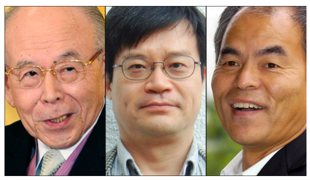
Band gaps and LEDs

The Nobel Prize in Physics 2014 was awarded jointly to Isamu Akasaki, Hiroshi Amano and Shuji Nakamura:

"for the invention of efficient blue light-emitting diodes which has enabled bright and energy-saving white light sources"



Day 36, Phys 2130
Questions? Bonds Bands and LEDs

Next up: band structure/ LEDs, Semiconductors
Tutorial?

Laser-- Light Amplification by Stimulated Emission of Radiation
lots of cloning of photons- LOTS of identical light.

Figure out conditions for l.a.s.e.r.
Important roles all played by:

- absorption
- stimulated emission
- spontaneous emission

Requires
1) more atoms in an upper level than a lower one
("population inversion")
(hard part of making laser)

2) Method of re-cycling photons to clone more times ("feedback"
(mirrors)

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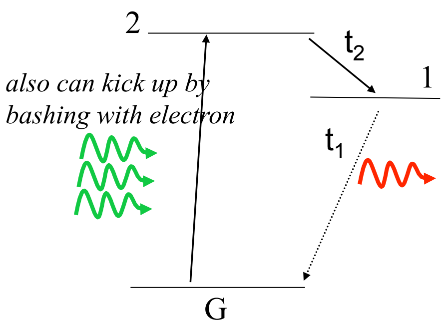
Getting a population inversion

need at least one more energy level involved.
Trick: use a second color of light
(why two levels (one color) won't work as HW problem (maybe))



"pumping" process to produce population inversion

To create population inversion between G and level 1 would need:

a. time spent in level 2 (t_2) before spontaneously jumping to 1 is long and time spent in level 1 (t_1) before jumping to G is short.

b. $t_1=t_2$

c. t_2 short, t_1 long

d. does not matter

ans. c. show on sim

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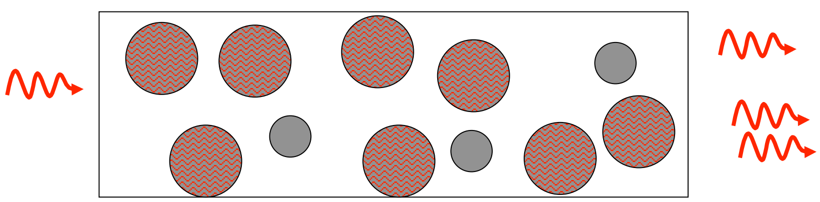
Amplifying light:

Population inversion⇒ give amplification of photons from left.



But much easier if not all light escapes.
Reuse. Use mirror to reflect the light. (sim)

If 3 in becomes 6 at end, What does 6 become?

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Laser Gain

One photon becomes two,
2 becomes 4,
4 becomes 8,
8 sixteen.. Etc…

Do you know the words of Al Bartlett? (the lack of understanding the exponential function is the great failure of the human race)

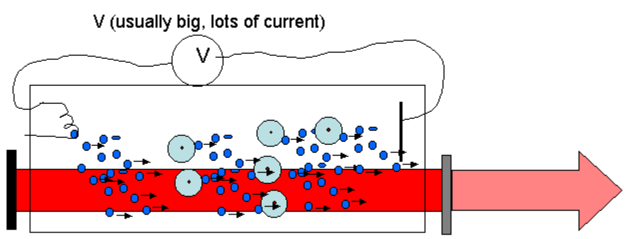
May be bad for human population. Good for photon population.

Number of photons between the mirrors, $n = n_0 e^{Gt}$

"gain" G >0 exponential increase.

Very quickly increases until nearly all input power is going into laser light. Use *partially* reflective mirror on one end.
Let some of laser light inside leak out --- that's what we see. 6

Two types of lasers: He-Ne and Diode



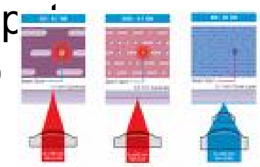
Gas laser like Helium Neon.
Just like neon sign with helium and neon mixture in it and mirrors on end.

