Physical Properties and Principles

I. Review of Fundamental Physics

A. Fundamental (Measurable) Physical Quantities

1. **Mass** - a measure of the amount of matter contained in a given quantity of material (measure of matter's resistance to motion or inertia; scalar quantity with magnitude only)
   a. mass units kg 1 kg = 1000 g; 1 g =1000 mg

2. **Length** - linear measure of distance (scalar quantity with magnitude only)
   a. length units m 1 m = 100 cm; 1 km = 1000 m

3. **Time** - passage of time measured in terms of motion or displacement of bodies in space
   a. time units sec 1 yr = 365 day; 1 day = 24 hr; 1 hr = 60 min, 1 min =60 sec

4. **Temperature** - measure of the amount of molecular kinetic energy ("heat") contained within a substance (i.e. > heat energy, >vibration rate of atoms / molecules, > temp.)

   a. temperature units degree celsius (C) degree Fahrenheit (F)

      (1) Conversion Factors:

         (a) From C to F: $F = 9/5C + 32^o$
         (b) From F to C: $C = 5/9(F - 32^o)$
            i) E.g. convert 40 C to F
               $F = 9/5(40) + 32 = 104^o$ F

5. **Force** - the push or pull action on an object. Force is required to start an object in motion from rest, or stop an object that is moving, or cause a moving object to speed up or slow down.

   a. force units N (newton) $1 N = 1 kg\text{-}m/s^2 = 1 kg\text{-}ms^{-2}$

B. Geometric (Measurable) Physical Quantities

1. **Angle** measured in degrees circle = 360^o
2. **Length** L units: m
3. **Area** $A = L^2$ units: m^2
4. **Volume** $Vol = L^3$ units: m^3

The SI unit of pressure is the *pascal*, symbol *Pa*, the special name given to a pressure of one newton per square metre (N/m^2). The relationships between the pascal and some other pressure units are shown in the table but note that not all are, or can be, expressed exactly. Note also that the term *standard atmosphere* is not a pressure unit(5).

Unit	**Symbol**	**No. of Pascals**
bar	bar	1×10^5 Pa (exactly)
millibar(1)	mbar	100 Pa (exactly)
hectopascal(1)	hPa	100 Pa (exactly)
conventional millimetre of mercury(2,3)	mmHg	133.322... Pa
conventional inch of mercury(2,3)	inHg	3 386.39... Pa
torr(4)	torr	101325/760 Pa (exactly)
pound-force per square inch	lbf/in^2	6 894.76... Pa

C. Kinematic (Measurable) Physical Quantities (kinematic = "in motion")

1. **Time** T units: sec
2. **Velocity** V = L / T units: m/sec (change in position over time)
3. **acceleration** a = V/T units: m/sec^2 (change in velocity over time)

   a. **g** - acceleration due to gravity = 9.8 m/sec^2

4. **Discharge** Q = Volume / T = L^3 /T units: m^3/sec (fluid flow rate)

D. Dynamic (Measurable) Physical Quantities (dynamic = "changeable")

1. **Force (weight)** F=mg units: $kg\text{-}m/sec^2$ = N

2. **Pressure** P = F/A (force per unit area)
   units: N/m^2 = Pa (paschal)

3. **Energy (work)** W = Fs (force x displacement) units: N-m
   1N-m = 1 kgm^2/sec^2 = 1 J (joule)

4. **Power** P = W/t (work per unit time) units: J/sec = watt (W)

5. **Momentum** M = mass x velocity units: kg-m/sec

6. **Mass Density** D = mass / volume units: kg/m^3

7. **Weight Density** Dw = weight / volume units: N/m^3

8. **Dynamic Viscosity** - resistance of a fluid to flow (due to intermolecular attractions)
   dimensional units: $N\text{-}sec/m^2$ = Pa-s

** dimensionless quantities are ones that have no units (e.g. a "dimensionless ratio" is a quantity in which all units "cancel out" **

II. Heat Energy and Thermodynamics (heat flow)

A. Heat - internal energy within a substance = kinetic molecular energy
1. high heat substances = high degree of kinetic molecular energy
   a. i.e. the higher the heat the faster the vibration of atoms and molecules

2. Temperature - measure of the average amount of heat energy in a substance - i.e. the average kinetic energy of a substance

