Corso di Laurea in Fisica - UNITS

Istituzioni di Fisica per il Sistema Terra

Fluids properties

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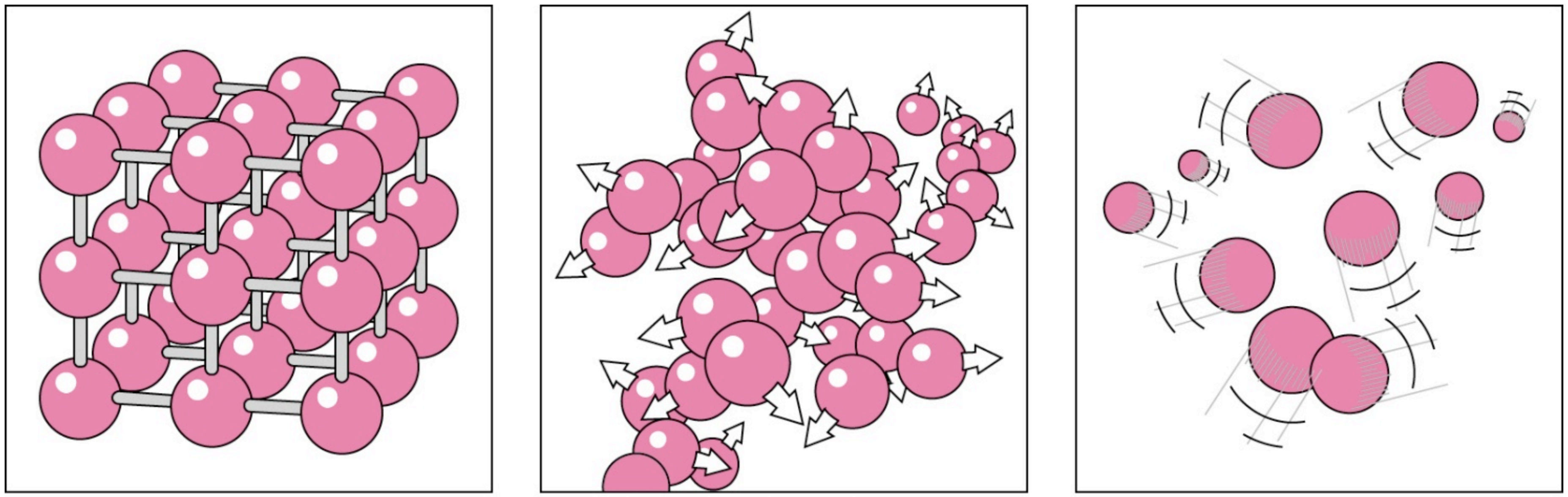
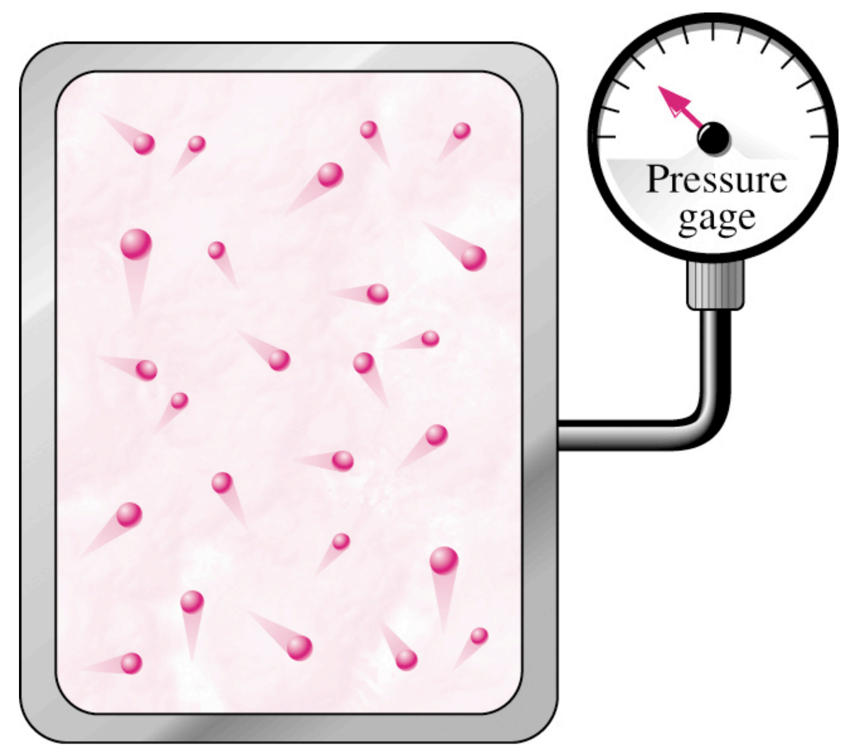
What is a fluid?



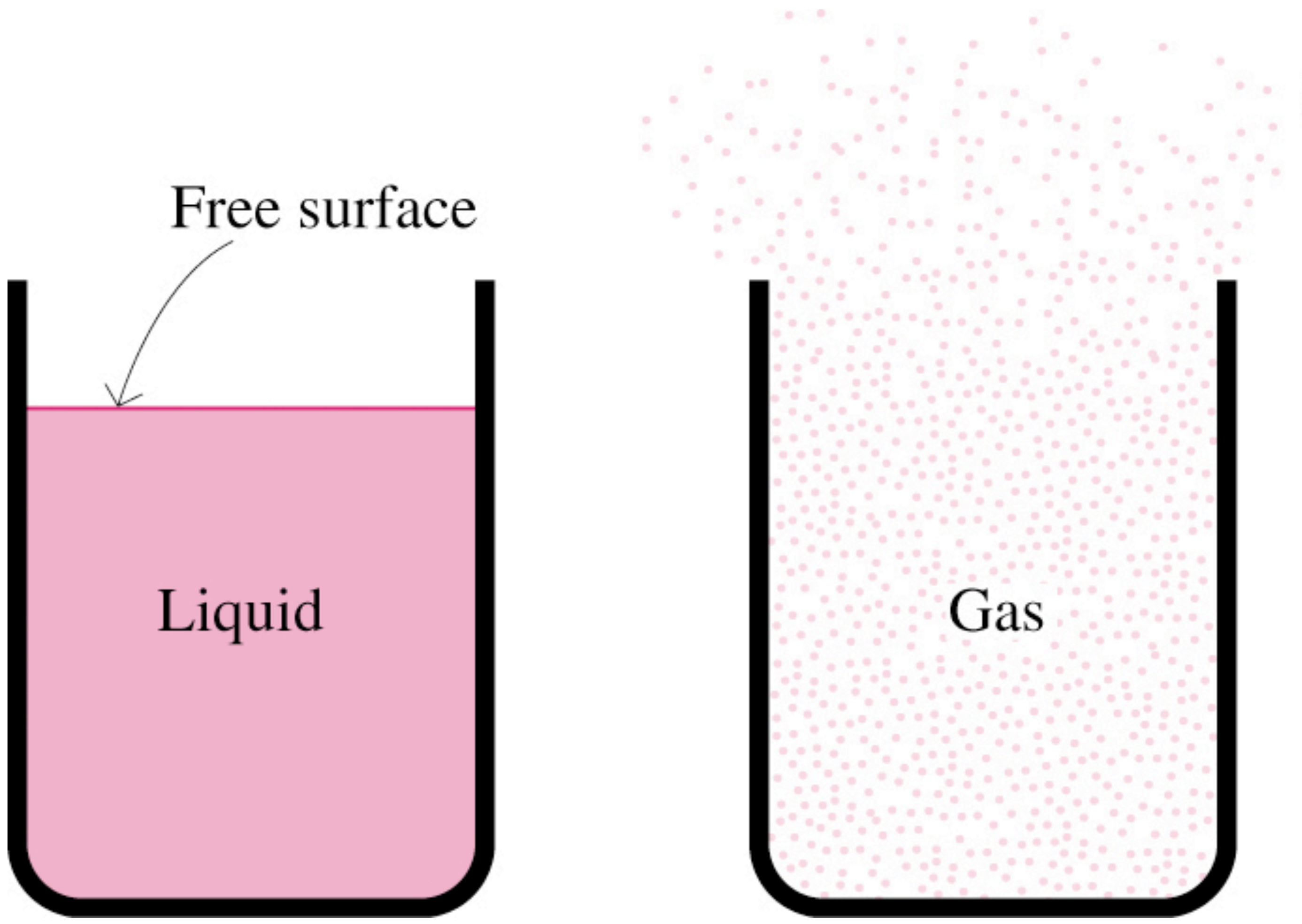
(a) solid

(b) liquid

(c) gas



What is a fluid?



- A liquid takes the shape of the container it is in and forms a free surface in the presence of gravity
- A gas expands until it encounters the walls of the container and fills the entire available space. Gases cannot form a free surface
- Gas and vapor are often used as synonymous words

What is a fluid?

- The word "fluid" traditionally refers to one of the states of matter, either liquid or gaseous, in contrast to the "solid" state.
- A material that exhibits flow if shear forces are applied
- Basically any material that appears as elastic or non-deformable, with a crystalline structure (i.e., belonging to the solid state) or with a disordered structure (e.g., a glass, which from a thermodynamic point of view belongs to the liquid state) can be irreversibly deformed (flow) when subjected to stresses for a long enough time.

https://www.youtube.com/watch?v=sMKJvYSYiOs

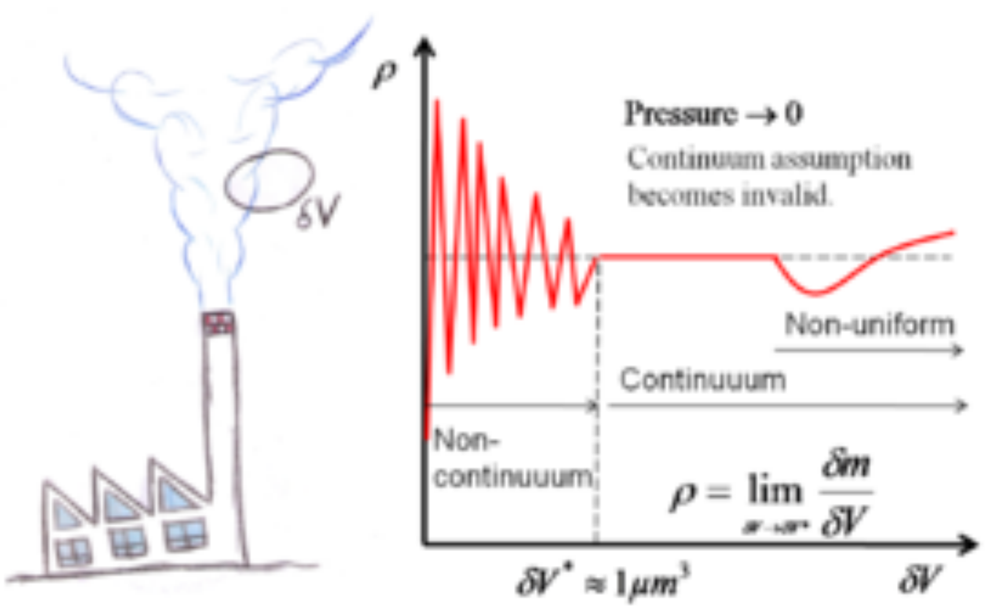
What is a fluid?

- The characteristic time constant of the geological processes related to mantle convection, typically 10 Myrs (3×10^{14} s), is so long that the mantle, although stronger than steel and able to transmit seismic shear waves, can be treated as a fluid.
- Similarly, ice, which is the solid form of water, is able to flow from mountain tops to valleys in the form of glaciers. A formalism that was developed for ordinary liquids or gases can therefore be used in order to study the inside of planets.
- Although the word "convection" is often reserved for flows driven by internal buoyancy anomalies of thermal origin, we will more generally use "convection" for any motion of a fluid driven by internal or external forcing.
  - Convection can be kinematically forced by boundary conditions or induced by density variations. The former is "forced" and the latter is "free convection" which can be of compositional or thermal origin.

https://www.youtube.com/watch?v=Ns-_q_mhjxM

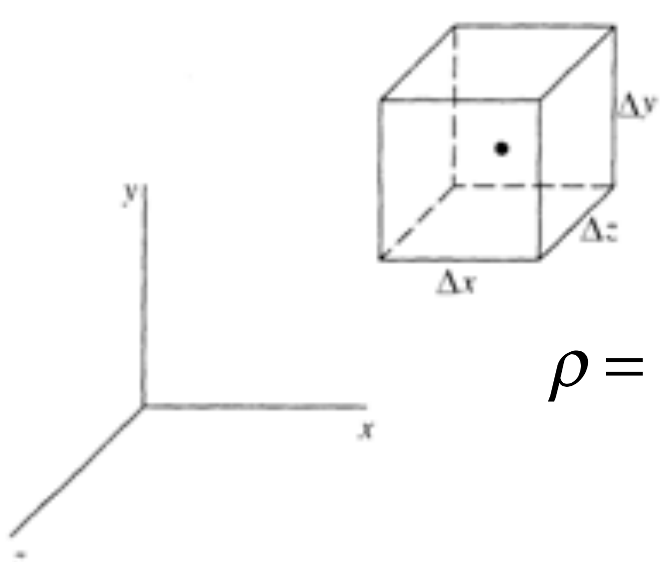
What is a fluid?

- The physics of fluid behavior, like the physics of elastic media is based on the general continuum hypothesis, requiring that quantities like density, temperature, or velocity are defined everywhere, continuously and at "points" or infinitesimal volumes that have a statistically meaningful number of molecules so that the quantity represents an average independent of microscopic molecular fluctuations.
  - This hypothesis seems natural for ordinary fluids at the laboratory scale. We will adopt the same hypothesis for the mantle although we know that it is heterogeneous at various scales and made of compositionally distinct grains.

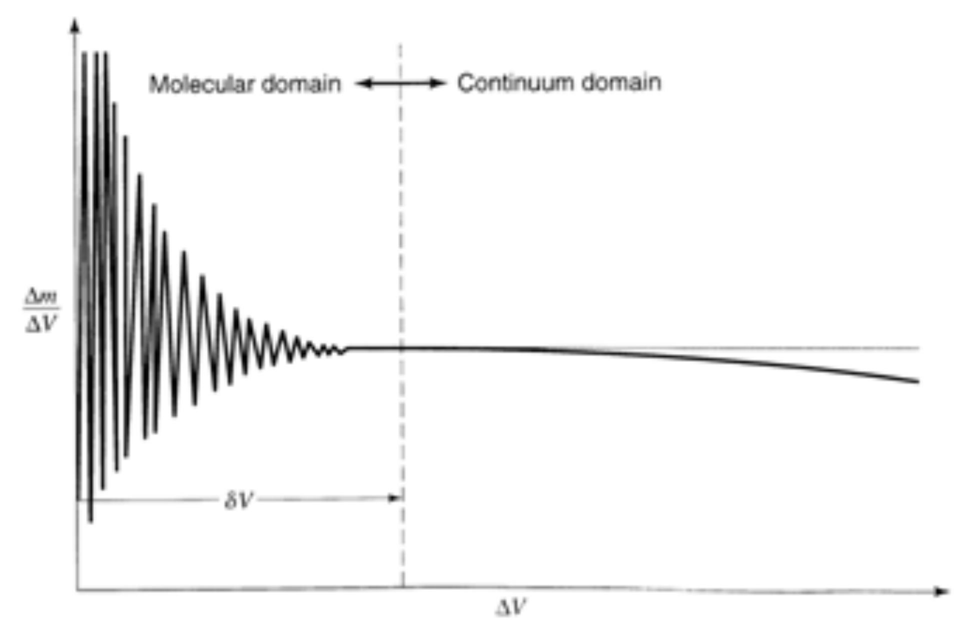


Continuum

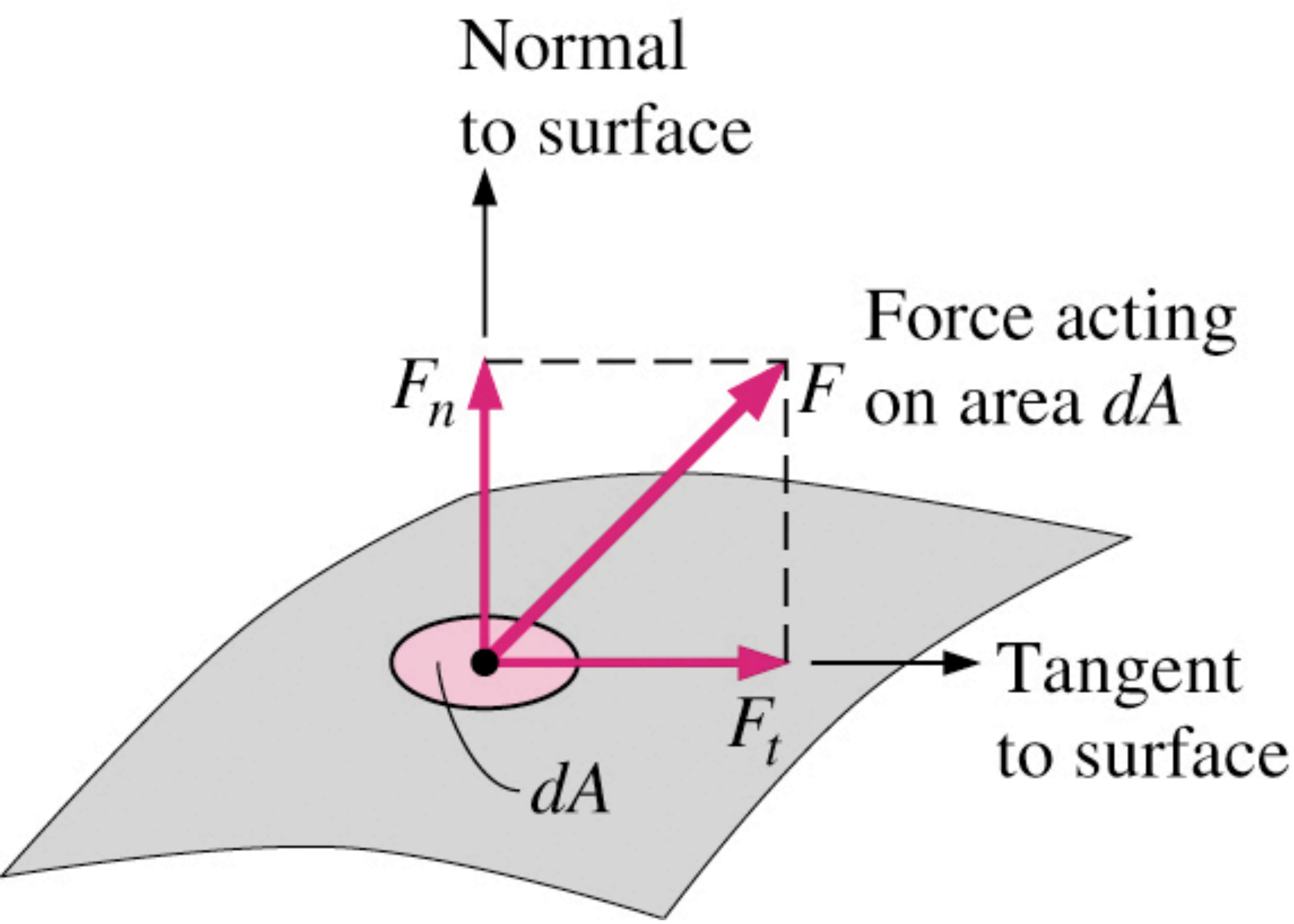
- Matter is made up of atoms that are spaced, but it is very convenient to disregard the atomic nature of a substance and view it as a continuous, homogeneous matter with no holes, that is, a continuum.
- The continuum idealization allows us to treat properties as point functions and to assume the properties vary continually in space with no jump discontinuities.
- This idealization is valid as long as the size of the system we deal with is large relative to the space between the molecules in the fluid.
- For density, the mass (m) per unit volume (V) in a substance, measured at a given point, will tend toward a constant value in the limit as the measuring volume shrinks down to zero.
  - A problem with this requirement is that, as the volume segment gets smaller, you reach a size where random molecular (thermal) motion causes the density to fluctuate, and the continuum approximation begins to break down:



$$\rho = \lim_{\Delta V \to 0} \frac{\Delta m}{\Delta V} = \frac{dm}{dV}$$

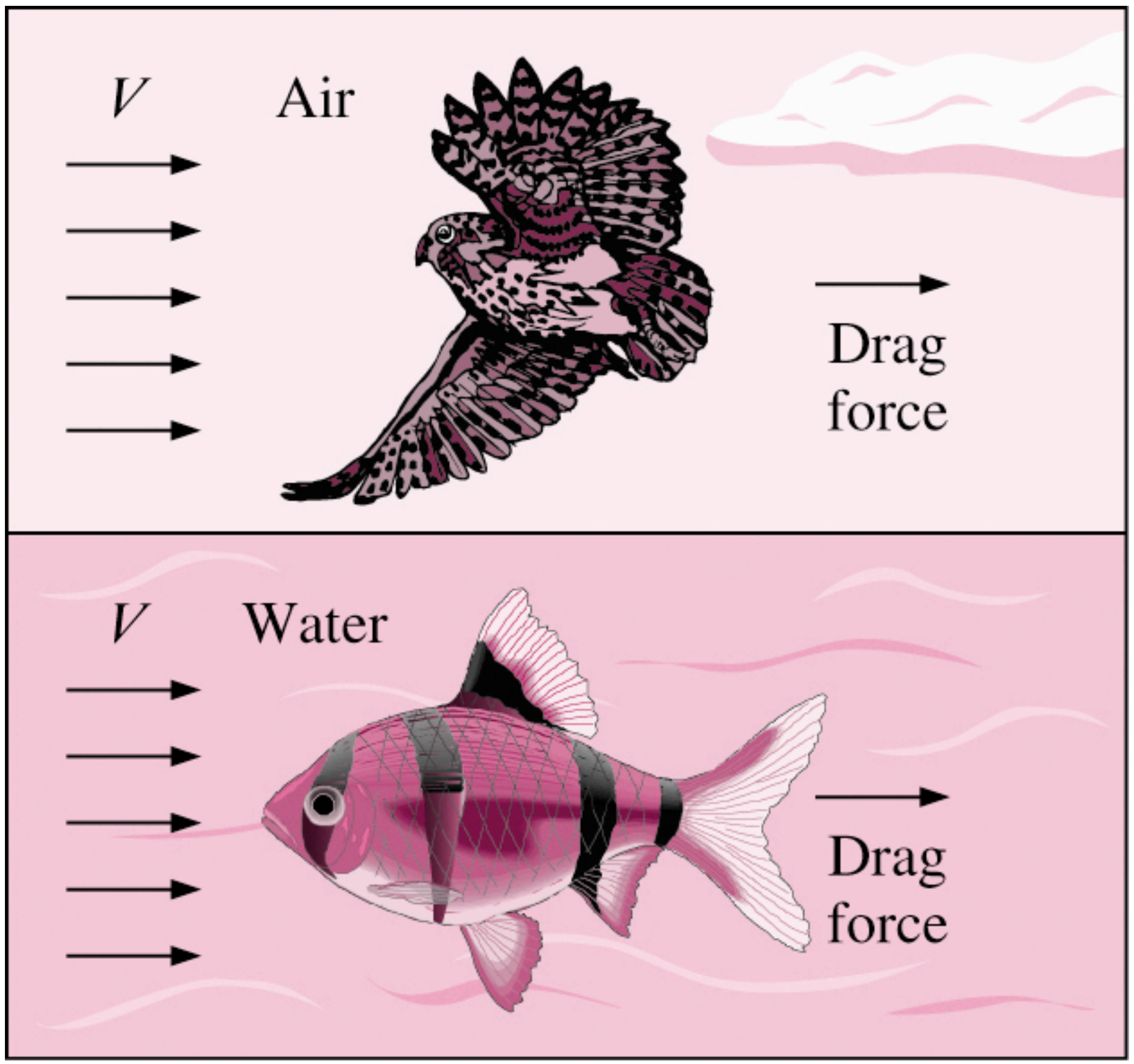


What is a fluid?



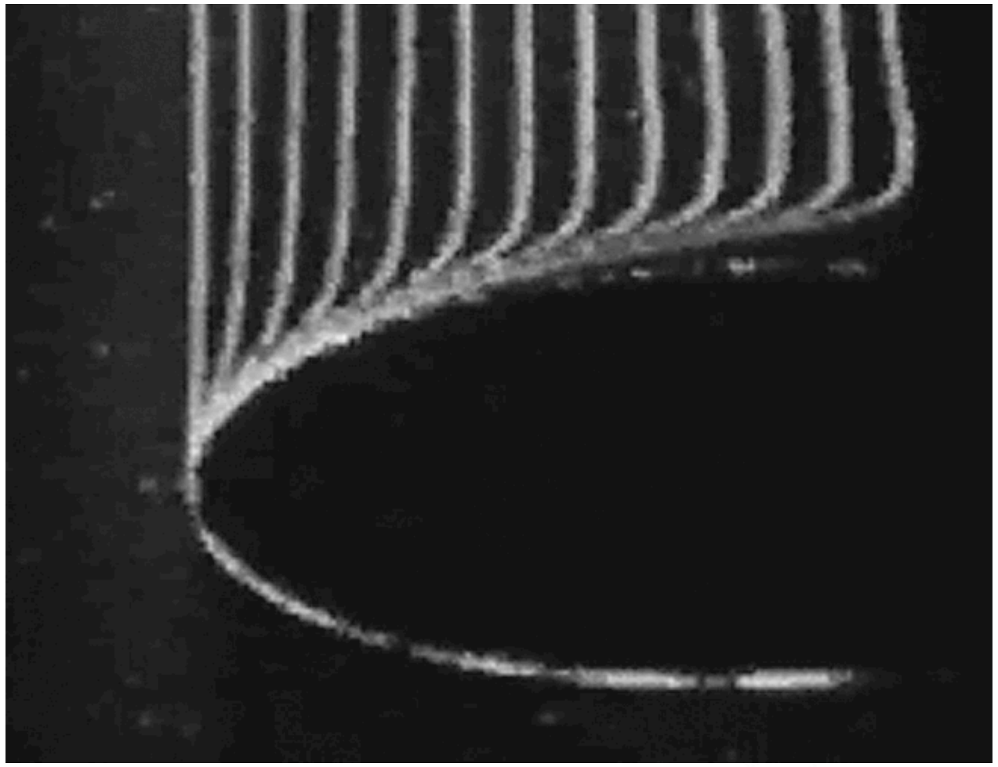
- Stress is defined as the force per unit area.
- Normal component: normal stress
  - In a fluid at rest, the normal stress is called pressure
- Tangential component: shear stress

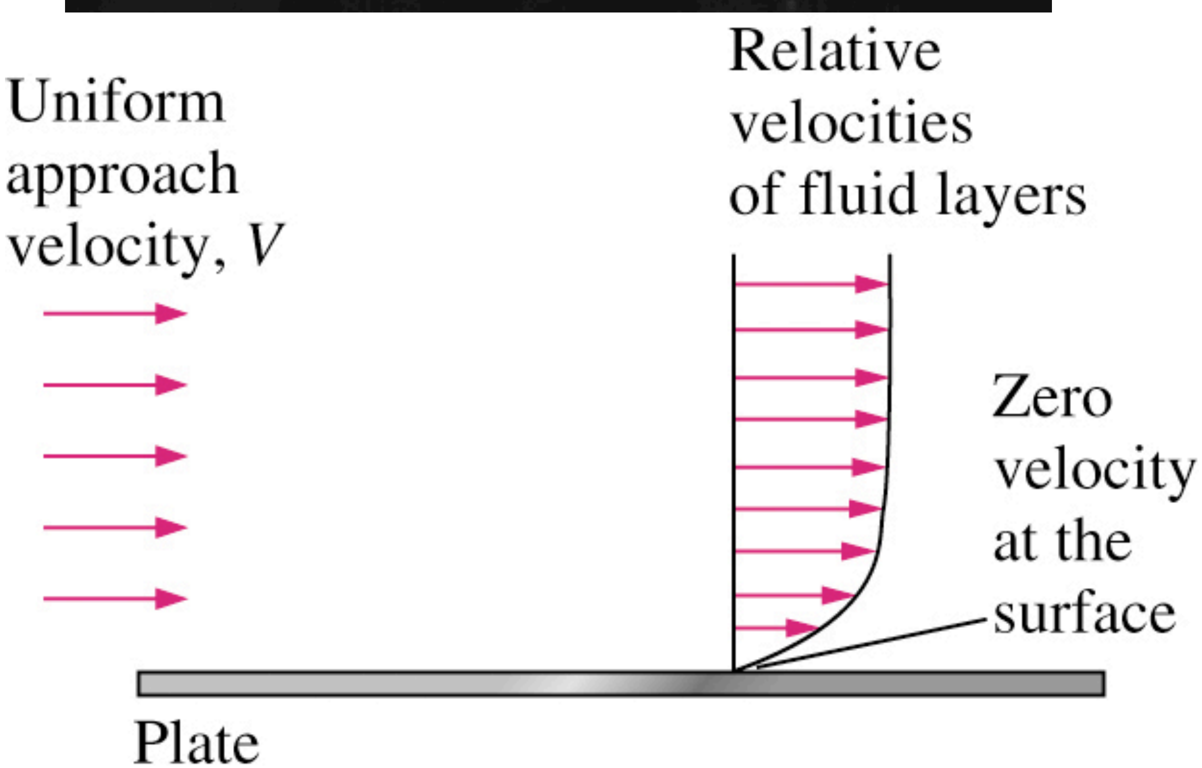
Viscosity



- Viscosity is a property that represents the internal resistance of a fluid to motion.
- The force a flowing fluid exerts on a body in the flow direction is called the drag force, and the magnitude of this force depends, in part, on viscosity.

No-slip condition





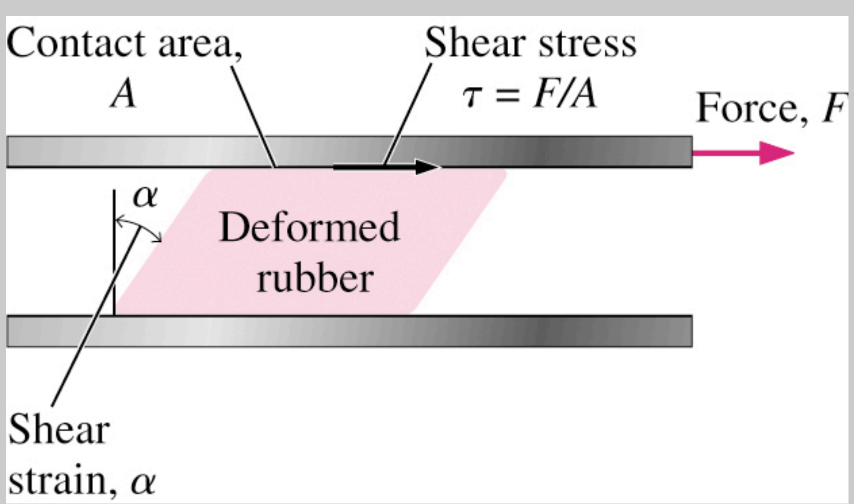
- No-slip condition: A fluid in direct contact with a solid "sticks" to the surface due to viscous effects
- Responsible for generation of wall shear stress τ_w, surface drag $D = \int \tau_w \, dA$, and the development of the boundary layer
- The fluid property responsible for the no-slip condition is viscosity
- Important boundary condition in formulating initial boundary value problem (IBVP) for analytical and computational fluid dynamics analysis

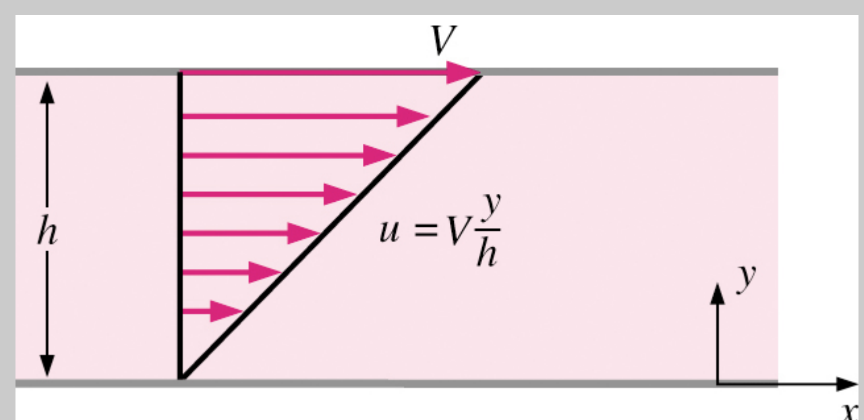
What is a fluid?

- A fluid is a substance in the gaseous or liquid form
- Distinction between solid and fluid?
  - Solid: can resist an applied shear by deforming. