

# Solid State Physics (PHY210)

**Vorlesung / Lectures:** Wednesday 13h00 – 15h45

**Raum / Room:** Y36-K-08

<http://www.physik.uzh.ch/lectures/fkp/>

**Exam: Oral (most likely 9-10<sup>th</sup> of June – details to be announced)**

Johan Chang

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**Übungen / Exercise class:** Fridays 15h00 – 15h45

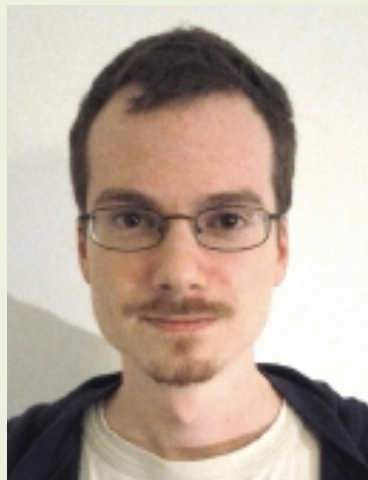
**Raum / Room:** Y36-K-08

Daniel Destraz

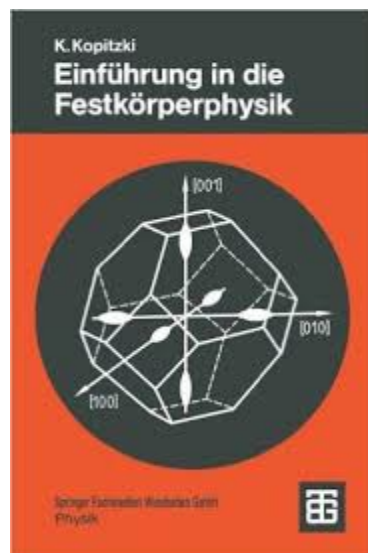
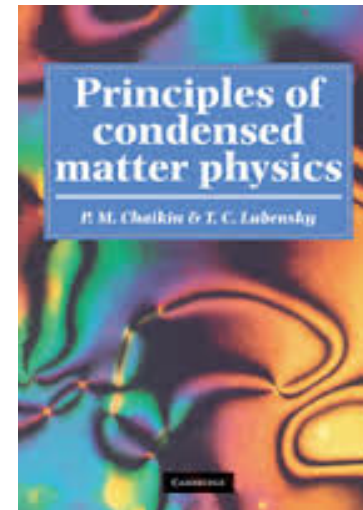
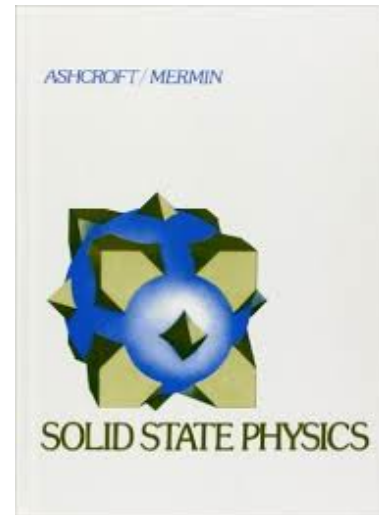
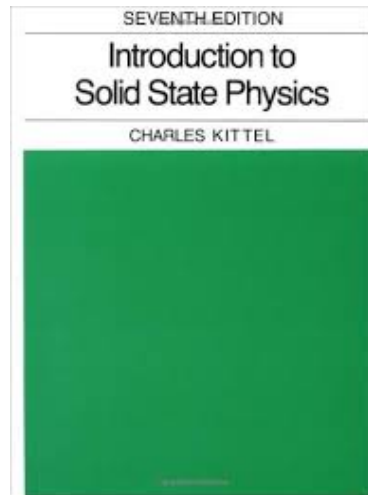
[destraz@physik.uzh.ch](mailto:destraz@physik.uzh.ch)

Stefan Holenstein

[stefan.holenstein@psi.ch](mailto:stefan.holenstein@psi.ch)



# Literature



# Google - power

The image shows a Google search interface. The search bar contains the text "kittel solid state physics". Below the search bar, there are navigation tabs for "All", "Images", "News", "Books", "Videos", "More", and "Search tools". The "All" tab is selected. The search results show "About 239.000 results (0,50 seconds)".

Three search results are visible:

- Introduction to Solid State Physics : Charles Kittel-8th ...**  
<https://archive.org/details/IntroductionToSolidStatePhysics>  
Perfect pedagogical introduction to Solid State Physics.
- Wiley: Introduction to Solid State Physics, 8th Edition ...**  
[www.wiley.com](http://www.wiley.com) > Home > Physics & Astronomy > Condensed Matter  
US\$ 203,95  
Introduction to Solid State Physics, 8th Edition (EHEP000803) cover image ... Charles Kittel did his undergraduate work in physics at M.I.T and at the Cavendish ...
- Introduction to Solid State Physics: Charles Kittel ...**  
[www.amazon.com](http://www.amazon.com) > Books > Science & Math > Physics  
Buy Introduction to Solid State Physics on Amazon.com ✓ FREE SHIPPING on qualified orders.

The main search result is a book preview for "Introduction to solid state physics" by Charles Kittel. The preview includes:

- Book title: **Introduction to solid state physics**
- Author: Book by Charles Kittel
- Rating: 3,5/5 · Goodreads
- Description: Introduction to Solid State Physics, 6th Edition The most widely used introduction to solid state physics in the world--now published in 15 languages. ...
- Source: Google Books
- Originally published: 1991
- Author: Charles Kittel

Below the book preview, there is a section titled "People also search for" with two categories of book covers:

- Charles Kittel books:** Thermal Physics, Quantum Theory of Solids, Elementary Statistical Physics.
- Other books:** Theory of Solids, Solid State Physics, Quantum Theory of Solids, Solid State Physics, Quantum Theory of Solids.

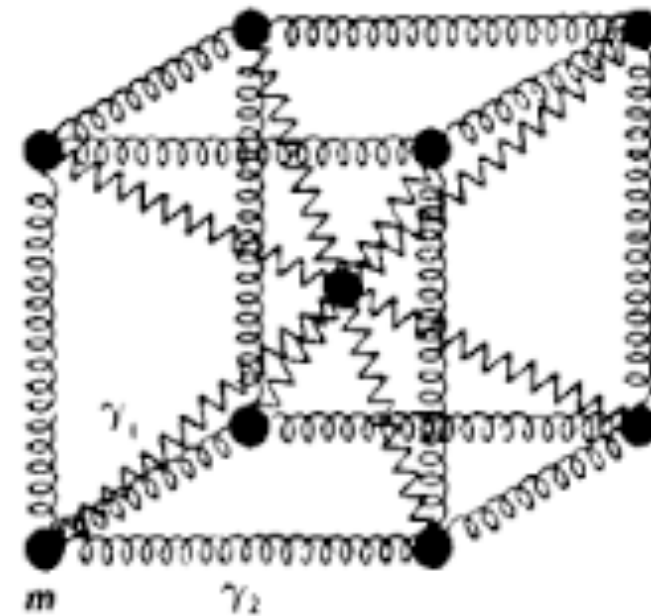
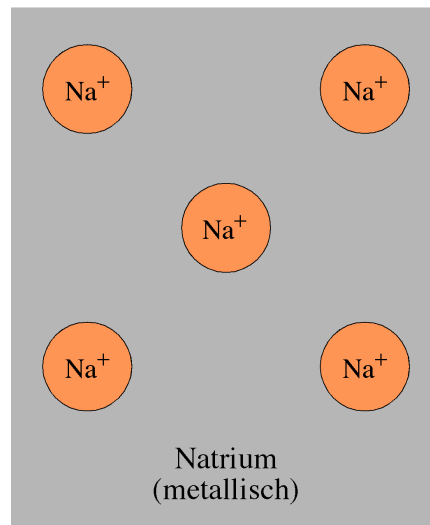
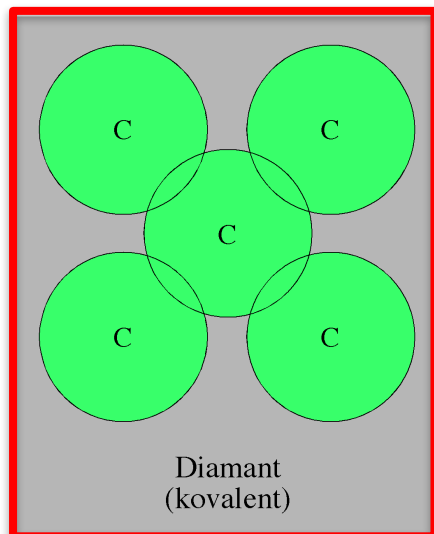
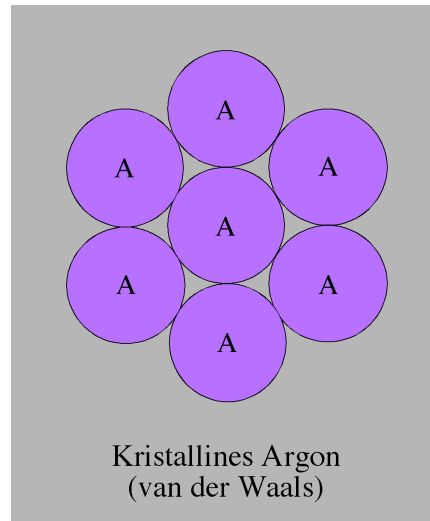
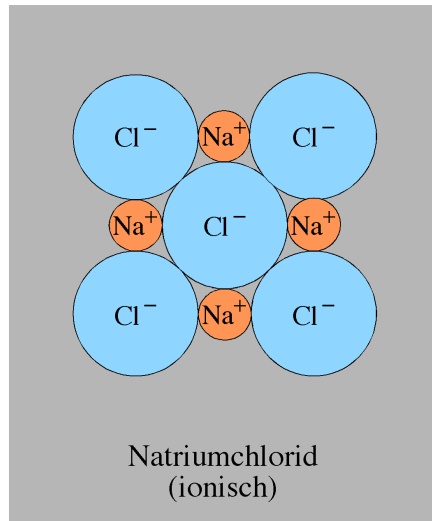
A "Feedback" link is located at the bottom right of the book preview section.