Diode laser-
Same basic idea, but light from diode at P-N diode junction. Mirrors on it. 7

Many applications of lasers

- High energy small area:
  - Cutting: surgery, laser welding
  - "communication" (and weapons)

- Focus light into extremely small sp
  - (diffraction limit, because in phase!)
  - CDs, DVDs, …



- Collimated beam
  - Tracking, leveling,
- Pure color
  - LIDAR….

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<u>End of general atomic spectra.</u>

- Understanding of what has been observed, how implies electrons in atoms only in certain energy levels.
- When hop from higher to lower give off light.
- Applications: neon lights, lasers

Questions?

<u>Next:</u>

Band structure / LEDs

Build from single atom / energy levels to more complex
what happens to energy levels
when atoms interact

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Bonding

- Main ideas:

1. involves outermost electrons and their wave functions

2. interference of wave functions
(one wave function from each atom) that produces situation where atoms want to stick together.

3. degree of sharing of an electron across 2 or more atoms determines the type of bond

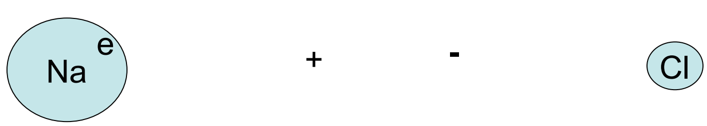
Degree of sharing of electron →

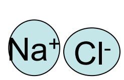
Ionic	Covalent	Metallic
electron completely transferred from one atom to the other	electron equally shared between two adjacent atoms	electron shared between all atoms in solid
$Li^+ F^-$	H_2	Solid Lead

Ionic Bond (NaCl)

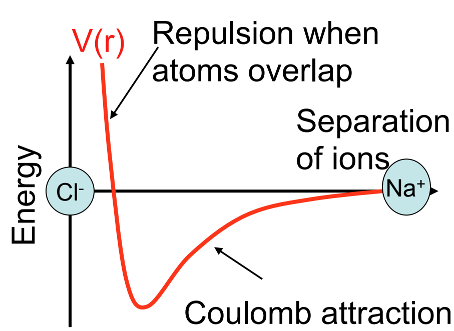
Na (outer shell $3s^1$)
Has one weakly bound electron
Low ionization energy

Cl (outer shell $3s^23p^5$)
Needs one electron to fill shell
Strong electron affinity





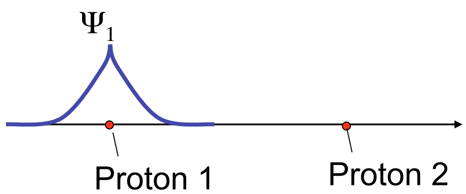
Attracted by coulomb attraction



Covalent Bond

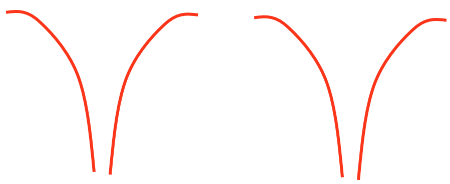
Sharing of an electron… look at example H_2^+
(2 protons (H nuclei), 1 electron)

Protons far apart …



Wave function if electron bound to proton 1

Potential energy curve



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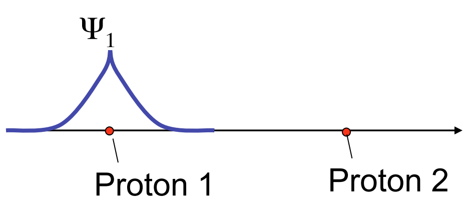

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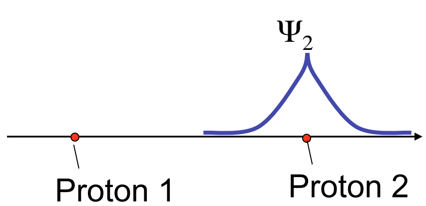


