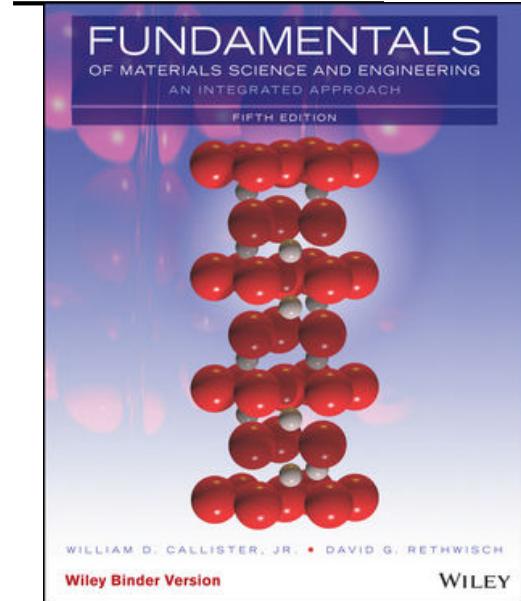


# 材料科學導論



## Fundamentals of Materials Science and Engineering: An Integrated Approach

Fifth Edition

William D. Callister, JR • David G. Rethwisch

## Chapter 2 Atomic Structure and Interatomic Bonding

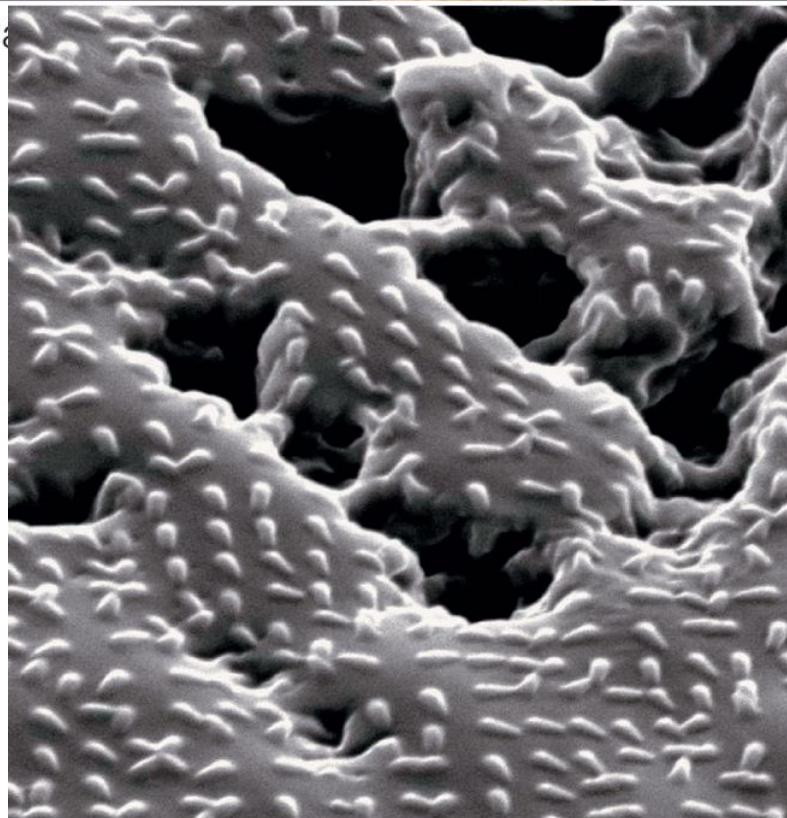
Ching-Li Tseng

Graduate Institute of Biomedical Engineering & Tissue engineering

[chingli@tmu.edu.tw](mailto:chingli@tmu.edu.tw)



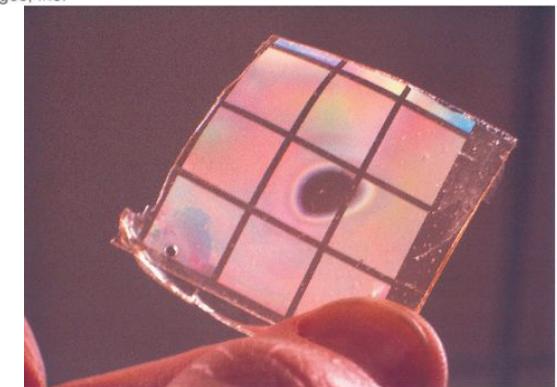
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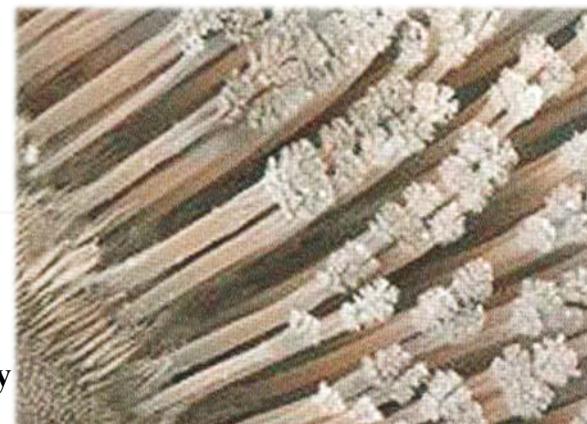
Courtesy Jeffrey Karp, Robert Langer and Alex Galakatos



Barbara Peacock/Photodisc/Getty Images, Inc.



Courtesy Jeffrey Karp, Robert Langer and Alex Galakatos



ey

Keratin hairs :  
200~500 nm

$10^{-7}$  N/hair  
 $10$  N/cm $^2$  ( 0.5 million hair/toe)

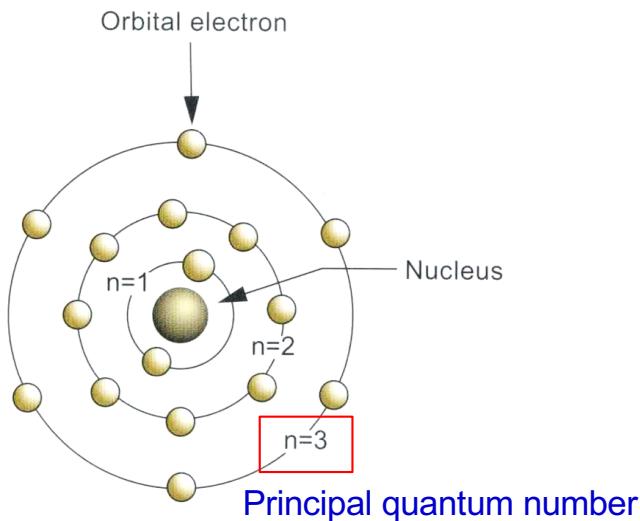
# Atomic Structure

H							F
Li	Be		B	C	N	O	Ne
Na	Mg		Al				
K	Ca			Ga			
Rb	Sr						
Cs	Ba						
Fr	Ra						

# Fundamental concept

## Atomic Structure (Freshman Chem.)

- atom – electrons –  $9.11 \times 10^{-31}$  kg  
protons + neutrons – }  $1.67 \times 10^{-27}$  kg nucleus
- atomic number ( $Z$ ) = # of protons in nucleus of atom  
原子序  
= # of electrons in neutral species



# Fundamental concept

**atomic mass ( $A$ )**  
原子質量

$A = \text{Atomic wt.}$

$$\bar{A}_M = \sum_i f_{i_M} A_{i_M}$$

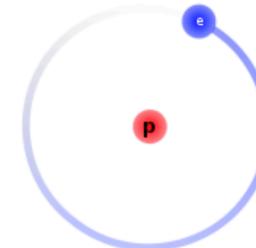
$$A \approx Z + N$$

**atomic mass unit**  = amu  
原子質量單位 =  $1/12$  mass of  $^{12}\text{C}$

$1 \text{ amu/atom} = 1 \text{ g/mol}$

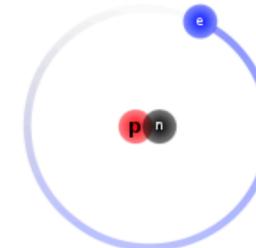
$A = \text{Atomic weight (wt.)}$   
 $= \text{wt. of } 6.022 \times 10^{23} \text{ molecules or atoms}$

isotopes



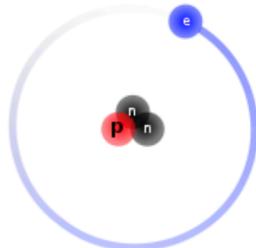
$^1\text{H}$

Protium



$^2\text{H}$

Deuterium



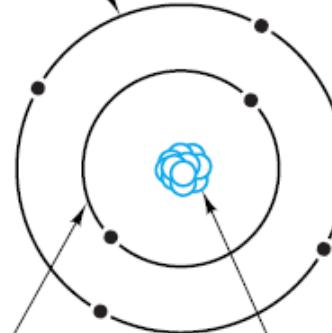
$^3\text{H}$

Tritium

Schematic of the planetary model of a  $^{12}\text{C}$  atom

Outer orbital  
(with four  $sp^3$  hybrid bonding electrons)

Inner orbital  
(with two  $1s$  electrons)



Nucleus (with six protons and six neutrons)

# Electron in atom

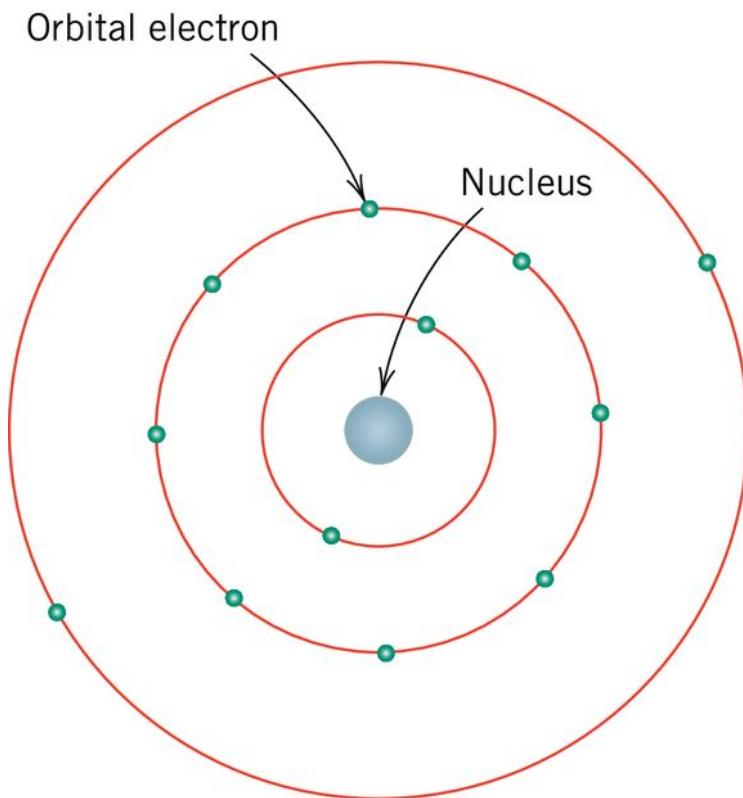
## Atomic model

### Quantum mechanics

#### Bohr atom model

固定軌域  
不連續

Electrons are assumed to revolve around the atomic nucleus in discrete orbitals, and the position of any particular electron is more or less well defined in terms of its orbital.



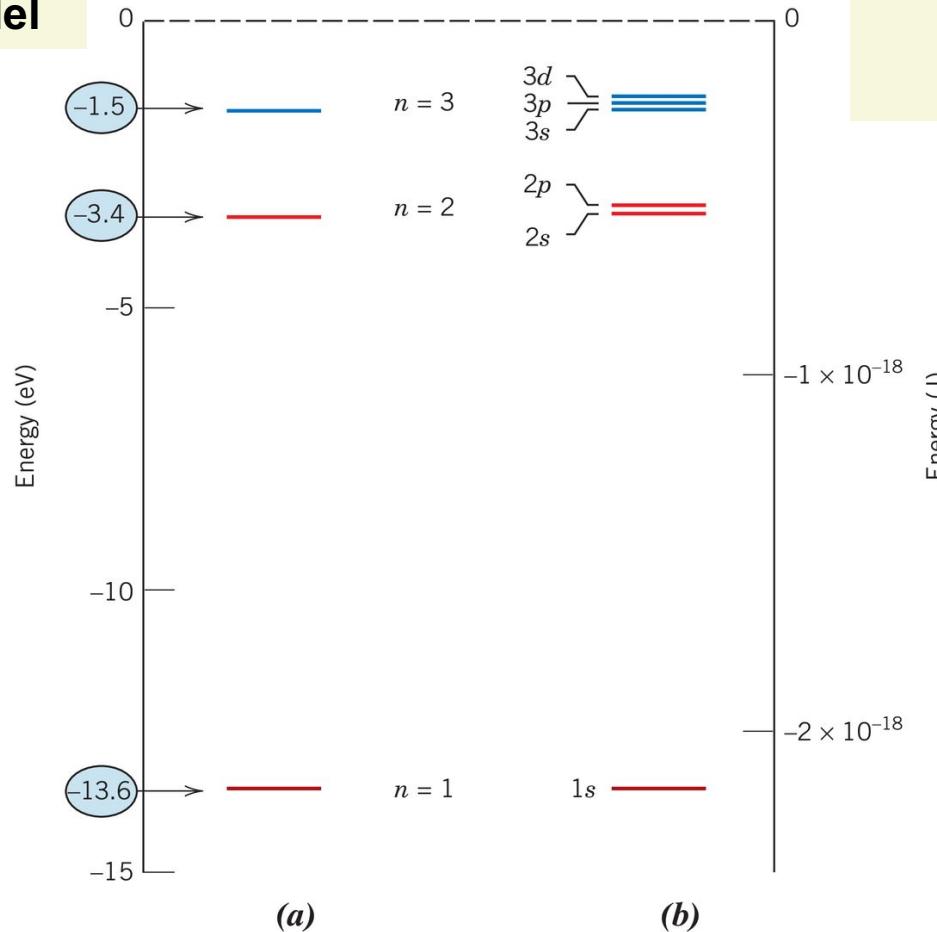
Fig\_2-1

# Atomic model

## Electron in atom

H

### Bohr model



Adapted from W. G. Moffatt, G. W. Pearsall, and J. Wulff, *The Structure and Properties of Materials*, Vol. I, Structure, p. 10. Copyright © 1964 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.

### Wave mechanical model (波動力學模型)

- The electron is considered to exhibit both wavelike and particle-like characteristics.

⇒ 混合性質兼具

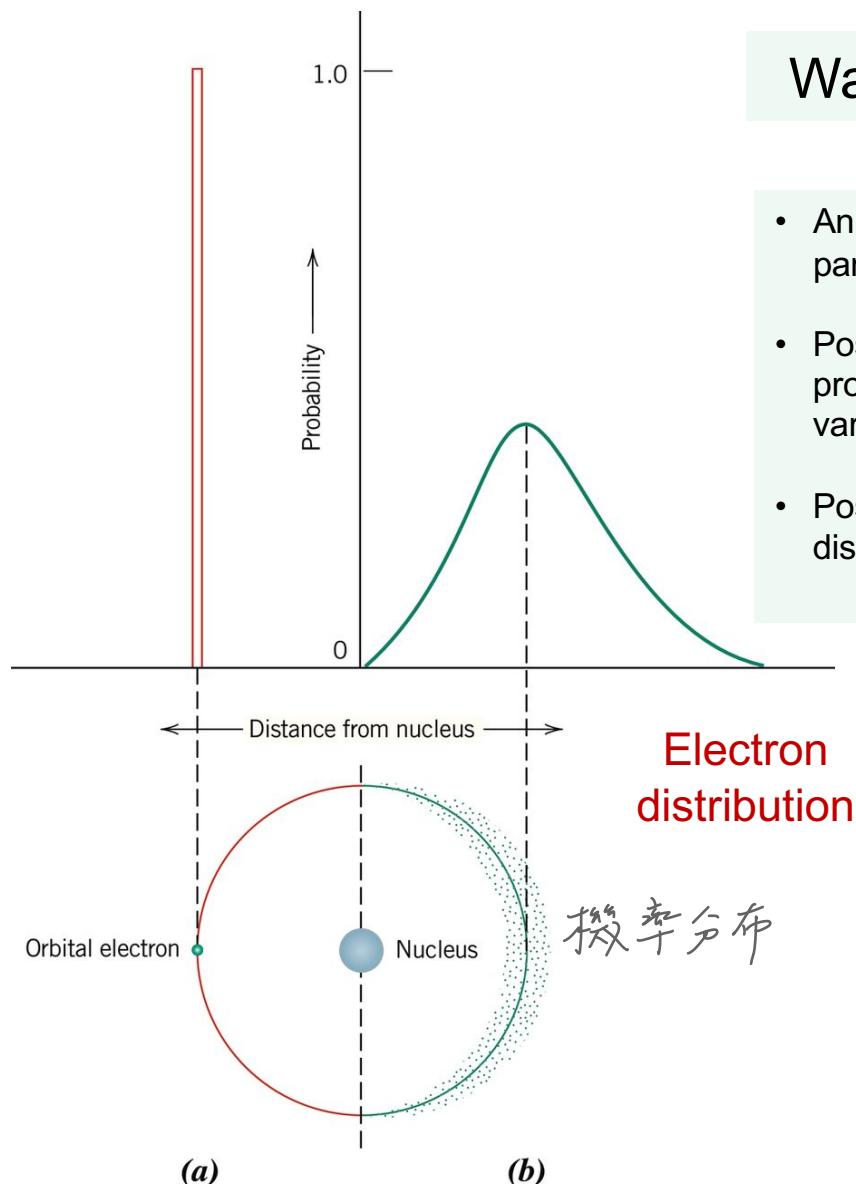
(a) The first three electron energy states for the Bohr hydrogen atom.

(b) Electron energy states for the first three shells of the wave-mechanical hydrogen atom.

# Quantum number

## Electron in atom

### Bohr model



### Wave mechanical model

- An electron is no longer treated as a particle moving in a discrete orbital.
- Position is considered to be the probability of an electron's being at various locations around the nucleus.
- Position is described by a probability distribution or electron cloud

Fig\_2-3

Adapted from Z. D. Jastrzebski, *The Nature and Properties of Engineering Materials*, 3rd edition, p. 4. Copyright © 1987 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.

## Electronic Structure

- Electrons have wave-like and particle-like characteristics.
- Two wave-like characteristics are
  - Electron position in terms of probability density
  - **shape, size, orientation** of probability density determined by quantum numbers  
量子數
  - Quantum Number Designation/Values

$n$  = principal (shell) 主量子數  $K, L, M, N, O$  (1, 2, 3, 4, etc.)

$\ell$  = azimuthal (subshell)  $s, p, d, f$  (0, 1, 2, 3, ...,  $n-1$ )

$m_\ell$  = magnetic (no. of orbitals) 1, 3, 5, 7 (- $\ell$  to + $\ell$ )

$m_s$  = spin  $\frac{1}{2}, -\frac{1}{2}$

# Quantum numbers (量子數)

$n = 1, 2, 3 \dots$  正整數

## 1. 主量子數(principal number)( $n$ ) : Shell

範圍  $\propto$  能量

- A **positive integer** which determines the size and energy level of the orbital.
- As  $n$  increases, the number of orbitals in a given shell as well as their size gets larger (electron far away the nucleus).
- Since energy is required to separate the negatively charged electron and positively charged nucleus, the further the electron from the atom's center, the more energy it must have and so the electrons occupying orbitals with higher values of  $n$  have higher energy levels.

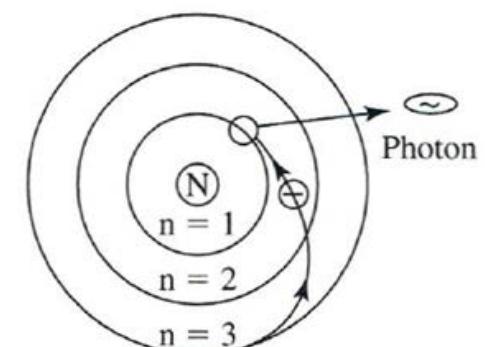
Shell rule:

$n = 1$  called **K** shell

$n = 2$  called **L** shell

$n = 3$  called **M** shell

$n = 4$  called **N** shell



# Quantum numbers (量子數)

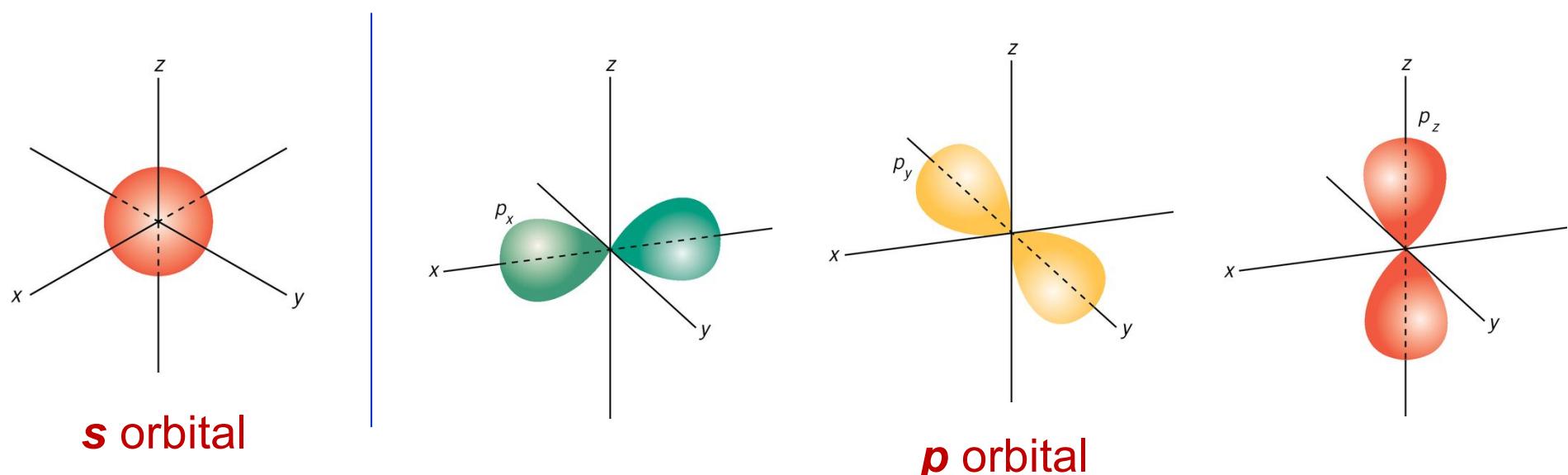
## Subshell

第二量子數( Second (azimuthal) momentum number)( $\ell$ )

(l) describes the three dimensional shape of an orbital.

$$\ell = n-1 \quad n=1,2,3\dots$$

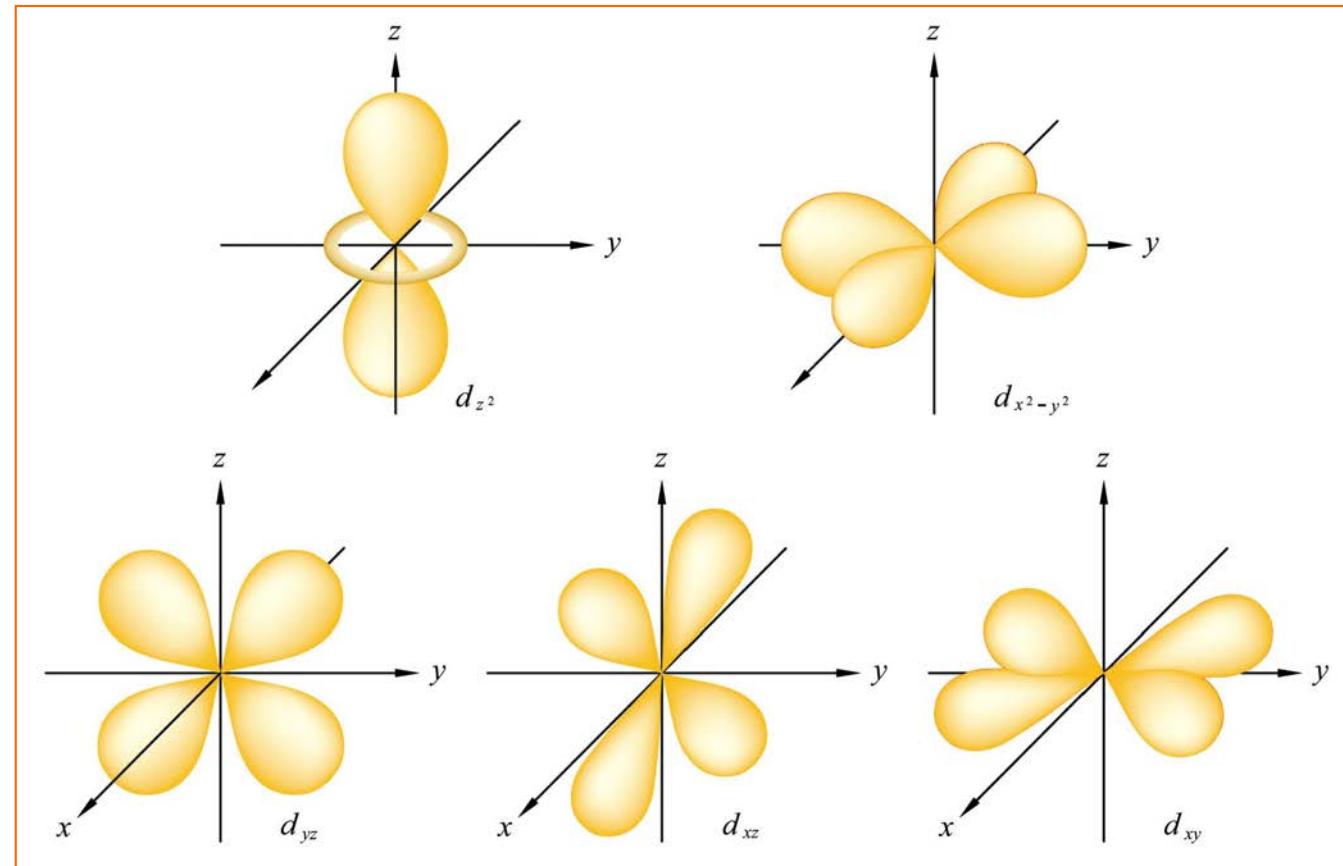
- when  $\ell = 0$  , the electron located in the orbital called **s** orbital
- when  $\ell = 1$  , the electron located in the orbital called **p** orbital
- when  $\ell = 2$ , the electron located in the orbital called **d** orbital



1s

2s, 2p

3s 3p 3d



$\ell$	Orbital name	Shape
0	s	Ball
1	p	Dumbbells
2	d	Dual-dumbbells
3	f	Complicated

### d orbital

$\ell$	0	1	2	3
名	s	p	d	f
形	球形	哑铃	双哑	複雜

Ball  
 Dumbbells  
 Dual-Dumbbells

# Quantum numbers (量子數)

## 第三量子數(magnetic number · 磁量子數) ( $m$ or $m\ell$ )

幾個主軸

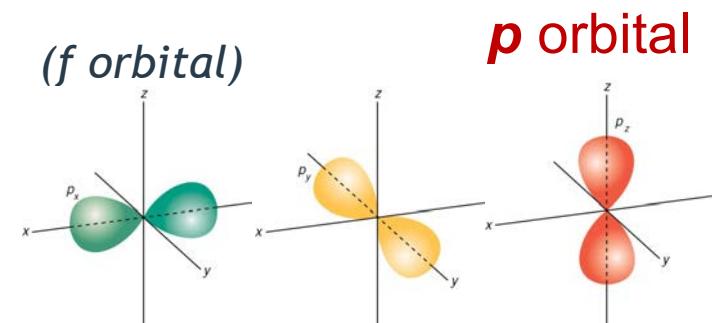
- Describes the **configuration of the orbitals** according to a set of axes in three dimensions.
- For any  $\ell$ , the magnetic quantum number can take on integer values from  $-\ell$  to  $+\ell$ .
- Hence  $m\ell=2\ell+1$  different orientations for each subshell.

if  $\ell=0$ ,  $m\ell = 1$  *(s orbital)*

if  $\ell=1$ ,  $m\ell = -1, 0, 1$  *(p orbital)*

if  $\ell=2$ ,  $m\ell = -2, -1, 0, 1, 2$  *(d orbital)*

if  $\ell=3$ ,  $m\ell = -3, -2, -1, 0, 1, 2, 3$  *(f orbital)*

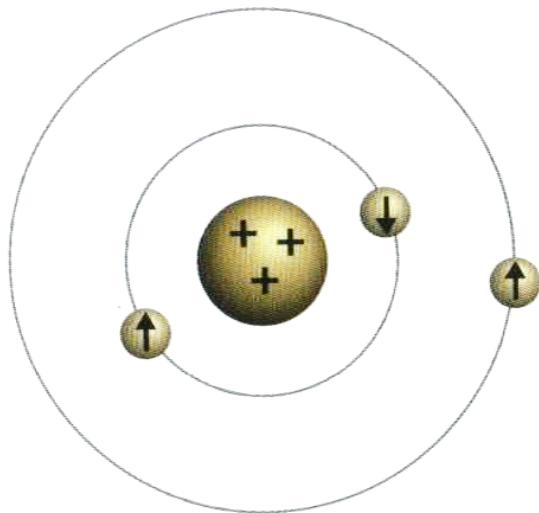


# Quantum numbers (量子數)

## 4.自旋量子數(spin number) ( S )

### Pauli Exclusion principle:

Two electrons can't get into exactly the same energy state



$s = +1/2$  , spin-up electron (clockwise)

↑ Spin-up electron

$s = -1/2$  , spin-down electron (anti-clockwise)

↓ Spin-down electron

# Quantum number

<i>Value of l</i>	<i>Letter Designation</i>
0	s
1	p
2	d
3	f

<i>Value of n</i>	<i>Value of l</i>	<i>Values of <math>m_l</math></i>	<i>Subshell</i>	<i>Number of Orbitals</i>	<i>Number of Electrons</i>
1	0	0	1s	1	2
2	0	0	2s	1	2
	1	-1, 0, +1	2p	3	6
3	0	0	3s	1	2
	1	-1, 0, +1	3p	3	6
	2	-2, -1, 0, +1, +2	3d	5	10
4	0	0	4s	1	2
	1	-1, 0, +1	4p	3	6
	2	-2, -1, 0, +1, +2	4d	5	10
	3	-3, -2, -1, 0, +1, +2, +3	4f	7	14

**Source:** From J. E. Brady and F. Senese, *Chemistry: Matter and Its Changes*, 4th edition. Reprinted with permission of John Wiley & Sons, Inc.

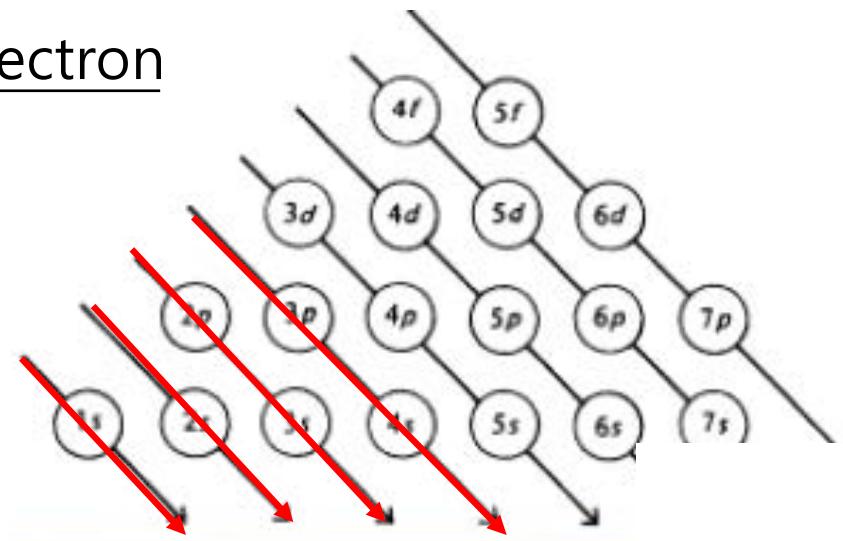
# Electron configuration 電子組態

## -電子填充軌域原則

(內層)

奧佛包程序(Aufbau process) : 低能階填到高能階

- in the ground state of an atom or ion, electrons fill atomic orbitals of the lowest available energy levels before occupying higher levels (e.g., 1s before 2s).
- In this way, the electrons of an atom or ion form the most stable electron configuration possible.



# Electron configuration 電子組態

## -電子填充軌域原則

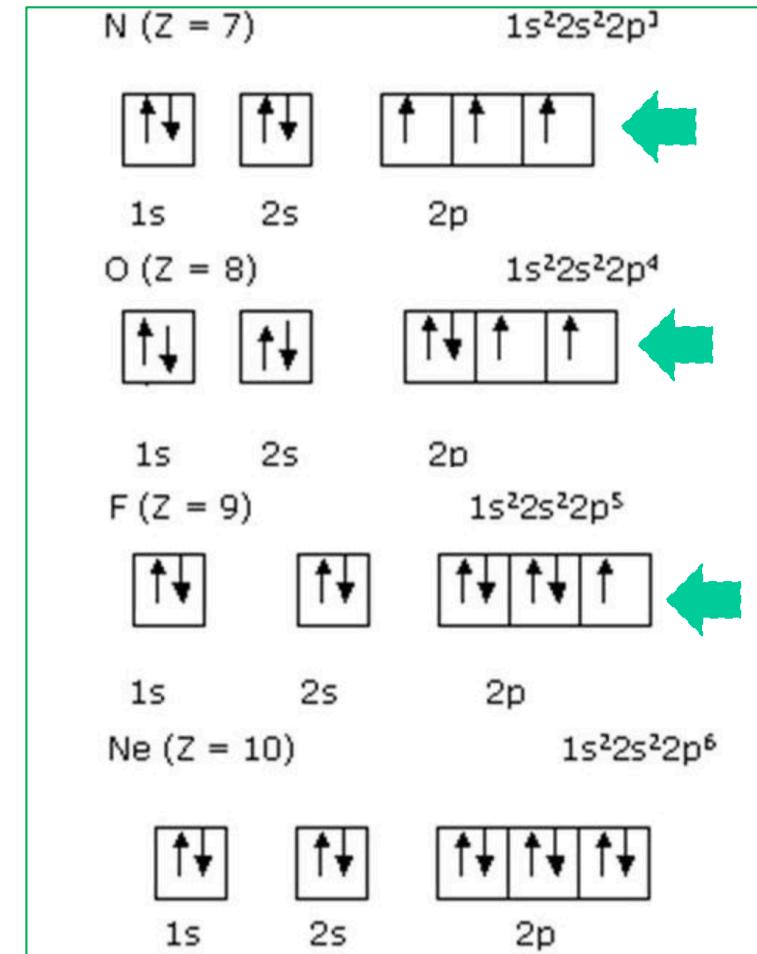
### Hund's rule (漢斯規則)

- Every orbital in a sublevel is singly occupied before any orbital is doubly occupied.  
先填半滿
- All of the electrons in singly occupied orbitals have the same spin (to maximize total spin).  
相同自旋方向

Aluminum : 13 electron

Electron configuration:  $1s^2 2s^2 2p^6 3s^2 3p^1$   
[Ne]  $3s^2 3p^1$

價電子  
結構  
Valent electron configuration:  $3s^2 3p^1$ ,  
Valent electron number:  $2 + 1 = 3$ 。



# Electron Configurations

## Electron in atom

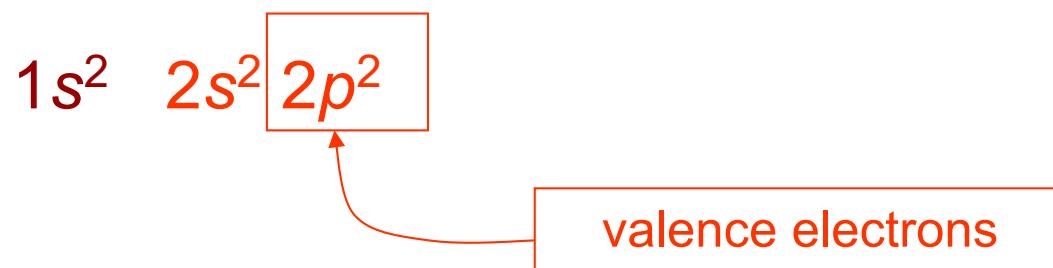
### 電子組態

價電子

- Valence electrons – those in **outer unfilled shells**
- Filled shells are more stable – require more energy to gain or lose electrons
- Valence electrons available for bonding and tend to determine an atom's chemical properties

決定化學性質

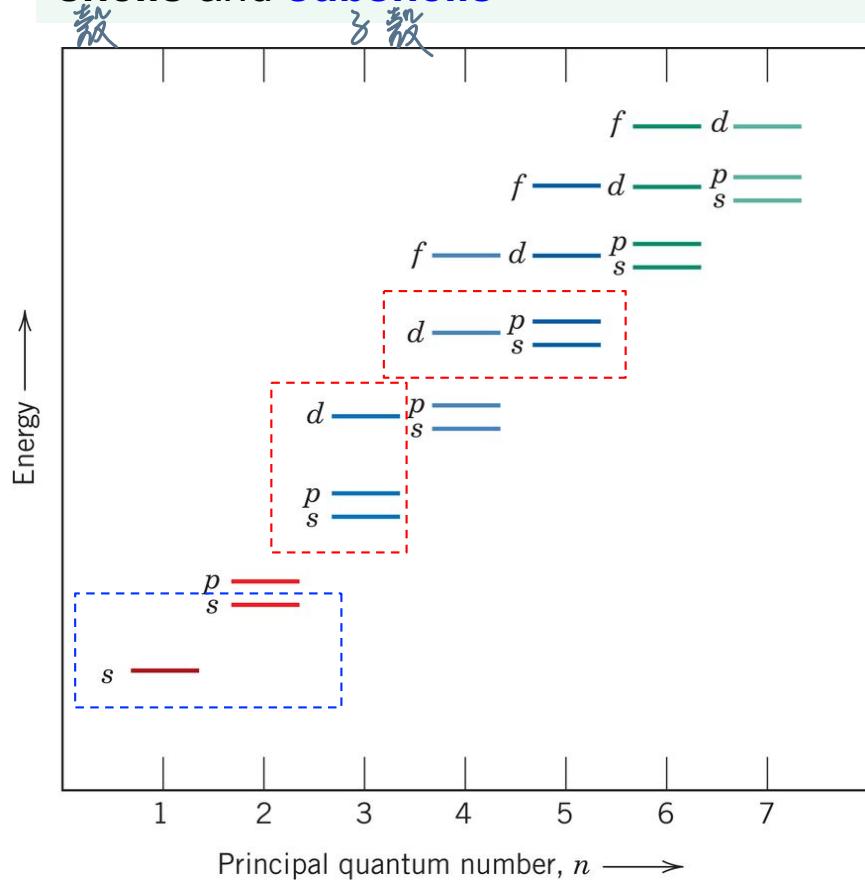
– example: C (atomic number = 6)



# Electron Configurations

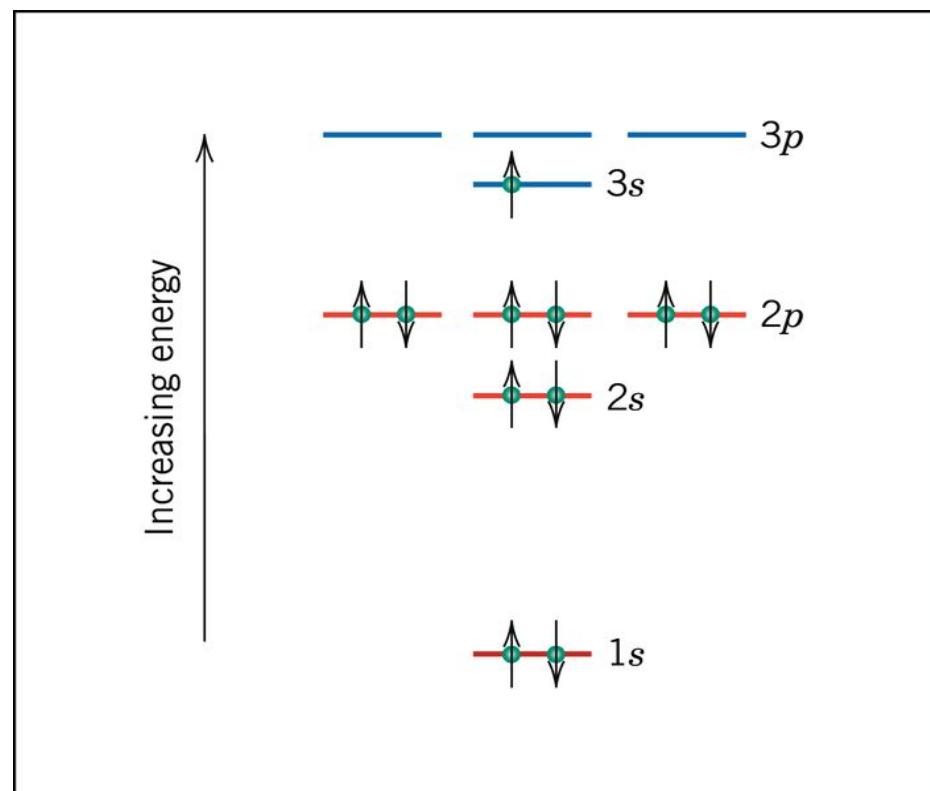
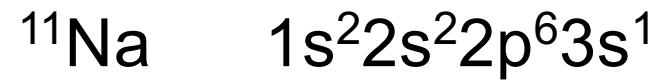
## Electron in atom

Relative energy of the electrons for the shells and subshells



From K. M. Ralls, T. H. Courtney, and J. Wulff, *Introduction to Materials Science and Engineering*, p. 22. Copyright © 1976 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.

Fig\_2-6

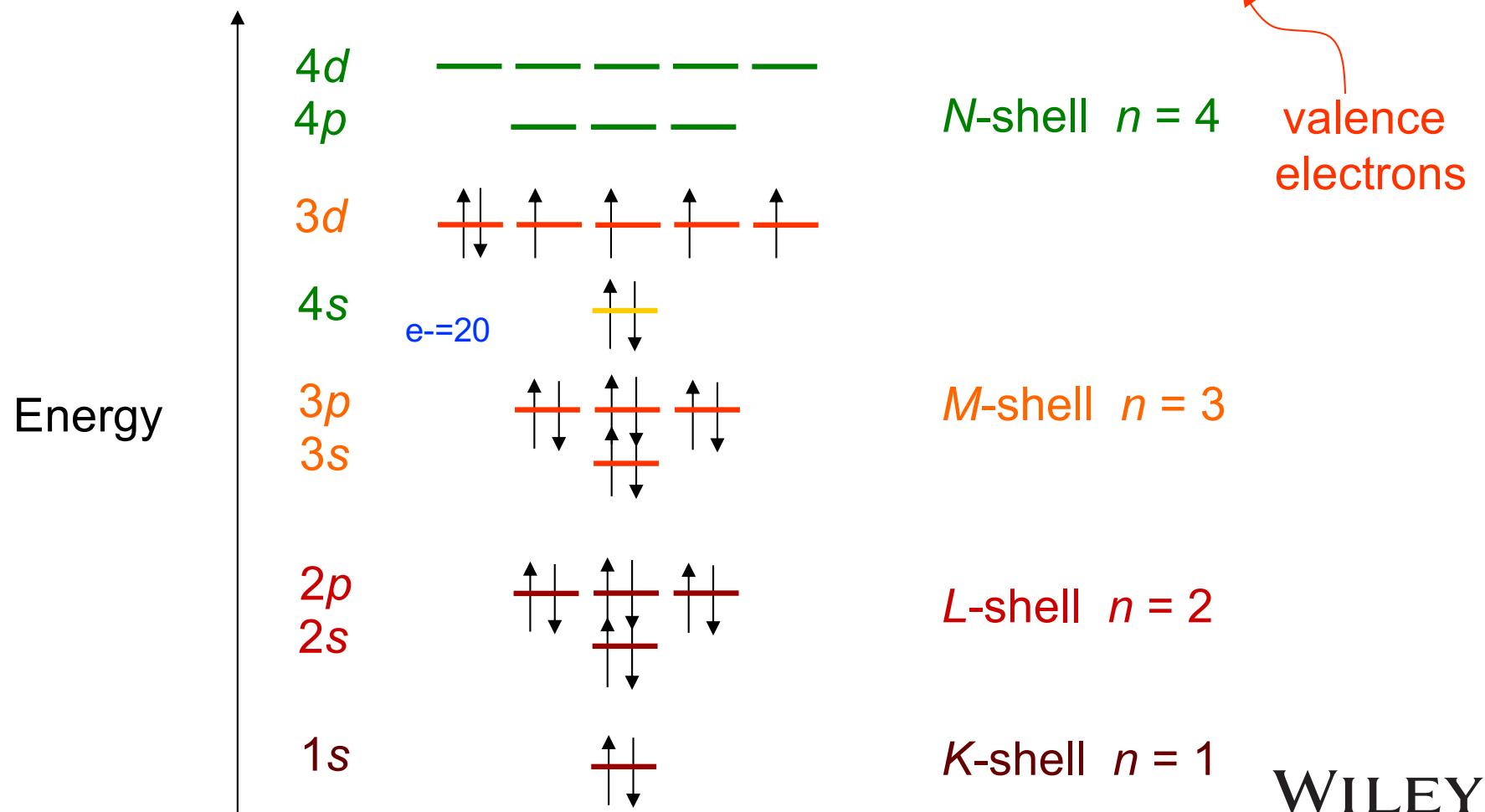


Fig\_2-7

# Electron Configurations

Fe (atomic # = 26)

Electron configuration     $1s^2$      $2s^2 2p^6$      $3s^2 3p^6$



- **Stable** : Outermost or valence electron shell are completely filled. 完全填滿
- Most elements: Electron configurations not stable.

<u>Element</u>	<u>Atomic #</u>	<u>Electron configuration</u>
Hydrogen	1	$1s^1$
✓ Helium	2	$1s^2$ (stable)
Lithium	3	$1s^2 2s^1$
Beryllium	4	$1s^2 2s^2$
Boron	5	$1s^2 2s^2 2p^1$
Carbon	6	$1s^2 2s^2 2p^2$
...		...
✓ Neon	10	$1s^2 2s^2 2p^6$ (stable)
Sodium	11	$1s^2 2s^2 2p^6 3s^1$
Magnesium	12	$1s^2 2s^2 2p^6 3s^2$
Aluminum	13	$1s^2 2s^2 2p^6 3s^2 3p^1$
...		...
✓ Argon	18	$1s^2 2s^2 2p^6 3s^2 3p^6$ (stable)
...		...
✓ Krypton	36	$1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10} 4s^2 4p^6$ (stable)



- Why not stable? Valence (outer) shell usually not completely filled.

# The Periodic Table

# Electron in atom

- Elements in each column: Similar valence electron structure

Na: 1s<sup>2</sup>2s<sup>2</sup>2p<sup>6</sup>3s<sup>1</sup>

- give up 1e-  
= give up 2e-  
= give up 3e-

Mg: 1s<sup>2</sup>2s<sup>2</sup>2p<sup>6</sup>3s<sup>2</sup>

**Electropositive elements:**  
Readily give up electrons  
to become + ions.

**Electronegative elements:**  
Readily acquire electrons  
to become - ions.

O:  $1s^2 2s^2 2p^4$

accept  $2e^-$

accept  $1e^-$

Ne: 1s<sup>2</sup>2s<sup>2</sup>2p<sup>6</sup>

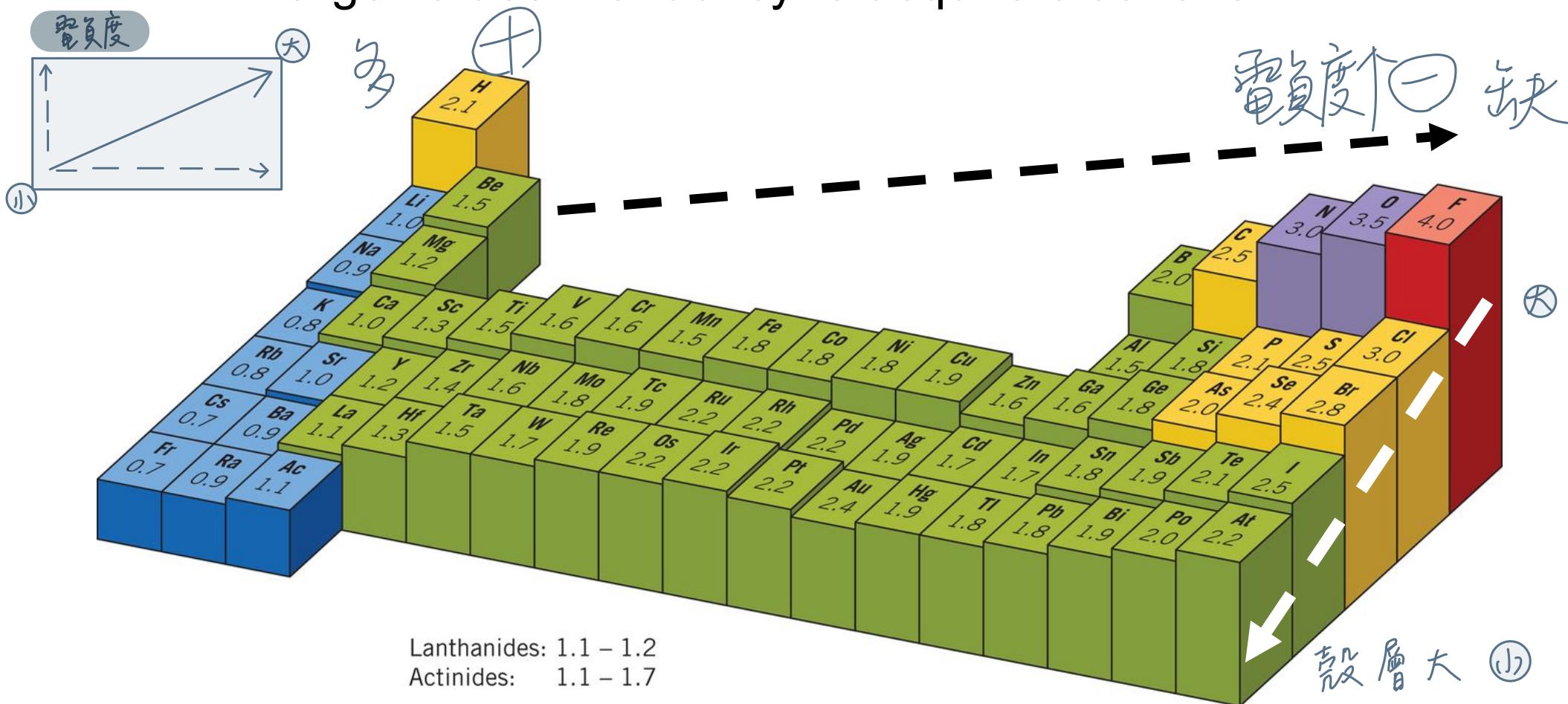
## Inert gases

# The Periodic Table

## Electronegativity

電負度 (拿到電子的能力)

- Ranges from 0.7 to 4.0,
- Large values: tendency to acquire electrons.



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EY

# **Atomic Binding in Solids**

## Two isolated atoms

孤立分子



- are brought into close proximity from an infinite separation.

At large distances



the interactions are negligible;

when atoms approach → each exerts forces on the other.  
**attractive & repulsive**

**F<sub>A</sub>** (**attractive force**): depends on the particular type of bonding that exists between the two atoms. Its magnitude varies with the distance,

**F<sub>R</sub>**(repulsive force ): when the outer electron shells of the two atoms begin to overlap comes into play.

與...重疊

**F<sub>N</sub>**(net force) : the sum of both attractive and repulsive components.

$$F_N = F_A + F_R$$

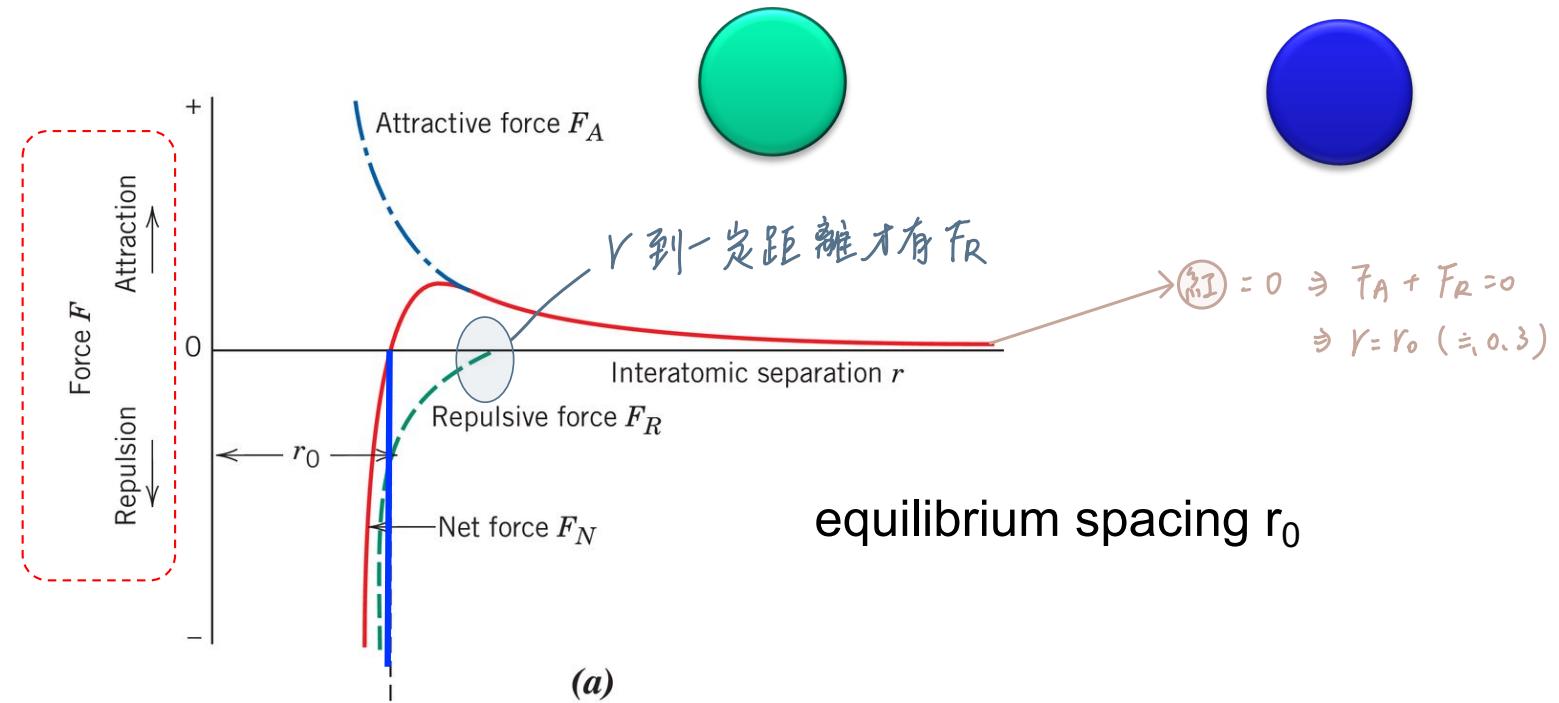
$$F_A + F_R = 0$$

$$F_R = -F_A$$

# Bonding forces and energies

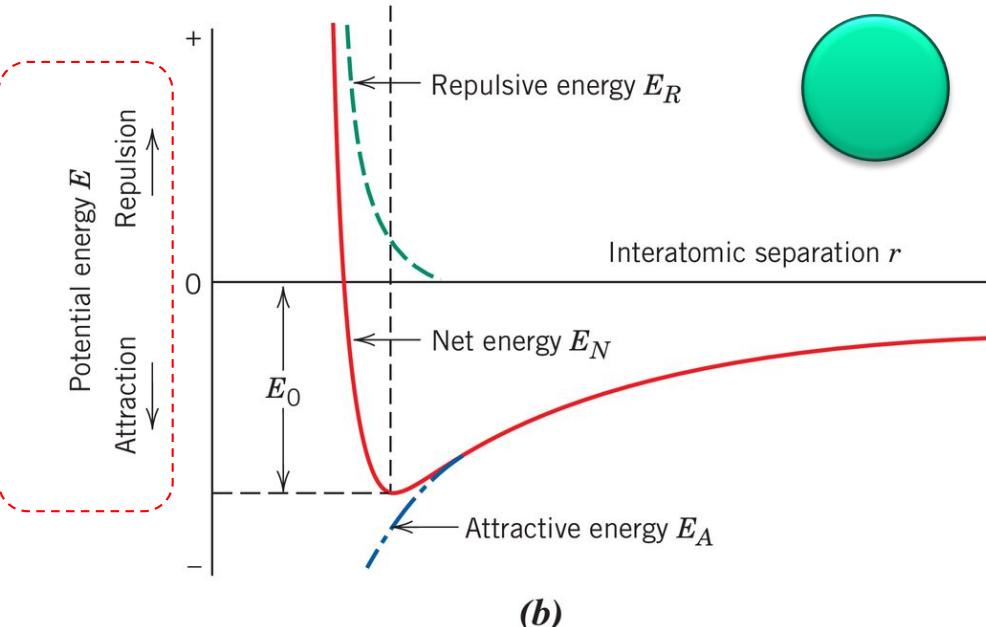
**Force**

$r_0$ : equilibrium space  
(0.3 nm)



斥力

**Potential energies**



Fig\_2-10

# Potential energies between two atoms

$$E = \int F dr$$

$$F = \frac{dE}{dr}$$

For two isolated and adjacent atoms

$$E_N = \int_r^\infty F_N dr$$

(r 原子的直徑)

靜位能

$$= \int_r^\infty F_A dr + \int_r^\infty F_R dr$$

$$= E_A + E_R$$

$$= \frac{dE_A}{dr} + \frac{dE_R}{dr}$$

$E_A$  (attractive energy)

$$E_A = -\frac{A}{r}$$

$E_R$  (Repulsive energy)

$$E_R = \frac{B}{r^n}$$

A, B, n = constant

電子的質量

$$A = \frac{1}{4\pi\epsilon_0} (|Z_1|e)(|Z_2|e)$$

常數      |價電子數|

$\epsilon_0$  真空穿透率

# Primary Interatomic Bonds

## Ionization Process

metal atom + nonmetal atom

↑  
給出  $e^-$   
donates  
electrons

↑  
接受  $e^-$   
accepts  
electrons

電負度差異大  $\Rightarrow$  離子化 (電子交換)

離子鍵 (有方向性)

Dissimilar electronegativities

ex: MgO

Mg     $1s^2 2s^2 2p^6$   $3s^2$   
[Ne]  $3s^2$

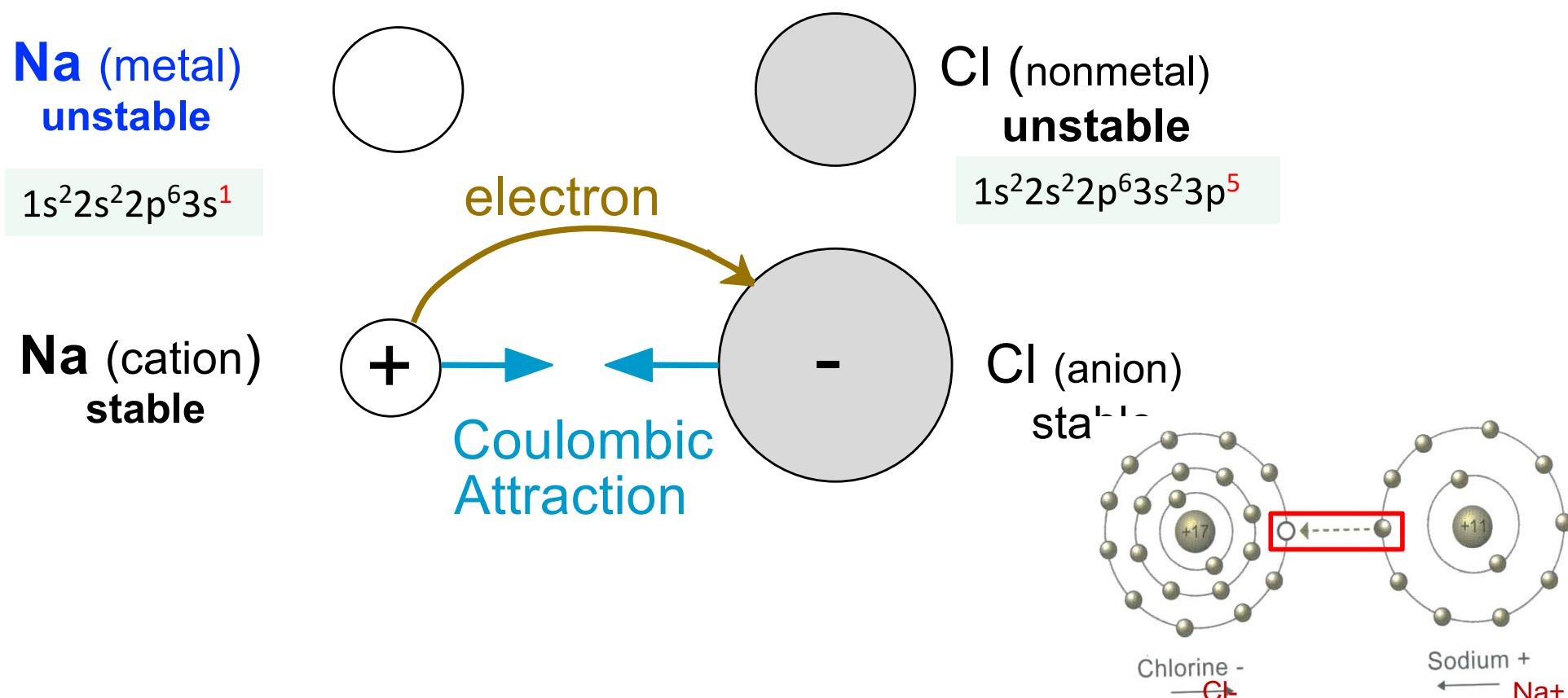
O     $1s^2 2s^2 2p^4$

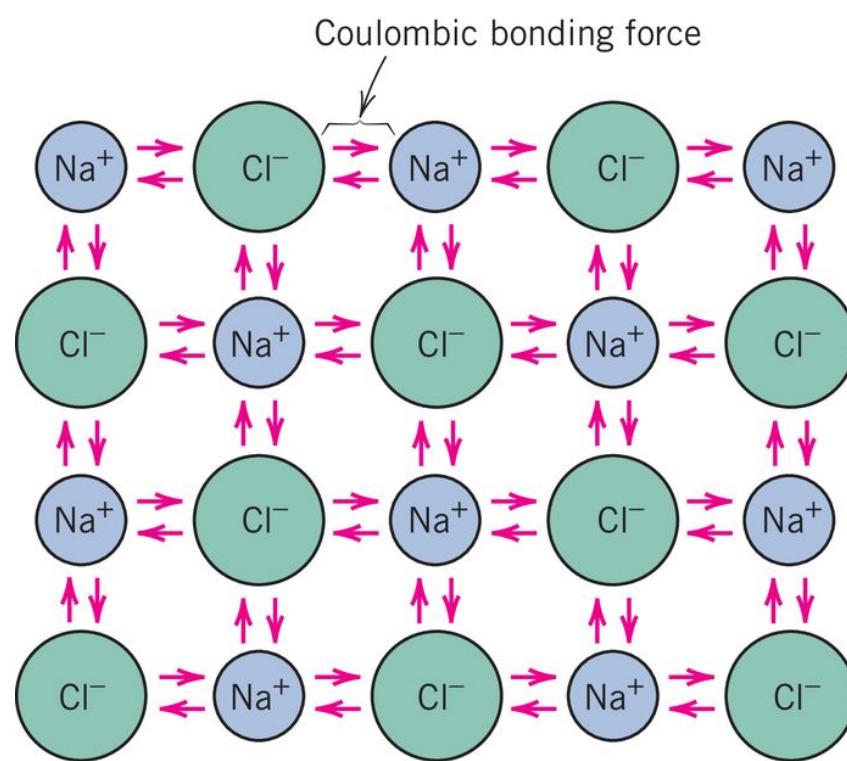
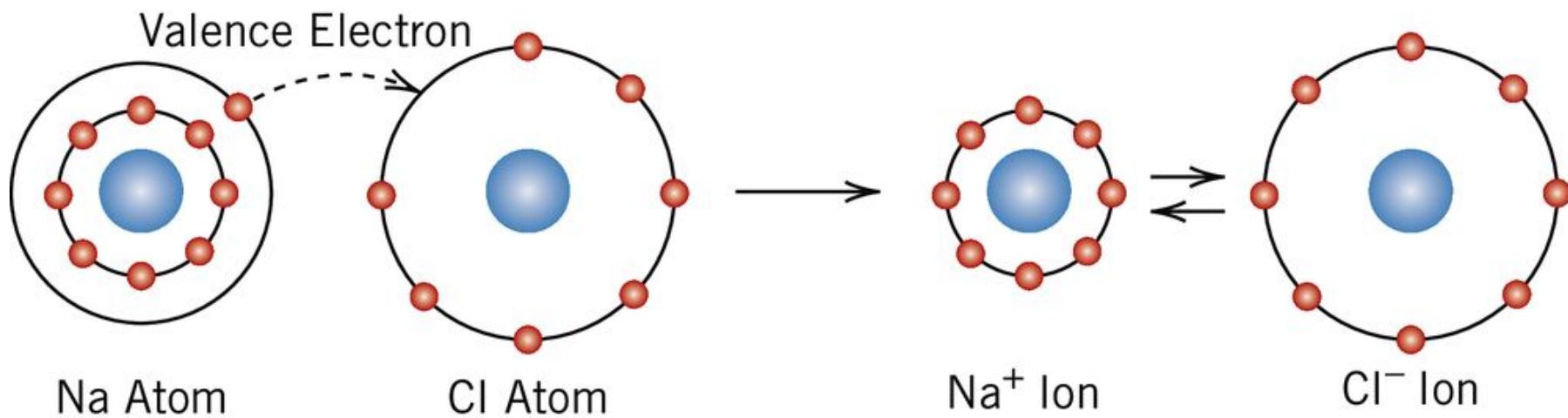
$Mg^{2+}$   $1s^2 2s^2 2p^6$   
[Ne]

$O^{2-}$   $1s^2 2s^2 2p^6$   
[Ne]

# Ionic Bonding

- Occurs between + and - ions.
- Requires electron transfer.
- Large difference in electronegativity required.
- Example: NaCl





# Ionic Bonding

- Energy – minimum energy most stable
  - Net energy = sum of **attractive** and **repulsive** energies
  - Equilibrium separation when net energy is a minimum

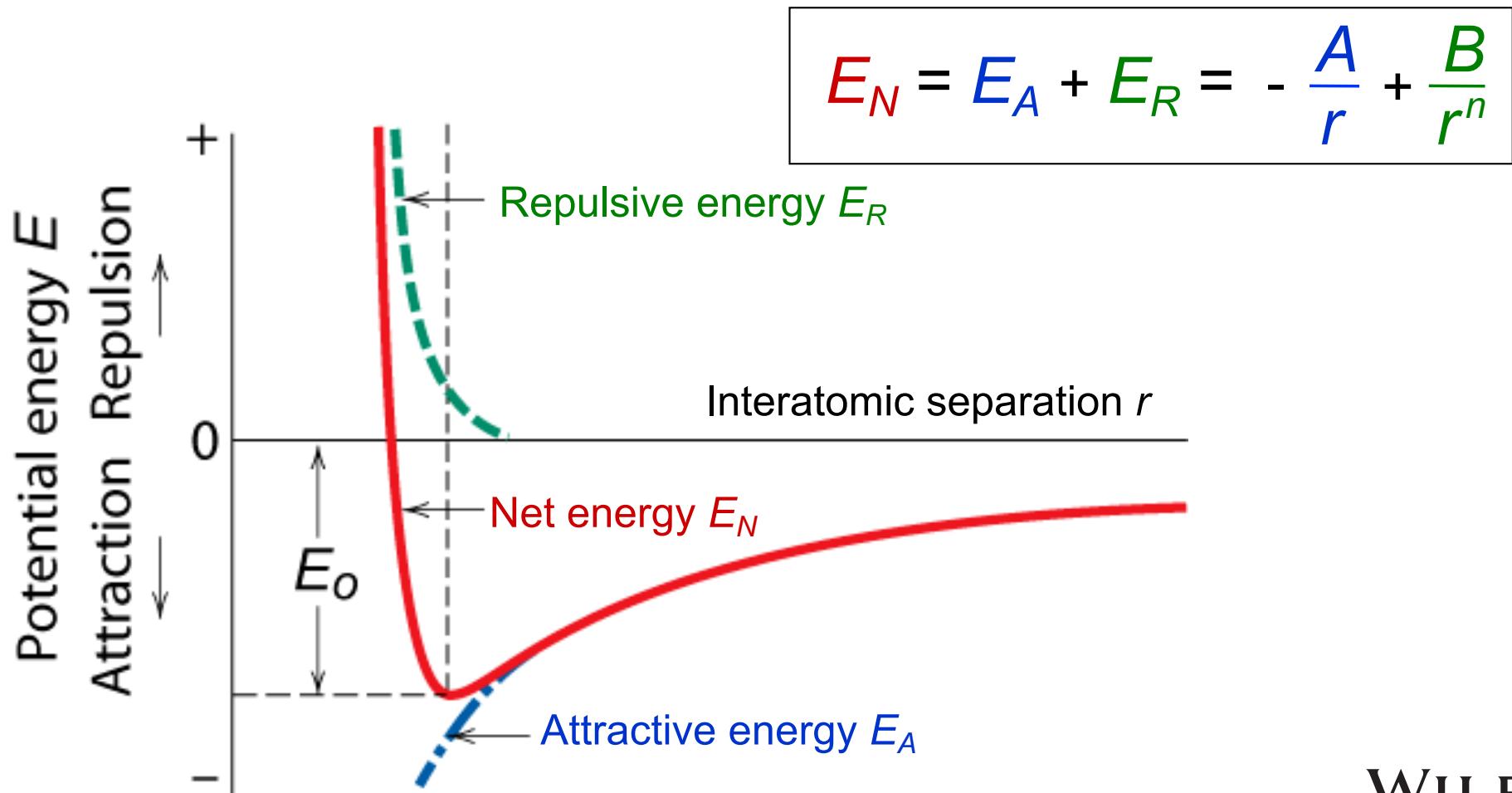


Fig. 2.10(b), Callister & Rethwisch 5e.

$$E_A = -\frac{A}{r}$$

dashed arrow pointing from  $E_A$  to  $F_A$

$$F_A = \frac{dE_A}{dr} = \frac{d\left(-\frac{A}{r}\right)}{dr} = -\left(\frac{-A}{r^2}\right) = \frac{A}{r^2} \quad (2.12)$$

$$F_A = \frac{1}{4\pi\varepsilon_0 r^2} (|Z_1|e)(|Z_2|e) \quad (2.13)$$

For example: **KBr**

$$\begin{aligned} F_A &= \frac{1}{4\pi(8.85 \times 10^{-12} \text{ F/m})(r^2)} [|Z_1|(1.602 \times 10^{-19} \text{ C})][|Z_2|(1.602 \times 10^{-19} \text{ C})] \\ &= \frac{(2.31 \times 10^{-28} \text{ N} \cdot \text{m}^2)(|Z_1|)(|Z_2|)}{r^2} = 2.07 \times 10^{-9} \text{ N} \end{aligned} \quad (2.14)$$

$$\begin{aligned} r_0 &= r_{\text{K}^+} + r_{\text{Br}^-} \\ &= 0.138 \text{ nm} + 0.196 \text{ nm} \\ &= 0.334 \text{ nm} \\ &= 0.334 \times 10^{-9} \text{ m} \end{aligned}$$

$$F_R = -F_A = -2.07 \times 10^{-9} \text{ N}$$

# Ionic Bonding

Predominant bonding in **Ceramics**

陶

Examples:

IA	NaCl																	0
IIA	MgO																	He
III A	CaF <sub>2</sub>																	Ne
IV A	CsCl																	Ar
V A	B C N O F																	
VI A	Al Si P S Cl																	
VII A	K Ca Sc Ti V Cr Mn Fe Co Ni Cu Zn Ga Ge As Se Br Kr																	
VIII	Rb Sr Y Zr Nb Mo Tc Ru Rh Pd Ag Cd In Sn Sb Te I Xe																	
IB	Cs Ba La Hf Ta W Re Os Ir Pt Au Hg Tl Pb Bi Po At Rn																	
IIIB	Fr Ra Ac																	

Lanthanides: 1.1-1.2  
Actinides: 1.1-1.7

Give up electrons

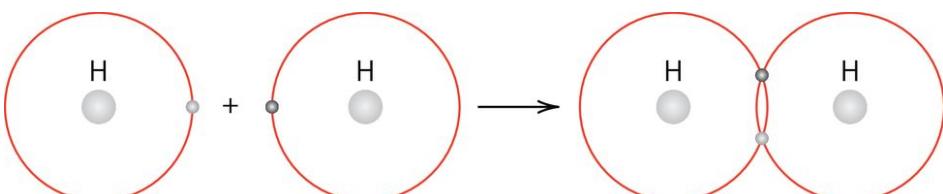
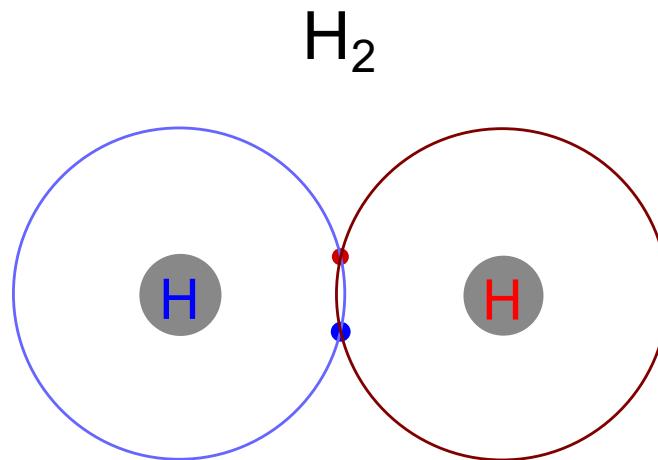
Acquire electrons

# Covalent Bonding

- Similar electronegativities ∴ share electrons
- Bonds involve valence electrons – normally *s* and *p* orbitals are involved
- Example:  $\text{H}_2$

Each H: has 1 valence  $e^-$ ,  
needs 1 more

Electronegativities are  
the same.



• shared 1s electron  
from 1st hydrogen  
atom

• shared 1s electron  
from 2nd hydrogen  
atom

Fig. 2.12, Calliser & Rethwisch 5e.

# Covalent Bonding: Bond Hybridization

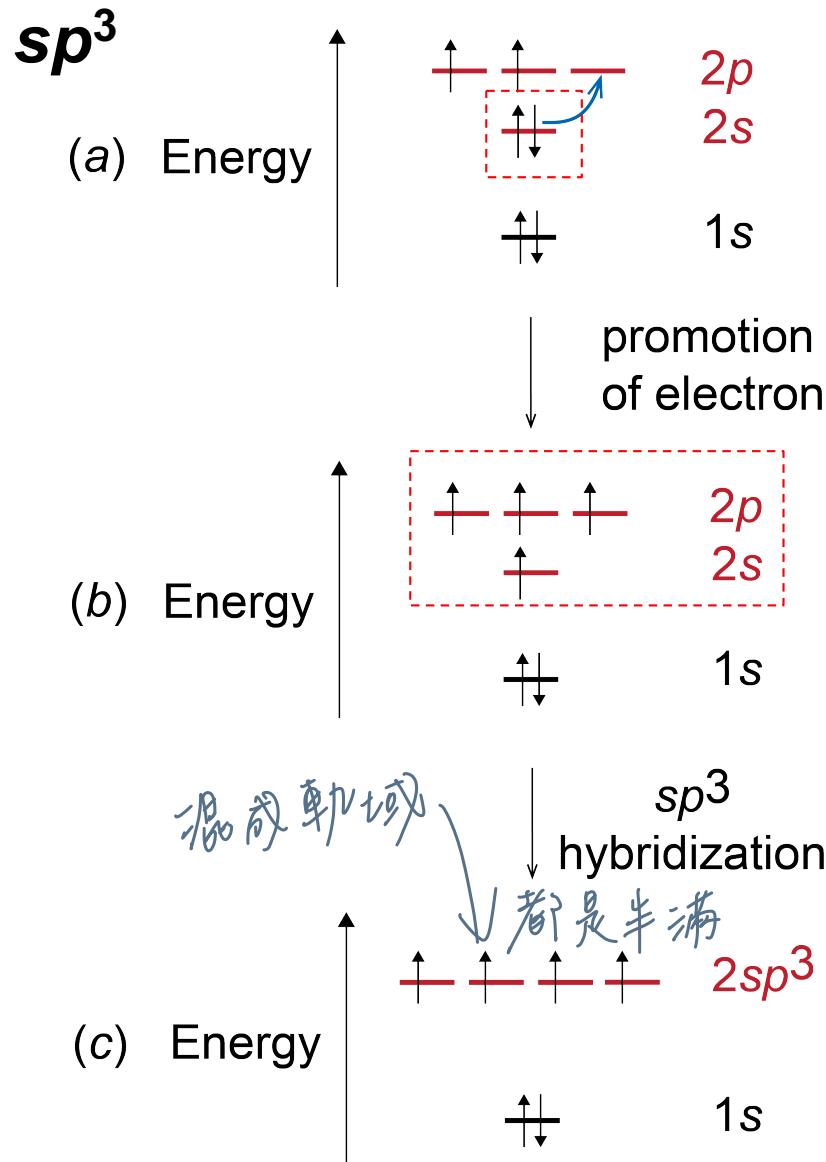


Fig. 2.13, Callister & Rethwisch 5e.

- Carbon can form  $sp^3$  hybrid orbitals

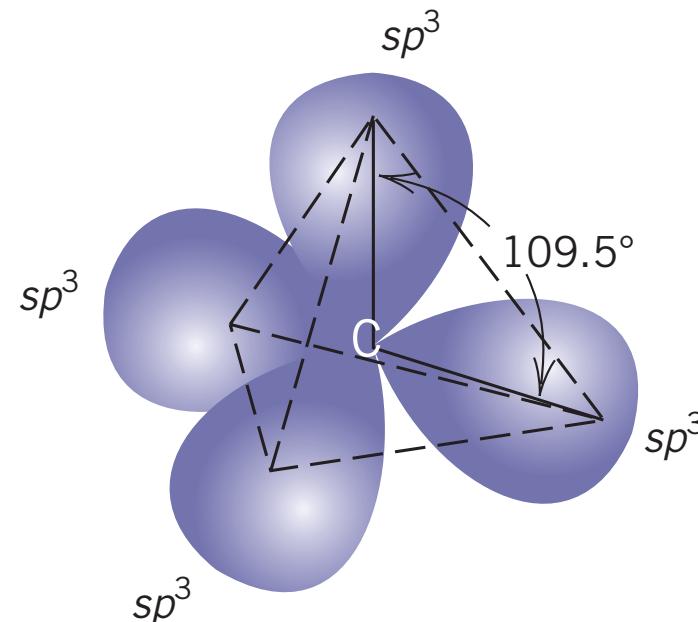


Fig. 2.14, Callister & Rethwisch 5e.  
(Adapted from J.E. Brady and F. Senese, *Chemistry: Matter and Its Changes*, 4<sup>th</sup> edition. Reprinted with permission of John Wiley and Sons, Inc.)

# Covalent Bonding

## Hybrid $sp^3$ bonding involving carbon

Example:  $\text{CH}_4$

電負度差異不大  
⇒ 共享電子

C: each has 4 valence electrons,  
needs 4 more (2.5 mV)

H: each has 1 valence electron,  
needs 1 more (2.1 mV)

Electronegativities of C and H are similar, so electrons are shared in  $sp^3$  hybrid covalent bonds.

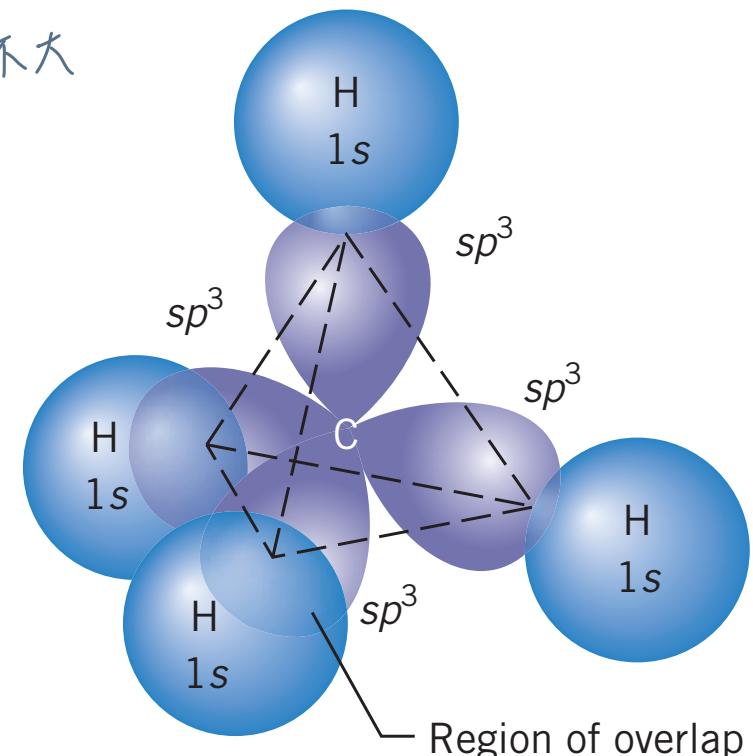
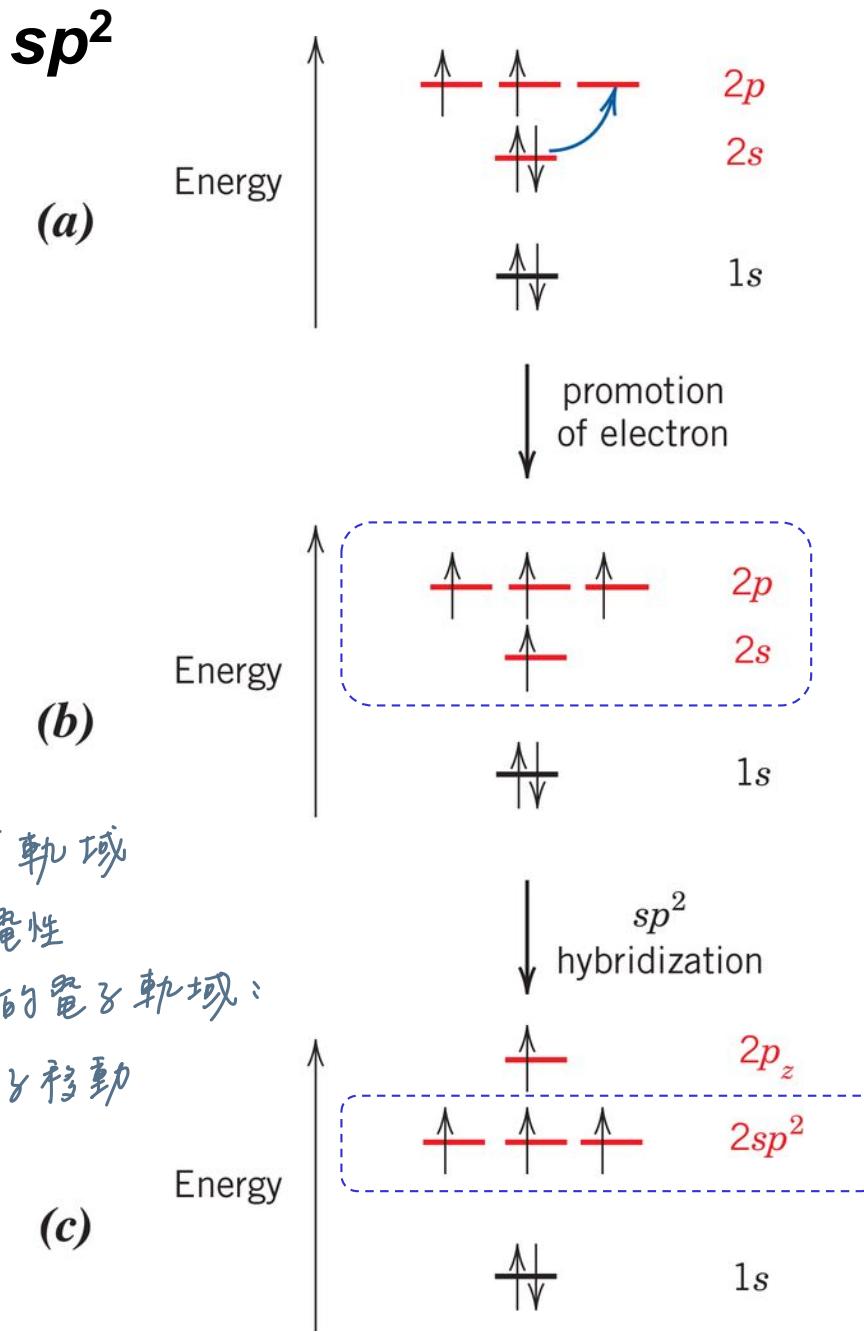
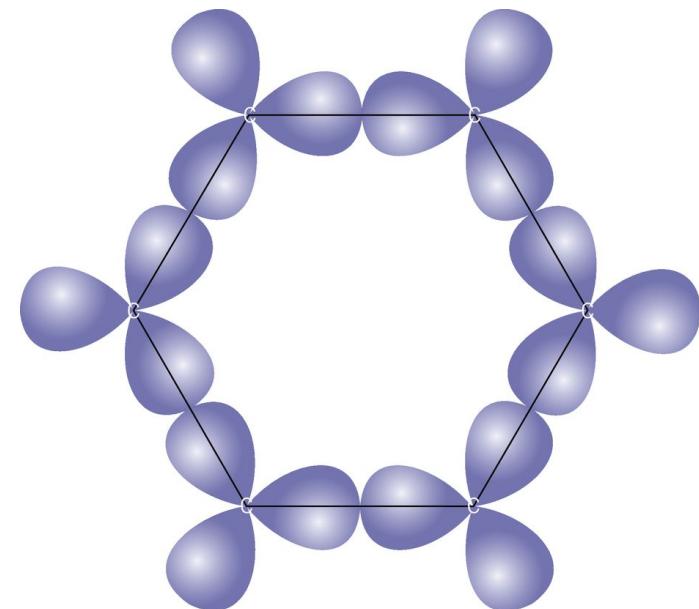


Fig. 2.15, Callister & Rethwisch 5e.  
(Adapted from J.E. Brady and F. Senese, *Chemistry: Matter and Its Changes*, 4<sup>th</sup> edition. Reprinted with permission of John Wiley and Sons, Inc.)



The diagram illustrates the trigonal planar geometry of a molecule. A central point labeled 'C' is surrounded by three large, semi-transparent blue circles representing  $sp^2$  hybrid orbitals. These orbitals are arranged in a triangular pattern, forming the vertices of an equilateral triangle. The angle between the axes of any two adjacent orbitals is labeled as  $120^\circ$ . The label  $sp^2$  is placed once at the top and once at the bottom left of the diagram.

From J. E. Brady and F. Senese, *Chemistry: Matter and Its Changes*, 4th edition. Reprinted with permission of John Wiley & Sons, Inc.



e<sup>-</sup>不固定在某個上  
是自由電子  
electrons cloud

↓  
無方向性  
↓  
延展性佳

“共價鍵”有方向性  
“離子、金屬鍵”無方向性(自由電子)

# Metallic Bonding

- Electrons delocalized to form an “electron cloud”

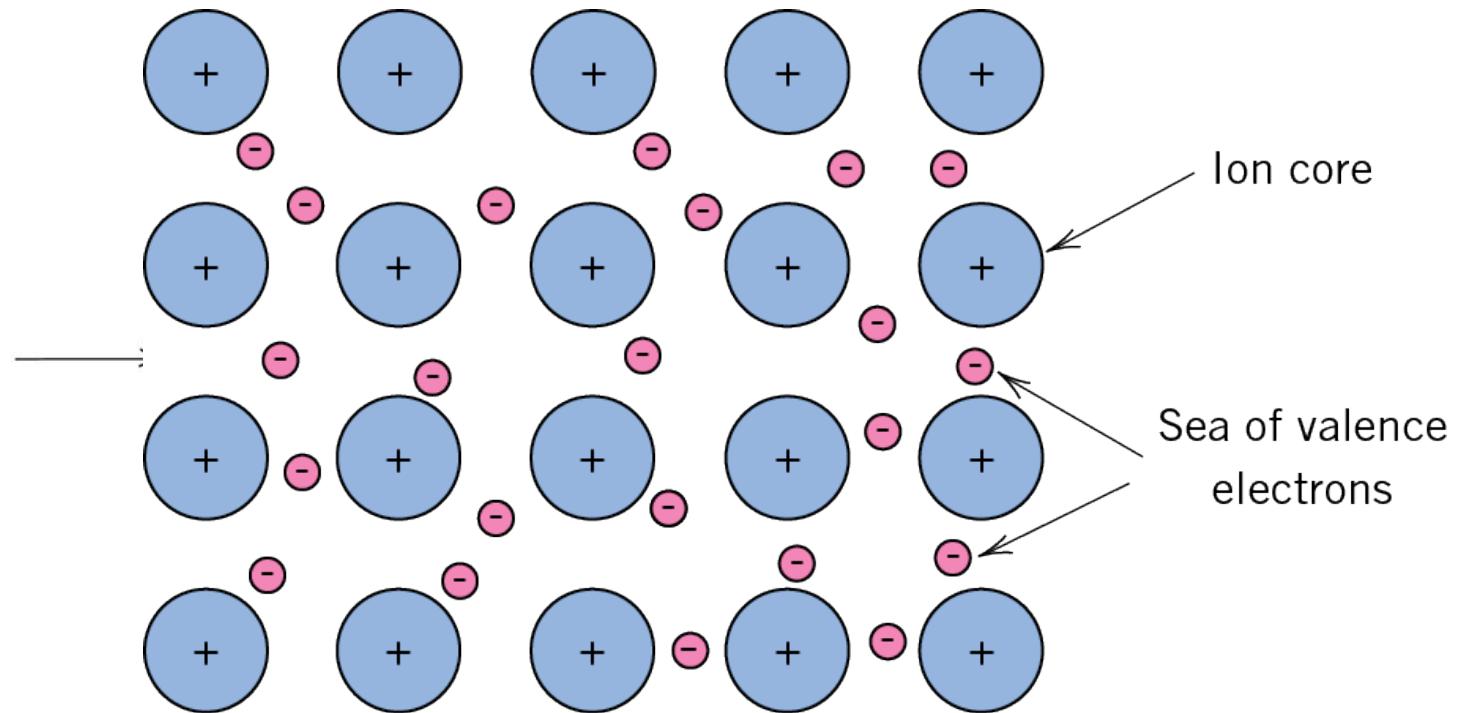
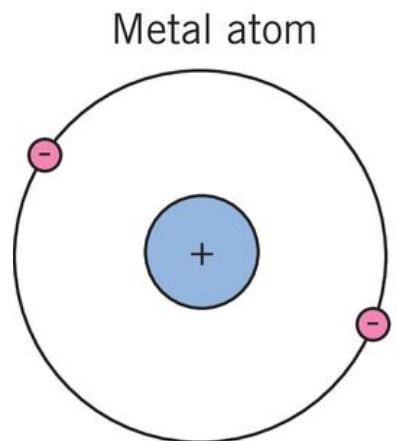


Fig. 2.19, Callister & Rethwisch 5e.

Table 2-3

答：

網狀離子體

<i>Substance</i>	<i>Bonding Energy (kJ/mol)</i>	<i>Melting Temperature (°C)</i>
<b>Ionic</b>		
NaCl	640	801
LiF	850	848
MgO	1000	2800
CaF <sub>2</sub>	1548	1418
<b>Covalent</b>		
Cl <sub>2</sub>	121	-102
Si	450	1410
InSb	523	942
C (diamond)	713	>3550
SiC	1230	2830
<b>Metallic</b>		
Hg	62	-39
Al	330	660
Ag	285	962
W	850	3414
<b>van der Waals<sup>a</sup></b>		
Ar	7.7	-189 (@ 69 kPa)
Kr	11.7	-158 (@ 73.2 kPa)
CH <sub>4</sub>	18	-182
Cl <sub>2</sub>	31	-101
<b>Hydrogen<sup>a</sup></b>		
HF	29	-83
NH <sub>3</sub>	35	-78
H <sub>2</sub> O	51	0

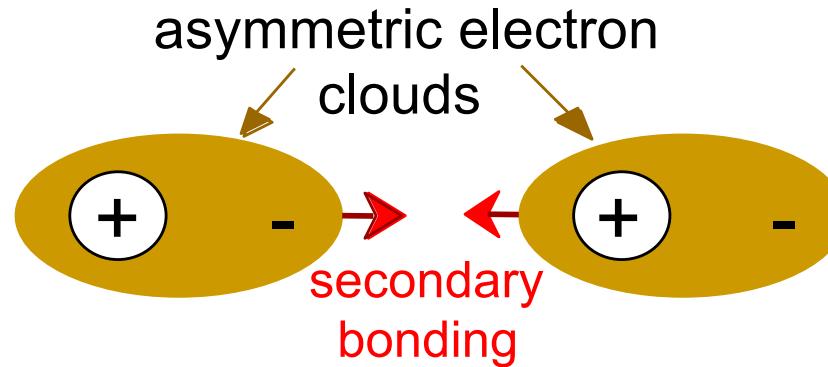
<sup>a</sup>Values for van der Waals and hydrogen bonds are energies *between* molecules or atoms (*intermolecular*), not between atoms within a molecule (*intramolecular*).

## **Secondary Bonding or Van Der Waals Bonding**

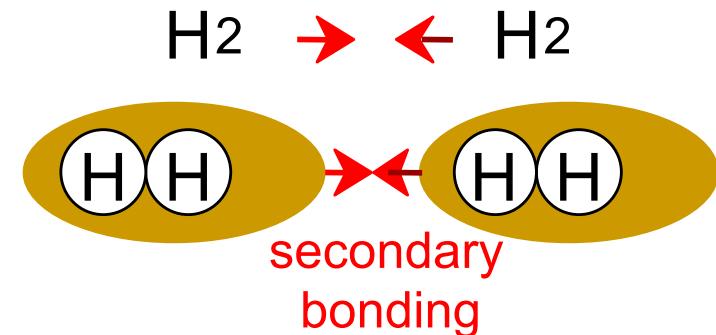
# Secondary Bonding

Arises from attractive forces between dipoles (偶極)

- Fluctuating dipoles (擾動偶極)



ex: liquid H<sub>2</sub>



- Permanent dipoles (永久偶極)

原子本身的電荷影響

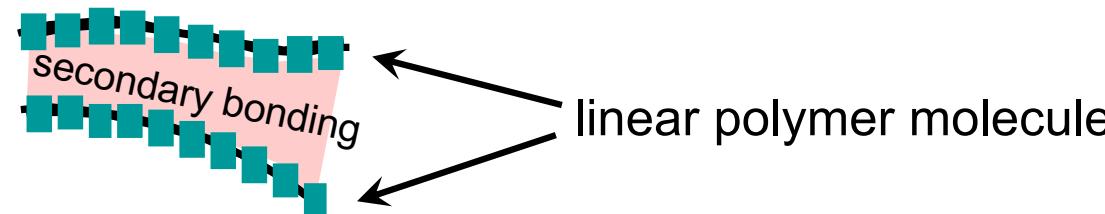
-general case:



-ex: liquid HCl

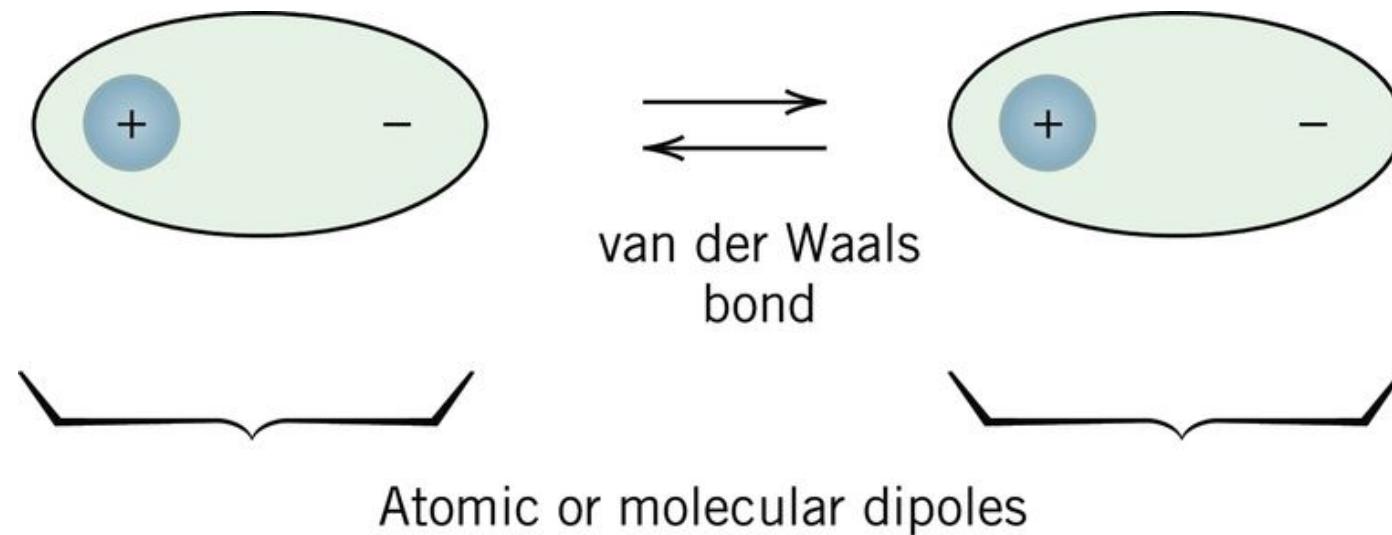


-ex: polymer



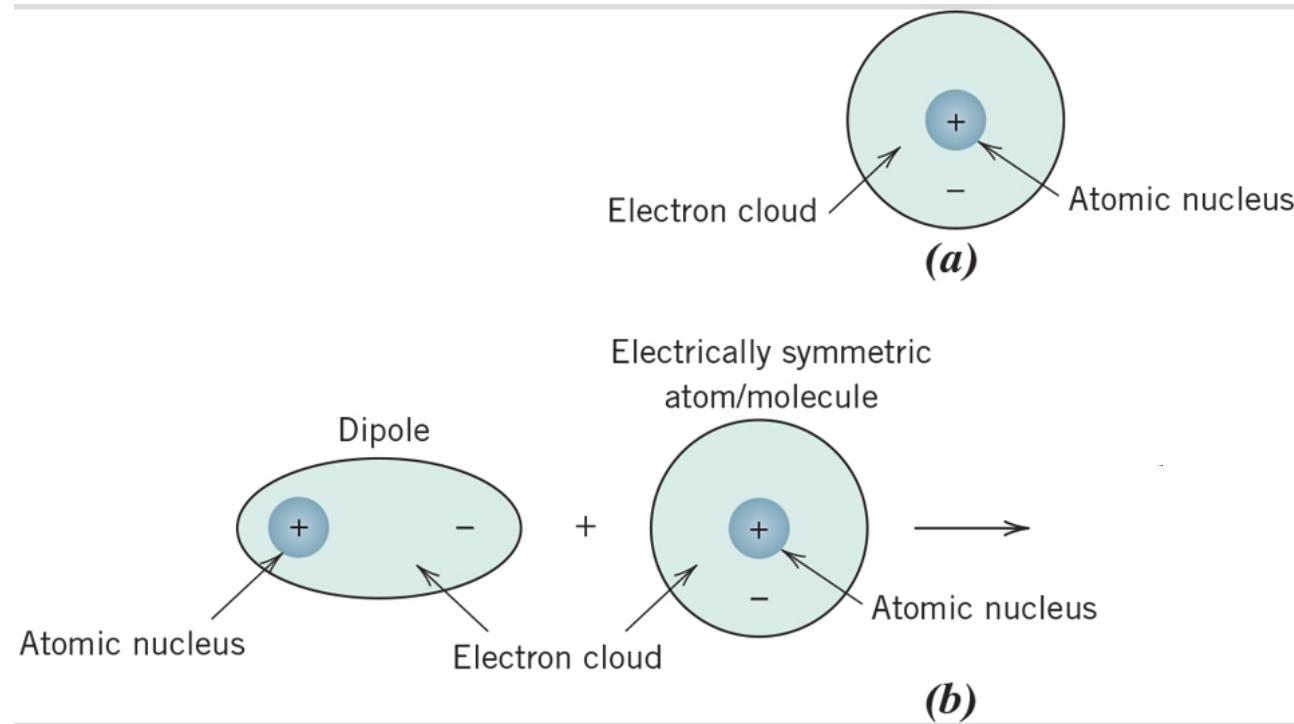
# Secondary Bonding

## Van Der Waals Bonding



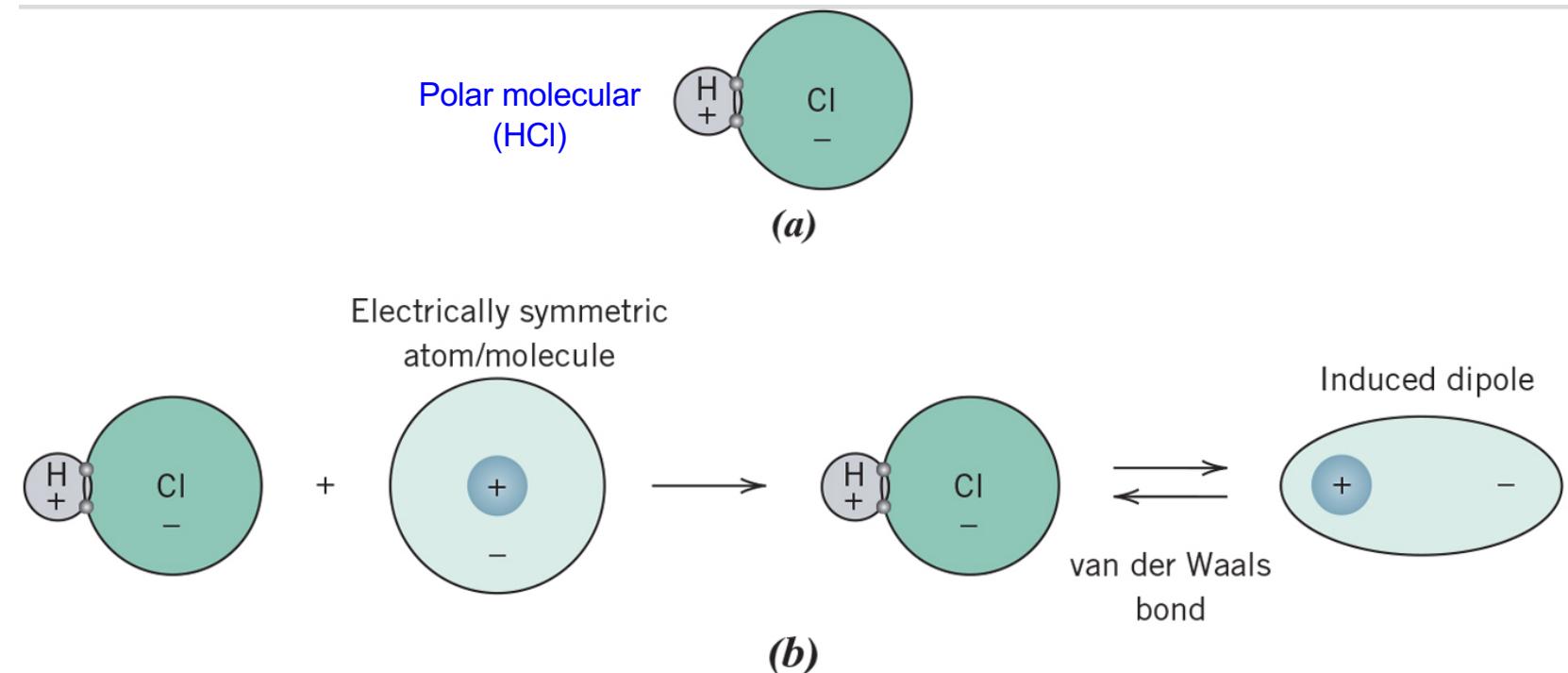
Fig\_2-20

## Fluctuating induced dipole bonds (擾動感應偶極鍵)

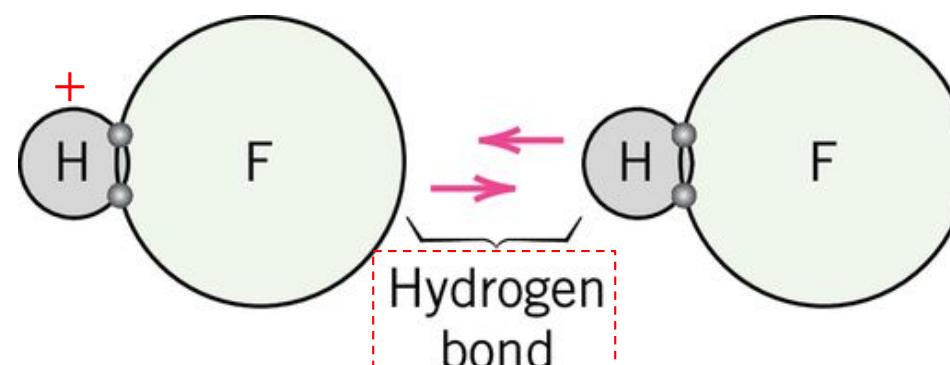


Fig\_2-21

# Polar molecule-induced dipole bonds (極性分子感應偶極鍵)



## Permanent dipole bonds (永久偶極鍵)



H-F (HF)

H-O (H<sub>2</sub>O)

H-N (NH<sub>3</sub>)

Fig\_2-23

H-bond: 51 kJ/mol

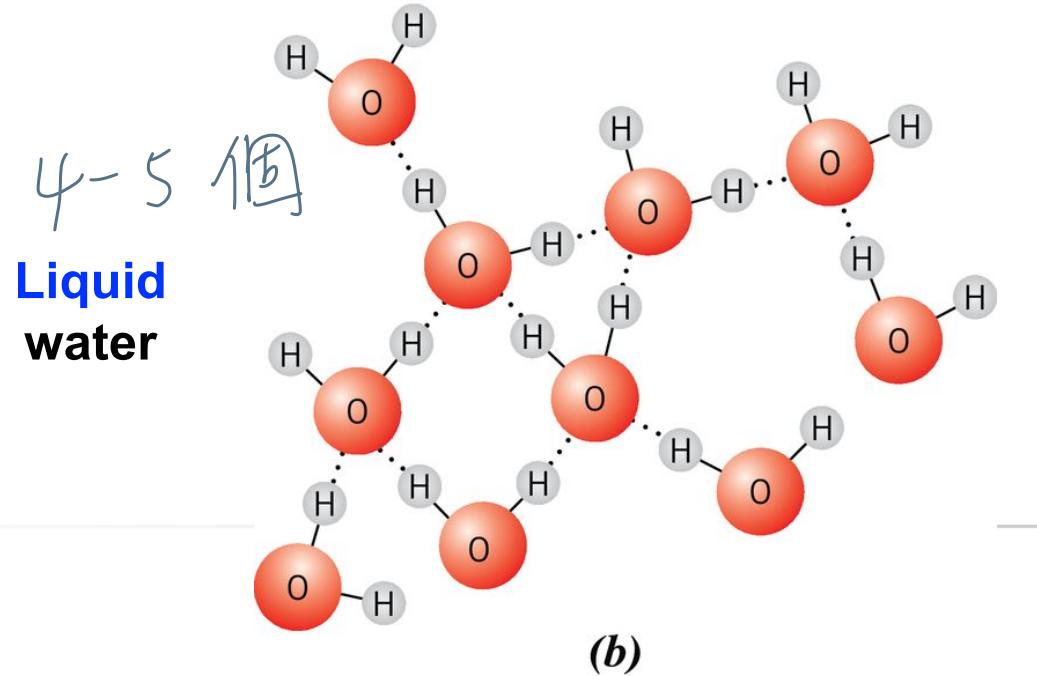
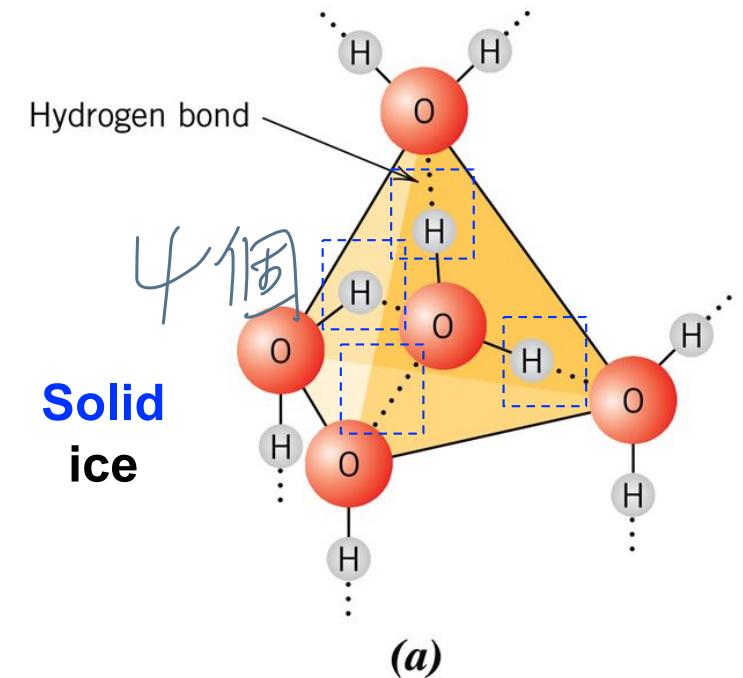
The strongest bond  
(secondary bonding)

# Water

*Volume expansion upon freezing*

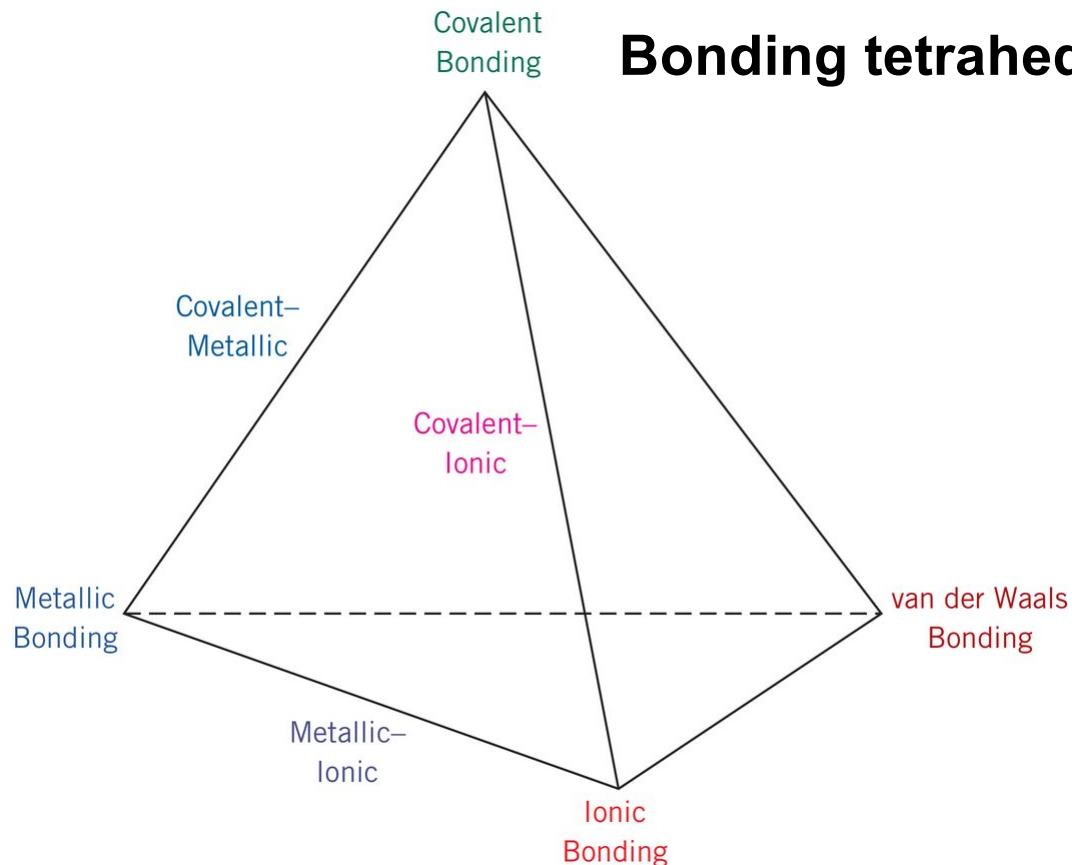


密度:  $D_l > D_s$

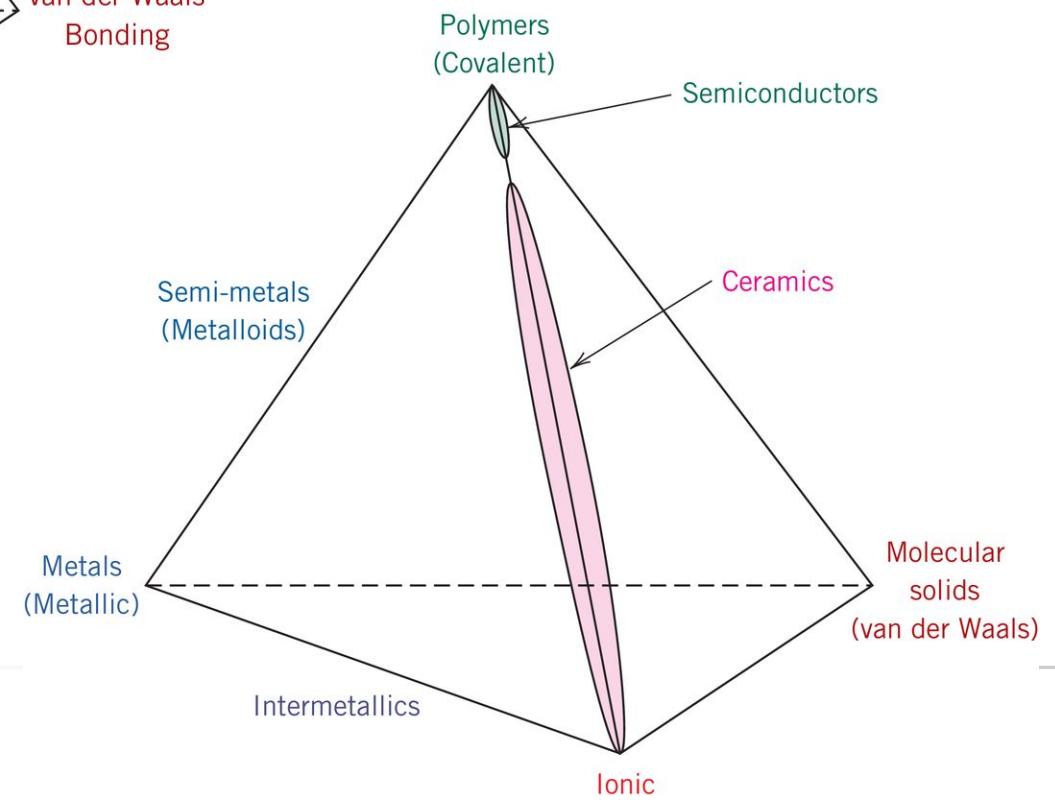


Fig\_2-24

## Bonding tetrahedron



## Material-type tetrahedron



Fig\_2-25a

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Fig\_2-25b

# Mixed Bonding

- Most common mixed bonding type is **Covalent-Ionic mixed bonding**

**電負度**

$$\% \text{ ionic character} = \left( 1 - e^{-\frac{(X_A - X_B)^2}{4}} \right) \times (100\%)$$

計算：偏離子 or 共價鍵

$$\% \text{ IC} = \{ 1 - \exp [ - (0.25)(X_A - X_B)^2 ] \} \times 100 \quad (2.16)$$

where  $X_A$  &  $X_B$  are **electronegativities** of the two elements participating in the bond

Ex: **MgO**

$$X_{\text{Mg}} = 1.3$$

$$X_{\text{O}} = 3.5$$

50% ↑ 偏離子

$$\% \text{ ionic character} = \left( 1 - e^{-\frac{(3.5 - 1.2)^2}{4}} \right) \times (100\%) = 73.4\%$$

## Equation Summary

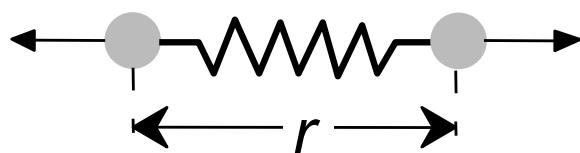
Equation Number	Equation	Solving For	Page Number
2.5a	$E = \int F dr$	Potential energy between two atoms	29
2.5b	$F = \frac{dE}{dr}$	Force between two atoms	29
2.9	$E_A = -\frac{A}{r}$	Attractive energy between two atoms	30
2.11	$E_R = \frac{B}{r^n}$	Repulsive energy between two atoms	31
2.13	$F_A = \frac{1}{4\pi\epsilon_0 r^2} ( Z_1 e)( Z_2 e)$	Force of attraction between two isolated ions	33
2.16	$\%IC = \{1 - \exp[-(0.25)(X_A - X_B)^2]\} \times 100$	Percent ionic character	41

公式

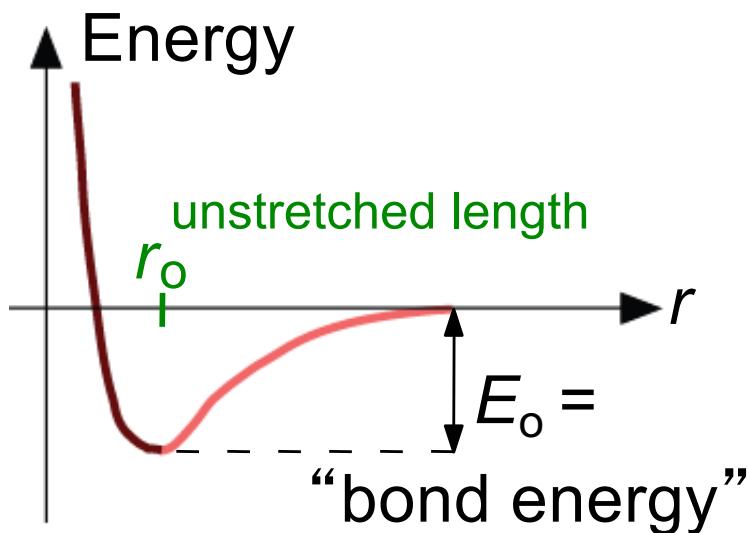
# Properties Related to Bonding I:

## Melting Temperature ( $T_m$ )

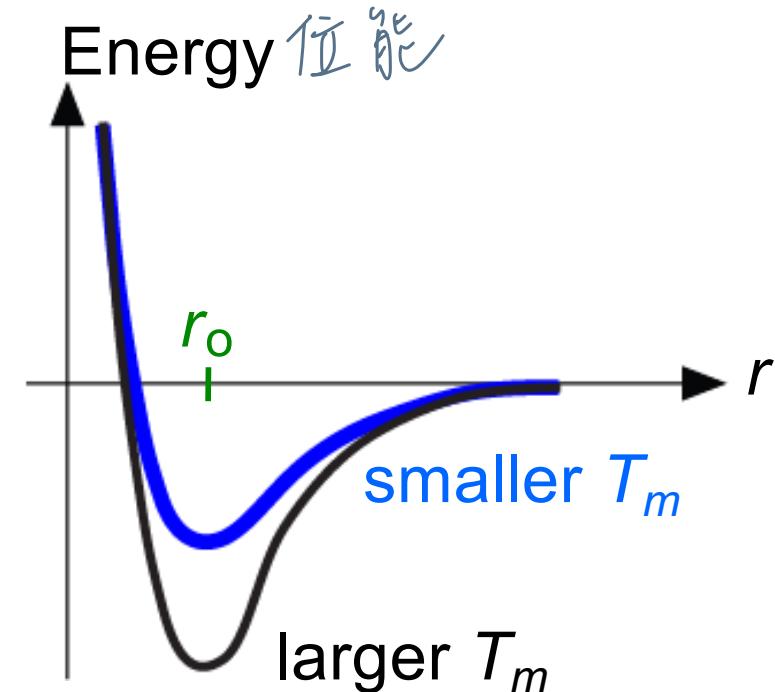
- Bond length,  $r$



- Bond energy,  $E_o$



- Melting Temperature,  $T_m$



The larger  $E_o$ , the higher  $T_m$ .

# Summary: Properties Related to Bonding Type and Bonding Energy

## Ceramics

(Ionic & covalent bonding):

Large bond energy

high  $T_m$

large  $E$

small  $\alpha_t$  热擴散係數 (隔熱)

## Metals

(Metallic bonding):

Variable bond energy

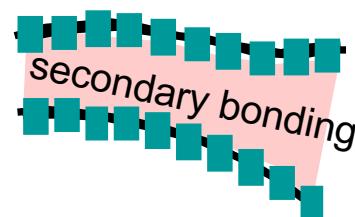
moderate  $T_m$

moderate  $E$

moderate  $\alpha_t$

## Polymers

(Covalent & Secondary):



Weak bond energy (between chains)

Secondary bonding responsible for most physical properties

low  $T_m$

small  $E$

large  $\alpha_t$

# SUMMARY

- A material's chemical, electrical, thermal, and optical properties are determined by **electronic configuration.**  
*電子組態*
- **Valence electrons** occupy the outermost unfilled electron shell.
- Primary bonding types include **covalent, ionic, and metallic bonding.**
- Secondary or van der Waals bonds are weaker than the primary bonding types.
- The percent **ionic character** of a covalent-ionic mixed bond between two elements depends on their **electronegativities.**