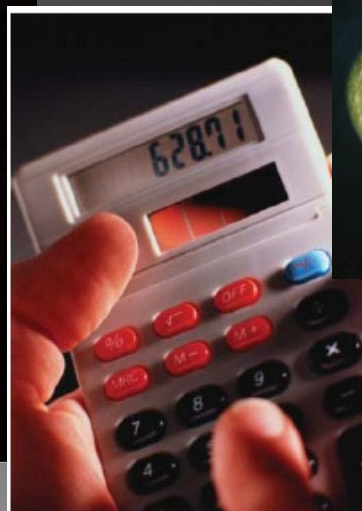
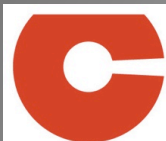


# Chemical Bonding: Magic numbers and the secrets of “stuff”



Scientific American—Bright Horizons 17  
Robert M. Hazen—14 July 2013



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INSTITUTION FOR  
SCIENCE

# Organizational Principles of the Cosmos

## THIS CRUISE:

**Ben: Particles and forces**

**Chris: Stars and planets**

**Robert S.: Mind and brain**

**Ken: Societies and culture**

# Organizational Principles of the Cosmos

## **FOUR FORCES:**

**Gravity, Electromagnetism,**

**Strong Force, Weak Force**

# **Organizational Principles of the Cosmos**

**MATTER:**

**Quarks and leptons**

# **Organizational Principles of the Cosmos**

## **ENERGY:**

**Some configurations of matter  
are more likely (i.e., have lower  
energy) than others.**

# **Organizational Principles of the Cosmos**

## **EVOLUTION:**

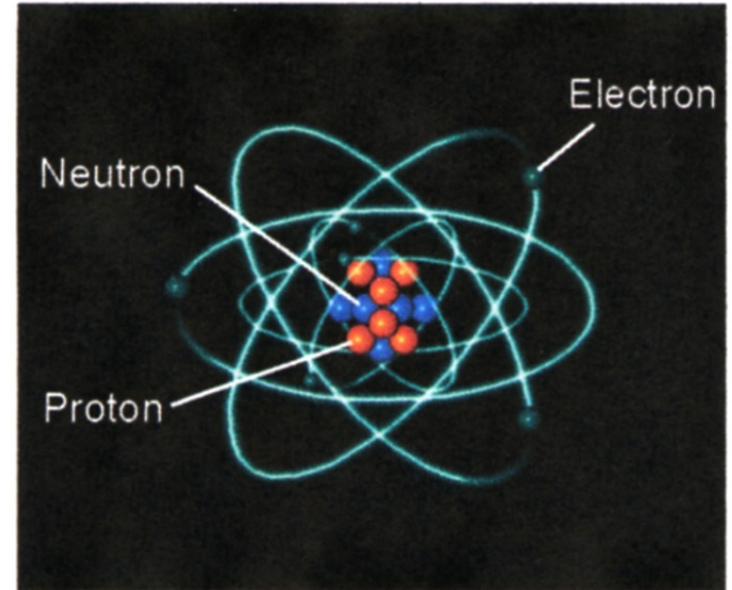
**Emergent complexity arises as  
selection operates on systems of  
many interacting particles.**

# What is an atom?

**A very small object that has:**

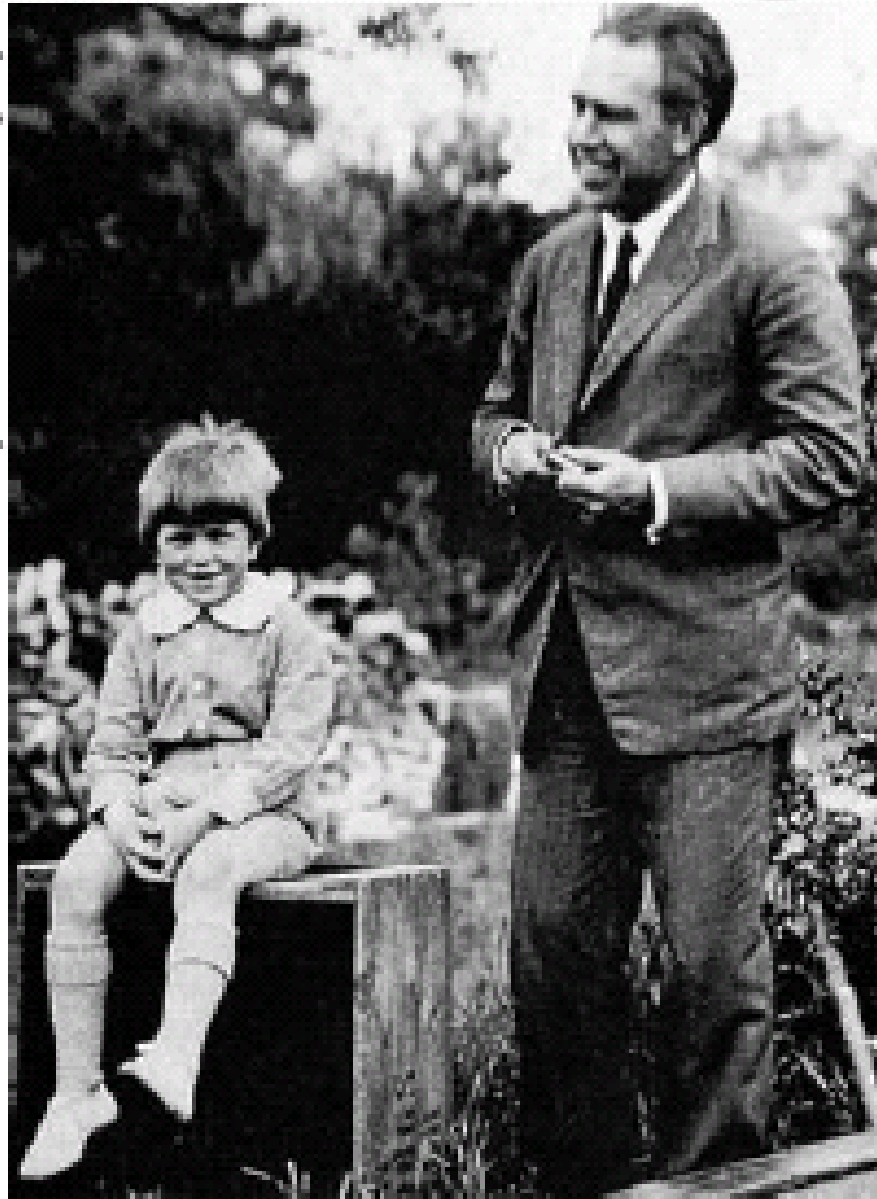
**At least one proton**

**At least one electron**





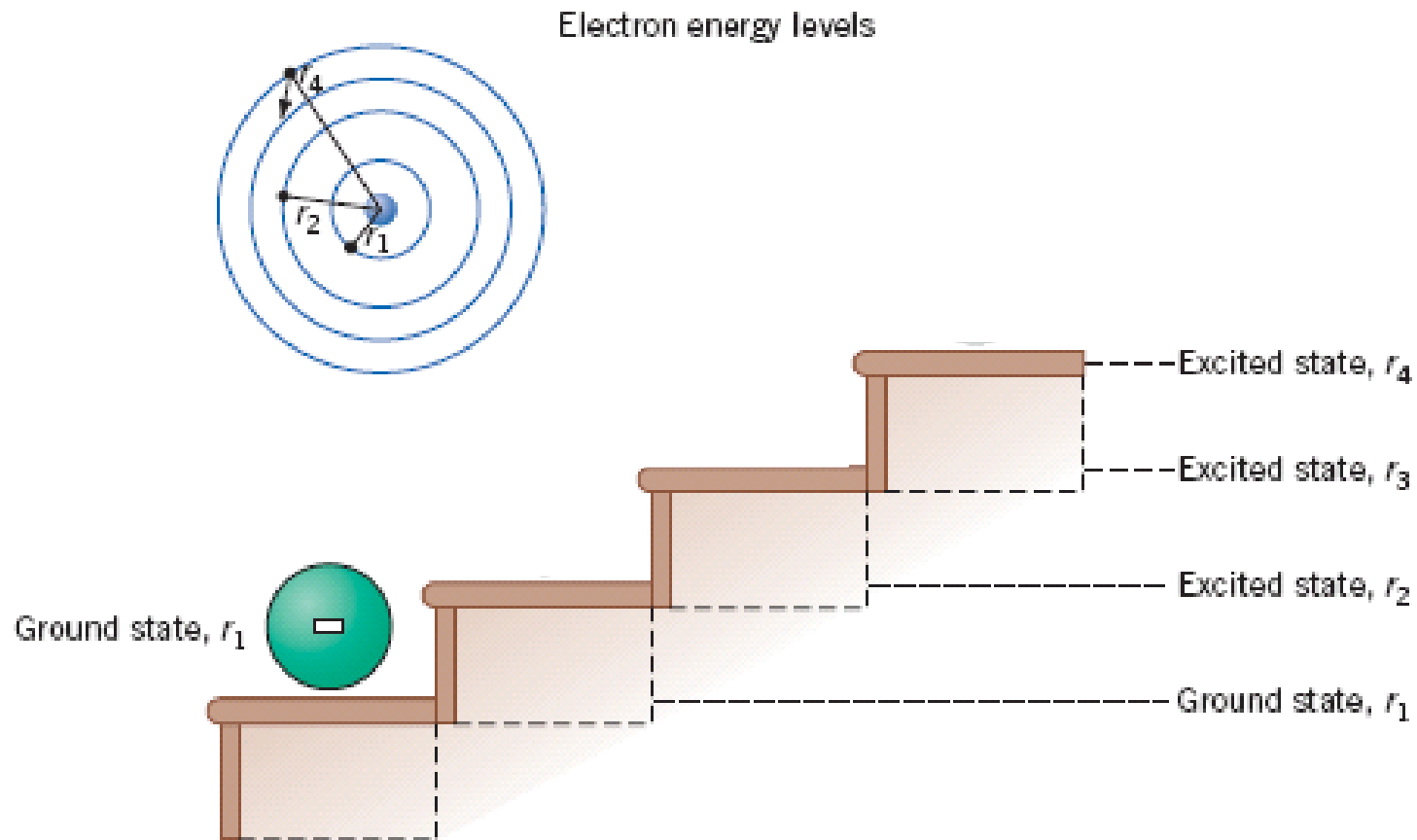
# Niels Bohr's Model of the Atom





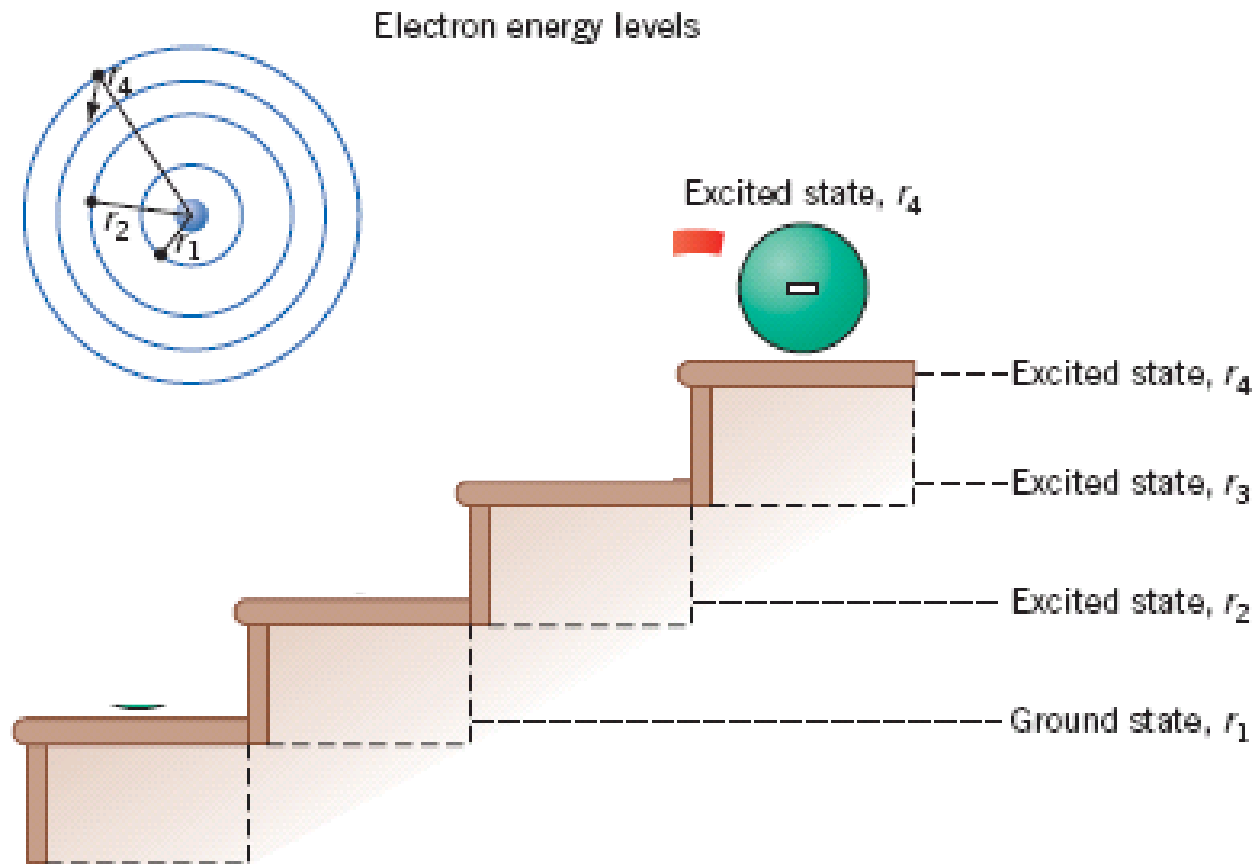
# Niels Bohr's Model of the Atom

Electrons occur in fixed energy levels (shells)



