶ DC Sweep

▶ Time Domain



Example 2: Multi-Diode Circuit



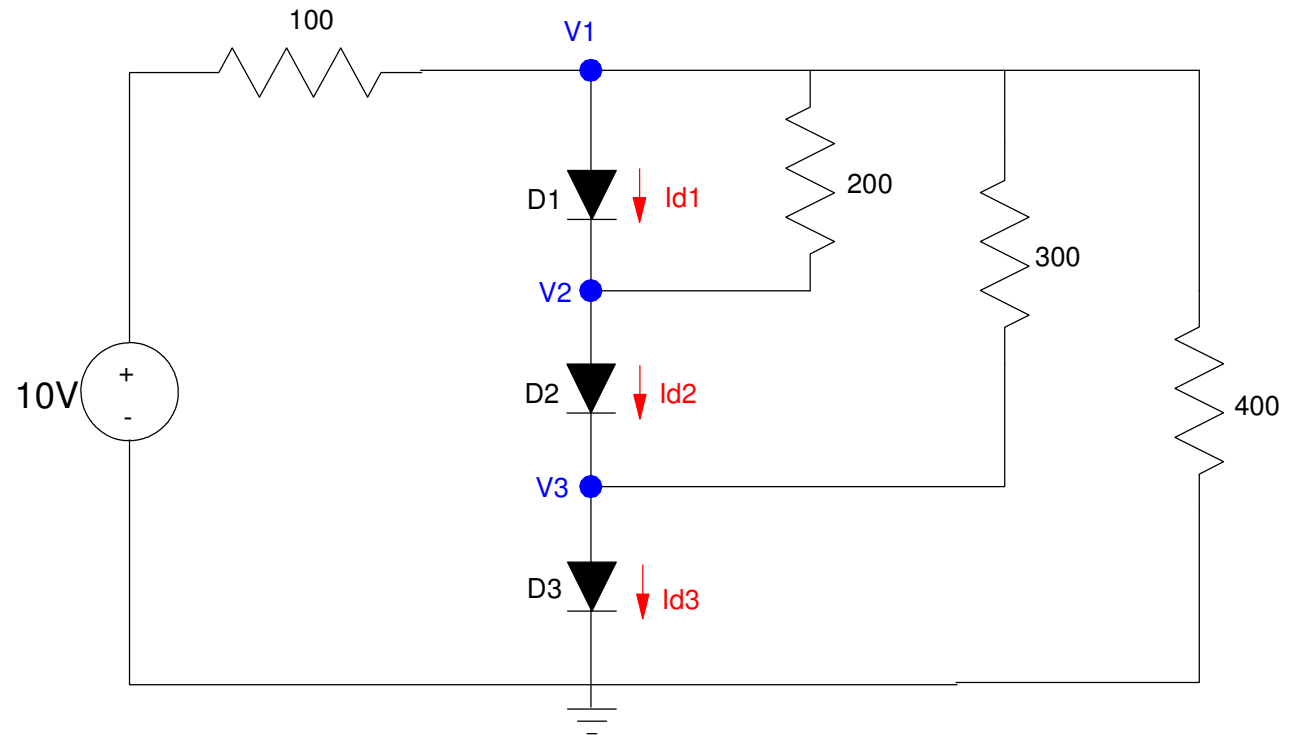
Numerical Solution

Load Lines won't work

- Need to plot in 6 dimensions

Numerical solution still works:

- Solve 6 equations for 6 unknowns
- `fminsearch`



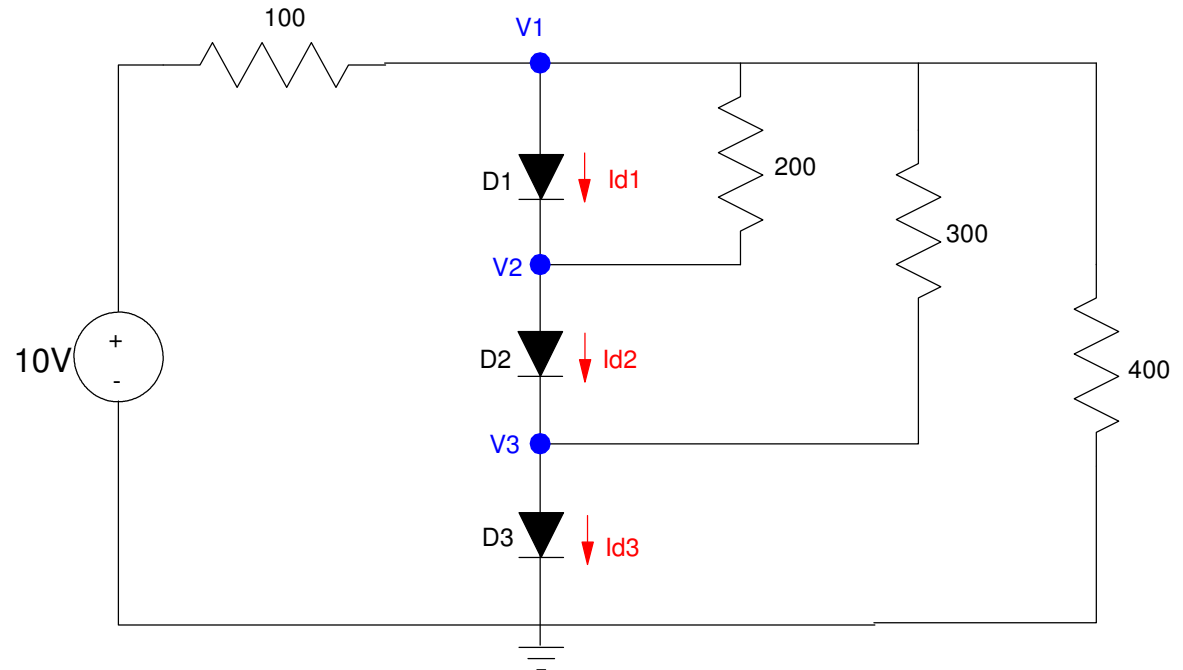
N-equations for N unknowns

Diode equations (1..3)

