

Unit 2

Atomic Structure and Properties

&

Chemical Bonding

Slide Color Codes

All Lectures

Required

Required

OK to Skip

Section Only

Useful

Not
Examable

Blueprint question

**How can you predict
engine part failure
BEFORE it happens?**



<http://www.spectro-oil.com/laboratory-services-aviation.html>

http://news.commercialaircraft.bombardier.com/wp-content/gallery/engine-run/right_engine.jpg

Learning Objectives

After mastering this unit you will be able to:

- Define the terms valence and core electrons
- Determine the number of valence electrons and core electrons based on electron configuration for atoms and ions
- Define, in words or using equations, effective nuclear charge (Z_{eff}), atomic and ionic radius, ionization energy, and electron affinity.
- Rank elements and ions according to their Z_{eff} , atomic size, ionization energy, and electron affinity.
- Rationalize the periodic trends of radii, relative ionization energies and electron affinities of atoms and ions based on nuclear charge and/or electron configurations.

Learning Objectives (continued)

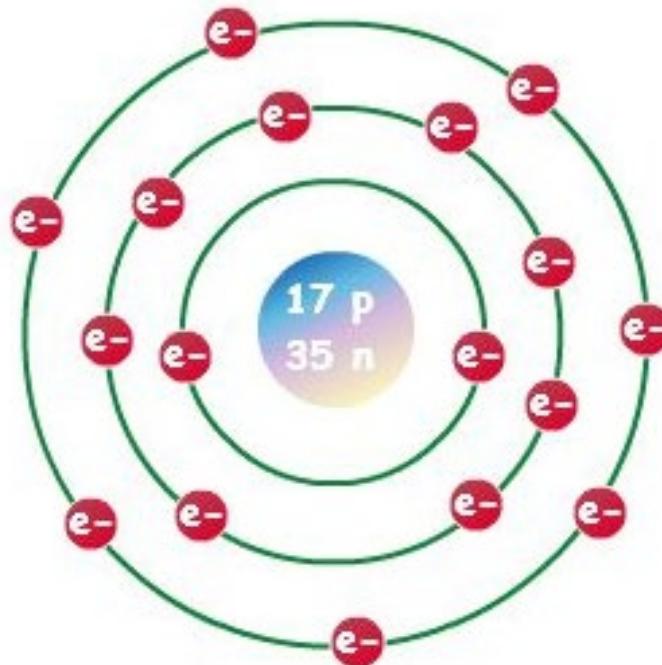
- Describe the nature of ionic and covalent bonds.
- Define electronegativity and describe how electronegativity varies with position in the periodic table.
- Predict the nature of a chemical bond (ionic/covalent, polar/nonpolar) and justify your prediction by comparing the relative electronegativities of the atoms involved.
- Predict lattice energy trends in ionic solids & justify your predictions.

Classical vs Quantum Mechanics

- Newton's second law

$$F = ma = m \frac{d^2x}{dt^2}$$

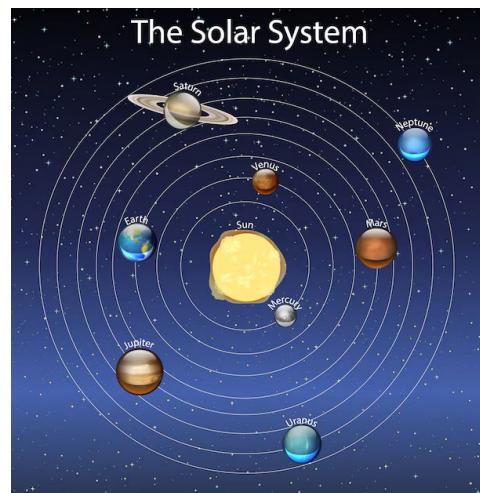
$$F = k \frac{q_1 \cdot q_2}{r^2}$$



Clicker Question

Which of the following represents the best analogy for the structure of an atom?

- a) Solar system
- b) Cotton ball
- c) Billiard Ball
- d) Onion
- e) Dumbbell



Wave properties of Electrons



Salient Features of Quantum Mechanics

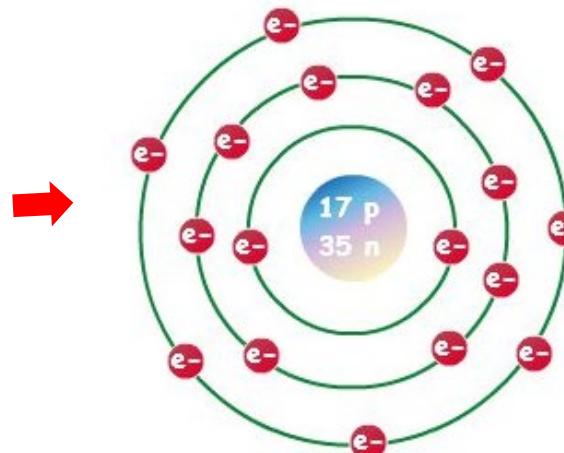
- Small objects, like electrons, behave as both particles and waves which means they can interfere, diffract and spread. Orbitals give the probability for finding electrons at particular points in space.
- Quantum mechanics is the theory explaining why energies and angular momenta of atoms and molecules are quantized, that is only have certain discrete values.

Classical vs Quantum Mechanics

- Newton's second law

$$F = ma = m \frac{d^2x}{dt^2}$$

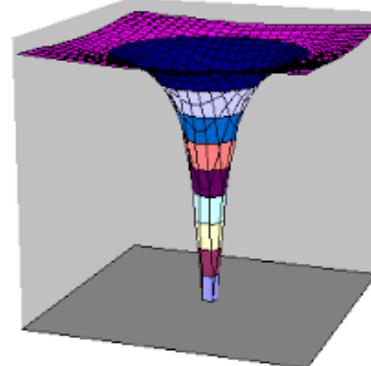
$$F = k \frac{q_1 \cdot q_2}{r^2}$$



- Schrodinger Equation

$$-\frac{\hbar^2}{2m} \left[\frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial y^2} + \frac{\partial^2 \Psi}{\partial z^2} \right] + U(x, y, z) \Psi(x, y, z) = E \Psi(x, y, z)$$

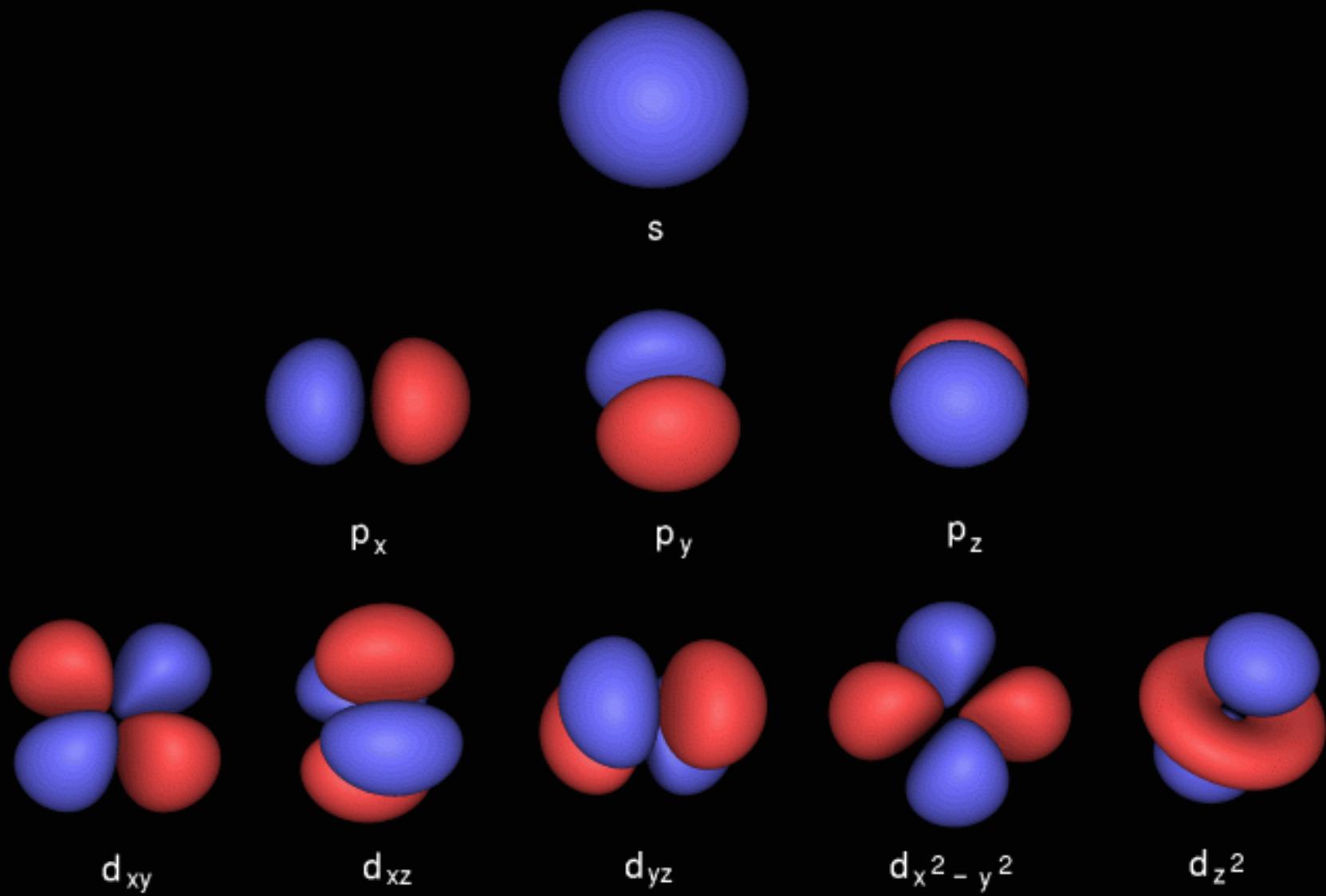
$$U = k \frac{q_1 \cdot q_2}{r}$$



Probability
Density of
Electron

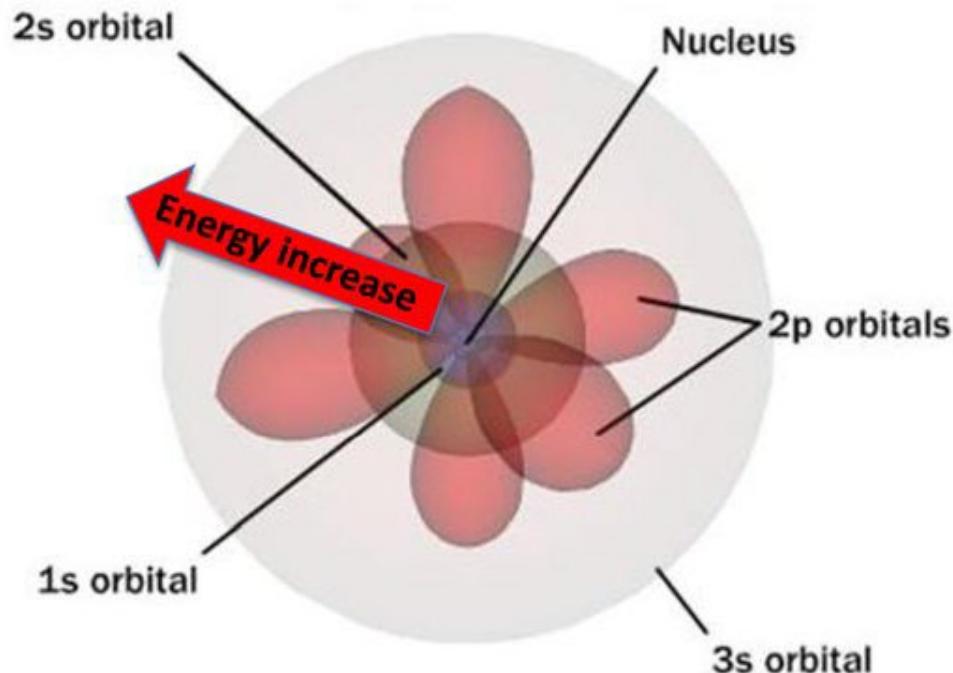
Atomic
Nucleus

Hydrogenic Orbitals

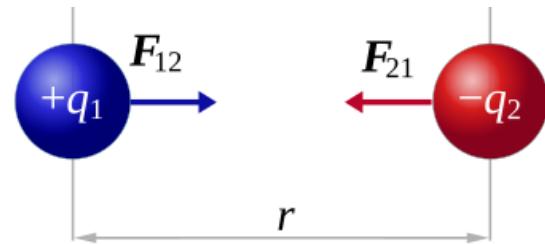


Shell Structure of Atoms

Orbitals become larger as the energy level increases



Coulomb's law



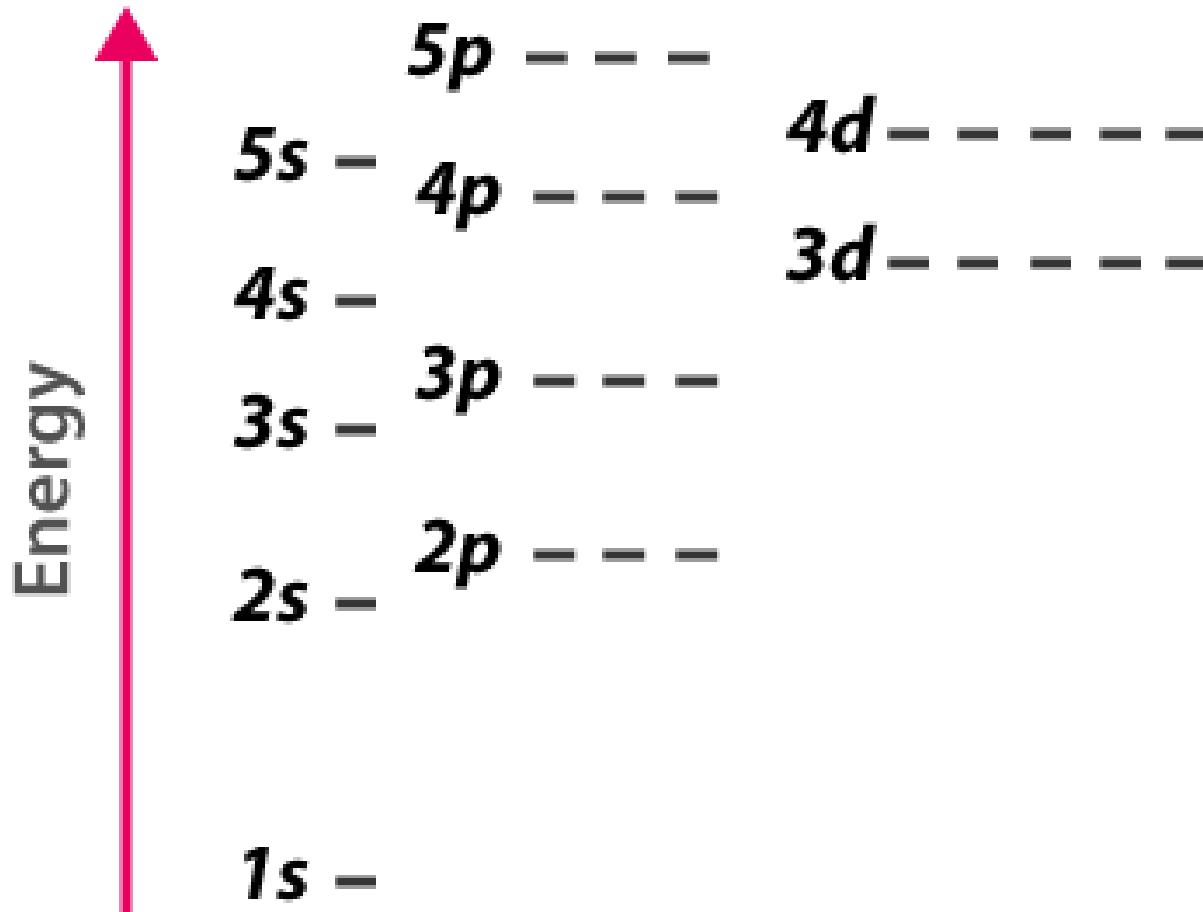
$$|F_{12}| = |F_{21}| = k_e \frac{|q_1 \times q_2|}{r^2}$$

- Electrons filling order : 1s, 2s 2p, 3s
- Orbitals arranged in order of increasing energy: 1s, 2s 2p, 3s
- Orbitals arranged in increasing size: (smallest) 1s < 2s < 2p < 3s (largest)

Electronic Structure

- Electrons have negative charge but are also tiny magnets. Spin is our way of describing the orientation of the poles of these magnets (“spin up \uparrow or “spin down \downarrow ”).
- The Pauli Principle states a maximum of 2 electrons can be assigned to any one orbital, and the electrons must have opposite spins ($\uparrow\downarrow$).
- Orbitals are arranged in shells, labelled by n, and sub-shells. Each shell contains only certain orbitals. Starting with the lowest shell, n=1, electrons are assigned to s, p, d orbitals until they are all accounted for. Note: orbitals get bigger as n increases (a 2s orbital is bigger than a 1s orbital) thus forming the shell structure of atoms.

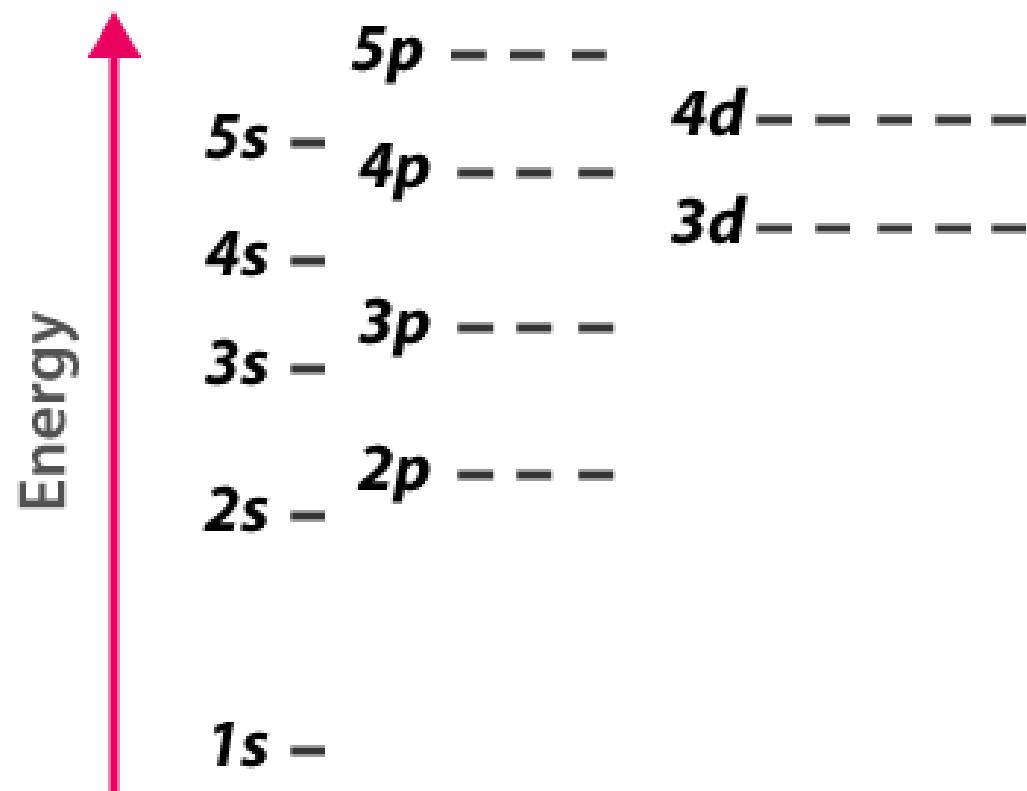
Energy of a Hydrogen Atom



Maximum Number of Electrons

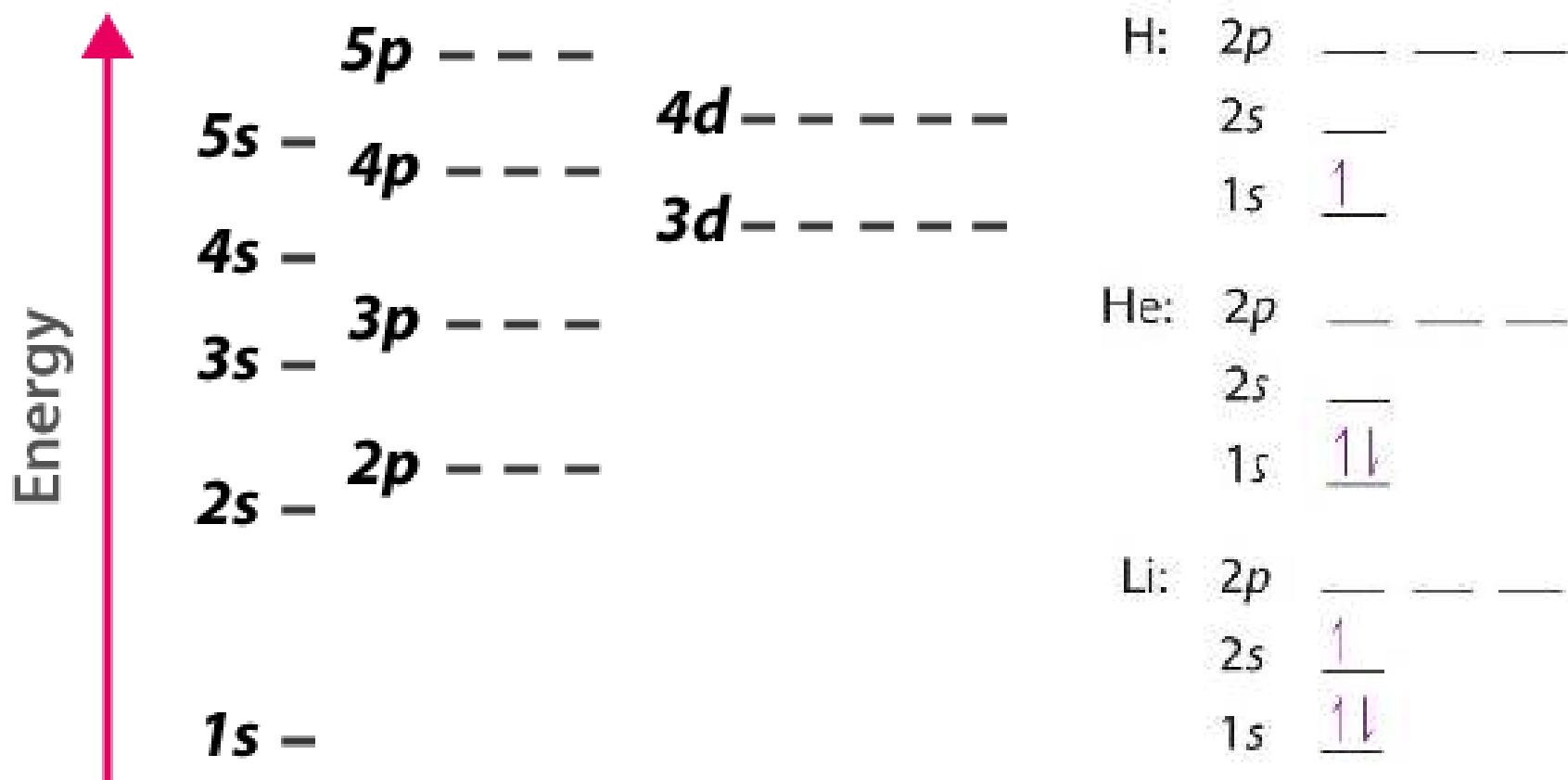
- The following table lists the first four types of subshells and the maximum number of electrons in each type of subshell:

Subshell	#e-
s	2
p	6
d	10
f	14



The Aufbau (Construction) Principle

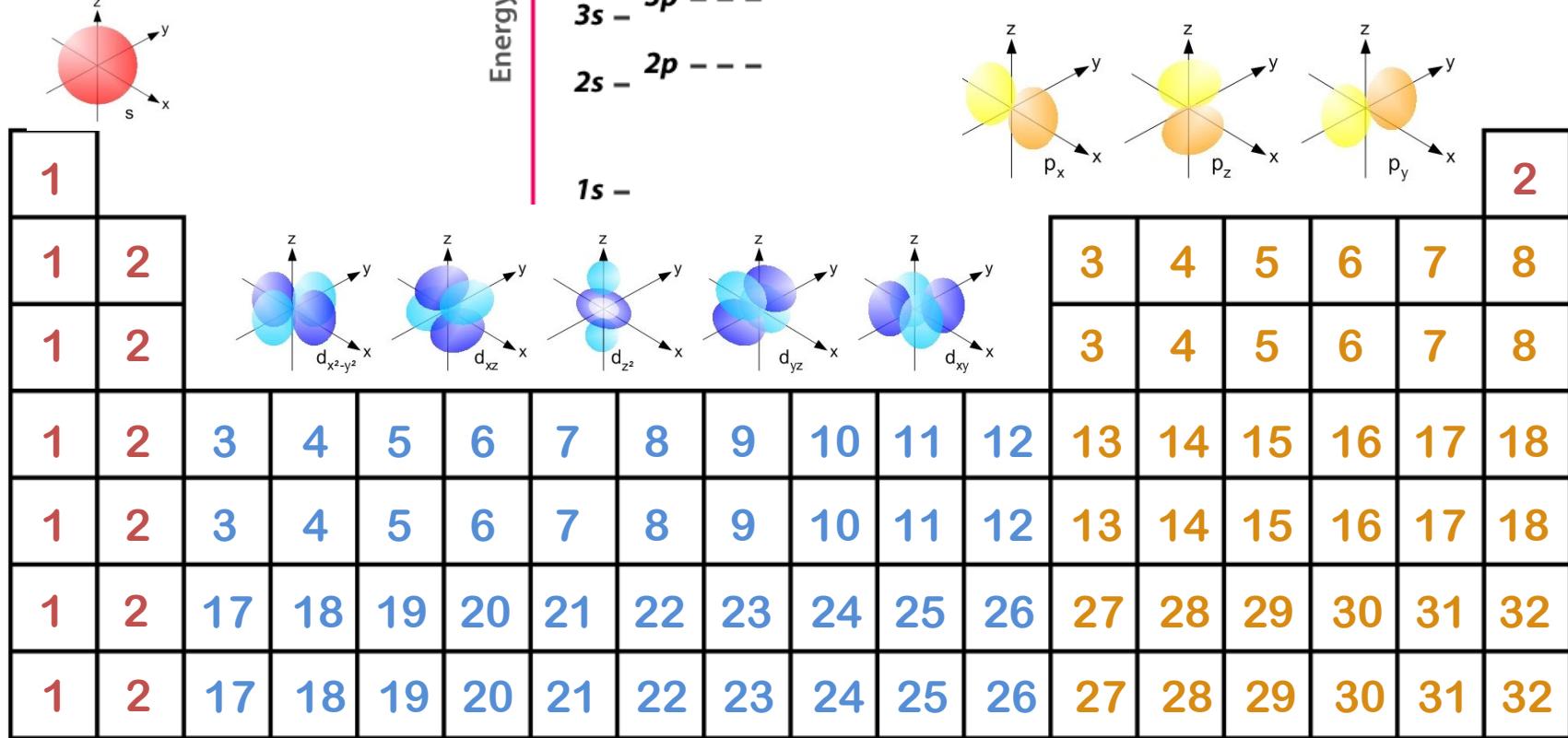
- electrons fill atomic orbitals starting from the lowest available energy level and then move to higher energy levels



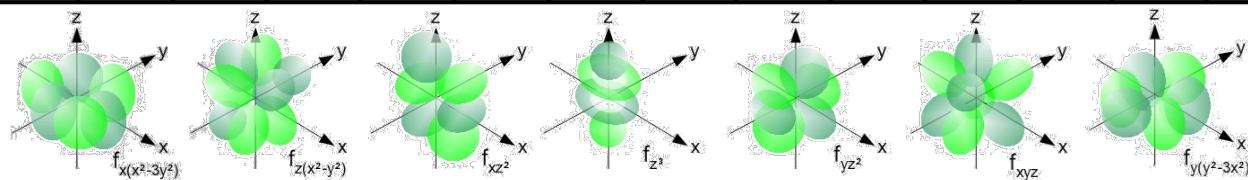
Shells and subshells

Shell (n)	Sub-shells	Max. # e ⁻ in subshells	
1	s	2	$2(1)^2 = 2$
2	s, p	$2 + 6 = 8$	$2(2)^2 = 8$
3	s, p, d	$2 + 6 + 10 = 18$	$2(3)^2 = 18$
4	s, p, d, f	$2 + 6 + 10 + 14 = 32$	$2(4)^2 = 32$

Fill in Electrons

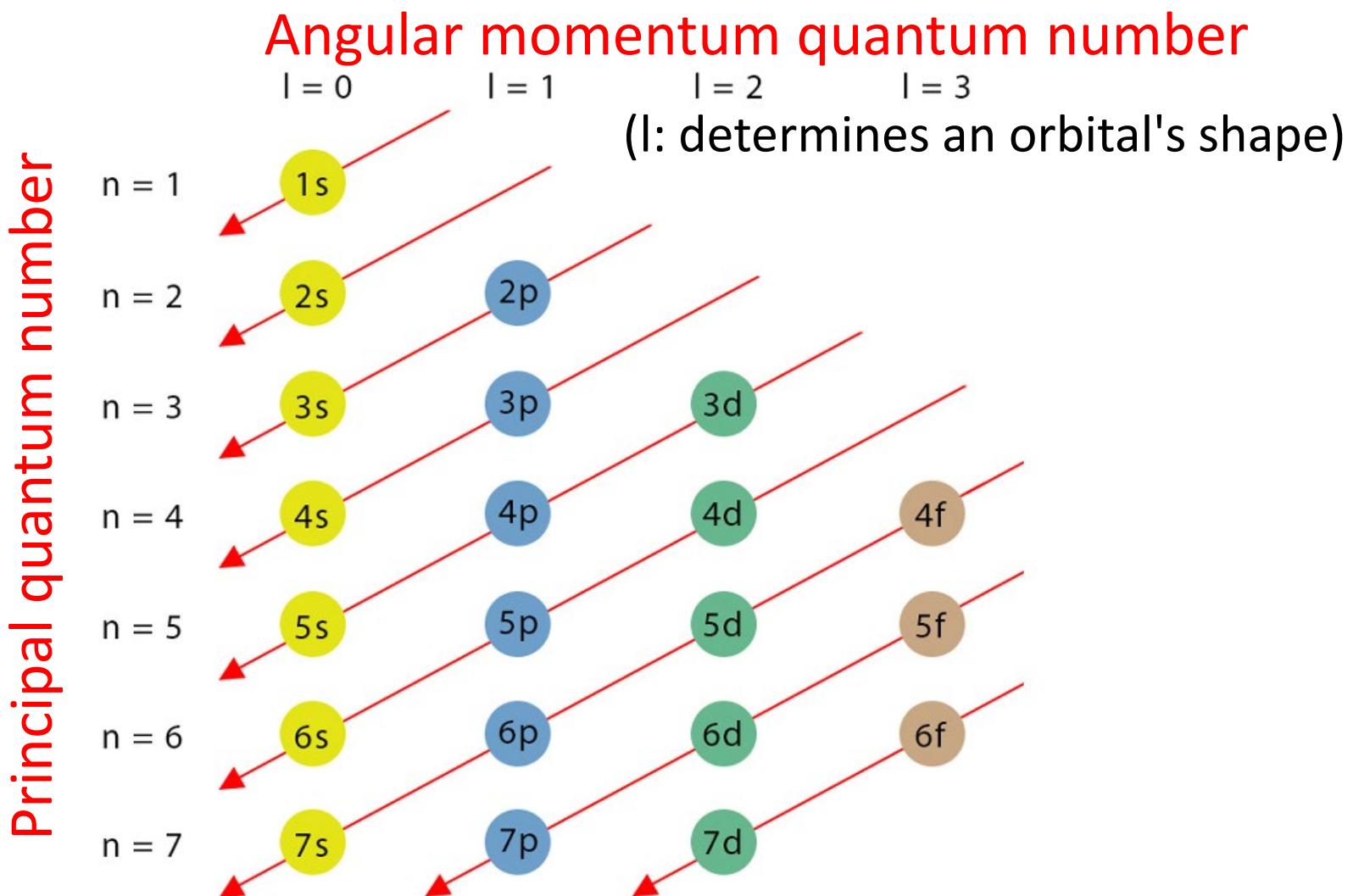


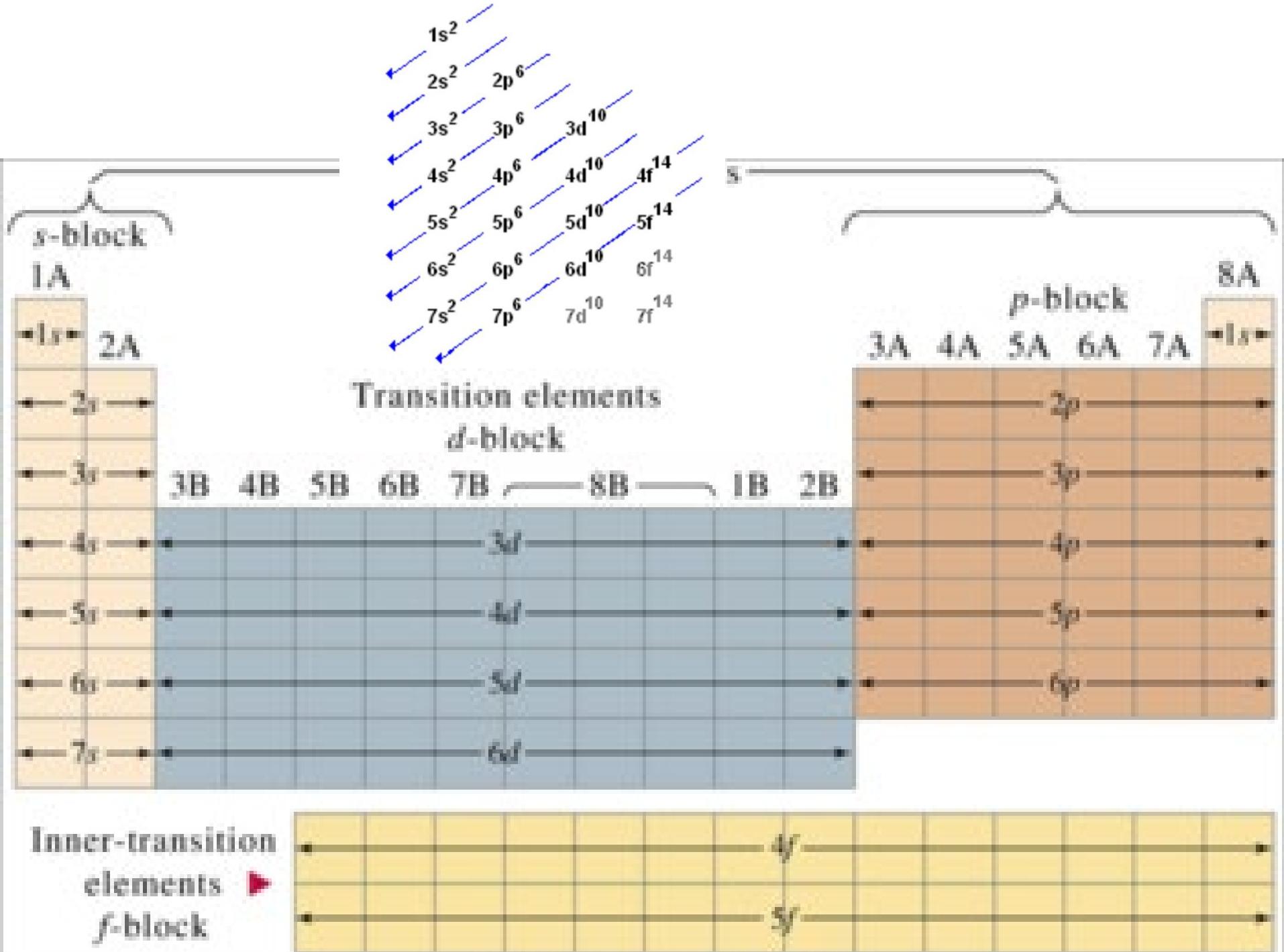
3	4	5	6	7	8	9	10	11	12	13	14	15	16
3	4	5	6	7	8	9	10	11	12	13	14	15	16



The Aufbau Principle

- electrons fill atomic orbitals starting from the lowest available energy level and then move to higher energy levels

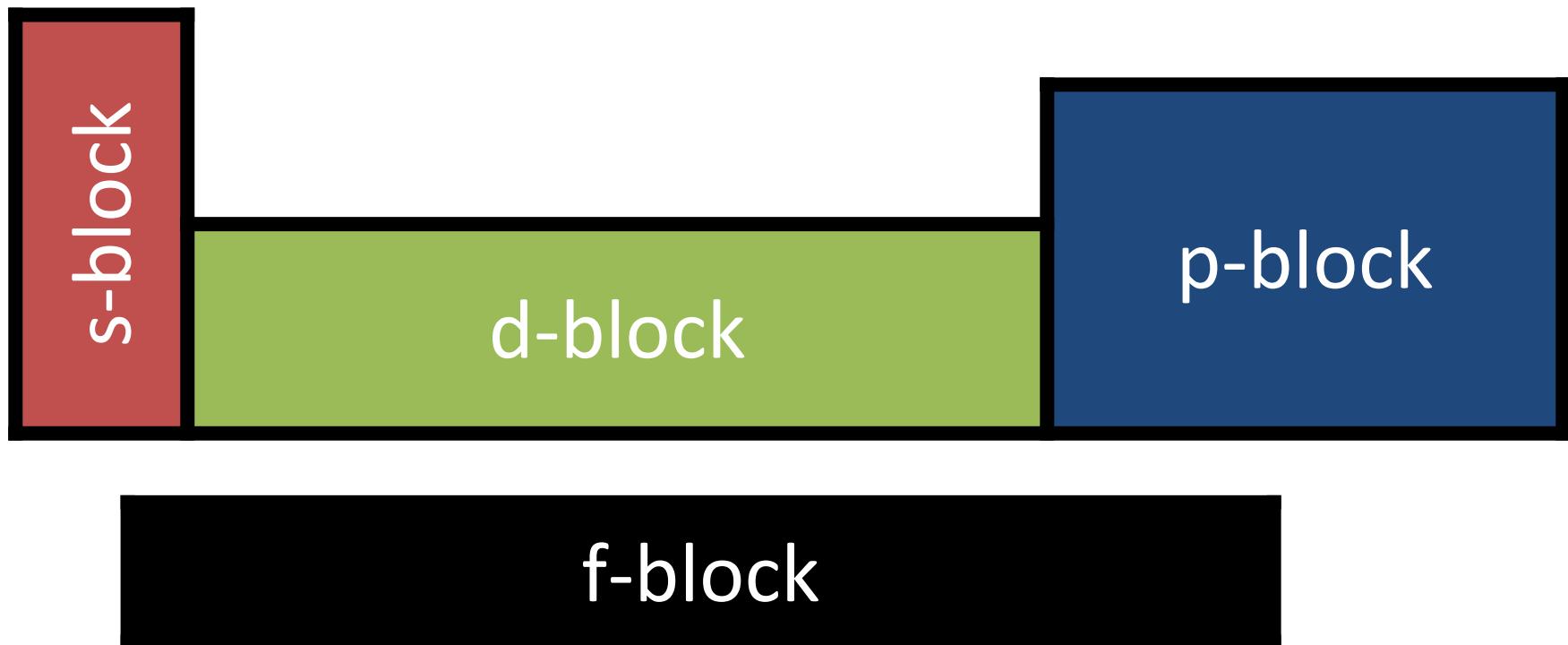




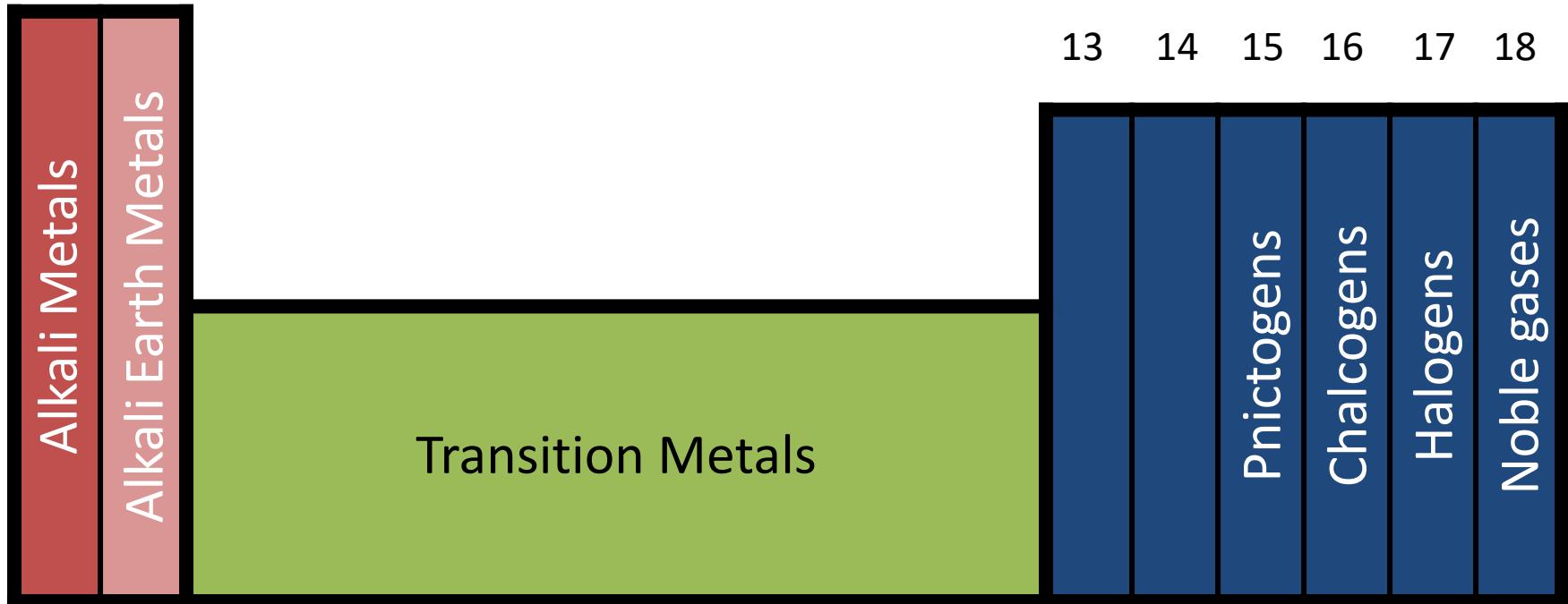
The Periodic Table

Columns in the periodic table are called groups.

Rows in the periodic table are called periods.

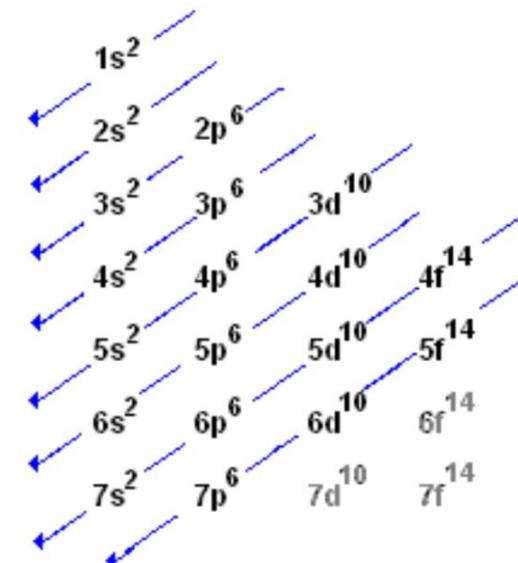
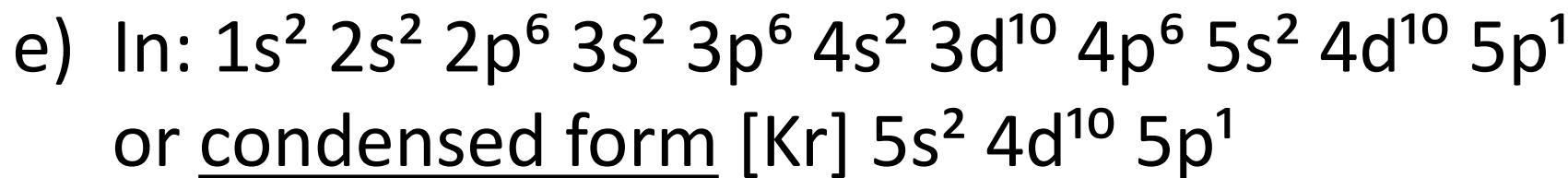
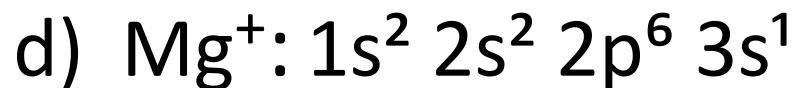
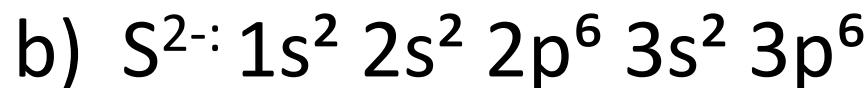
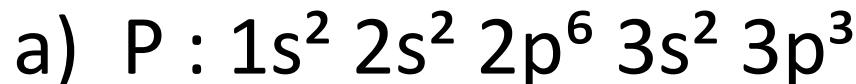


The Periodic Table



Worksheet Question #2

Write the electron configurations for the following chemical species:



Condensed Form

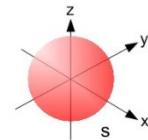
- Locate the element: on the periodic table.
- Identify the preceding noble gas: from the periodic table.
- Place the symbol of that noble gas: in square brackets.
- Add the remaining electrons: in the order of their energy levels (s, p, d, f).
- Ex:

Na: $1s^2 2s^2 2p^6 3s^1$ or [Ne]3s¹

K: $1s^2 2s^2 2p^6 3s^2 3p^6 4s^1$ or [Ar]4s¹

Br: [Ar] 4s² 3d¹⁰ 4p⁵

Fill in electrons



1

[He]

1

2

[Ne]

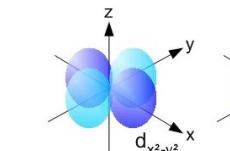
1

2

[Ar]

1

2



3

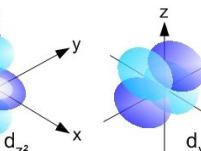
4

5

6

7

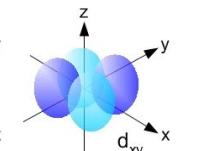
8



9

10

11



12



3

4

5

6

7

8

2

[Kr]

1

2



3

4

5

6

7

8

9

10

11

12

13

14

15

16

17

18

[Xe]

1

2



17

18

19

20

21

22

23

24

25

26

27

28

29

30

31

32

[Rn]

1

2



17

18

19

20

21

22

23

24

25

26

27

28

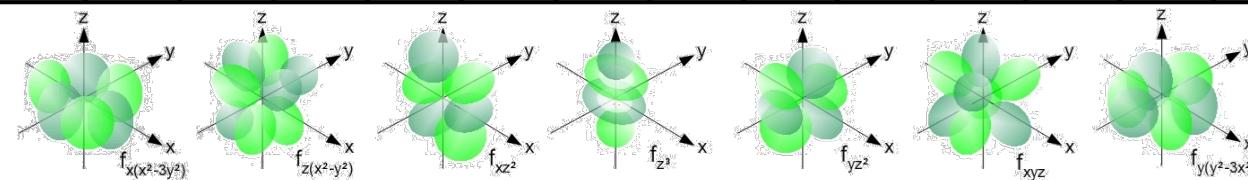
29

30

31

32

3	4	5	6	7	8	9	10	11	12	13	14	15	16
3	4	5	6	7	8	9	10	11	12	13	14	15	16



Valence Electrons

For elements in the **s- and p-blocks only**

The electrons occupying the *s* and *p* subshells with the largest *n* (for the neutral element) are called valence electrons, and the collection of occupied subshells is called the valence shell.