Wave function if electron bound to proton 2

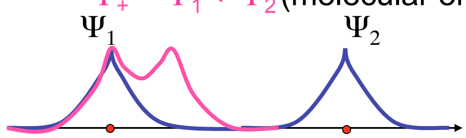
Covalent Bond

Sharing of an electron… look at example H_2^+

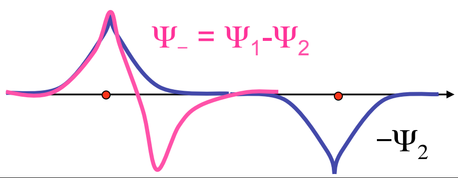
(2 protons (H nuclei), 1 electron)

If Ψ_1 and Ψ_2 are both valid solutions,
then **any combination** is also valid solution.

$\Psi_+ = \Psi_1 + \Psi_2$ (molecular orbitals)

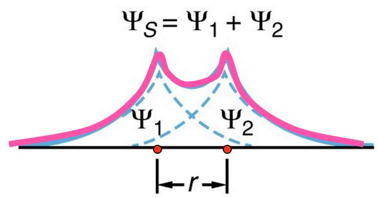


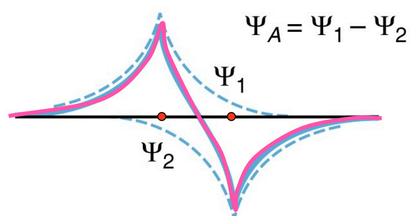
Add solutions (symmetric):
$\Psi_+ = \Psi_1 + \Psi_2$ and



Subtract solutions (antisymmetric):
$\Psi_- = \Psi_1 - \Psi_2$

Look at what happens to these wave functions as bring protons closer…



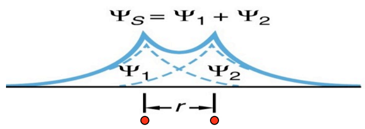


Visualize how electron cloud is distributed… for which wave function would this cloud distribution tend to keep protons together? (bind atoms?) … what is your reasoning?

a. Ψ_S or Ψ_+

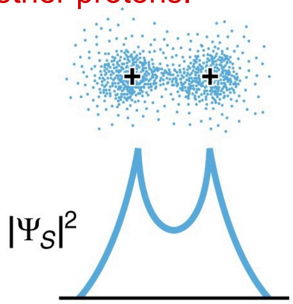
b. Ψ_A or Ψ_-

Look at what happens to these wave functions as bring protons closer…



Ψ_+ puts electron density between protons .. glues together protons.

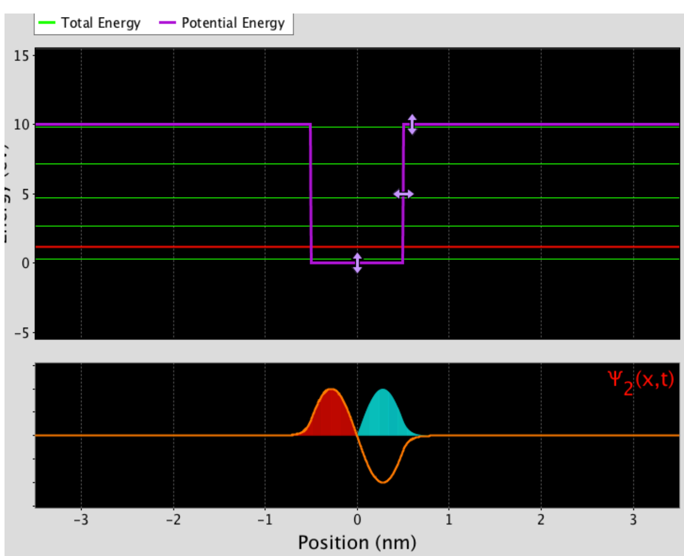
between protons … protons repel (not stable)



Bonding Orbital

Antibonding Orbital

Quantum Bound State Sim



Big Picture. ***Now almost infinite power!***

Know how to predict **everything** about behavior of atoms and electrons or anything made out of them:

1. Write down all contributions to potential energy, includes e-e, nuc.-nuc., nuc.-e for all electrons and nuclei.

$q_1q_2/r_{1-2} + q_2q_3/r_{1-3} + q_{nuc1}q_{nuc2}/r_{qnuc1-qnuc2} + q_1q_{nuc1}/r_{1-nuc1} +$

one spin up and one down electron per state req....

