CH-110 Advanced General Chemistry I

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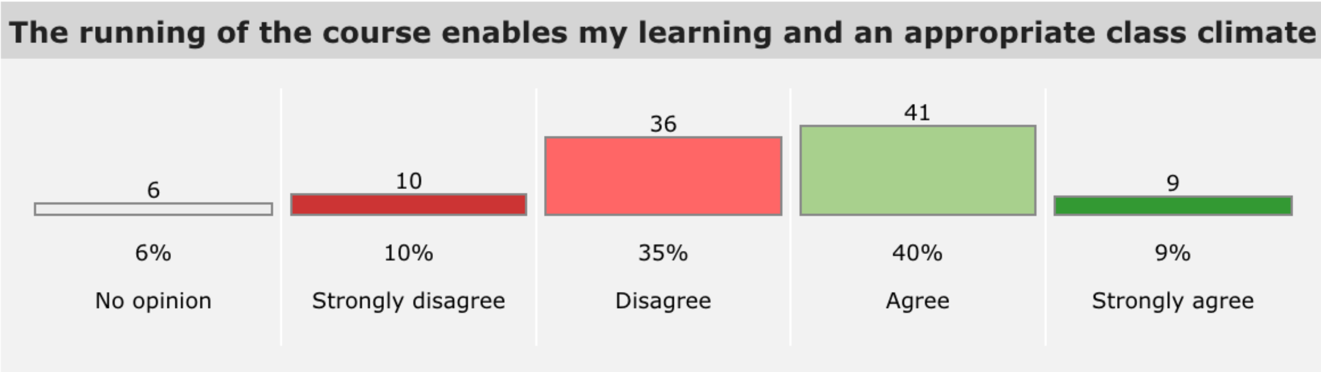
Indicative feedback

- 102 responses out of 146 registered students:

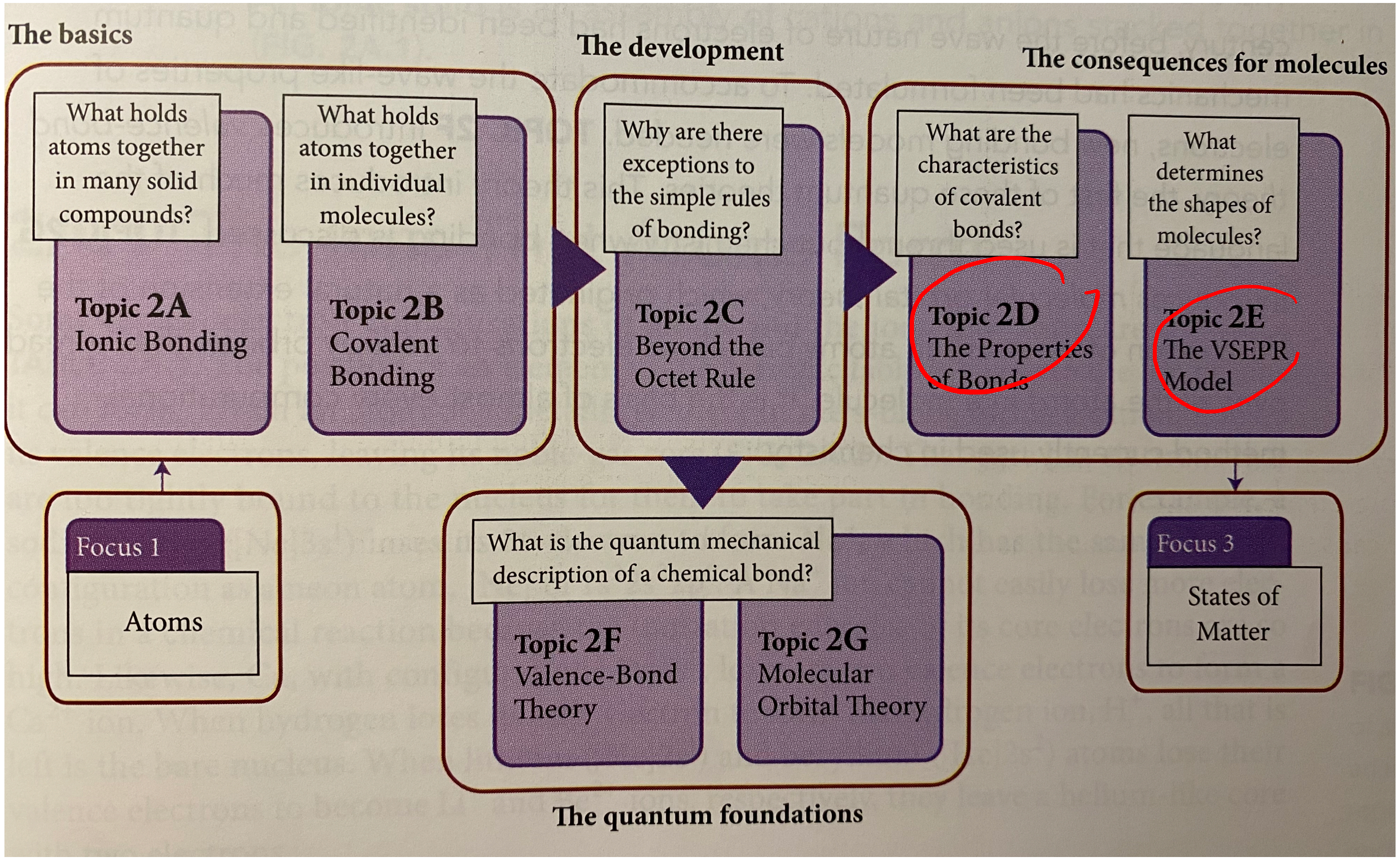


Feedback	Implementation
Clear(er) learning goals and structure than last year.	Thank you.
Highlighting of important formulas is appreciated.	Thank you.
Responsiveness and openness to feedback is appreciated.	Thank you
TAs are very helpful.	That's great, will let them know!

Indicative feedback

Feedback	Implementation
Class too dense and fast-paced. Too many slides, difficult to know what is important.	I've **reduced the number of slides and eliminated content** significantly compared to last year. Will do my best to cut even more to essentials. **Study guides** on Moodle should help with prioritizing. Recommendation: **To study for the exam, solve exercises (handouts and extra in book)**. This helps you prioritize what you need to learn.
Course sometimes feels like reading slides, not enough additional explanation or conceptual links.	I'll make a greater effort to explain the logic behind formulas and connect concepts beyond what's written on the slides.
Visual materials: some people don't like AI-generated images.	Will keep them. I use conventional (non-AI) generated images when they exist.
Language support, difficulty with English	We provide all materials in French. Most TAs speak French. You can ask questions in French if you prefer.
Lecture and exercises could be more closely aligned.	Integrate more exercises into lectures if time allows. Will double-check that lecture materials contain all info to solve exercises.
Volume and speed at the end of lectures.	I'll be more attentive to pacing and audibility throughout the lecture. Reminder to you: be quiet for your classmates' sake.