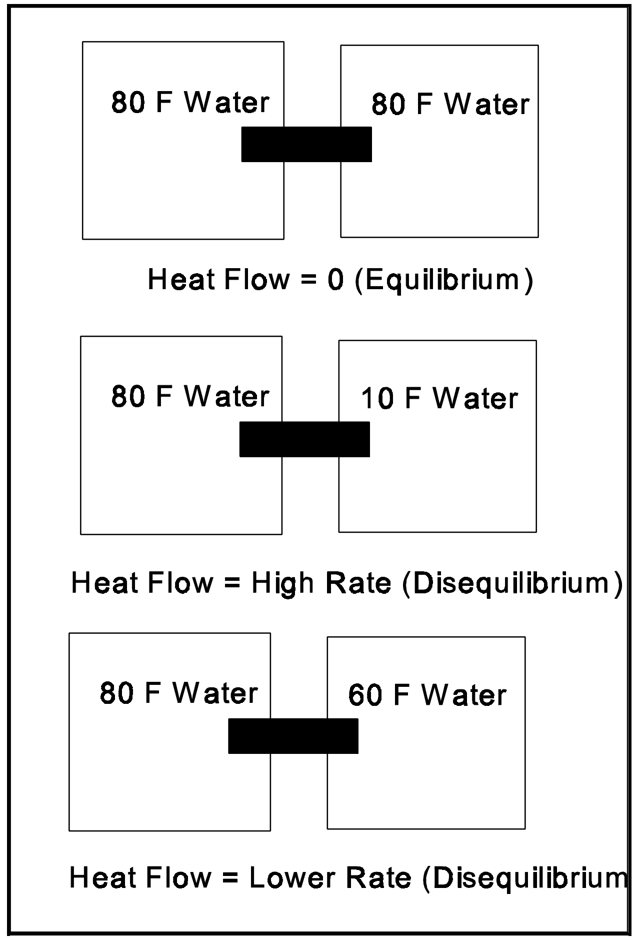
B. Heat Flow

1. "Thermodynamics" = study of heat, heat flow and behavior of heat

2. Heat Flow : An Equilibrium Process
   a. Temperature Imbalance Causes Heat to Flow or Transfer
   b. Substances at Same Temperature = Temperature Equilibrium

3. Heat Flows from High Temperature Regions to Low Temperature Regions
   a. At temperature equilibrium: net heat flow = 0
   b. The higher the temperature differential, the faster the heat flow
   c. The lower the temperature differential, the slower the heat flow

Consider an experiment with two vessels of water, with variable heat-content. They are connected by a tube that allows heat to exchange between the two vessels.



   d. Specific Heat Capacity
      (1) Amount of heat required to raise the temperature of 1 gram of a substance, 1 degree C

      (2) E.g. Water has high heat capacity compared to rock
         (a) takes a higher amount of heat to raise the temperature of water, compared to rock
         (b) Result: water heats and cools more slowly than earth /rocks

C. Heat, Expansion, Contraction

1. Expansion of Hot Matter

a. Increase heat, increase temperature, increase vibrational kinetic energy of atoms / molecules

(1) atoms/molecules vibrate faster - move farther apart to make room

(2) Net Result: Expansion and Volume Increase

2. Contraction of Cold Matter

a. Opposite Relation: remove heat, < temperature ... volume decrease / contraction

3. Density Relations to Heat-Induced Volume Changes

a. Density = mass / volume

(1) assuming mass is constant, when volume decreases, density increases

(2) assuming mass is constant, when volume increases, density decreases

(a) i.e. an "inverse relationship" between density and volume

b. Heat Loss = Cooling = < kinetic energy = < volume = > density

c. Heat gain = Warming = >kinetic energy = > volume = < density

(1) e.g. Hot Air Balloon: Hot Air = volume increase = density decrease

(a) less dense hot air rises relative to more dense cold air

4. States of Matter vs. Volume Change / Density Change

a. Solids = decreased temperature = decreased kinetic energy = decreased volume = increased density

b. Gases = increased kinetic energy = increased volume = decreased density

5. Special Consideration: Water

a. Most substances are more dense in a solid state compared to a liquid state

b. Water is the opposite

(1) Density of Ice (solid water) = 0.92 gm/cm^3

(2) Density of Water (liquid) = ~1.0 gm/cm^3

(a) Result: Ice Floats in Water

(3) Why? Because the crystal structure of ice takes up more space (greater volume) than the structure of liquid water molecules

c. Importance: A good thing, otherwise oceans and lakes would freeze from the bottom - up... resulting in destruction of all aquatic life!!!

(1) Luckily: Lakes / oceans freeze with ice on the surface, and liquid water insulated from freezing at depth.