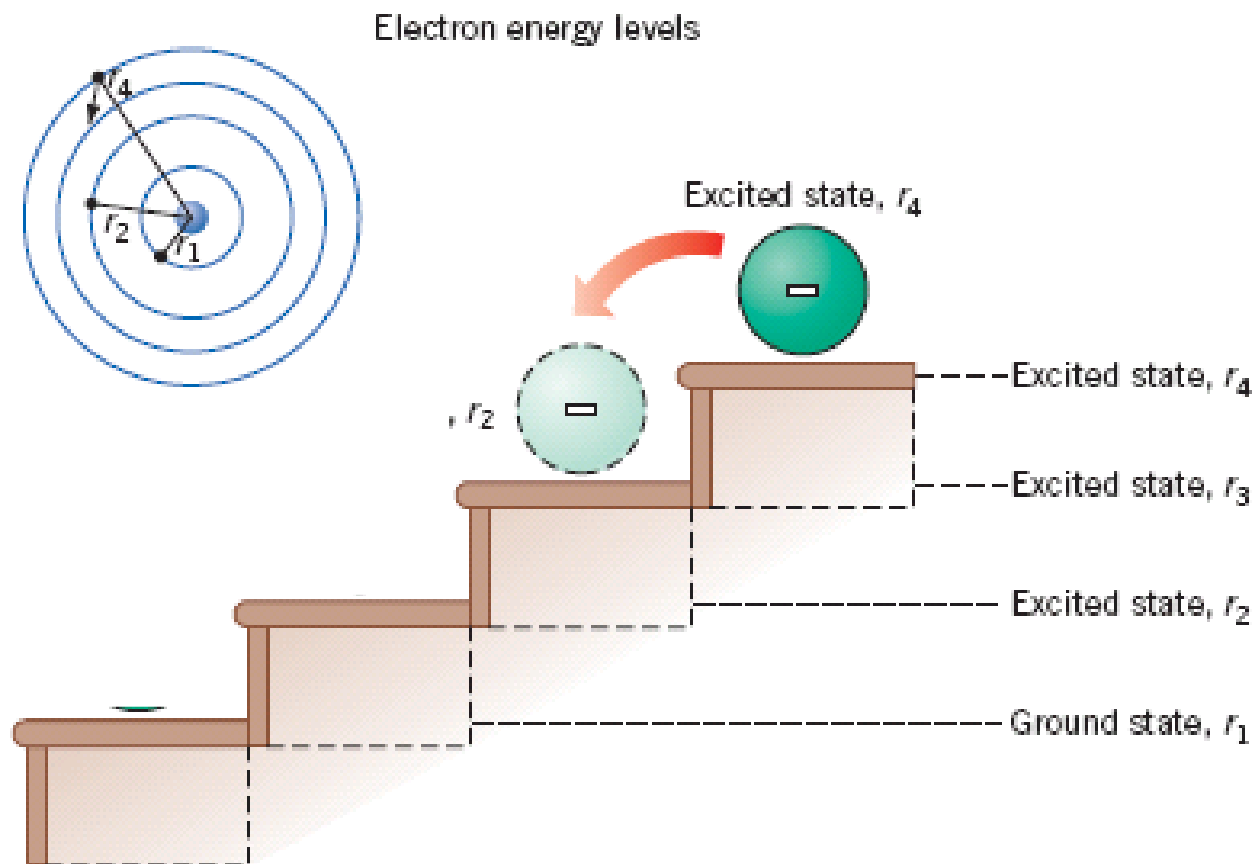
# Niels Bohr's Model of the Atom

Electrons occur in fixed energy levels (shells)



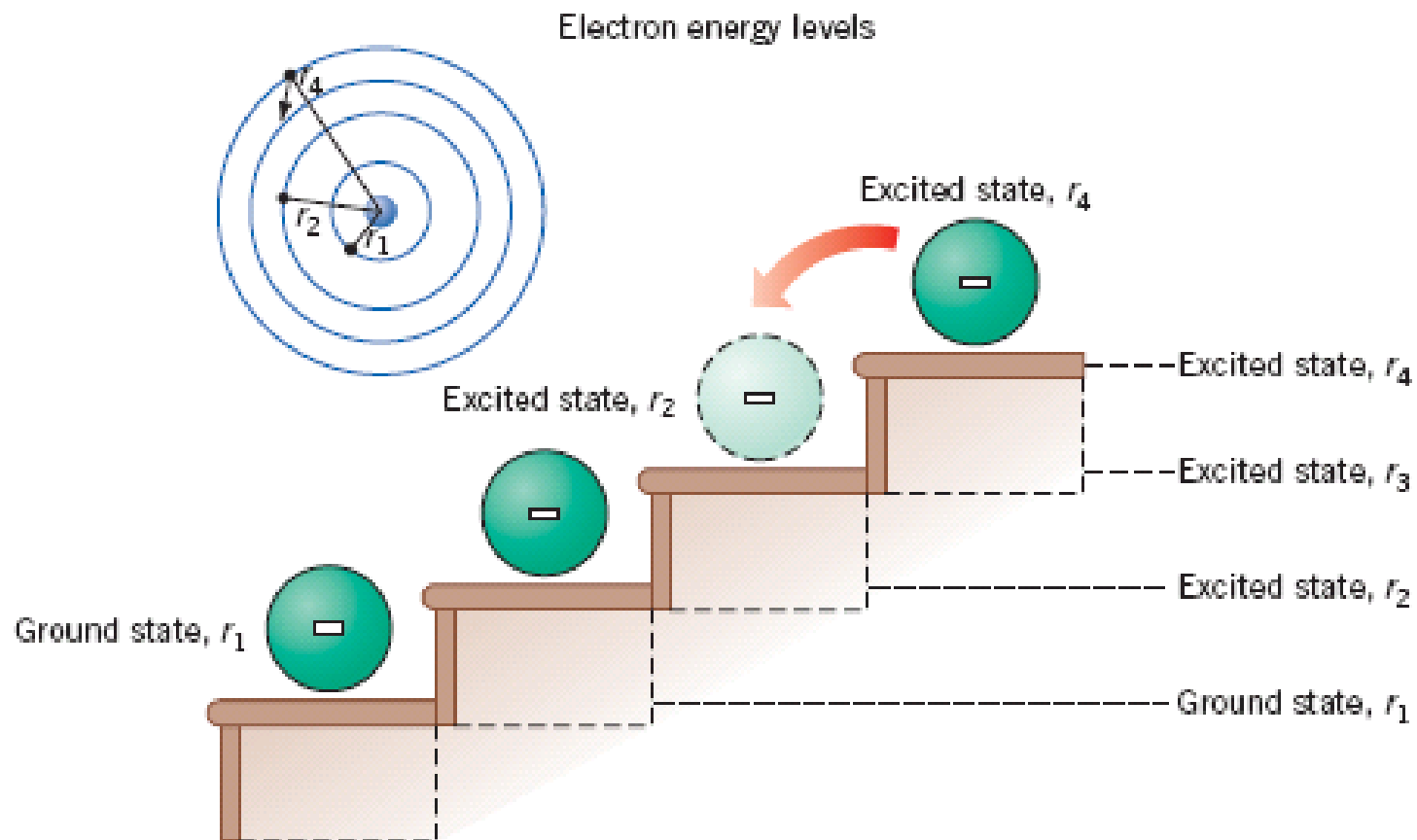
# Niels Bohr's Model of the Atom

Electrons occur in fixed energy levels (shells)



# Niels Bohr's Model of the Atom

Electrons occur in fixed energy levels (shells)



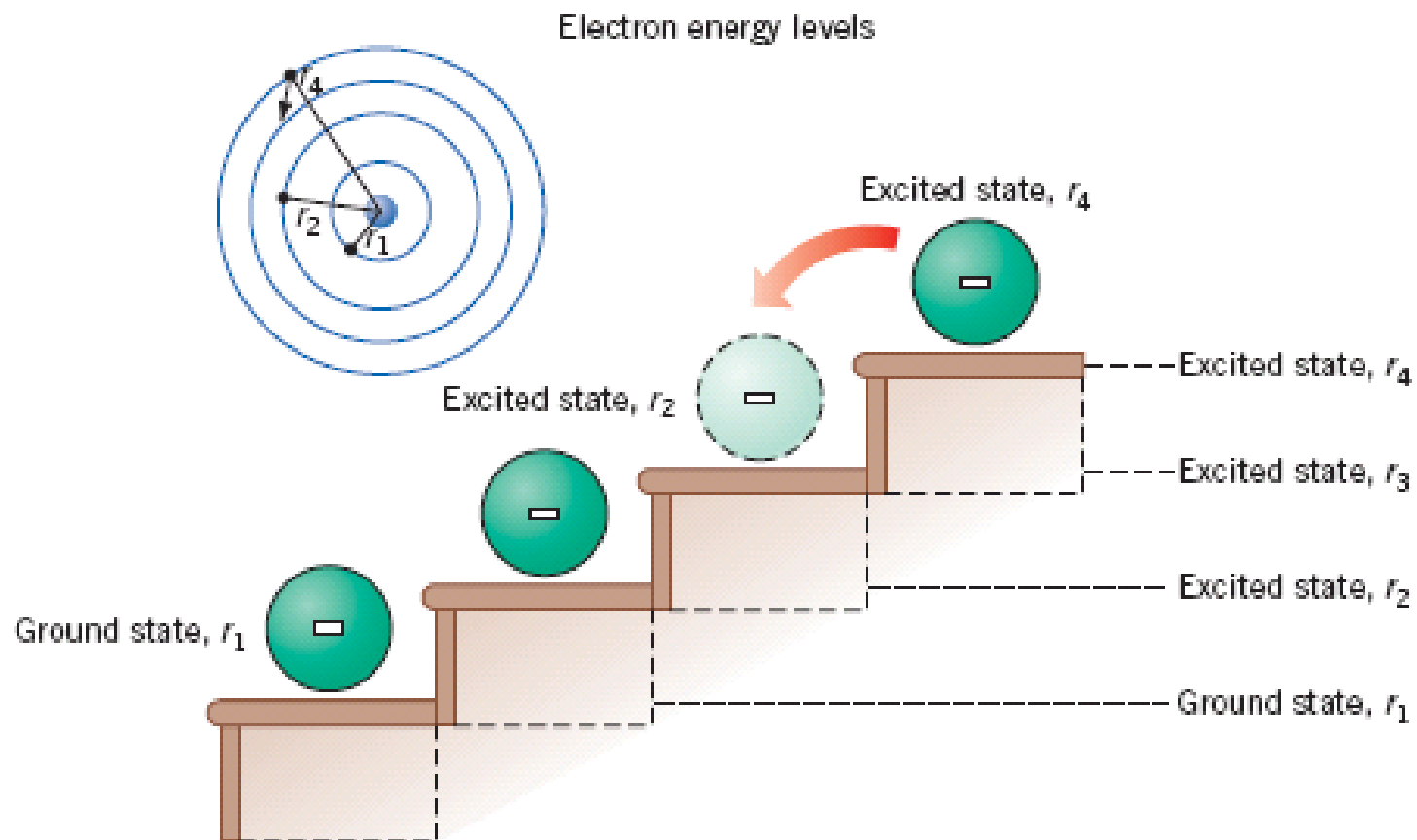
# Quantum Mechanics

- **At the scale of atoms, everything comes in “quanta” (bundles).**
- **At the scale of atoms, you can't measure a property without changing the object that you are trying to measure.**



# Niels Bohr's Model of the Atom

Electrons occur in fixed energy levels (shells)



# Three Rules of Electrons in Atoms

- 1. Each electron can exist in a number of different states.**
- 2. No two electrons can occupy the same state in one atom.**
- 3. Some combinations of electrons have lower energies than others.**



# Chemical Bonding

**Key Idea: Atoms link together by the rearrangement of their electrons**

1. “Magic” numbers of electrons (i.e. 2, 10, 18, or 36) form very stable atoms.

Schroedinger's wave equation

$$\frac{-\hbar^2}{2m} \nabla^2 \Psi + V \Psi = i \hbar \frac{\partial}{\partial t} \Psi$$

# Chemical Bonding

**Key Idea: Atoms link together by the rearrangement of their electrons**

- 1. “Magic” numbers of electrons (i.e. 2, 10, 18, or 36) form very stable atoms.**