Overview Chapter 2 (Focus 2: Bonds Between Atoms)



The Properties of Bonds

Topic 2D

Topic 2D.1 Correcting the covalent model: electronegativity
Topic 2D.2 Correcting the ionic model: polarizability
Topic 2D.3 Bond strengths
Topic 2D.4 Bond lengths

WHY DO YOU NEED TO KNOW THIS MATERIAL?

- Properties of bonds vary widely. Variations in bond strength, bond length, and the distribution of electrons in a bond, are used to explain the physical and chemical properties of molecules.

WHAT DO YOU NEED TO KNOW ALREADY?

- Periodic trends (Topic 1F)
- Concept of resonance (Topic 2B)
- Role of electron-pair sharing in covalent bonding (Topic 2B)

Correcting the Covalent Model: Electronegativity

Topic 2D.1

2D.1 Correcting the covalent model: electronegativity

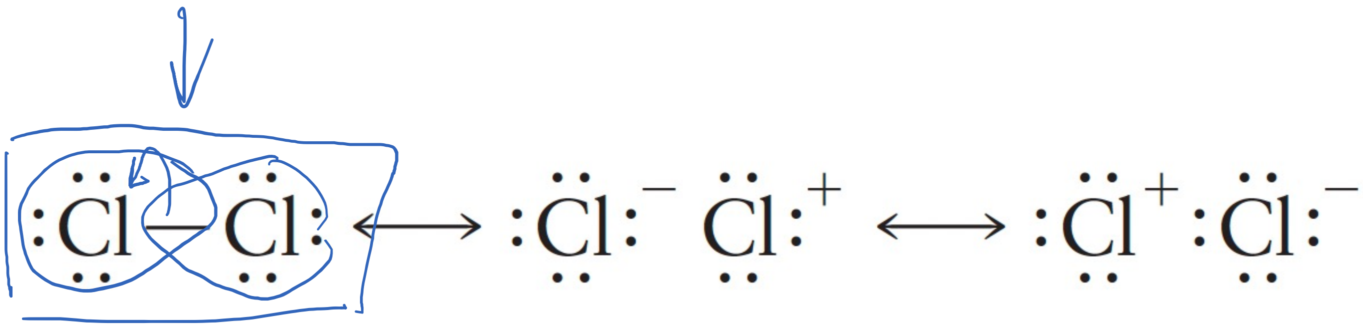
Two extremes

Covalent bonding ⟷ Ionic bonding

Many compounds exist
somewhere in the middle

2D.1 Correcting the covalent model: electronegativity

Two extremes

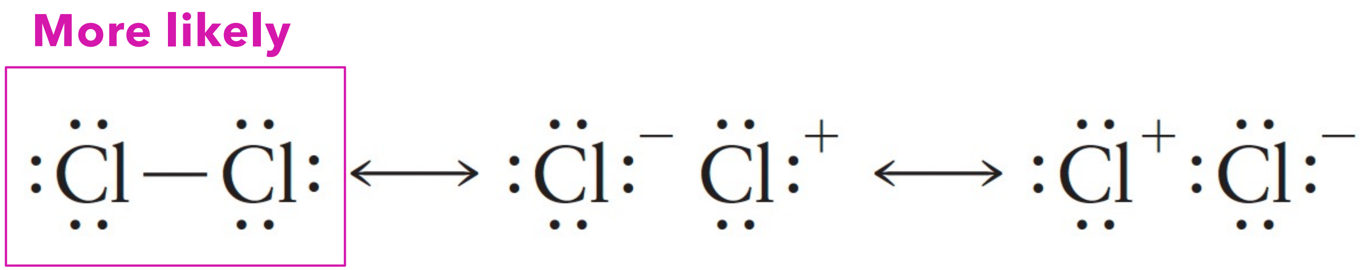


Covalent bonding ⟷ Ionic bonding

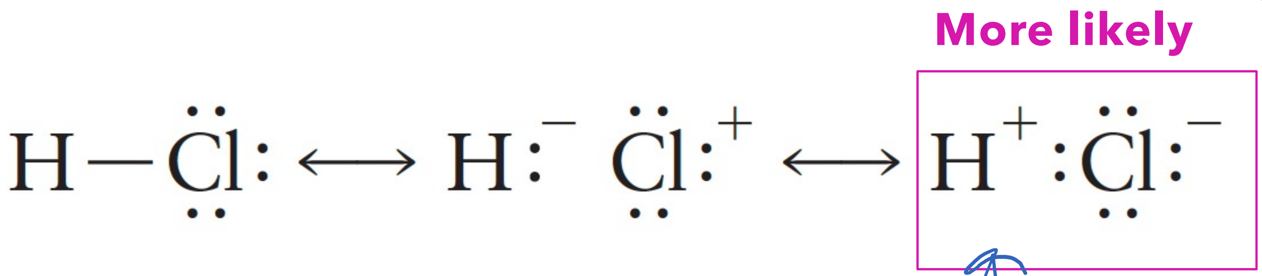
All molecules should be viewed as **resonance hybrids of purely covalent and purely ionic structures**

2D.1 Correcting the covalent model: electronegativity

Two extremes



Covalent bonding ⟷ Ionic bonding



F > O > N/Cl > Br > I > S > C/Se > H

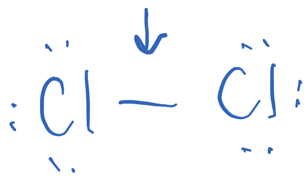
2D.1 Correcting the covalent model: electronegativity

Partial charges

- Outcome of resonance favoring in H–Cl: small negative charge on Cl, small positive charge on H (**partial charges**)

$$^{\delta+}\mathrm{H{-}Cl}^{\delta-}$$

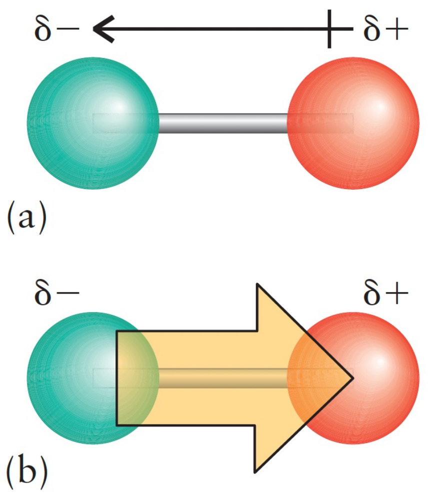
- A bond with nonzero partial charge: **polar covalent bond**
- A bond with zero partial charge: **nonpolar bond**



2D.1 Correcting the covalent model: electronegativity

Electric dipole :

partial pos. charge next to an equal and opposite partial neg. charge



- **Partial charges** on the two atoms in polar covalent bond form **an electric dipole.**

(a) Dipole represented by arrow that points to negative partial charge (chemistry)

(b) Modern convention (used here): arrows point to positive partial charge in this class

