Soil Phases

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Today’s Lecture

- **Basic properties of the soil's solid, liquid, and gas phases**
  - Read all of Notes 1.pdf (18 pages)
- **Water saturation in soils**
  - Read pages 1-2 of Notes 2.pdf (stop at §1.2).

In Moodle you can find also a list of terms with English-French translation and self-check material for Notes 1.

(These notes are based on: Or, Tuller, & Wraith, 1994-2018, Vadoze Zone Hydrology / Environmental Soil Physics)

Soil physics

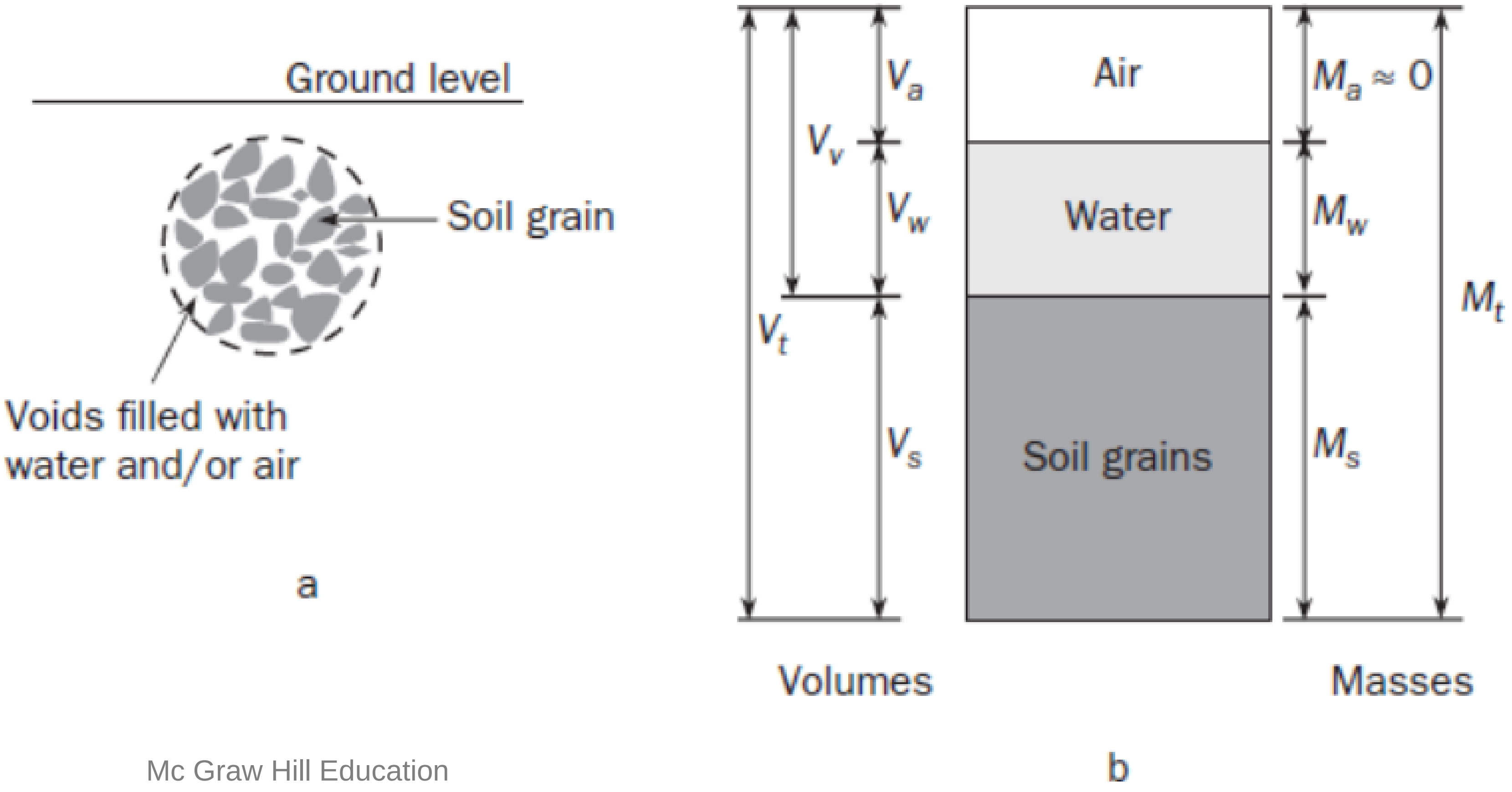
Soil physics is concerned with the application of physical principles to:

- characterize **soil properties** (e.g., *particle and pore size distributions, water retention and hydraulic conductivity, thermal capacity*);
- describe a variety of **dynamic processes** occurring in soils (e.g., *water infiltration, solute transport, heat flow, soil-plant-atmosphere interactions*).

Soil as a three-phase system:

1. the **solid** phase constitutes the soil matrix
2. the **liquid** phase consists of soil water or soil solution (water + dissolved substances)
3. the **gaseous** phase or soil air

Soil phases



Mc Graw Hill Education

Volume and mass relations

- **Density of Solids (Masse volumique réelle, kg/m³):**

$$\rho_s = \frac{M_s}{V_s}$$

Density is mass per unit volume. In many mineral soils the mean particle density is about 2600 to 2700 kg/m^3 (2.6 to 2.7 g/cm^3). Note, the value for water is approx. 1000 kg/m^3

- **Dry Bulk Density (Masse volumique sèche, kg/m³):**

$$\rho_b = \frac{M_s}{V_t}$$

The value of ρ_b is affected primarily by the structure and texture of a given soil, including aggregation and particle size distribution. If the pores constitute half the bulk volume, ρ_b is one-half ρ_s, or 1300 to 1350 kg/m^3

Volume and mass relations

- **Porosity (Porosité totale, -):**

$$n = \frac{V_v}{V_t} = \frac{V_a + V_w}{V_s + V_a + V_w}$$

The porosity indicates relative pore volume in the soil and its value generally lies in the range **0.3 to 0.6**, with coarse-textured soils tending to have less total pore space than fine-textured soils

- **Void ratio (-):**

$$e = \frac{V_v}{V_s} = \frac{V_a + V_w}{V_s} = \frac{V_v}{V_t - V_s}$$

A fundamental difference between void ratio and porosity is that changes in pore volume are related to a fixed quantity (Vs) in the denominator for void ratio, whereby both numerator and denominator (Vt) change simultaneously for porosity.

Volume and mass relations

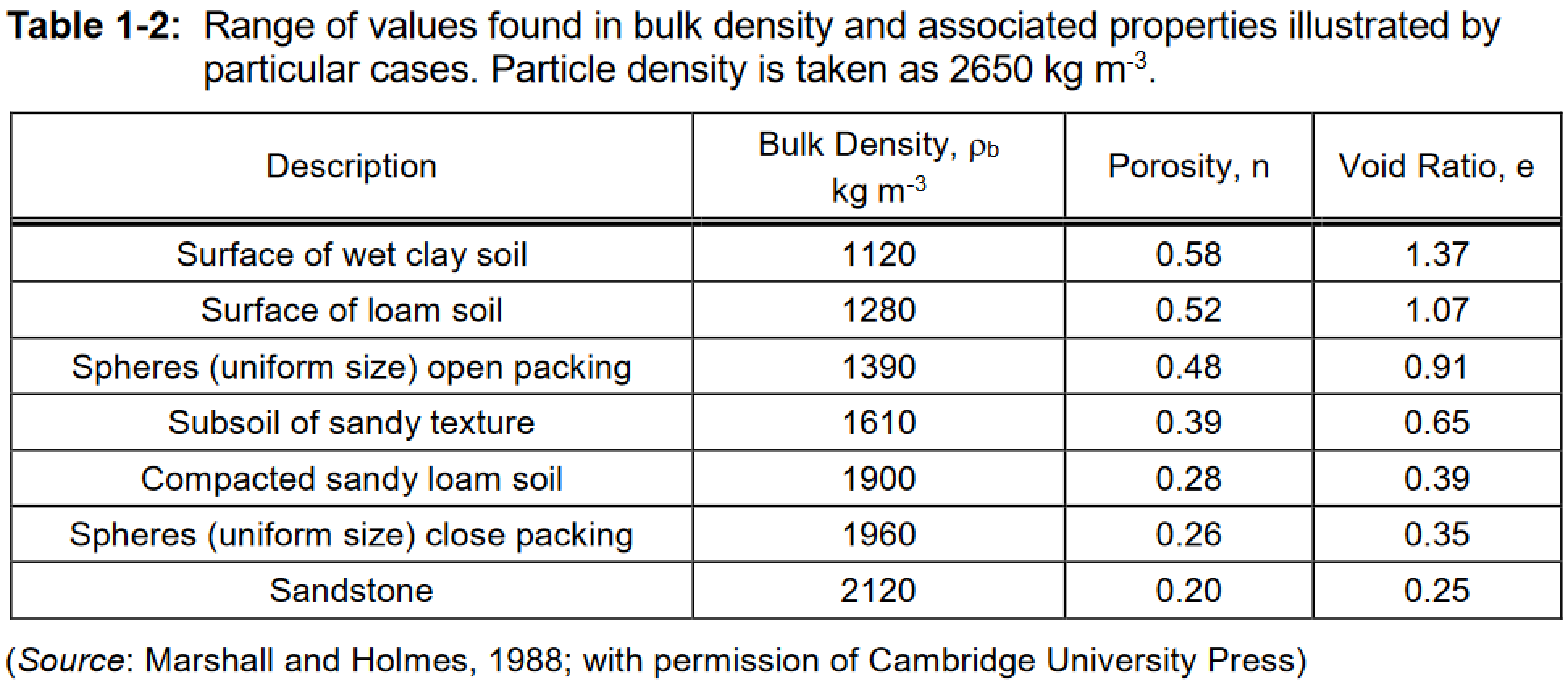


Table 1-2: Range of values found in bulk density and associated properties illustrated by particular cases. Particle density is taken as 2650 kg m^{-3}.

Description	Bulk Density, ρ_b kg m^{-3}	Porosity, n	Void Ratio, e
Surface of wet clay soil	1120	0.58	1.37
Surface of loam soil	1280	0.52	1.07
Spheres (uniform size) open packing	1390	0.48	0.91
Subsoil of sandy texture	1610	0.39	0.65
Compacted sandy loam soil	1900	0.28	0.39
Spheres (uniform size) close packing	1960	0.26	0.35
Sandstone	2120	0.20	0.25

(*Source*: Marshall and Holmes, 1988; with permission of Cambridge University Press)

From: Or, Tuller, & Wraith, 1994-2018

Volume and mass relations

- **Water content (-):**
  - Mass Basis (gravimetric water content): $\theta_m = \frac{M_w}{M_s}$
  - Volume Basis (volumetric water content): $\theta_v = \frac{V_w}{V_t} = \frac{V_w}{V_s+V_a+V_w}$
  - Degree of saturation: $S = \frac{V_w}{V_v} = \frac{V_w}{V_a+V_w}$

- **Additional relations:**
  - $e = \frac{n}{1-n}$
  - $\theta_v = S \cdot n$
  - $n = 1 - \frac{\rho_b}{\rho_s}$

- **Other volumetric fractions:**
  - $\varepsilon_s = \frac{V_s}{V_t}$ (solid phase)
  - $\varepsilon_g = \frac{V_a}{V_t}$ (gas phase)
  - $n = \varepsilon_g + \theta_v$

Volume and mass relations

Measurement of the soil dry bulk density ($\rho_b = \frac{M_s}{V_t}$) requires estimation of the dry mass and the volume occupied by the soil. In the **core method**, which is the most commonly used, a cylindrical metal sampler is driven into the soil to remove a known volume of soil (a core) which is then oven-dried at 105ºC to remove non-structural soil water

Source: Or, Tuller, & Wraith, 1994-2018

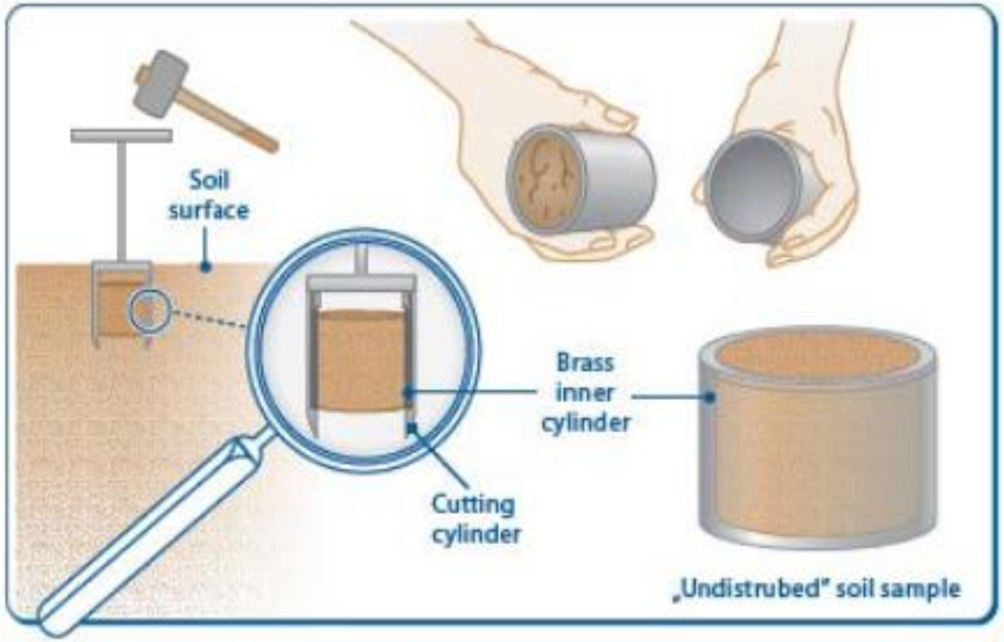


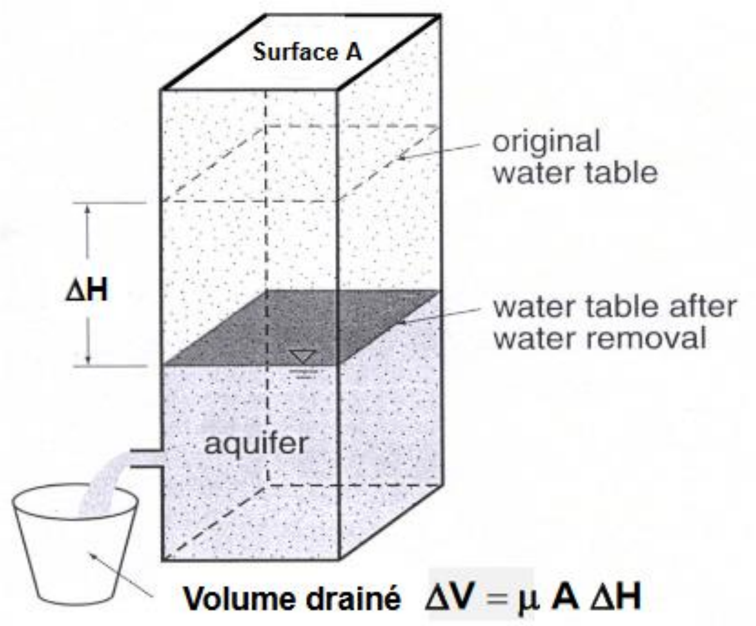
Fig.1-13: Soil sampler for obtaining undisturbed soil cores for bulk density determination.

Volume and mass relations

- **Drainable porosity (Porosité de drainage, -):**

$$\mu = \frac{\Delta V}{A \cdot \Delta H}$$

This is the volume of water drained (by gravity) from a saturated soil per unit of soil volume. For coarse soils, μ is close to the porosity



Note: the soil drains rapidly at first, then more slowly, so the «porosité de drainage» depends on the drainage time if the drainage has not completed. However, after some time no more water will drain (residual water is retained through capillarity – we'll see this in a moment!)

Volume and mass relations

The Representative Elementary Volume

The definitions of mass-volume relationships in a porous medium do not apply below a certain scale of observation. Clearly, the definition of porosity, n, is meaningless for a single void or a single grain of soil. The representative elementary volume (**REV**) is the smallest soil volume for which a property has physical significance.