- Electrons which aren't valence electrons are called core electrons.
- In solids, valence orbitals on atoms overlap to form valence bands extending throughout the material.
- Valence electrons are fundamental to chemistry because they are involved in the formation of bonds. Core electrons are not involved in chemical bonding.

Valence electrons for neutral elements

1													2
1	2												3
1	2												4
1	2												5
1	2												6
1	2												7
1	2												8

EXCEPTION



Clicker Question

- Which of the following species has six valence electrons?

1
Group

- a) S^{2-}
- b) B
- c) Ge^{2-}
- d) C
- e) Ar^+

The Periodic Table shows the following elements highlighted with red boxes:

- Group 13: B (10.811), Al (26.982)
- Group 14: C (12.011), Si (28.086)
- Group 15: N (14.007), P (30.974)
- Group 16: O (15.999), S (32.064)
- Group 17: F (18.998), Cl (35.453)
- Group 18: Ne (4.003), Ar (39.948)
- Period 6: Ge (72.59), Cd (112.41), In (114.82), Sn (118.69), Sb (121.75), Te (127.6), I (126.9), Xe (131.3)
- Period 7: Hg (200.59), Tl (204.37), Pb (207.2), Bi (208.98), Po (209.00), At (210.00), Rn (222.00)
- Period 8: Lu (174.97)

The table also includes the following information:

- Group 1:** H (1.008), Li (6.941), Na (22.99), K (39.098), Rb (85.468), Cs (132.9)
- Group 2:** Be (9.012), Mg (24.305), Ca (40.08), Sc (44.956), Ti (47.9), V (50.941), Cr (51.996), Mn (54.938), Fe (55.847), Co (58.933), Ni (58.7), Cu (63.546), Zn (65.38), Ga (69.72), Ge (72.59)
- Group 17:** F (18.998), Cl (35.453), Br (79.904), Kr (83.8), I (126.9), Xe (131.3)
- Group 18:** He (4.003), Ne (10.179), Ar (39.948)
- Actinides:** Ac# (227.03), Th (232.04), Pa (231.04), U (238.03), Np (237.05), Pu (244), Am (243), Cm (247), Bk (247), Cf (251), Es (252), Fm (257), Md (258), No (259), Lr (260)
- Rutherfordium (Rf):** Rf (104), Db (105), Sg (106), Bh (107), Hs (108), Mt (109)
- Curium (Cm):** Cm (96), Bk (97), Cf (98), Es (99), Fm (100), Md (101), No (102), Lr (103)
- Lanthanides:** Ce (58), Pr (59), Nd (60), Pm (61), Sm (62), Eu (63), Gd (64), Tb (65), Dy (66), Ho (67), Er (68), Tm (69), Yb (70), Lu (71)
- Other:** Hf (72), Ta (73), W (74), Re (75), Os (76), Ir (77), Pt (78), Au (79), Hg (80), Tl (81), Pb (82), Bi (83), Po (84), At (85), Rn (86)

Clicker Question

How many valence electrons does Li have?

- a) 0
- b) 1
- c) 2
- d) 8
- e) 4

Group																						
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18					
H 1.000	Be 9.012	Li 6.941	Na 22.99	Mg 24.305	K 39.098	Ca 40.08	Sc 44.956	Ti 47.9	V 50.941	Cr 51.996	Mn 54.938	Fe 55.847	Co 58.933	Ni 58.7	Cu 63.546	Zn 65.38	B 10.811	C 12.011	N 14.007	O 15.999	F 18.998	He 4.003
Rb 85.468	Sr 87.62	Y 88.906	Zr 91.22	Nb 92.906	Mo 95.94	Tc "(98)"	Ru 101.07	Rh 102.9	Pd 106.4	Ag 107.87	Cd 112.41	In 114.82	Sn 118.69	Sb 121.75	Te 127.6	I 126.9	Xe 131.3					
Cs 132.9	Ba 137.33	La* 138.91	Hf 178.49	Ta 180.95	W 183.85	Re 186.21	Os 190.2	Ir 192.22	Pt 195.09	Au 196.97	Hg 200.59	Tl 204.37	Pb 207.2	Bi 208.98	Po "(209)"	At "(210)'	Rn "(222)"					
Fr 223	Ra 226.03	Ac# 227.03	Rf $\{261\}$	Db 104	Sg 105	Bh 106	Hs 107	Mt 108														
*		Ce 140.12	Pr 140.91	Nd 144.24	Pm 145	Sm 150.4	Eu 151.96	Gd 157.25	Tb 158.92	Dy 162.5	Ho 164.93	Er 167.26	Tm 168.93	Yb 173.04	Lu 174.97							
#		Th 232.04	Pa 231.04	U 238.03	Np 237.05	Pu 244	Am 243	Cm 247	Bk 247	Cf 251	Es 252	Fm 257	Md 258	No 259	Lr 260							

Clicker Question

How many valence electrons does Li^+ have?

- a) 0
- b) 1
- c) 2
- d) 8
- e) 4

Clicker Question

How many valence electrons does O²⁻ have?

- a) 0
- b) 1
- c) 2
- d) 8
- e) 4

Group																			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18		
¹ H 1.008												⁵ B 10.811	⁶ C 12.011	⁷ N 14.007	⁸ O 15.999		⁹ F 18.998		² He 4.003
³ Li 6.941	⁴ Be 9.012											¹³ Al 26.982	¹⁴ Si 28.086	¹⁵ P 30.974	¹⁶ S 32.064		¹⁷ Cl 35.453		¹⁸ Ar 39.948
¹¹ Na 22.99	¹² Mg 24.305																		
¹⁹ K 39.098	²⁰ Ca 40.08	²¹ Sc 44.956	²² Ti 47.9	²³ V 50.941	²⁴ Cr 51.996	²⁵ Mn 54.938	²⁶ Fe 55.847	²⁷ Co 58.933	²⁸ Ni 58.7	²⁹ Cu 63.546	³⁰ Zn 65.38	³¹ Ga 69.72	³² Ge 72.59	³³ As 74.922	³⁴ Se 78.96	³⁵ Br 79.904	³⁶ Kr 83.8		
³⁷ Rb 85.468	³⁸ Sr 87.62	³⁹ Y 88.906	⁴⁰ Zr 91.22	⁴¹ Nb 92.906	⁴² Mo 95.94	⁴³ Tc "(98)"	⁴⁴ Ru 101.07	⁴⁵ Rh 102.9	⁴⁶ Pd 106.4	⁴⁷ Ag 107.87	⁴⁸ Cd 112.41	⁴⁹ In 114.82	⁵⁰ Sn 118.69	⁵¹ Sb 121.75	⁵² Te 127.6	⁵³ I 126.9	⁵⁴ Xe 131.3		
⁵⁵ Cs 132.9	⁵⁶ Ba 137.33	⁵⁷ La* 138.91	⁷² Hf 178.49	⁷³ Ta 180.95	⁷⁴ W 183.85	⁷⁵ Re 186.21	⁷⁶ Os 190.2	⁷⁷ Ir 192.22	⁷⁸ Pt 195.09	⁷⁹ Au 196.97	⁸⁰ Hg 200.59	⁸¹ Tl 204.37	⁸² Pb 207.2	⁸³ Bi 208.98	⁸⁴ Po "(209)"	⁸⁵ At "(210)'	⁸⁶ Rn "(222)"		
⁸⁷ Fr 223	⁸⁸ Ra 226.03	⁸⁹ Ac# 227.03	¹⁰⁴ Rf {261}	¹⁰⁵ Db	¹⁰⁶ Sg	¹⁰⁷ Bh	¹⁰⁸ Hs	¹⁰⁹ Mt											
*			⁵⁸ Ce 140.12	⁵⁹ Pr 140.91	⁶⁰ Nd 144.24	⁶¹ Pm 145	⁶² Sm 150.4	⁶³ Eu 151.96	⁶⁴ Gd 157.25	⁶⁵ Tb 158.92	⁶⁶ Dy 162.5	⁶⁷ Ho 164.93	⁶⁸ Er 167.26	⁶⁹ Tm 168.93	⁷⁰ Yb 173.04	⁷¹ Lu 174.97			
#			⁹⁰ Th 232.04	⁹¹ Pa 231.04	⁹² U 238.03	⁹³ Np 237.05	⁹⁴ Pu 244	⁹⁵ Am 243	⁹⁶ Cm 247	⁹⁷ Bk 247	⁹⁸ Cf 251	⁹⁹ Es 252	¹⁰⁰ Fm 257	¹⁰¹ Md 258	¹⁰² No 259	¹⁰³ Lr 260			

Exercises

1. For each of the following species, determine the number of valence electrons.

(a) P (5)

1

1	2	3	4	5	6	7	8
H	Be	C	N	O	F	Ne	He
Li	Mg	B	P	S	Cl	Ar	
Na	Mg	Al	Si	S	Cl	Ar	
K	Ca	Ga	Ge	As	Se	Br	Kr
Rb	Sr	In	Sn	Sb	Te	I	Xe
Cs	Ba	Tl	Pb	Bi	Po	At	Rn
Fr	Rn	La	Os	Hg			
		Hf	Ir	Tl			
		Ta	Pt	Pb			
		W	An	Bi			
		Re	Hg				
		Os					
		Ir					
		Pt					
		An					
		Hg					
		Tl					
		Pb					
		Bi					
		Po					
		At					
		Rn					

(b) Cl⁻ (8)

2

(c) Mg⁺ (1)

(d) Ca²⁺ (0)

(e) S²⁻ (8)

(f) B⁻ (4)

(g) Rb⁺ (0)

The Periodic Table of the Elements

58 Ce Cerium (140)	59 Pr Praseodymium (141)	60 Nd Neodymium (142)	61 Pm Promethium (143)	62 Sm Samarium (145)	63 Eu Europium (146)	64 Gd Gadolinium (147)	65 Tb Terbium (148)	66 Dy Dysprosium (149)	67 Ho Holmium (149)	68 Er Erbium (152)	69 Tm Thulium (153)	70 Yb Ytterbium (154)	71 Lu Lutetium (155)
90 Th Thorium (141)	91 Pa Protactinium (141)	92 U Uranium (141)	93 Np Neptunium (143)	94 Pu Plutonium (144)	95 Am Americium (145)	96 Cm Curium (146)	97 Bk Berkelium (147)	98 Cf Californium (148)	99 Es Einsteinium (152)	100 Fm Fermium (153)	101 Md Mendelevium (155)	102 No Neptunium (158)	103 Lr Lawrencium (158)

Lab Connection

EXPT. 22 – *Using WebMO to understand Periodic/ atomic/ molecular properties*

- Effective nuclear charge
- Atomic radius/ ionic radius/ metallic radius
- Ionization energy
- Electron affinity
- Electronegativity
- Orbitals – wave representations of the space with highest probability of finding the electron
- Types and sizes of orbitals – s, p, d, f and variation based on the “n” value and type of species (atom, cation, anion)

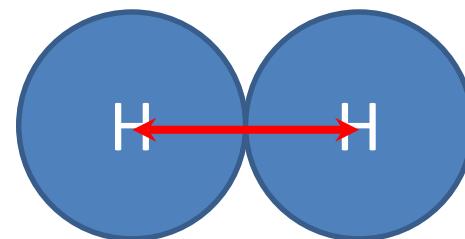
Periodic Properties

- Atomic radius
- Effective nuclear charge (Z_{eff})
- Ionization energy
- Electron affinity
- Electronegativity (EN)

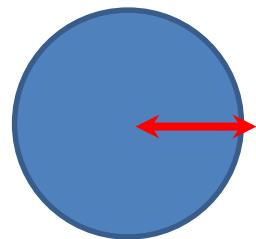
Atomic Radius

- Atomic radius is calculated by measuring the **internuclear distance and dividing by 2**

Internuclear distance:



$$\text{Atomic Radius} = \frac{\text{Internuclear distance}}{2}$$



- The bond distance for H_2 is 0.74 Å, half of which is 0.37 Å.
- The calculated radius is 0.53 Å using the Bohr model.
- $1 \text{ \AA} = 1 \times 10^{-10} \text{ m}$

Relative Orbital Sizes

s



p



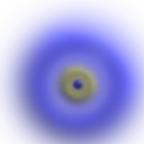
d



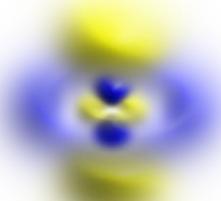
f

1

2



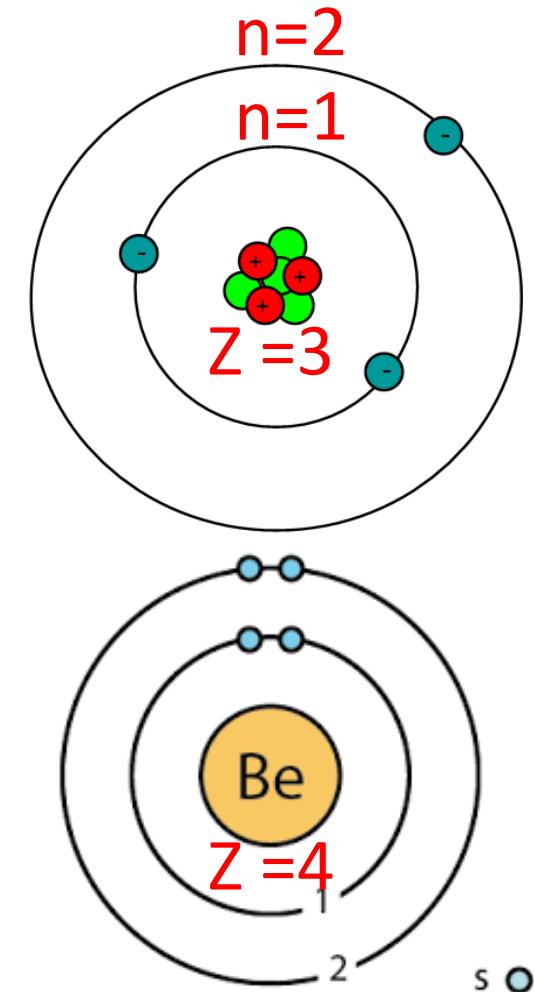
3



4

Atomic Radius (across a period)

Element	Radius (Å)
Li	1.28
Be	0.96
B	0.84
C	0.76
N	0.71
O	0.66
F	0.57
Ne	n/a no diatomic molecule

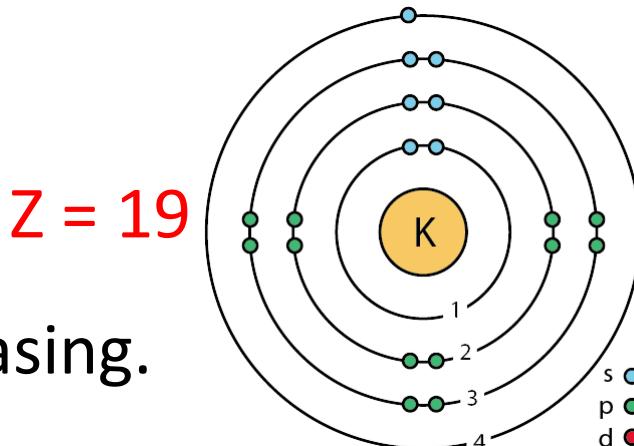
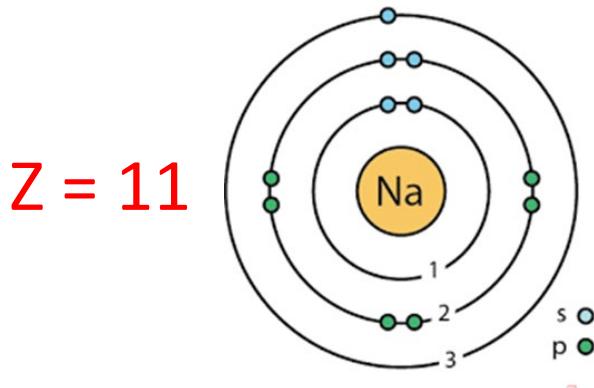
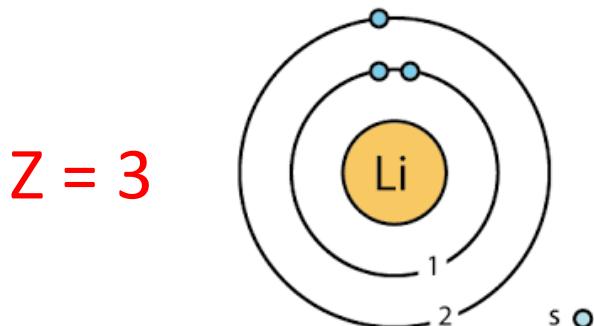


- Z is increasing but n is constant.

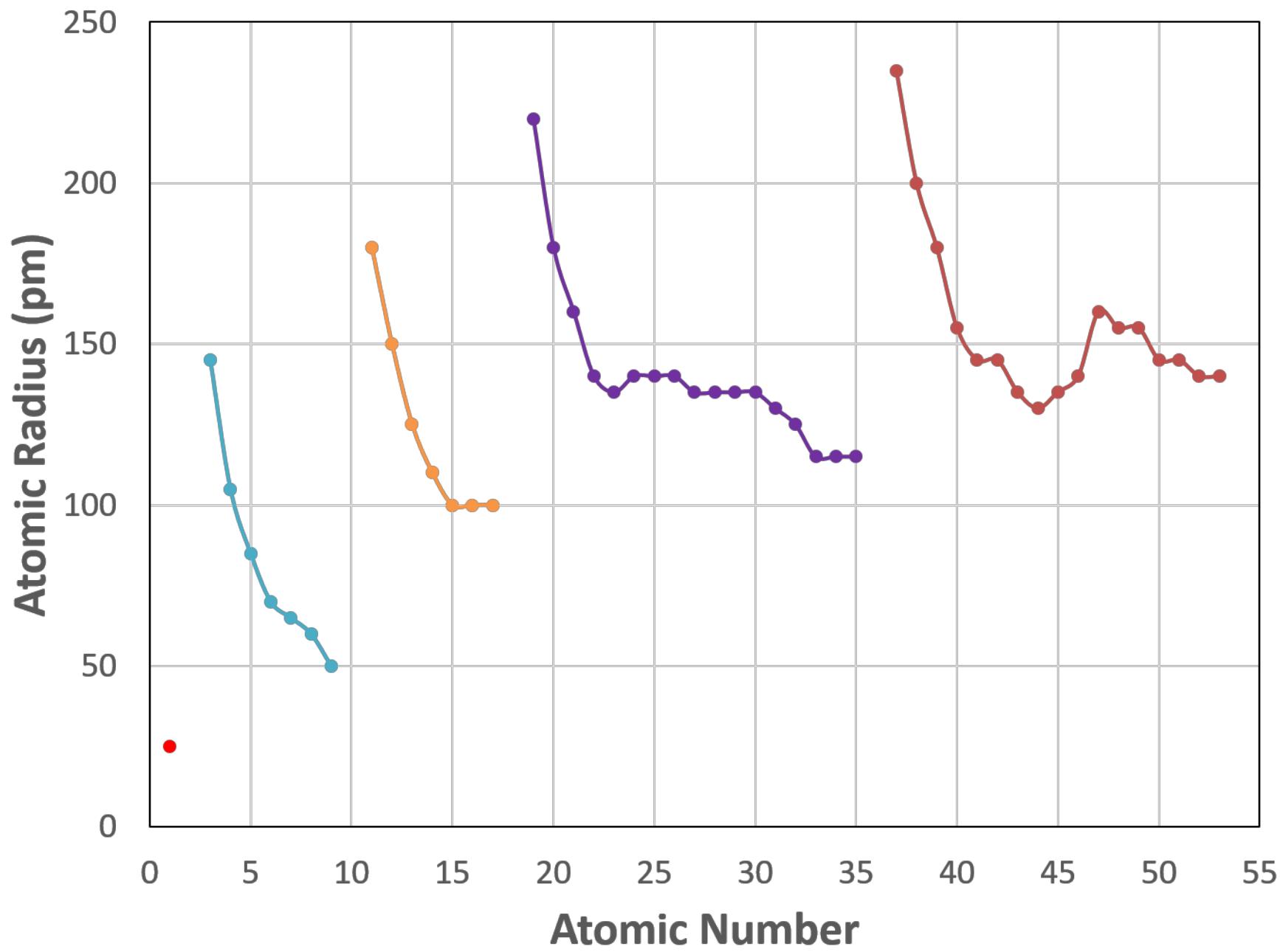
Atomic radius (down a group)

Element	Radius (Å)
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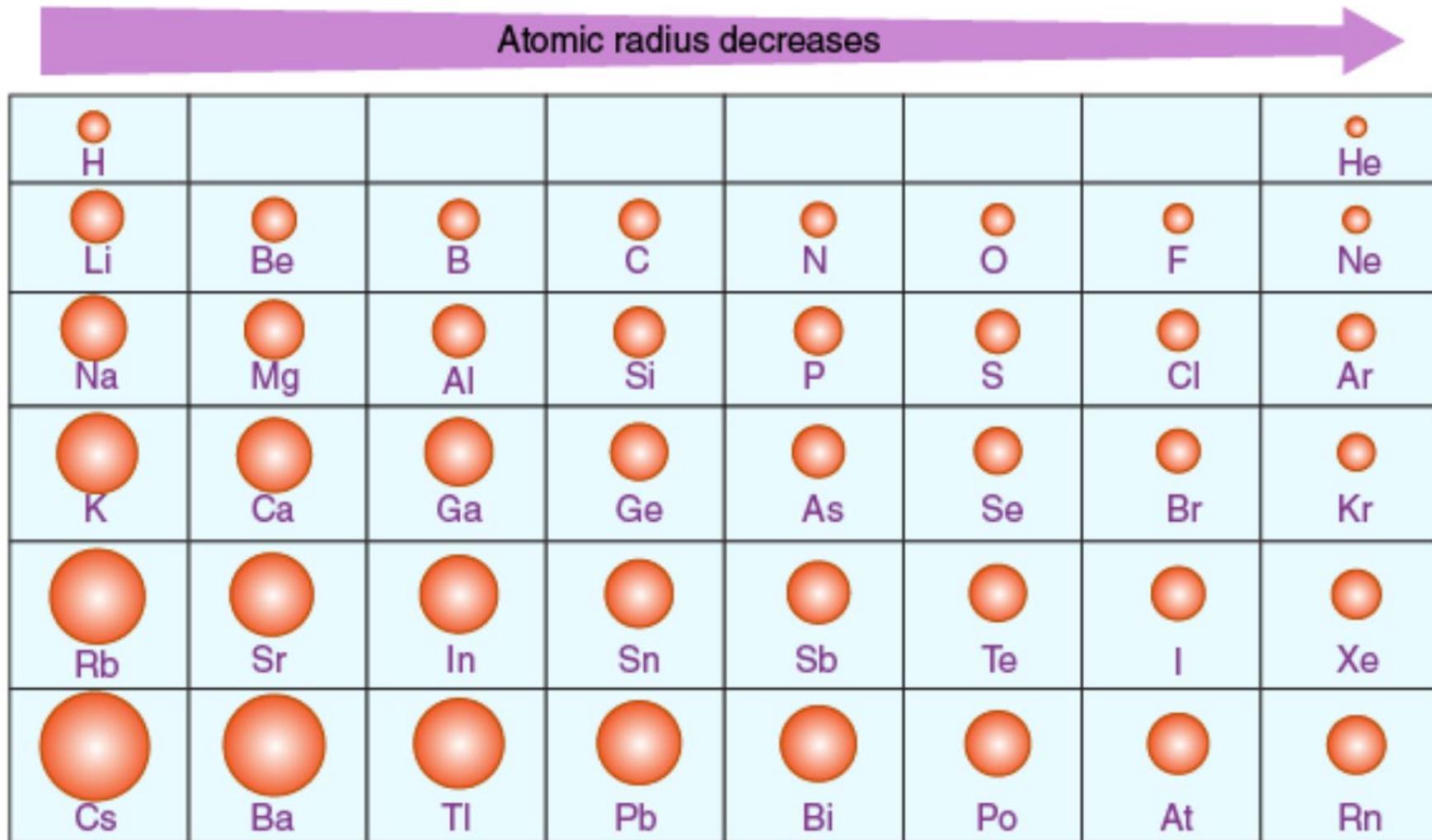
Li	1.28
Na	1.66
K	2.03
Rb	2.20
Cs	2.44
Fr	n/a



- Down a group, both Z and n are increasing.

