

CMSC 313
COMPUTER ORGANIZATION
&
ASSEMBLY LANGUAGE
PROGRAMMING

LECTURE 20, SPRING 2013



TOPICS TODAY

- **Project 8**
- **Semiconductors, Transistors & Gates**



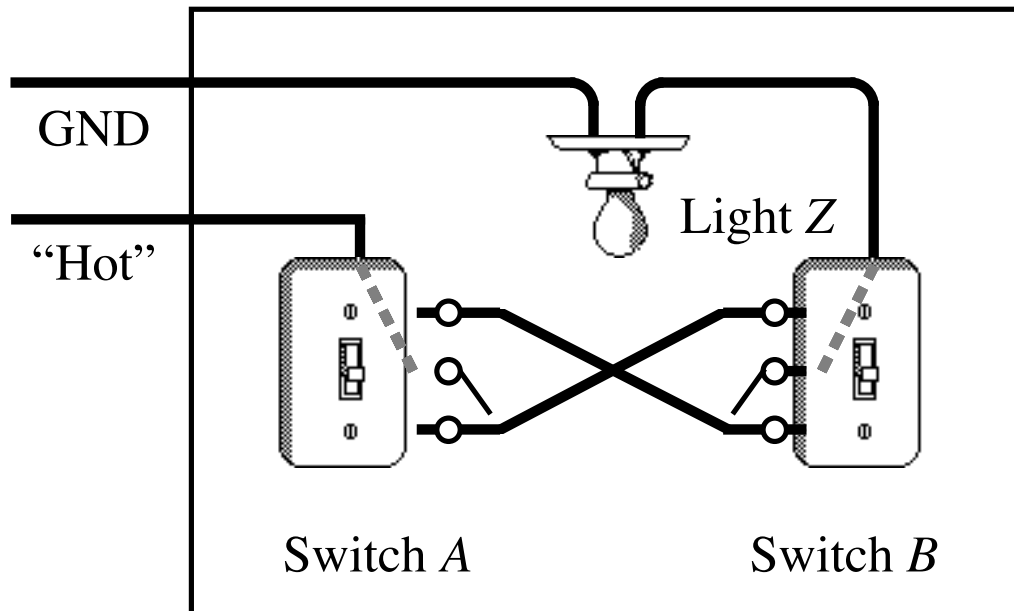
SEMICONDUCTORS, TRANSISTORS & GATES



How do we make gates???

A Truth Table

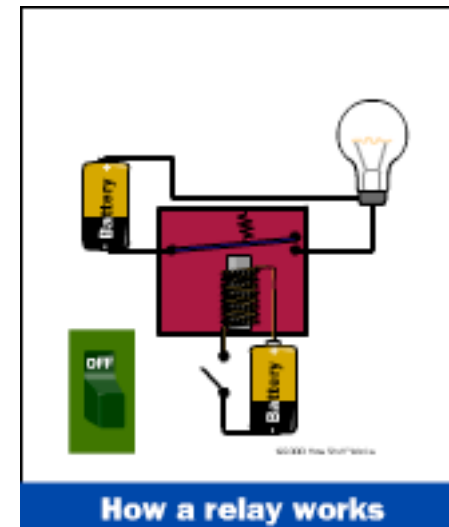
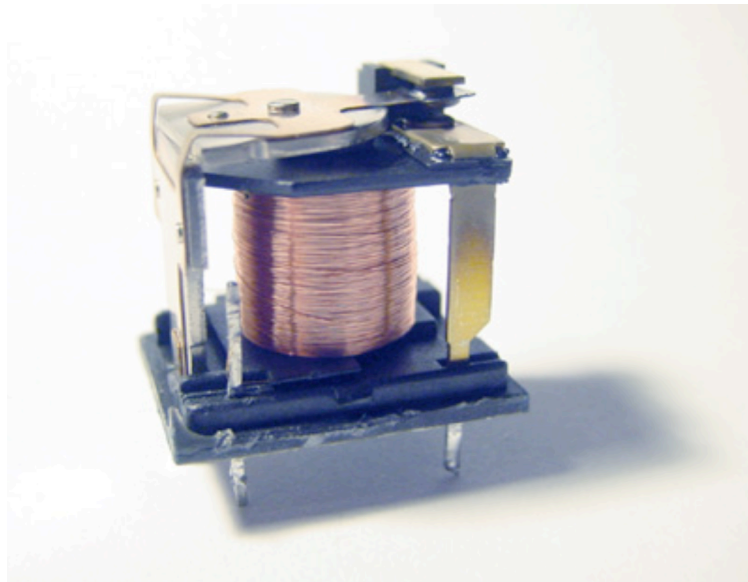
- Developed in 1854 by George Boole.
- Further developed by Claude Shannon (Bell Labs).
- Outputs are computed for all possible input combinations (how many input combinations are there?)
- Consider a room with two light switches. How must they work?



Inputs		Output
A	B	Z
0	0	0
0	1	1
1	0	1
1	1	0

Electrically Operated Switch

- **Example: a relay**



source: <http://www.howstuffworks.com/relay.htm>

Semiconductors

- **Electrical properties of silicon**
- **Doping: adding impurities to silicon**
- **Diodes and the P-N junction**
- **Field-effect transistors**

Periodic Table of the Elements

Group																		
Period	1											13	14	15	16	17	18	
	IA											IIIA	IVA	VA	VIA	VIIA	VIIIA	
	1A											3A	4A	5A	6A	7A	8A	
1	1 <u>H</u> 1.008	2 <u>He</u> 4.003											13 <u>B</u> 10.81	14 <u>C</u> 12.01	15 <u>N</u> 14.01	16 <u>O</u> 16.00	17 <u>F</u> 19.00	18 <u>Ne</u> 20.18
2	3 <u>Li</u> 6.941	4 <u>Be</u> 9.012											5 <u>B</u> 10.81	6 <u>C</u> 12.01	7 <u>N</u> 14.01	8 <u>O</u> 16.00	9 <u>F</u> 19.00	10 <u>Ne</u> 20.18
3	11 <u>Na</u> 22.99	12 <u>Mg</u> 24.31	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 ----- ----- 8	9 VIII ----- ----- 8	10 ----- ----- 8	11 IB 1B	12 IIB 2B	13 <u>Al</u> 26.98	14 <u>Si</u> 28.09	15 <u>P</u> 30.97	16 <u>S</u> 32.07	17 <u>Cl</u> 35.45	18 <u>Ar</u> 39.95
4	19 <u>K</u> 39.10	20 <u>Ca</u> 40.08	21 <u>Sc</u> 44.96	22 <u>Ti</u> 47.88	23 <u>V</u> 50.94	24 <u>Cr</u> 52.00	25 <u>Mn</u> 54.94	26 <u>Fe</u> 55.85	27 <u>Co</u> 58.47	28 <u>Ni</u> 58.69	29 <u>Cu</u> 63.55	30 <u>Zn</u> 65.39	31 <u>Ga</u> 69.72	32 <u>Ge</u> 72.59	33 <u>As</u> 74.92	34 <u>Se</u> 78.96	35 <u>Br</u> 79.90	36 <u>Kr</u> 83.80
5	37 <u>Rb</u> 85.47	38 <u>Sr</u> 87.62	39 <u>Y</u> 88.91	40 <u>Zr</u> 91.22	41 <u>Nb</u> 92.91	42 <u>Mo</u> 95.94	43 <u>Tc</u> (98)	44 <u>Ru</u> 101.1	45 <u>Rh</u> 102.9	46 <u>Pd</u> 106.4	47 <u>Ag</u> 107.9	48 <u>Cd</u> 112.4	49 <u>In</u> 114.8	50 <u>Sn</u> 118.7	51 <u>Sb</u> 121.8	52 <u>Te</u> 127.6	53 <u>I</u> 126.9	54 <u>Xe</u> 131.3
6	55 <u>Cs</u> 132.9	56 <u>Ba</u> 137.3	57 <u>La*</u> 138.9	72 <u>Hf</u> 178.5	73 <u>Ta</u> 180.9	74 <u>W</u> 183.9	75 <u>Re</u> 186.2	76 <u>Os</u> 190.2	77 <u>Ir</u> 190.2	78 <u>Pt</u> 195.1	79 <u>Au</u> 197.0	80 <u>Hg</u> 200.5	81 <u>Tl</u> 204.4	82 <u>Pb</u> 207.2	83 <u>Bi</u> 209.0	84 <u>Po</u> (210)	85 <u>At</u> (210)	86 <u>Rn</u> (222)
7	87 <u>Fr</u> (223)	88 <u>Ra</u> (226)	89 <u>Ac~</u> (227)	104 <u>Rf</u> (257)	105 <u>Db</u> (260)	106 <u>Sg</u> (263)	107 <u>Bh</u> (262)	108 <u>Hs</u> (265)	109 <u>Mt</u> (266)	110 --- (0)	111 --- (0)	112 --- (0)	114 --- (0)	116 --- (0)	118 --- (0)			

Lanthanide Series*

58 <u>Ce</u> 140.1	59 <u>Pr</u> 140.9	60 <u>Nd</u> 144.2	61 <u>Pm</u> (147)	62 <u>Sm</u> 150.4	63 <u>Eu</u> 152.0	64 <u>Gd</u> 157.3	65 <u>Tb</u> 158.9	66 <u>Dy</u> 162.5	67 <u>Ho</u> 164.9	68 <u>Er</u> 167.3	69 <u>Tm</u> 168.9	70 <u>Yb</u> 173.0	71 <u>Lu</u> 175.0
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Actinide Series~

90 <u>Th</u> 232.0	91 <u>Pa</u> (231)	92 <u>U</u> (238)	93 <u>Np</u> (237)	94 <u>Pu</u> (242)	95 <u>Am</u> (243)	96 <u>Cm</u> (247)	97 <u>Bk</u> (247)	98 <u>Cf</u> (249)	99 <u>Es</u> (254)	100 <u>Fm</u> (253)	101 <u>Md</u> (256)	102 <u>No</u> (254)	103 <u>Lr</u> (257)
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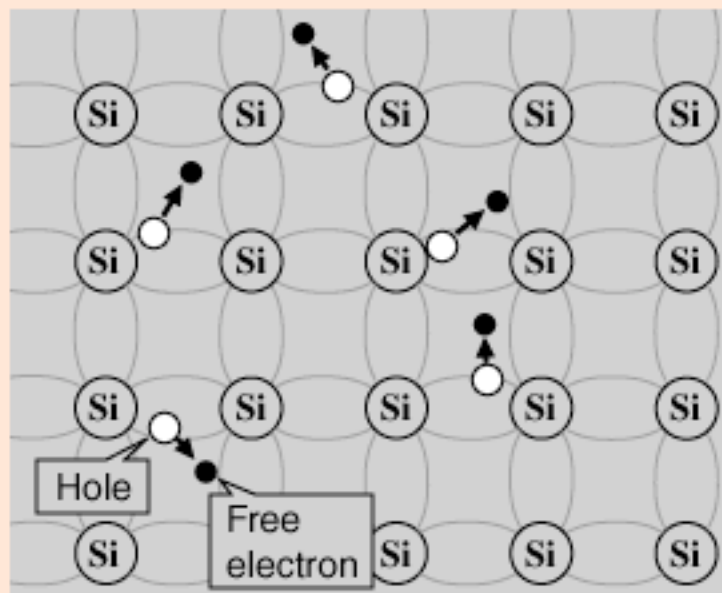
Intrinsic Semiconductor

A silicon crystal is different from an [insulator](#) because at any temperature above absolute zero temperature, there is a finite probability that an electron in the [lattice](#) will be knocked loose from its position, leaving behind an electron deficiency called a "[hole](#)".

If a voltage is applied, then both the electron and the hole can contribute to a small [current](#) flow.

The conductivity of a semiconductor can be modeled in terms of the [band theory](#) of solids. The band model of a semiconductor suggests that at ordinary temperatures there is a finite possibility that electrons can reach the [conduction band](#) and contribute to electrical conduction.

The term intrinsic here distinguishes between the properties of pure "intrinsic" silicon and the dramatically different properties of [doped n-type](#) or [p-type](#) semiconductors.

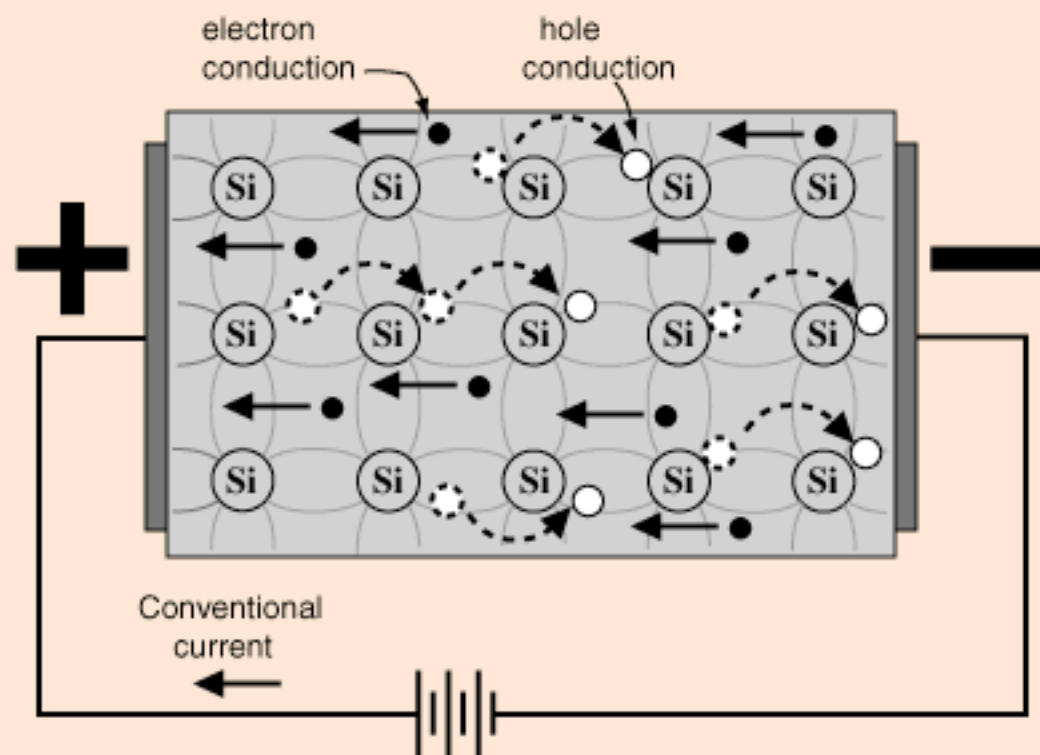


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Semiconductor Current

Both [electrons and holes](#) contribute to current flow in an [intrinsic semiconductor](#).



[Further discussion](#)

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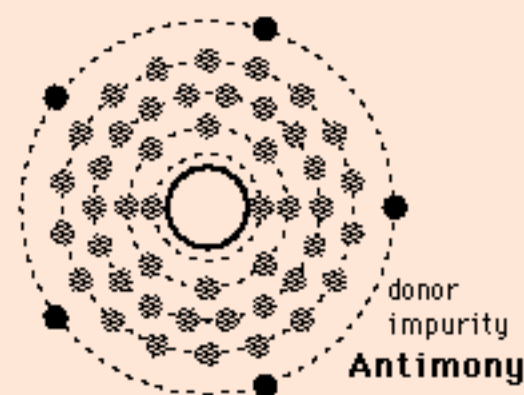
The Doping of Semiconductors

The addition of a small percentage of foreign atoms in the regular [crystal lattice](#) of silicon or germanium produces dramatic changes in their electrical properties, producing [n-type](#) and [p-type](#) semiconductors.

Pentavalent
impurities

(5 [valence electrons](#)) produce
n-type
semiconductors
by contributing
extra electrons.