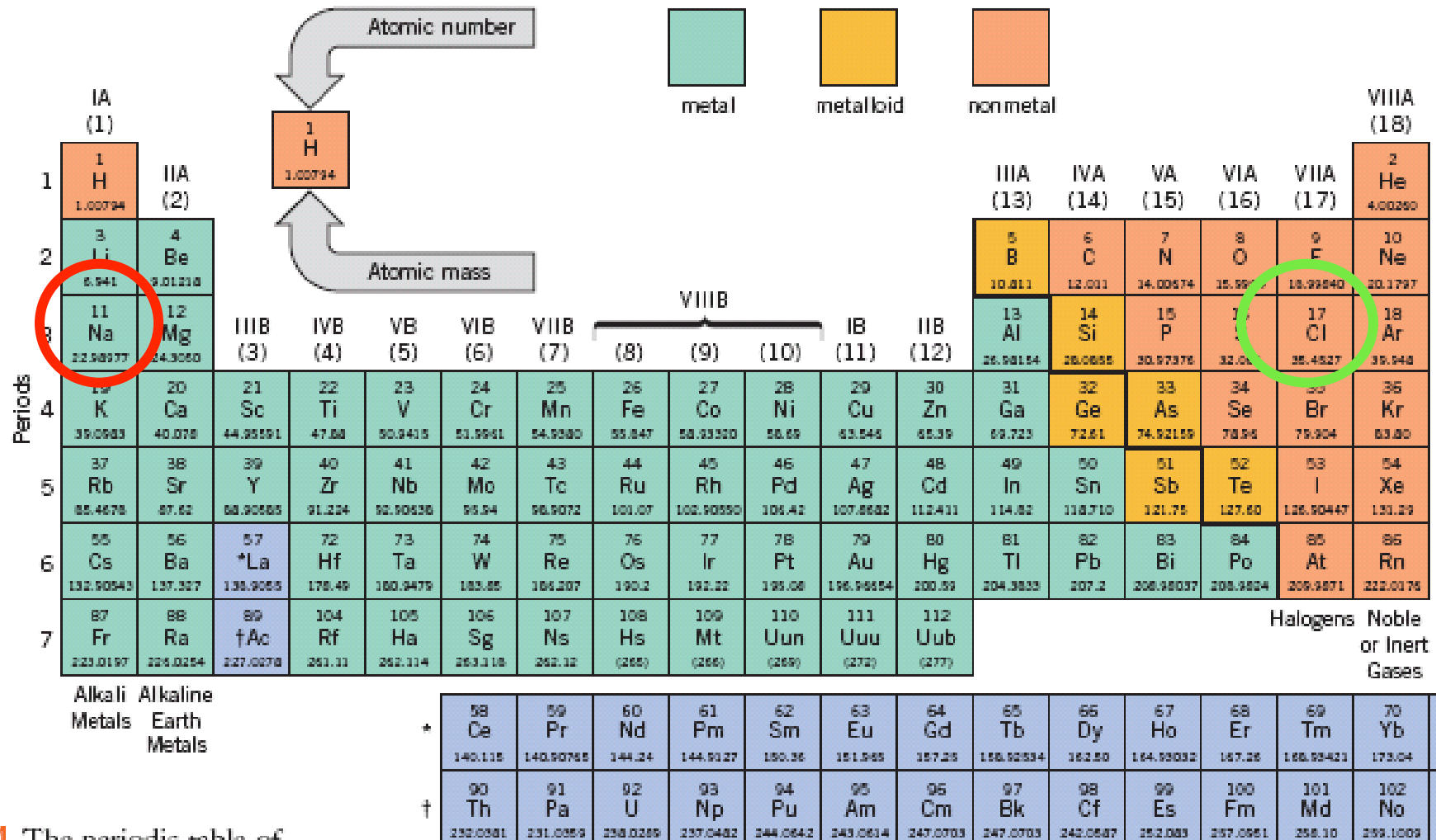


# Chemical Bonding

**Key Idea: Atoms link together by the rearrangement of their electrons.**

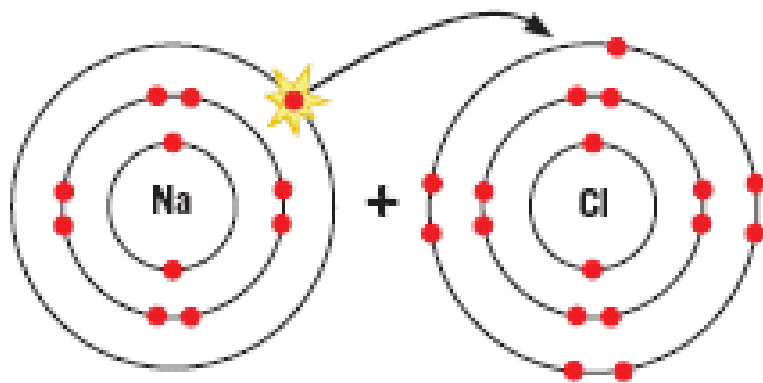
- 1. “Magic” numbers of electrons (i.e. 2, 10, 18 and 36) form very stable atoms.**
- 2. Electrons can be transferred between, or shared among, atoms to form stable chemical bonds.**
- 3. The result is ionic, metallic, or covalent bonds.**