$$I_{d1} = I_{dss} \left(\exp \left(\frac{V_1 - V_2}{nV_T} \right) - 1 \right)$$

$$I_{d2} = I_{dss} \left(\exp \left(\frac{V_2 - V_3}{nV_T} \right) - 1 \right)$$

$$I_{d3} = I_{dss} \left(\exp \left(\frac{V_3 - 0}{nV_T} \right) - 1 \right)$$

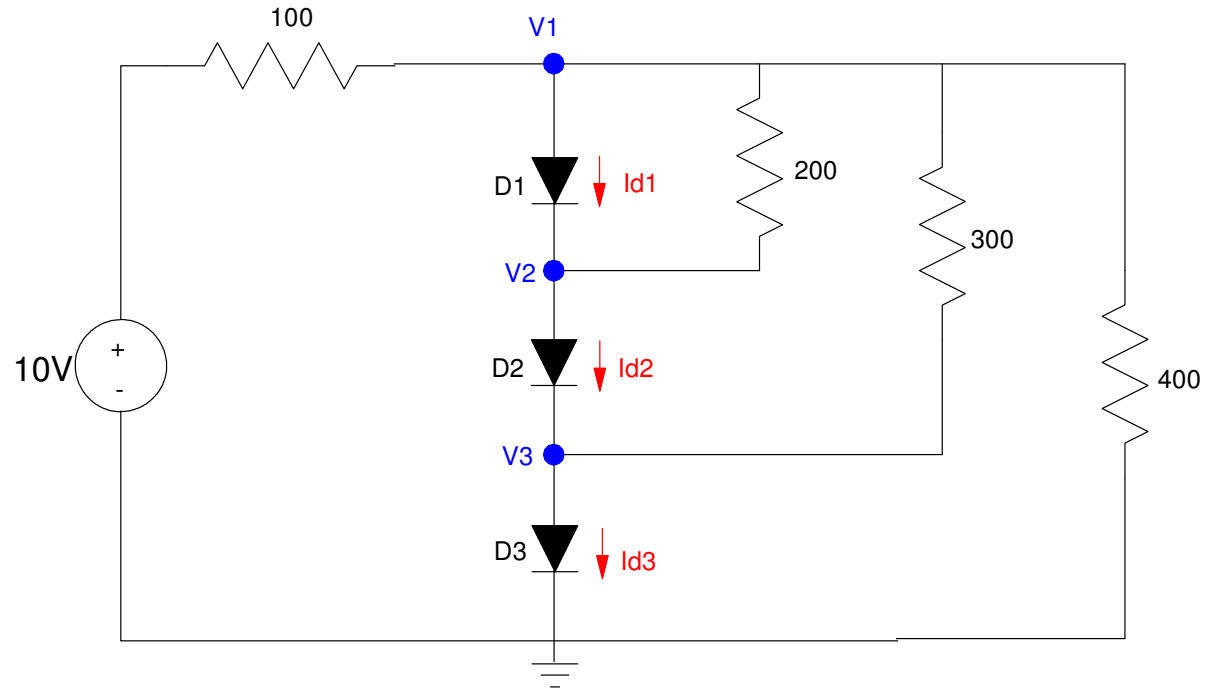


Voltage Node equations (4..6)

$$\left(\frac{V_1-10}{100}\right) + I_{D1} + \left(\frac{V_1-V_2}{200}\right) + \left(\frac{V_1-V_3}{300}\right) + \left(\frac{V_1-0}{400}\right) = 0$$

$$\left(\frac{V_2-V_1}{200}\right) - I_{D1} + I_{D2} = 0$$

$$\left(\frac{V_3-V_1}{300}\right) - I_{D2} + I_{D3} = 0$$



Procedure:

i) Guess the voltages (V_1, V_2, V_3)

ii) Compute the diode currents:

$$I_{d1} = I_{dss} \left(\exp \left(\frac{V_1 - V_2}{nV_T} \right) - 1 \right)$$

$$I_{d2} = I_{dss} \left(\exp \left(\frac{V_2 - V_3}{nV_T} \right) - 1 \right)$$

$$I_{d3} = I_{dss} \left(\exp \left(\frac{V_3 - 0}{nV_T} \right) - 1 \right)$$

iii) Find the excess current (error) from each node:

$$e_1 = \left(\frac{V_1 - 10}{100} \right) + I_{d1} + \left(\frac{V_1 - V_2}{200} \right) + \left(\frac{V_1 - V_3}{300} \right) + \left(\frac{V_1}{400} \right)$$

$$e_2 = \left(\frac{V_2 - V_1}{200} \right) - I_{d1} + I_{d2}$$

$$e_3 = \left(\frac{V_3 - V_1}{300} \right) - I_{d2} + I_{d3}$$

iv) Compute the sum square error

$$J = e_1^2 + e_2^2 + e_3^2$$

```
function [ J ] = Diode3( z )
```

```
V1 = z(1);
```

```
V2 = z(2);
```

```
V3 = z(3);
```

```
Idss = 7.69e-11;
```

```
nVt = 0.0377;
```

```
Id1 = Idss* exp( (V1 - V2)/nVt - 1 );
```

```
Id2 = Idss* exp( (V2 - V3)/nVt - 1 );
```

```
Id3 = Idss* exp( (V3 - 0)/nVt - 1 );
```

```
e1 = (V1 - 10)/100 + Id1 + (V1-V2)/200 + (V1-V3)/300 + (V1/400);
```

```
e2 = (V2-V1)/200 - Id1 + Id2;
```

```
e3 = (V3-V1)/300 - Id2 + Id3;
```