Antimony
Arsenic
Phosphorous



Trivalent
impurities

(3 valence
electrons) produce
p-type
semiconductors by
producing a "[hole](#)
" or electron
deficiency.

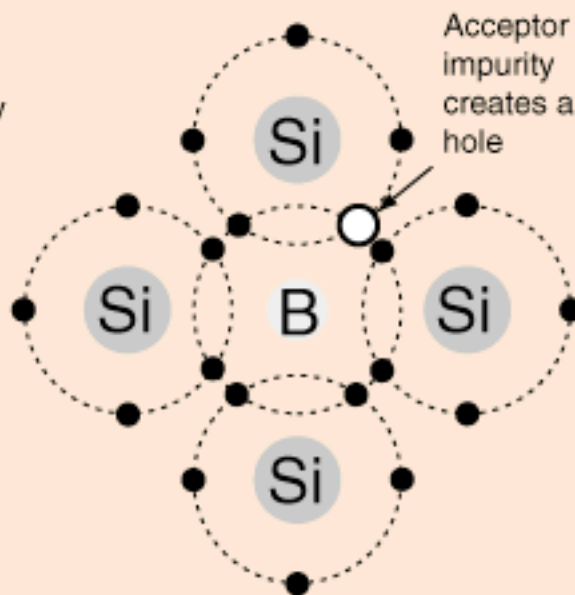
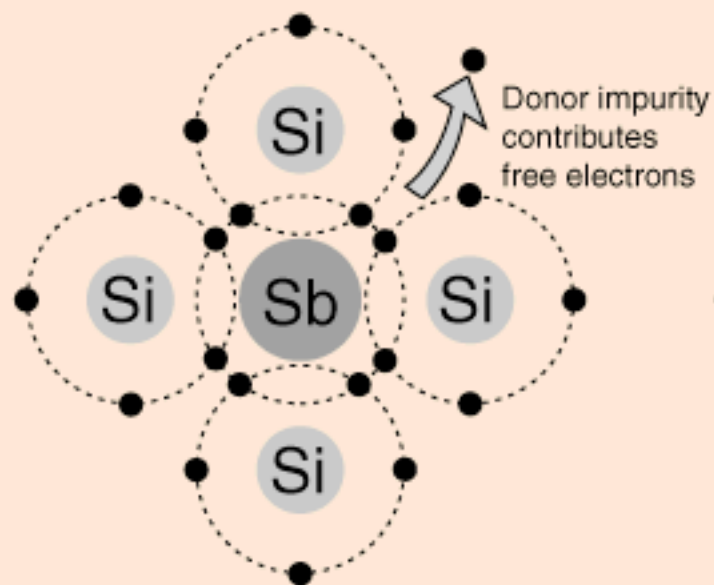
Boron
Aluminum
Gallium



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P- and N- Type Semiconductors

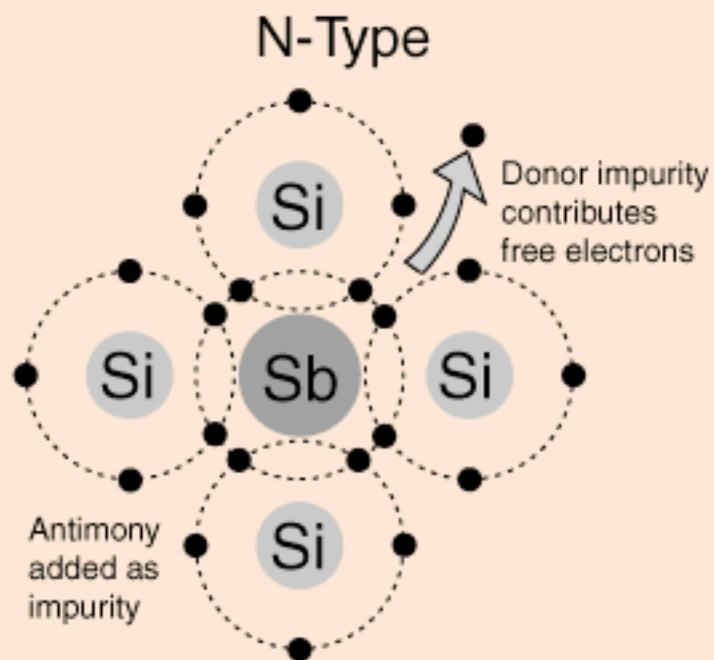


Click on either for further information.

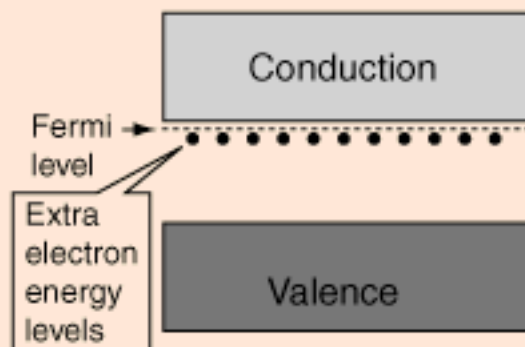
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N-Type Semiconductor



The addition of pentavalent impurities such as antimony, arsenic or phosphorous contributes free electrons, greatly increasing the conductivity of the intrinsic semiconductor. Phosphorous may be added by diffusion of phosphine gas (PH_3).

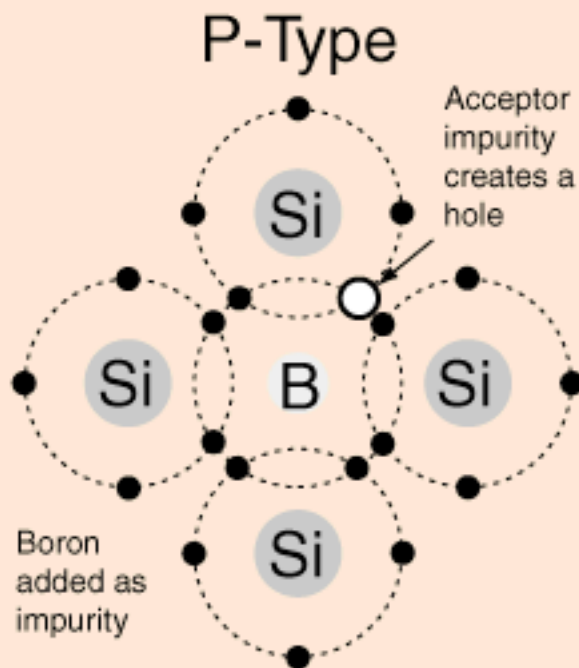
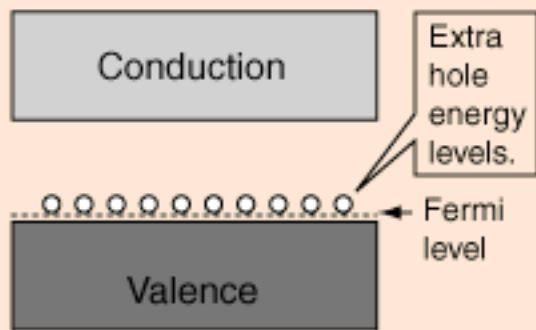


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P-Type Semiconductor

The addition of trivalent [impurities](#) such as boron, aluminum or gallium to an [intrinsic semiconductor](#) creates deficiencies of valence electrons, called "holes". It is typical to use B_2H_6 diborane gas to diffuse boron into the silicon material.