D. Heat Transfer

1. Mechanisms of Heat Transfer

a. Conduction: heat and vibrational kinetic energy is passed from molecule to molecule, without actual transfer of mass
(1) heat transfer without mass transfer
(2) e.g. heating an iron rod, the heat is transferred from one end to the other without transfer of mass

(3) Examples
(a) Good conductors of heat = iron / metal (rapidly transmit heat)
(b) Poor conductors of heat = adobe / brick, fiber glass insulation
(c) Poor conductor = "good insulator"

b. Convection - heat transferred via transfer of mass

(1) e.g. "fluid currents" transfer heat

(2) Convection cells common in ocean, atmosphere, and earth's interior
(a) e.g. Warm air rises, cools, sinks
(b) e.g. Warm ocean water rises, cools, sinks

c. Radiation - heat transfer via electromagnetic radiation
(1) infrared radiation = "thermal radiation"
(2) remember: infrared = wavelengths longer than visible spectrum

(3) Emitters of radiant energy
(a) Sun (hydrogen fusion)
(b) Earth (radioactive decay of elements)

E. Temperature, Energy and Influence on Physical State

1. Three physical states of matter (water in this case) - dependent on amount of heat energy (vibrational kinetic energy) contained within matter
a. solid (low energy)
(1) crystalline atomic structure
b. liquid (medium energy)
(1) fluid - material changes shape easily
c. gas (high energy)
(1) fluid - material changes shape easily

2. Transformation Processes related to energy input and entropy of water: heating of water, > atomic activity of the water molecules, i.e. > vibrational energy of water atoms.

ICE ----------HEAT----- WATER-------HEAT -------WATER VAPOR
(<32 degrees) (32-212) (>212 degrees F)

3. Evaporation- process of transforming water from liquid to gaseous state (Heat Gain)

4. Freezing- process of transforming water from liquid to solid state (Heat Loss)

5. Condensation- transformation of water vapor to liquid form (Heat Loss)

6. Sublimation- process of transforming ice to water vapor directly through superheating, bypassing liquid form. (Heat Gain)

F. Thermal Budget and States

1. States of matter a function of amount of heat in system, which in turn influences the vibrational rates of molecules
   a. gas - high rate of vibration, high heat condition
   b. liquid- medium rate of vibration, medium heat system
   c. solid- low rate of vibration, low heat system

2. Heat Energy
   a. measured in calories
      (1) amount of energy required to raise the temperature of 1 gram of water 1 degree C

3. Heat and State Transformation
   a. Evaporation: water liquid to vapor = system must absorb 600 Cal of energy
      (1) energy absorbed by molecules, > rate of vibration to allow phase change

      (2) latent heat of vaporization = "stored heat" that is exchanged to cause phase change

   b. Condensation: water vapor to liquid = system must lose 600 Cal of energy
      (1) < vibratory motion
      (2) latent heat of condensation
      (3) Condensation/heat transfer
         (a) drives storm systems
         (b) affects climate
         (c) transfers heat from equator to poles
         (d) results in cloud phenomena

   c. Melting: solid ice changed to liquid = system must gain 80 calories of energy

   d. Freezing: liquid to solid = system must lose 80 calories of energy
      (1) latent heat of fusion for water

e. Sublimation: solid to gas or gas to solid = system must gain 680 cal of energy or lose 680 cal of energy respectively for transformation to occur

(1) e.g. dry ice sublimates to gaseous carbon dioxide with no intervening liquid phase

G. Basic Laws of Classical Physics

1. Conservation of Mass - mass is neither created nor destroyed
2. Conservation of Energy - energy is neither created nor destroyed
3. Newton's Second Law of Motion: F = ma (force is equal to mass x acceleration)

Example Conservation Equation in Hydrology

Total Water In = Total Water Out (for example in an aquifer or a watershed)

thus,

$$I - Q = \Delta S$$

where I = water into a system, Q = water flow out of a system, ΔS = change in storage of system

Example Problem: A reservoir is full to the brim and holds 10 km^3 of water. During the course of a given year, the reservoir receives 0.58 km^3 of water via rainfall. Meanwhile, a local city uses 2.3 km^3 of water, what is the net change in reservoir storage for the year?

Show all of your math work.

What is the absolute volume of water in storage at the reservoir after the year in question?

III. Physical Properties of Water

A. Can exist in all three physical states: liquid, solid (ice), and gas (water vapor)

B. Transformation Processes related to energy input and entropy of water: heating of water, > atomic activity of the water molecules, i.e. > vibrational energy of water atoms.