# Ionic Bonding



14 The periodic table of

# Ionic Bonding



A sodium  
atom

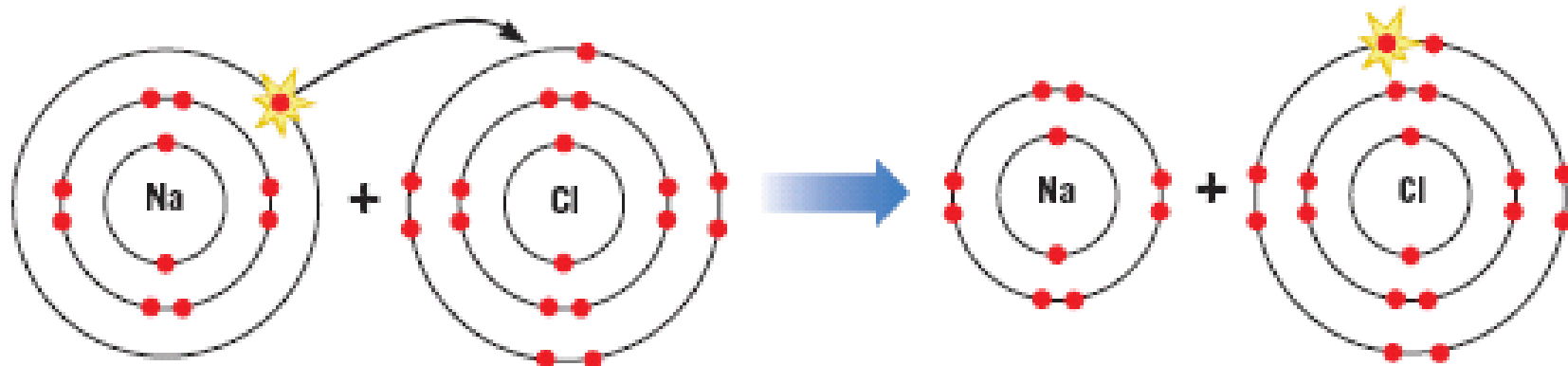
A chloride  
atom

**Na**

**+**

**Cl**

# Ionic Bonding



A sodium atom

A chloride atom

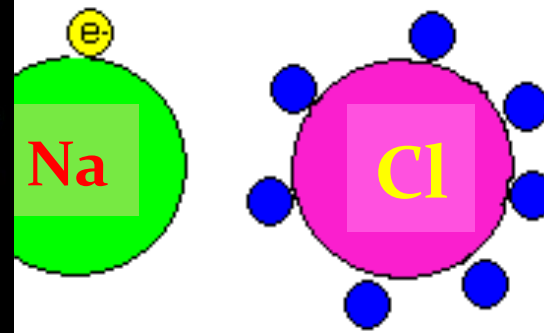
A sodium cation

A chloride anion

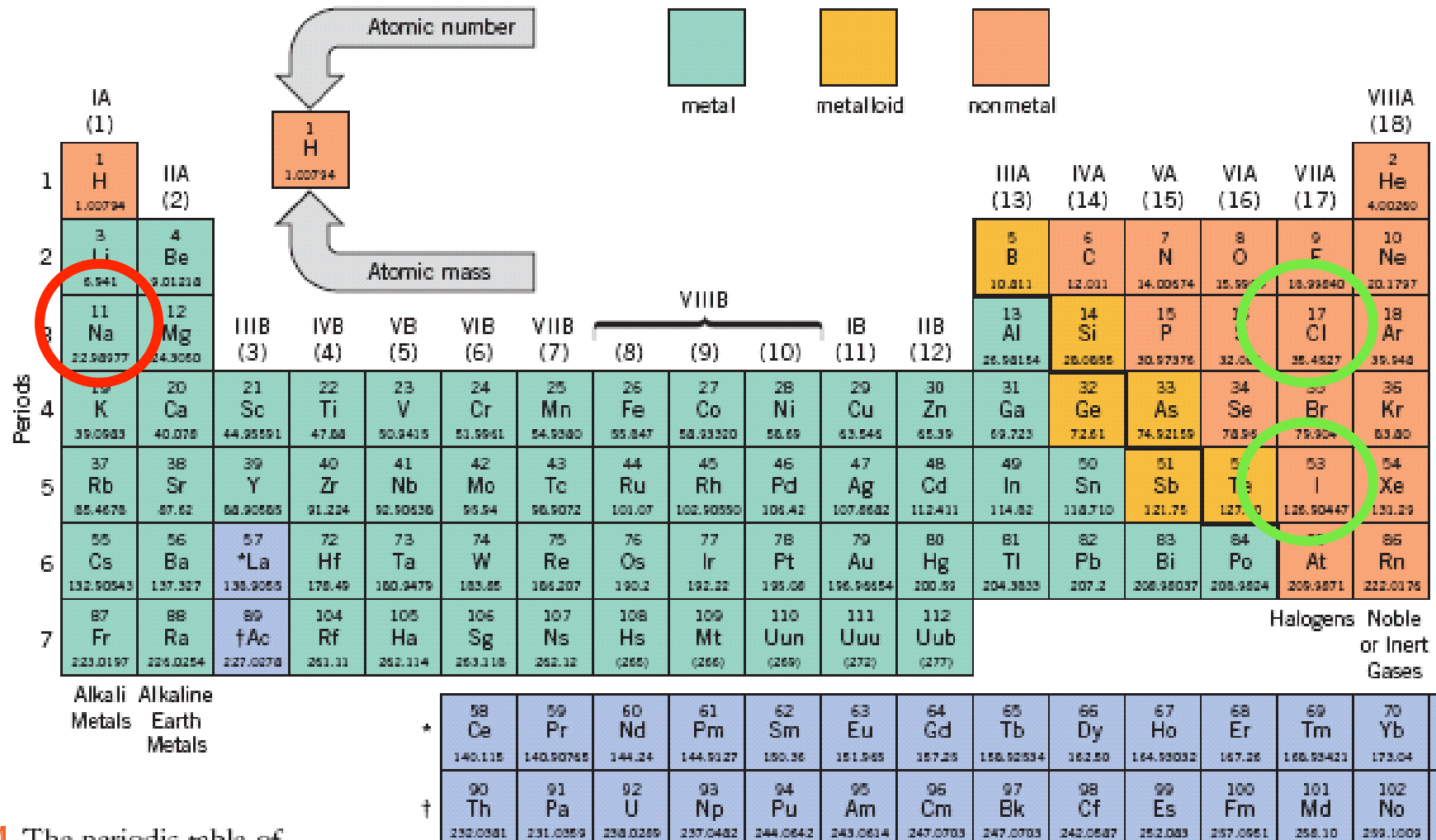
$\text{Na}^+$

+

$\text{Cl}^-$



# Ionic Bonding



14 The periodic table of



# Ionic Bonding

Atomic number

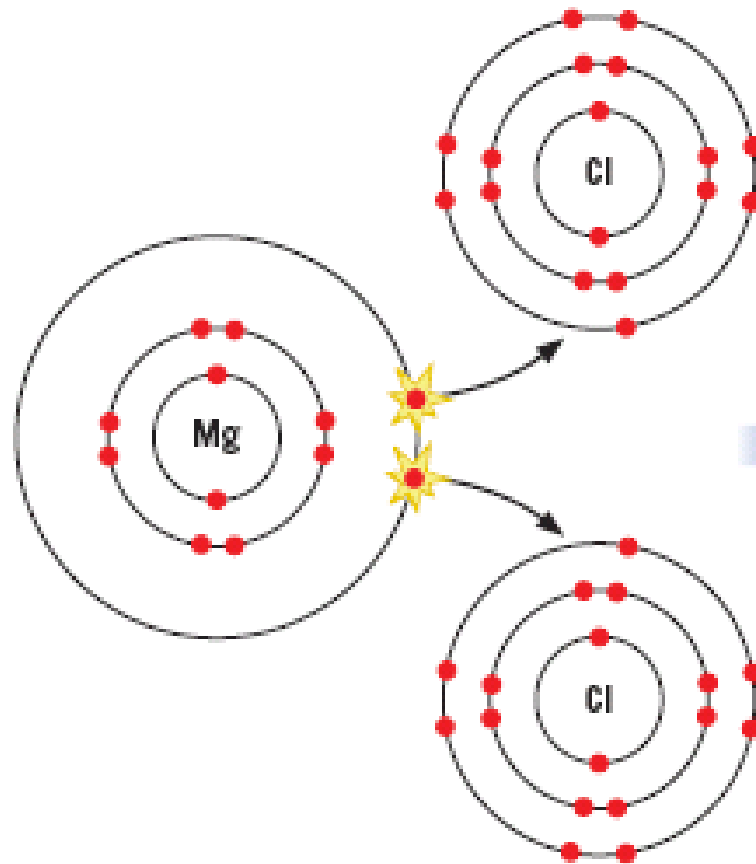
metal      metalloid      non metal

Atomic mass

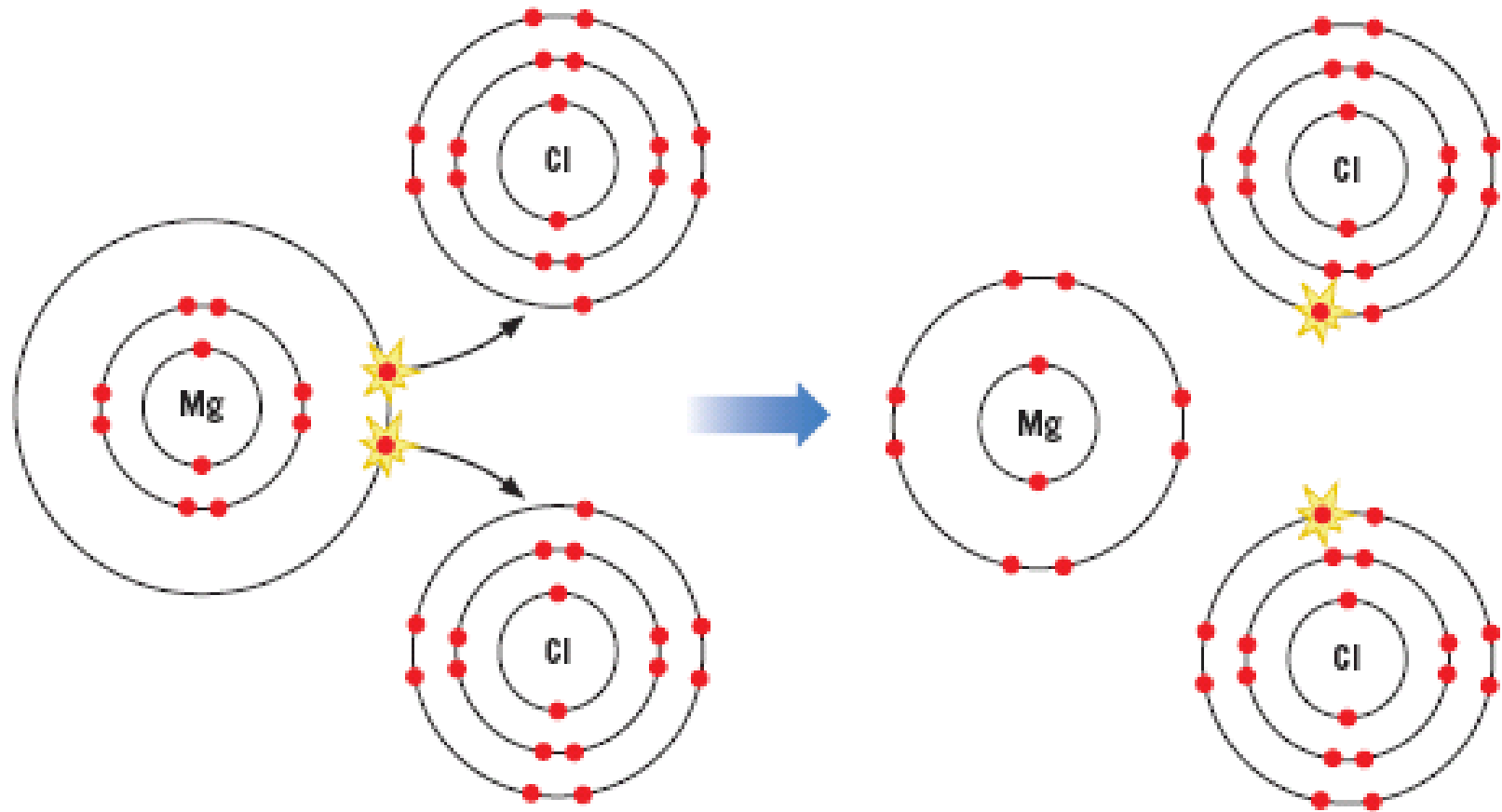
	IA (1)											IIIA (13)	IVA (14)	VA (15)	VIA (16)	VIIA (17)	VIIIA (18)	
1	1 H 1.00794											5 B 10.811	6 C 12.011	7 N 14.00674	8 O 15.999	9 F 18.99840	10 Ne 20.1797	
2	3 Li 6.941	4 Be 9.01218											13 Al 26.98154	14 Si 28.0855	15 P 30.97376	16 S 32.06	17 Cl 35.4527	18 Ar 39.948
3	11 Na 22.98977	12 Mg 24.3050	IIIB (3)	IVB (4)	VB (5)	VIB (6)	VIIIB (7)	VIII B (8) (9) (10)			IB (11)	IIB (12)	31 Ga 69.723	32 Ge 72.61	33 As 74.92159	34 Se 78.96	35 Br 79.904	36 Kr 83.80
4	19 K 39.0983	20 Ca 40.078	21 Sc 44.95591	22 Ti 47.88	23 V 50.9415	24 Cr 51.9961	25 Mn 54.9380	26 Fe 55.847	27 Co 58.93320	28 Ni 58.69	29 Cu 63.546	30 Zn 65.39	31 Ga 69.723	32 Ge 72.61	33 As 74.92159	34 Se 78.96	35 Br 79.904	36 Kr 83.80
5	37 Rb 85.4678	38 Sr 87.62	39 Y 88.90585	40 Zr 91.224	41 Nb 92.90638	42 Mo 95.94	43 Tc 98.9062	44 Ru 101.07	45 Rh 102.90550	46 Pd 106.42	47 Ag 107.8682	48 Cd 112.411	49 In 114.82	50 Sn 118.710	51 Sb 121.75	52 Te 127.60	53 I 126.90447	54 Xe 131.29
6	55 Cs 132.90543	56 Ba 137.327	57 *La 138.9055	72 Hf 178.49	73 Ta 180.9479	74 W 183.85	75 Re 186.207	76 Os 190.2	77 Ir 192.22	78 Pt 195.08	79 Au 196.96654	80 Hg 200.59	81 Tl 204.3833	82 Pb 207.2	83 Bi 208.98037	84 Po 209	85 At 209	86 Rn 222.0175
7	87 Fr 223.0187	88 Ra 226.0254	89 †Ac 227.0278	104 Rf 261.10	105 Ha 262.104	106 Sg 263.108	107 Ns 262.12	108 Hs (265)	109 Mt (266)	110 Uun (266)	111 Uuu (272)	112 Uub (277)	Halogens Noble or Inert Gases					
	Alkali Metals	Alkaline Earth Metals																
			+	58 Ce 140.116	59 Pr 140.90768	60 Nd 144.24	61 Pm 144.9127	62 Sm 150.36	63 Eu 151.965	64 Gd 157.25	65 Tb 158.92534	66 Dy 162.50	67 Ho 164.93032	68 Er 167.26	69 Tm 168.93421	70 Yb 173.04	71 Lu 174.967	
			†	90 Th 232.0381	91 Pa 231.0362	92 U 238.0289	93 Np 237.0482	94 Pu 244.0642	95 Am 243.0614	96 Cm 247.0703	97 Bk 247.0703	98 Cf 247.0703	99 Es 252.083	100 Fm 257.0951	101 Md 258.10	102 No 259.1009	103 Lr 260.105	

1A The periodic table of

# Ionic Bonding



# Ionic Bonding



# Ionic Bonding

## Fluorite—CaF<sub>2</sub>

	IA (1)		IIA (2)	
1	1 H 1.00794			
2	3 Li 6.941		4 Be 9.01218	
3	11 Na 22.989768		12 Mg 24.3050	IIIB (3)
4	19 K 39.0983		20 Ca 40.078	21 Sc 44.955912
5	37 Rb 85.4678		38 Sr 87.62	39 Y 88.905848
6	55 Cs 132.905451		56 Ba 137.327	57 *La 138.90487
7	87 Fr 223.0187		88 Ra 226.0254	89 †Ac 227.03
	Alkali Metals		Alkaline Earth Metals	



			VIIIA (18)
	VIA (16)	VIIA (17)	2 He 4.00260
2	8 O 15.9994	9 F 18.998403	10 Ne 20.1797
3	16 S 32.065	17 Cl 35.4527	18 Ar 39.948
4	34 Se 78.96	35 Br 79.904	36 Kr 83.80
5	52 Te 127.60	53 I 126.90447	54 Xe 131.29
6	84 Po 209	85 At 209	86 Rn 222

Halogens Noble  
or Inert  
Gases

68 Er 147.26	69 Tm 168.93421	70 Yb 173.04	71 Lu 174.967
100 Fm 257	101 Md 258	102 No 259	103 Lr 260

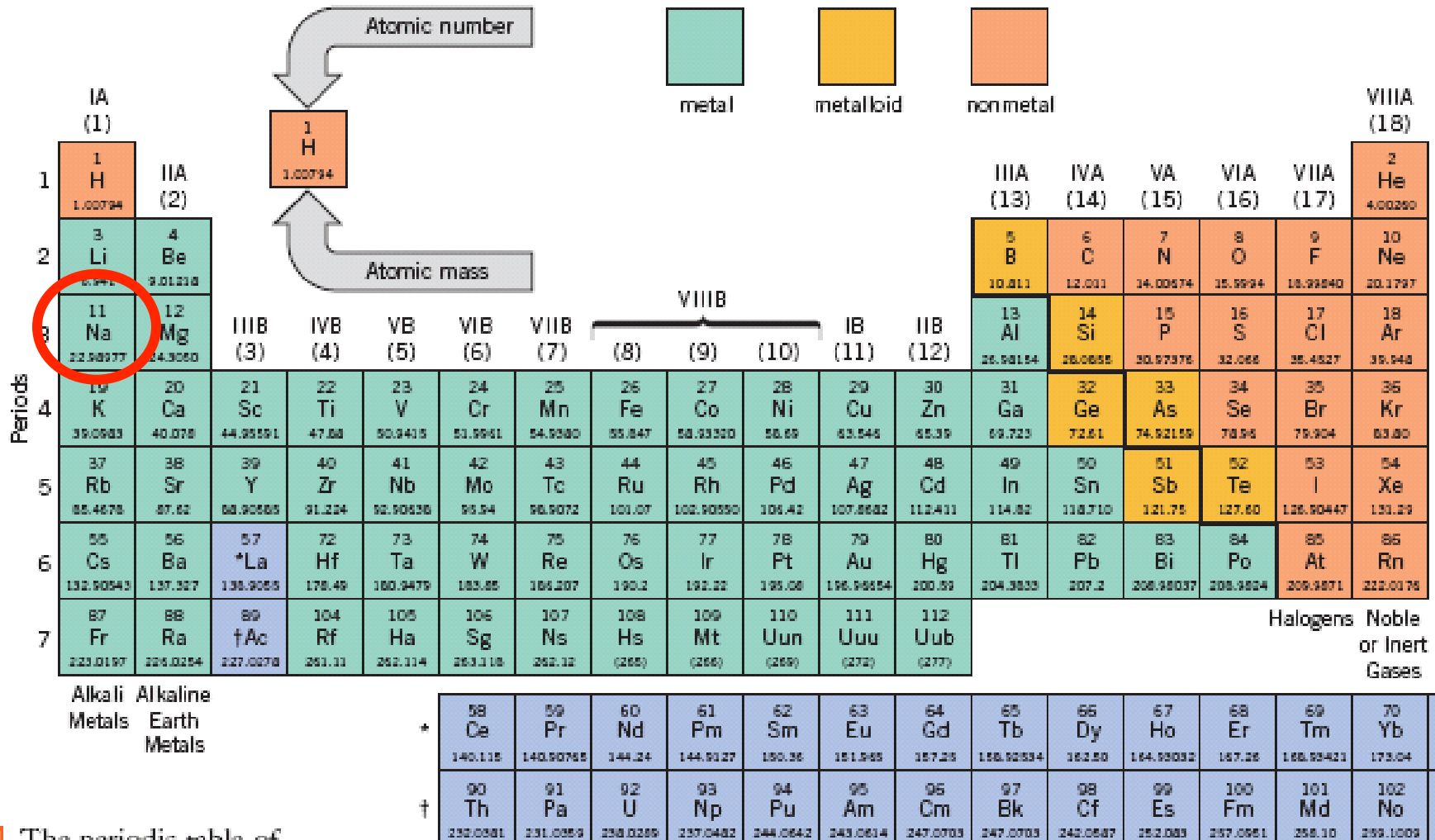
14 The periodic table of

# Ionic Bonding

Two properties of materials with ionic bonds:

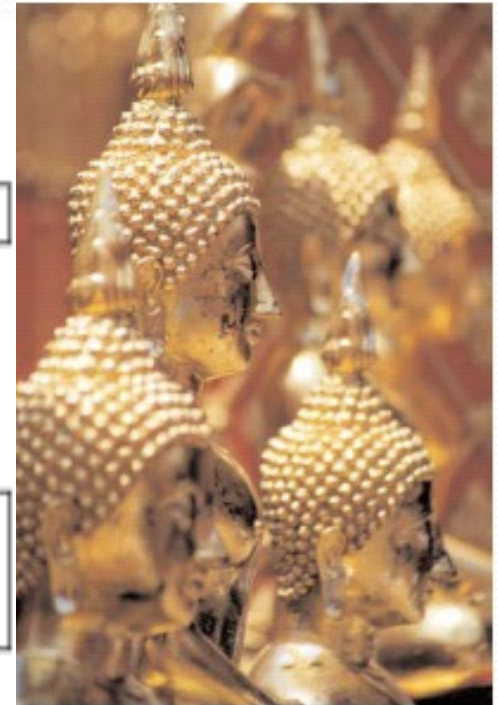
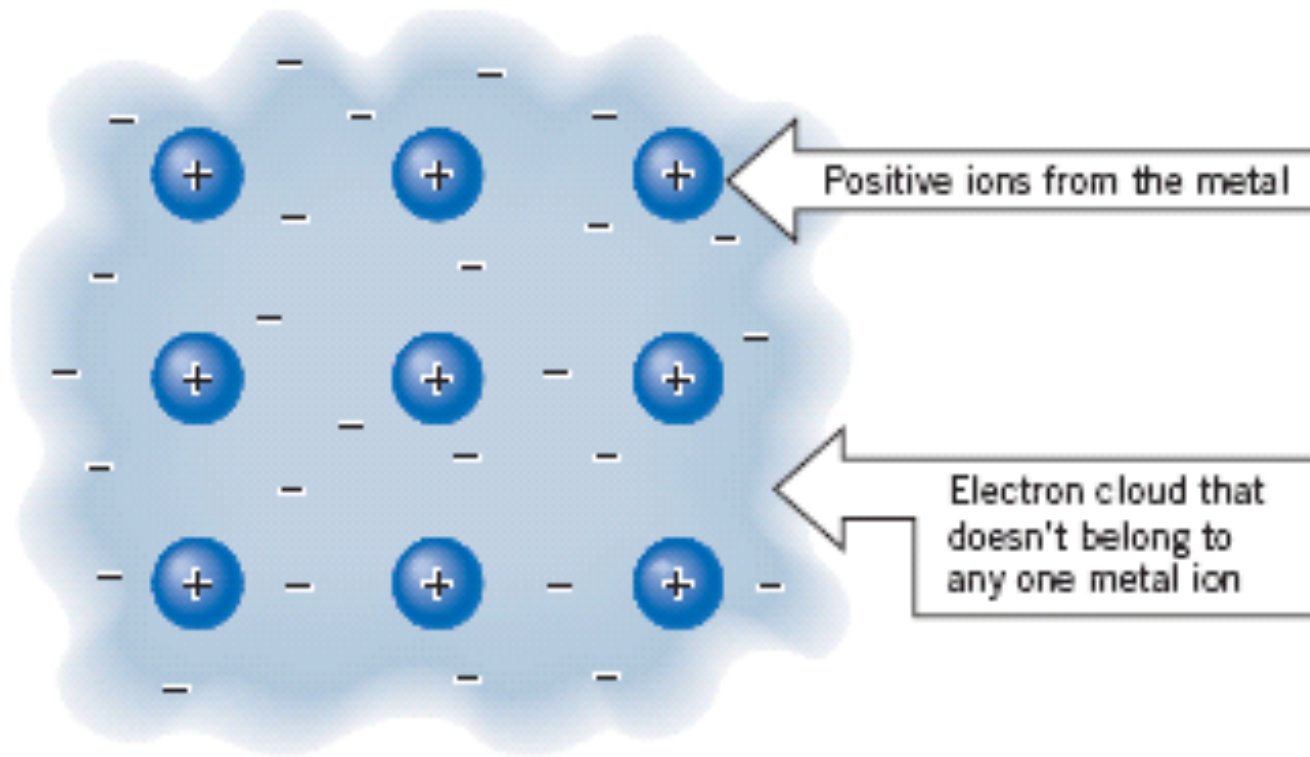
1. Insulates electricity (electrons don't move)
2. Tough but brittle

# Metallic Bonding



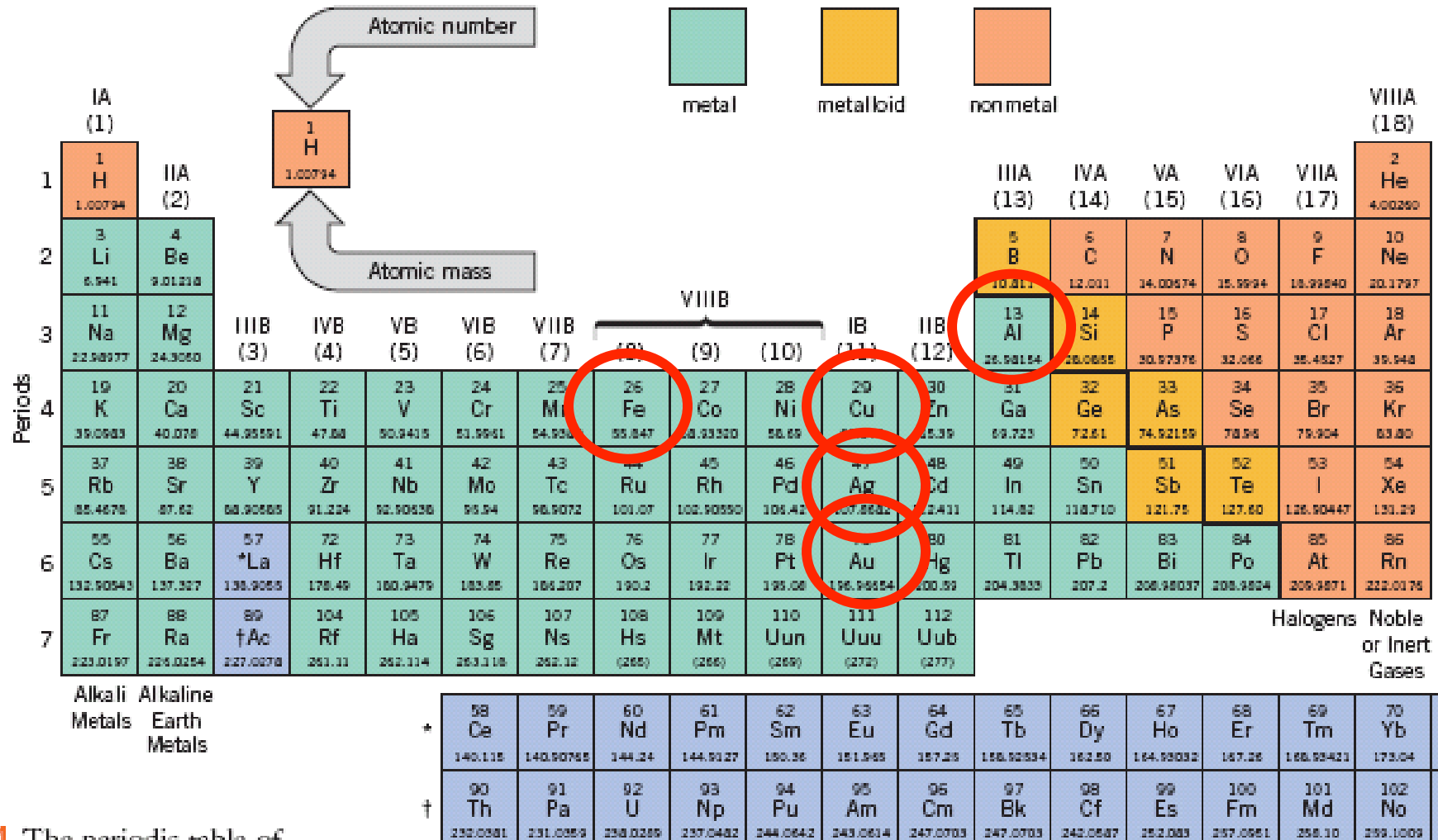
1A The periodic table of

# Metallic Bonding





# Metallic Bonding



1A The periodic table of

# Metallic Bonding

Three properties of materials

With metallic bonds:

1. Conducts electricity  
(electrons free to move)
2. Malleable.
3. Shiny

# Covalent Bonding

Atomic number

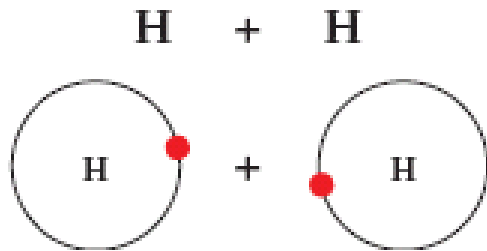
metal      metalloid      nonmetal

Atomic mass

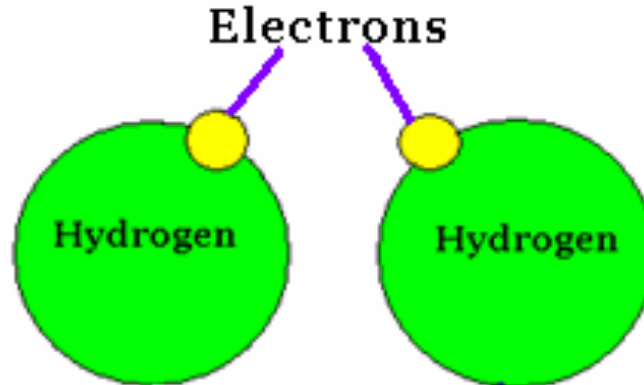
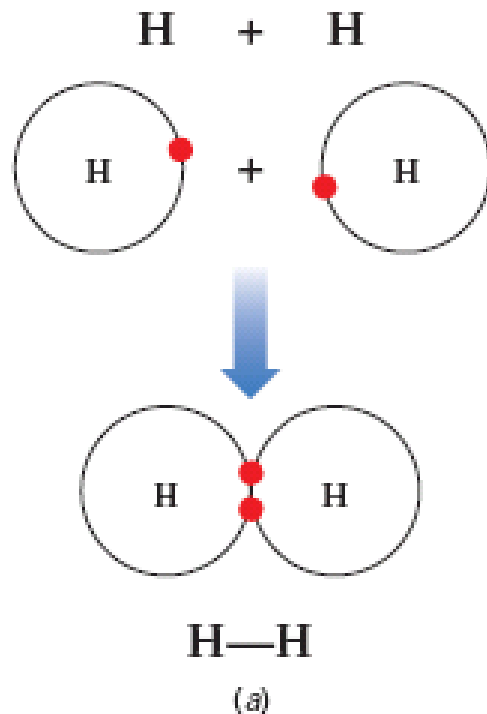
	IA (1)											IIIA (13)	IVA (14)	VA (15)	VIA (16)	VIIA (17)	VIIIA (18)			
1	1 H 1.00794																2 He 4.00260			
2	3 Li 6.941	4 Be 9.01218											5 B 10.811	6 C 12.011	7 N 14.00674	8 O 15.9994	9 F 18.99840	10 Ne 20.1797		
3	11 Na 22.98977	12 Mg 24.3050	IIIB (3)	IVB (4)	VB (5)	VIB (6)	VII B (7)	VIII B (8) (9) (10)			IB (11)	IIB (12)	13 Al 26.98154	14 Si 28.0855	15 P 30.97376	16 S 32.065	17 Cl 35.4527	18 Ar 39.948		
4	19 K 39.0983	20 Ca 40.078	21 Sc 44.95591	22 Ti 47.88	23 V 50.9415	24 Cr 51.9961	25 Mn 54.9380	26 Fe 55.847	27 Co 58.93320	28 Ni 58.69	29 Cu 63.546	30 Zn 65.39	31 Ga 69.723	32 Ge 72.61	33 As 74.92159	34 Se 78.96	35 Br 79.904	36 Kr 83.80		
5	37 Rb 85.4678	38 Sr 87.62	39 Y 88.90585	40 Zr 91.224	41 Nb 92.90638	42 Mo 95.94	43 Tc 98.9062	44 Ru 101.07	45 Rh 102.90550	46 Pd 106.42	47 Ag 107.8682	48 Cd 112.411	49 In 114.82	50 Sn 118.710	51 Sb 121.75	52 Te 127.60	53 I 126.90447	54 Xe 131.29		
6	55 Cs 132.90543	56 Ba 137.327	57 *La 138.9055	72 Hf 178.49	73 Ta 180.9479	74 W 183.85	75 Re 186.207	76 Os 190.2	77 Ir 192.22	78 Pt 195.08	79 Au 196.96654	80 Hg 200.59	81 Tl 204.3833	82 Pb 207.2	83 Bi 208.98037	84 Po 208.9824	85 At 208.9871	86 Rn 222.0176		
7	87 Fr 223.0187	88 Ra 226.0254	89 †Ac 227.0278	104 Rf 261.10	105 Ha 262.104	106 Sg 263.1018	107 Ns 262.12	108 Hs (265)	109 Mt (266)	110 Uun (269)	111 Uuu (272)	112 Uub (277)	Halogens Noble or Inert Gases							
	Alkali Metals		Alkaline Earth Metals																	
	+																			
	58 Ce 140.116	59 Pr 140.90768	60 Nd 144.24	61 Pm 144.9127	62 Sm 150.36	63 Eu 151.965	64 Gd 157.25	65 Tb 158.92534	66 Dy 162.50	67 Ho 164.93032	68 Er 167.26	69 Tm 168.93421	70 Yb 173.04	71 Lu 174.967						
	†																			
	90 Th 232.0381	91 Pa 231.0362	92 U 238.0289	93 Np 237.0482	94 Pu 244.0642	95 Am 243.0614	96 Cm 247.0703	97 Bk 247.0703	98 Cf 247.0652	99 Es 252.083	100 Fm 257.0851	101 Md 258.10	102 No 259.1009	103 Lr 260.105						

IA The periodic table of

# Covalent Bonding



# Covalent Bonding



# Covalent Bonding

Atomic number

metal      metalloid      nonmetal

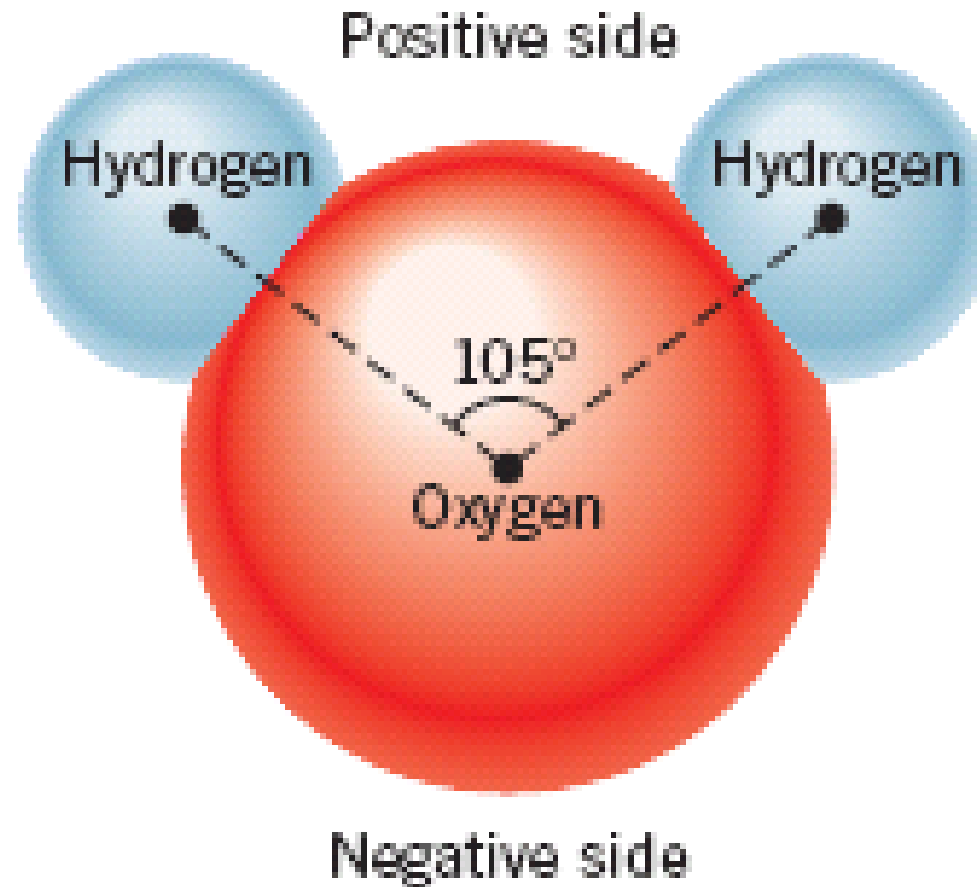
Atomic mass

	IA (1)											IIIA (13)	IVA (14)	VA (15)	VIA (16)	VIIA (17)	VIIIA (18)		
1	1 H 1.00794											5 B 10.811	6 C 12.011	7 N 14.0064	8 O 15.9994	9 F 18.99840	10 Ne 20.1797		
2	3 Li 6.941	4 Be 9.01218											13 Al 26.98154	14 Si 28.0855	15 P 30.97376	16 S 32.065	17 Cl 35.4527	18 Ar 39.948	
3	11 Na 22.98977	12 Mg 24.3050	IIIB (3)	IVB (4)	VB (5)	VIB (6)	VIIA (7)	VIII (8) (9) (10)			IB (11)	IIB (12)	31 Ga 69.723	32 Ge 72.61	33 As 74.92159	34 Se 78.96	35 Br 79.904	36 Kr 83.80	
4	19 K 39.0983	20 Ca 40.078	21 Sc 44.95591	22 Ti 47.88	23 V 50.9415	24 Cr 51.9961	25 Mn 54.9380	26 Fe 55.847	27 Co 58.93320	28 Ni 58.69	29 Cu 63.546	30 Zn 65.39	31 Ga 69.723	32 Ge 72.61	33 As 74.92159	34 Se 78.96	35 Br 79.904	36 Kr 83.80	
5	37 Rb 85.4678	38 Sr 87.62	39 Y 88.90585	40 Zr 91.224	41 Nb 92.90638	42 Mo 95.94	43 Tc 98.9062	44 Ru 101.07	45 Rh 102.90550	46 Pd 106.42	47 Ag 107.8682	48 Cd 112.411	49 In 114.82	50 Sn 118.710	51 Sb 121.75	52 Te 127.60	53 I 126.90447	54 Xe 131.29	
6	55 Cs 132.90543	56 Ba 137.327	57 *La 138.9055	72 Hf 178.49	73 Ta 180.9479	74 W 183.85	75 Re 186.207	76 Os 190.2	77 Ir 192.22	78 Pt 195.08	79 Au 196.96654	80 Hg 200.59	81 Tl 204.3833	82 Pb 207.2	83 Bi 208.98037	84 Po 208.9824	85 At 208.9871	86 Rn 222.0176	
7	87 Fr 223.0187	88 Ra 226.0254	89 †Ac 227.0278	104 Rf 261.10	105 Ha 262.104	106 Sg 263.1018	107 Ns 262.12	108 Hs (265)	109 Mt (266)	110 Uun (269)	111 Uuu (272)	112 Uub (277)	Halogens Noble or Inert Gases						
	Alkali Metals		Alkaline Earth Metals																
					58 Ce 140.116	59 Pr 140.90768	60 Nd 144.24	61 Pm 144.9127	62 Sm 150.36	63 Eu 151.965	64 Gd 157.25	65 Tb 158.92534	66 Dy 162.50	67 Ho 164.93032	68 Er 167.26	69 Tm 168.93421	70 Yb 173.04	71 Lu 174.967	
					90 Th 232.0381	91 Pa 231.0362	92 U 238.0289	93 Np 237.0482	94 Pu 244.0642	95 Am 243.0614	96 Cm 247.0703	97 Bk 247.0703	98 Cf 247.0652	99 Es 252.083	100 Fm 257.0851	101 Md 258.10	102 No 259.1009	103 Lr 260.105	

†

1. The periodic table of

# Covalent Bonding





# Covalent Bonding

Atomic number

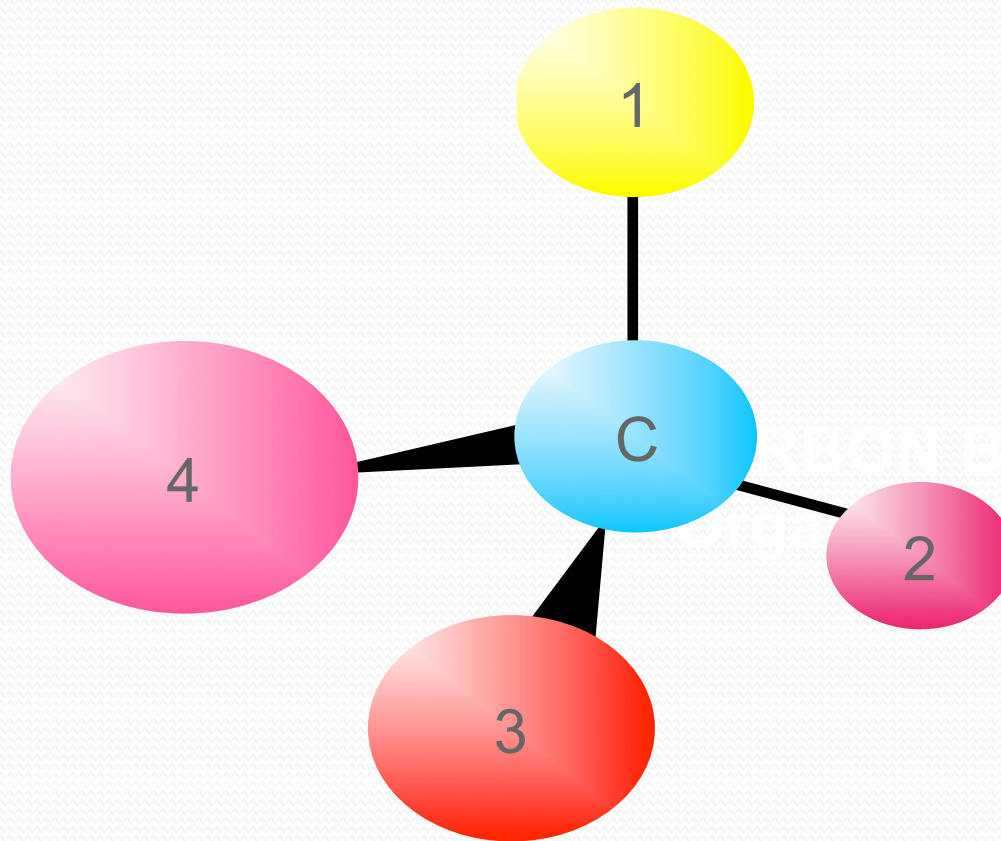
metal      metalloid      nonmetal

Atomic mass

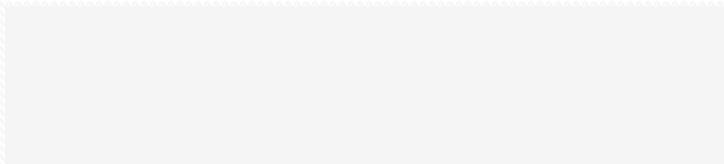
Periods

	IA (1)												IIIA (13)	IVA (14)	VA (15)	VIA (16)	VIIA (17)	VIIIA (18)	
1	1 H 1.00794																	2 He 4.00260	
2	3 Li 6.941	4 Be 9.01218											5 B 10.81	6 C 12.011	7 N 14.00674	8 O 15.9994	9 F 18.99840	10 Ne 20.1797	
3	11 Na 22.98977	12 Mg 24.3050						VIII B (8) (9) (10)						13 Al 26.98154	14 Si 28.0855	15 P 30.97376	16 S 32.065	17 Cl 35.4527	18 Ar 39.948
4	19 K 39.0983	20 Ca 40.078	21 Sc 44.95591	22 Ti 47.88	23 V 50.9415	24 Cr 51.9961	25 Mn 54.9380	26 Fe 55.847	27 Co 58.93320	28 Ni 58.69	29 Cu 63.546	30 Zn 65.39	31 Ga 69.723	32 Ge 72.61	33 As 74.92159	34 Se 78.96	35 Br 79.904	36 Kr 83.80	
5	37 Rb 85.4678	38 Sr 87.62	39 Y 88.90585	40 Zr 91.224	41 Nb 92.90636	42 Mo 95.94	43 Tc 98.9062	44 Ru 101.07	45 Rh 102.90550	46 Pd 106.42	47 Ag 107.8682	48 Cd 112.411	49 In 114.82	50 Sn 118.710	51 Sb 121.75	52 Te 127.60	53 I 126.90447	54 Xe 131.29	
6	55 Cs 132.90543	56 Ba 137.327	57 *La 138.9055	72 Hf 178.49	73 Ta 180.9479	74 W 183.85	75 Re 186.207	76 Os 190.2	77 Ir 192.22	78 Pt 195.08	79 Au 196.96654	80 Hg 200.59	81 Tl 204.3833	82 Pb 207.2	83 Bi 208.98037	84 Po 208.9824	85 At 208.9871	86 Rn 222.0176	
7	87 Fr 223.0187	88 Ra 226.0254	89 †Ac 227.0278	104 Rf 261.10	105 Ha 262.104	106 Sg 263.1038	107 Ns 262.12	108 Hs (265)	109 Mt (266)	110 Uun (269)	111 Uuu (272)	112 Uub (277)	Halogens Noble or Inert Gases						
	Alkali Metals	Alkaline Earth Metals																	
			†	58 Ce 140.116	59 Pr 140.90768	60 Nd 144.24	61 Pm 144.9127	62 Sm 150.36	63 Eu 151.965	64 Gd 157.25	65 Tb 158.92534	66 Dy 162.50	67 Ho 164.93032	68 Er 167.26	69 Tm 168.93421	70 Yb 173.04	71 Lu 174.967		
			†	90 Th 232.0381	91 Pa 231.0362	92 U 238.0289	93 Np 237.0482	94 Pu 244.0642	95 Am 243.0614	96 Cm 247.0703	97 Bk 247.0703	98 Cf 247.0687	99 Es 252.083	100 Fm 257.0851	101 Md 258.10	102 No 259.1009	103 Lr 260.105		

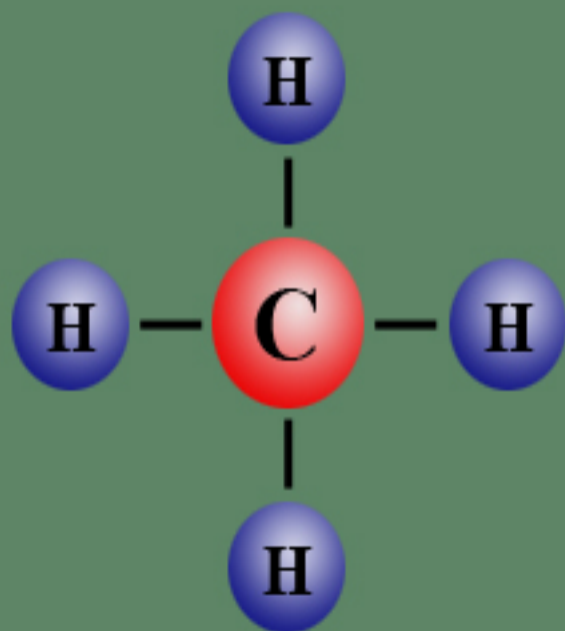
# Covalent Bonding: Carbon



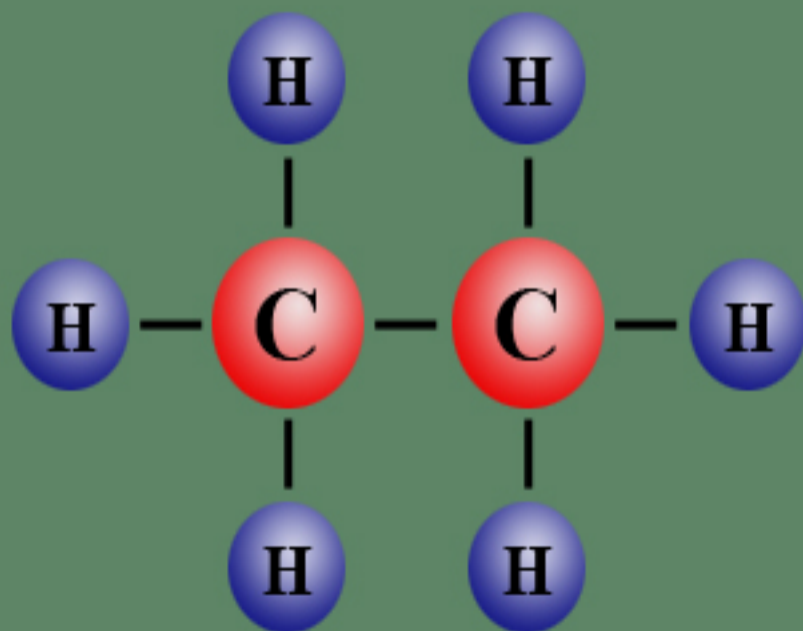
CARBON BONDING  
Single Bonding



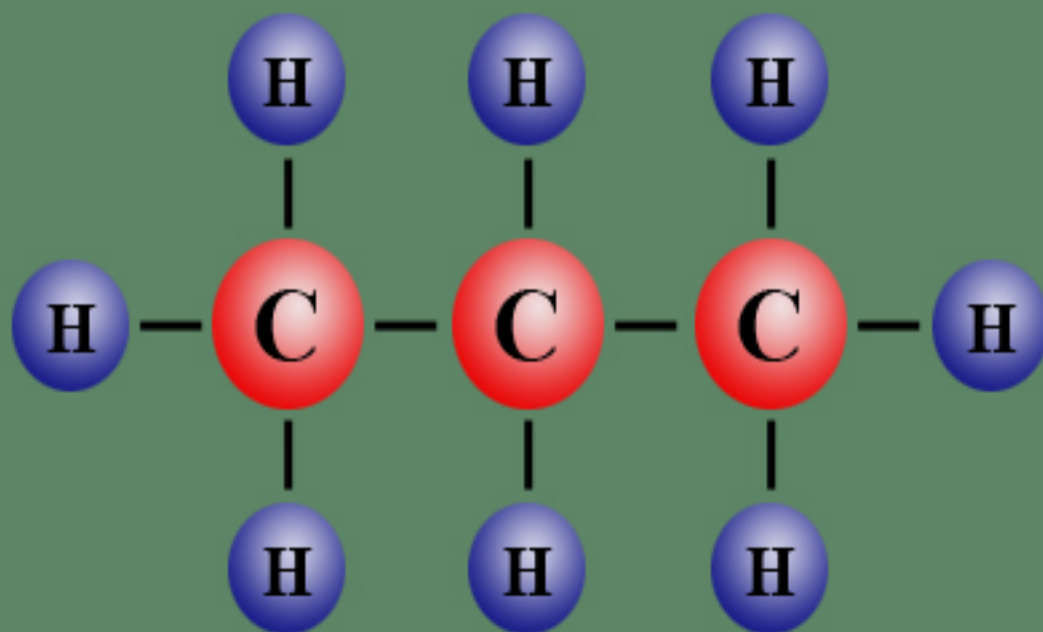
# METHANE



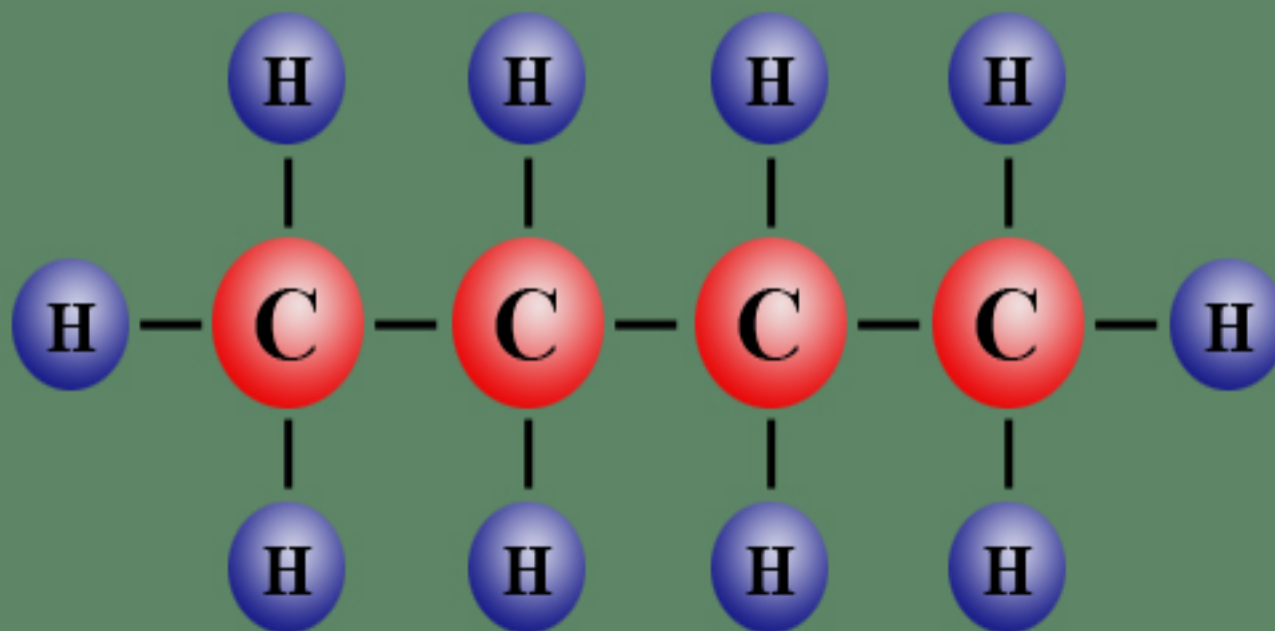
# ETHANE



# PROPANE



# BUTANE





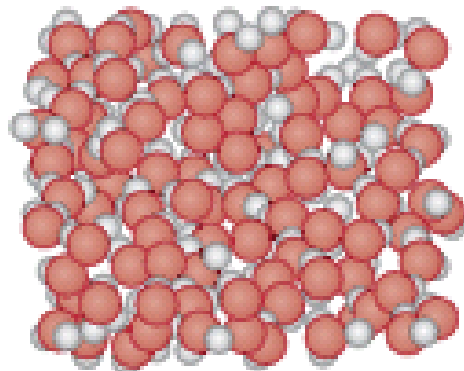
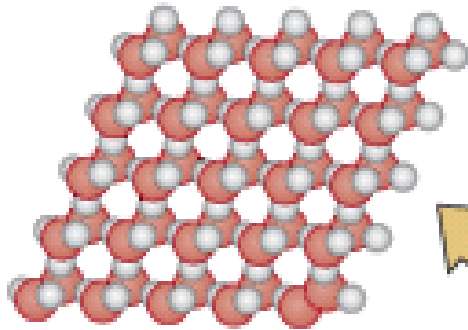
# **Properties of Materials**

**The properties of material arise from the kinds of atoms and how they are bonded together.**

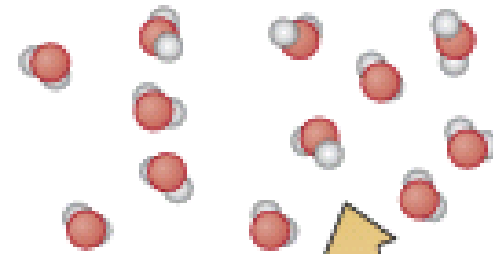


# States of Matter

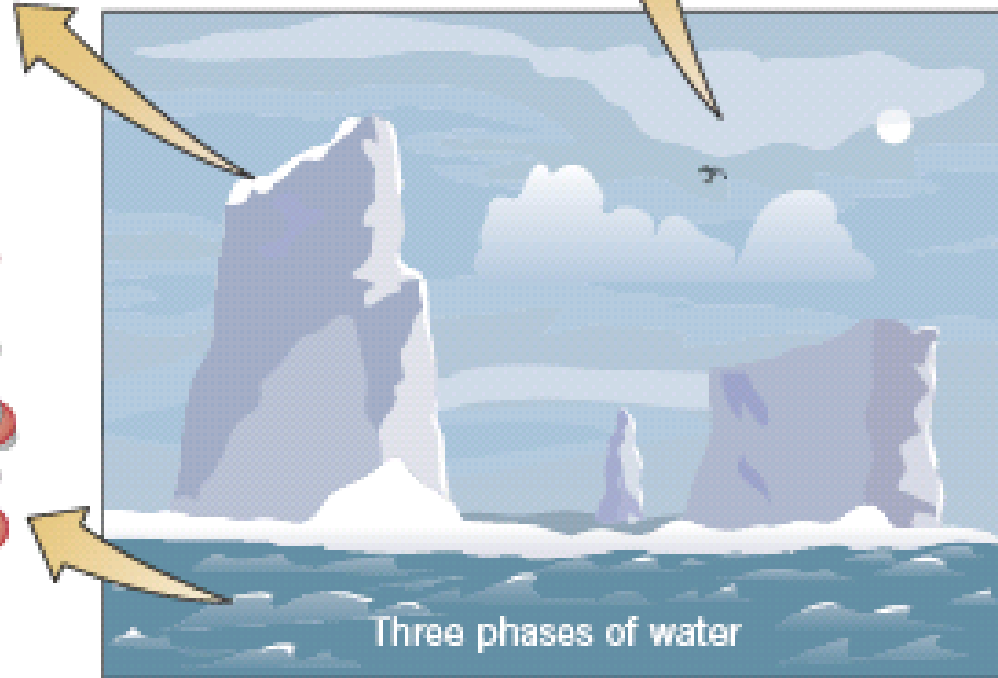
Solid, molecules stay rigidly in place



Liquid, molecules slide past one another



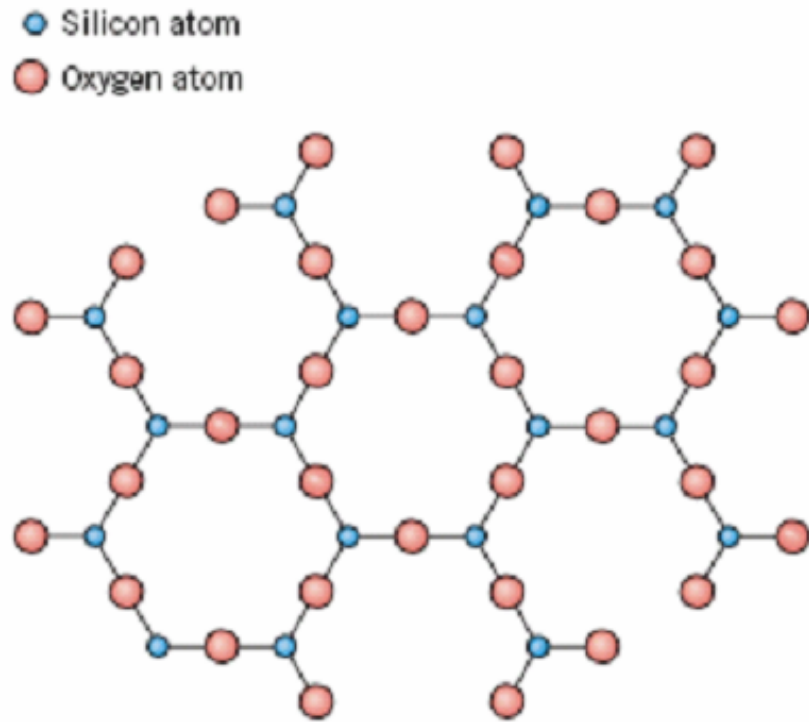
Gas, molecules widely spaced apart



Three phases of water

# SOLIDS

(fixed volume and shape)



(a)



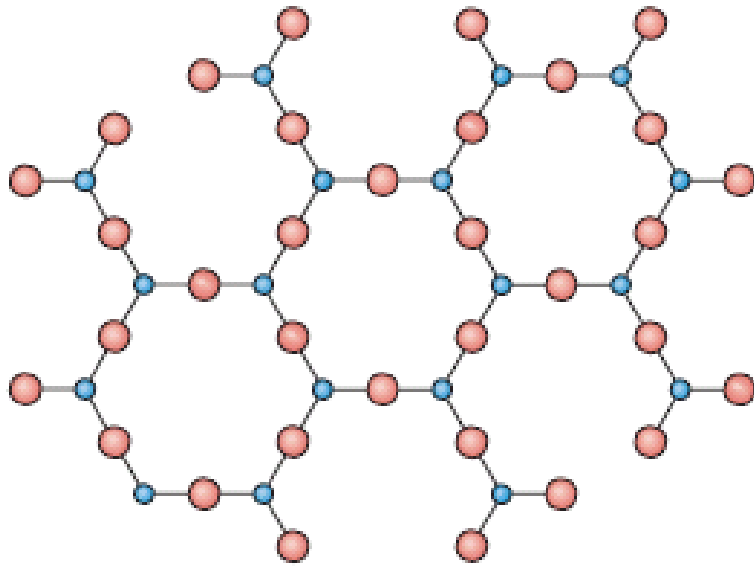
**Crystal – regular atomic arrangement**

# SOLIDS

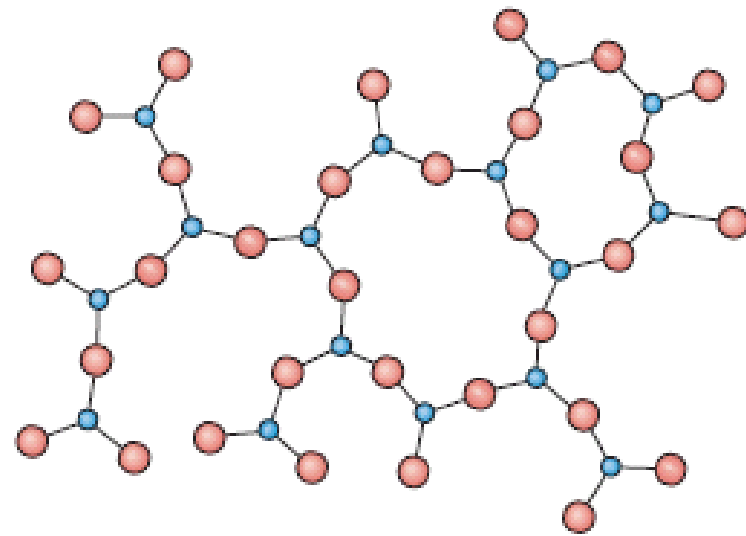
(fixed volume and shape)

● Silicon atom

● Oxygen atom



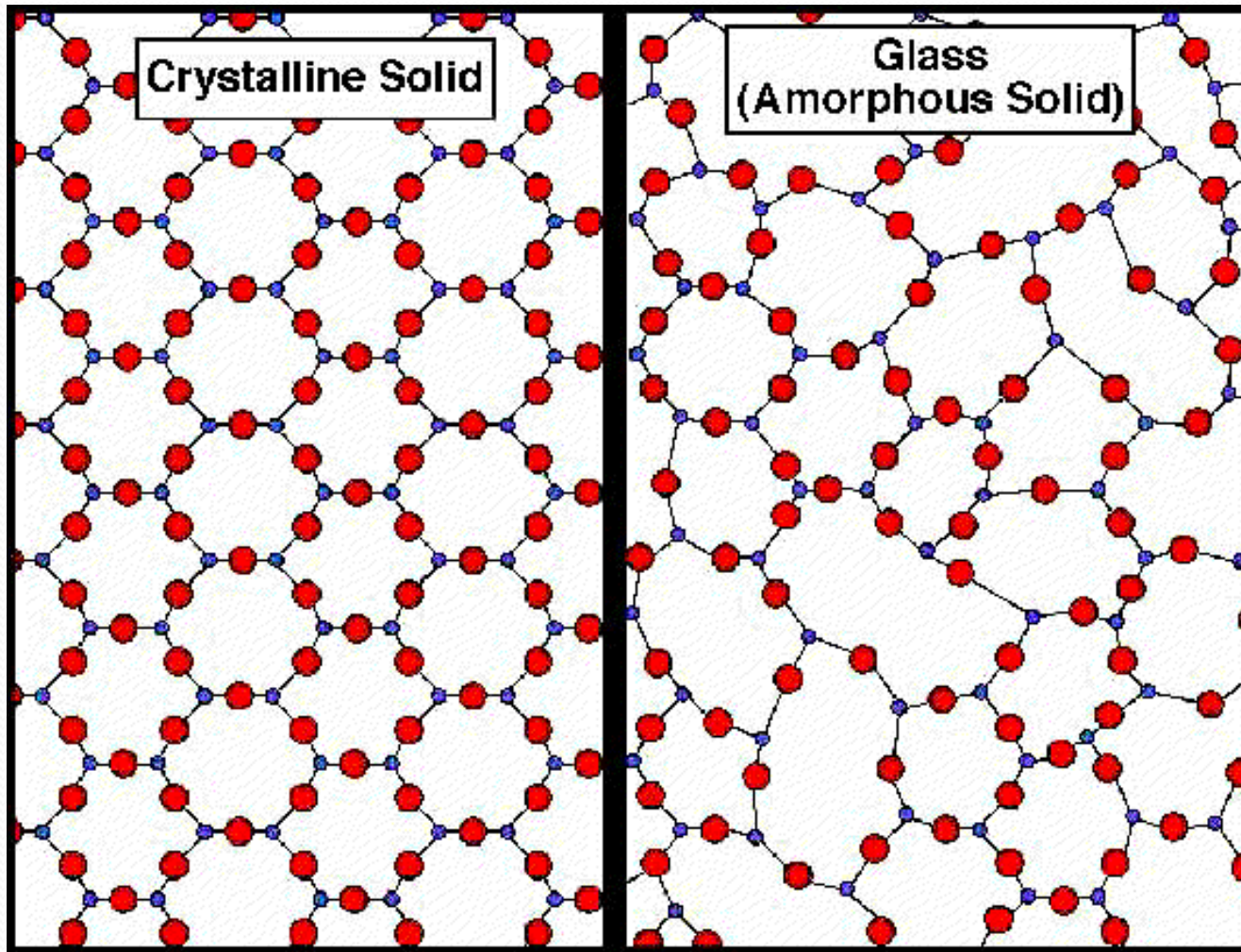
(a)



(b)

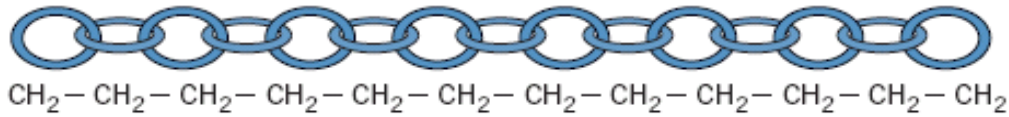
**Glass: Atoms not periodic**

# Glass vs. Crystal Structure

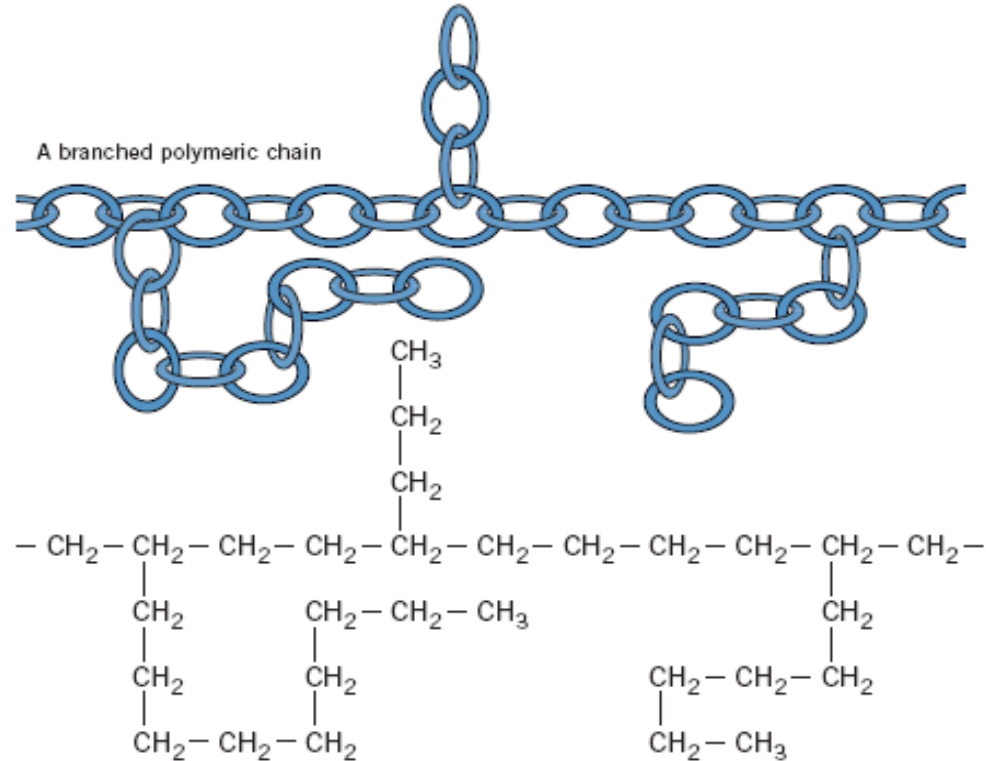


# Solids: Plastics

An unbranched polymeric chain



A branched polymeric chain



**Plastics: Formed from chains of molecules**

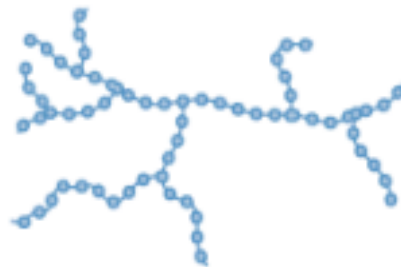
# Plastic Recycling

**Table 10-1** Recycling Plastic

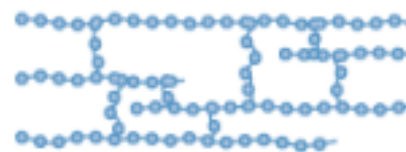
No.	Name	Principal Uses
1	PET	The most common recycled plastic, used for food and beverage containers
2	HDPE	Rigid, narrow-neck containers for detergent and milk; grocery bags
3	PVC	Plastic pipe, outdoor furniture, sturdy containers
4	LDPE	Trash and produce bags, food storage containers
5	PP	Aerosol caps, drinking straws
6	PS	Packing peanuts, cups, and plastic tableware



(a) Linear polymer



(b) Branched polymer



(c) Cross-linked polymer

CHEMICAL REACTIONS AND THE FORMER





# LIQUIDS

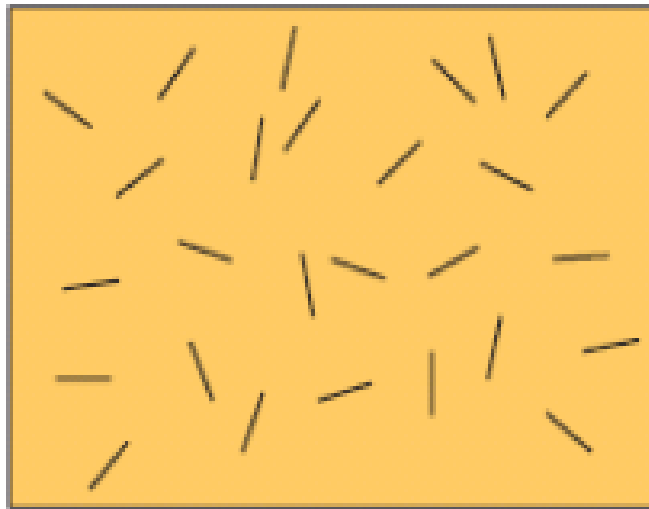
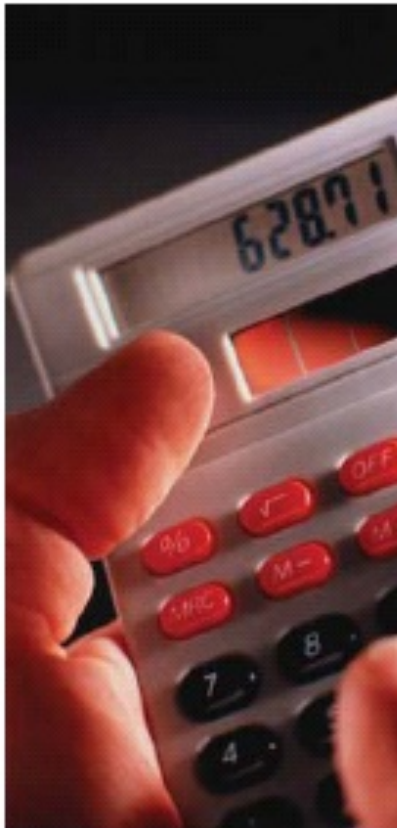
(fixed volume, variable shape)



# LIQUIDS

(fixed volume, variable shape)

**Liquid Crystals: Molecules line up under an electric field**



(a)



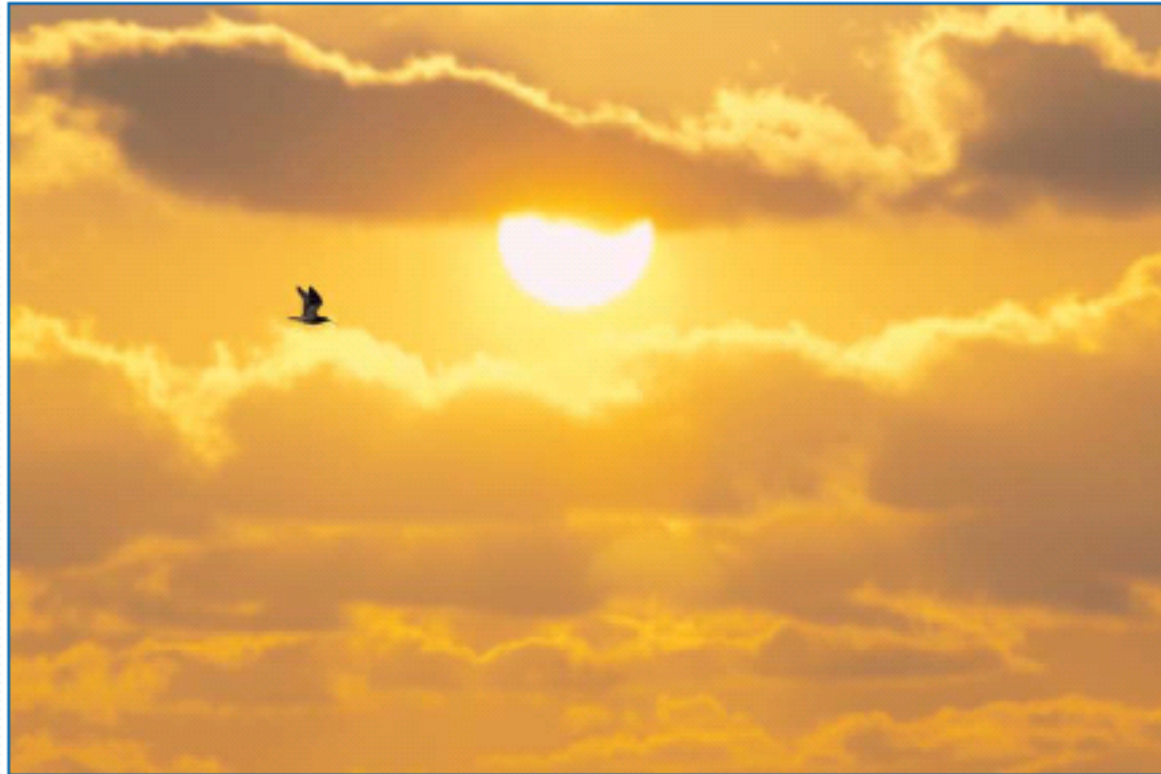
# **GAS**

**(variable volume and shape)**



# PLASMA

(Gas with free electrons)



**By far the most abundant state of matter in the universe!!!**



# Tensile Strength: (Strength against pulling)—1D

- Wire
- Rope
- Chains



# Compressive Strength: (Strength against squeezing)—2D

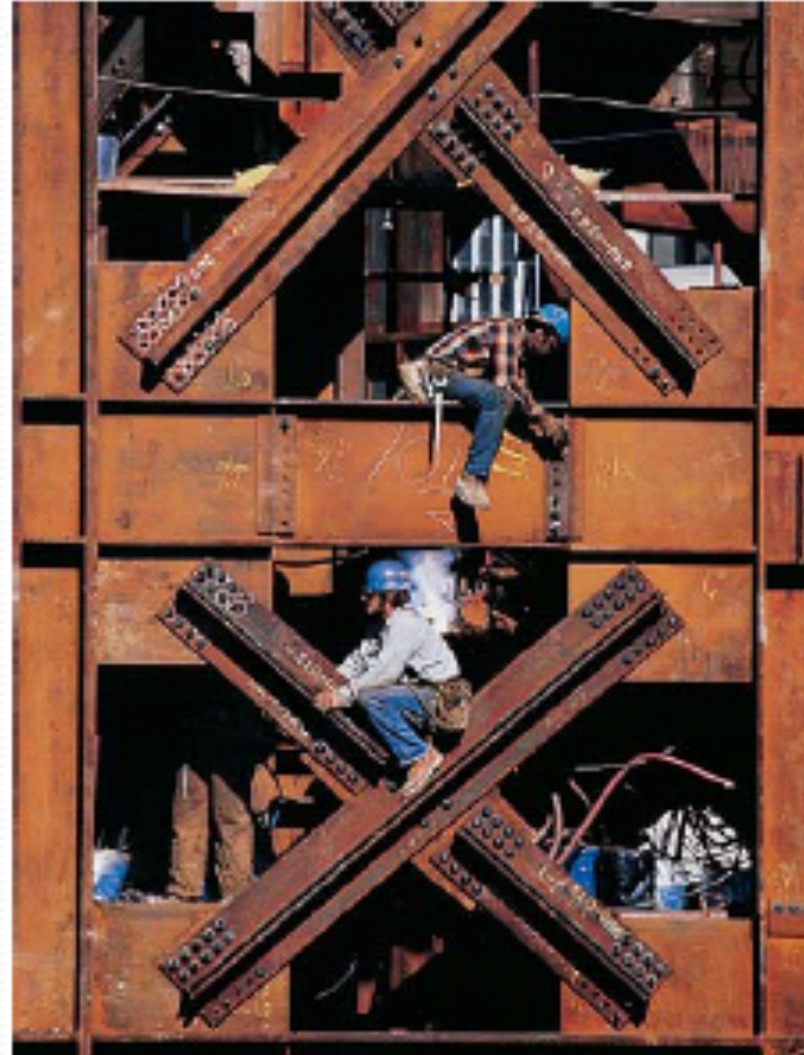
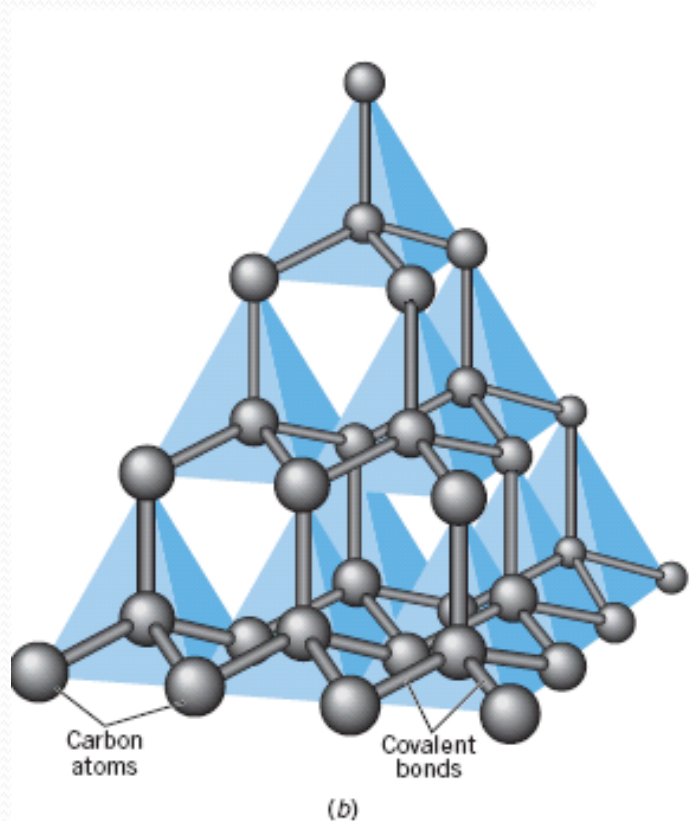
- Stack of paper
- Masonry
- Wood





# Shear Strength: (Strength against twisting)-3D

- Girder network
- Diamond



# Organizational Principles of the Cosmos

- **Forces**
- **Matter**
- **Energy**
- **Evolution**
- **We're all trying to understand why the cosmos is the way it is.**