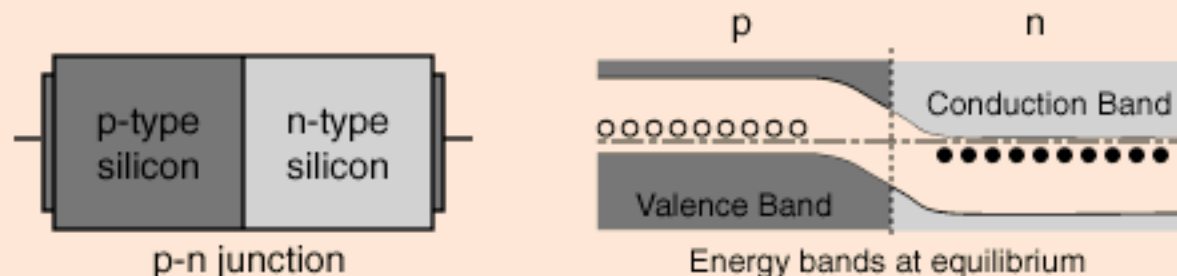


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P-N Junction

One of the crucial keys to [solid state electronics](#) is the nature of the P-N junction. When [p-type](#) and [n-type](#) materials are placed in contact with each other, the junction behaves very differently than either type of material alone. Specifically, current will flow readily in one direction ([forward biased](#)) but not in the other ([reverse biased](#)), creating the basic [diode](#). This non-reversing behavior arises from the nature of the charge transport process in the two types of materials.



The open circles on the left side of the junction above represent "holes" or deficiencies of electrons in the lattice which can act like positive charge carriers. The solid circles on the right of the junction represent the available electrons from the n-type dopant. Near the junction, electrons diffuse across to combine with holes, creating a "[depletion region](#)". The energy level sketch above right is a way to visualize the [equilibrium condition](#) of the P-N junction. The upward direction in the diagram represents increasing electron energy.

[Electron and hole conduction](#)

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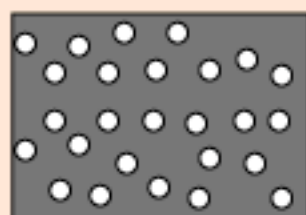
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Depletion Region

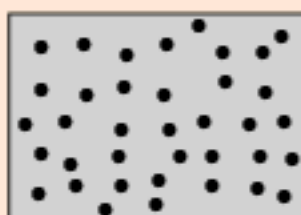
When a [p-n junction](#) is formed, some of the free electrons in the n-region diffuse across the junction and combine with [holes](#) to form negative ions. In so doing they leave behind positive ions at the donor [impurity](#) sites.

p-type
semiconductor
region



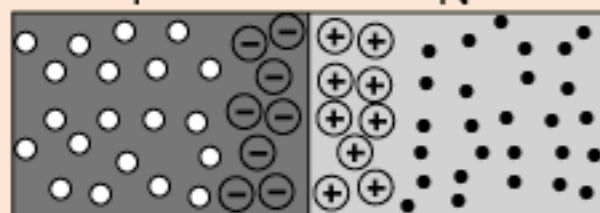
P

n-type
semiconductor
region



N

The combining of electrons and holes in the p-region and the electrons in the n-region near the junction.



depletion
region

- electron
- hole
- ⊖ negative ion from filled hole
- ⊕ positive ion from removed electron

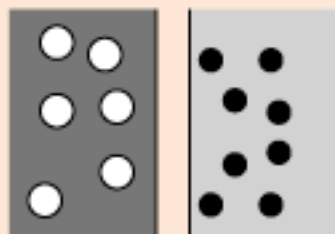
[Show more detail of depletion region.](#)

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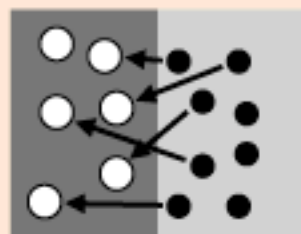
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Depletion Region Details



In the [p-type](#) region there are holes from the acceptor [impurities](#) and in the [n-type](#) region there are extra electrons.



When a [p-n junction](#) is formed, some of the electrons from the n-region which have reached the [conduction band](#) are free to diffuse across the junction and combine with holes.



Filling a hole makes a negative ion and leaves behind a positive ion on the n-side. A space charge builds up, creating a [depletion region](#) which inhibits any further electron transfer unless it is helped by putting a [forward bias](#) on the junction.

● Electron ○ Hole

⊖ Negative ion from filling of p-type vacancy.

⊕ Positive ion from removal of electron from n-type impurity.

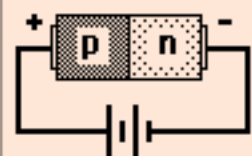
[Show effects of biasing.](#)

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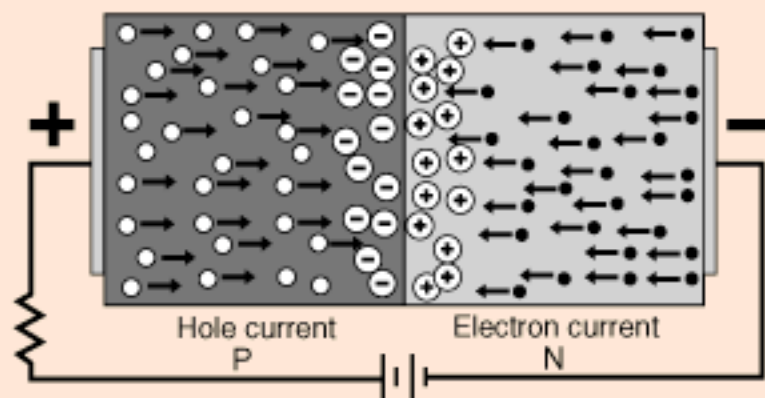
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Forward Biased P-N Junction



Forward biasing the [p-n junction](#) drives holes to the junction from the [p-type](#) material and electrons to the junction from the [n-type](#) material. At the junction the electrons and holes [combine](#) so that a continuous current can be maintained.



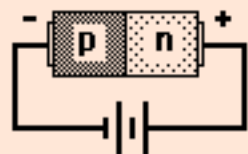
[Show energy bands.](#) [Compare to reverse bias.](#)

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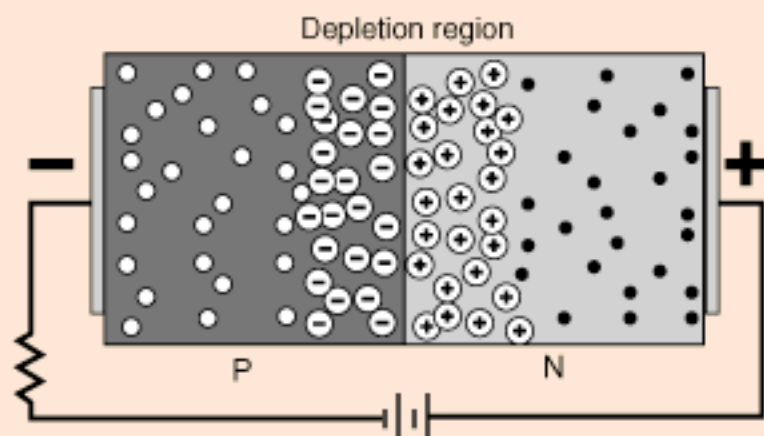
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Reverse Biased P-N Junction



The application of a reverse voltage to the [p-n junction](#) will cause a transient current to flow as both [electrons](#) and [holes](#) are pulled away from the junction. When the potential formed by the widened [depletion layer](#) equals the applied voltage, the current will cease except for the small [thermal current](#).



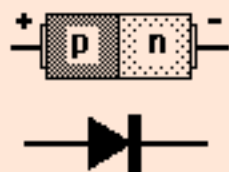
[Show energy bands.](#) [Compare to forward bias.](#)

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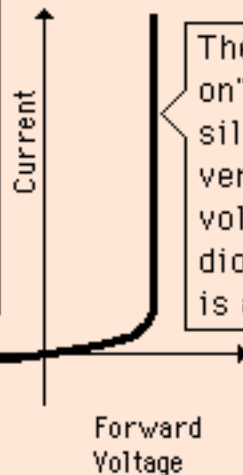
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The P-N Junction Diode



The nature of the [p-n junction](#) is that it will conduct current in the [forward](#) direction but not in the [reverse](#) direction. It is therefore a basic tool for [rectification](#) in the building of DC power supplies.

The reverse current is on the order of 10^{-8} amperes and is almost independent of voltage until the breakdown point is reached.