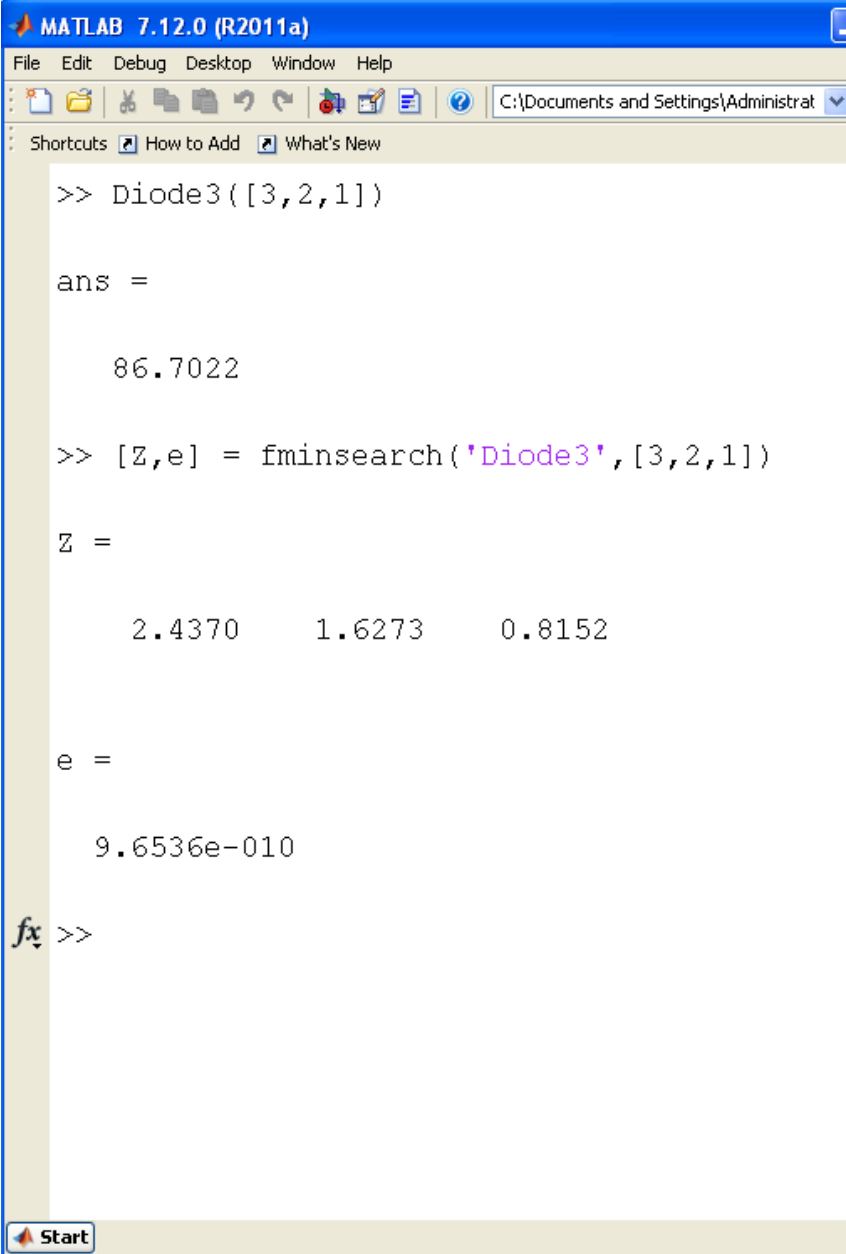
```
J = (e1)^2 + (e2)^2 + (e3)^2;
```

```
end
```