1. ICE ----------HEAT----- WATER-------HEAT -------WATER VAPOR
(<32 degrees) (32-212) (>212 degrees F)

C. Water is one of few earth substances that remains in a liquid state at the operating surface temperatures of the earth.

1. The liquidity of water makes it a dominant and pervasive component of all earth processes

D. Water has High Heat Capacity- it has a capacity to absorb and hold energy with only a small amount of temperature rise.

1. important for water-based organisms to regulate temperature
2. produces the moderating effects of oceans on climate
    a. oceans = warm residual heat in winter (warms air temp.)
    b. oceans = slow rate of heating in summer (cools air temp.)

E. Water expands in volume when it freezes/ becomes colder, in contrast to majority of substances (which contract when colder)

1. Result Density of ice < Density of water: thus ice floats on water

F. Water strongly influenced by the force of gravity, constantly driven downward, and can possess great erosive/ landscape carving force

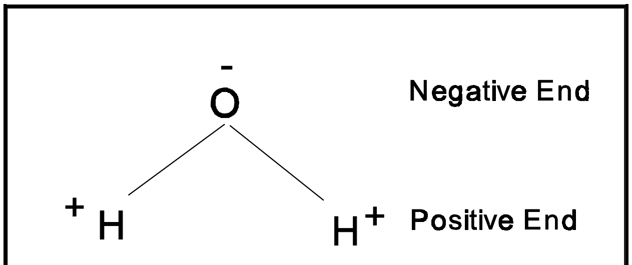
G. Water has property of high surface tension, ability to have strong molecular attractive forces (sticks to itself and electrostatically attracts ionic forms of elements)

1. Capillarity- phenomena of water moving upward against the force of gravity, due to strong electrostatic adhesive forces, most notable in narrow, restricted pore spaces where surface to surface contact in high.

H. Water acts as a "universal solvent" and can dissolve most any substance over time. Water + carbon dioxide forms a mild carbonic acid solution naturally in hydrosphere, as an acid can result in cationic exchange with positive ionic species, and result in chemical breakdown of substances.

1. Bipolar Water Molecule H_2O

2. Covalent bonds between hydrogen and oxygen (strong bond, via sharing of electrons)
    a. Hydrogen: 1 valence electron (atomic no. of 1)
    b. Oxygen: 6 valence electrons (atomic no. of 8)



Bipolar Water Molecule

3. Hydrogen bonds- given a mass of water molecules, the opposite ends will attract molecularly, forming hydrogen bonds
   a. hydrogen bond between molecules is weaker than covalent within molecules
      (1) water mass is fluid, but molecules are difficult to dissociate

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Overview of Physical Properties of Water

A. Temperature-Density-Viscosity Relations

Temp. (C)	Density (gm/cm3)	Viscosity (centipoises)
5	0.999965	1.5188
10	0.997000	1.3097
15	0.999099	1.1447
20	0.998203	1.0087
25	0.997044	0.8949
30	0.995646	0.8004
35	0.99403	0.7208
100	0.95865	

B. Weight Density of Water

at 40 F, weight density = 62.4 lb/ft^3 (1 ft^3 = 7.48 gallons)
at 200 F, weight density = 60.135 lb/ft^3

C. Boiling Points of Water vs. Elevation (atmospheric pressure)

Elevation (ft)	Boiling Point (F)
-1000	213.8
0	121
5000	202.9
10,000	193.7

In-Class Exercise - Examining the Physical Properties of Water

Draw two generalized graphs depicting the relationship between water temperature (x axis) vs. density (y-axis) and viscosity (y-axis).

Describe the general relationships between water temperature, density, and viscosity.

What effect will the temperature-density relationship have on ocean circulation? Discuss and draw a cross-sectional diagram to support your discussion.

How many pounds will 500 gallons of water weigh? Show all of your math work.

If someone were to give you 3000 pounds of water, how many gallons would you have? How many cubic feet? Show all of your math work.

Draw a generalized graph of elevation (y-axis) vs. air pressure (x-axis). On the same graph, but in a different color (or line style), graph the boiling points of water (x-axis). What is the general relationship between elevation, air pressure, and the boiling point of water? Given these relations, what is the temperature of boiling water inside a pressure cooker, compared to that in a sauce pan on the stove?