The forward current "turns on" at about 0.5 volts for a silicon diode and can reach very high currents by 0.7 volts. For a germanium diode the turn-on voltage is about 0.2 volts.

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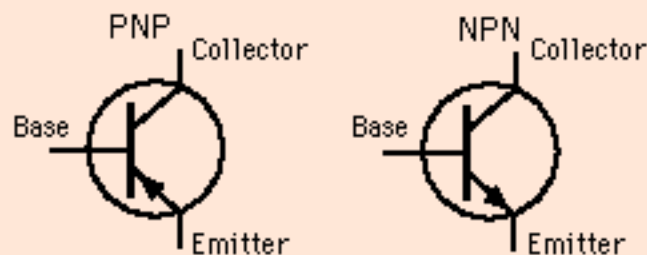
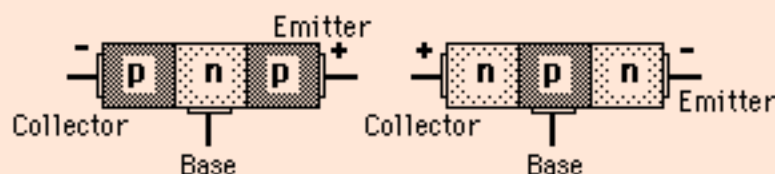
[Diode varieties](#)

[PIN diode](#)

[Step-recovery diode](#)

[Diode applications](#)

The Junction Transistor



A bipolar junction transistor consists of three regions of [doped](#) semiconductors. A small current in the center or base region can be used to control a [larger current](#) flowing between the end regions (emitter and collector). The device can be characterized as a [current amplifier](#), having many applications for [amplification](#) and [switching](#).

[Constraints on operation](#) [Transistor operating conditions](#)

[Varieties of Transistors](#) [Details about conduction in transistors](#)

[Determining collector current](#) [Details about base-emitter junction](#)

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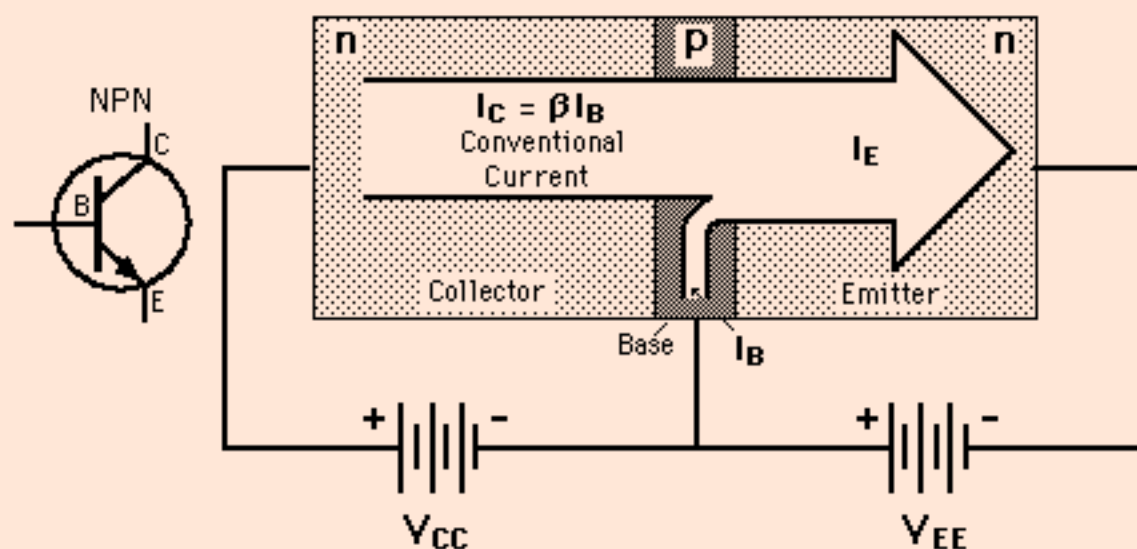
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Transistor as Current Amplifier

The larger [collector current](#) I_C is proportional to the base current I_B according to the relationship $I_C = \beta I_B$, or more precisely it is proportional to the base-emitter voltage V_{BE} . The smaller base current controls the larger collector current, achieving current amplification.

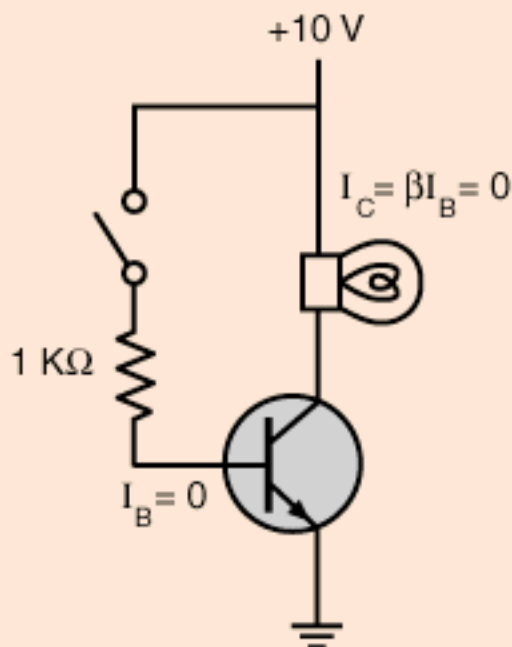

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Reference
[Diefenderfer / Holton](#)
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Transistor Switch Example

The switch is open.

Close the switch



There is no current to the base, so the transistor is in the cut off condition with no collector current. All the voltage drop is across the transistor.

[Transistor operation for switch conditions](#)

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[Horowitz & Hill](#)
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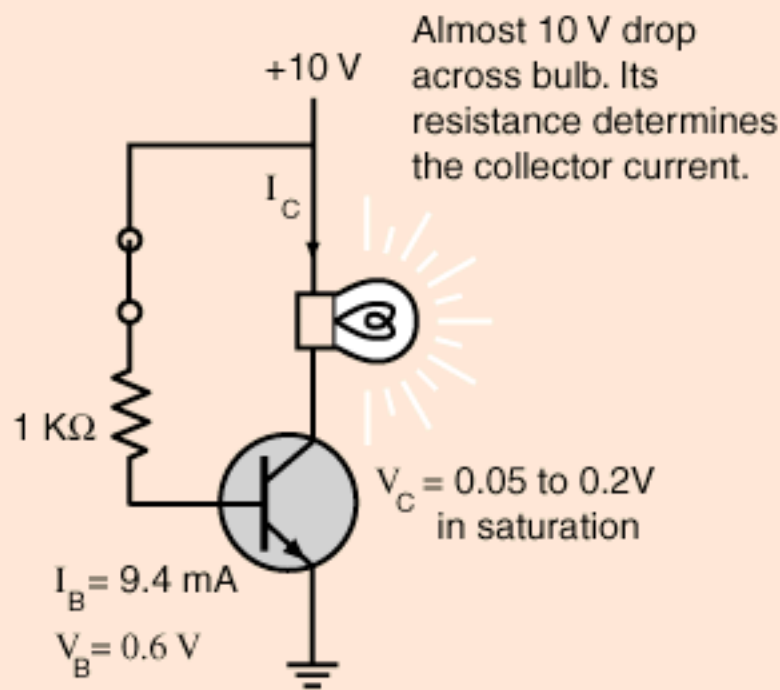
Transistor Switch Example

The switch is closed.

[Open the switch](#)

The base resistor is chosen small enough so that the base current drives the transistor into [saturation](#).

In this example the mechanical switch is used to produce the base current to close the transistor switch to show the principles. In practice, any voltage on the base sufficient to drive the transistor to saturation will close the switch and light the bulb.