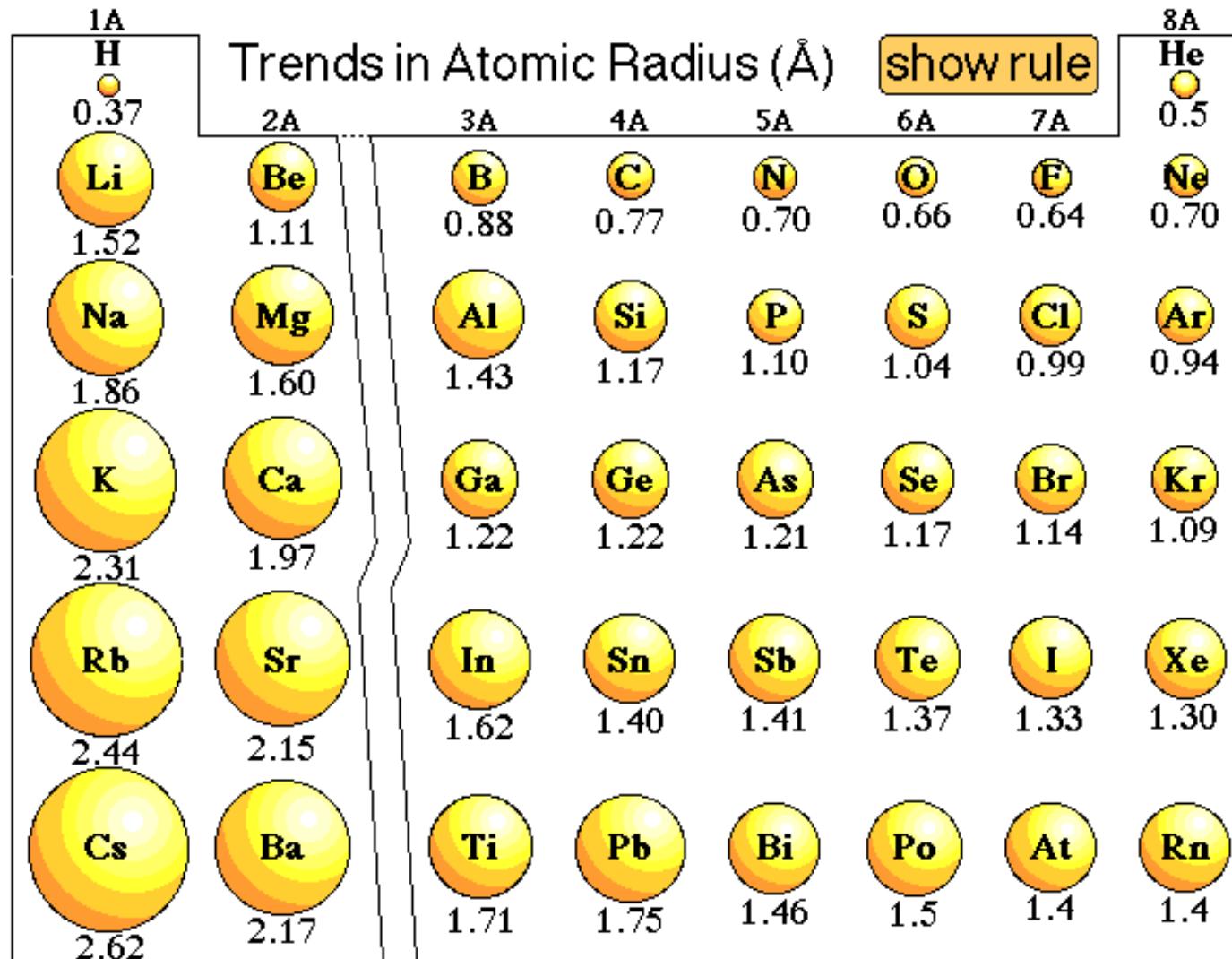


Atomic Radius



Atomic Radius

You do NOT need to know the values for exams but you should know the trend



Worksheet Question #4

Calculate the atomic radius of silicon (one of the most important elements in the microelectronics industry), given the following information:



- the H-H bond distance in H_2 is 0.74 Å
- the Si-H bond distance in SiH_4 is 1.46 Å

$$\text{Ans: } 1.46 - (0.74/2) = 1.10 \text{ Å}$$

Clicker Question

Select the sequence of atoms that are correctly listed in order of increasing size.

- a) F < Br < Ge < K
- b) Na < Al < P < S
- c) Ba < Ca < Mg < Be
- d) Cl < Si < C < B

Clicker Question

a) F < Br < Ge < K

The Periodic Table of the Elements

H Hydrogen 1.00794														F Fluorine 18.99847			
Li Lithium 6.941	Be Boron 9.012182													Ne Neon 20.1307			
11 Na Sodium 22.98970	12 Mg Magnesium 24.30118																
19 K Potassium 39.0983	20 Ca Calcium 40.078	21 Sc Scandium 44.95590	22 Tl Thallium 41.987	23 V Vanadium 50.9415	24 Cr Chromium 51.986	25 Mn Manganese 54.93814	26 Fe Iron 55.845	27 Co Cobalt 58.93110	28 Ni Nickel 58.694	29 Cu Copper 63.546	30 Zn Zinc 65.403	31 Ga Gallium 69.721	32 Ge Germanium 72.640	33 As Arsenic 74.94787	34 Se Selenium 78.356	35 Br Bromine 80.004	36 Kr Krypton 83.800
37 Rb Rubidium 83.41671	38 Sr Strontium 87.620	39 Y Yttrium 88.90184	40 Zr Zirconium 91.224	41 Nb Niobium 92.90618	42 Mo Molybdenum 95.941	43 Tc Technetium 98.007	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.90550	46 Pd Palladium 106.451	47 Ag Silver 107.868	48 Cd Cadmium 112.411	49 In Indium 113.463	50 Sn Tin 118.700	51 Sb Antimony 121.760	52 Te Tellurium 127.603	53 I Iodine 126.90411	54 Xe Xenon 131.335
55 Cs Cesium 132.91345	56 Ba Barium 137.317	57 La Lanthanum 138.90540	58 Hf Hafnium 138.412	59 Ta Tantalum 138.9479	60 W Tungsten 183.814	61 Re Rhenium 186.207	62 Os Osmium 186.917	63 Ir Iridium 190.203	64 Pt Platinum 190.9038	65 Au Gold 196.68633	66 Hg Mercury 200.59	67 Tl Thallium 204.3803	68 Pb Lead 207.2021	69 Bi Bismuth 208.0894	70 Po Polonium 210.018	71 At Astatine 210.0	72 Rn Radium 222.0
87 Fr Francium (223)	88 Rn Radon (222)	89 Ac Actinium (227)	104 Rf Rutherfordium (261)	105 Db Dubnium (262)	106 Sg Sgadolinium (263)	107 Hs Hassium (265)	108 Mt Meitnerium (268)	109 L Livermorium (269)	110 Mc Moscovium (268)	111 Cn Copernicium (285)	112 Fl Florium (289)	113 Mc Moscovium (289)	114 Pa Protactinium (231)				

58 Ce Cerium 140.1135	59 Pr Praseodymium 140.90763	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.32	63 Eu Europium 151.90264	64 Gd Gadolinium 157.21	65 Tb Terbium 158.92134	66 Dy Dysprosium 162.50	67 Ho Holmium 164.91651	68 Er Erbium 167.26	69 Tm Thulium 169.95423	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
90 Tb Thorium 139.90181	91 Pa Protactinium 131.93583	92 U Uranium 138.9289	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (247)	98 Cf Californium (250)	99 Es Espresso (252)	100 Fm Fermium (253)	101 Md Mendelevium (256)	102 No Neptunium (259)	103 Lr Lawrencium (262)

Clicker Question

b) Na < Al < P < S

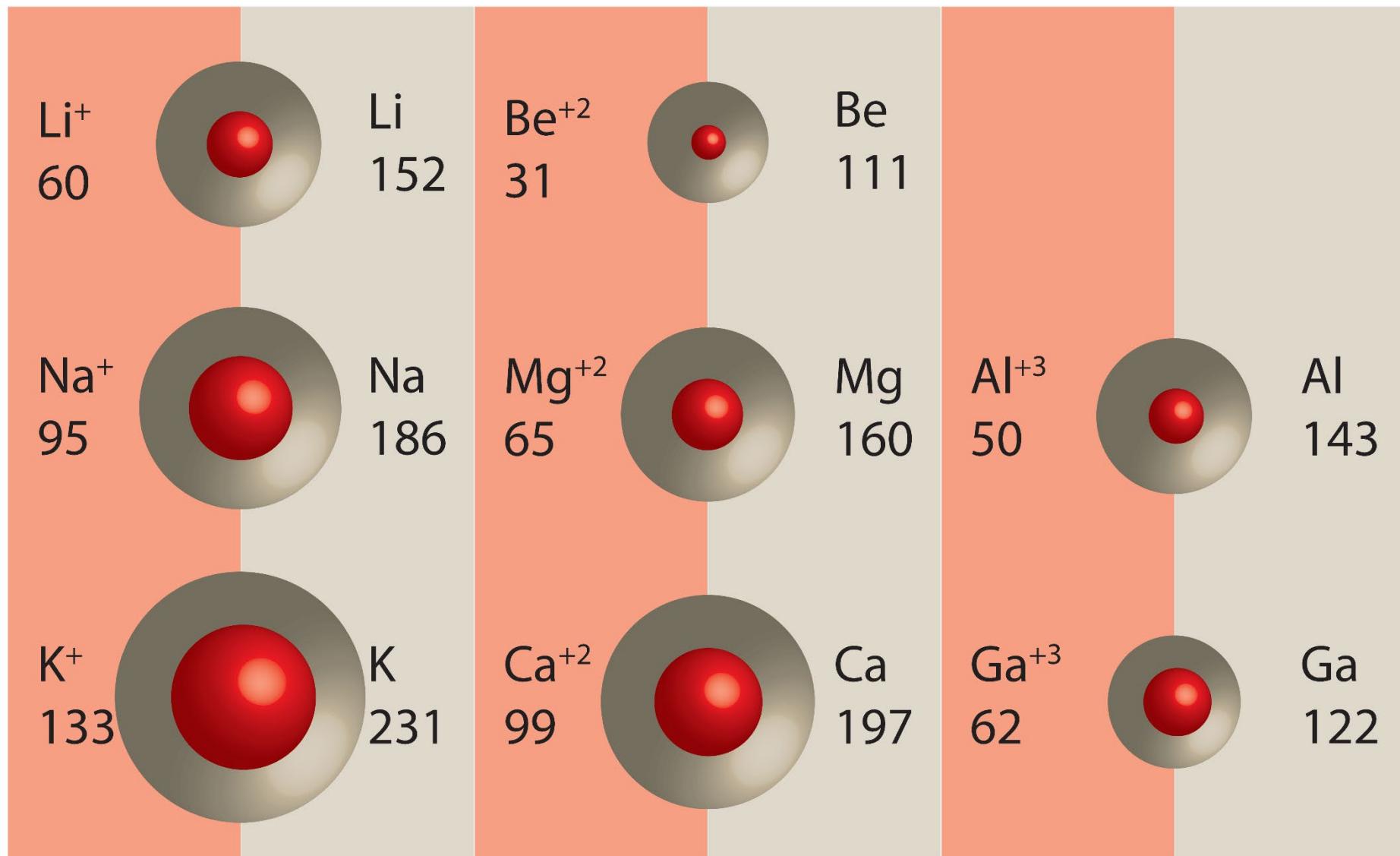
The Periodic Table of the Elements

H Hydrogen 1.00794													He Helium 4.00260				
Li Lithium 6.941	Be Boron 9.012182												Ne Neon 20.1587				
Na Sodium 22.98977	Mg Magnesium 24.3014												Ar Argon 39.948				
K Potassium 39.0983	Ca Calcium 40.078	Tl Thallium 204.2000	V Vanadium 50.9415	Cr Chromium 51.996	Mn Manganese 54.93814	Fe Iron 55.845	Co Cobalt 58.93110	Ni Nickel 58.694	Cu Copper 63.546	Zn Zinc 65.43	Al Aluminum 26.98154	Si Silicon 28.0855	P Phosphorus 30.97376	S Sulfur 32.063	Cl Chlorine 35.4537	Ar Argon 39.948	
Rb Rubidium 82.9113	Sr Strontium 87.62	Y Yttrium 88.9053	Zr Zirconium 91.224	Nb Niobium 92.90618	Mo Molybdenum 95.94	Tc Technetium 98.0	Ru Ruthenium 101.07	Rh Rhodium 102.9055	Pd Palladium 106.45	Ag Silver 107.8682	Cd Cadmium 112.411	In Indium 113.482	Sn Tin 118.70	Sb Antimony 121.76	Te Tellurium 127.6011	I Iodine 127.00	Xe Xenon 131.335
Cs Cesium 132.91145	Ba Barium 137.317	La Lanthanum 138.9054	Hf Hafnium 178.442	Ta Tantalum 180.9479	W Tungsten 183.81	Re Rhenium 186.207	Os Osmium 187.50	Ir Iridium 192.117	Pt Platinum 195.078	Au Gold 196.68633	Hg Mercury 200.59	Tl Thallium 204.3813	Pb Lead 207.2	Bi Bismuth 208.0894	Po Polonium 210.0	At Astatine 218.0	Rn Radium 226.0
Fr Francium (223)	Rn Radium (223)	Ac Actinium (227)	Rf Rutherfordium (261)	Ds Darmstadtium (262)	Sg Seaborgium (263)	Hs Hassium (265)	Mt Meitnerium (268)	107 (269)	108 (269)	109 (270)	110 (270)	111 (271)	112 (271)	113 (271)	114 (271)		

58 Ce Cerium 140.1135	59 Pr Praseodymium 140.90763	60 Nd Neodymium 144.24	61 Pm Promethium (145)	62 Sm Samarium 150.32	63 Eu Europium 151.90264	64 Gd Gadolinium 157.21	65 Tb Terbium 158.92134	66 Dy Dysprosium 162.50	67 Ho Holmium 164.91651	68 Er Erbium 167.26	69 Tm Thulium 169.95423	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.967
90 Tb Thorium 178.0161	91 Pa Protactinium 178.63763	92 U Uranium 178.62689	93 Np Neptunium (237)	94 Pu Plutonium (244)	95 Am Americium (243)	96 Cm Curium (247)	97 Bk Berkelium (249)	98 Cf Californium (250)	99 Es Espresso (252)	100 Fm Fermium (253)	101 Md Mendelevium (256)	102 No Neptunium (259)	103 Lr Lawrencium (262)

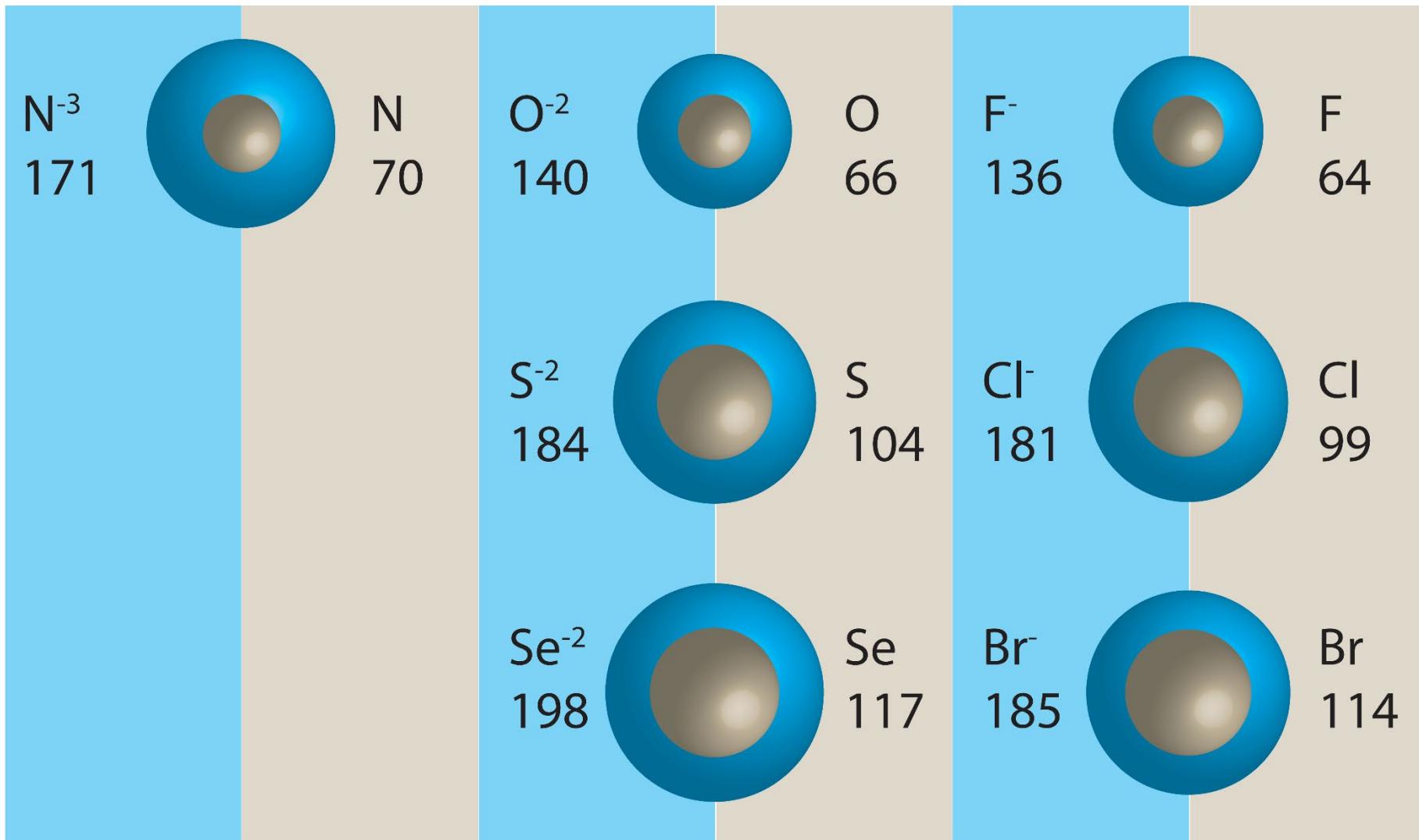
Cationic radii

For a given atom, its **cation** is always **smaller** than the neutral species.



Anionic radii

For a given atom, its **anion** is always **larger** than the neutral species.

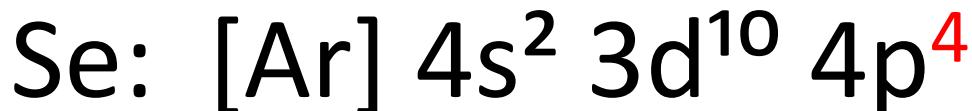


Worksheet Question #5

Rationalize the difference in the atomic and ionic radii of the following species:

(a) Se (117 pm) and Se^{2-} (198 pm)

(b) K (231 pm) and K^+ (133 pm)



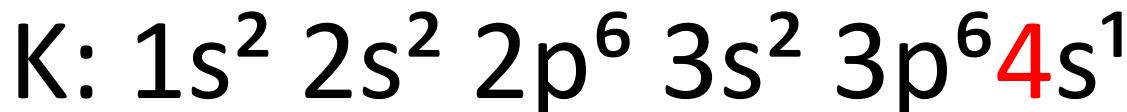
- gaining two electrons increases electron-electron repulsion

Worksheet Question #5

Rationalize the difference in the atomic and ionic radii of the following species:

(a) Se (117 pm) and Se^{2-} (198 pm)

(b) K (231 pm) and K^+ (133 pm)



- The radius of K is determined by the 4th shell.
- The radius of K^+ is determined by the 3rd shell.

Isoelectronic species

Atoms and ions with the **same number of electrons** are said to be *isoelectronic*. In a set of isoelectronic species, the most negative species has the largest radius.



Increasing Atomic or Ionic Radius

Isoelectronic species

K^+

Ar

Cl^-

$Z = 19 > Z = 18 > Z = 17c$

Larger Z , smaller radius

1 H Proton 1.66704	4 Be Boron 3.01302	11 Na Magnesium 2.33970	12 Mg Magnesium 2.33970	19 K Calcium 2.0083	20 Ca Scandium 4.0083	21 Sc Tin 4.0083	22 Tl V 3.0083	23 V Chromium 3.0083	24 Cr Manganese 3.0083	25 Mn Iron 3.0083	26 Fe Cobalt 3.0083	27 Co Nickel 3.0083	28 Ni Copper 3.0083	29 Cu Zinc 3.0083	30 Zn Gallium 3.0083	31 Ga Germanium 3.0083	32 Ge Arsenic 3.0083	33 As Selenium 3.0083	34 Se Bromine 3.0083	35 Br Krypton 3.0083	36 Kr														
37 Rb Rubidium 22.467	38 Sr Strontium 22.467	39 V Yttrium 22.467	40 Zr Zirconium 22.467	41 Nb Niobium 22.467	42 Mo Molybdenum 22.467	43 Tc Technetium 22.467	44 Ru Ruthenium 22.467	45 Rh Rhodium 22.467	46 Pd Palladium 22.467	47 Ag Silver 22.467	48 Cd Cadmium 22.467	49 In Indium 22.467	50 Sn Tin 22.467	51 Sb Antimony 22.467	52 Te Tellurium 22.467	53 I Iodine 22.467	54 Xe Xenon 22.467	55 Cs Cesium 22.467	56 Ba Barium 22.467	57 La Lanthanum 22.467	58 Hf Hafnium 22.467	59 Ta Tantalum 22.467	60 W Tungsten 22.467	61 Re Rhenium 22.467	62 Os Osmium 22.467	63 Ir Iridium 22.467	64 Pt Platinum 22.467	65 Au Gold 22.467	66 Hg Mercury 22.467	67 Tl Thallium 22.467	68 Pb Lead 22.467	69 Bi Bismuth 22.467	70 Po Polonium 22.467	71 At Astatine 22.467	72 Rn Radon 22.467
87 Fr Francium 22.467	88 Rn Radium 22.467	89 Ac Actinium 22.467	104 Rf Rutherfordium 22.467	105 Db Dubnium 22.467	106 Sg Singapore 22.467	107 Hs Hassium 22.467	108 Hs Hassium 22.467	109 Mt Meitnerium 22.467	110 Cf Curium 22.467	111 Bk Berkelium 22.467	112 Cf Curium 22.467	113 Bk Berkelium 22.467	114 Cf Curium 22.467																						
90 Th Thorium 22.467	91 Pa Protactinium 22.467	92 U Uranium 22.467	93 Np Neptunium 22.467	94 Pu Plutonium 22.467	95 Am Americium 22.467	96 Cm Curium 22.467	97 Bk Berkelium 22.467	98 Cf Curium 22.467	99 Ea Einsteinium 22.467	100 Fm Fermium 22.467	101 Md Mendelevium 22.467	102 No Neptunium 22.467	103 Lr Lawrencium 22.467																						

5 B Boron 1.0083	6 C Carbon 1.0083	7 N Nitrogen 1.0083	8 O Oxygen 1.0083	9 F Fluorine 1.0083	10 Ne Neon 1.0083
13 Al Aluminum 1.0083	14 Si Silicon 1.0083	15 P Phosphorus 1.0083	16 S Sulfur 1.0083	17 Cl Chlorine 1.0083	18 Ar Argon 1.0083
31 Ga Gallium 1.0083	32 Ge Germanium 1.0083	33 As Arsenic 1.0083	34 Se Selenium 1.0083	35 Br Bromine 1.0083	36 Kr Krypton 1.0083
37 In Indium 1.0083	38 Sn Tin 1.0083	39 Sb Antimony 1.0083	40 Te Tellurium 1.0083	41 I Iodine 1.0083	42 Xe Xenon 1.0083
55 Tl Thallium 1.0083	56 Pb Lead 1.0083	57 Bi Bismuth 1.0083	58 Po Polonium 1.0083	59 At Astatine 1.0083	60 Rn Radium 1.0083
87 Cs Cesium 1.0083	88 Ba Barium 1.0083	89 La Lanthanum 1.0083	90 Hf Hafnium 1.0083	91 Ta Tantalum 1.0083	92 W Tungsten 1.0083
87 Fr Francium 1.0083	88 Rn Radium 1.0083	89 Ac Actinium 1.0083	90 Rf Rutherfordium 1.0083	91 Db Dubnium 1.0083	92 Sg Singapore 1.0083
90 Th Thorium 1.0083	91 Pa Protactinium 1.0083	92 U Uranium 1.0083	93 Np Neptunium 1.0083	94 Pu Plutonium 1.0083	95 Am Americium 1.0083
96 Ce Cerium 1.0083	97 Pr Praseodymium 1.0083	98 Nd Neodymium 1.0083	99 Pm Promethium 1.0083	100 Sm Samarium 1.0083	101 Eu Europium 1.0083
96 La Lanthanum 1.0083	97 Lu Lutetium 1.0083	98 Hf Hafnium 1.0083	99 Tb Terbium 1.0083	100 Dy Dysprosium 1.0083	101 Ho Holmium 1.0083
96 Ac Actinium 1.0083	97 Rf Rutherfordium 1.0083	98 Db Dubnium 1.0083	99 Sg Singapore 1.0083	100 Pm Plutonium 1.0083	101 Am Americium 1.0083
102 Fr Francium 1.0083	103 Rn Radium 1.0083	104 Ac Actinium 1.0083	105 Rf Rutherfordium 1.0083	106 Db Dubnium 1.0083	107 Sg Singapore 1.0083
102 Fr Francium 1.0083	103 Rn Radium 1.0083	104 Ac Actinium 1.0083	105 Rf Rutherfordium 1.0083	106 Db Dubnium 1.0083	107 Sg Singapore 1.0083

58 Ce Cerium 1.0083	59 Pr Praseodymium 1.0083	60 Nd Neodymium 1.0083	61 Pm Promethium 1.0083	62 Sm Samarium 1.0083	63 Eu Europium 1.0083	64 Gd Gadolinium 1.0083	65 Tb Terbium 1.0083	66 Dy Dysprosium 1.0083	67 Ho Holmium 1.0083	68 Er Erbium 1.0083	69 Tm Thulium 1.0083	70 Yb Ytterbium 1.0083	71 Lu Lutetium 1.0083
90 Th Thorium 1.0083	91 Pa Protactinium 1.0083	92 U Uranium 1.0083	93 Np Neptunium 1.0083	94 Pu Plutonium 1.0083	95 Am Americium 1.0083	96 Cm Curium 1.0083	97 Bk Berkelium 1.0083	98 Cf Curium 1.0083	99 Ea Einsteinium 1.0083	100 Fm Fermium 1.0083	101 Md Mendelevium 1.0083	102 No Neptunium 1.0083	103 Lr Lawrencium 1.0083

Clicker Question

Which of the following isoelectronic species is expected to have the **largest radius**?

- a. O²⁻
- b. N³⁻
- c. Na⁺
- d. F⁻

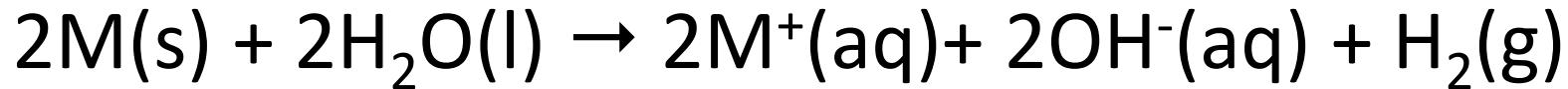
1 H Hydrogen 1.00794	4 Be Boron 6.941
3 Li Lithium 6.941	12 Mg Magnesium 24.312
11 Na Sodium 22.98970	12 Mg Magnesium 24.312
19 K Potassium 39.0983	20 Ca Calcium 40.078
37 Rb Rubidium 85.4671	38 Sr Strontium 87.67
55 Cs Cesium 132.91045	56 Ba Barium 137.321
87 Fr Francium 223	88 Rn Radium (223)

smallest Z

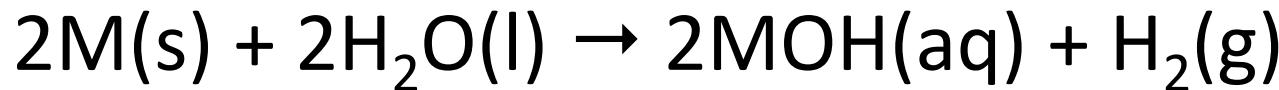
5 B Boron 10.811	6 C Carbon 12.011	7 N Nitrogen 14.012	8 O Oxygen 15.999	9 F Fluorine 18.998	10 He Helium 4.003
13 Al Aluminum 26.98153	14 Si Silicon 28.085	15 P Phosphorus 31.002	16 S Sulfur 32.064	17 Cl Chlorine 35.457	18 Ar Argon 39.948
31 Ga Gallium 69.721	32 Ge Germanium 72.61	33 As Arsenic 74.93160	34 Se Selenium 78.36	35 Br Bromine 79.904	36 Kr Krypton 83.805
50 In Indium 114.818	51 Sn Tin 118.700	52 Te Tellurium 121.601	53 I Iodine 126.90417	54 Xe Xenon 131.29	
75 Tl Thallium 204.393	76 Pb Lead 207.2	77 Bi Bismuth (207.1)	78 Po Polonium (208.993)	79 At Astatine (210)	80 Rn Radium (220)



DEMO TIME



Or

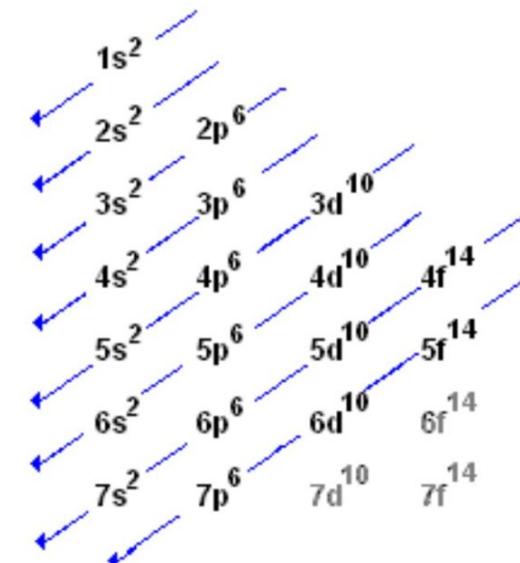
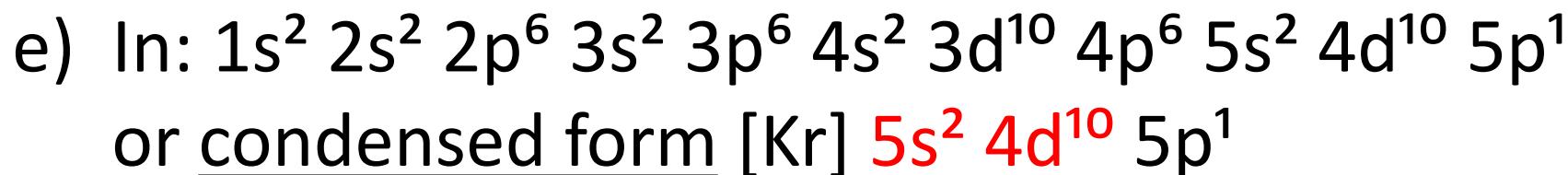
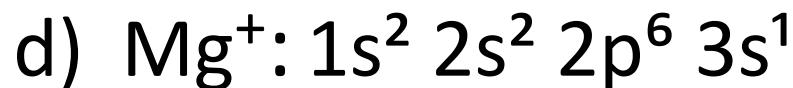
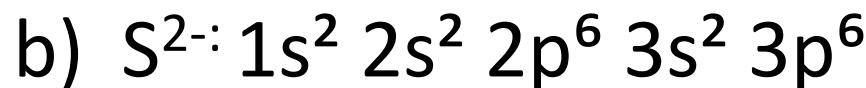
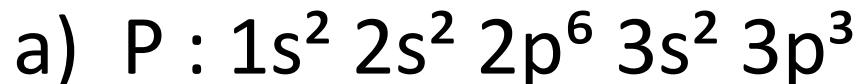


where M = Li, Na, K.

- Metals are ionized.
- The solution become more basic since OH^- is being produced.
- Reactivity Order K > Na > Li

Worksheet Question #2

Write the electron configurations for the following chemical species:



Effective nuclear charge (Z_{eff})

Coulomb's Law

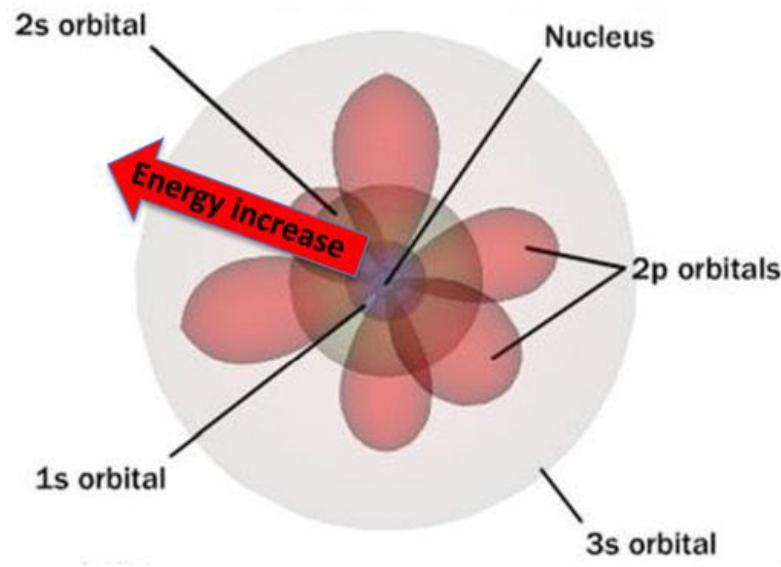
$$U = k \frac{q_1 \cdot q_2}{r}$$

Core electrons are close to the nucleus and effectively screen some of its positive charge from valence electrons further away. Valence electrons also partially screen each other from the nuclear charge. Thus, a valence electron “feels” an effective nuclear charge (Z_{eff}) that is less than the actual nuclear charge Z .

Note: Z_{eff} is a theoretically calculated property.

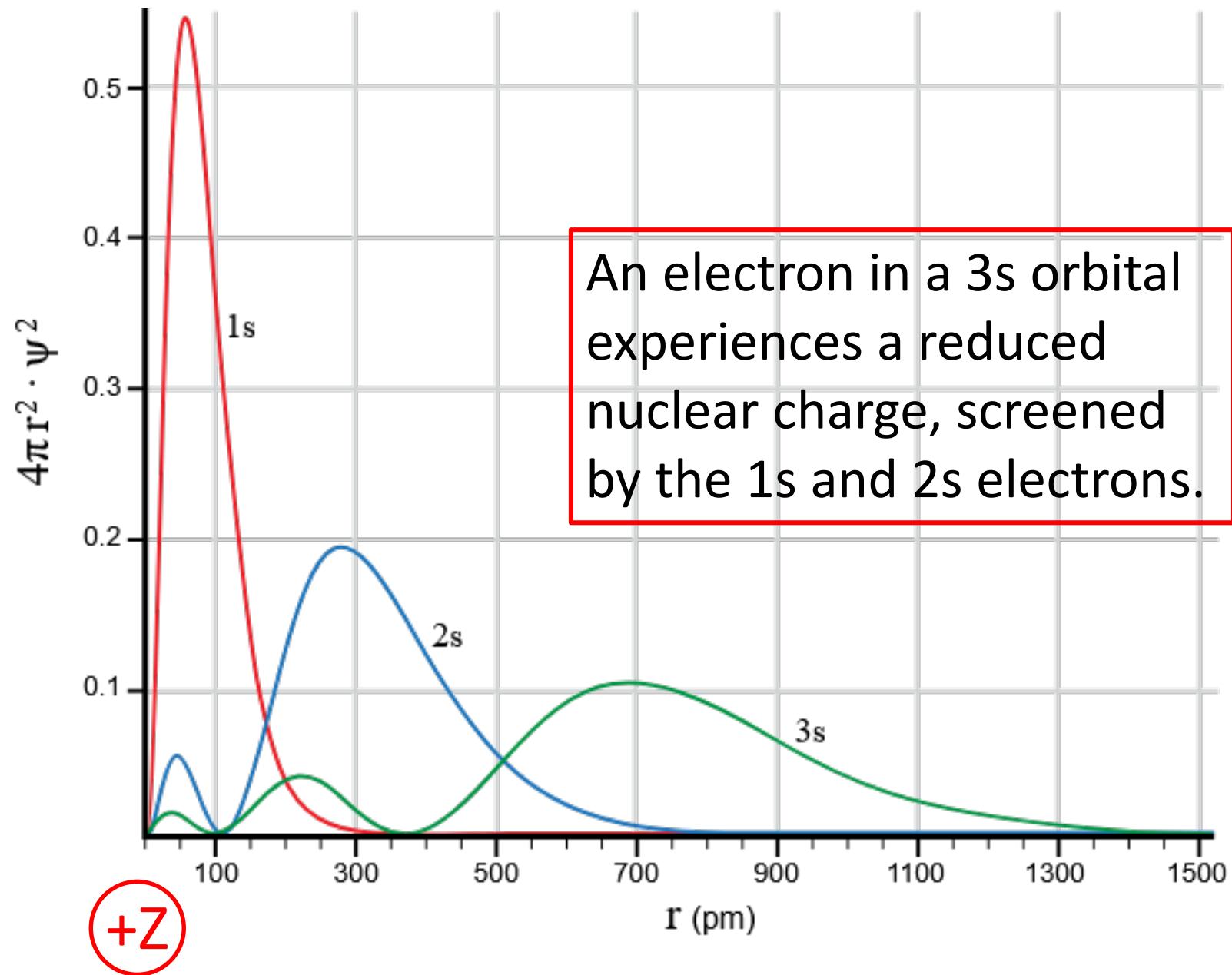
Shell Structure of Atoms

Orbitals become larger as the energy level increases



- Electrons filling order : 1s, 2s 2p, 3s
- Orbitals arranged in order of increasing energy: 1s, 2s 2p, 3s
- Orbitals arranged in increasing size: (smallest) 1s <2s <2p < 3s (largest)

Radial Distribution Functions of Orbitals

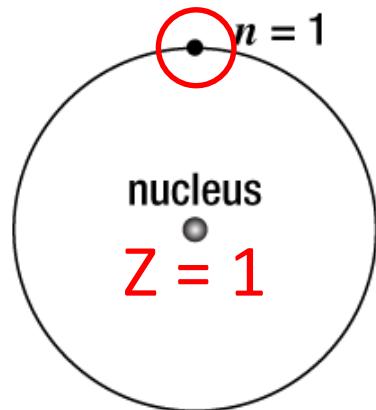


Effective nuclear charge

- **Effective nuclear charge (Z_{eff})**

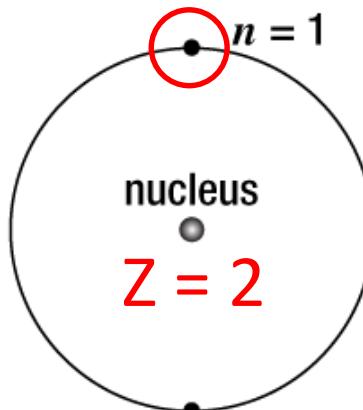
- the net positive charge experienced by an electron

$$\text{Coulomb's Law } F = k \frac{q_1 \cdot q_2}{r^2} ; \text{ Potential Energy } U = k \frac{q_1 \cdot q_2}{r}$$



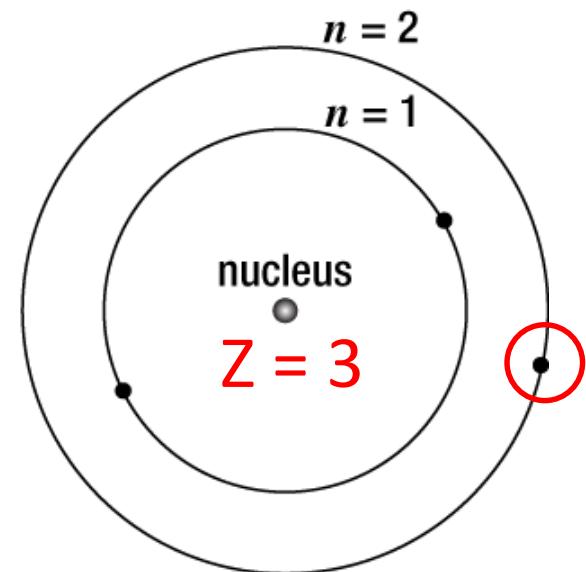
Hydrogen

$$Z_{\text{eff}} = 1$$



Helium

$$Z_{\text{eff}} = 1.7$$

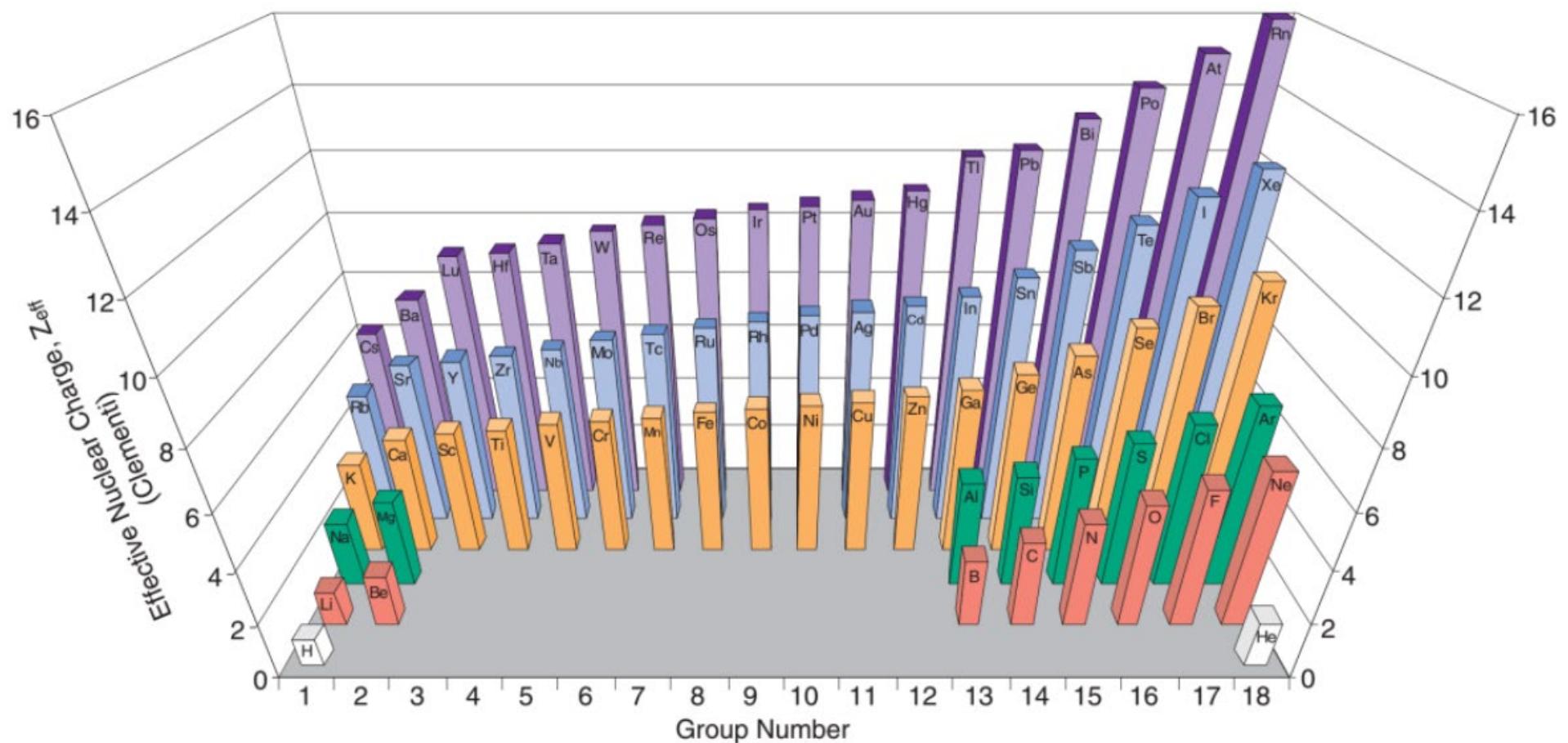


Lithium

$$1s: Z_{\text{eff}} = 2.69$$

$$2s: Z_{\text{eff}} = 1.28$$

Z_{eff} experienced by the valence electrons



Effective Nuclear Charge Z_{eff}

The diagram illustrates the periodic table with a pink arrow pointing from left to right, labeled "Increasing Effective Nuclear Charge (Z_{eff})". A vertical pink arrow on the left points downwards, labeled "Increases slightly". The table is color-coded: groups 1A, 2A, and He are in light green; groups 3A through 7A are in light pink; and group 8A is in light blue.