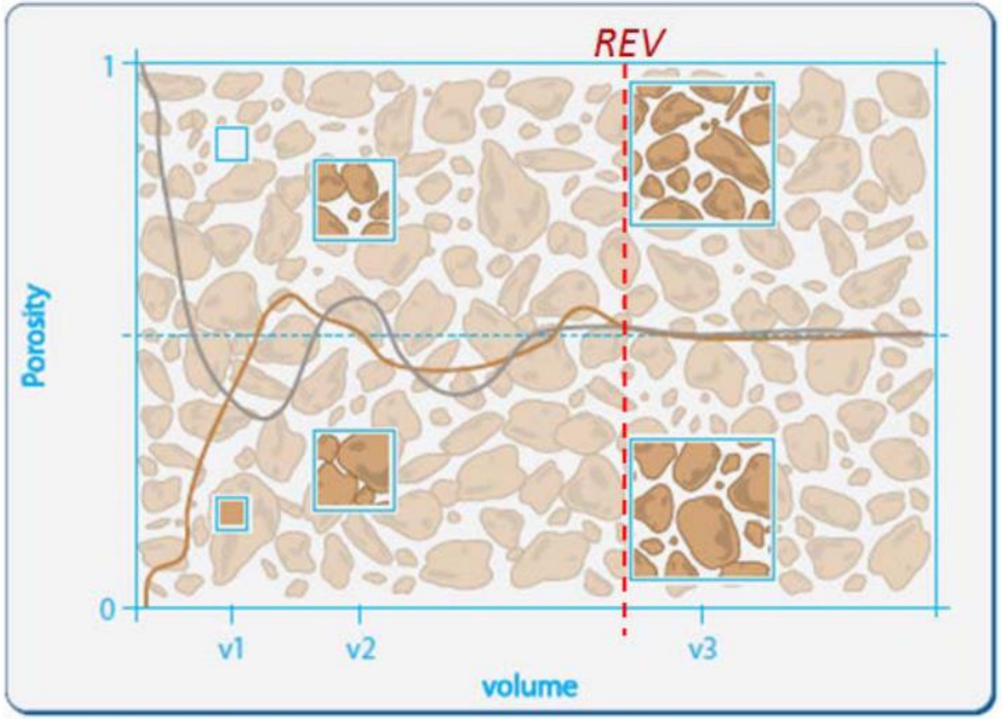


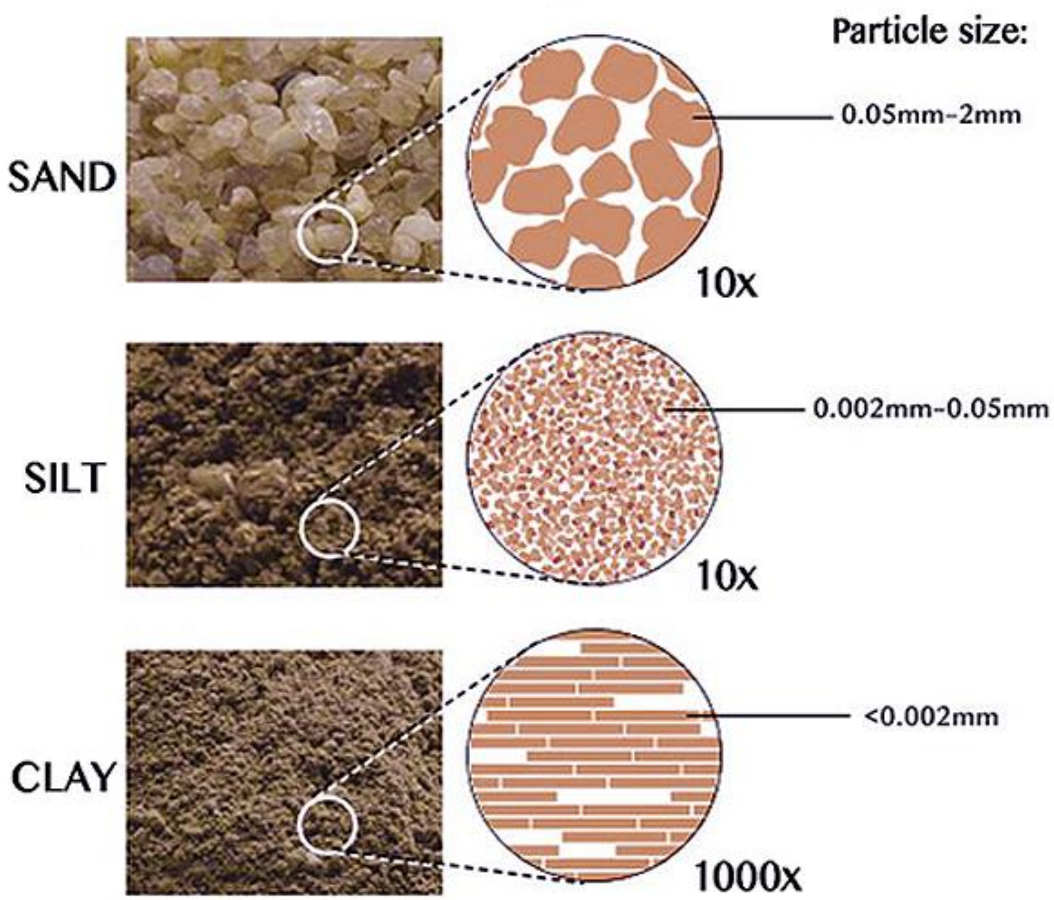
Fig.1-2: Definition sketch for the REV concept illustrating the effect of observation scale on porosity.

Source: Or, Tuller, & Wraith, 1994-2018

Characterization of the solid phase

The most important characteristics of the particles making up the solid phase of a soil are their size distribution and shapes. These attributes affect *pore geometry*, *porosity*, *pore size distribution*, and *total solid surface area* (an important attribute affecting many chemical and physical processes). Specifically:

- The term **soil texture** refers to the **size distribution** an **fractions** of primary soil particles.
- The term **soil structure** refers to the **arrangement** and **organization** of particles and voids is the.



https://theconstructor.org/

Solid phase: soil texture

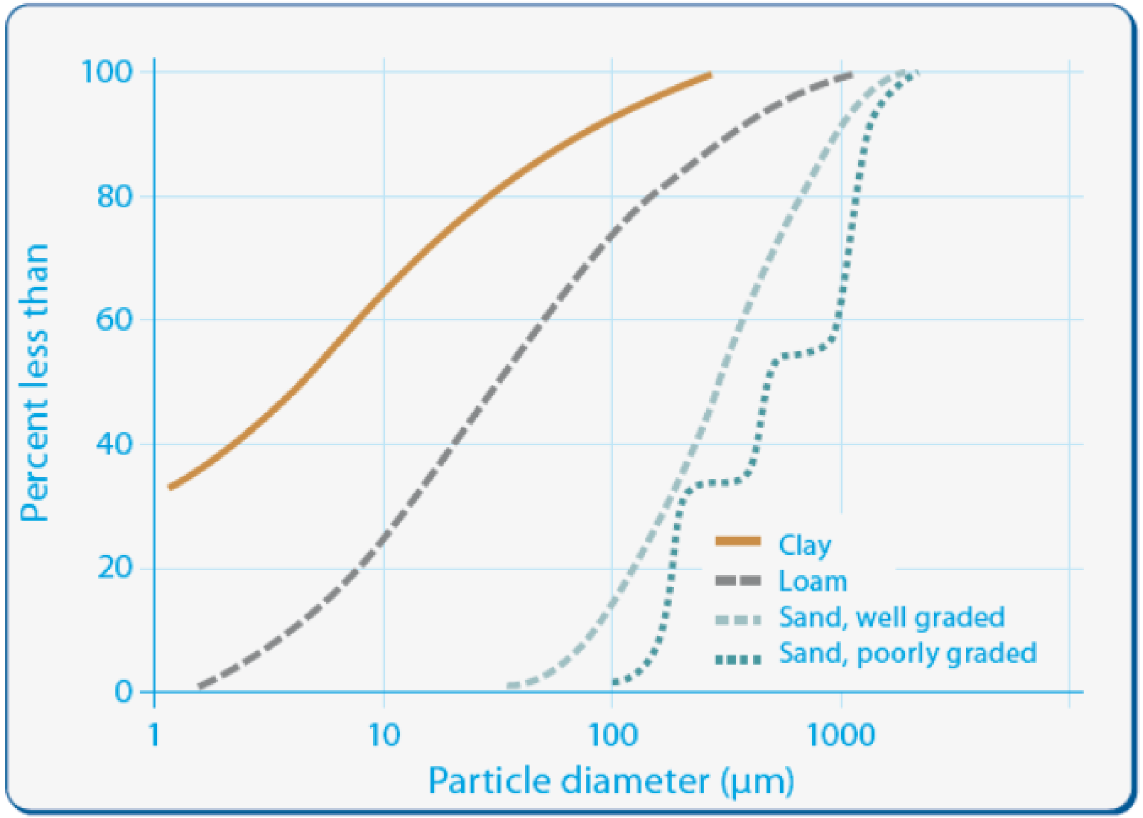


Fig.1-5: (top) Example of particle size distribution versus frequency of occurrence for several soils;

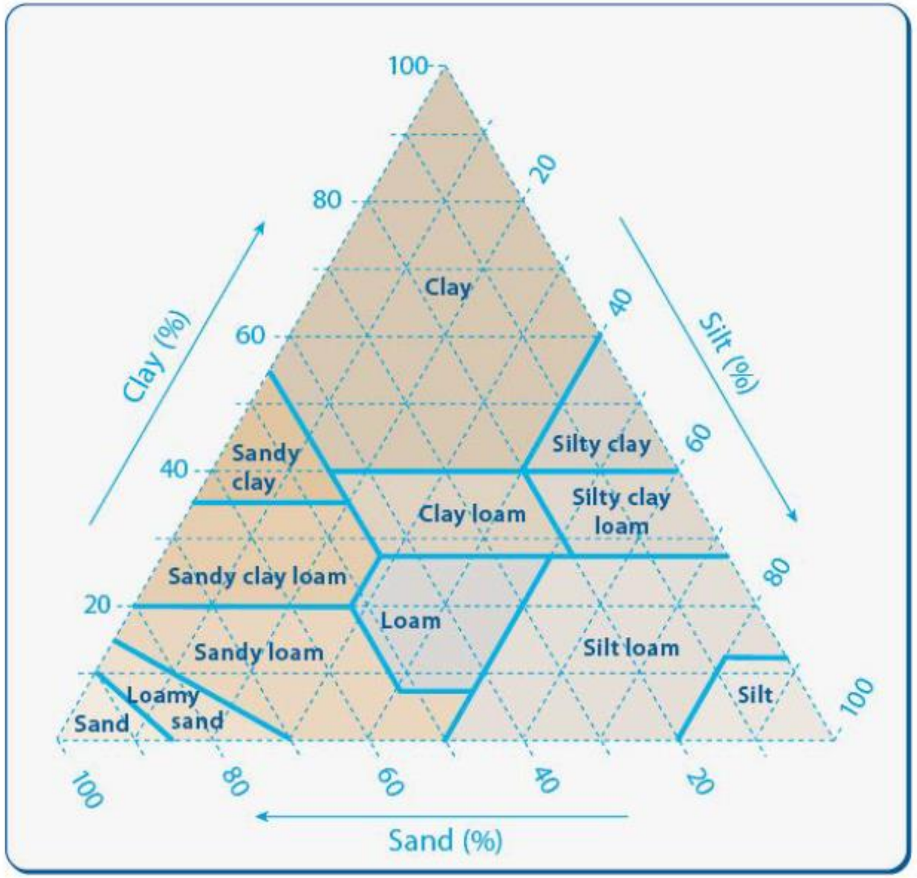
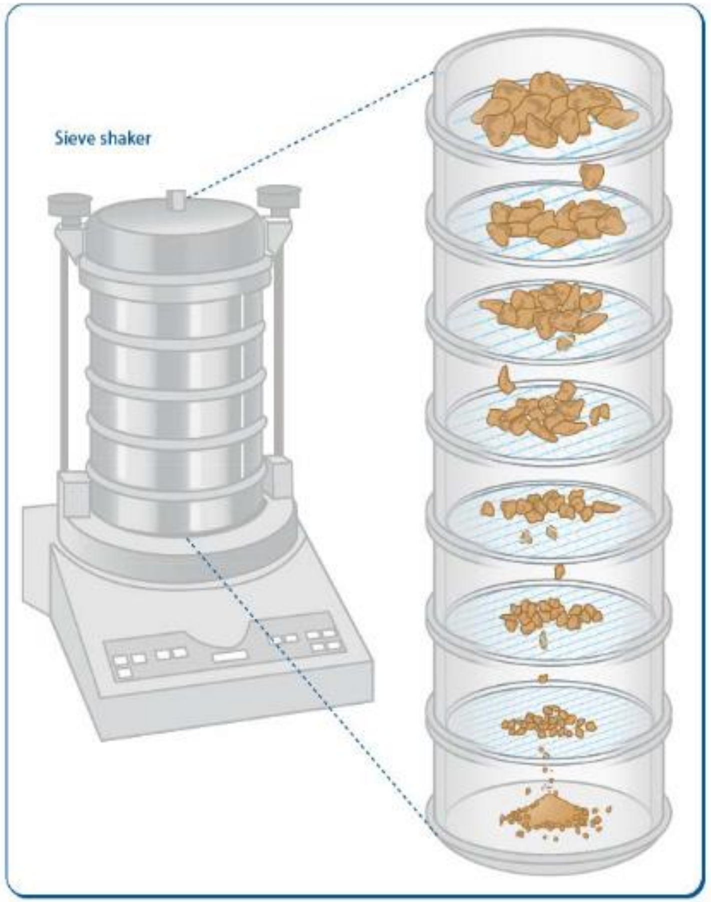


Fig.1-6: Textural triangle showing percentages of clay (< 0.002 mm), silt (0.002 to 0.05 mm), and sand (0.05 to 2.0 mm) in the basic USDA textural classes.

Source: Or, Tuller, & Wraith, 1994-2018

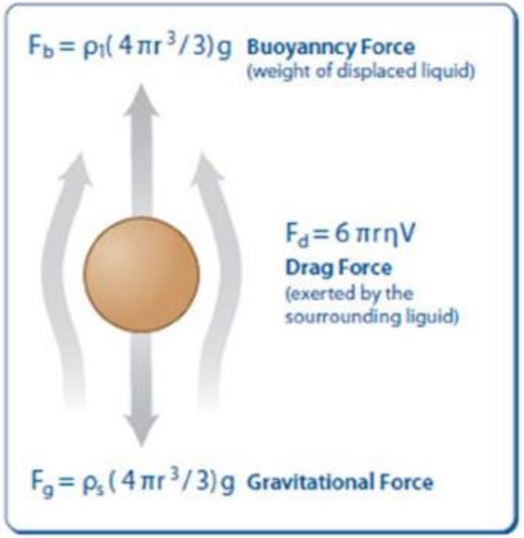
Solid phase: soil texture (example)

Sieving



	Equivalent Particle Diameter [mm]	Weight Passing [g]	Weight Passing [%]
Sieving Weight in % is related to 1 kg	> 4.760	1000	100.0
	4.760	955	95.5
	2.000	840	84.0
	0.840	800	80.0
	0.420	790	79.0
	0.250	690	69.0
	0.147	620	62.0
Hydrometer Weight in % is related to 40 g (related to 1 kg)	0.067	19 (475)	**47.5**
	0.048	17 (425)	**42.5**
	0.028	15 (375)	**37.5**
	0.005	8 (200)	**20.0**
	0.003	6 (150)	**15.0**
	0.002	5 (125)	**12.5**

Sedimentation



Source: Or, Tuller, & Wraith, 1994-2018

Solid phase: soil texture (example)

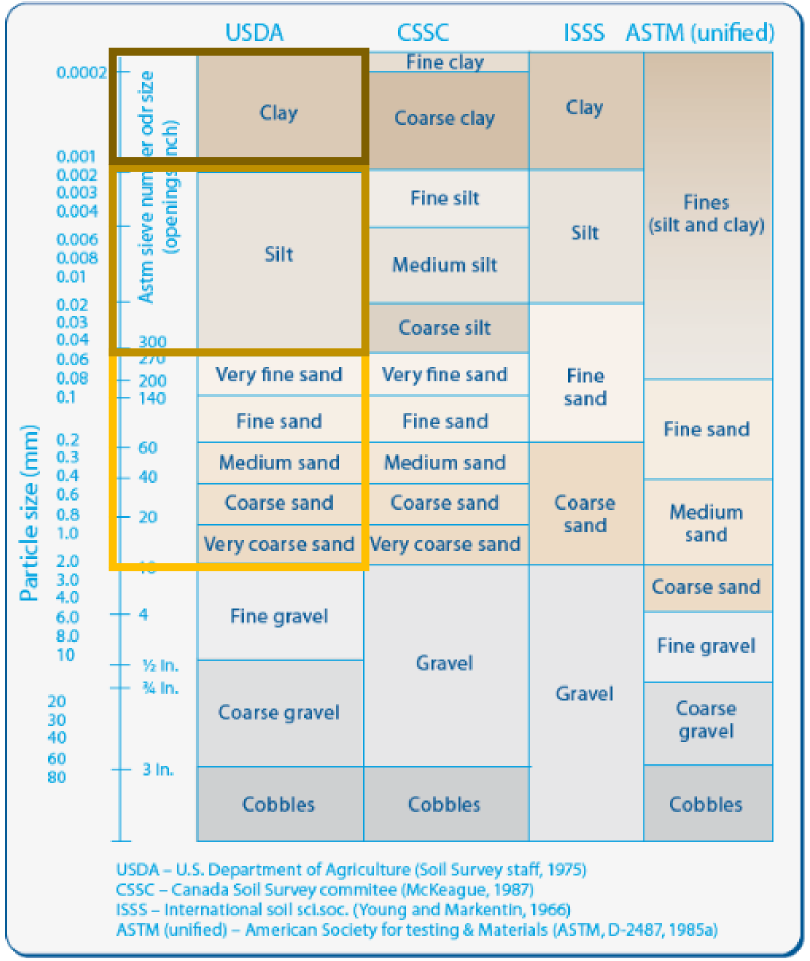


Fig.1-5: (top) Example of particle size distribution versus frequency of occurrence for several soils; (bottom) Summary of common classification schemes