[Transistor operation for switch conditions](#)

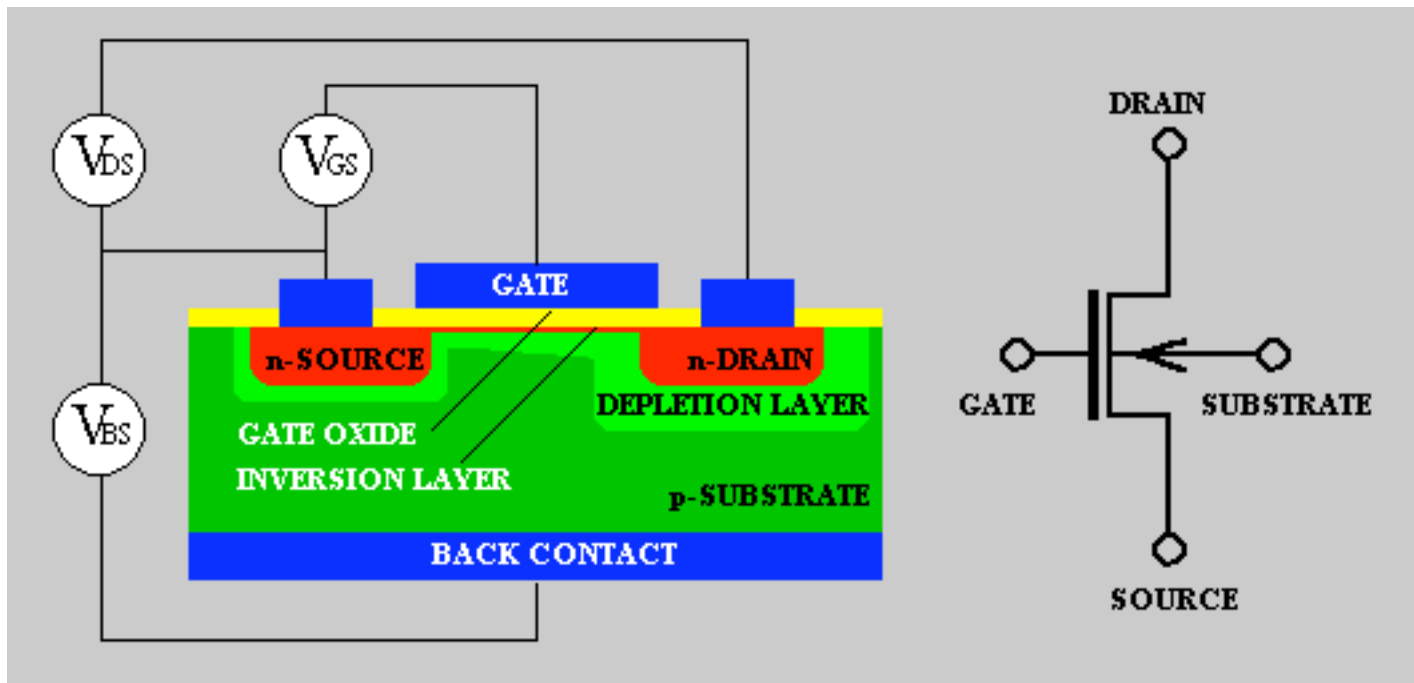
[Transistor Switches](#)

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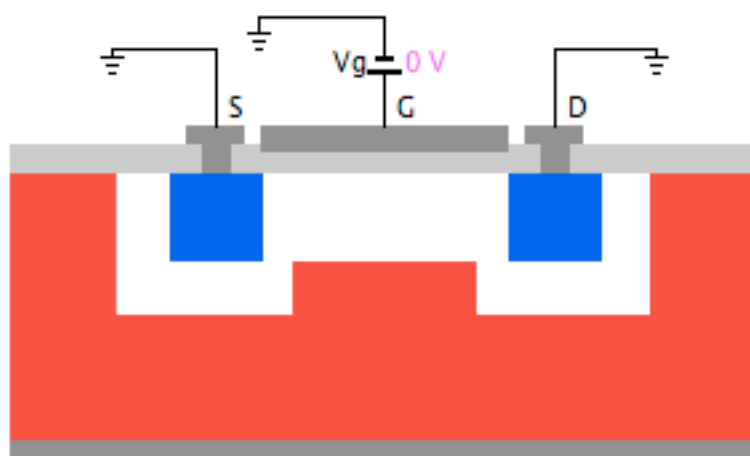
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Reference
[Horowitz & Hill](#)
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from: <http://ece-www.colorado.edu/~bart/book/mosintro.htm>



Enhancement-mode (Normally-off) MOSFET

N-channel

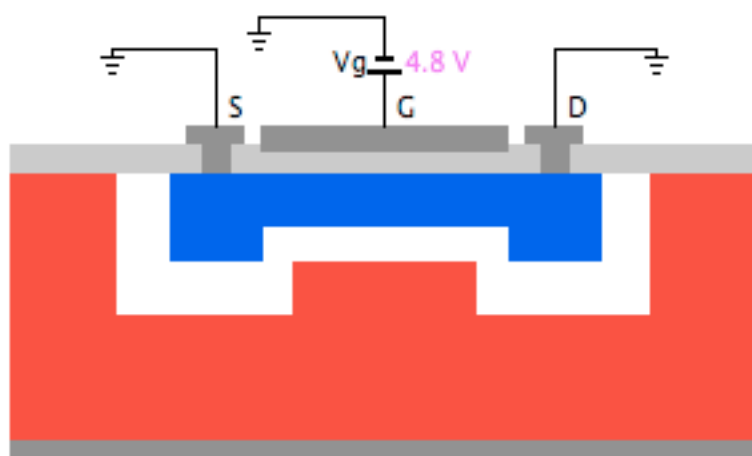
$V_g < V_t$: gate bias is less positive than the threshold voltage.

Not enough electrons and no inversion channel is formed.

V_g ▲
▼

VT = 1.0 V

N-channel



Enhancement-mode (Normally-off) MOSFET

N-channel

$V_g > V_t$: gate bias is more positive than the threshold voltage.
Sufficient electrons accumulate and forms the inversion channel.