1A		Increasing Effective Nuclear Charge (Z_{eff})							8A
H		3A	4A	5A	6A	7A		He	
Li	Be	B	C	N	O	F		Ne	
Na	Mg	Al	Si	P	S	Cl		Ar	
K	Ca	Ga	Ge	As	Se	Br		Kr	
Rb	Sr	In	Sn	Sb	Te	I		Xe	

- Across a period, the number of core electrons doesn't increase, so majority of increase in Z passes through to Z_{eff} .
- Going down a group, the valence shell is the same but add core electrons.

Ionization Energy (IE)

For atoms, molecules or ions: the minimum energy required to remove a single electron from an atom, molecule or ion in its gaseous state.



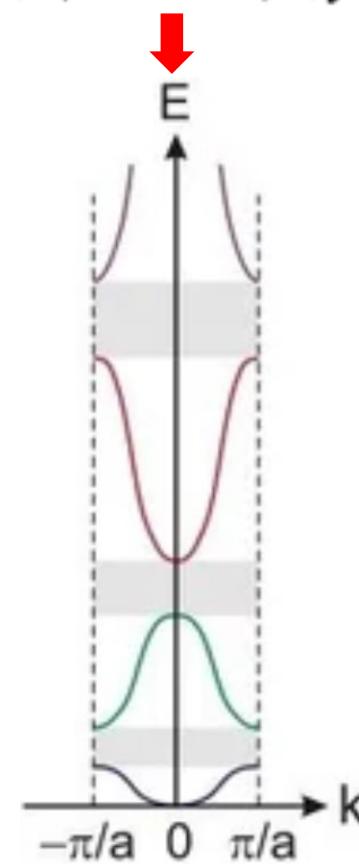
For solids: the minimum energy required to remove an electron from the valence band of the solid.

As many elements are solids, values may be available for both, and differ due to the nature of bonding in solids. The elemental values always refer to the gas phase.

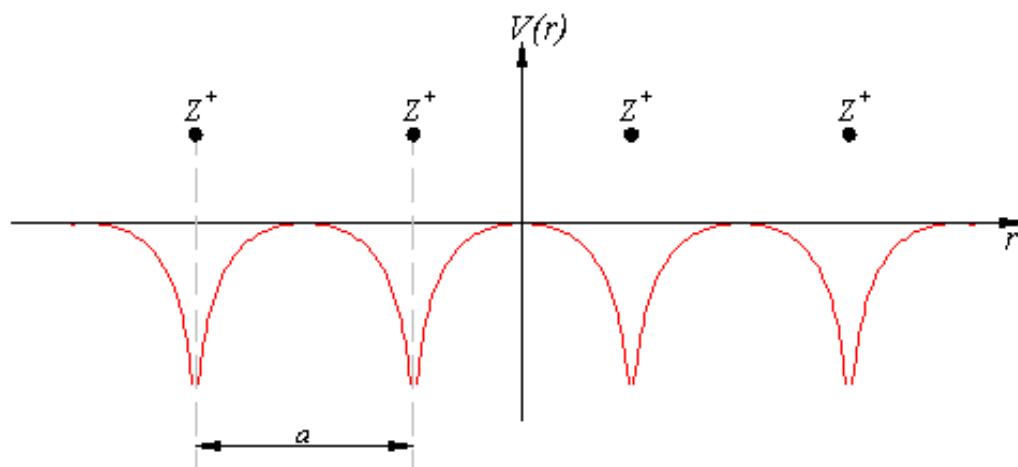
Valence band

- Schrodinger Equation

$$\frac{-\hbar^2}{2m} \left[\frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial y^2} + \frac{\partial^2 \Psi}{\partial z^2} \right] + U(x,y,z) \Psi(x,y,z) = E \Psi(x,y,z)$$



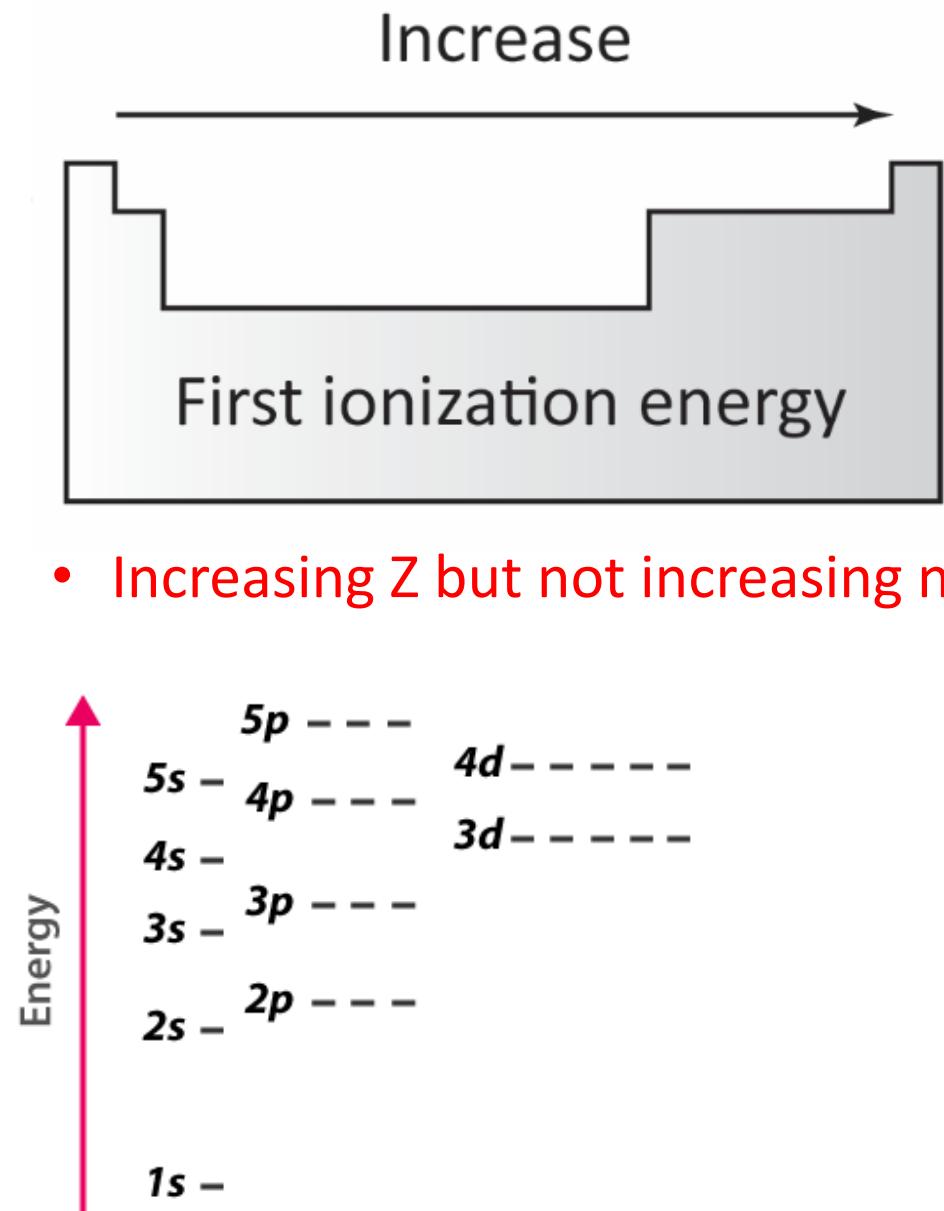
- Potential in a solid:



Valence band: the highest-energy band of electrons that are normally present at 0K.

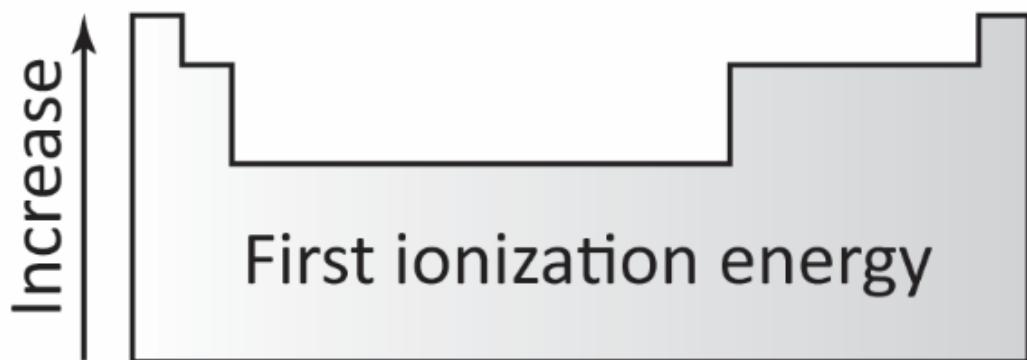
Ionization Energy

Element	IE_1 (kJ/mol)
Li	520
Be	899
B	801
C	1086
N	1402
O	1314
F	1681
Ne	2081



Ionization Energy

Element	IE_1 (kJ/mol)
Li	520
Na	496
K	419
Rb	403
Cs	376
Fr	~375

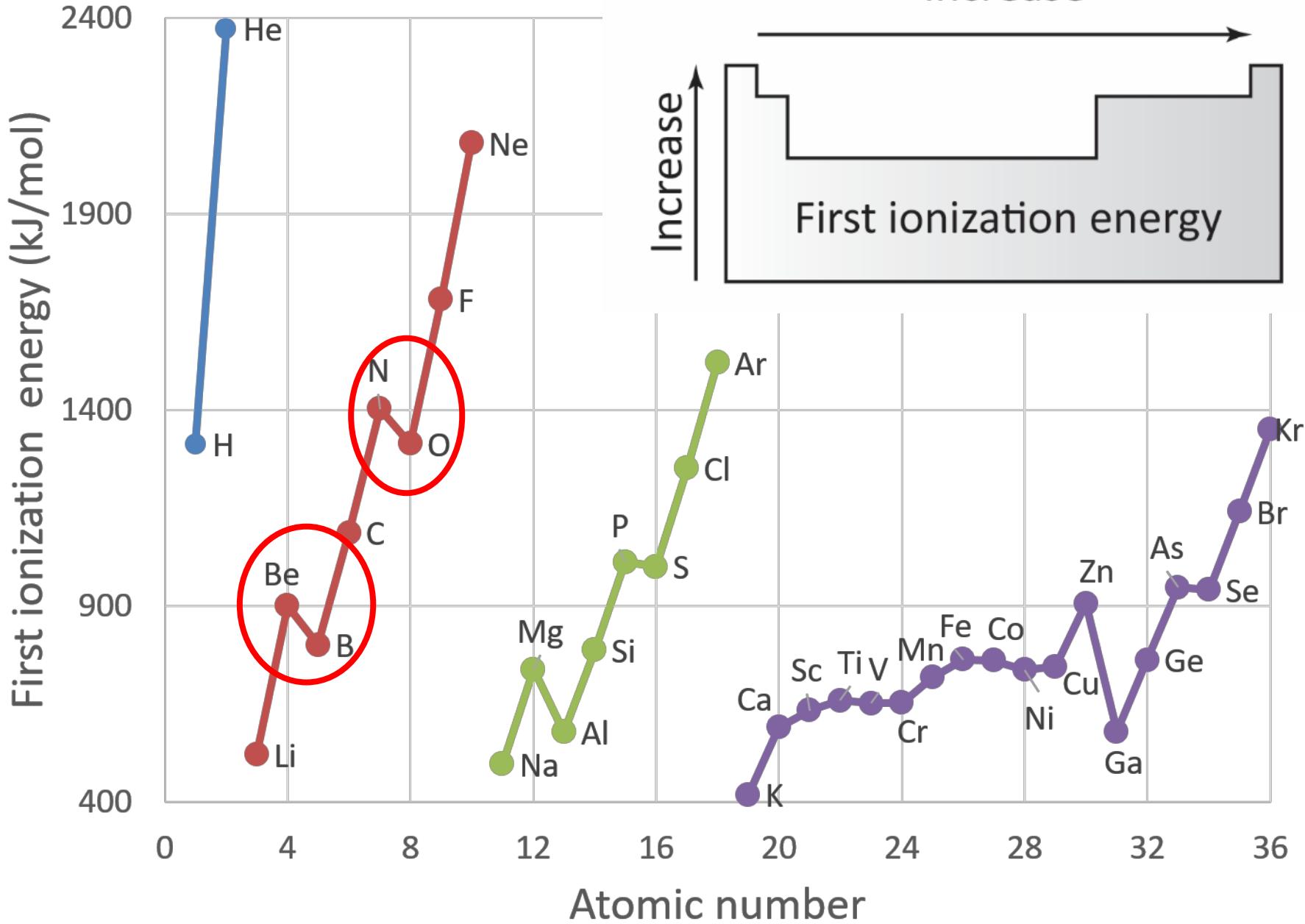


- Decreasing n, so electrons are closer nucleus.

Ionization Energy

You do NOT need to know the values for exams but you should know the trend

1	H	1312.0	2	375.7 kJ/mol										2372.3 kJ/mol	13	14	15	16	17	18	
2	Li	520.2	Be	899.5											B	C	N	O	F	He	
3	Na	495.8	Mg	737.7	3	4	5	6	7	8	9	10	11	12	800.6	1086.5	1402.3	1313.9	1681.0	2372.3	
4	K	418.8	Ca	589.8	633.1	658.8	650.9	652.9	717.3	762.5	760.4	737.1	745.5	906.4	577.5	786.5	1011.8	999.6	1251.2	2080.7	
5	Rb	403.0	Sr	549.5	599.9	640.1	652.1	684.3	702	710.2	719.7	804.4	731.0	867.8	558.3	708.6	830.6	869.3	1008.4	1170.3	
6	Cs	375.7	Ba	502.9	538.1	La	Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg	Tl	Pb	Bi	Po	At	Rn
7	Fr	393.0	Ra	509.3	498.8	Ac	Rf	Db	Sg	Bh	Hs	Mt	Ds	Rg	Uub	Uut	Uuq	Uup			
Lanthanides			Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu					
			534.4	528.1	533.1	538.6	544.5	547.1	593.4	565.8	573.0	581.0	589.3	596.7	603.4	523.5					
Actinides			Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr					
			608.5	568	597.6	604.5	581.4	576.4	578.1	598.0	606.1	619	627	635	642	472.8					



Increase

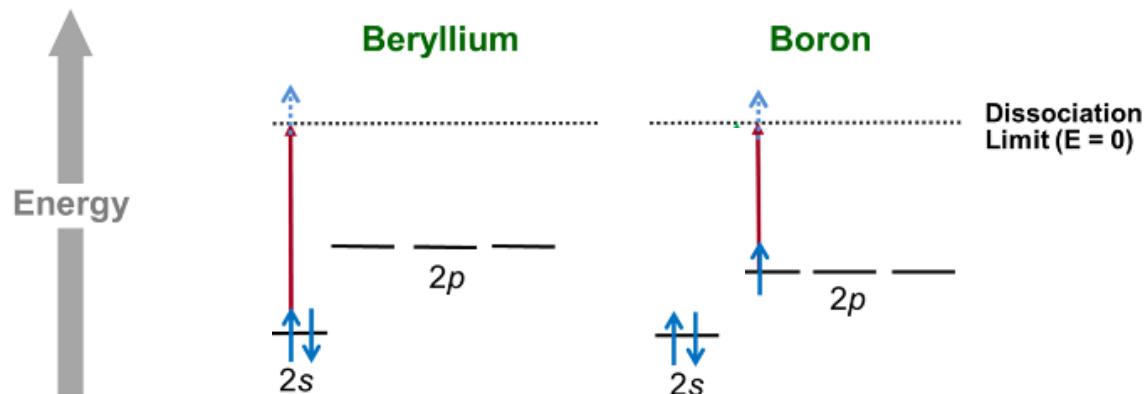
First ionization energy

Ionization Energy

The IE_1 drops or decreases modestly on changing from ionization of a lower energy ns electron to ionization of a higher energy np^1 electron.

The ionization energy is lower than expected because the higher energy of the np orbital more than compensates for the decrease in orbital energy due to increasing Z^* and the lack of Coulombic repulsion.

Example: Be (group 2) and B (group 13)



	1	ns ²	ns ² np ¹	
1	H			
2	Li	Be	B	
3	Na	Mg	Al	
4	K	Ca	Ga	
5	Rb	Sr	In	
6	Cs	Ba	Tl	
7	Fr	Ra	Uut	Uu

A yellow box highlights the second period (Li, Be, B). A red circle highlights Be and B. An orange box highlights the third period (Na, Mg, Al).

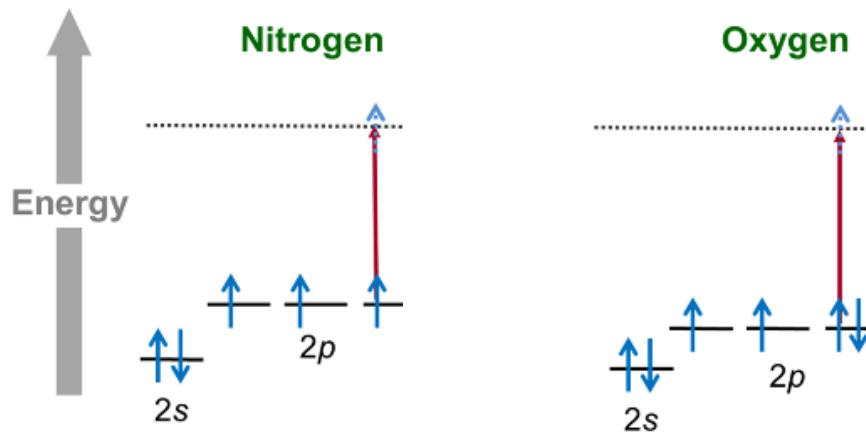
Ionization Energy

The IE_1 drops or decreases modestly on changing from ionization of a electron from a singly occupied p orbital in the pnictides to ionization of an electron from a double occupied p orbital in the chalcogenides

			18	
4				
		$\text{ns}^2\text{np}^3 \text{ ns}^2\text{np}^4$		
	15	16	17	He 2372.3
6.5	N 1402.3	O 1313.9	F 1681.0	Ne 2080.7
5.5	P 1011.8	S 999.6	Cl 1251.2	Ar 1520.6
2.2	As 944.5	Se 941.0	Br 1139.9	Kr 1350.8
3.6	Sb 830.6	Te 869.3	I 1008.4	Xe 1170.3
5.6	Bi 703.0	Po 812.1	At	Rn 1037.1
uq	Uup			

The ionization energy is lower than expected because of the Coulombic repulsion energy associated with the doubly occupied p orbital.

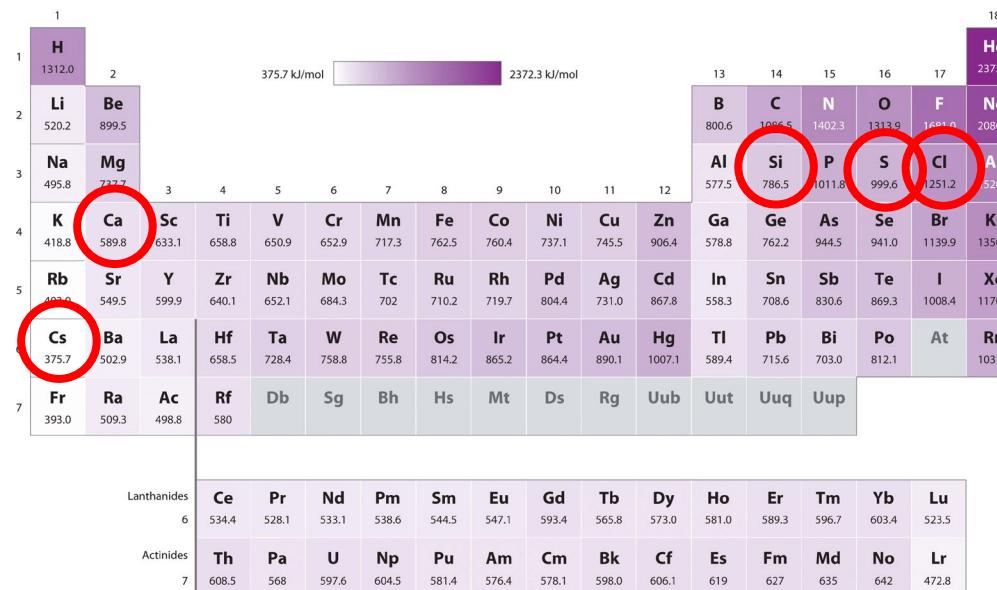
Example: Nitrogen (5A) and Oxygen (6A)



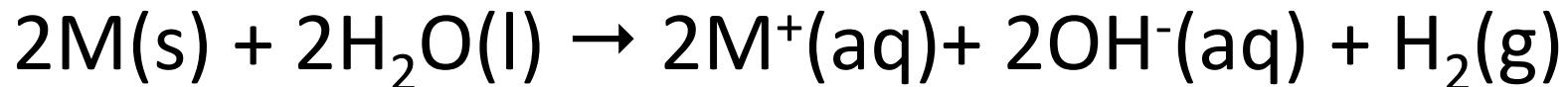
Clicker Question

Arrange the following species in order of increasing ionization energy: Cl, Si, Ca, S, Cs.

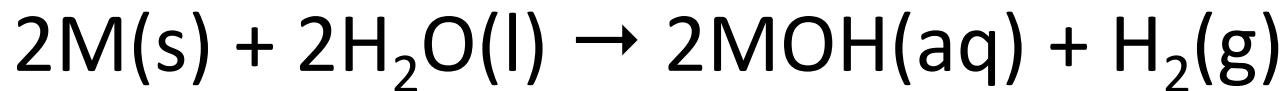
- a. Cs < S < Si < Ca < Cl
- b. Cs < Si < Ca < S < Cl
- c. Cl < Ca < Si < S < Cs
- ✓ d. Cs < Ca < Si < S < Cl



DEMO TIME



Or



where M = Li, Na, K.