	Equivalent Particle Diameter [mm]	Weight Passing [g]	Weight Passing [%]
Sieving Weight in % is related to 1 kg	> 4.760	1000	100.0
	4.760	955	95.5
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Source: Or, Tuller, & Wraith, 1994-2018

From the table we find:

Sand [%]:
84.0 - 42.5 = 41.5%

Silt [%]:
42.5 - 12.5 = 30.0%

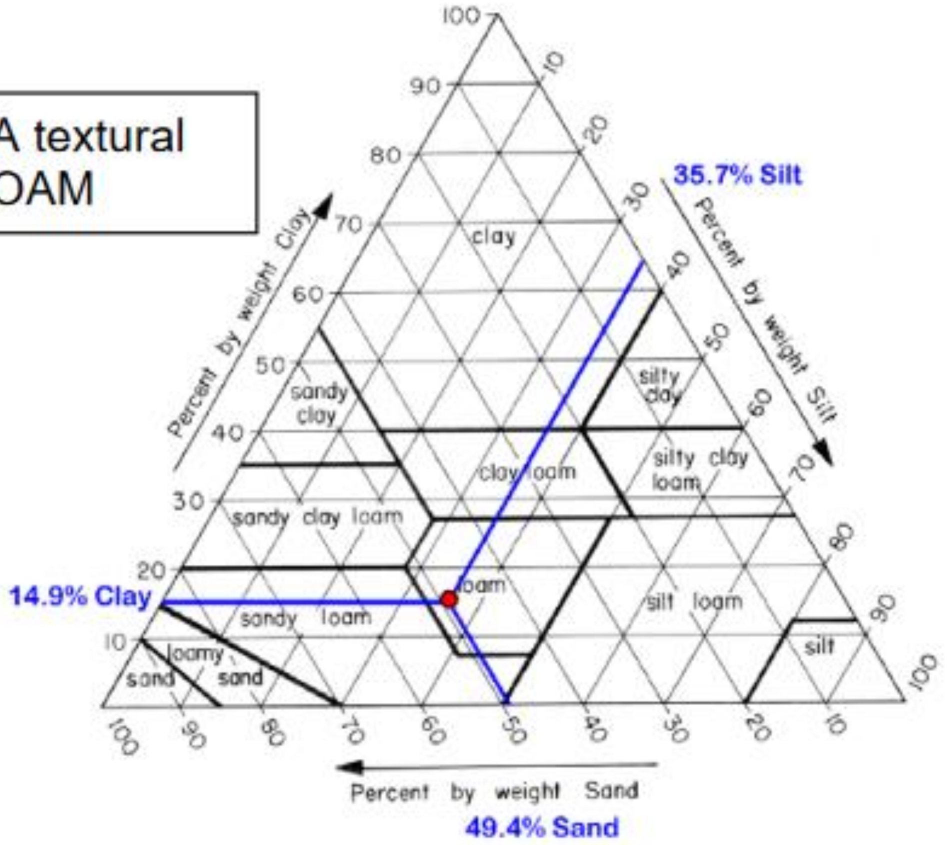
Clay [%]:
12.5%

Solid phase: soil texture (example)

The USDA soil textural classification only takes into account the particle fractions smaller than 2 mm. Since 16% of the particles of our sample are larger 2 mm (100-84=16, see table), we have to modify the values calculated before:

Sand [%] = 41.5 * (100 / 84) = **49.4**
Silt [%] = 30.0 *(100 / 84) = **35.7**
Clay [%] = 12.5 *(100 / 84) = **14.9**

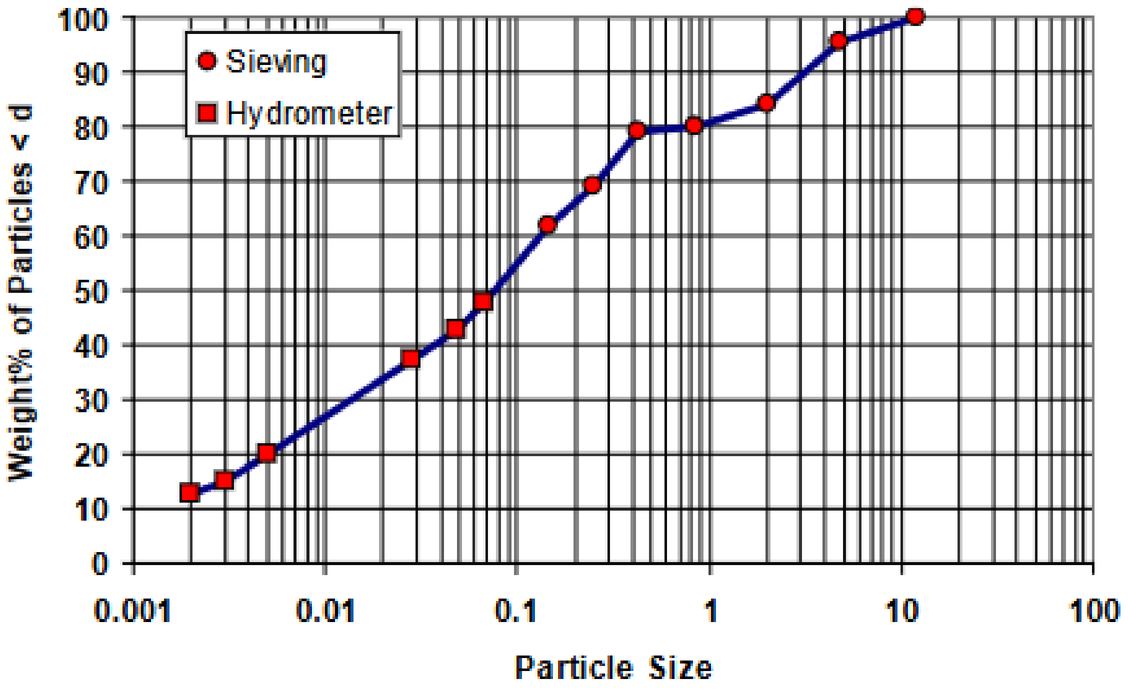
The USDA textural class is LOAM



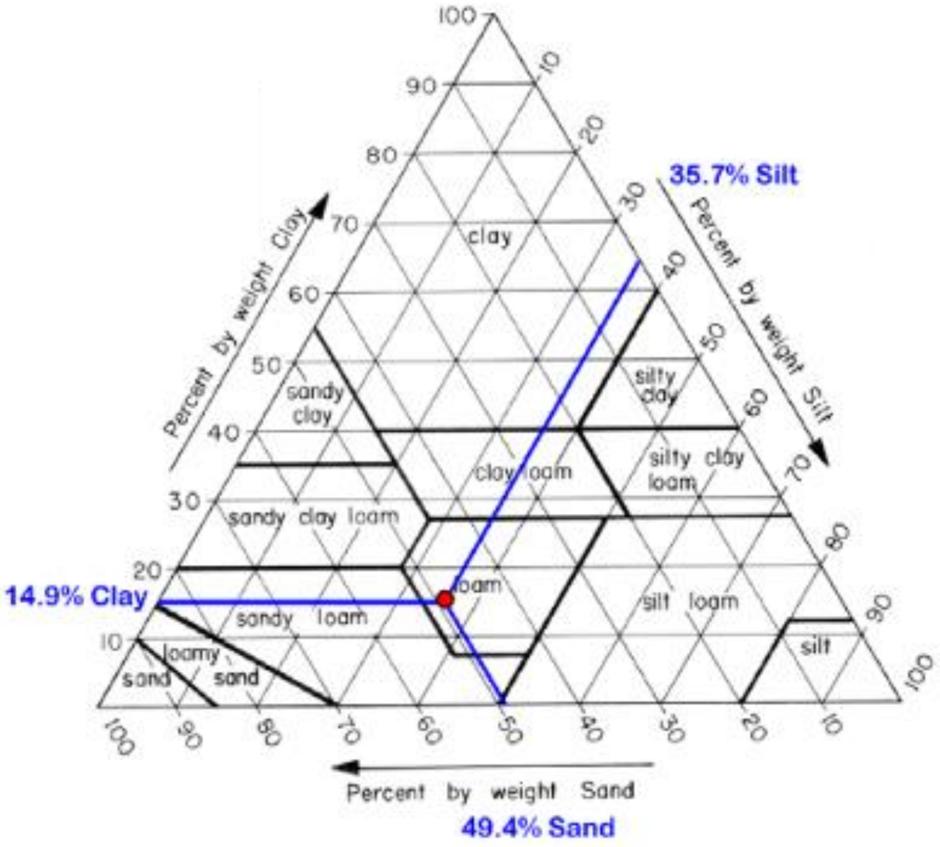
Source: Or, Tuller, & Wraith, 1994-2018

Solid phase: soil texture (example)

Particle size distribution diagram



USDA textural class



Source: Or, Tuller, & Wraith, 1994-2018

Solid phase: soil texture description (example)

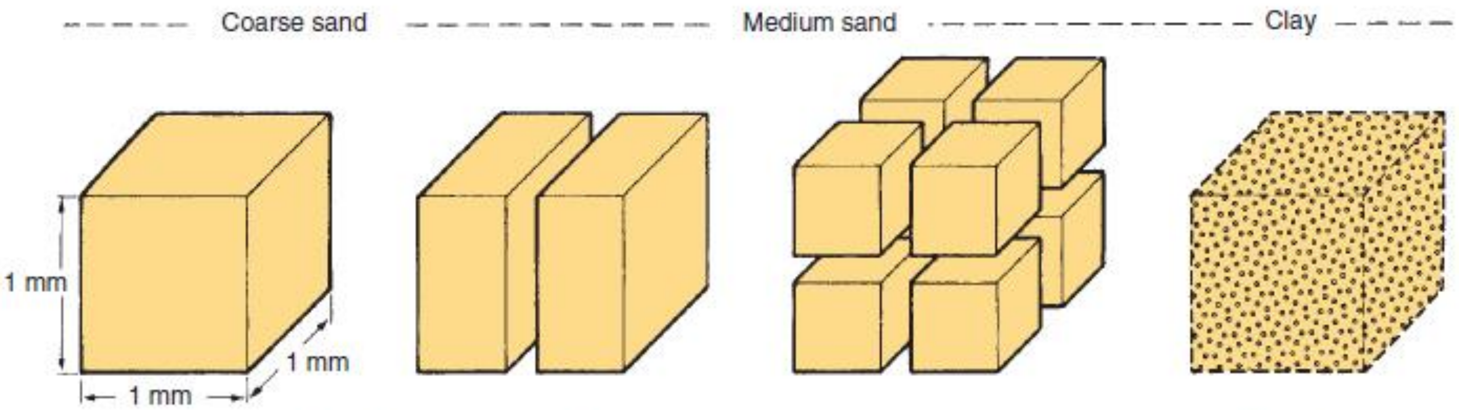
- **Sands** feel gritty to the touch and are not sticky. When moist, sands will form a very weak cast, as if molded by the hand, that crumbles when touched
- **Loam** tends to be rather soft and friable. It has a slightly gritty feel, yet is fairly smooth and slightly sticky and plastic when moist. Casts formed from such soils can be handled quite freely without breaking
- **Silt**, when moistened, feels smooth and rather silky. Silt-sized particles are somewhat plastic, and casts can be formed that will bear careful handling
- **Clay** usually forms extremely hard clods or lumps when dry and is extremely sticky and plastic when wet. When containing the proper amount of moisture, it can be “ribboned out” to a remarkable degree by squeezing between thumb and forefinger, and may be rolled into a long, very thin wire

Self-Study

Solid phase: specific surface area

Surface Area of Soil Particles (surface spécifique)

The specific surface area of soil particles may be defined as total surface area per unit of mass (A_m), per unit volume of particles (A_p), or per unit volume of soil (A_s). The specific surface area of a soil is a very important physical property affecting **soil hydraulic properties** and the **adsorption and release of minerals and chemical pollutants**.



Volume	1 mm^3	1 mm^3	1 mm^3	1 mm^3
No of pieces	1	2	8	1000 million
Total surface area	6 mm^2	8 mm^2	12 mm^2	6000 mm^2

https://biocyclopedia.com/

Solid phase: specific surface area

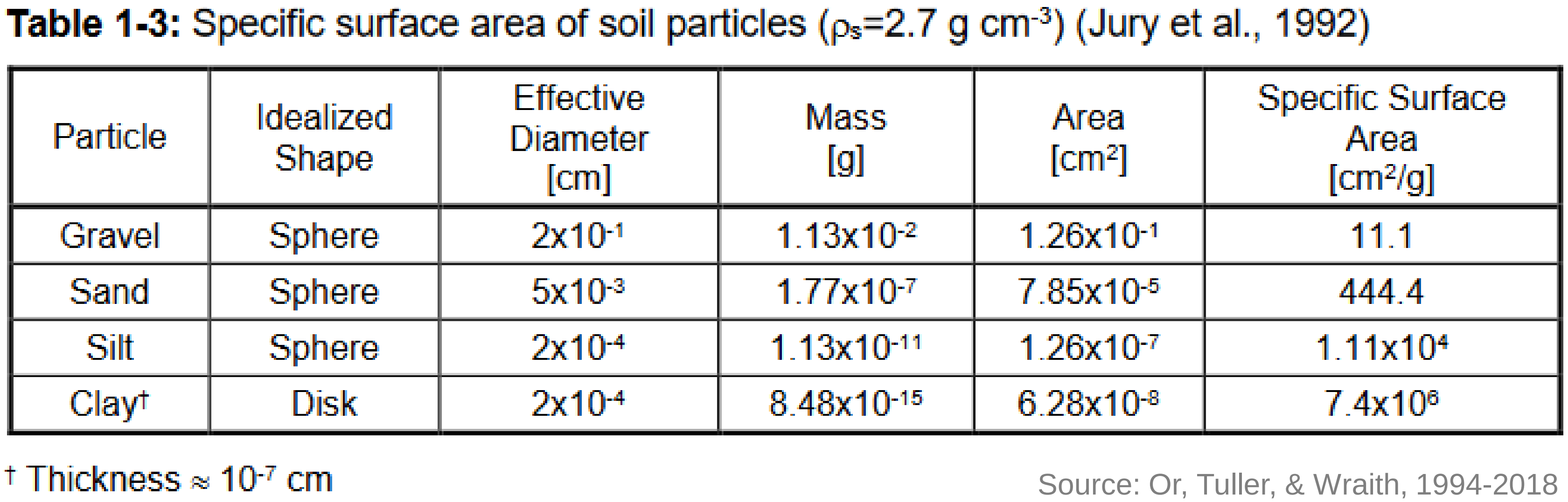


Table 1-3: Specific surface area of soil particles (ρ_s=2.7 g cm^{-3}) (Jury et al., 1992)

Particle	Idealized Shape	Effective Diameter [cm]	Mass [g]	Area [cm^2]	Specific Surface Area [cm^2/g]
Gravel	Sphere	2x10^{-1}	1.13x10^{-2}	1.26x10^{-1}	11.1
Sand	Sphere	5x10^{-3}	1.77x10^{-7}	7.85x10^{-5}	444.4
Silt	Sphere	2x10^{-4}	1.13x10^{-11}	1.26x10^{-7}	1.11x10^{4}
Clay†	Disk	2x10^{-4}	8.48x10^{-15}	6.28x10^{-8}	7.4x10^{6}

† Thickness ≈ 10^{-7} cm

Source: Or, Tuller, & Wraith, 1994-2018

Solid phase: specific surface area

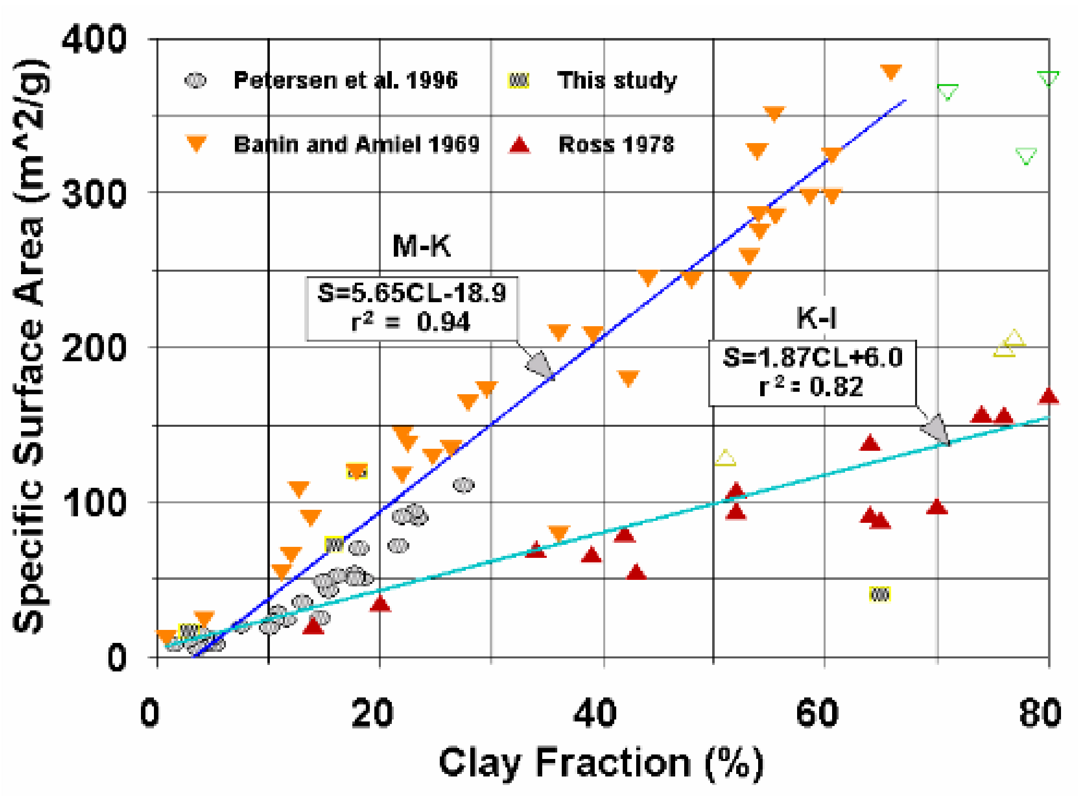


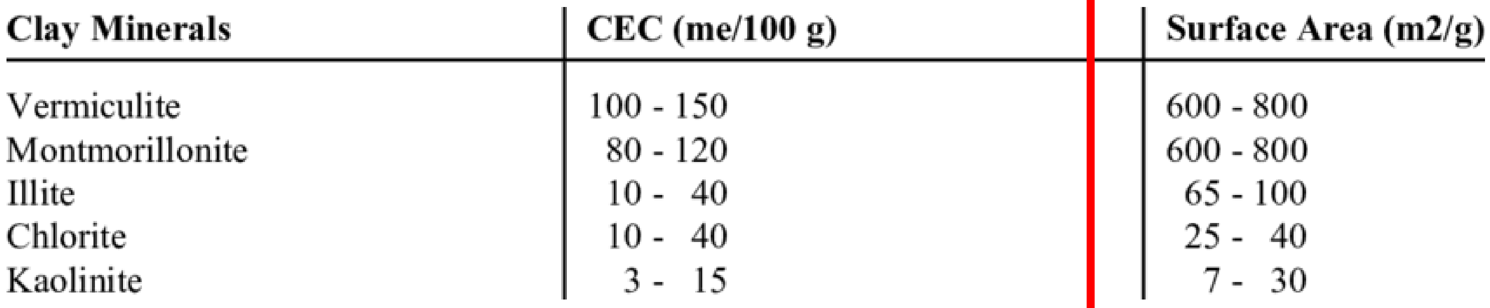
Fig.1-9: Relationships between soil specific surface area and clay fraction. The M-K curve is fitted to soils whose clay fraction is a mixture of montmorillonite-kaolinite. The K-I curve is for soils with kaolinite-illite dominated clay fraction. (Or and Wraith, 1999b).

Source: Or, Tuller, & Wraith, 1994-2018

Solid phase: specific surface area

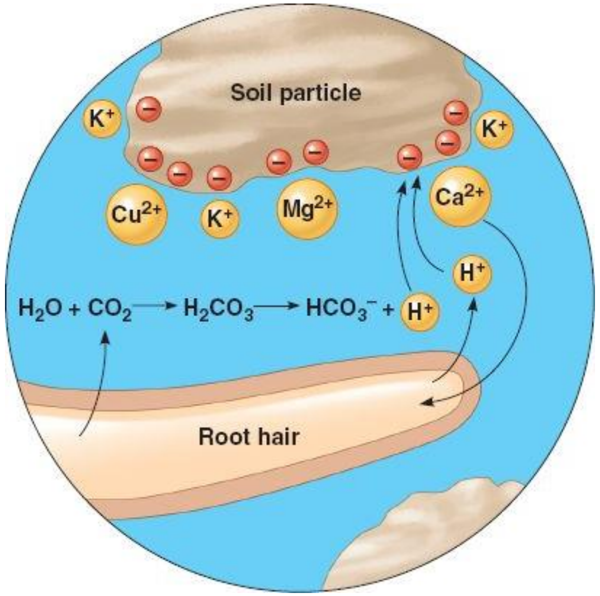
Cation-exchange capacity (**CEC**) is a measure of how many cations can be retained on soil particle surfaces.[1] Negative charges on the surfaces of soil particles bind positively-charged atoms or molecules (cations) but allow these to exchange with other positively charged particles in the surrounding soil water. CEC affects many aspects of soil chemistry, and is used as a measure of soil fertility, as it indicates the capacity of the soil to retain several nutrients (e.g. K^+, NH_4^+, Ca^{2+}) in plant-available form. It also indicates the capacity to retain pollutant cations (e.g. Pb^{2+}).

https://en.wikipedia.org/wiki/Cation-exchange_capacity



Clay Minerals	CEC (me/100 g)	Surface Area (m2/g)
Vermiculite	100 - 150	600 - 800
Montmorillonite	80 - 120	600 - 800
Illite	10 - 40	65 - 100
Chlorite	10 - 40	25 - 40
Kaolinite	3 - 15	7 - 30

Katsube et al. (2003)



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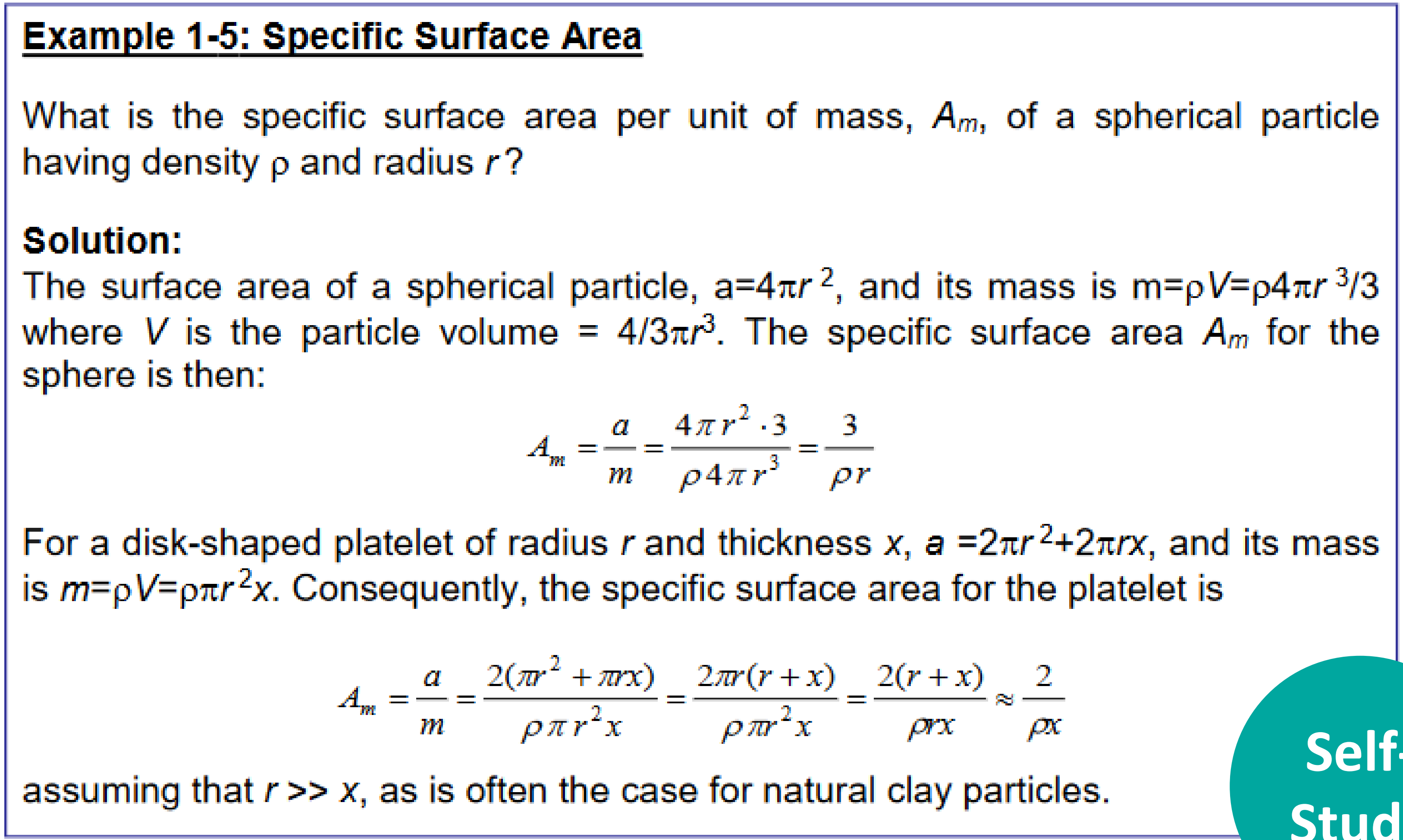
Solid phase: specific surface area



Example 1-5: Specific Surface Area

What is the specific surface area per unit of mass, A_m, of a spherical particle having density ρ and radius r?

Solution:

The surface area of a spherical particle, $a=4\pi r^2$, and its mass is $m=\rho V=\rho 4\pi r^3/3$ where V is the particle volume = $4/3\pi r^3$. The specific surface area A_m for the sphere is then:

$$A_m = \frac{a}{m} = \frac{4\pi r^2 \cdot 3}{\rho 4\pi r^3} = \frac{3}{\rho r}$$

For a disk-shaped platelet of radius r and thickness x, $a=2\pi r^2+2\pi rx$, and its mass is $m=\rho V=\rho\pi r^2 x$. Consequently, the specific surface area for the platelet is

$$A_m = \frac{a}{m} = \frac{2(\pi r^2 + \pi rx)}{\rho \pi r^2 x} = \frac{2\pi r(r+x)}{\rho \pi r^2 x} = \frac{2(r+x)}{\rho rx} \approx \frac{2}{\rho x}$$

assuming that $r >> x$, as is often the case for natural clay particles.

Source: Or, Tuller, & Wraith, 1994-2018

Self-Study

Solid phase: soil structure

Particle arrangement in the bulk soil varies depending upon the texture (i.e., coarse-grained or clayey soil) and ambient conditions (chemical and biological activity, water content, loading history, etc.). Hillel (1980) classifies soil structure into three broad classes:

- **Single grained**: particles are entirely unattached and the structure is loose as in sand dunes;
- **Massive**: tightly packed soil blocks such as dried clay;
- **Aggregated**: where soil particles are associated in small clods or aggregates (peds).

The structure of many untilled soils or deeper layers in tilled soils may not necessarily conform to any of the above classes. It often exhibits considerable **macroporosity** resulting from cumulative effects of **biological activity** (e.g., earthworms, decaying roots, etc. developing over many years)

Source: Or, Tuller, & Wraith, 1994-2018

Solid phase: soil structure

https://soil.evs.buffalo.edu/index.php/Soil_Structures

Solid phase: soil structure (uniform spherical grains)

The relationship between the mode of packing expressed by the angle (σ) and the soil **porosity** (n) is given by (Mayer and Stowe, 1965):

$$n = 1 - \frac{\pi}{6}\left(1 - 3\cos^2\sigma + 2\cos^3\sigma\right)^{-\frac{1}{2}} \qquad 60^\circ \leq \sigma \leq 90^\circ$$

n=0.26
(cubic)

n=0.48
(rhombohedral)

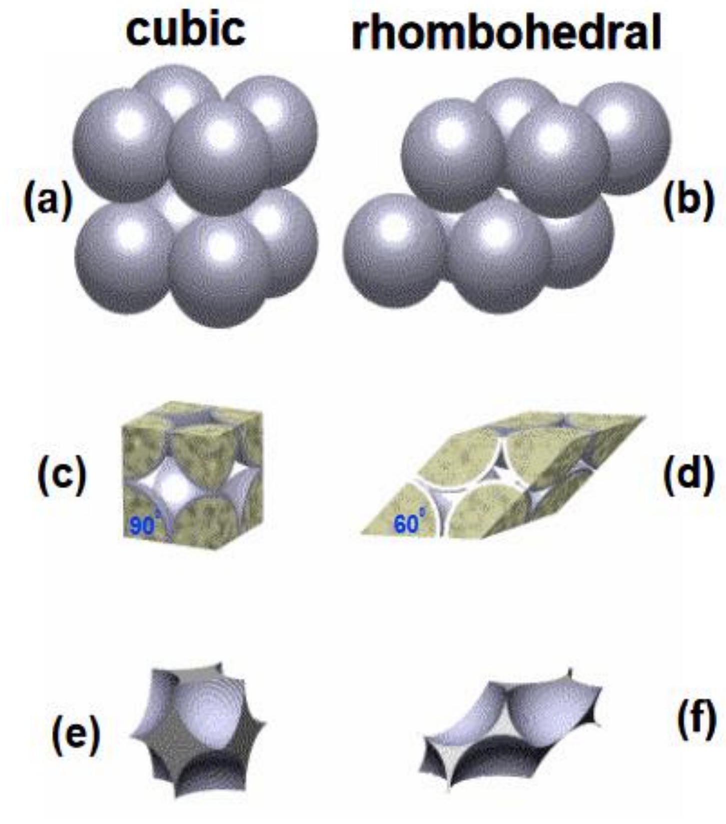


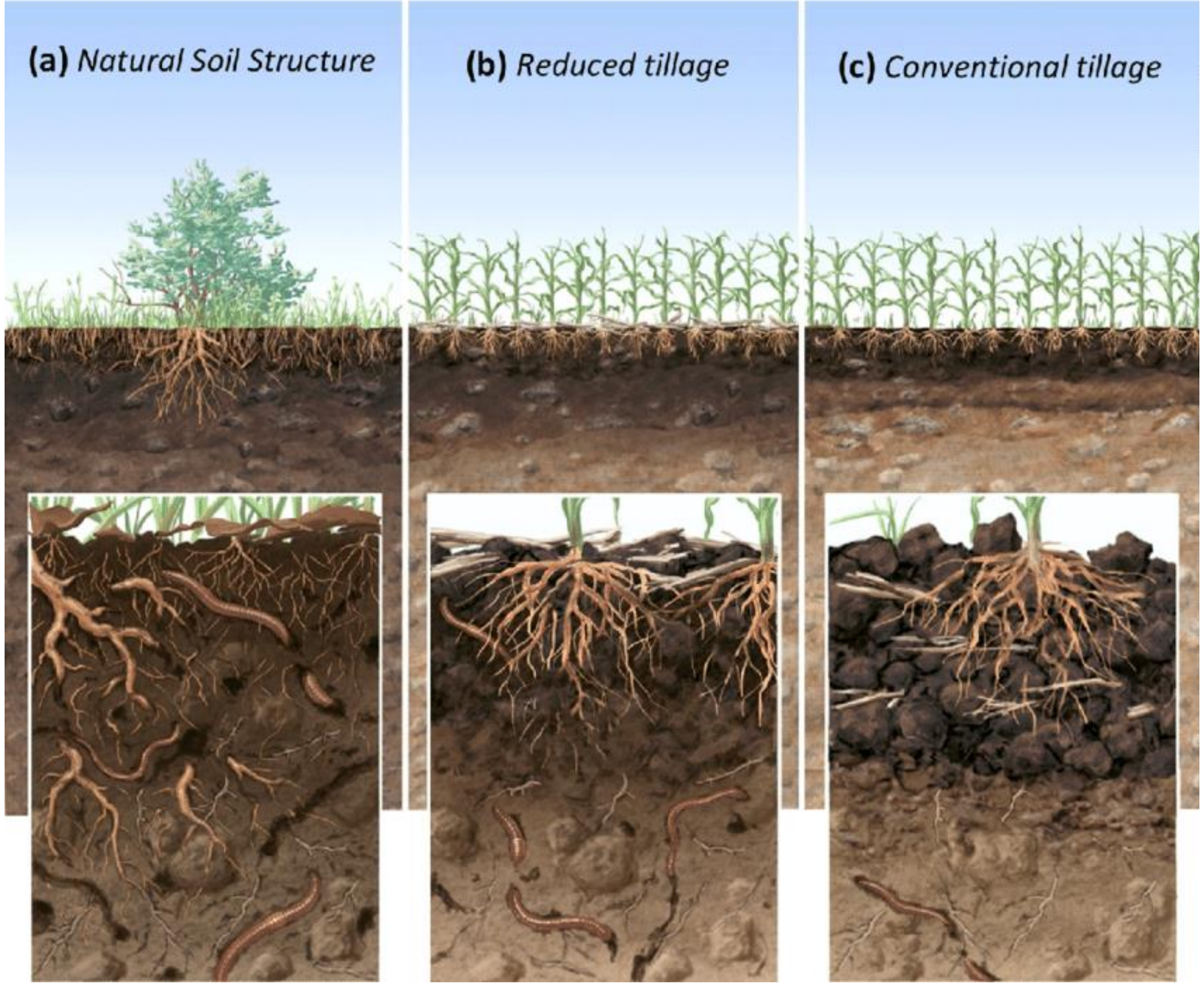
Fig.1-11: Cubic (a) and rhombohedral (b) packing of identical spheres. The unit cells are defined by a rhombohedron with (c) σ = 90° and (d) σ = 60° respectively. The (e) and (f) unit voids for both packing arrangements are also shown (based on Graton and Fraser, 1935).

Source: Or, Tuller, & Wraith, 1994-2018

Solid phase: soil structure

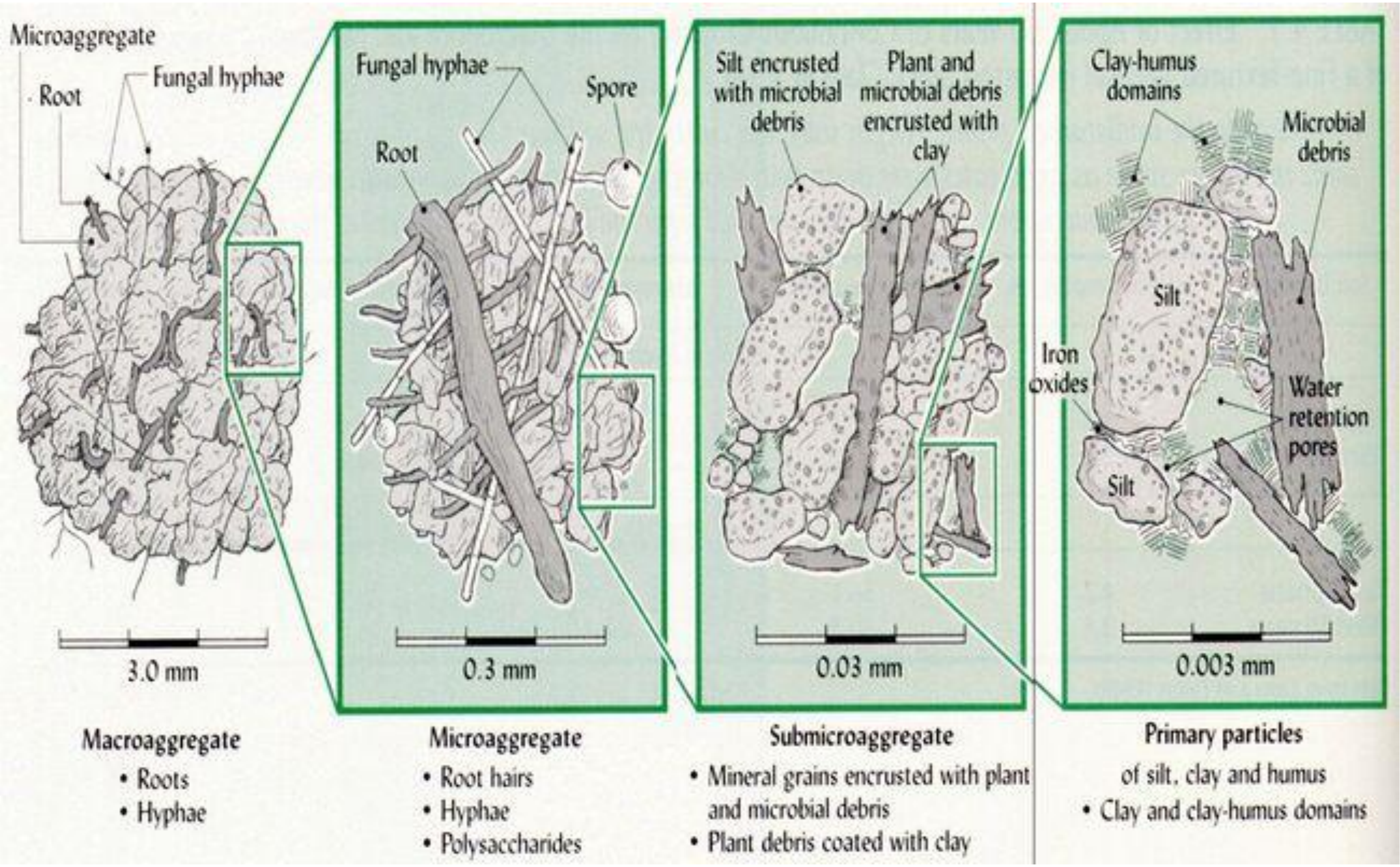
anthropocenemagazine.org

Solid phase: soil structure



A sketch of natural and managed soil structure characteristics
(Source: Or et al., 2021, Soil and Tillage Research)

Solid phase: soil structure



Soil Microaggregates. Note the influence of root fibers, hyphae, and microbial debris. Image From Tisdall & Oades, 1982. Source: https://soil.evs.buffalo.edu/index.php/Soil_Structures

Liquid phase: water properties

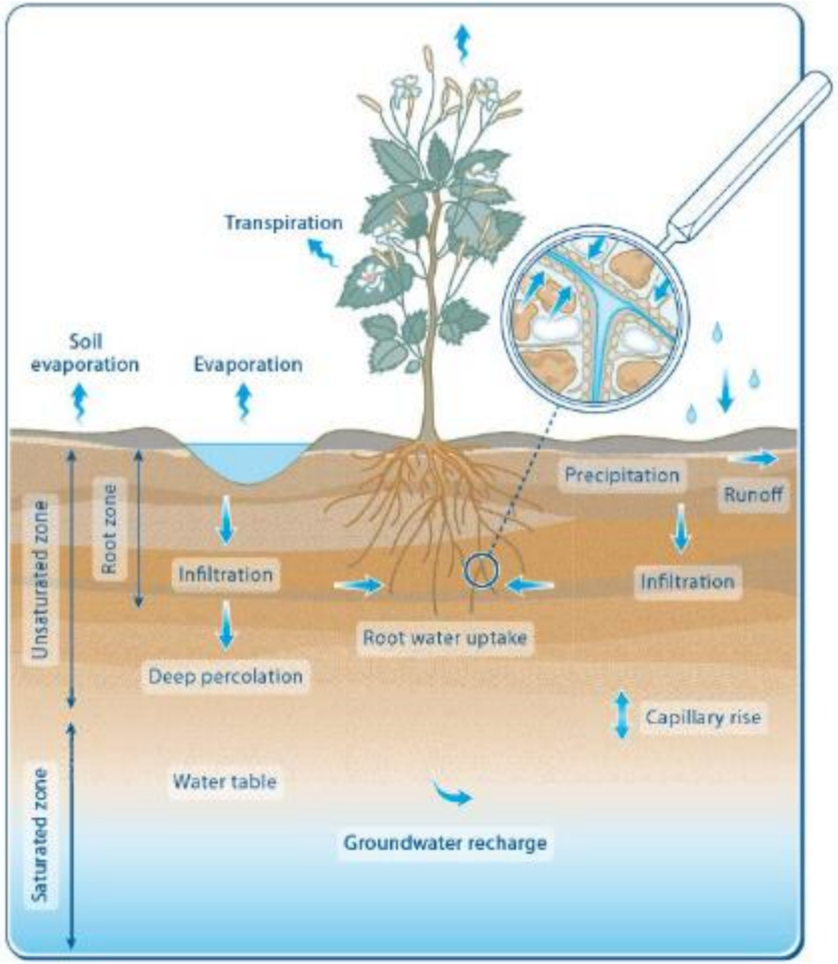


Fig.1-19: Components of the local-scale water balance.

Source: Or, Tuller, & Wraith, 1994-2018

“Our planet is the planet of life primarily because it is blessed with the precise ranges of temperature and pressure that make possible the existence in the liquid state of a singular substance called water”

Hillel, 2003

“Life is animated water”

Vladimir Vernadsky

“Thousands have lived without love, no one has lived without water”

W. H. Auden

Liquid phase: water properties

One cubic meter of liquid water at 20°C contains some 3.4×10^{28} (34 billion billion billion) molecules, the diameter of which is about 3×10^{-10} meter (3×10^{-4} micrometers (μm), or 3 angstrom units).

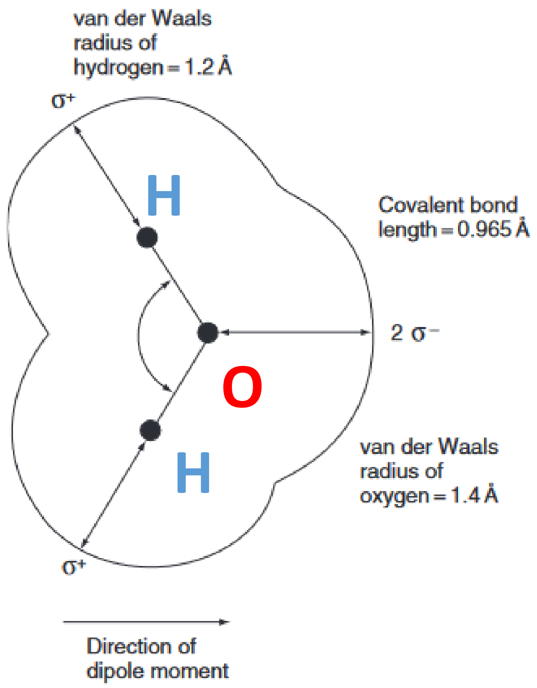
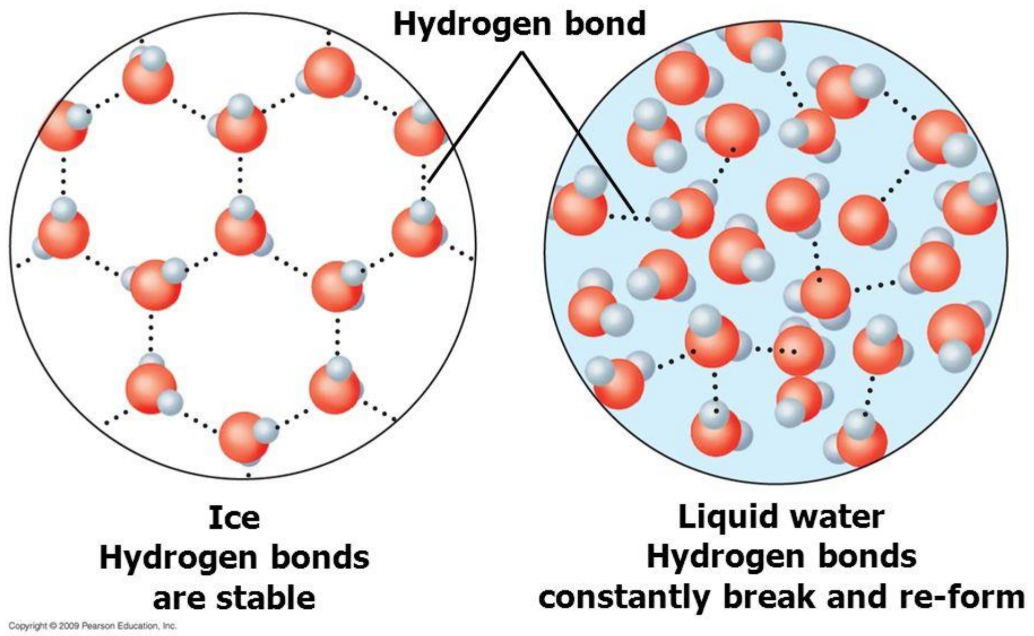


Fig. 2.1. Model of a water molecule. The curved lines represent the borders at which van der Waals attractions are counterbalanced by repulsive forces.

Hillel (2003)

Liaison (pont) hydrogène



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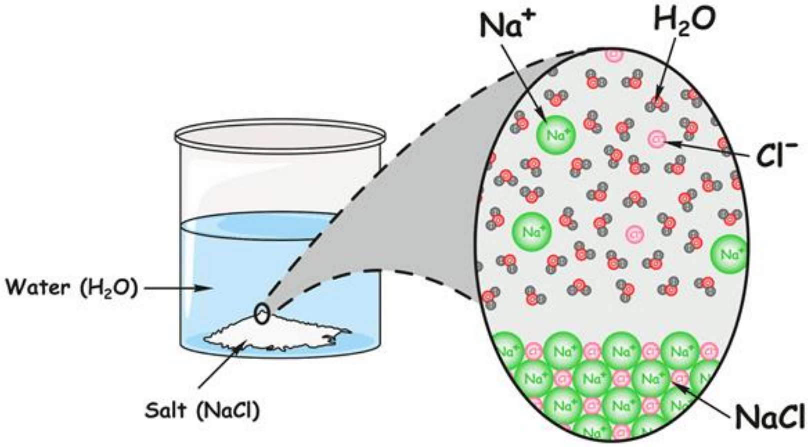
Liquid phase: water properties

The dielectric constant (ε) influences the intensity of the attractive forces between ions. Consider two ions with electric charges e_1 and e_2 of opposite sign and at distance d. Then, according to the **Coulomb's law** there is an attractive force F equal to:

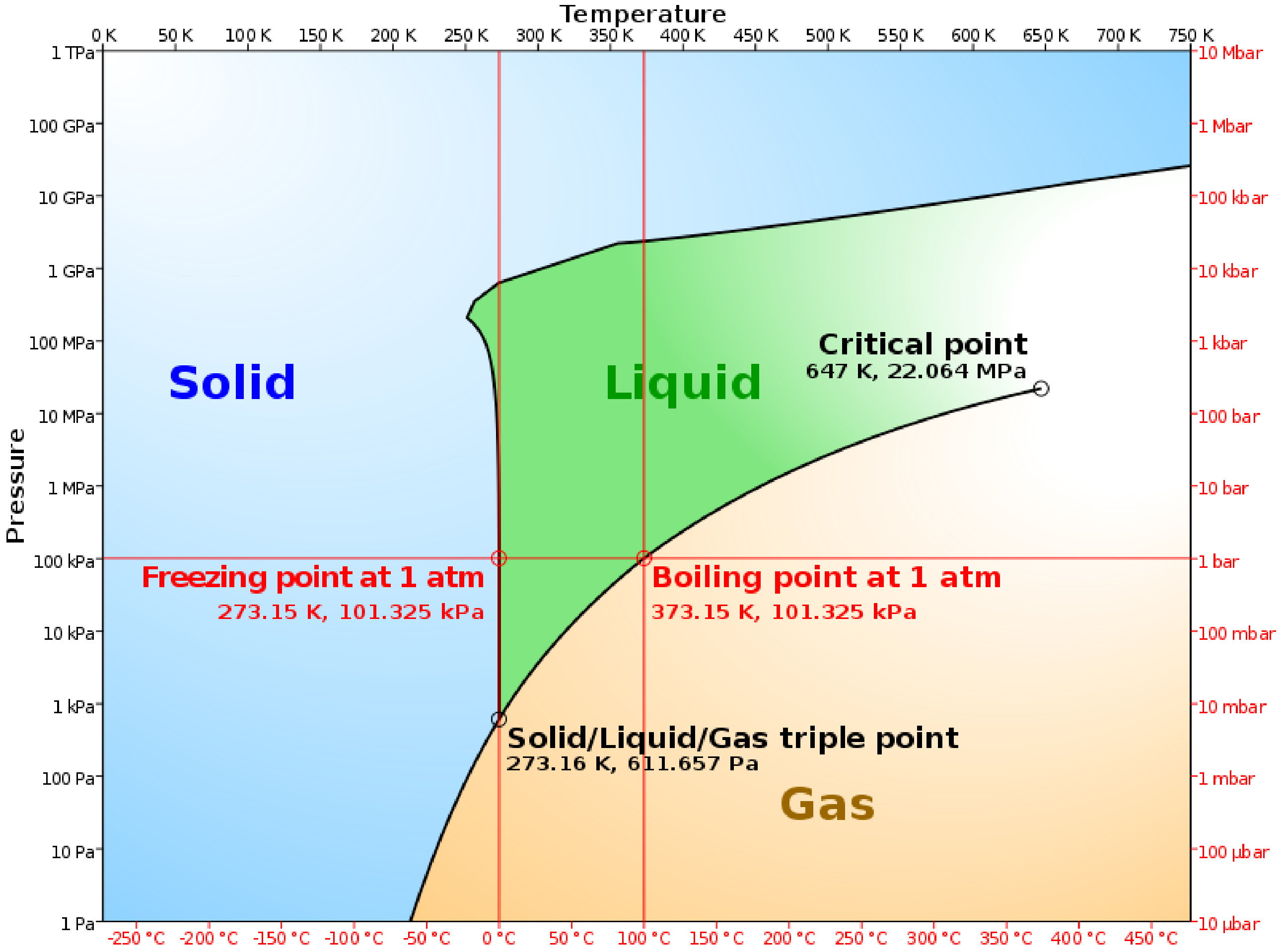
$$F = \frac{K}{\varepsilon} \cdot \frac{e_1 \cdot e_2}{d^2}$$

At 25°C, the dielectric constant of **water** is **80.4**, that of benzene is 2.28 and that of dry soil varies from 3 to 5. The high value of the dielectric constant of water (a polar substance) is at the root of its **solvent properties**. For example, ions of opposite signs are subject to an attraction force approximately 40 times smaller in water than in benzene (a non-polar substance). This facilitates significantly the hydration of ions and the dissolution of salts in water.



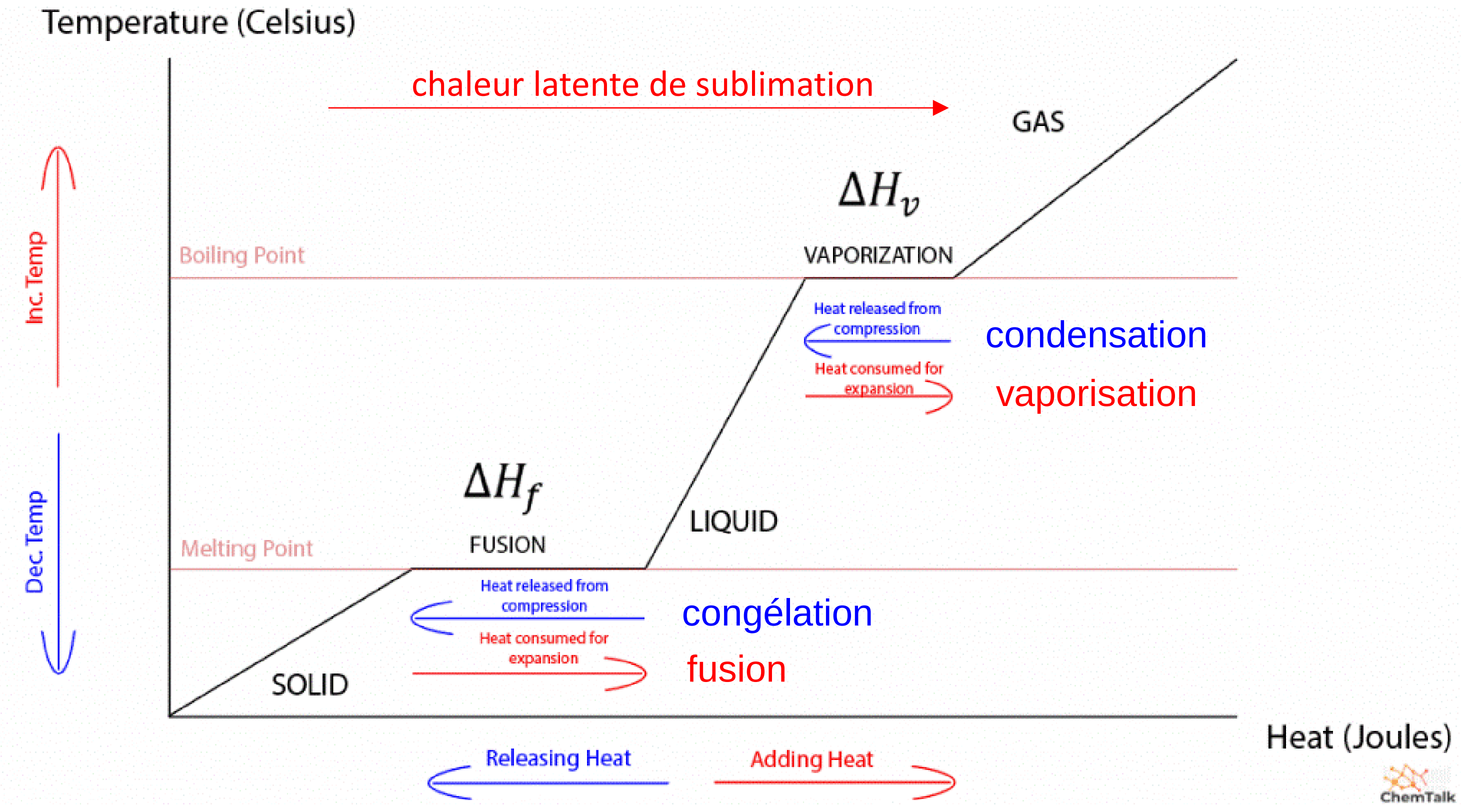
Dissolution of Sodium Chloride

Liquid phase: water



Wikipedia

Liquid phase: water



→

rupture de ponts hydrogène
(consommation d'énergie,
processus endothermique)

←

reconstitution de ponts
hydrogène
(libération d'énergie,
processus exothermique)

ΔH_v = chaleur latente ou enthalpie de vaporisation
ΔH_f = chaleur latente ou enthalpie de fusion

Liquid phase: water

Heat capacity or thermal capacity is a physical property of matter, defined as the amount of heat to be supplied to an object to produce a unit change in its temperature. The SI unit of heat capacity is joule per kelvin (J/K).

Heat capacity is an extensive property. The corresponding intensive property is **the specific heat capacity**, found by dividing the heat capacity of an object by its mass or volume:

- Massic heat capacity / capacité thermique massique (c_F, J kg^{-1} K^{-1})

  Indicative values:
  - Water = 4200 J kg^{-1} K^{-1}
  - Dry soil = 800 J kg^{-1} K^{-1}
  - Air = 966 J kg^{-1} K^{-1}

- Volumetric heat capacity / capacité thermique volumique ($C_F = \rho\, c_F$, J m^{-3} K^{-1})

Liquid phase: dynamic viscosity

When a fluid is moved in shear (i.e., when adjacent layers of fluid are made to slide over each other), the force required is proportional to the velocity of shear. The proportionality factor is called the **viscosity**. The coefficient of viscosity μ is defined as the force per unit area necessary to maintain a velocity difference of 1 m/sec between two parallel layers of fluid that are 1 m apart. The viscosity equation is:

$$\tau = \frac{F_s}{A} = \mu \frac{du}{dy}$$

where τ is the shearing stress, consisting of a force F_s acting on an area *A*; μ [dimensions: mass/ (length × time)] is the coefficient of **dynamic viscosity**; and *du/dy* is the velocity gradient perpendicular to the stressed area *A*.

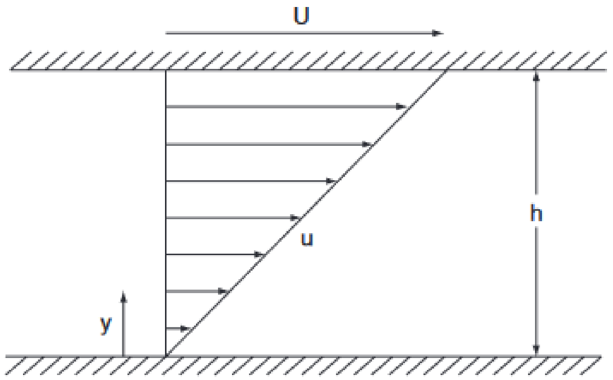


Fig. 7.1. Velocity distribution in a viscous fluid between two parallel plates, the upper one moving at a velocity *U* relative to the lower one.

Hillel (2003)

Note: the viscosity of water diminishes by over 2% per 1°C rise in temperature

Liquid phase: kinematic viscosity

The ratio of the dynamic viscosity of a fluid to its density is called the **kinematic viscosity** (or "diffusivity of momentum"):

$$\upsilon = \frac{\mu}{\rho} \quad (\text{m s}^{-2})$$

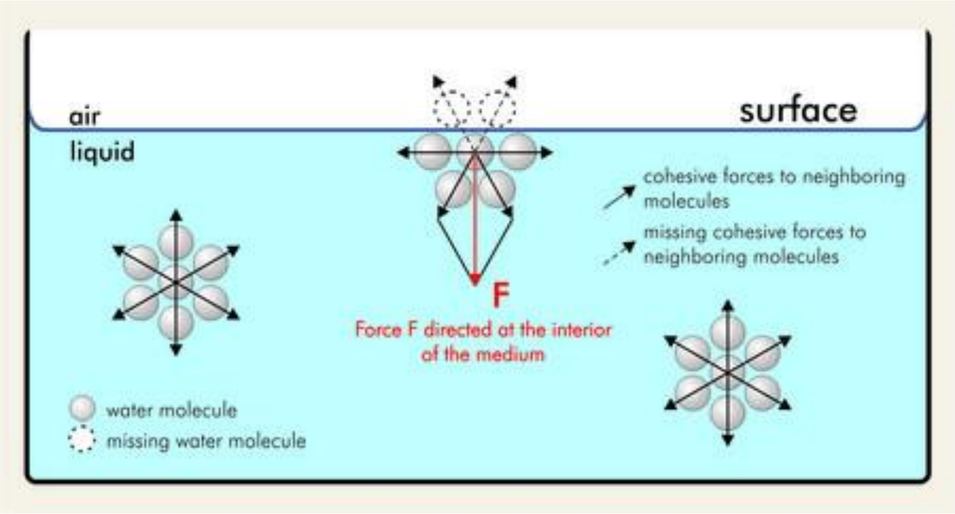
T = 15°C P =1 bar	Water	Air
ρ (kg m^{-3})	999.1	1.225
μ (kg m^{-1} s^{-1})	1.14×10^{-3}	1.78×10^{-5}
υ (m s^{-2})	1.14×10^{-6}	1.45×10^{-5}

Liquid phase: surface tension

Surface Tension: At the **interface** between water and solids or other fluids (e.g., air), water molecules are exposed to different forces than are molecules within the bulk water. For example, water molecules inside the liquid are attracted by equal cohesive forces to form hydrogen bonds on all sides, whereas molecules at the air-water interface feel a net attraction into the liquid because the density of water molecules on the air-side of the interface is much lower and all hydrogen bonds are towards the liquid.

The result is a **membrane-like water surface** having a tendency to contract; thus energy is stored in the form of surface tension, as in a stretched spring. Different liquids vary in their **surface tension $\boldsymbol{\sigma}$**, expressed as energy per unit area (= force per unit of length). For example:

$$\sigma_{water/air} = 0.0727 \text{ N/m} = \text{J/m}^2 \text{ (at } 20^{o}\text{C)}$$



Source: Google images

Liquid phase: capillarity

Wetting and contact angle: If liquid is placed in contact with a solid in the presence of a gas (three-phase system), the angle measured from the solid-liquid (SL) interface to the liquid-gas (LG) interface is the **contact angle (ϑ)**. The contact angle is determined by the balance between **adhesive forces** (acting between the liquid and the solid and causing the liquid drop to spread across the surface) and **cohesive forces** (acting within the liquid and causing the drop to ball up and avoid contact with the surface).

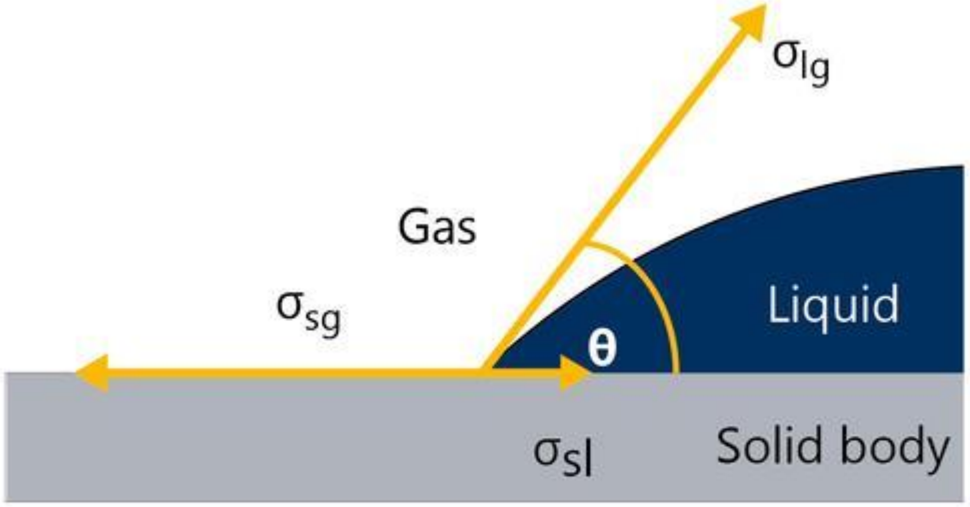
For a drop resting on a solid surface under equilibrium, the vector sum of the forces acting to spread the drop (outward) is equal to the opposing forces as summarized by **Young's equation**:

$$\sigma_{GS} = \sigma_{SL} + \sigma_{LG} cos\vartheta$$

$$\Downarrow$$

$$cos\vartheta = \frac{\sigma_{GS} - \sigma_{SL}}{\sigma_{LG}}$$

For further details, see this video
Thermodynamic derivation in Roura and Fort (2004)



Source: Google images

Liquid phase: capillarity

When liquid is attracted to the solid (adhesion) more than to other liquid molecules (cohesion), the angle ϑ is **small** and the solid is said to be **"wettable" by the liquid**. Conversely, when the cohesive force of the liquid is larger than the adhesive force, the liquid **"repels"** the solid and ϑ is **large**

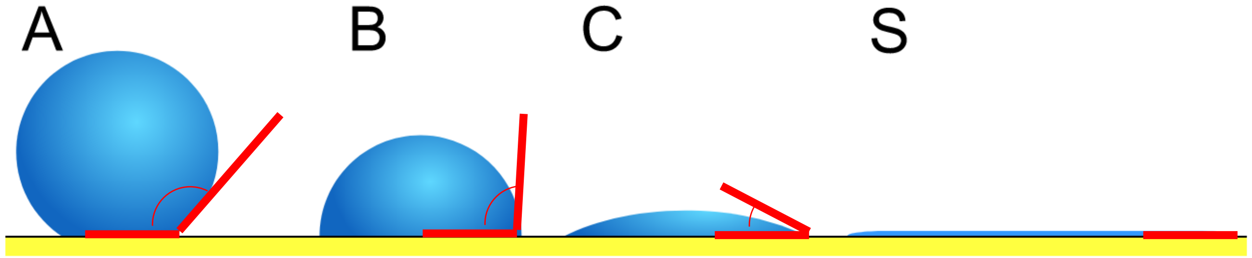


Figure 2: Wetting of different fluids: A shows a fluid with very little wetting, while C shows a fluid with "perfect" wetting. A has a large contact angle, and C has a small contact angle (Wikipedia).

C $0 < \vartheta < 90^\circ$	B $\vartheta = 90^\circ$	A $90^\circ < \vartheta < 180^\circ$
Adh > Coh	Adh = Coh	Adh < Coh
$p_L < p_a$	$p_L = p_a$	$p_L > p_a$
Hydrophils solide surface	No atraction, no repulsion	Hydrophobic solide surface

When the liquid-gas interface is curved rather than planar (flat), the resultant surface tension force normal to the liquid-gas interface creates a **pressure difference** across the interface (see table: p_L=liquid pressure, p_a=atmospheric pressure).

Liquid phase: capillarity

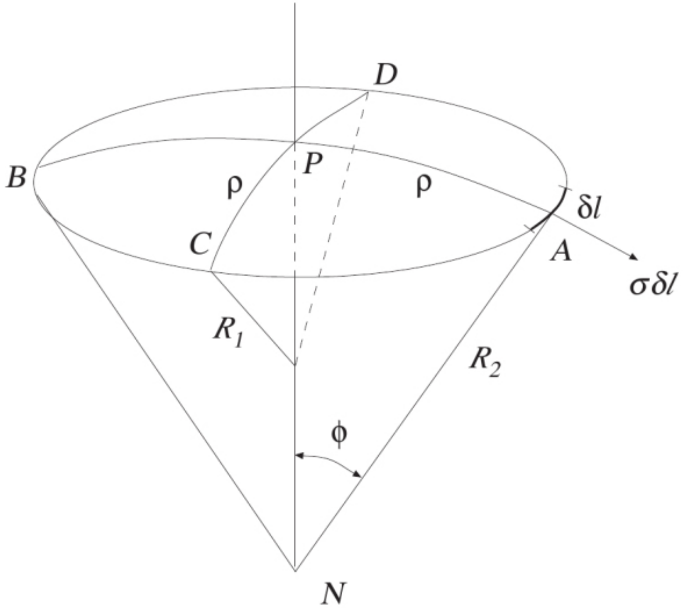
For a hemispherical liquid-gas interface having radius of curvature R, the pressure difference is given by the **Young-Laplace equation**:

$$\Delta p = \frac{2\sigma}{R}$$

where $\Delta p = p_{liquid} - p_{gas}$ when the interface curves into the gas (e.g., water droplet in air); or $\Delta p = p_{gas} - p_{liquid}$ when the interface curves into the liquid (e.g., air bubble in water, water in a small glass tube).

In many instances a bubble may not be spherical, or an element of liquid may be confined by irregular solid surfaces resulting in two or more different radii of curvature. The Young-Laplace equation for this case is given by:

$$\Delta p = \sigma\left(\frac{1}{R_1} + \frac{1}{R_2}\right)$$



If interested, see derivation of the Young-Laplace equation here: video or article

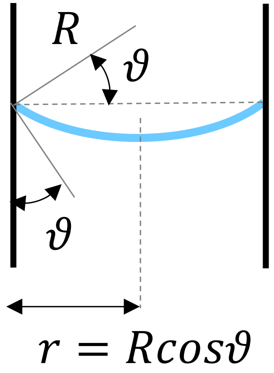
Liquid phase: capillarity

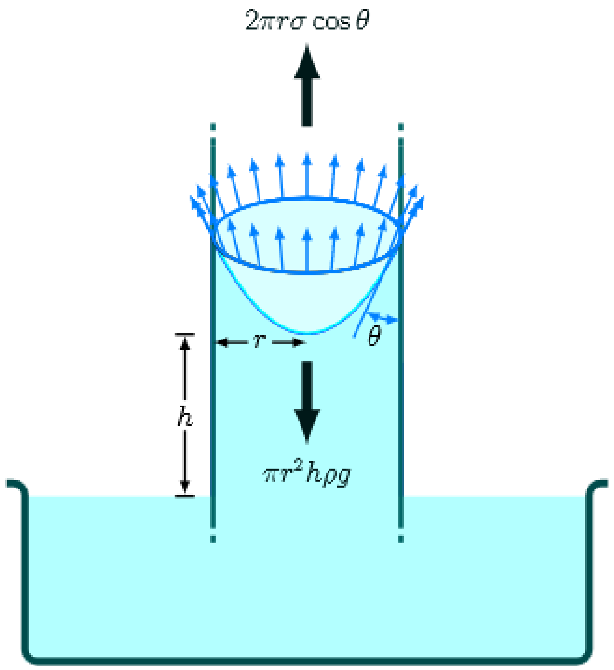
The Capillary Rise Model: When a small cylindrical glass tube (capillary) is dipped in free water a meniscus is formed that balances the contact angle between water and tube walls and minimizes interfacial energy. The smaller the tube the larger the degree of curvature, resulting in larger pressure difference across the air-water interface. The pressure at the water side (p_w) will be lower than atmospheric pressure (p_0) and the radius of meniscus curvature is $R = r/cos\vartheta$ where r is the tube radius and ϑ is the contact angle.