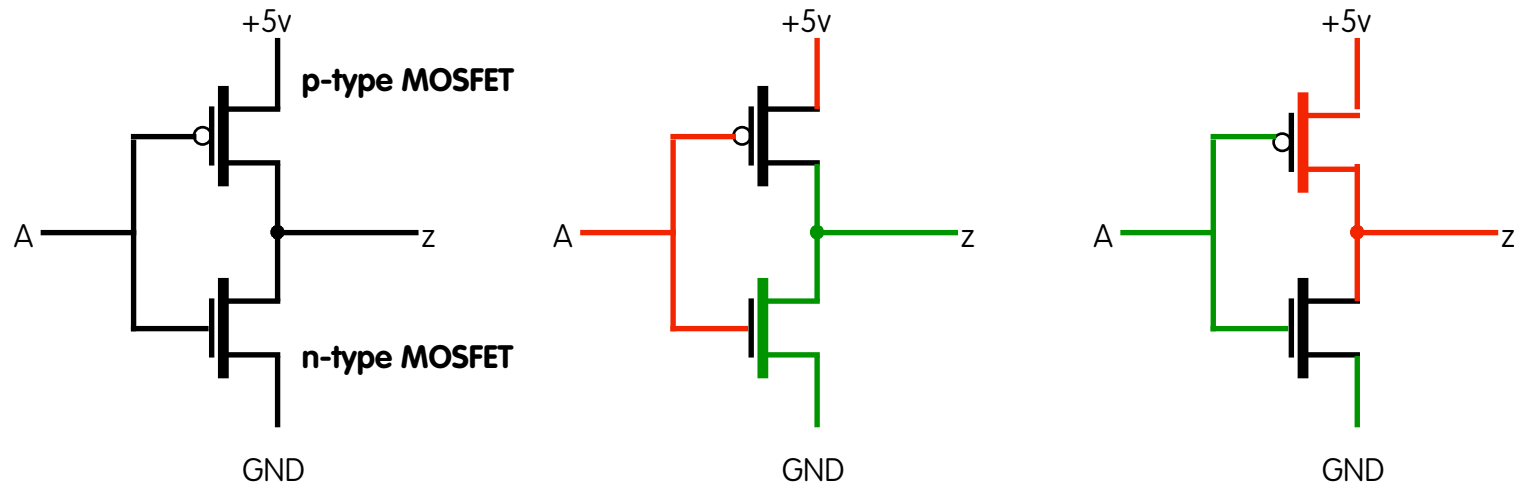
V_g ▲
▼

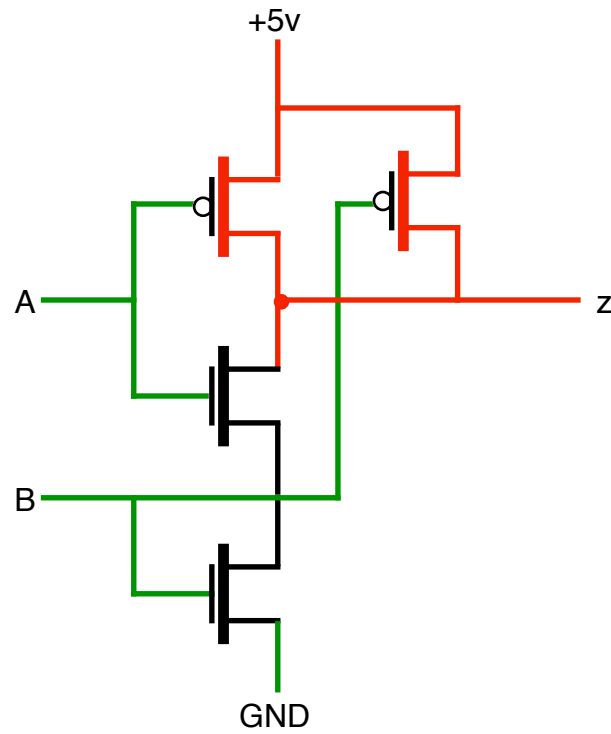
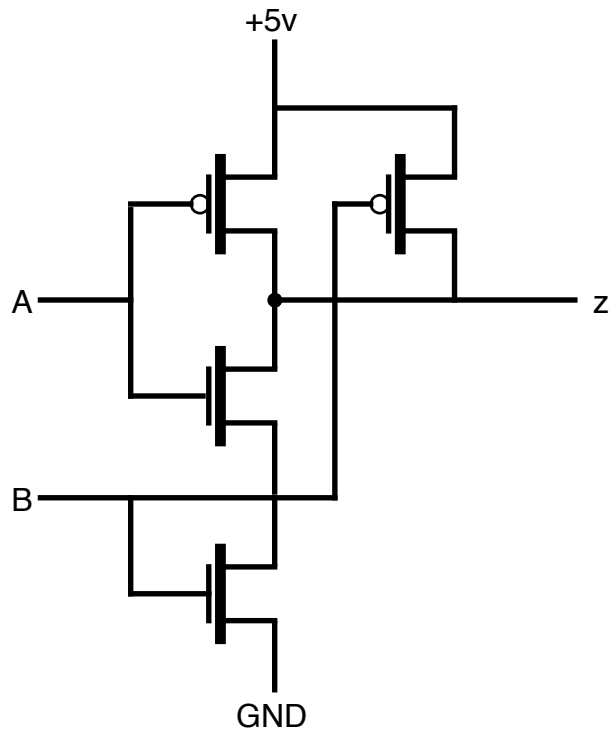
VT = 1.0 V

N-channel

An Inverter using MOSFET

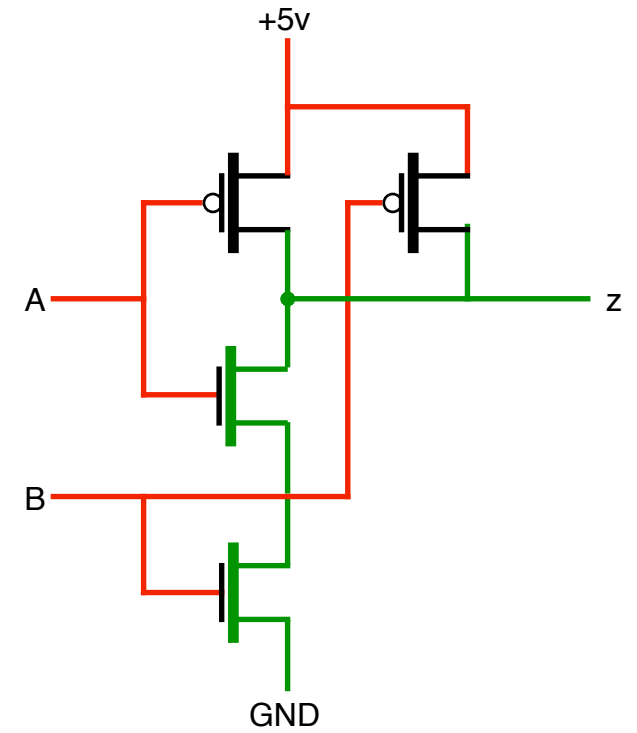
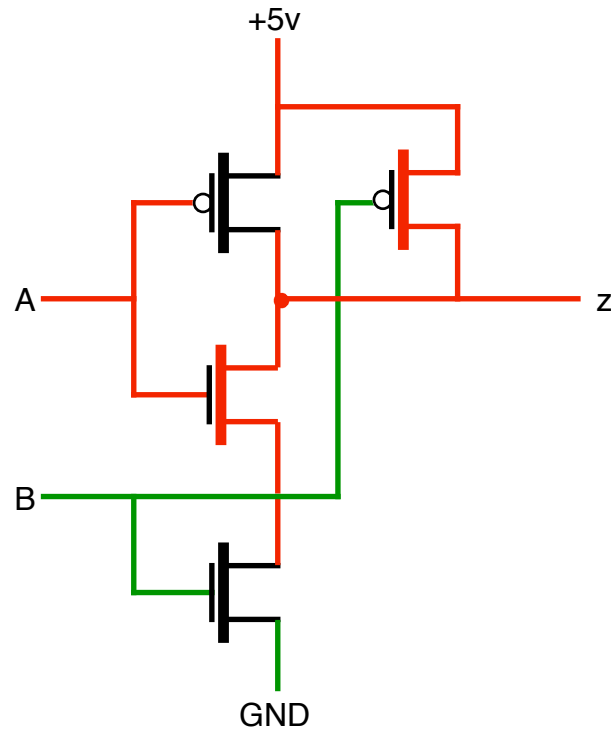
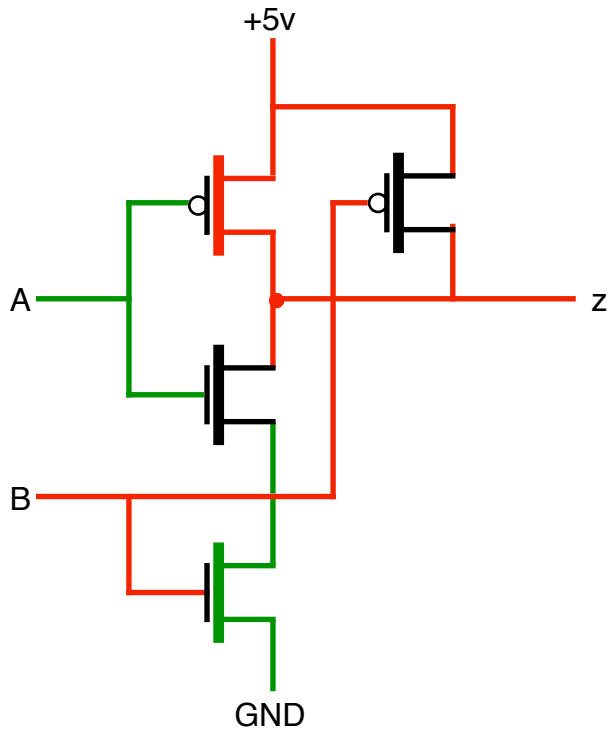
- **CMOS** = complementary metal oxide semiconductor
- **P-type transistor conducts when gate is low**
- **N-type transistor conducts when gate is high**

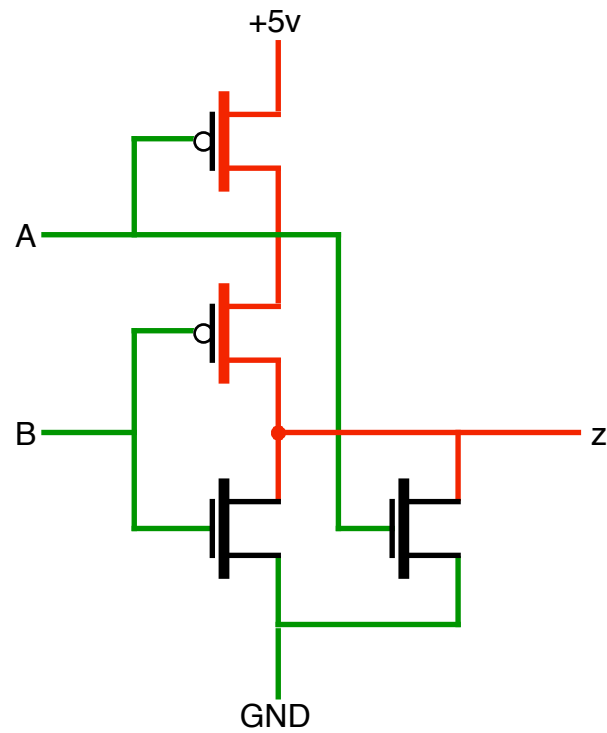
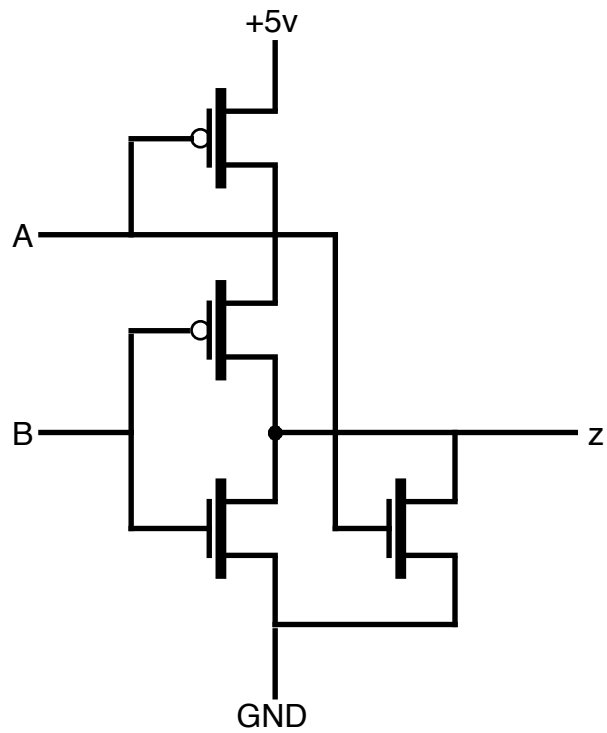




NAND GATE

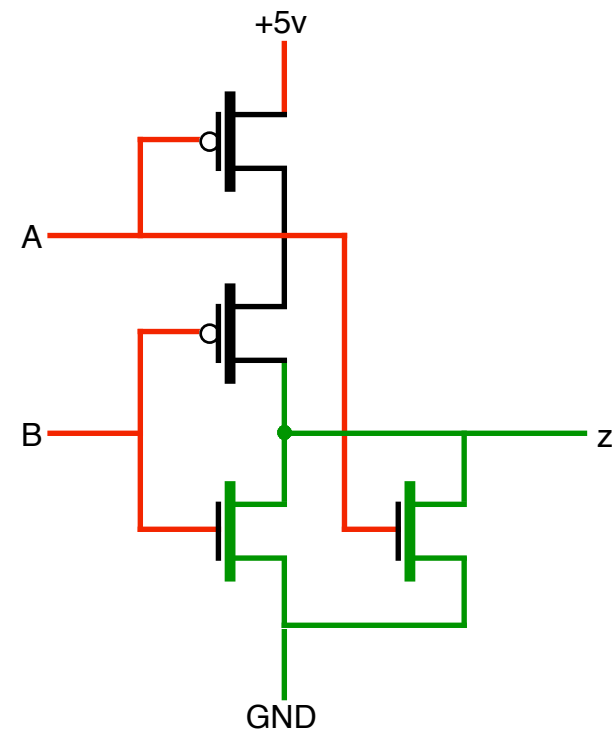
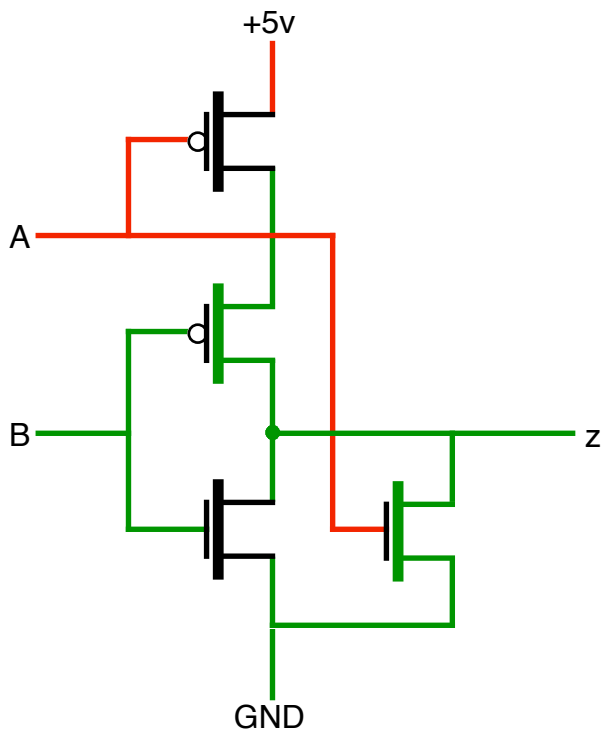
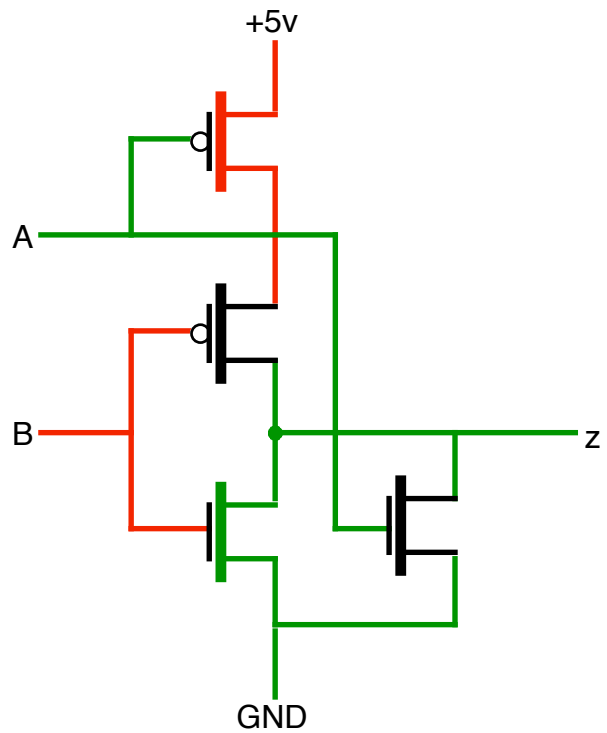
A	B	z
0	0	1
0	1	1
1	0	1
1	1	0





NOR GATE

A	B	z
0	0	1
0	1	0
1	0	0
1	1	0



CMOS Logic vs Bipolar Logic

- **MOSFET transistors are easier to miniaturize**
- **CMOS logic has lower current drain**
- **CMOS logic is easier to manufacture**

NEXT TIME

- Circuits for Addition
- Standard components



References

- **Materials on semiconductors, PN junction and transistors taken from the HyperPhysics web site:**

<<http://hyperphysics.phy-astr.gsu.edu/hbase/hframe.html>>