Last weeks exercise 2 solved in chapter 3 (page 71 in my version)  
Last weeks exercise 3 is exercise 5 of chapter 3 in Kittel. Solution can actually be googled.  
(Last weeks exercise 1a,b was basically solved during the lecture.)

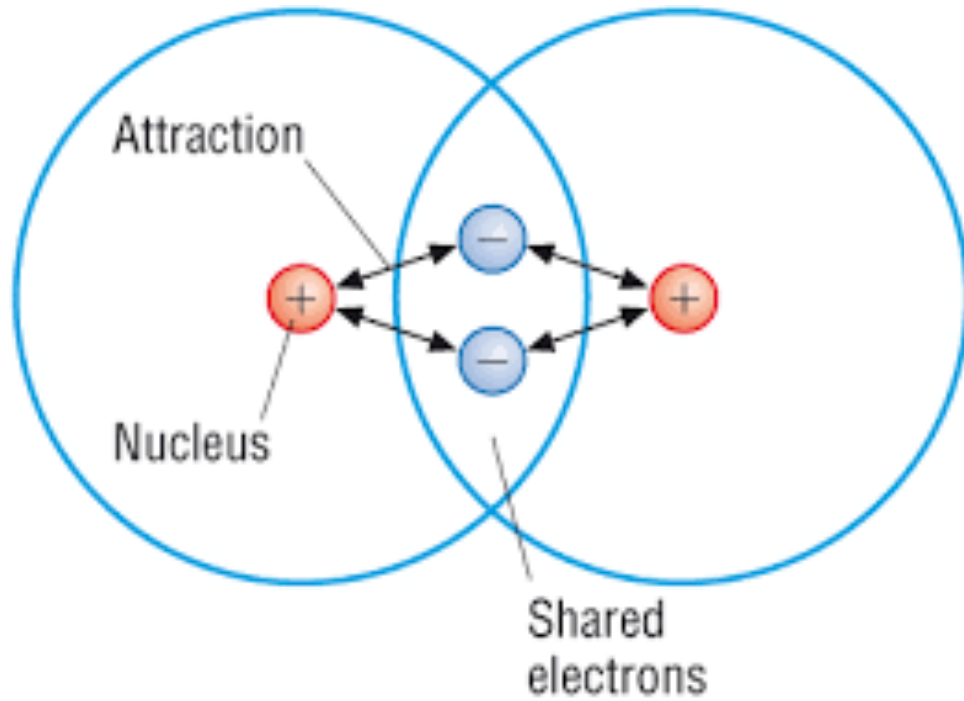
# Today's lecture

## Crystal binding mechanisms

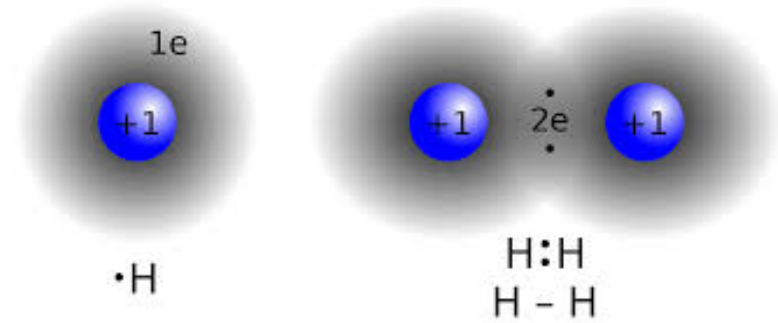
## Lattice vibrations



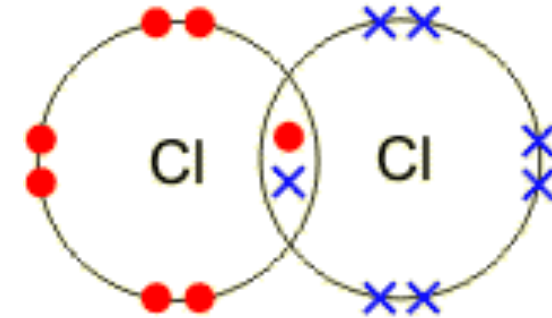
# Covalent Crystals



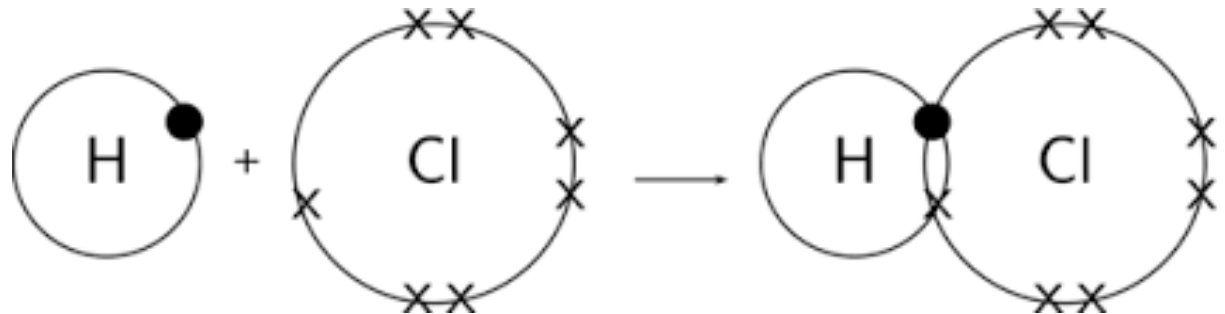
Example 1



Example 2



Example 3



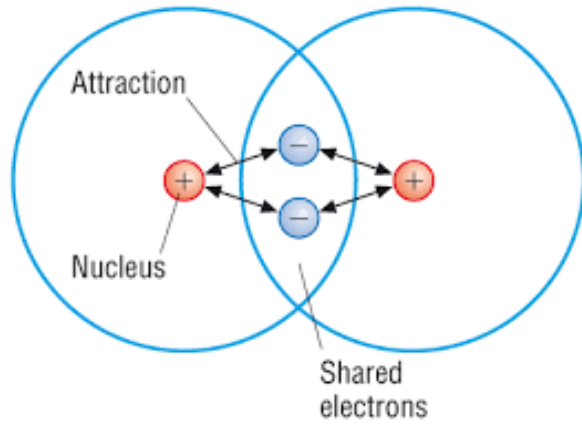
# Periodic table

**Periodic Table of the Elements**

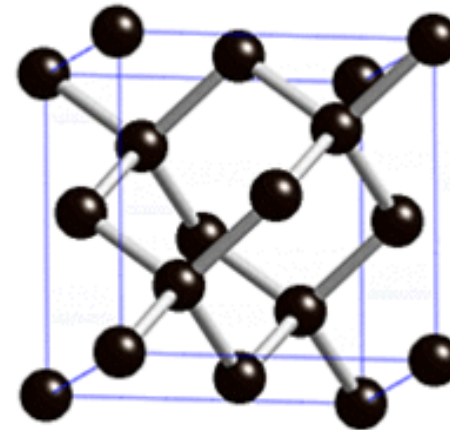
s
p
d
f

		Atomic Number										Atomic Mass									
		Symbol										Name									
		Electron Configuration																			
1 IA 1A	2 IIA 2A											13 IIIA 3A	14 IVA 4A	15 VA 5A	16 VIA 6A	17 VIIA 7A	18 VIIIA 8A				
1 H Hydrogen 1s <sup>1</sup> 1.008		3 Li Lithium [He]2s <sup>1</sup> 6.941	4 Be Beryllium [He]2s <sup>2</sup> 9.012											5 B Boron [He]2s <sup>2</sup> 2p <sup>1</sup> 10.811	6 C Carbon [He]2s <sup>2</sup> 2p <sup>2</sup> 12.011	7 N Nitrogen [He]2s <sup>2</sup> 2p <sup>3</sup> 14.007	8 O Oxygen [He]2s <sup>2</sup> 2p <sup>4</sup> 15.999	9 F Fluorine [He]2s <sup>2</sup> 2p <sup>5</sup> 18.998	10 Ne Neon [He]2s <sup>2</sup> 2p <sup>6</sup> 20.180		
11 Na Sodium [Ne]3s <sup>1</sup> 22.990	12 Mg Magnesium [Ne]3s <sup>2</sup> 24.305	3 IIIB 3B	4 IVB 4B	5 VB 5B	6 VIB 6B	7 VIIB 7B	8 VIII 8	9 VIII 8	10 VIII 8	11 IB 1B	12 IIB 2B	13 Al Aluminum [Ne]3s <sup>2</sup> 3p <sup>1</sup> 26.982	14 Si Silicon [Ne]3s <sup>2</sup> 3p <sup>2</sup> 28.086	15 P Phosphorus [Ne]3s <sup>2</sup> 3p <sup>3</sup> 30.974	16 S Sulfur [Ne]3s <sup>2</sup> 3p <sup>4</sup> 32.066	17 Cl Chlorine [Ne]3s <sup>2</sup> 3p <sup>5</sup> 35.453	18 Ar Argon [Ne]3s <sup>2</sup> 3p <sup>6</sup> 39.948				
19 K Potassium [Ar]4s <sup>1</sup> 39.098	20 Ca Calcium [Ar]4s <sup>2</sup> 40.078	21 Sc Scandium [Ar]3d <sup>1</sup> 4s <sup>2</sup> 44.956	22 Ti Titanium [Ar]3d <sup>2</sup> 4s <sup>2</sup> 47.88	23 V Vanadium [Ar]3d <sup>3</sup> 4s <sup>2</sup> 50.942	24 Cr Chromium [Ar]3d <sup>5</sup> 4s <sup>1</sup> 51.996	25 Mn Manganese [Ar]3d <sup>5</sup> 4s <sup>2</sup> 54.938	26 Fe Iron [Ar]3d <sup>6</sup> 4s <sup>2</sup> 55.845	27 Co Cobalt [Ar]3d <sup>7</sup> 4s <sup>2</sup> 58.933	28 Ni Nickel [Ar]3d <sup>8</sup> 4s <sup>2</sup> 58.693	29 Cu Copper [Ar]3d <sup>10</sup> 4s <sup>1</sup> 63.546	30 Zn Zinc [Ar]3d <sup>10</sup> 4s <sup>2</sup> 65.38	31 Ga Gallium [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>1</sup> 69.723	32 Ge Germanium [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>2</sup> 72.631	33 As Arsenic [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>3</sup> 74.922	34 Se Selenium [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>4</sup> 78.971	35 Br Bromine [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>5</sup> 79.904	36 Kr Krypton [Ar]3d <sup>10</sup> 4s <sup>2</sup> 4p <sup>6</sup> 84.798				
37 Rb Rubidium [Kr]5s <sup>1</sup> 84.468	38 Sr Strontium [Kr]5s <sup>2</sup> 87.62	39 Y Yttrium [Kr]4d <sup>1</sup> 5s <sup>2</sup> 88.906	40 Zr Zirconium [Kr]4d <sup>2</sup> 5s <sup>2</sup> 91.224	41 Nb Niobium [Kr]4d <sup>4</sup> 5s <sup>1</sup> 92.906	42 Mo Molybdenum [Kr]4d <sup>5</sup> 5s <sup>1</sup> 95.95	43 Tc Technetium [Kr]4d <sup>5</sup> 5s <sup>2</sup> 98.907	44 Ru Ruthenium [Kr]4d <sup>7</sup> 5s <sup>1</sup> 101.07	45 Rh Rhodium [Kr]4d <sup>8</sup> 5s <sup>1</sup> 102.906	46 Pd Palladium [Kr]4d <sup>10</sup> 106.42	47 Ag Silver [Kr]4d <sup>10</sup> 5s <sup>1</sup> 107.868	48 Cd Cadmium [Kr]4d <sup>10</sup> 5s <sup>2</sup> 112.414	49 In Indium [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>1</sup> 114.818	50 Sn Tin [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>2</sup> 118.711	51 Sb Antimony [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>3</sup> 121.760	52 Te Tellurium [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>4</sup> 127.6	53 I Iodine [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>5</sup> 126.904	54 Xe Xenon [Kr]4d <sup>10</sup> 5s <sup>2</sup> 5p <sup>6</sup> 131.29				
55 Cs Cesium [Xe]6s <sup>1</sup> 132.905	56 Ba Barium [Xe]6s <sup>2</sup> 137.328	57-71 Lanthanide Series	72 Hf Hafnium [Xe]4f <sup>14</sup> 5d <sup>2</sup> 6s <sup>2</sup> 178.49	73 Ta Tantalum [Xe]4f <sup>14</sup> 5d <sup>3</sup> 6s <sup>2</sup> 180.948	74 W Tungsten [Xe]4f <sup>14</sup> 5d <sup>4</sup> 6s <sup>2</sup> 183.84	75 Re Rhenium [Xe]4f <sup>14</sup> 5d <sup>5</sup> 6s <sup>2</sup> 186.207	76 Os Osmium [Xe]4f <sup>14</sup> 5d <sup>6</sup> 6s <sup>2</sup> 190.23	77 Ir Iridium [Xe]4f <sup>14</sup> 5d <sup>7</sup> 6s <sup>2</sup> 192.217	78 Pt Platinum [Xe]4f <sup>14</sup> 5d <sup>9</sup> 6s <sup>1</sup> 195.085	79 Au Gold [Xe]4f <sup>14</sup> 5d <sup>10</sup> 6s <sup>1</sup> 196.967	80 Hg Mercury [Xe]4f <sup>14</sup> 5d <sup>10</sup> 6s <sup>2</sup> 200.592	81 Tl Thallium [Xe]4f <sup>14</sup> 5d <sup>10</sup> 6s <sup>2</sup> 6p <sup>1</sup> 204.383	82 Pb Lead [Xe]4f <sup>14</sup> 5d <sup>10</sup> 6s <sup>2</sup> 6p <sup>2</sup> 207.2	83 Bi Bismuth [Xe]4f <sup>14</sup> 5d <sup>10</sup> 6s <sup>2</sup> 6p <sup>3</sup> 208.980	84 Po Polonium [Xe]4f <sup>14</sup> 5d <sup>10</sup> 6s <sup>2</sup> 6p <sup>4</sup> [209]	85 At Astatine [Xe]4f <sup>14</sup> 5d <sup>10</sup> 6s <sup>2</sup> 6p <sup>5</sup> [209]	86 Rn Radon [Xe]4f <sup>14</sup> 5d <sup>10</sup> 6s <sup>2</sup> 6p <sup>6</sup> 222.018				
87 Fr Francium [Rn]7s <sup>1</sup> 223.020	88 Ra Radium [Rn]7s <sup>2</sup> 226.025	89-103 Actinide Series	104 Rf Rutherfordium [Rn]5f <sup>14</sup> 6d <sup>2</sup> 7s <sup>2</sup> [261]	105 Db Dubnium [Rn]5f <sup>14</sup> 6d <sup>3</sup> 7s <sup>2</sup> [262]	106 Sg Seaborgium [Rn]5f <sup>14</sup> 6d <sup>4</sup> 7s <sup>2</sup> [266]	107 Bh Bohrium [Rn]5f <sup>14</sup> 6d <sup>5</sup> 7s <sup>2</sup> [264]	108 Hs Hassium [Rn]5f <sup>14</sup> 6d <sup>6</sup> 7s <sup>2</sup> [269]	109 Mt Meitnerium [Rn]5f <sup>14</sup> 6d <sup>7</sup> 7s <sup>2</sup> [268]	110 Ds Darmstadtium [Rn]5f <sup>14</sup> 6d <sup>8</sup> 7s <sup>2</sup> [269]	111 Rg Roentgenium [Rn]5f <sup>14</sup> 6d <sup>9</sup> 7s <sup>2</sup> [272]	112 Cn Copernicium [Rn]5f <sup>14</sup> 6d <sup>10</sup> 7s <sup>2</sup> [277]	113 Uut Ununtrium [Rn]5f <sup>14</sup> 6d <sup>10</sup> 7s <sup>2</sup> 7p <sup>1</sup> [289]	114 Fl Flerovium [Rn]5f <sup>14</sup> 6d <sup>10</sup> 7s <sup>2</sup> 7p <sup>2</sup> [289]	115 Uup Ununpentium [Rn]5f <sup>14</sup> 6d <sup>10</sup> 7s <sup>2</sup> 7p <sup>3</sup> [289]	116 Lv Livermorium [Rn]5f <sup>14</sup> 6d <sup>10</sup> 7s <sup>2</sup> 7p <sup>4</sup> [289]	117 Uus Ununseptium [Rn]5f <sup>14</sup> 6d <sup>10</sup> 7s <sup>2</sup> 7p <sup>5</sup> [289]	118 Uuo Ununoctium [Rn]5f <sup>14</sup> 6d <sup>10</sup> 7s <sup>2</sup> 7p <sup>6</sup> [289]				
		57 La Lanthanum [Xe]5d <sup>1</sup> 6s <sup>2</sup> 138.905	58 Ce Cerium [Xe]4f <sup>1</sup> 5d <sup>1</sup> 6s <sup>2</sup> 140.116	59 Pr Praseodymium [Xe]4f <sup>3</sup> 6s <sup>2</sup> 140.908	60 Nd Neodymium [Xe]4f <sup>4</sup> 6s <sup>2</sup> 144.243	61 Pm Promethium [Xe]4f <sup>5</sup> 6s <sup>2</sup> 144.913	62 Sm Samarium [Xe]4f <sup>6</sup> 6s <sup>2</sup> 150.36	63 Eu Europium [Xe]4f <sup>7</sup> 6s <sup>2</sup> 151.964	64 Gd Gadolinium [Xe]4f <sup>7</sup> 5d <sup>1</sup> 6s <sup>2</sup> 157.25	65 Tb Terbium [Xe]4f <sup>9</sup> 6s <sup>2</sup> 158.925	66 Dy Dysprosium [Xe]4f <sup>10</sup> 6s <sup>2</sup> 162.500	67 Ho Holmium [Xe]4f <sup>11</sup> 6s <sup>2</sup> 164.930	68 Er Erbium [Xe]4f <sup>12</sup> 6s <sup>2</sup> 167.259	69 Tm Thulium [Xe]4f <sup>13</sup> 6s <sup>2</sup> 168.934	70 Yb Ytterbium [Xe]4f <sup>14</sup> 6s <sup>2</sup> 173.055	71 Lu Lutetium [Xe]4f <sup>14</sup> 5d <sup>1</sup> 6s <sup>2</sup> 174.967					
		89 Ac Actinium [Rn]6d <sup>1</sup> 7s <sup>2</sup> 227.028	90 Th Thorium [Rn]6d <sup>2</sup> 7s <sup>2</sup> 232.038	91 Pa Protactinium [Rn]5f <sup>2</sup> 6d <sup>1</sup> 7s <sup>2</sup> 231.036	92 U Uranium [Rn]5f <sup>3</sup> 6d <sup>1</sup> 7s <sup>2</sup> 238.029	93 Np Neptunium [Rn]5f <sup>4</sup> 6d <sup>1</sup> 7s <sup>2</sup> 237.048	94 Pu Plutonium [Rn]5f <sup>6</sup> 7s <sup>2</sup> 244.064	95 Am Americium [Rn]5f <sup>7</sup> 7s <sup>2</sup> 243.061	96 Cm Curium [Rn]5f <sup>7</sup> 6d <sup>1</sup> 7s <sup>2</sup> 247.070	97 Bk Berkelium [Rn]5f <sup>9</sup> 7s <sup>2</sup> 247.070	98 Cf Californium [Rn]5f <sup>10</sup> 7s <sup>2</sup> 251.080	99 Es Einsteinium [Rn]5f <sup>11</sup> 7s <sup>2</sup> [254]	100 Fm Fermium [Rn]5f <sup>12</sup> 7s <sup>2</sup> 257.085	101 Md Mendelevium [Rn]5f <sup>13</sup> 7s <sup>2</sup> 258.1	102 No Nobelium [Rn]5f <sup>14</sup> 7s <sup>2</sup> 259.101	103 Lr Lawrencium [Rn]5f <sup>14</sup> 6d <sup>1</sup> 7s <sup>2</sup> [262]					