- **The electric dipole moment** (μ) describes the magnitude of an electric dipole, units: debye (D)

$$\mu = q \times r$$

2D.1 Correcting the covalent model: electronegativity

Electronegativity (χ): Pauling vs. Mullikan

Electronegativity (χ) : **the electron-pulling power of an atom in a molecule**

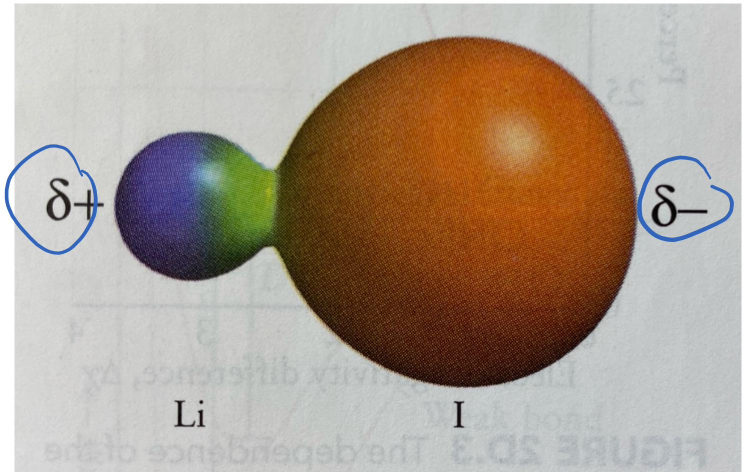


Figure 2D.1

2D.1 Correcting the covalent model: electronegativity

Electronegativity (χ): Pauling vs. Mullikan

- Pauling's electronegativities were based on dissociation energies between bonds.
- For two elements, A and B, what are the energies needed to break bonds A–A, B–B, and A–B.

A – B

- **Pauling** defined the difference in electronegativity of the two elements A and B as:

$$|\chi_A - \chi_B| = \left\{D(A-B) - \frac{1}{2}[D(A-A) + D(B-B)]\right\}$$ (no need to know by heart)

- **Mullikan** (see Topic 1F.5) used a different strategy:

$$\chi = \frac{1}{2}(I_I + E_{ea})$$

Pauling and Mullikan's electronegativities are **qualitatively similar.**

2D.1 Correcting the covalent model: electronegativity

Electronegativity (χ): Pauling values

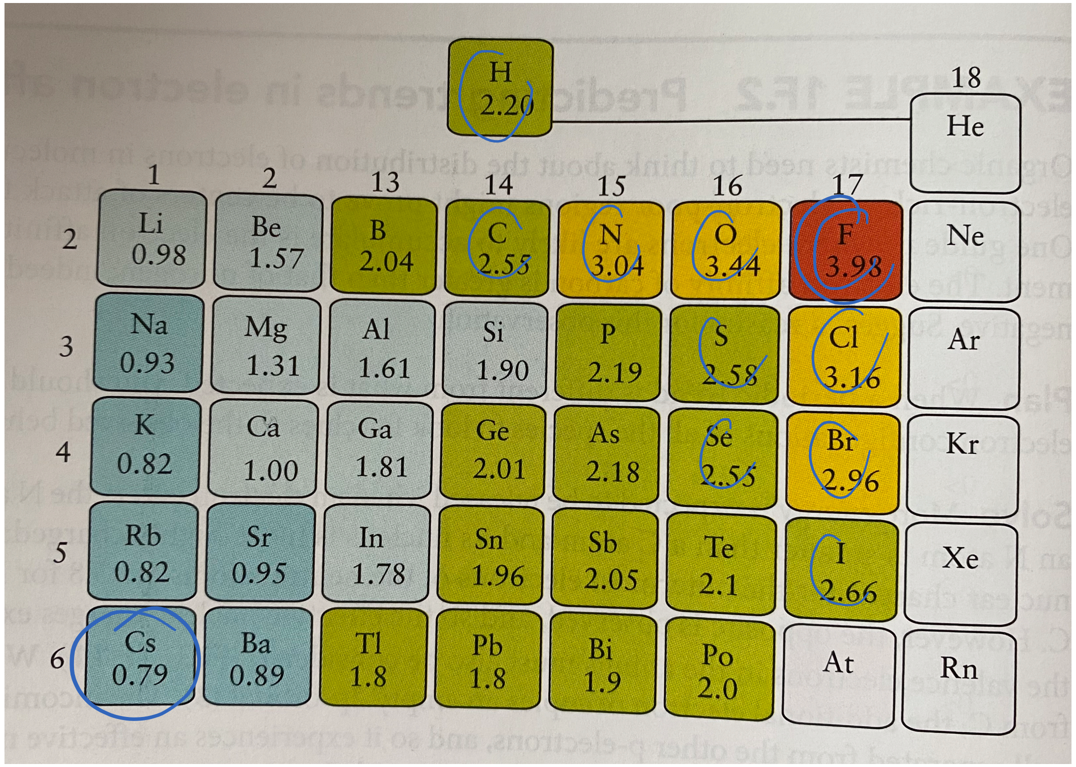


Figure 1F.12 and 2D.2

- Elements with **high ionization energies and high electron affinities**: highly electronegative
- Elements **with low ionization energies and low electron affinities**: low electronegativity.
- Careful: electropositive is used for a different concept and is NOT the opposite of electronegative.

2D.1 Correcting the covalent model: electronegativity

Two extremes

Small differences in electronegativity between atoms
→ Small partial charges
→ resulting dipole moments also small

Large differences in electronegativity
→ high partial charges
→ resulting dipole moment is high

Covalent bond ⟷ **Ionic bond**

Equal sharing of electrons

:Cl–Cl:

Electronegativity
→ unequal sharing of electrons
→ partial charge

Complete transfer of electrons ←

↓

polarizability to account for partial sharing of electrons

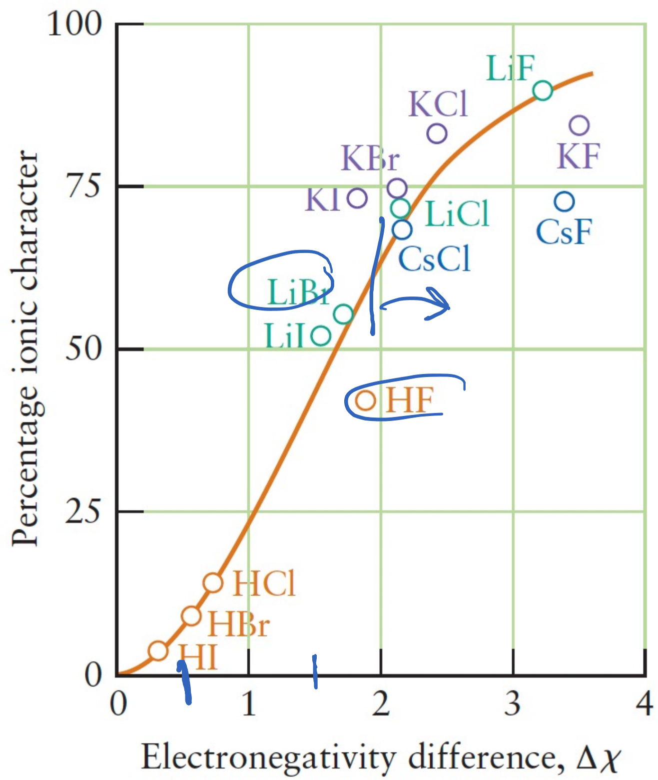
2D.1 Correcting the covalent model: electronegativity

Rules of thumb for A-B bonds:

$(\chi_A - \chi_B) \geq 2$:	Bond is *essentially* **ionic**
$1.7 \leq (\chi_A - \chi_B) \leq 2.0$:	Strongly polar covalent / partially ionic (**gray zone**)
$0.5 \leq (\chi_A - \chi_B) \leq 1.7$:	Bond is **polar covalent**
$(\chi_A - \chi_B) \leq 0.5$:	Bond is *essentially* **covalent**

Important information. Need to know.

Figure 2D.3



In which of the following compounds do the bonds have greater ionic character:

A. CO_2

B. NO_2

$\chi_C = 2.55$

$\chi_O = 3.44$

$\chi_N = 3.04$

$\chi_C - \chi_O = 2.55 - 3.44 \simeq 1.0$

$\chi_N - \chi_O = 3.04 - 3.44 \simeq 0.4$

In which of the following compounds do the bonds have greater ionic character:

A. CO_2 (correct)

B. NO_2

2D.1 Correcting the covalent model: electronegativity

Summary

Electronegativity is a measure of the pulling power of an atom on the electrons in a bond. A **polar covalent bond** is a bond between two atoms with partial electric charges arising from their difference in electronegativity. The presence of partial charges can give rise to an electric dipole moment.

Correcting the Ionic Model: Polarizability

Topic 2D.2

2D.2 Correcting the ionic model: polarizability

From the perspective of ionic bonds

- All bonds have some covalent character.
- Monoatomic anions (Cl^-) next to cations (Na^+): cation's positive charge pulls on anion's electrons
- Electron cloud becomes polarized
- Distortion of spherical electron cloud

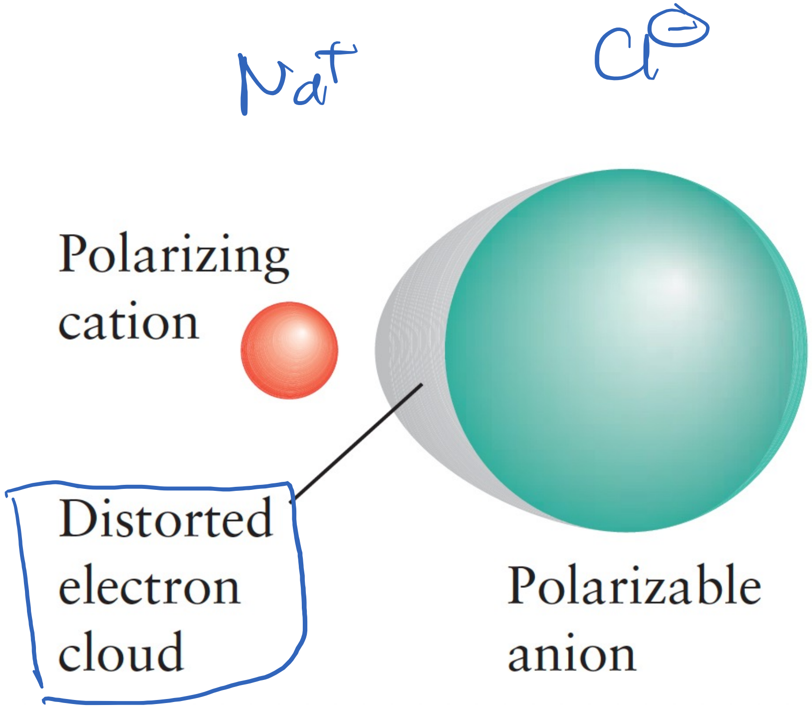


Figure 2D.4

2D.2 Correcting the ionic model: polarizability

Polarizable atoms and ions

- If atoms and ions have electron clouds that readily undergo large distortion, they are said to be **polarizable**.
- Examples: Large anions,

e.g. iodide ion (I^-), Br^-, Cl^-, I, Br, Cl

Image source: ChatGPT (2024)
A squishy ball illustrating the concept of polarizability.

2D.2 Correcting the ionic model: polarizability

Polarizing power

cation!

- Atoms and ions that cause large distortions are said to be **polarizing**.
- Polarizing power increases as size decreases and increases as charge of cation increases
- Examples: Small and highly charged cations, Li^{+}, Be^{2+}, Mg^{2+}, and Al^{3+}

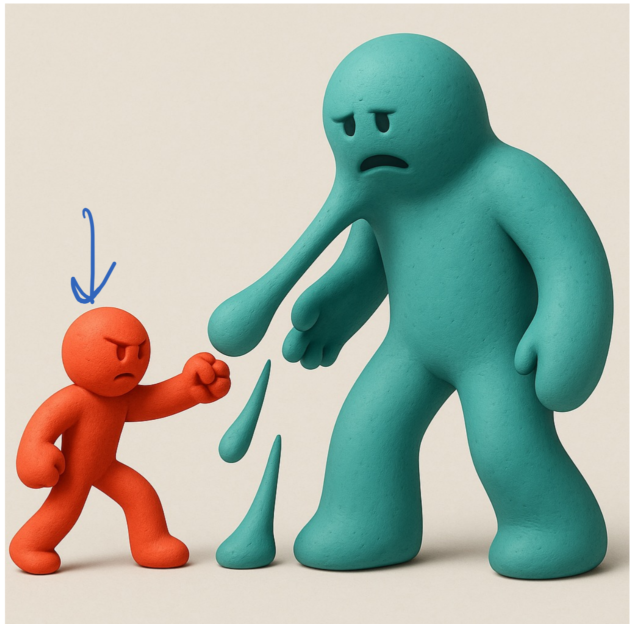


Image source: ChatGPT (2025)
A polarizing red character.

2D.2 Correcting the ionic model: polarizability

Trends

→ Cations get smaller and more highly charged from left to right → more polarizing

For example: Be^{2+} is more polarizing than Li^{+}

→ Cations get larger down a group → less polarizing

For example, Na^{+} is less strongly polarizing than Li^{+}, Mg^{2+} is less polarizing than Be^{2+}

Diagonal relationships: Polarizing power increases from Li^{+} to Be^{2+}, decreases from Be^{2+} to Mg^{2+}. Li^{+} and Mg^{2+} should be similar.