Solving with *fminsearch*

The solution found by MATLAB is

- $V1 = 2.4370\text{V}$
- $V2 = 1.6273\text{V}$
- $V3 = 0.8152\text{V}$



```
MATLAB 7.12.0 (R2011a)
File Edit Debug Desktop Window Help
C:\Documents and Settings\Administrat
Shortcuts How to Add What's New

>> Diode3([3,2,1])

ans =

    86.7022

>> [Z,e] = fminsearch('Diode3',[3,2,1])

Z =

    2.4370    1.6273    0.8152

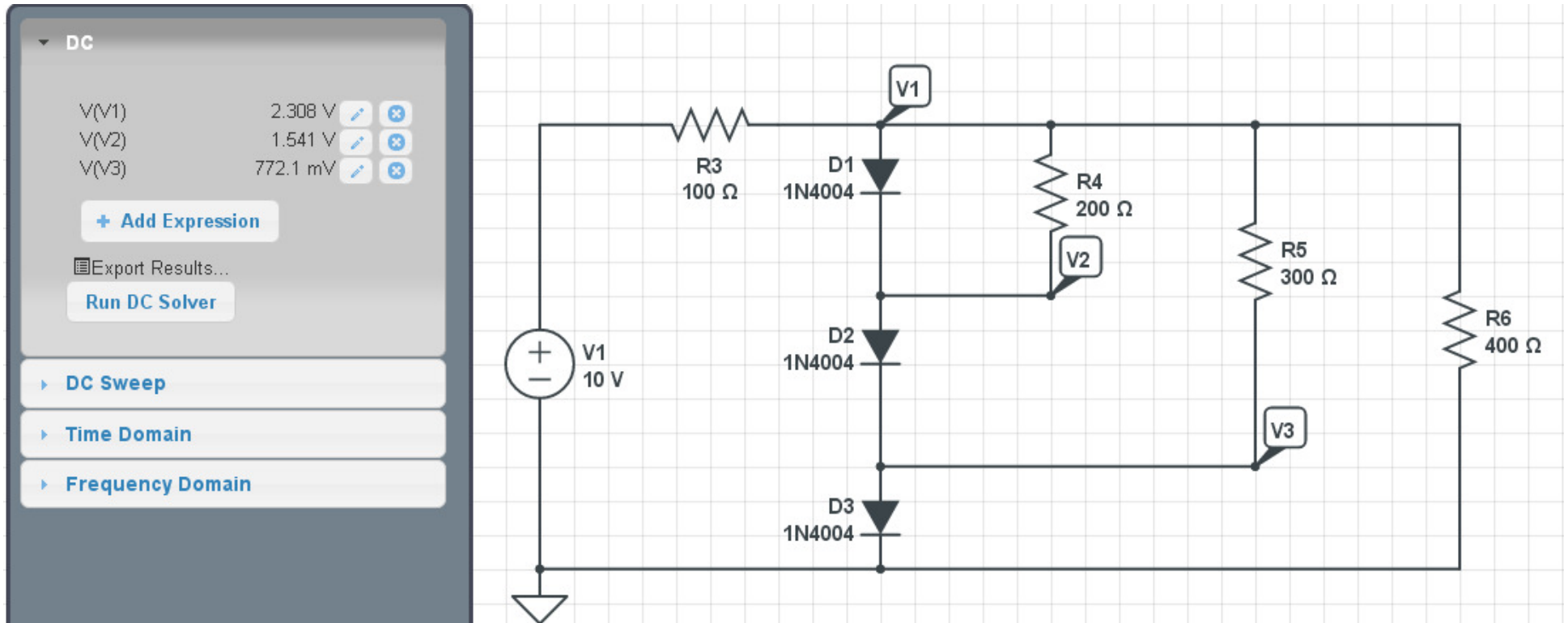
e =

    9.6536e-010

fx >>
```

Check with CircuitLab

- Matlab Solution: $V1 = 2.4370V$, $V2 = 1.6273V$, $V3 = 0.8152V$
- Answers are slightly different (slightly different diode model used for a 1N4004)



Summary

In Electronics, you deal with nonlinear circuit elements

- Thermistors, Diodes, Transistors, MOSFETs, SCR's, etc.

Voltage Nodes, Current Loops still apply

- Solve N equations for N unknowns
- Only now, they are N nonlinear equations

fminsearch is a very useful tool. With it

- You can solve N equations for N unknowns
 - Even when the equations are nonlinear
-