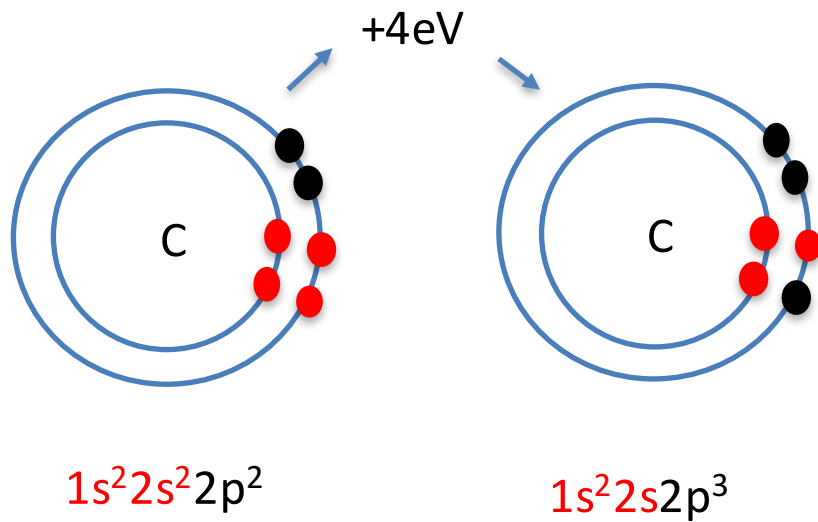
# Covalent Crystals



Diamond structure

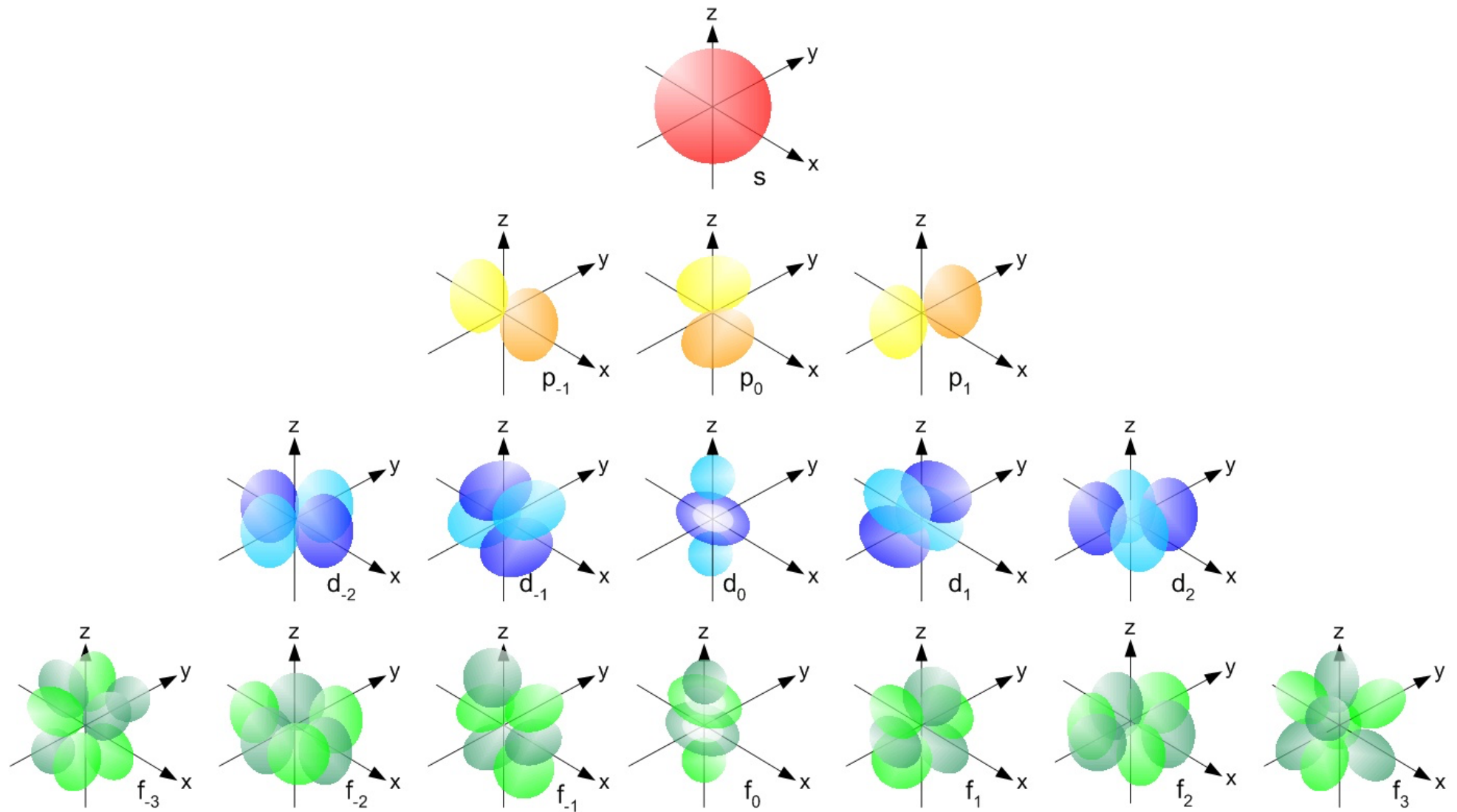


4 covalent bonds



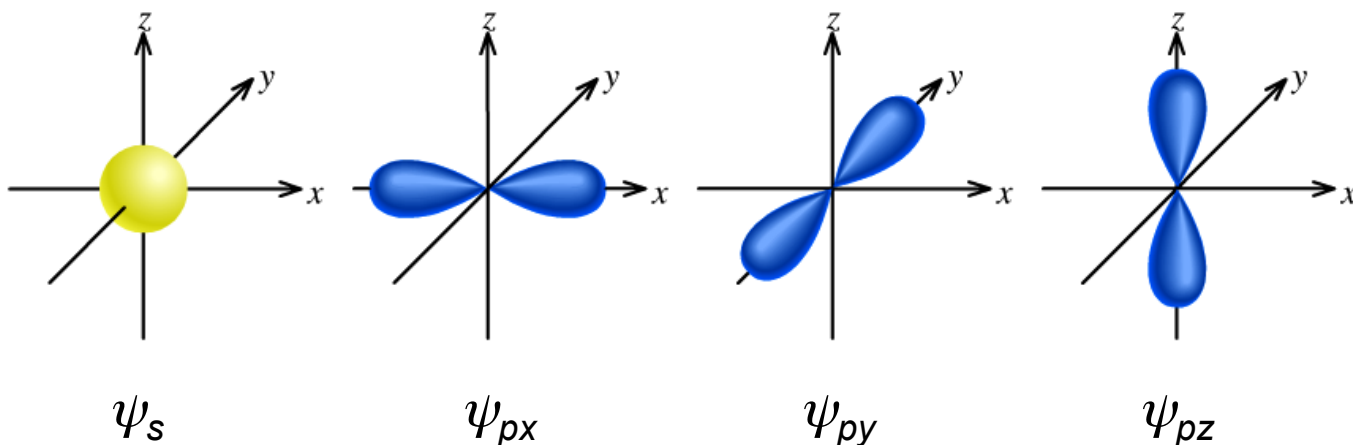


# Electronic orbitals





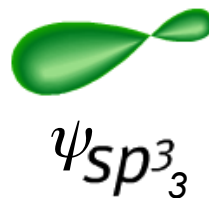
# Orbital hybridization



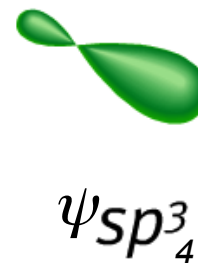
$$\frac{1}{2}(\psi_s + \psi_{px} + \psi_{py} + \psi_{pz})$$



$$\frac{1}{2}(\psi_s + \psi_{px} - \psi_{py} - \psi_{pz})$$

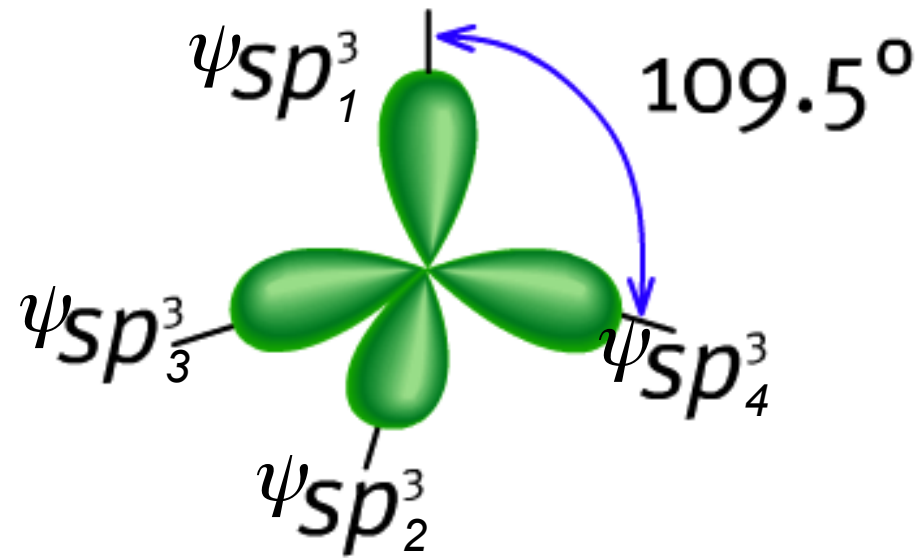


$$\frac{1}{2}(\psi_s - \psi_{px} + \psi_{py} - \psi_{pz})$$



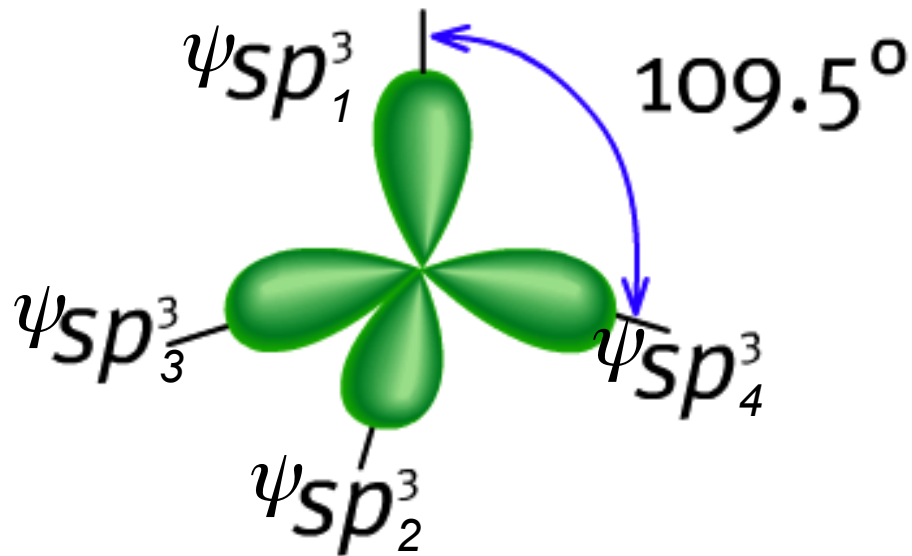
$$\frac{1}{2}(\psi_s - \psi_{px} - \psi_{py} + \psi_{pz})$$

# Orbital hybridization

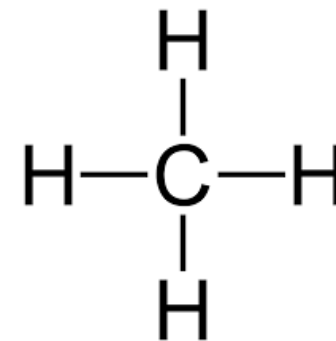
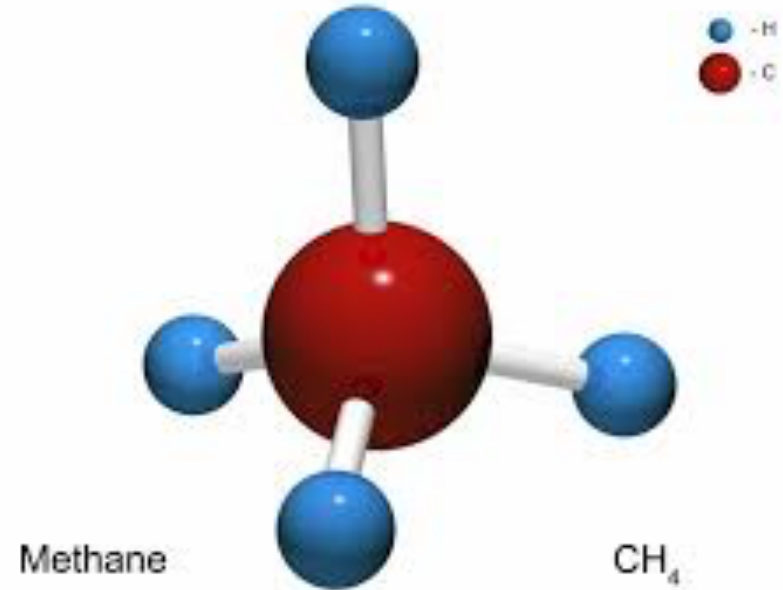


Tetraeder

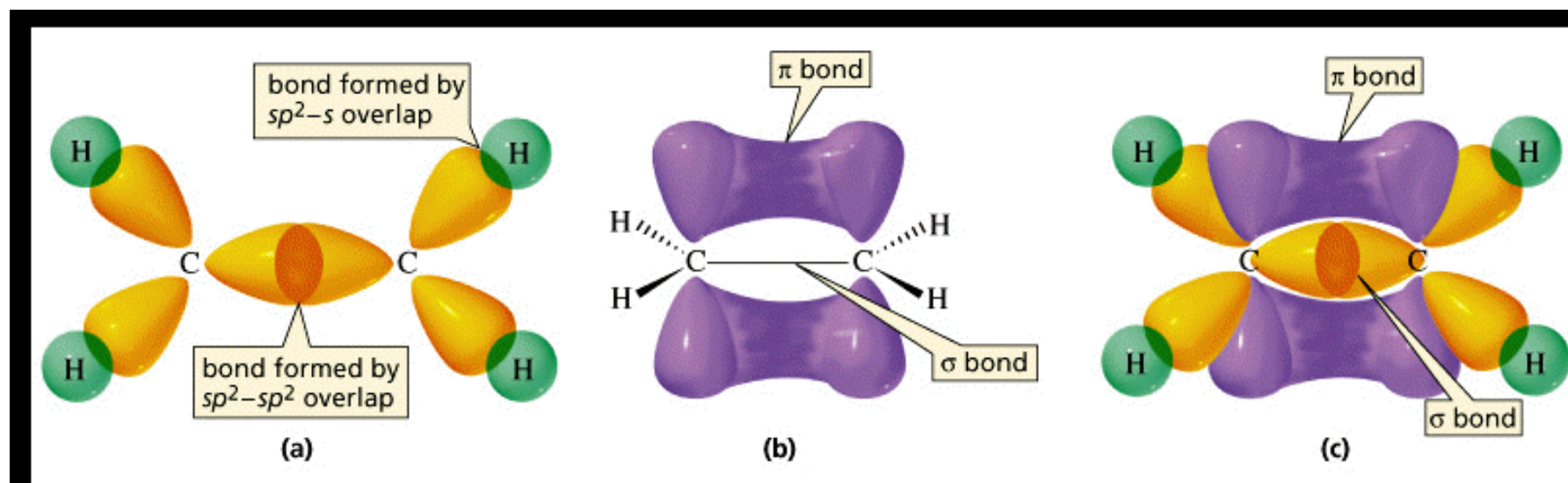
# Orbital molecular theory: Example CH<sub>4</sub> (Methane)



Tetraeder

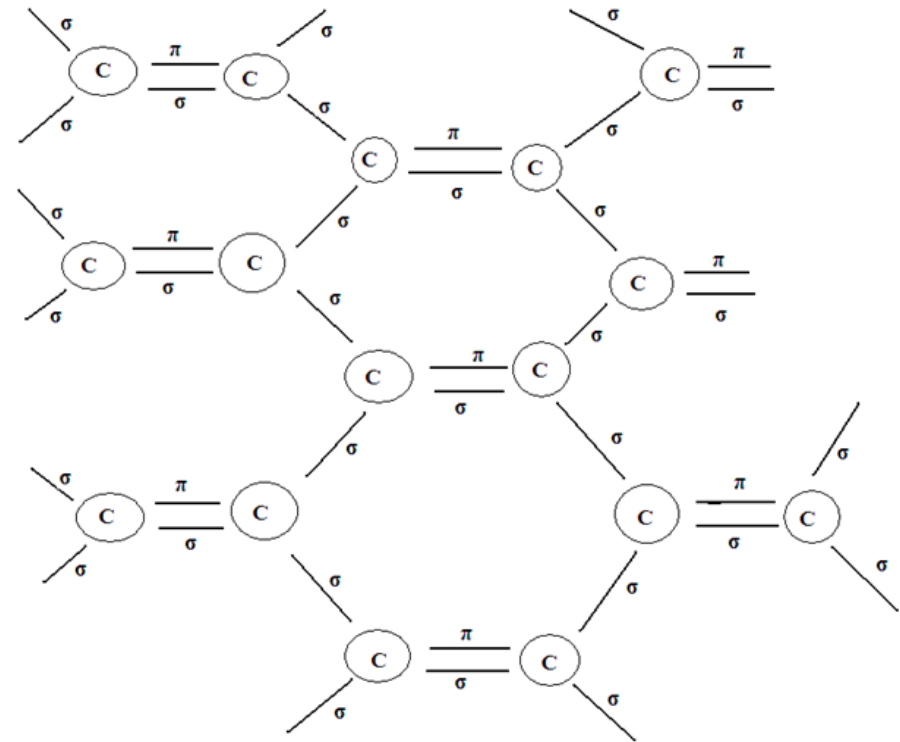
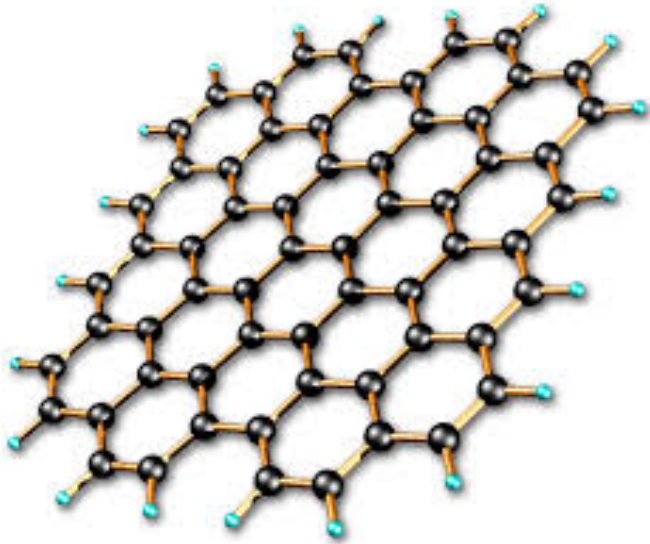


# Orbital molecular theory: $\sigma$ and $\pi$ bonding

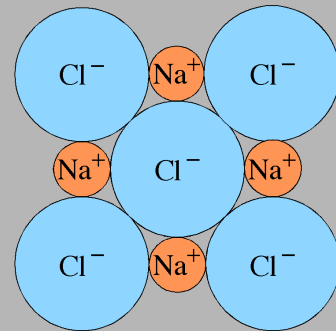


# Graphene: $\sigma$ and $\pi$ bonding

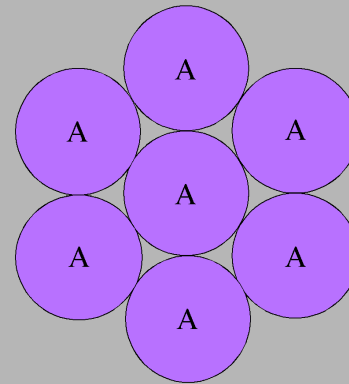
Graphene



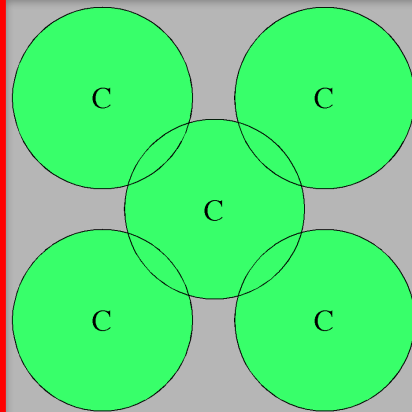
# Today's lecture



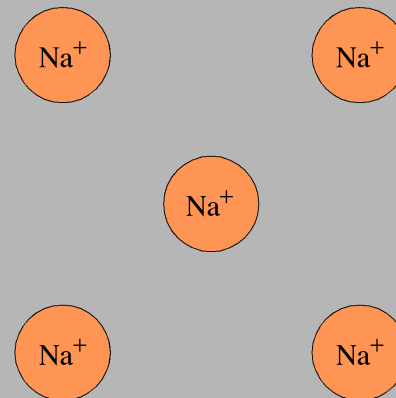
Natriumchlorid  
(ionisch)



Kristallines Argon  
(van der Waals)



Diamant  
(kovalent)



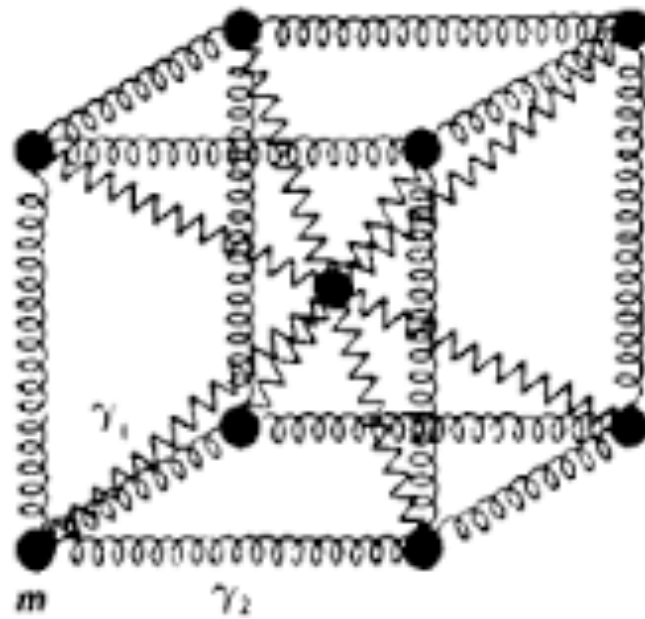
Natrium  
(metallisch)

# Summary

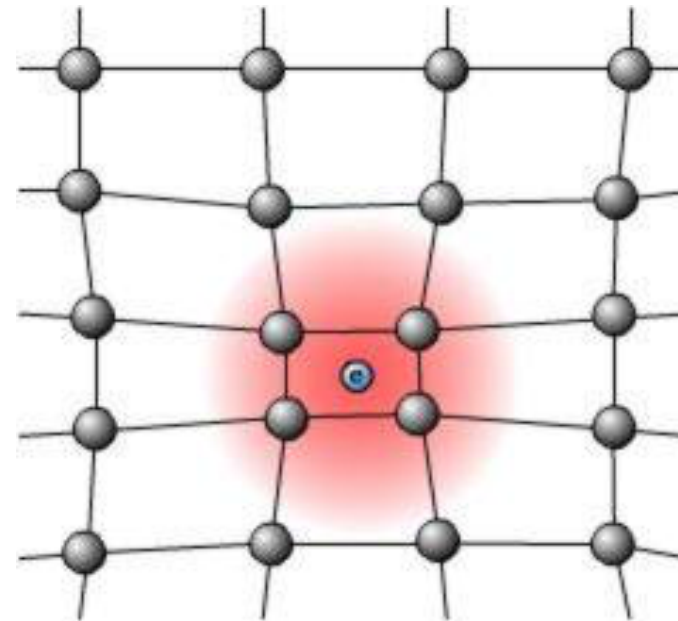
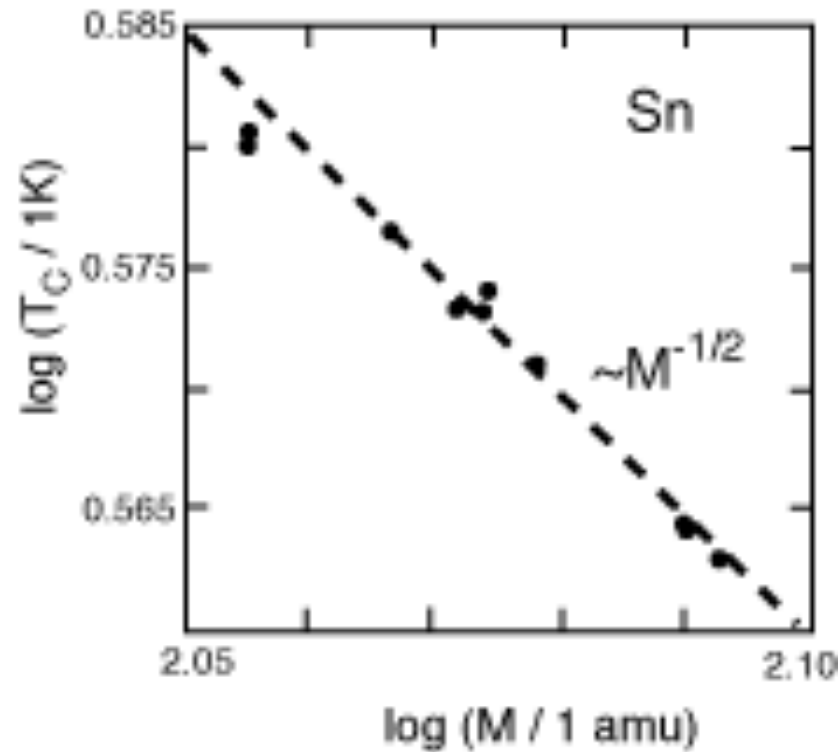
Bindungstyp	Beispiel	Bindungsenergie (eV)
Ionisch	NaCl	8.23
	LiF	10.92
Van-der-Waals	Ar	0.080
	Kr	0.116
Kovalent	Diamant	7.36
	Si	4.64
Metallisch	Na	1.13
	Fe	4.29
	W	8.66
Wasserstoff- Brücken	H <sub>2</sub> O	0.52
	HF	0.30



# Phonon – Lattice Vibrations



# Phonons can make superconductivity

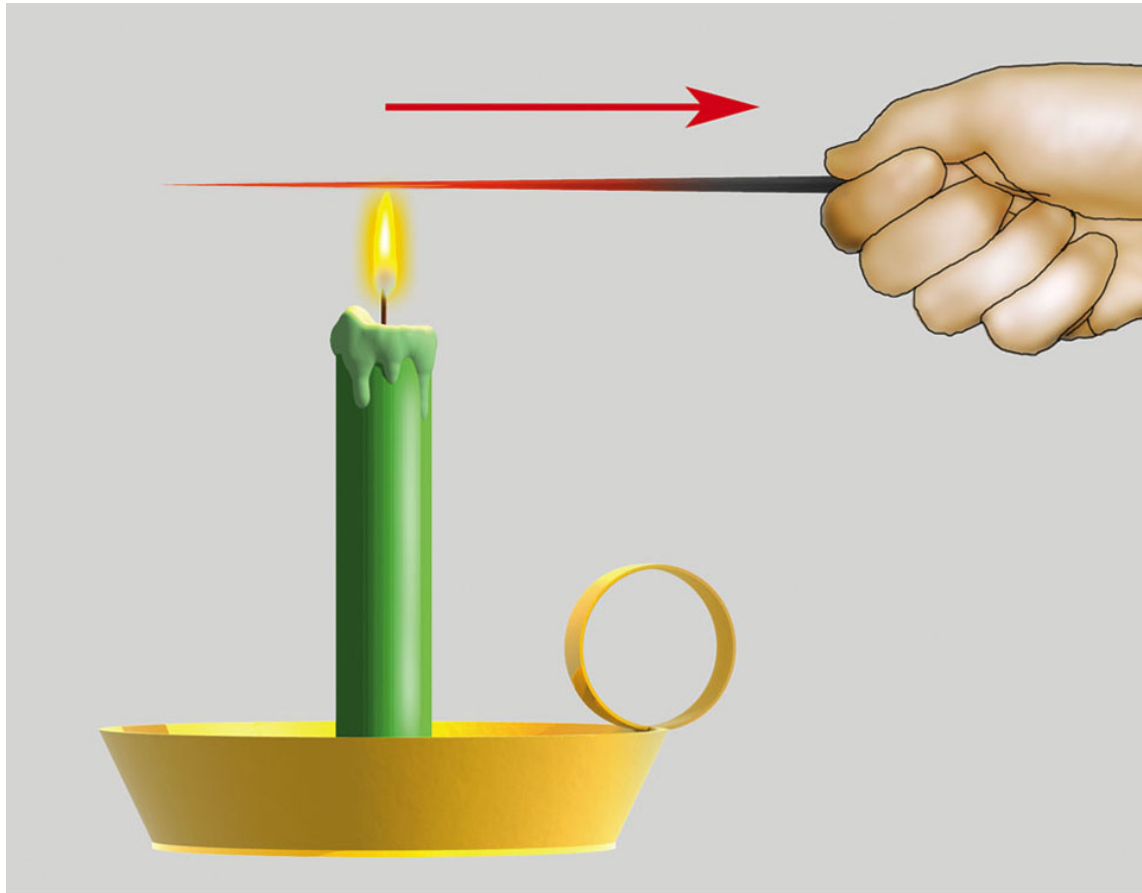


E. Maxwell, Phys. Rev. **86**, 235 (1952) and  
B. Serin et al., Phys. Rev. B **86** 162 (1952))

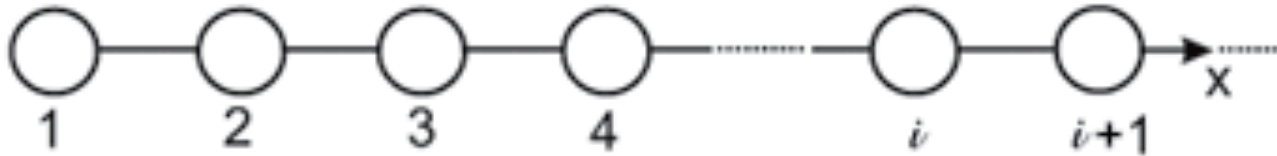
<http://www.chm.bris.ac.uk/webprojects2000/igrant/theory.htm>

|

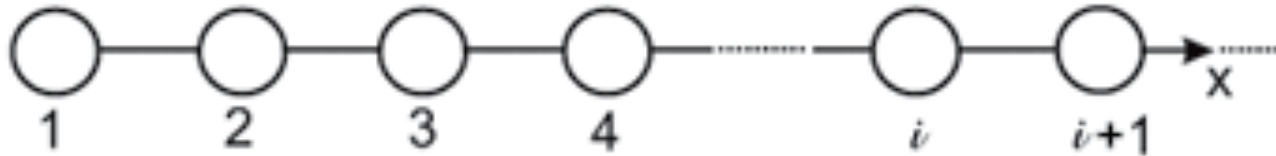
# Phonons can conduct heat



# Linear chain -Models

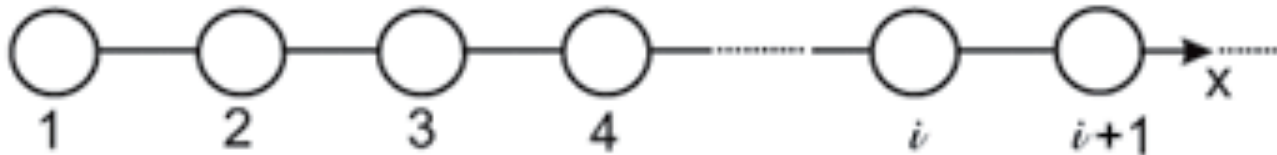


**Structure factor:  $S = \sum_i e^{-iqr_i}$**



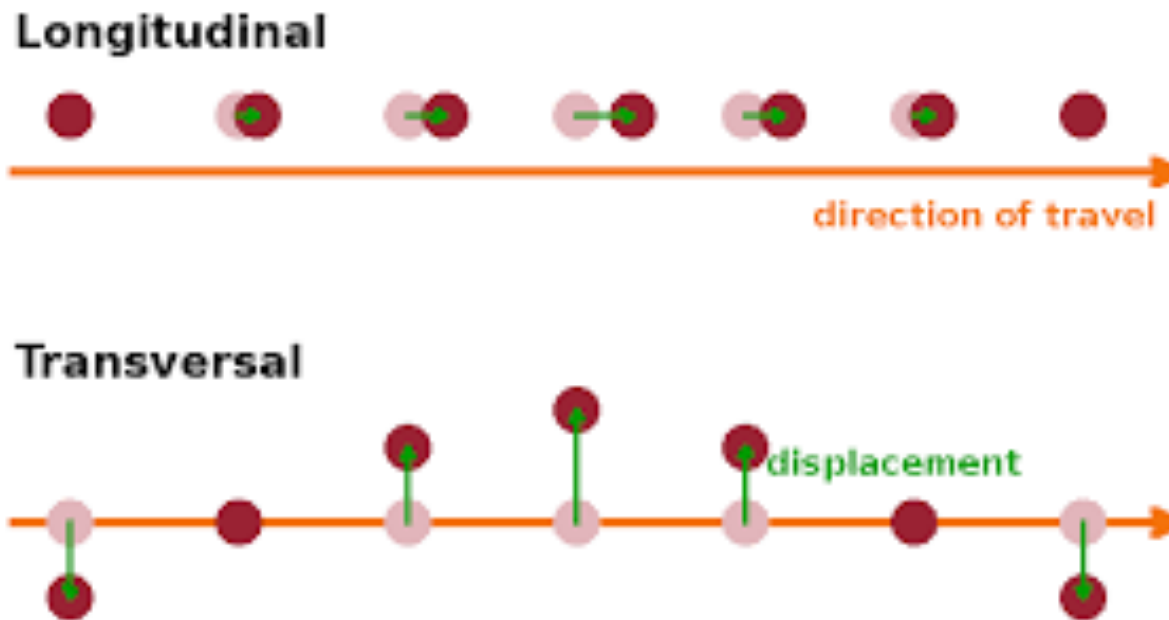
**Madelung constant:  $\alpha = 2 \ln(2)$**

**Distortion Energy :  $E = 0.5 * \text{constant} * \delta^2$**



**Phonon dispersion:  $\omega =$**

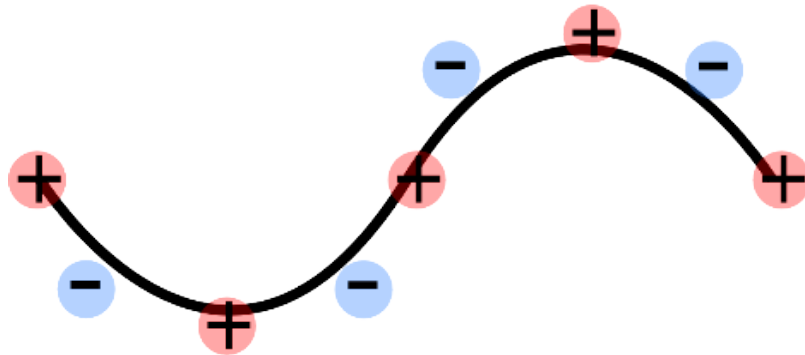
# Longitudinal and Transverse Phonons



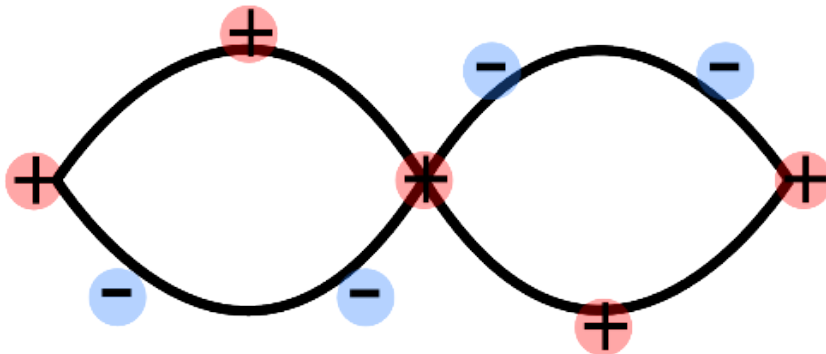
LA = Longitudinal Acoustic  
LO = Longitudinal Optical  
TA = Transversal Acoustic  
TO = Transversal Optical

# Acoustic and optical modes

Acoustical Mode



Optical Mode



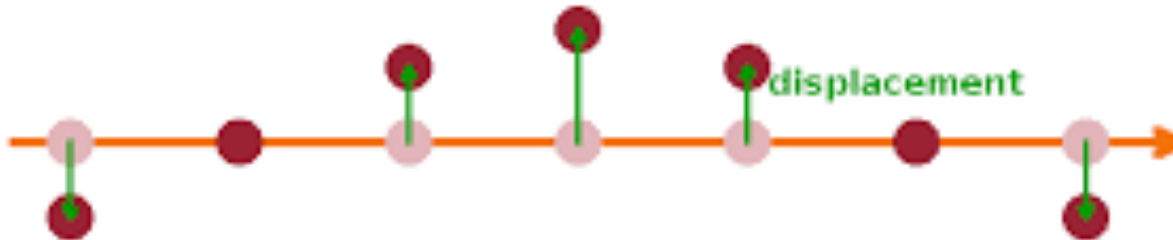
LA = Longitudinal Acoustic  
LO = Longitudinal Optical  
TA = Transversal Acoustic  
TO = Transversal Optical

# Number of phonon branches

## Longitudinal



## Transversal



LA = Longitudinal Acoustic  
LO = Longitudinal Optical  
TA = Transversal Acoustic  
TO = Transversal Optical

$p$  = number of atoms in the primitive cell

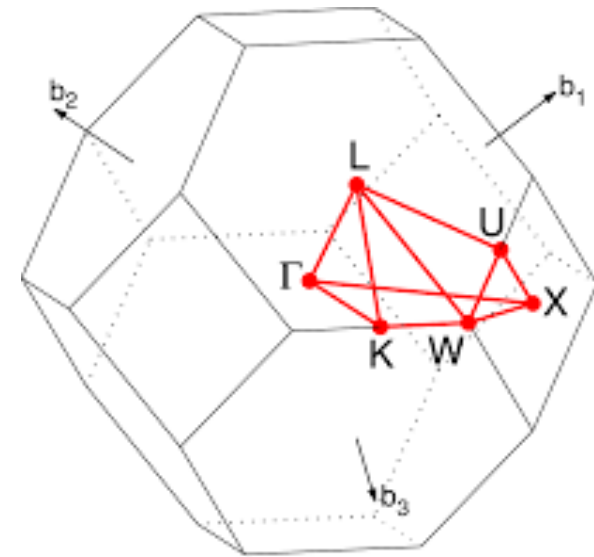
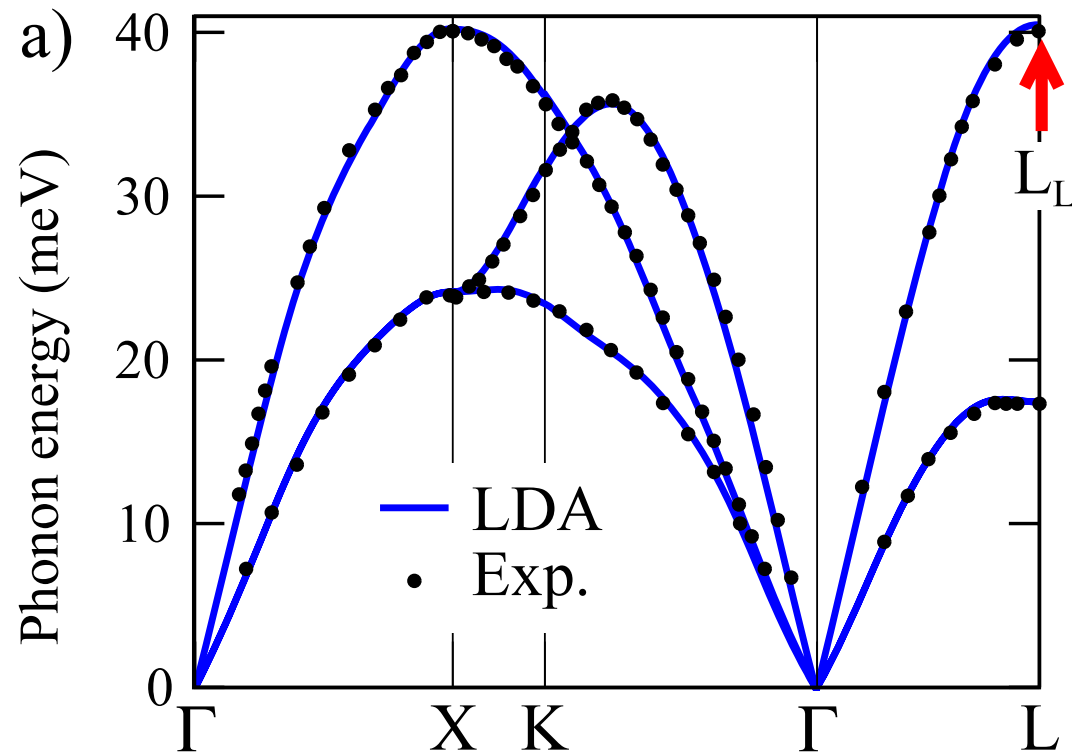
3 acoustic branches

$3p-3$  optical branches

Total  $3p$  phonon branches



# Phonons in aluminium

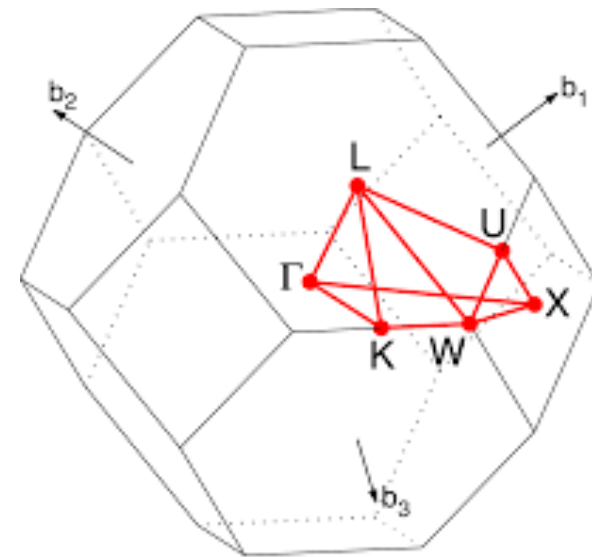
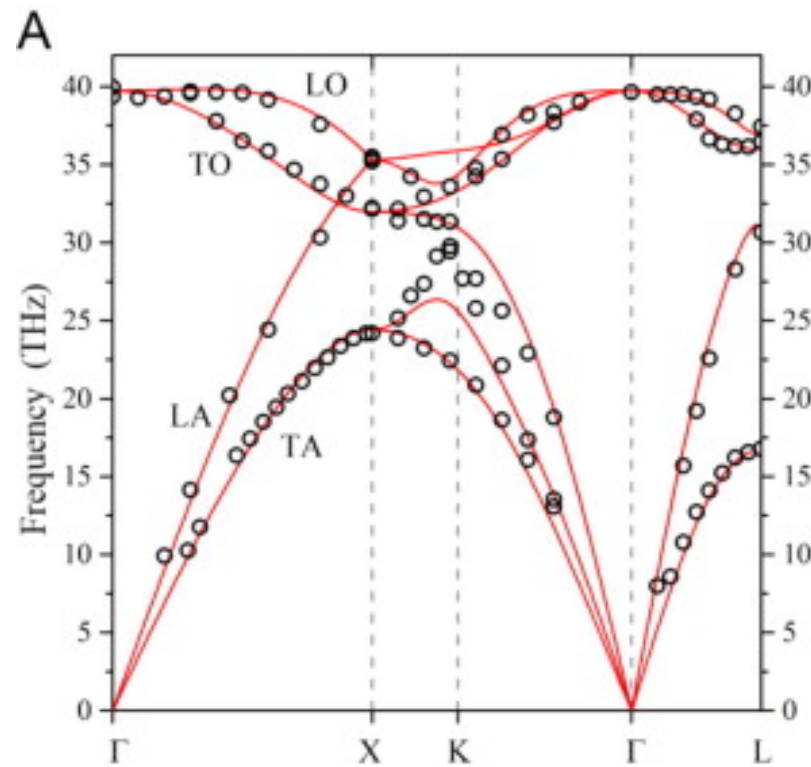


FCC path:  $\Gamma$ -X-W-K- $\Gamma$ -L-U-W-L-K|U-X

[Setyawan & Curtarolo, DOI: 10.1016/j.commatsci.2010.05.010]

<http://iopscience.iop.org/article/10.1088/0953-8984/24/5/053202>

# Phonons in diamond



FCC path:  $\Gamma$ -X-W-K- $\Gamma$ -L-U-W-L-K|U-X

[Setyawan & Curtarolo, DOI: 10.1016/j.commatsci.2010.05.010]

1 THz = 4.14... meV