PERIODIC TABLE OF THE ELEMENTS

Period \ Group	1 I IA	2 II IIA	3 IIIB	4 IVB	5 VB	6 VIB	7 VIIB	8 VIIIB	9 VIIIB	10 VIIIB	11 IB	12 IIB	13 III IIIA	14 IV IVA	15 V VA	16 VI VIA	17 VII VIIA	18 VIII VIIA
1	1 H hydrogen 1.0079 $1s^1$																	2 He helium 4.00 $1s^2$
2	3 Li lithium 6.94 $2s^1$	4 Be beryllium 9.01 $2s^2$											5 B boron 10.81 $2s^22p^1$	6 C carbon 12.01 $2s^22p^2$	7 N nitrogen 14.01 $2s^22p^3$	8 O oxygen 16.00 $2s^22p^4$	9 F fluorine 19.00 $2s^22p^5$	10 Ne neon 20.18 $2s^22p^6$
3	11 Na sodium 22.99 $3s^1$	12 Mg magnesium 24.31 $3s^2$											13 Al aluminum 26.98 $3s^23p^1$	14 Si silicon 28.09 $3s^23p^2$	15 P phosphorus 30.97 $3s^23p^3$	16 S sulfur 32.06 $3s^23p^4$	17 Cl chlorine 35.45 $3s^23p^5$	18 Ar argon 39.95 $3s^23p^6$
4	19 K potassium 39.10 $4s^1$	20 Ca calcium 40.08 $4s^2$	21 Sc scandium 44.96 $3d^14s^2$	22 Ti titanium 47.87 $3d^24s^2$	23 V vanadium 50.94 $3d^34s^2$	24 Cr chromium 52.00 $3d^54s^1$	25 Mn manganese 54.94 $3d^54s^2$	26 Fe iron 55.84 $3d^64s^2$	27 Co cobalt 58.93 $3d^74s^2$	28 Ni nickel 58.69 $3d^84s^2$	29 Cu copper 63.55 $3d^{10}4s^1$	30 Zn zinc 65.41 $3d^{10}4s^2$	31 Ga gallium 69.72 $4s^24p^1$	32 Ge germanium 72.64 $4s^24p^2$	33 As arsenic 74.92 $4s^24p^3$	34 Se selenium 78.96 $4s^24p^4$	35 Br bromine 79.90 $4s^24p^5$	36 Kr krypton 83.80 $4s^24p^6$
5	37 Rb rubidium 85.47 $5s^1$	38 Sr strontium 87.62 $5s^2$	39 Y yttrium 88.91 $4d^15s^2$	40 Zr zirconium 91.22 $4d^25s^2$	41 Nb niobium 92.91 $4d^45s^1$	42 Mo molybdenum 95.94 $4d^55s^1$	43 Tc technetium (98) $4d^55s^2$	44 Ru ruthenium 101.07 $4d^75s^1$	45 Rh rhodium 102.90 $4d^85s^1$	46 Pd palladium 106.42 $4d^{10}$	47 Ag silver 107.87 $4d^{10}5s^1$	48 Cd cadmium 112.41 $4d^{10}5s^2$	49 In indium 114.82 $5s^25p^1$	50 Sn tin 118.71 $5s^25p^2$	51 Sb antimony 121.76 $5s^25p^3$	52 Te tellurium 127.60 $5s^25p^4$	53 I iodine 126.90 $5s^25p^5$	54 Xe xenon 131.29 $5s^25p^6$
6	55 Cs cesium 132.91 $6s^1$	56 Ba barium 137.33 $6s^2$	57 La lanthanum 138.91 $5d^16s^2$	72 Hf hafnium 178.49 $5d^26s^2$	73 Ta tantalum 180.95 $5d^36s^2$	74 W tungsten 183.84 $5d^46s^2$	75 Re rhenium 186.21 $5d^56s^2$	76 Os osmium 190.23 $5d^66s^2$	77 Ir iridium 192.22 $5d^76s^2$	78 Pt platinum 195.08 $5d^96s^1$	79 Au gold 196.97 $5d^{10}6s^1$	80 Hg mercury 200.59 $5d^{10}6s^2$	81 Tl thallium 204.38 $6s^26p^1$	82 Pb lead 207.2 $6s^26p^2$	83 Bi bismuth 208.98 $6s^26p^3$	84 Po polonium (209) $6s^26p^4$	85 At astatine (210) $6s^26p^5$	86 Rn radon (222) $6s^26p^6$
7	87 Fr francium (223) $7s^1$	88 Ra radium (226) $7s^2$	89 Ac actinium (227) $6d^17s^2$	104 Rf rutherfordium (261) $6d^27s^2$	105 Db dubnium (262) $6d^37s^2$	106 Sg seaborgium (266) $6d^47s^2$	107 Bh bohrium (264) $6d^57s^2$	108 Hs hassium (267) $6d^67s^2$	109 Mt meitnerium (268) $6d^77s^2$	110 Ds darmstadtium (271) $6d^87s^2$	111 Rg roentgenium (272) $6d^{10}7s^1$	112*	113	114	115	116	117	118

	Period														
Lanthanoids (lanthanides)	6	58 Ce cerium 140.12 $4f^15d^16s^2$	59 Pr praseodymium 140.91 $4f^36s^2$	60 Nd neodymium 144.24 $4f^46s^2$	61 Pm promethium (145) $4f^56s^2$	62 Sm samarium 150.36 $4f^66s^2$	63 Eu europium 151.96 $4f^76s^2$	64 Gd gadolinium 157.25 $4f^75d^16s^2$	65 Tb terbium 158.93 $4f^96s^2$	66 Dy dysprosium 162.50 $4f^{10}6s^2$	67 Ho holmium 164.93 $4f^{11}6s^2$	68 Er erbium 167.26 $4f^{12}6s^2$	69 Tm thulium 168.93 $4f^{13}6s^2$	70 Yb ytterbium 173.04 $4f^{14}6s^2$	71 Lu lutetium 174.97 $5d^16s^2$
Actinoids (actinides)	7	90 Th thorium 232.04 $6d^27s^2$	91 Pa protactinium 231.04 $5f^26d^17s^2$	92 U uranium 238.03 $5f^36d^17s^2$	93 Np neptunium (237) $5f^46d^17s^2$	94 Pu plutonium (244) $5f^67s^2$	95 Am americium (243) $5f^77s^2$	96 Cm curium (247) $5f^76d^17s^2$	97 Bk berkelium (247) $5f^97s^2$	98 Cf californium (251) $5f^{10}7s^2$	99 Es einsteinium (252) $5f^{11}7s^2$	100 Fm fermium (257) $5f^{12}7s^2$	101 Md mendelevium (258) $5f^{13}7s^2$	102 No nobelium (259) $5f^{14}7s^2$	103 Lr lawrencium (262) $6d^17s^2$

Molar masses (atomic weights) quoted to the number of significant figures given here can be regarded as typical of most naturally occurring samples.

*The names of the elements 112 and higher have not yet been determined; both 112 and 114 have been confirmed.

In which of the compounds CaS and CaO do the bonds have greater covalent character?

A. CaS

B. CaO

Ca^{2+} + S^{2-} → large anion
→ more polarizable
↓
more covalent character

+ O^{2-}

Only size? and charge

Down group:
CaO
CaS
CaSe
CaTe
↓
more covalent

2D.1 Correcting the covalent model: electronegativity

Self-test 2D.2B

- In which of the compounds CaS and CaO do the bonds have greater covalent character?
- Solution: CaS
- Moving down a group, the bonds become more covalent as the polarizability (also size) of the anion increases ($O^{2-} < S^{2-}$). Same trend is true for $Cl^- < Br^- < I^-$

2D.2 Correcting the ionic model: polarizability

Summary

Compounds composed of highly polarizing cations and highly polarizable anions have significant covalent character in their bonding.