(plus little terms involving spin, magnetism, applied voltage)

2. Plug potential energy into Schrod. eq., add boundary. cond.

3. Solve for wave function $\Psi_{elec1, elec2, nuc1, nuc2, ...}(r_1, r_2, r_{nuc1}, ...)$

get energy levels for system

calculate/predict everything there is to know!!

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Demo

- Which is more reactive?
- He_2
- H_2

Limitations of Schrodinger

- With three objects (1 nuclei + 2 electrons) solving eq. very hard.
- Gets much harder with each increment in number of electrons and nuclei !!

Give up on solving S. E. exactly--

Use various models and approximations.

Not perfect but very useful, tell a lot.

(lots of room for cleverness, creativity, intuition)

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How does atom-atom interaction lead to band structure?

1. Energy levels and spacings in atoms ⇒ molecules ⇒ solids
2. How energy levels determine how electrons move. Insulators, conductors, semiconductors.
3. Using this physics for nifty stuff like (old) copying machines, diodes and transistors (all electronics), light-emitting diodes.

Spacing of gap to the next higher, open energy level for electron is the critical feature.

Small, large, in middle compared to kT (~1/40 eV)?

What happens to energy levels as put bunch of atoms together?

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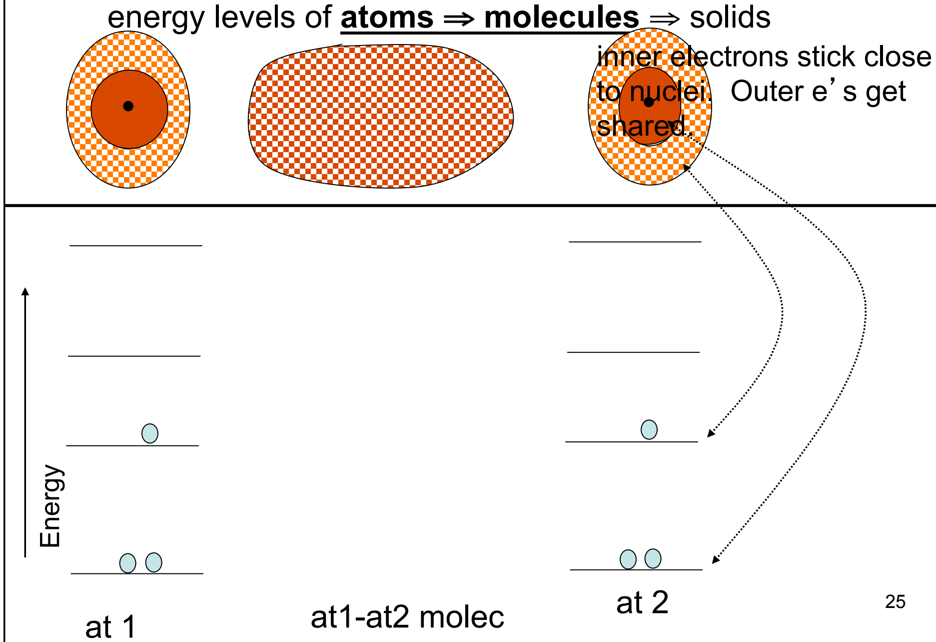
QM of electrical conduction

multielectron atoms

energy levels of **atoms ⇒ molecules** ⇒ solids

inner electrons stick close to nuclei. Outer e's get shared.