- Metals are ionized.
- The solution become more basic since OH^- is being produced.
- Reactivity Order K > Na > Li

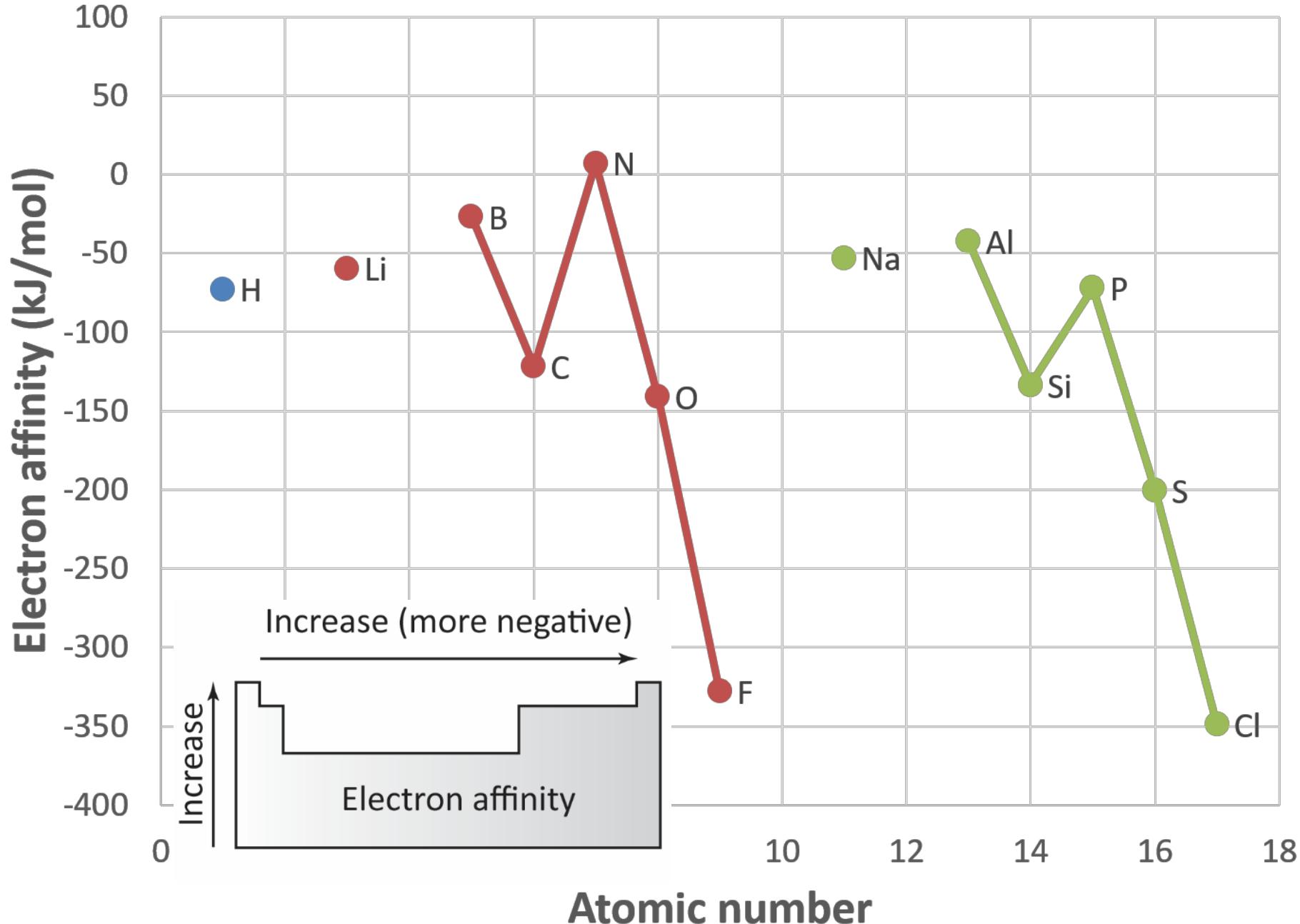
Electron Affinity (EA)

For atoms or molecules: the energy change resulting from the addition of a single electron to an atom or molecule in its gaseous state.



For solids: the minimum energy change resulting from adding an electron to the lowest lying electronic states (of the conduction band) of the solid.

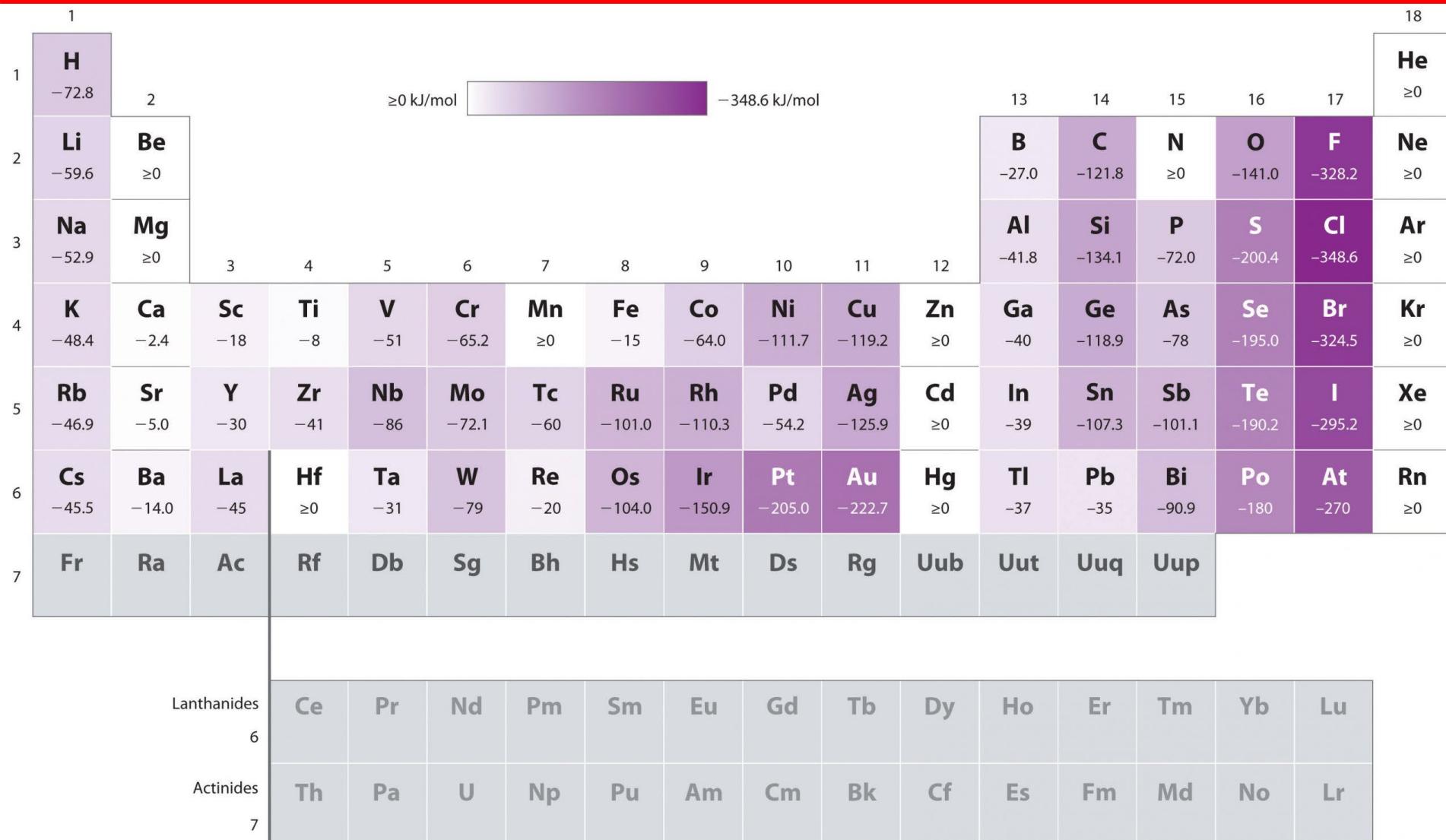
As many elements are solids, values may be available for both, and differ due to the nature of bonding in solids. The elemental values always refer to the gas phase.



He, Be, Ne and Ar do NOT form stable anions.

Electron affinities

You do NOT need to know the values for exams but you should know the trend



Clicker Question

Which equation describes the first ionization energy of Al?

- a) $\text{Al}_{(g)} + \text{e}^- \rightarrow \text{Al}^-_{(g)} + \text{energy}$
- b) $\text{Al}_{(g)} + \text{energy} \rightarrow \text{Al}^+_{(g)} + \text{e}^-$
- c) $\text{Al}^+_{(g)} + \text{energy} \rightarrow \text{Al}^{2+}_{(g)} + \text{e}^-$
- d) $\text{Al}^-_{(g)} + \text{energy} \rightarrow \text{Al}_{(g)} + \text{e}^-$
- e) $\text{Al}_{(s)} + \text{energy} \rightarrow \text{Al}^+_{(aq)} + \text{e}^-$

Clicker Question

Which equation describes the first ionization energy of Al?

- a) $\text{Al}_{(g)} + \text{e}^- \rightarrow \text{Al}^-_{(g)} + \text{energy}$ (not ionization)
- b) $\text{Al}_{(g)} + \text{energy} \rightarrow \text{Al}^+_{(g)} + \text{e}^-$
- c) $\text{Al}^+_{(g)} + \text{energy} \rightarrow \text{Al}^{2+}_{(g)} + \text{e}^-$ (2nd ionization)
- d) $\text{Al}^-_{(g)} + \text{energy} \rightarrow \text{Al}_{(g)} + \text{e}^-$ (not ionization)
- e) $\text{Al}_{(s)} + \text{energy} \rightarrow \text{Al}^+_{(\text{aq})} + \text{e}^-$ (aqueous)

Clicker Question

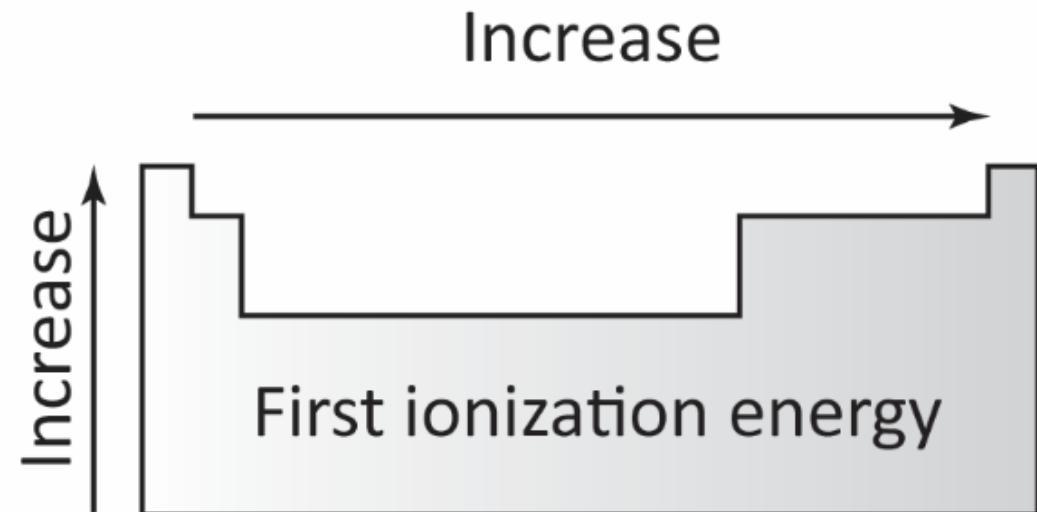
Which equation describes the electron affinity of Al?

- a) $\text{Al}_{(g)} + \text{e}^- \rightarrow \text{Al}^-_{(g)} + \text{energy}$
- b) $\text{Al}_{(g)} + \text{energy} \rightarrow \text{Al}^+_{(g)} + \text{e}^-$
- c) $\text{Al}^+_{(g)} + \text{energy} \rightarrow \text{Al}^{2+}_{(g)} + \text{e}^-$
- d) $\text{Al}^-_{(g)} + \text{energy} \rightarrow \text{Al}_{(g)} + \text{e}^-$
- e) $\text{Al}_{(s)} + \text{energy} \rightarrow \text{Al}^+_{(aq)} + \text{e}^-$

Clicker Question

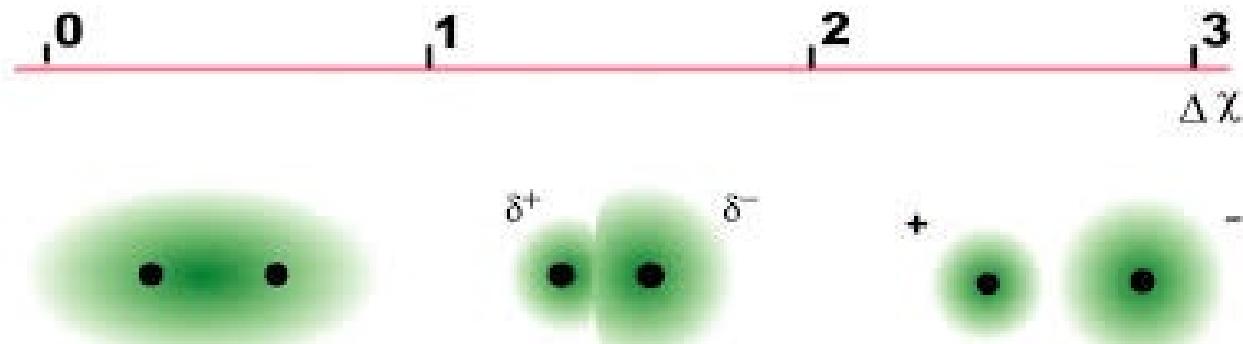
Rank the following elements in terms of increasing ionization energy:

- a) Li < Na < K
- b) K < Na < Li
- c) Na < K < Li
- d) Na < Li < K



Electronegativity (EN or χ)

- The ability of an atom to attract shared electrons to itself in a chemical bond.
- greater χ = greater affinity for e^-
- not an *atomic* property because it refers to atoms in a bond
- is a calculated value, not measured
- correlates with IE and EA
- The greater the electronegativity difference, $\Delta\chi$, the more polarized a chemical bond.



Electronegativity χ Definitions

Several different prescriptions exist for χ (in kJ/mol):

- Mulliken used IE and EA values

$$\chi_{\text{Mulliken}} = 1.93 \times 10^{-3} (\text{IE} + |\text{EA}|) + 0.19$$

- Pauling used bond dissociation energies, E_d , to calculate EN differences between atoms A and B

$$\chi(A) - \chi(B) = 0.102 \sqrt{E_d(AB) - \frac{1}{2}(E_d(AA) + E_d(BB))}$$

Dissociation energy: the amount of energy required to break a chemical bond in a molecule

$E_d(AB)$: dissociation energy of A-B bond

$E_d(AA)$: dissociation energy of A-A bond

$E_d(BB)$: dissociation energy of B-B bond

Pauling Electronegativity

- Mulliken's method has no information about bonding in the Mulliken method.
- Pauling's electronegativity of an atom is a relative value of that atom's ability to attract electron density toward itself when it bonds to another atom.
- **Fluorine (F)** is assigned the **highest electronegativity value of 3.98**.
- Every electronegativity value on the Pauling scale is relative to fluorine's electronegativity of 3.98.

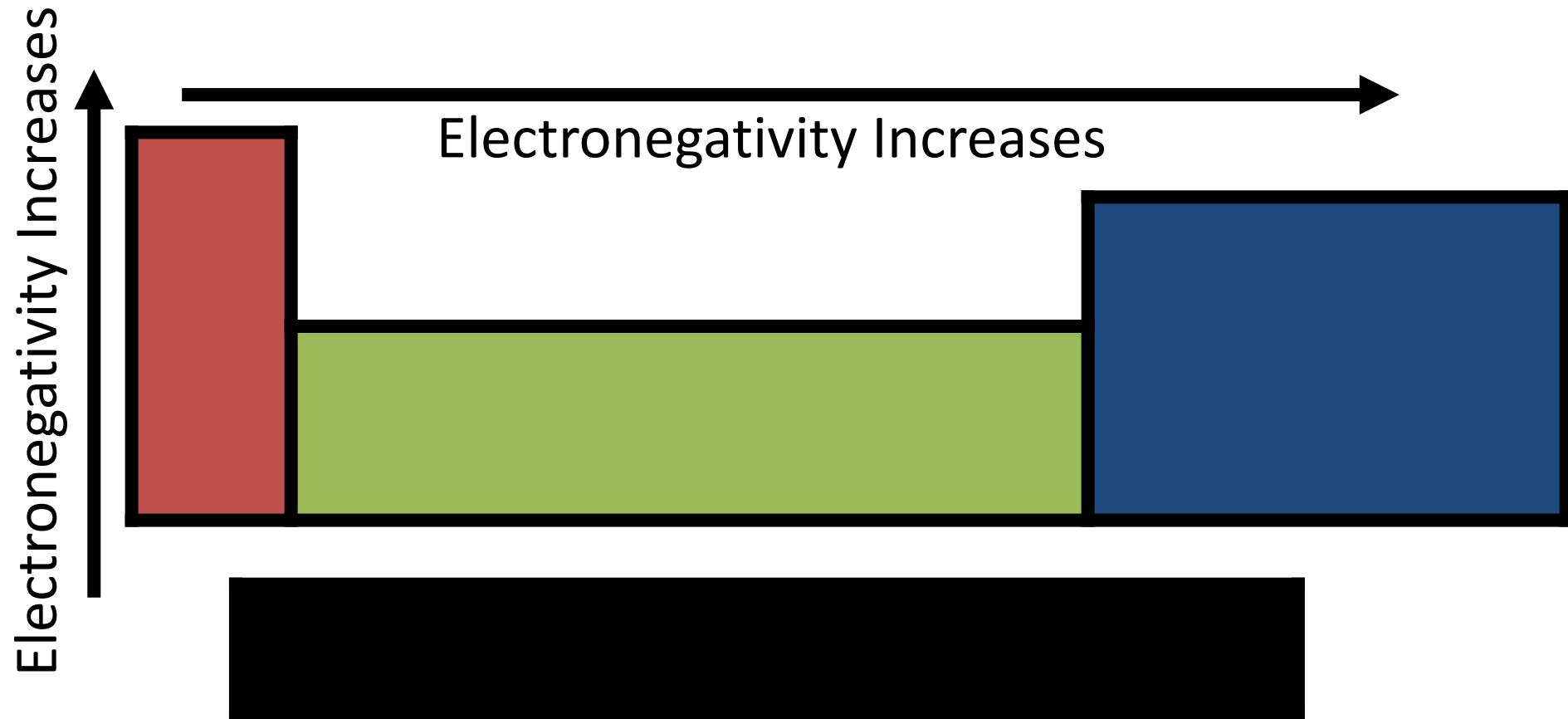
You do NOT need to know electronegativity values for exams but you MUST know the overall trend (mnemonic: FOCIN BrISCH)

H 2.20		Pauling Electronegativities												He
Li 0.98	Be 1.57													B 2.04
Na 0.93	Mg 1.31													C 2.55
K 0.82	Ca 1.00	Sc 1.36	Ti 1.54	V 1.63	Cr 1.66	Mn 1.55	Fe 1.83	Co 1.88	Ni 1.91	Cu 1.90	Zn 1.65			N 3.04
Rb 0.82	Sr 0.95	Y 1.22	Zr 1.33	Nb 1.6	Mo 2.18	Tc 1.9	Ru 2.2	Rh 2.28	Pd 2.20	Ag 1.93	Cd 1.69	Al 1.61	Si 1.90	O 3.44
Cs 0.79	Ba 0.89	La 1.1	Hf 1.3	Ta 1.5	W 2.36	Re 1.9	Os 2.2	Ir 2.20	Pt 2.28	Au 2.54	Hg 2.00	Ga 1.81	Ge 2.01	F 3.98
Fr 0.7	Ra 0.9	Ac 1.1										Ar	Cl 3.16	Ne
Ce 1.12	Pr 1.13	Nd 1.14	Pm 1.13	Sm 1.17	Eu 1.2	Gd 1.2	Tb 1.1	Dy 1.22	Ho 1.23	Er 1.24	Tm 1.25	Yb 1.1	Lu 1.27	
Th 1.3	Pa 1.5	U 1.38	Np 1.36	Pu 1.28	Am 1.13	Cm 1.28	Bk 1.3	Cf 1.3	Es 1.3	Fm 1.3	Md 1.3	No 1.3	Lr 1.3	

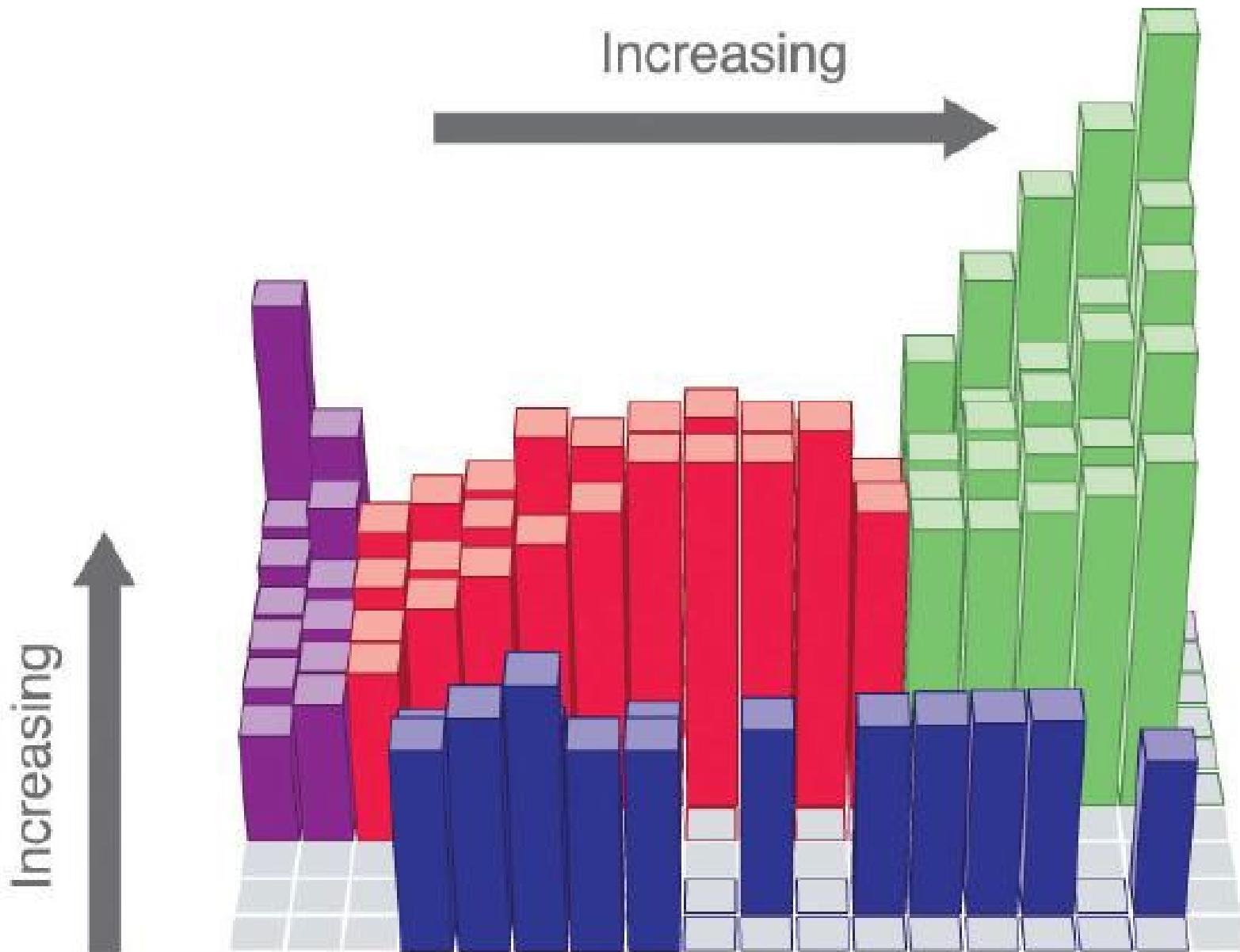
Ce 1.12	Pr 1.13	Nd 1.14	Pm 1.13	Sm 1.17	Eu 1.2	Gd 1.2	Tb 1.1	Dy 1.22	Ho 1.23	Er 1.24	Tm 1.25	Yb 1.1	Lu 1.27	
Th 1.3	Pa 1.5	U 1.38	Np 1.36	Pu 1.28	Am 1.13	Cm 1.28	Bk 1.3	Cf 1.3	Es 1.3	Fm 1.3	Md 1.3	No 1.3	Lr 1.3	

Electronegativity and the Periodic Table

Electronegativity generally increases from left to right of the periodic table and from bottom to top.



Pauling Electronegativity



Clicker Question

Select the sequence of atoms that are correctly listed in order of increasing electronegativity.