The pressure difference will cause water to rise into the capillary tube until the upward force across the water-air interface is balanced by the weight of water in the tube. Hence, the height that water will rise in a capillary tube of radius r with contact ϑ is:

$$h = \frac{2\sigma\ cos\vartheta}{\rho_w\ g\ r}$$

Jurin's law

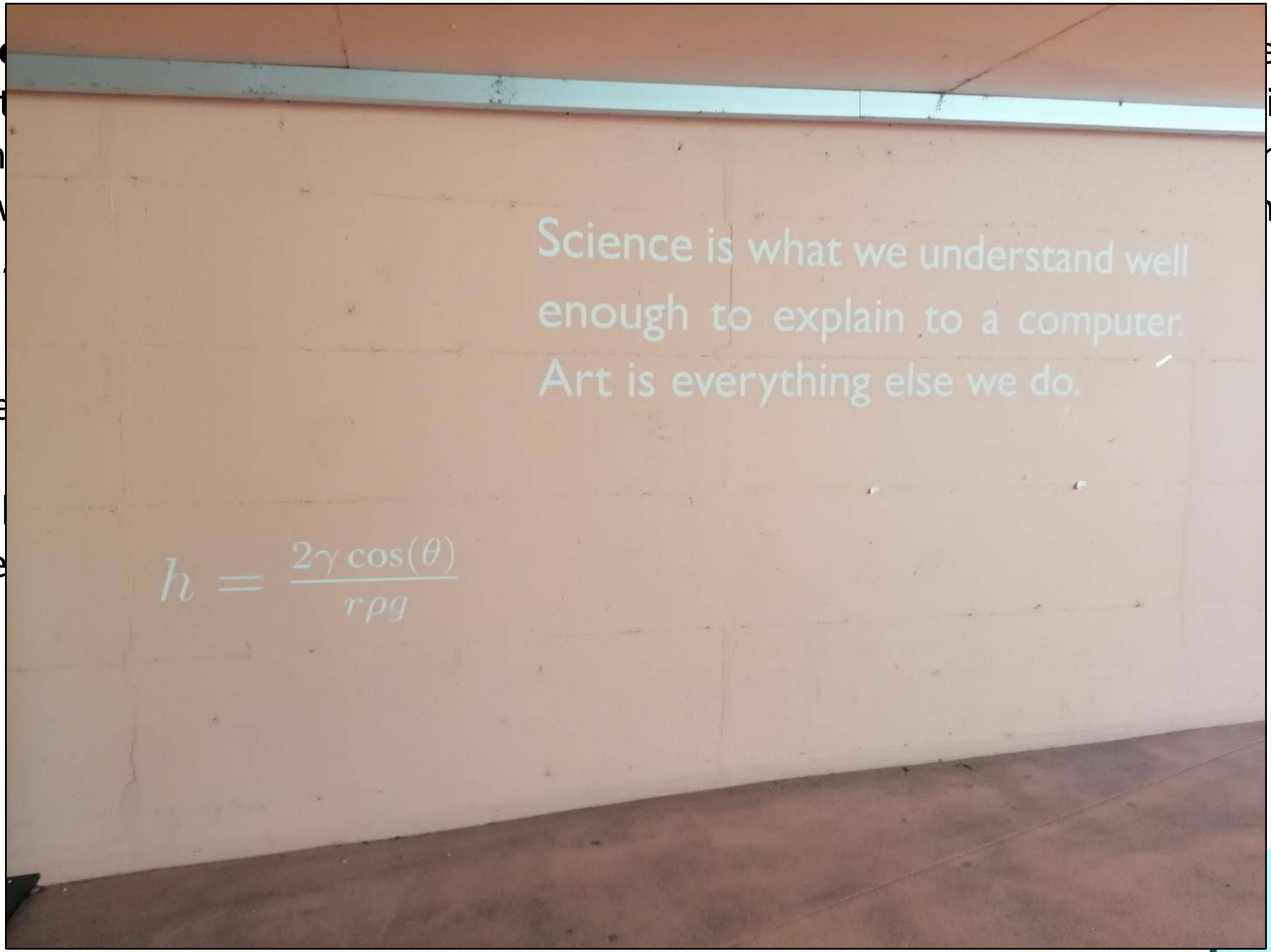




Source: Google images

Liquid phase: capillarity

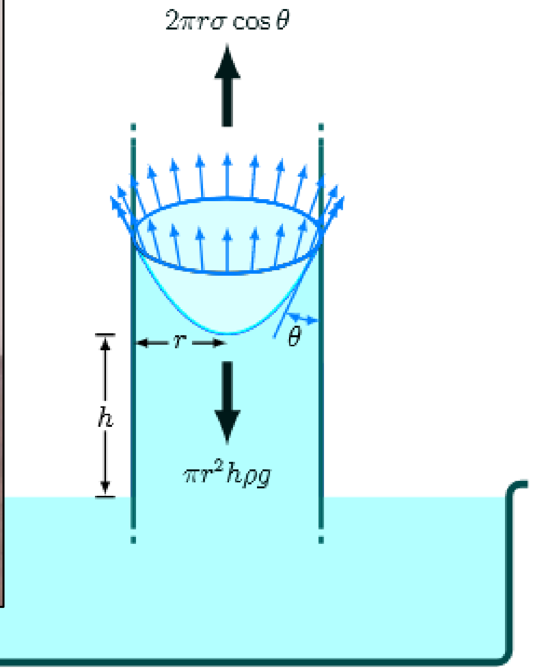
The Capillary Rise M … e water a meniscus is
formed that balances t … ial energy. The smaller
the tube the larger th … he air-water interface.
The pressure at the … he radius of meniscus
curvature is $R = r/co$



Science is what we understand well enough to explain to a computer. Art is everything else we do.

$$h = \frac{2\gamma\cos(\theta)}{r\rho g}$$

The pressure differe
capillary tube until
interface is balanced
the height that wate
with contact ϑ is:



Source: Google images

Liquid phase: capillarity

Depression causing the water meniscus: $$\Delta p = \frac{2\sigma}{R} = \frac{2\sigma\, cos\vartheta}{r}$$

Hydrostatic pressure exerted by the water column in the capillary: $$p_w = \rho_w g\ h$$

Capillary pressure: $$p_c = p_l - p_a = -\Delta p \quad (p_l < p_a)$$

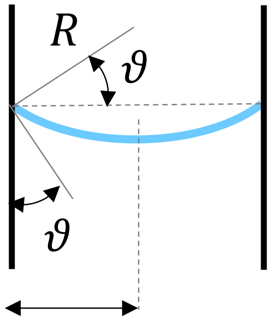
At equilibrium: $$\Delta p = p_w$$

$$h = \frac{2\sigma\, cos\vartheta}{\rho_w\ g\ r}$$

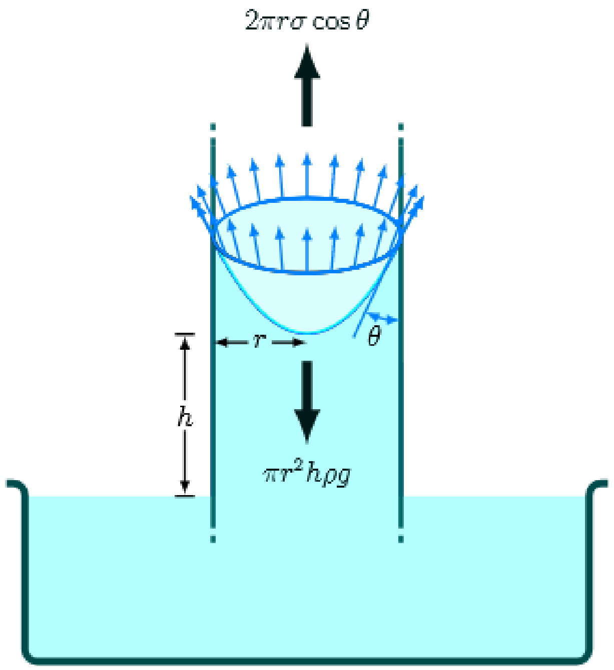
$\mathbf{0 < \vartheta < 90^{\circ}}$

Adh > Coh

$p_L < p_a$



$$r = Rcos\vartheta$$

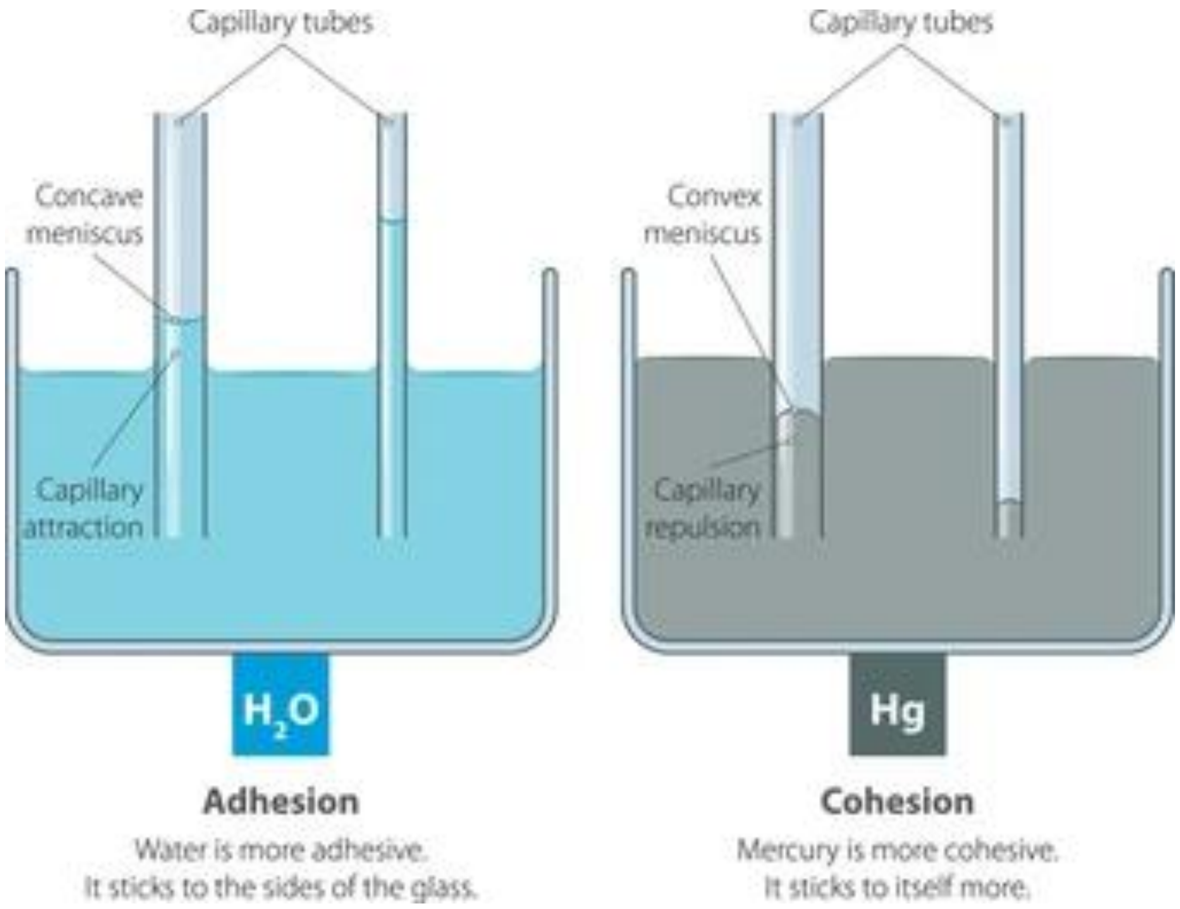


Source: Google images

Liquid phase: capillarity

The water is therefore under tension or depressurized in relation to atmospheric pressure.

The smaller the capillary radius, the greater the tension.



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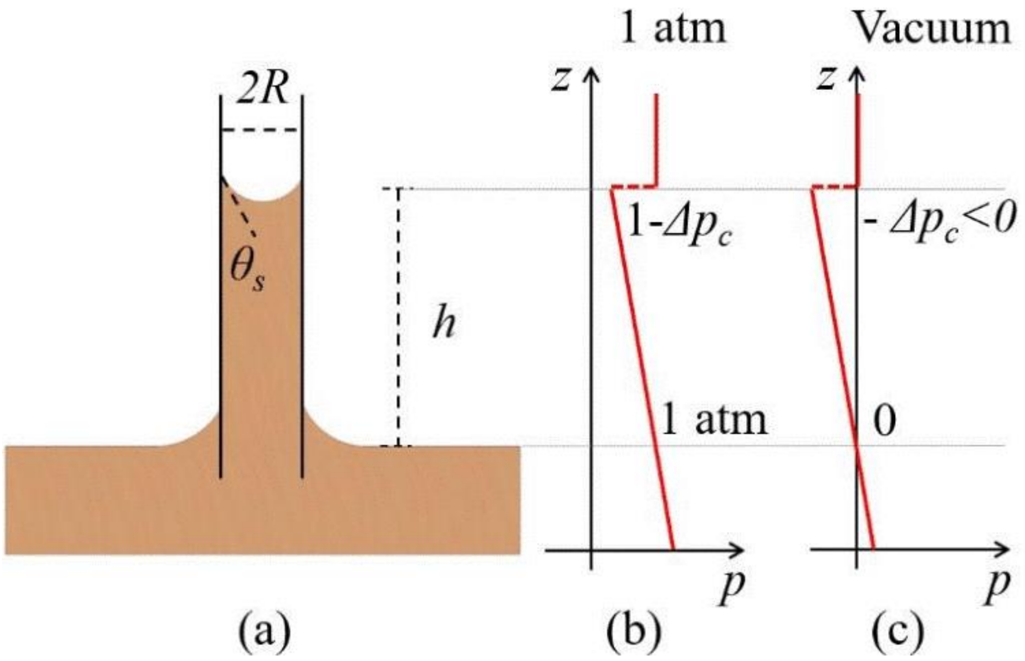
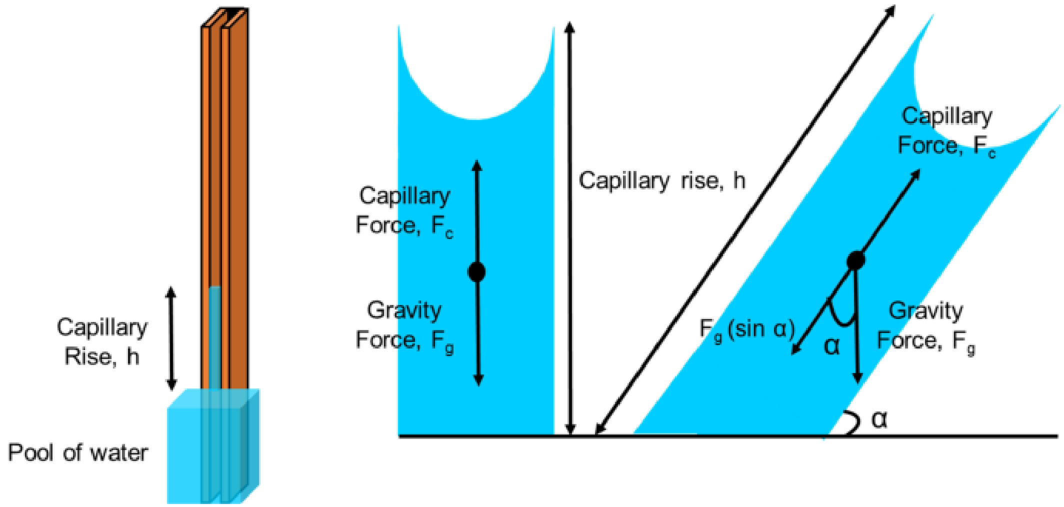
Liquid phase: capillarity



(a) Capillary rise in a narrow tube, (b) liquid pressure distribution under 1 atmospheric pressure, and (c) liquid pressure distribution under vacuum (Source: Zobeiry & Duffner, 2018).



When we tilt the capillaries at an angle, the capillary force stays the same, but is now in equilibrium with only the vertical component of the gravitational force (Source: Abadi & Bahrami, 2020)

Liquid phase: capillarity

Models for Water in Soil Pore Space

The complex geometry of soil pore space creates numerous combinations of interfaces, capillaries and wedges around which films of water are formed, resulting in a variety of air-water and solid-water contact angles. Water is thus drawn into and/or held by these interstices in proportion to the resulting capillary forces. In addition, water is adsorbed onto solid surfaces, with considerable force at close distances.

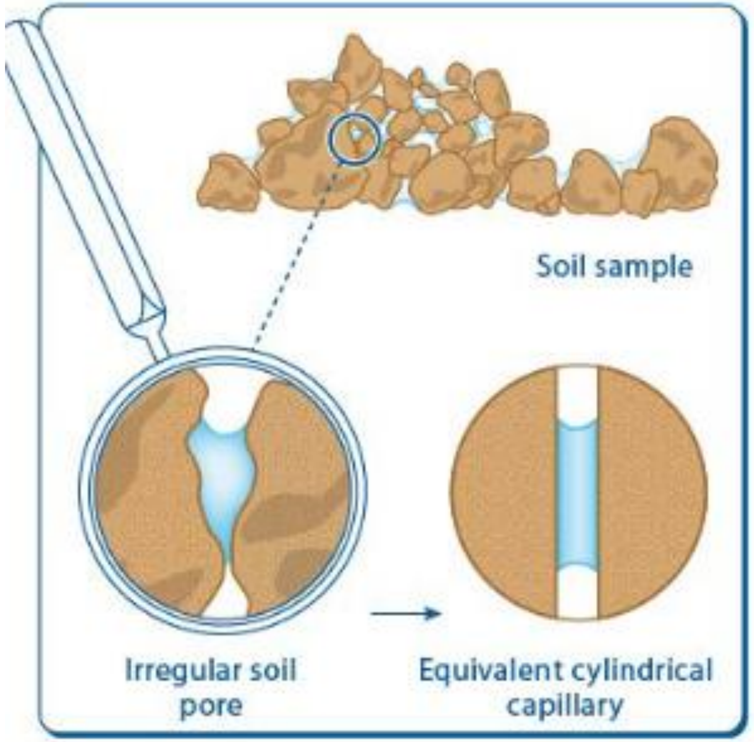


Fig.1-28: Conceptual representation of soil pores as equivalent capillaries.

Source: Or, Tuller, & Wraith, 1994-2018

Liquid phase: osmotic pressure

Owing to the constant thermal motion of all molecules in a fluid, solute species spread throughout the solution in a spontaneous tendency toward a state of equal concentration throughout (= diffusion).

If a physical barrier is interposed across the path of diffusion, and if that barrier is permeable to molecules of the solvent but not to those of the solute (i.e. selective or semipermeable membrane), the former will diffuse through the barrier in a process called **osmosis** (from the Greek “push”). As in the case of unhindered diffusion, this process tends toward a state of uniform concentration, even across the barrier.

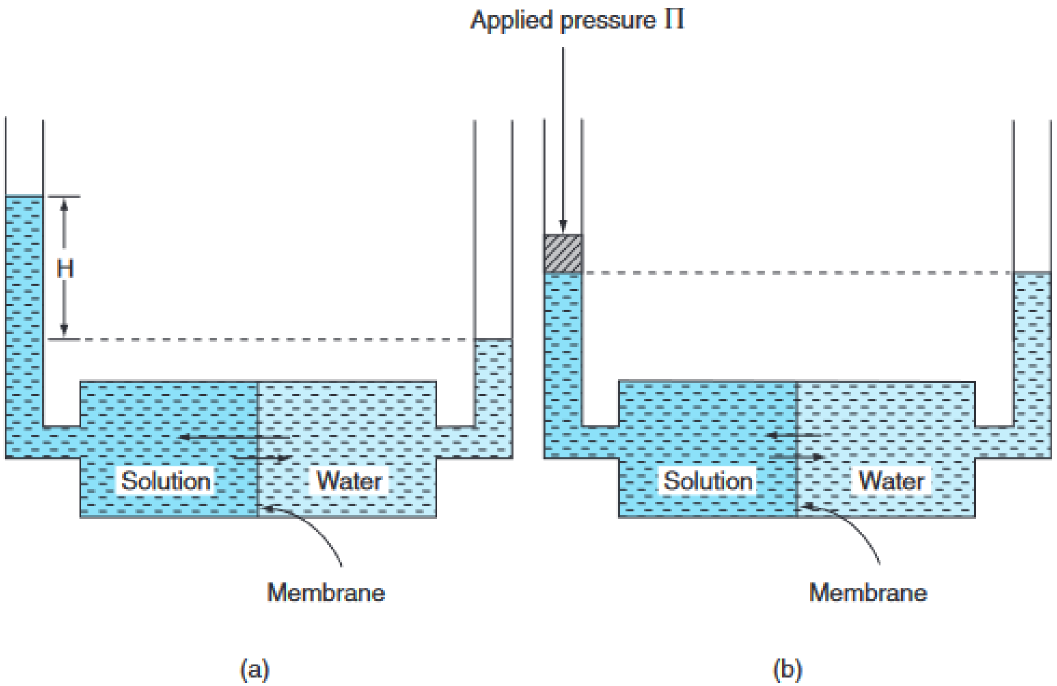


Fig. 2.4. Osmosis and osmotic pressure: (a) In osmosis, the flow of water molecules through the membrane into the solutions is at first greater than the reverse flow from the solution into the water compartment. The hydrostatic pressure due to the column of expanded solution increases the rate of water flow from the solution to the water compartment until, at equilibrium, the opposite flows are equal. (b) The osmotic pressure of the solution is equal to the hydrostatic pressure Π that must be applied to the solution to equalize the rate of flow to and from the solution and produce a net flow of zero.

Hillel (2003)

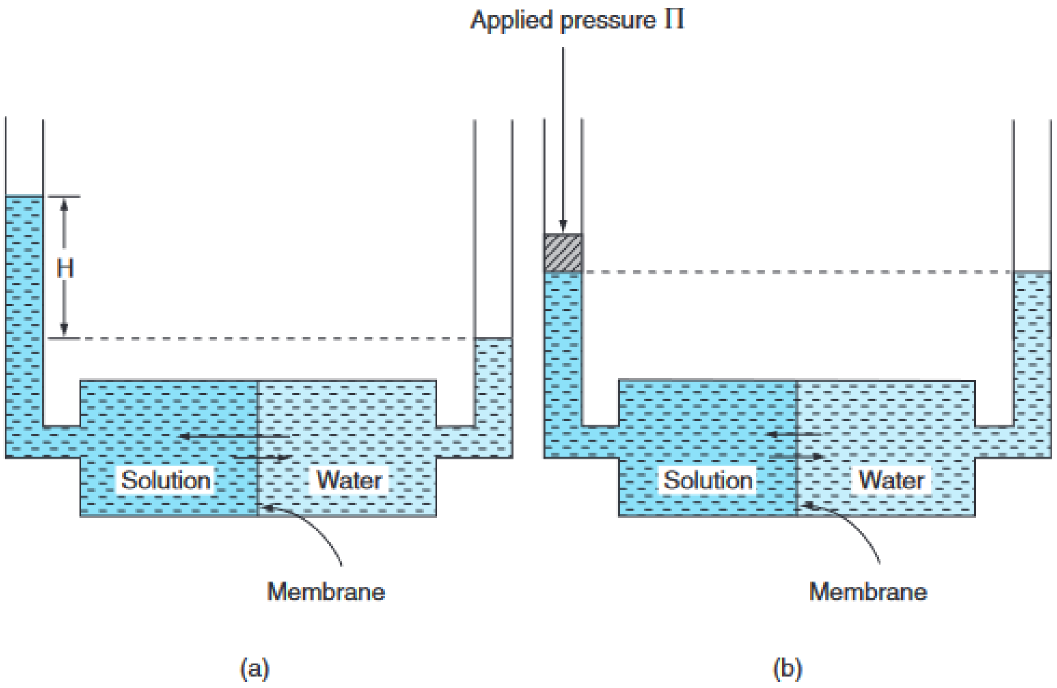
Liquid phase: osmotic pressure

In dilute solutions, the osmotic pressure is:

$$\Pi = MRT$$

Here Π is the osmotic pressure in atmospheres (to be multiplied by 0.101 to obtain megapascal units), *M* is the total molar concentration of the solute (whether molecules or dissociated ions), *T* is the temperature in degrees Kelvin, and *R* is the gas constant (0.08205 L atm/deg mole)

$$H = \frac{\Pi}{\rho_w g}$$



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Hillel (2003)

Gas phase: the atmosphere of the soil

Source: Or, Tuller, & Wraith, 1994-2018

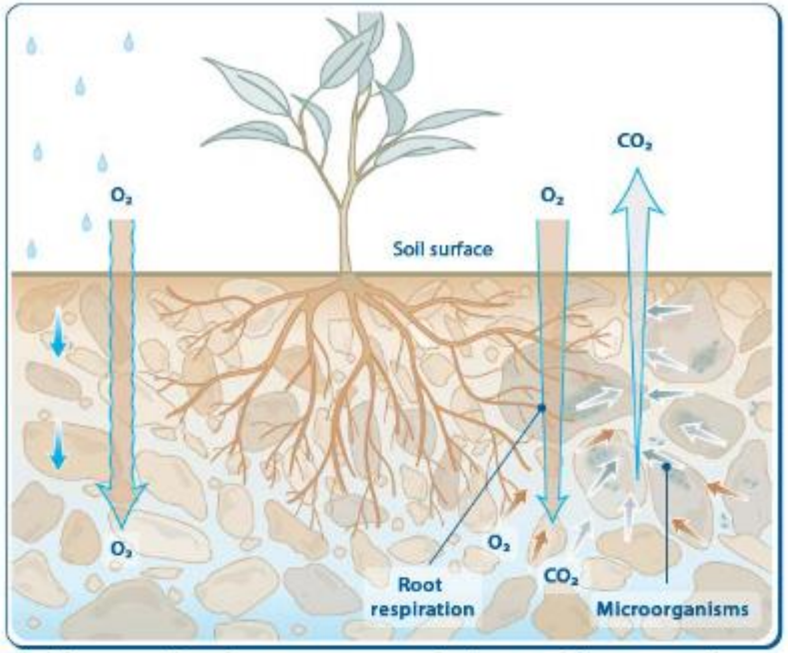
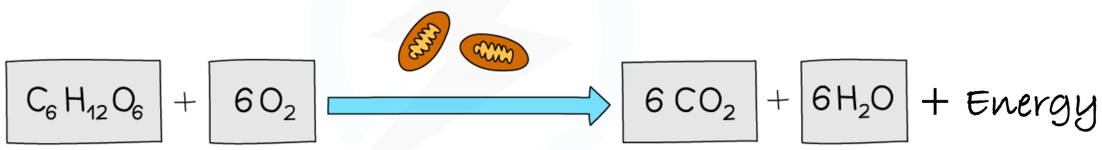


Fig.6-1: Schematic diagram of exchange processes between soil gaseous phase and the atmosphere.

	Air in the Atmosphere	Air in the Soil
Nitrogen	78%	78-80%
Oxygen	21%	<21%
Other gasses	1%	1%
CO_2	0.03%	0.2%
Water vapor	Variable	Near saturation



$$C_6H_{12}O_6 + 6O_2 \rightarrow 6\,CO_2 + 6H_2O + \text{Energy}$$

Aerobic respiration

In the soil: $CO_2 + O_2 \approx 20\ \%$

Average daily production of CO_2: $3 – 5\ g/m^2$

Gas phase: the atmosphere of the soil

- In general, oxygen (**O_2**) is consumed in below ground biological reactions and carbon dioxide (**CO_2**) is produced in the process of aerobic respiration. As oxygen is depleted and its concentration in the soil gaseous phase decreases, O_2 from the atmosphere moves into the soil along the partial pressure gradient in the process of gaseous diffusion; CO_2 may diffuse in the opposite direction.

- Insufficient O_2 in the soil, or **anaerobic conditions**, also affects the state of other soil constituents, rendering them unavailable for plant growth and other biological activities. For example, nitrates NO_3 are reduced to toxic nitrites NO_2 or to free nitrogen gas N_2, organic matter may be reduced to methane, and reduced inorganic compounds are formed, e.g., sulfides, ferrous and manganese compounds.

- Traditionally, the interest in **soil aeration** and gas transport was motivated by its influence on plant growth but, nowadays, there is growing interest in application of modern bioremediation methods to a variety of soil contaminants.

Self-Study

Gas phase: the atmosphere of the soil

Dalton's law (pressure of a mixture of gases): $p = \sum_i p_i \rightarrow \quad p_i = p \cdot x_i$ (where x_i is the mole fraction)

Ideal gas law: $\underset{}{pV = \overset{\text{\# moles}}{n}RT} \rightarrow pV = \frac{m}{M}RT \rightarrow p = \frac{m}{V}\frac{R}{M}T = \rho R_{specific}T \rightarrow pv = R_{specific}T$

moles

Mass (kg)

Molar mass (kg/mole)

(specific volume: $v = 1/\rho$)

For the i-th component of a gas mixture (such as air):

- Volumetric fraction (m³ /m³): $\varepsilon_i = \frac{V_i}{V}$
- Concentration (kg /m³): $C_i = \frac{m_i}{V} = \rho_i \varepsilon_i = \frac{p_i M_i}{RT}$
- Partial pressure (Pa): $p_i = \varepsilon_i\, p_a$ (p_a= atmospheric pressure)

Self-Study

Gas phase: vapor pressure

The **vapour pressure of water** is the pressure exerted by molecules of water vapor in gaseous form (whether pure or in a mixture with other gases such as air).

Moist air (≈ ideal gas):

densities

- Pressure: $p = p_d + e = R_d \rho_d T + R_v \rho_v T$ (ideal gas law valid for each component)

pressure of dry air

water vapor pressure

- Density: $\rho = \rho_d + \rho_v = \frac{p-e}{R_d T} + \frac{e}{R_v T}$ → $\rho = \frac{p}{R_d T}\left[1 - \frac{e}{p}\left(1 - \overset{\frac{R_d}{R_v}}{0.622}\right)\right]$

Self-Study

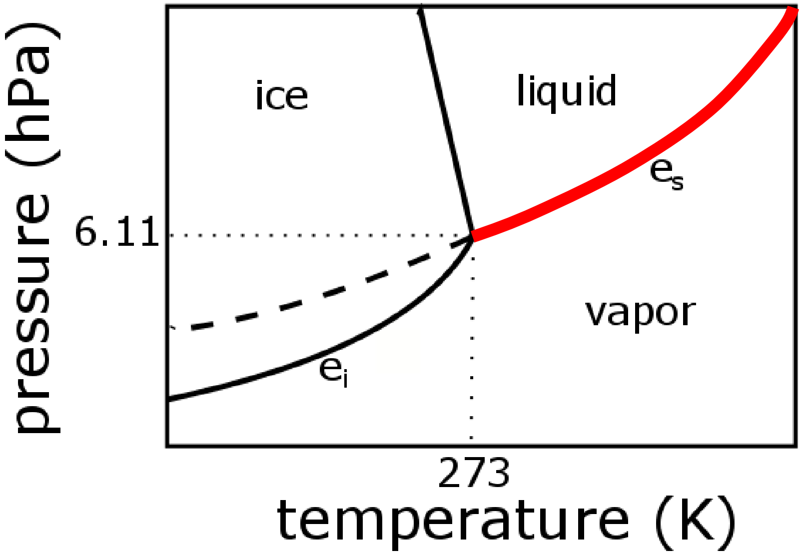
Gas phase: vapour pressure

The **saturation vapour pressure** is the pressure at which water vapour is in thermodynamic equilibrium with its condensed state. The saturation vapour pressure of water increases with increasing temperature and can be determined with the **Clausius–Clapeyron relation**:

$$e_s(T) = e_0 \cdot exp\left[\frac{\lambda}{R_v}\left(\frac{1}{T_0} - \frac{1}{T}\right)\right] \rightarrow e_s(T) = 611 \cdot exp\left[\frac{17.27\,T}{T + 237.3}\right]$$

August-Roche-Magnus equation

T in °C
e^* in Pa



- Relative humidity: $RH = 100\frac{e}{e_s}$
- Specific humidity: $q = \frac{m_v}{m_d+m_v} = \frac{\rho_v}{\rho_d+\rho_v}$
- Vapor concentration: $C_V = \frac{m_v}{V} = \frac{n_v M_v}{V} = \frac{p_v M_v}{RT}$

Gas phase: mass concentration

Total mass concentration of gases in soil

A particular volatile component may be found in the gaseous, liquid or solid phases of the soil. The total concentration C_T of the gas in question, in kg per m^3 of soil, is:

$$C_T = \varepsilon_a C_G + \theta C_L + \rho C_S$$

Where:

- C_T = total mass concentration $kg_{gas}\, m^{-3}_{soil}$
- C_G = mass concentration in the gas phase $kg_{gas}\, m^{-3}_{air}$
- C_L = mass concentration in the liquid phase $kg_{gas}\, m^{-3}_{water}$
- C_S = mass concentration in the solid phase $kg_{gas}\, kg^{-3}_{soil}$
- ε_a = volumetric fraction of the gas phase $m^{3}_{air}\ m^{-3}_{soil}$
- θ = volumetric water content $m^{3}_{water}\ m^{-3}_{soil}$
- ρ = dry bulk density $kg_{soil}\, m^{-3}_{soil}$

If the gas is insoluble and not subject to sorption: $C_T = \varepsilon_a C_G$

Self-Study

This week exercises & assignments

- **Exercises** for **Weeks 1 and 2** are available in Moodle.
  - These exercises are to be completed in the first 2 weeks of this part of the course.
  - Solutions will be provided the week after the exercises are completed.
- **Computer Lab:** brief intro to modeling and programming for solving common problems in soil sciences (Pyhton, Jupiter Notes)
- **For next week:** read pages 2-13 of Notes 2.pdf