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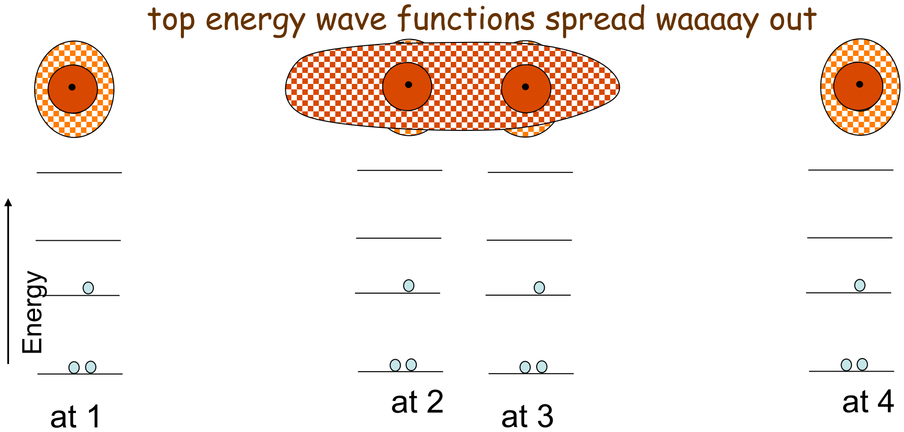
QM of electrical conduction

energy levels of **atoms ⇒ molecules** ⇒ solids

top energy wave functions spread waaaay out



many levels!

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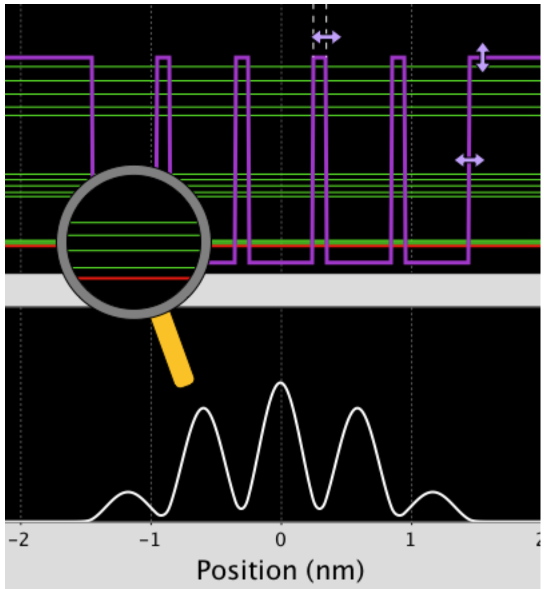
Bound State Sim.. Many Wells



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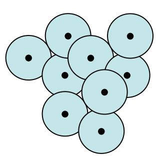
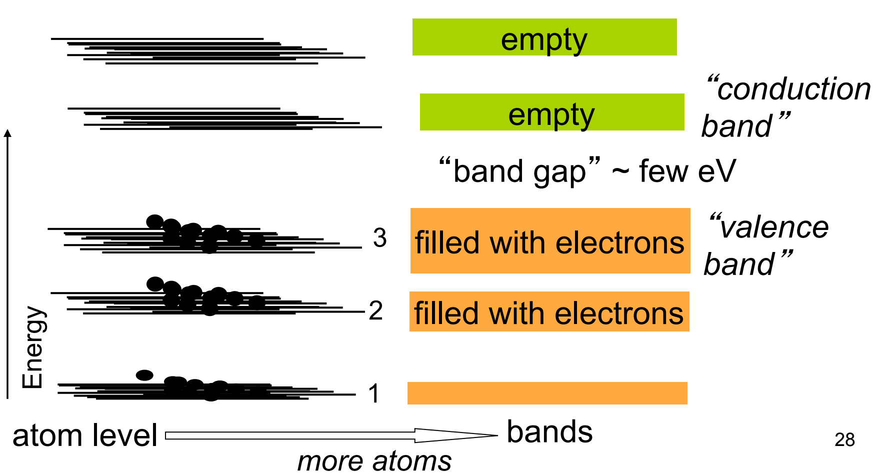
In solid, `10^{22} atoms/cm^3, many!! electrons, and levels



countless levels smeared together, individual levels indistinguishable. ⇒"bands" of levels. Each level filled with 2 electrons until run out.



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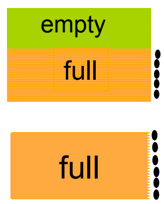
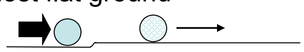
conductor- empty levels very close

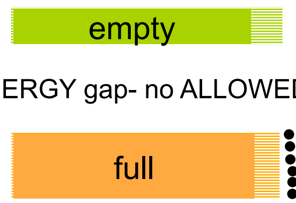


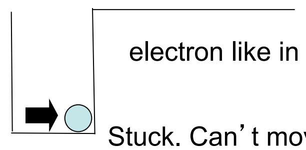
electron like ball rolling on almost flat ground



move easily

insulator- big jump to empties.

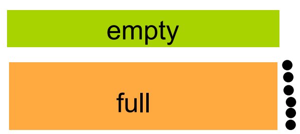


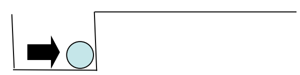


electron like in pit.

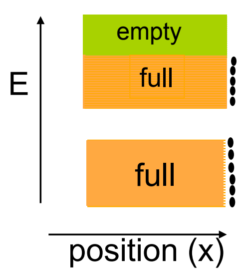
Stuck. Can't move without big boost.

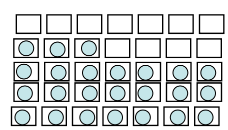
semiconductor-- half way in between. Little gap to empty levels, shallow pit.



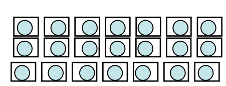


The seating analogy

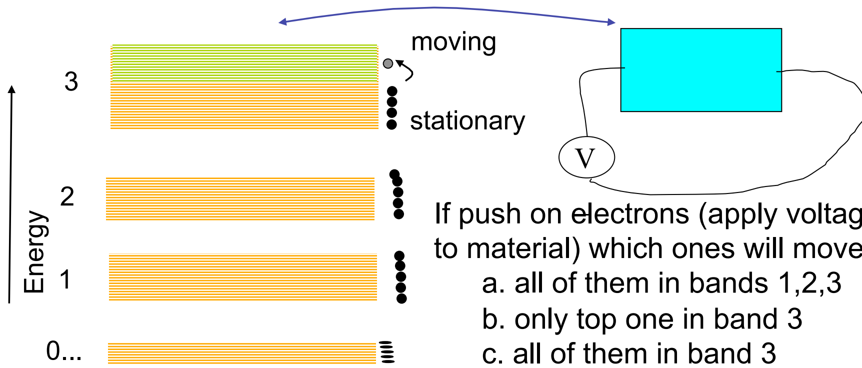




How about these e's?



Easy to push to right?



If push on electrons (apply voltage to material) which ones will move?

a. all of them in bands 1,2,3
b. only top one in band 3
c. all of them in band 3
d. only the top few in band three
e. none of them will move