Bond Strengths

Topic 2D.3

2D.3 Bond strengths

Dissociation energy

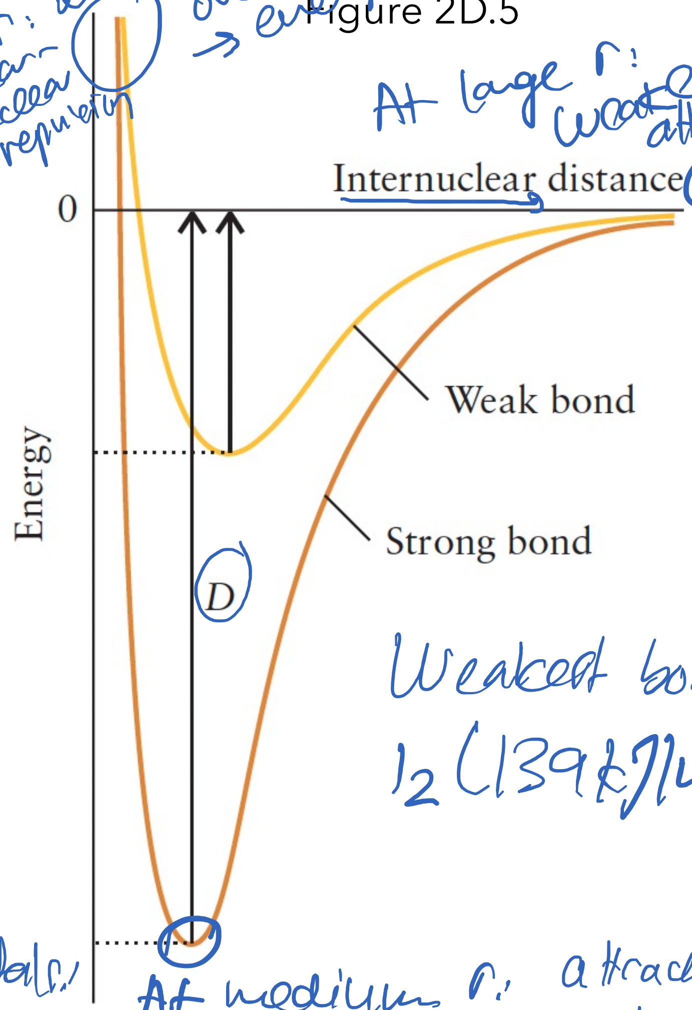
The strength of a bond is measured by its dissociation energy, D, the energy required to separate the bonded atoms completely.

- Homolytic bond cleavage:

$$H{-}Cl(g) \rightarrow \cdot H(g) + \cdot Cl(g)$$

- Depth of well → strength of bond
- Strongest known bond between nonmetals: C≡O (1062 kJ/mol)

Figure 2D.5



At very small r: e⁻ cloud overlap & nuclear–nuclear repulsion → energy rises steeply

At large r: weaker attraction

At medium r: attractive & repulsive are balanced: bond form

Weakest bond: I_2 (139 kJ/mol)

2D.3 Bond strengths

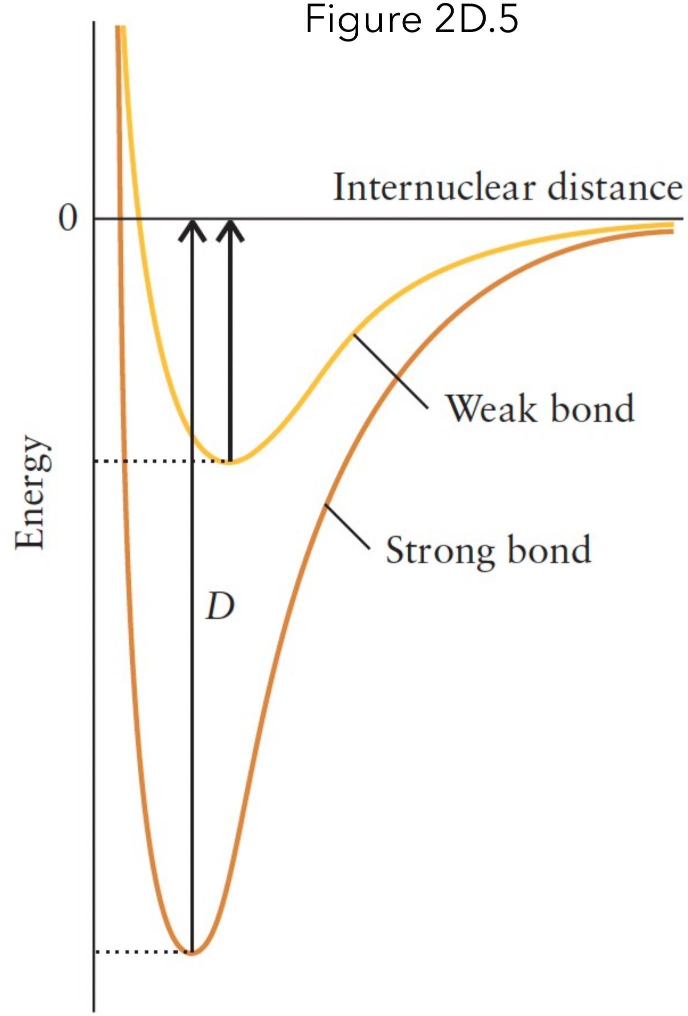
Dissociation energy

- The **strength of a bond** is measured by its **dissociation energy**, *D*, the energy required to separate the bonded atoms completely.
- For these values, upon dissociation, each atom retains one electron (**homolytic**):

$$\text{H—Cl(g)} \rightarrow \cdot\text{H(g)} + \cdot\text{Cl(g)}$$

- Depth of the well indicates (approximately) the strength of bond
- **Strongest known bond** between nonmetals: Carbon monoxide triple bond: C≡O (1062 kJ/mol)
- Weakest bond: iodine in I_2 (139 kJ/mol)

Figure 2D.5



2D.3 Bond strengths

Dissociation energies of diatomic molecules

TABLE 2.3 Bond Dissociation Energies of Diatomic Molecules ($kJ \cdot mol^{-1}$)

Molecule	Bond dissociation energy
H_2	424
N_2	932
O_2	484
CO	1062
F_2	146
Cl_2	230
Br_2	181
I_2	139
HF	543
HCl	419
HBr	354
HI	287

TREND (look at Lewis structures) for diatomic molecules:

- $N_2 > O_2 > F_2$: triple > double > single bond:

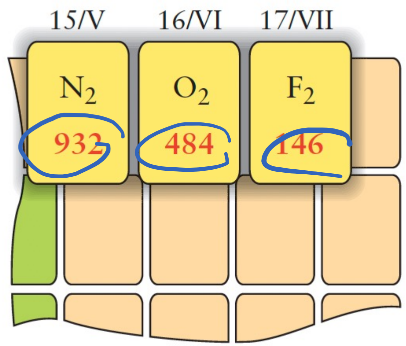


Figure 2D.6

2D.3 Bond strengths

C–C vs. C=C vs. C≡C

- A double bond is not twice as strong as a single bond: One C=C bond (623 kJ/mol) vs. two single C–C bonds (696 kJ/mol)
- One C≡C bond (837 kJ/mol) vs. three single C–C bonds (1044 kJ/mol)
- **Why is there a loss in energy for multiple bonds?** Repulsions between electron pairs in a multiple bond, not quite as effective at bonding as one pair in a single bond

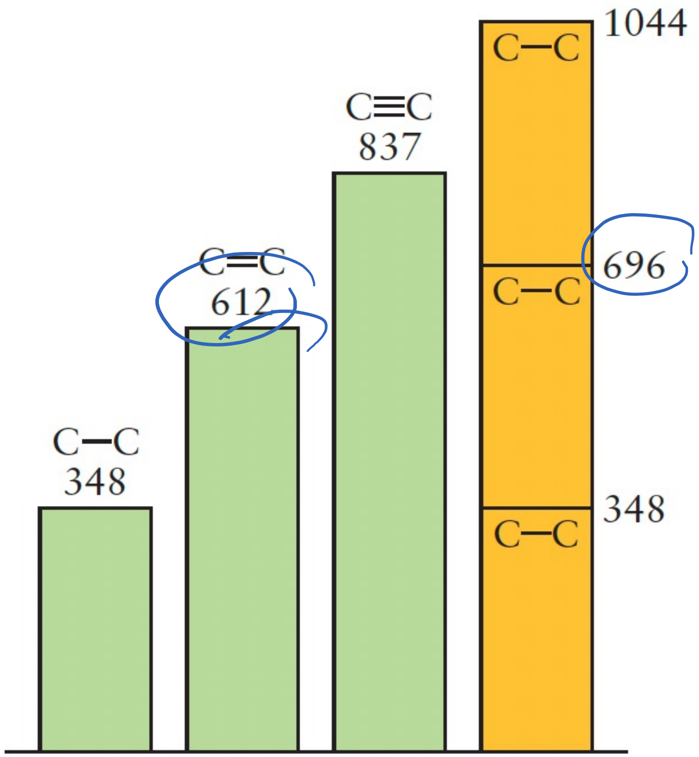


Figure 2D.7

2D.3 Bond strengths

Average bond dissociation energies

- Average for one type of bond, precise bond dissociation energy depends on **context**
- For example, C–H bond could be in methane (CH_4), ethane (C_2H_6) and ethene (C_2H_4)

TABLE 2.4 Average Bond Dissociation Energies ($kJ \cdot mol^{-1}$)

Bond	Average bond dissociation energy	Bond	Average bond dissociation energy
C—H	412	C—I	238
C—C	348	N—H	388
C=C	612	N—N	163
C┅C*	518	N=N	409
C≡C	837	N—O	210
C—O	360	N=O	630
C=O	743	N—F	195
C—N	305	N—Cl	381
C—F	484	O—H	463
C—Cl	338	O—O	157
C—Br	276		

*In benzene.

2D.3 Bond strengths

Summary: **Factors that influence bond strength**

- Bond order: C≡C > C=C > C–C
- Resonance: C=C > C–C(benzene) > C–C
- Lone pairs on neighbouring atoms: F-F < H-H
- Atomic radii: HF > HCl > HBr > HI

The smaller the radius, the stronger the bond.

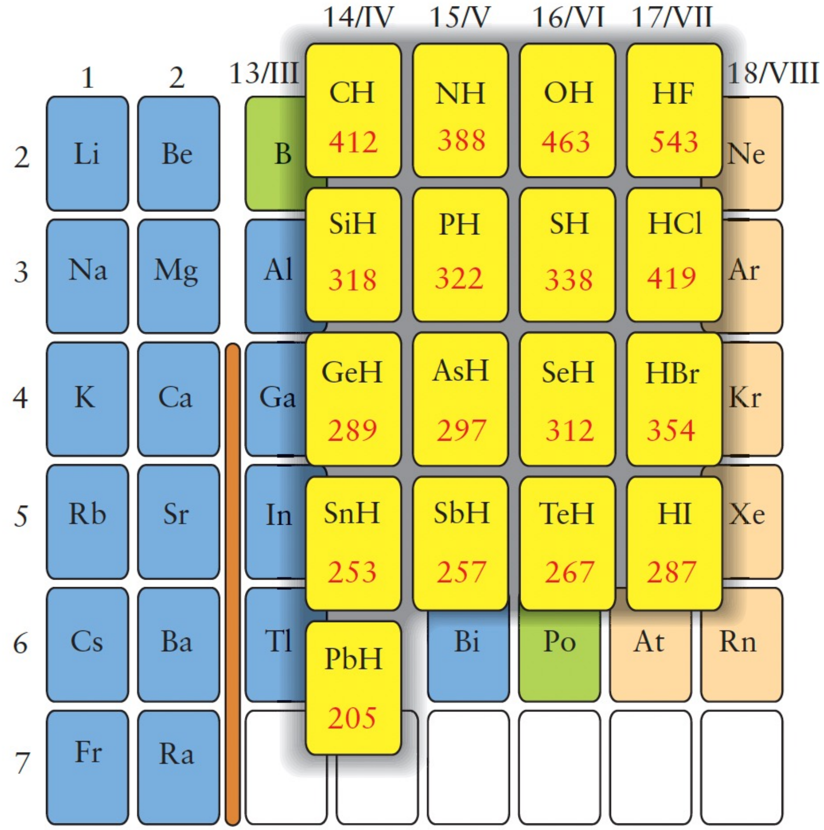


Figure 2D.8

2D.3 Bond strengths

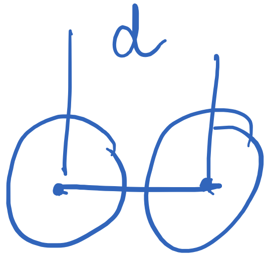
Summary

The strength of a bond between two atoms is measured by its dissociation energy: the greater the dissociation energy, the stronger the bond. Bond strength between the same two atoms increases as the multiplicity of a bond increases, decreases as the number of lone pairs on neighbouring atoms increases, and decreases as the atomic radii increase.

Bond Lengths

Topic 2D.4

2D.4 Bond lengths



Bond length

- **Internuclear distance between the centers of two atoms = bond length**
- Bond lengths affect **size and shape of molecule**
- For example: DNA replication, enzyme binding into active sites
- Determined by spectroscopy or x-ray diffraction

2D.4 Bond lengths

Bond lengths

TABLE 2.5 Average and Actual Bond Lengths

Bond	Average bond length (pm)	Molecule	Bond length (pm)
C—H	109	H_2	74
C—C	154	N_2	110
C=C	134	O_2	121
C⋯C*	139	F_2	142
C≡C	120	Cl_2	199
C—O	143	Br_2	228
C=O	112	I_2	268
O—H	96		
N—H	101		
N—O	140		
N=O	120		

*In benzene.

2D.4 Bond lengths

Summary: **Factors that influence bond length**

- Bond order: C≡C < C=C < C–C
- Resonance: C=C < C–C(benzene) < C–C
- Lone pairs on neighbouring atoms: F-F > H-H
- Atomic radii: HF < HCl < HBr < HI

The smaller the radius, the shorter the bond (Figure 2D.9).

These trends are **opposite** of the ones for bond strength.

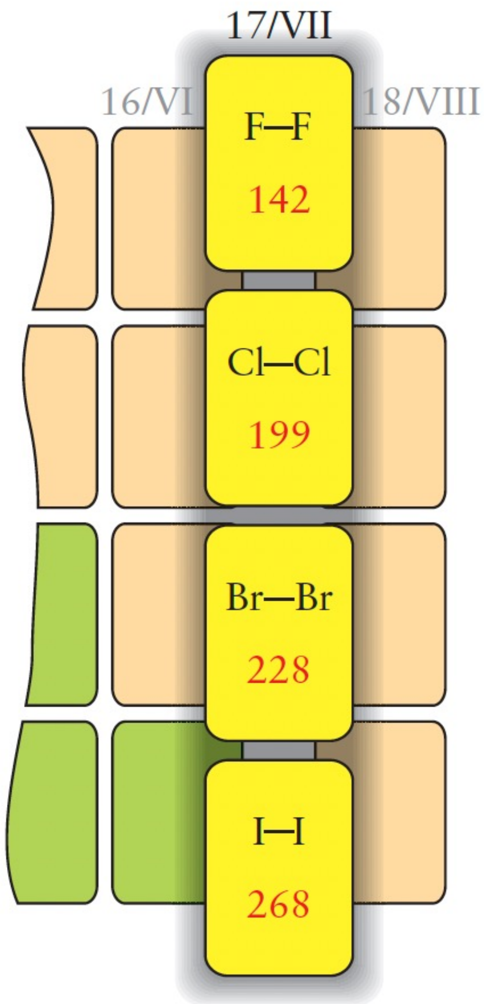


Figure 2D.9

2D.4 Bond lengths

Covalent radius

- **Contribution an atom makes to the length of a covalent bond = covalent radius**
- Measured as half of the distance between the centers (nuclei) of neighboring atoms joined by a covalent bond (*for identical atoms*)
- Covalent radii may be added to estimate bond lengths in molecules
- Tabulated values are averages of radii in polyatomic molecules

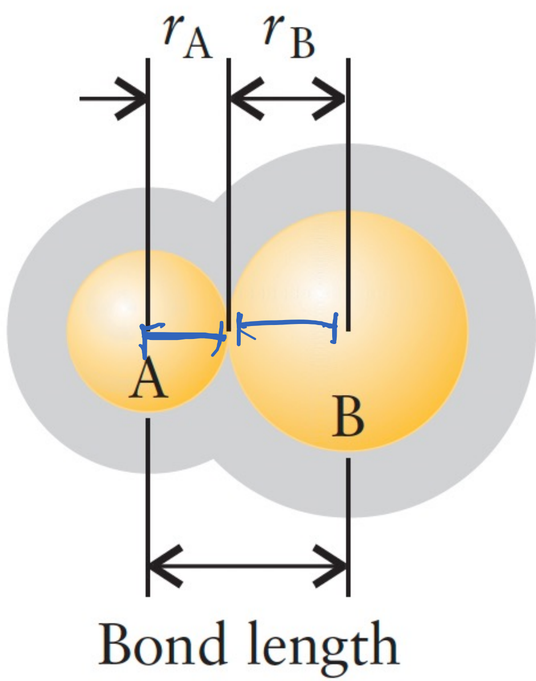
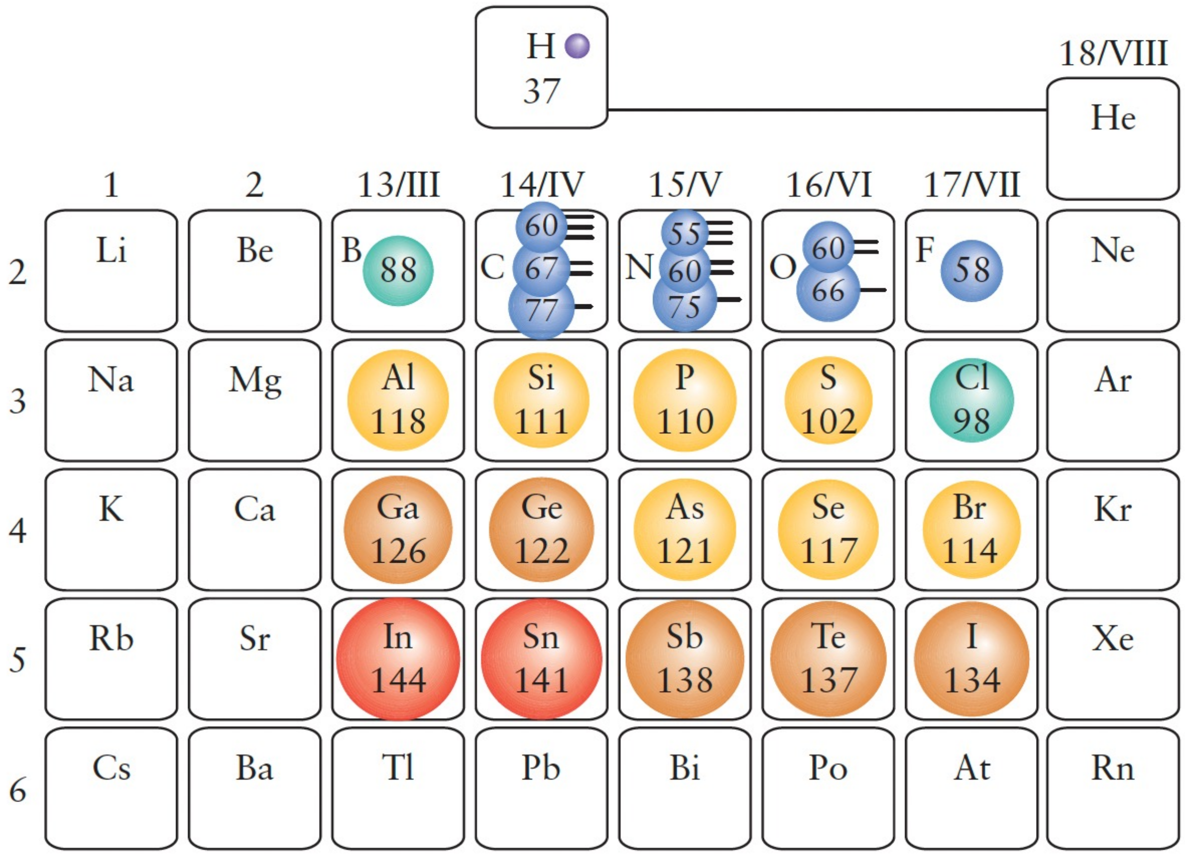


Figure 2D.8

2D.4 Bond lengths

Figure 2D.5

Covalent radii of hydrogen and p-block elements (in pm)



2D.4 Bond lengths

Summary

The covalent radius of an atom is the contribution it makes to the length of a covalent bond; covalent radii are added together to estimate the lengths of bonds in molecules.

The skills you have mastered are the ability to

- Explain the concept of electronegativity and use it to assess whether a bond is polar.
- Explain how resonance is used to improve the description of a covalent bond by introducing ionic character into it.
- Estimate relative ionic or covalent character.
- Explain how the concept of polarizability is used to improve the description of an ionic bond.
- Predict and explain periodic trends in the polarizability of anions and the polarizing power of cations.
- Predict and explain relative bond strengths and bond lengths

Summary: You have learned that the electronegativity of an element enables you to identify which atom in a bond has the greater share of the electron pair. Chemical bonds show a range of character, from completely covalent to completely ionic. You have seen that bond strengths are approximately transferrable between molecules and that atoms make characteristic contributions to the length of bonds.