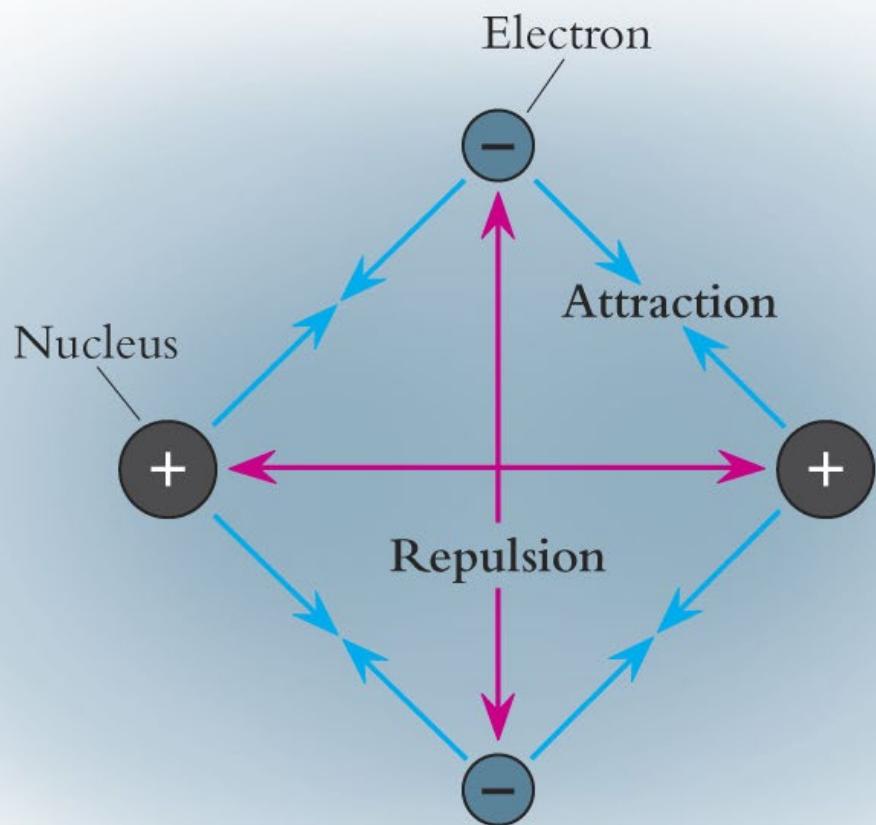
- a) F < N < Si < Mg
- b) Si < N < F < Mg
- c) Mg < Si < F < N
- d) N < Si < Mg < F
- ✓ e) Mg < Si < N < F

H 2.20	
Li 0.98	Be 1.57
Na 0.93	Mg 1.31
K 0.82	Ca 1.00

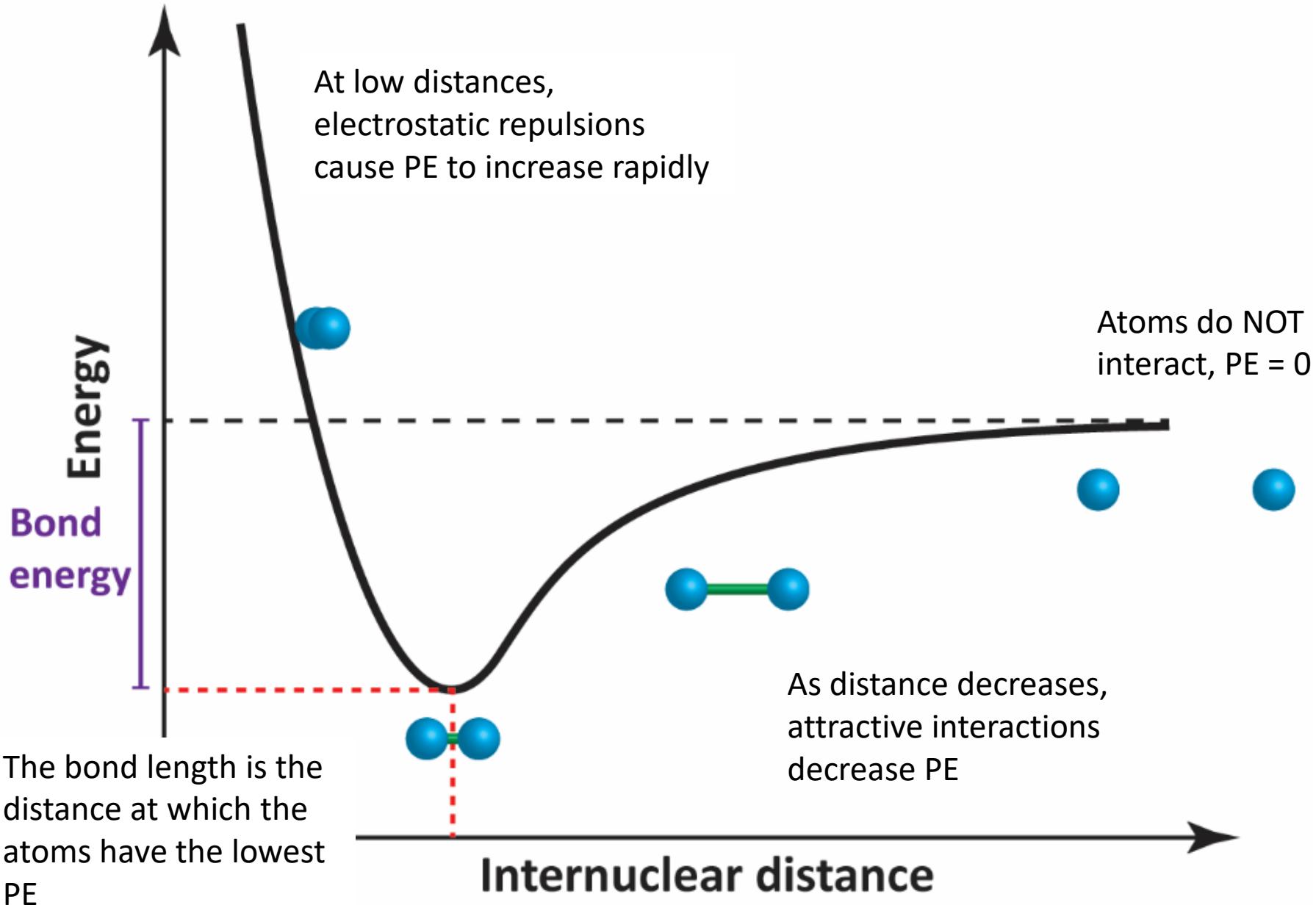
Pauling Electronegativities

B 2.04	C 2.55	N 3.04	O 3.44	F 3.98	Ne
Al 1.61	Si 1.90	P 2.19	S 2.58	Cl 3.16	Ar
Ga 1.81	Ge 2.01	As 2.18	Se 2.55	Br 2.96	Kr
In 1.78	Sn 1.96	Sb 2.05	Te 2.1	I 2.66	Xe 2.60
Tl 1.62	Pb 1.87	Bi 2.02	Po 2.0	At 2.2	Rn 2.2

Bonding Context



Why do bonds form?



Bond energies and bond orders

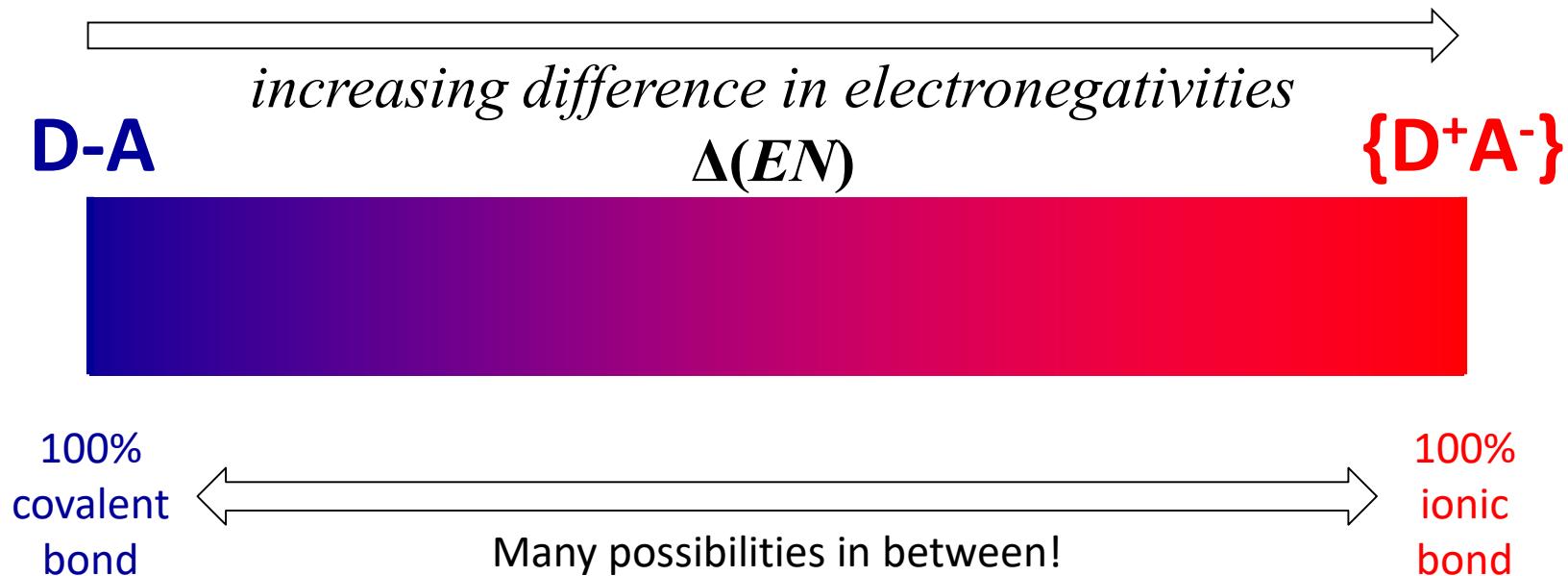
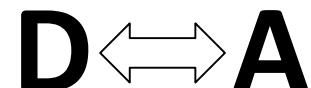
- When a bond is formed, energy is released (exothermic process).
- The **bond energy** is the energy required to break a covalent bond, and the **bond order** is the number of electron pairs shared by two atoms in a covalent bond.
- The **lattice energy** is the energy required to dissociate an ionic solid into its separate ions, and increases with the charges on the ions or as the distance between charges decreases.

Bond energies and bond orders

Bond	Bond energy (kJ/mol)	Bond order
C-F	485	1
C-H	415	1
O-F	190	1
O-H	460	1
C – C	346	1
C = C	602	2
C ≡ C	835	3

What type of bond will form?

Can range from covalent (where a pair of electrons are shared between two atoms with no net charge) to ionic (where an electron is transferred from a donor to acceptor)



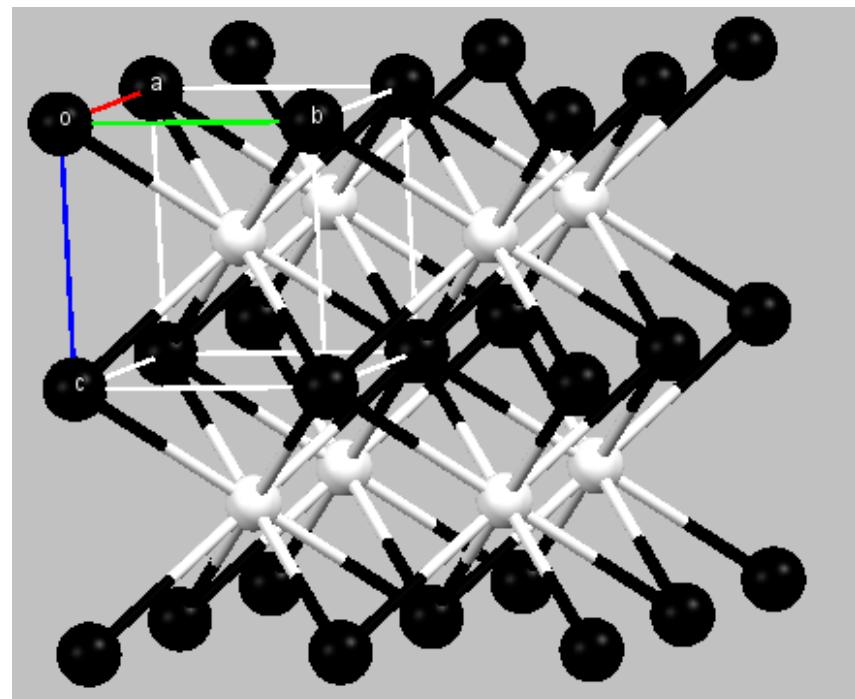
Ionic Bonding

Cesium cations (white) are electrostatically attracted to chloride anions (black). In a crystalline state, the ions form an "infinite", 3D array or lattice.

Rule of Thumb:

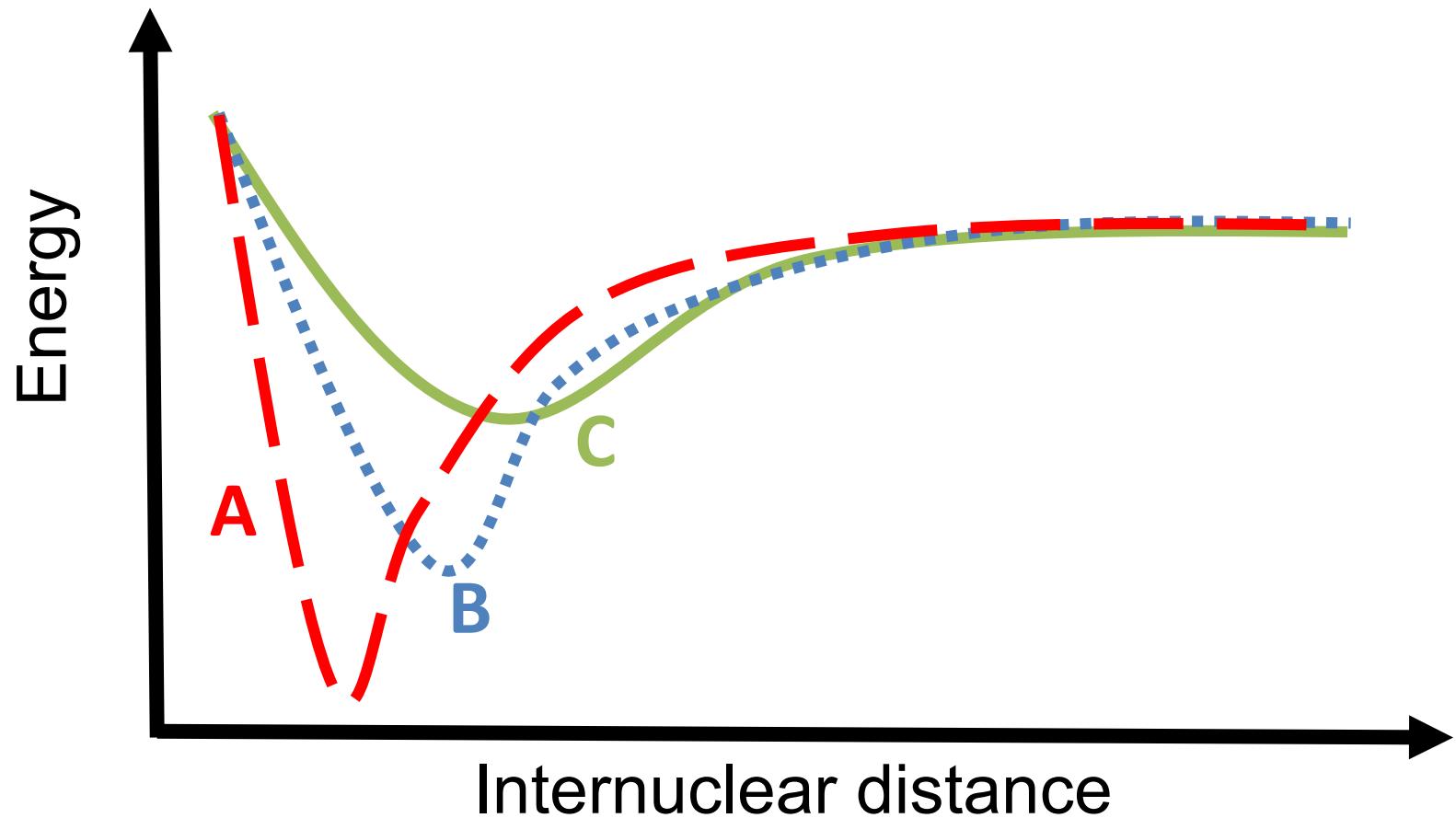
$\Delta(EN) \gtrsim 1.7$

for ionic bonding



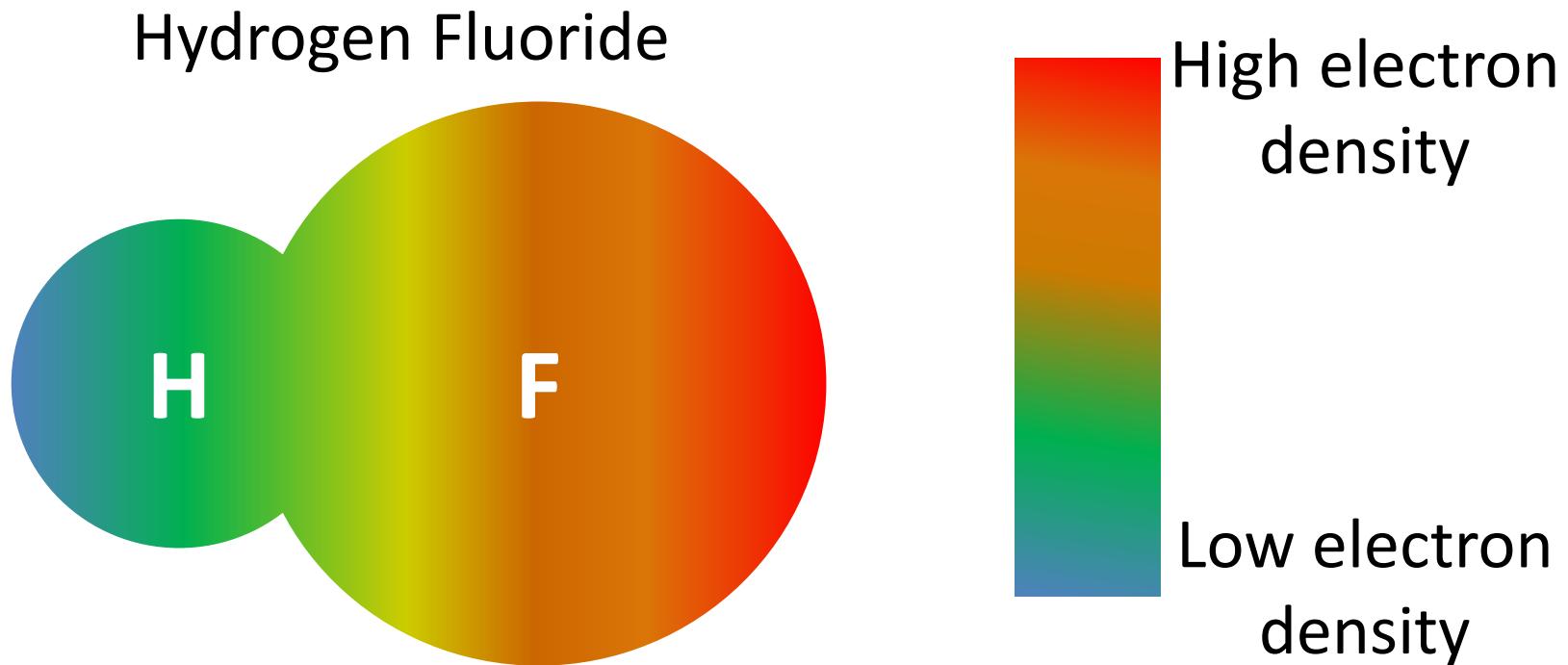
Bond Strength

- Stronger bond
 - lower potential energy
 - smaller internuclear distance



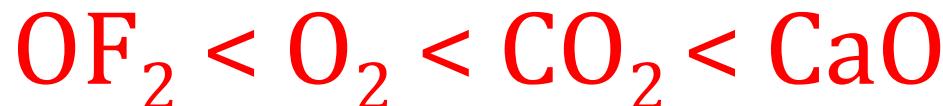
Polar covalent bonds

- In some covalent bonds electrons are not equally shared (electron density is higher in one atom than in another) due to differences in electronegativity.



Worksheet Question #9 – GOOD QUESTION

Arrange the following species in order of increasing electron density on each oxygen atom. O_2 , CaO , OF_2 , CO_2 . (*Hint: think about what type of bonds are present*).



- OF_2 (polar covalent): F is more **electronegative** than O.
- O_2 (nonpolar covalent): equal electronegativity.
- CO_2 (polar covalent) : O is more **electronegative** than C.
- CaO (ionic bond): Ca is **electropositive**.

Blueprint question

**How can you predict
engine part failure
BEFORE it happens?**



<http://www.spectro-oil.com/laboratory-services-aviation.html>

http://news.commercialaircraft.bombardier.com/wp-content/gallery/engine-run/right_engine.jpg

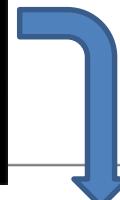


FEATURED CASE STUDY

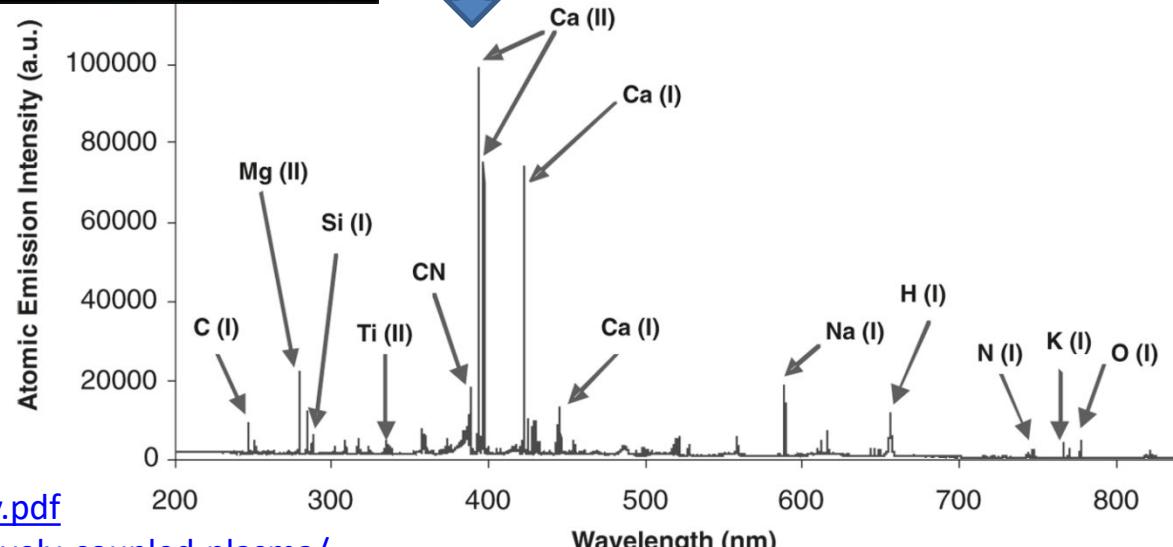
The benefits of routine SOAP checks

Spectrometric Oil Analysis Program

Engine oil filtered
to capture metal
wear particles



Analysis of particles
by **atomic emission**
to determine metal
composition and
origin (which part?)



http://www.spectro-oil.com/borsc_case_study.pdf

<http://blog.labplanet.com/2011/12/19/inductively-coupled-plasma/>

Hosseini makarem & Tavassoli, J Biomed Optics. 2011, 16(5), 057002. doi:10.1117/1.3574757