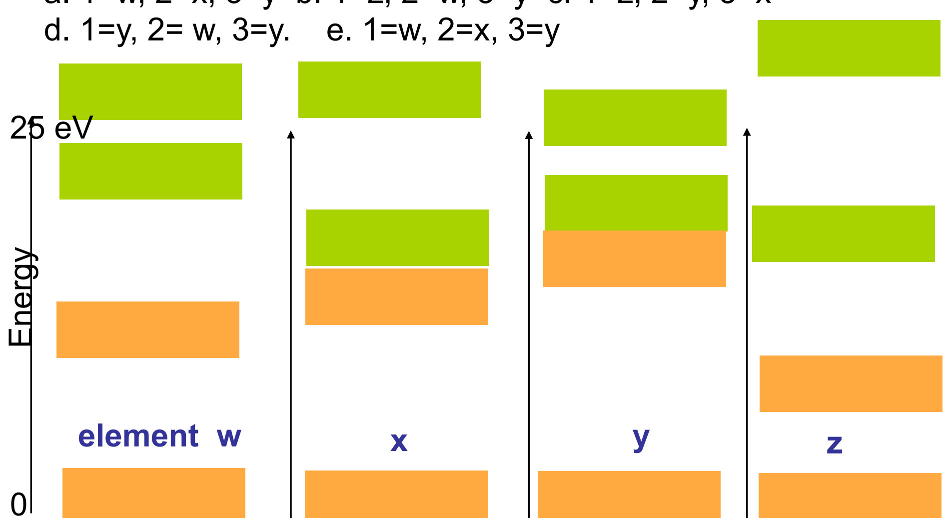
d. only the top few in band 3.
The others have no higher level they can move into, all filled with other electrons. *After top one has gotten pushed up, is room to move next one below it. so include those within ~kT =1/40 eV of top (room temp). Band gaps and widths ~ eVs. Small fraction, still big #.*

Which band structure goes with which material?
(be ready to give reasoning)

empty
full

1. Diamond **2. copper** **3. germanium (poor conductor)**

a. 1=w, 2=x, 3=y b. 1=z, 2=w, 3=y c. 1=z, 2=y, 3=x
d. 1=y, 2= w, 3=y. e. 1=w, 2=x, 3=y



only top 2 filled and lowest 2 empty bands shown

Which band structure goes with which material?

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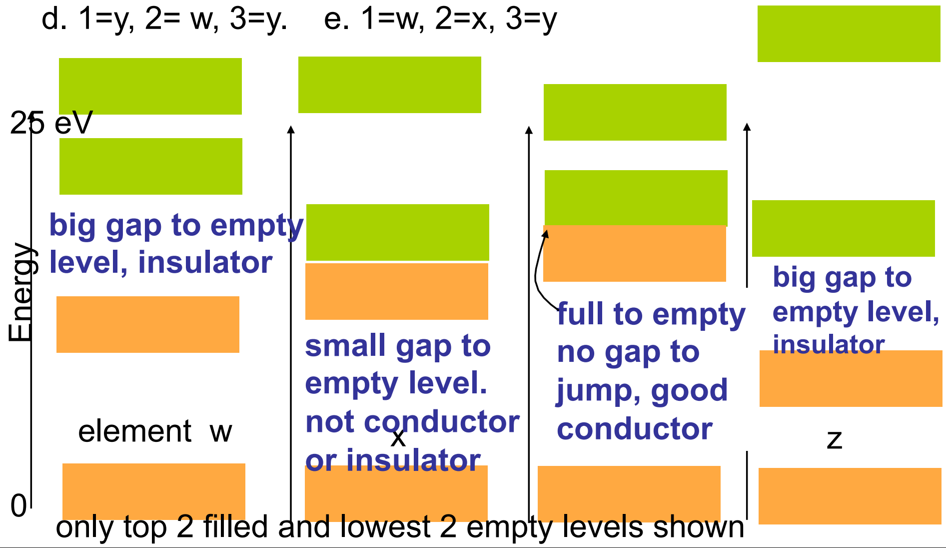
full

1. Diamond 2. copper 3. germanium (poor conductor)

a. 1=w, 2=x, 3=y. b. 1=z, 2=w, 3=y. c. 1=z, 2=y, 3=x
d. 1=y, 2= w, 3=y. e. 1=w, 2=x, 3=y



Which band structure goes with which material?