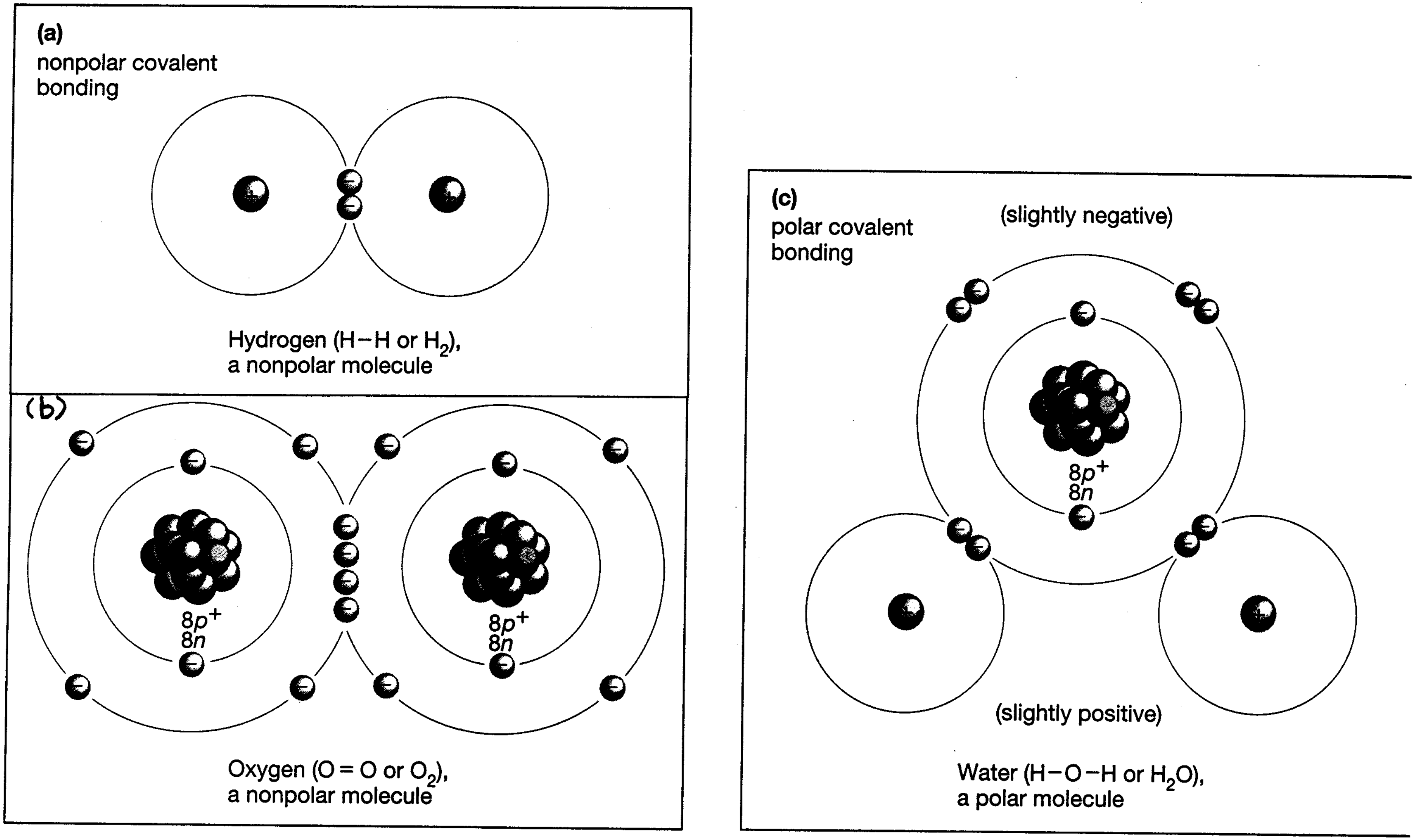

***Figure 2-4** Covalent bonds*

Electrons are shared between atoms to form covalent bonds. ***(a)*** In hydrogen gas, one electron from each hydrogen atom is shared, forming a single covalent bond. The resulting molecule of hydrogen gas is represented as H–H or H_2. ***(b)*** In oxygen gas, two oxygen atoms share four electrons, forming a double bond (O=O or O_2). ***(c)*** Oxygen lacks two electrons to fill its outer shell, so oxygen can make two single bonds, one with each of two hydrogen atoms to form water (H–O–H or H_2O). Oxygen exerts a greater pull on the electrons than does hydrogen, so the oxygen end of the molecule has a slight negative charge and the hydrogen end has a slight positive charge. This is an example of polar covalent bonding. The water molecule with its slightly charged ends is called a polar molecule.