empty
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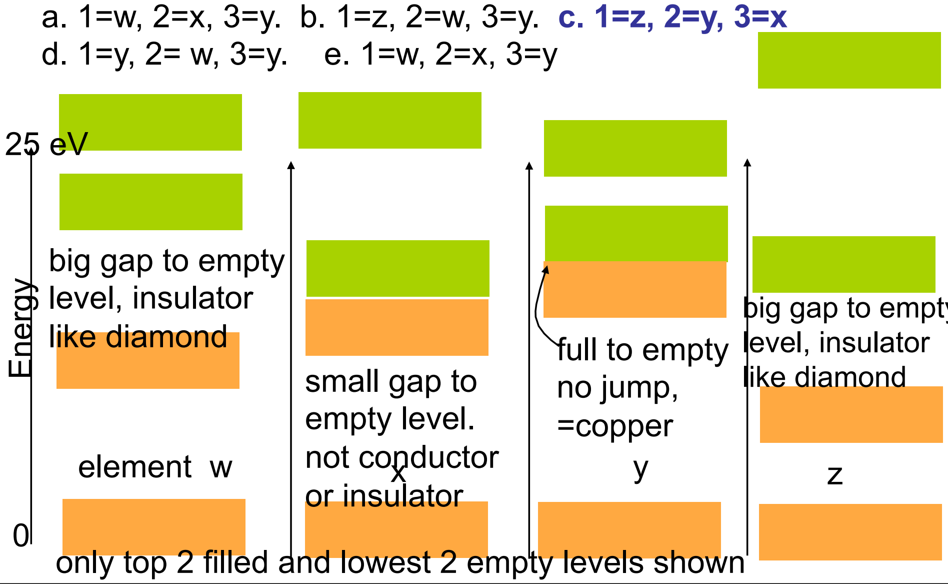
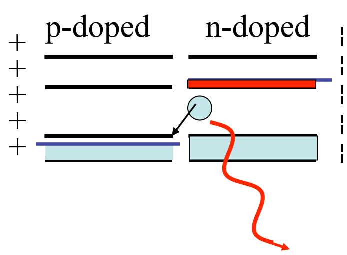
1. Diamond 2. copper 3. germanium (poor conductor)

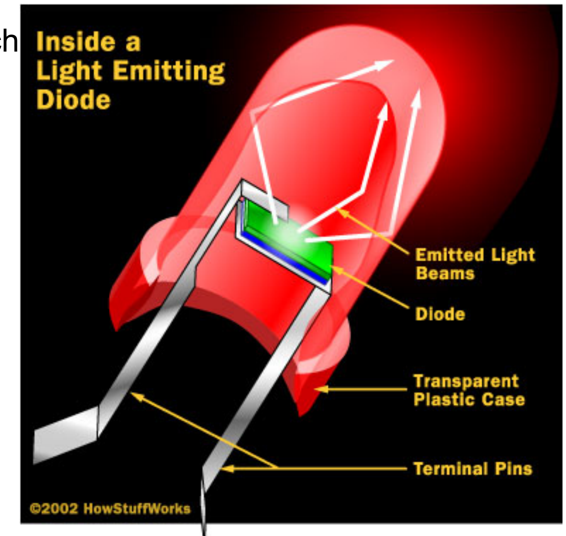
a. 1=w, 2=x, 3=y. b. 1=z, 2=w, 3=y. **c. 1=z, 2=y, 3=x**
d. 1=y, 2= w, 3=y. e. 1=w, 2=x, 3=y



LEDs -- don't burn out, high efficiency. Stoplights, bike lights, fancy flashlights.

Really good LEDs reach laser conditions--
diode lasers





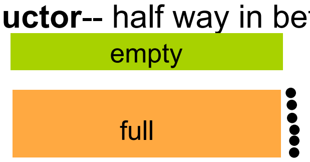
http://www.howstuffworks.com/index.htm

Insulators and conductors

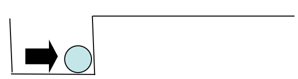
Good in wires, electricity for lights and heating, electric motors, telegraph (I=V/R stuff).

For more interesting electrical stuff need more control- small currents &voltages control higher powers ("nonlinear circuit elements").

Semiconductor-- half way in between. Little gap to empty levels.



how many have class on semicond?



sensitive enough so people can affect conductivity of material

What are possible ways could get electron to higher empty level (out of pit), so could move to conduct electricity?
Discuss as many as can think of that are practical.

n.b. Applying a voltage across (battery) will not work… why? Think about voltage /electron…. (how much V how many e's…?)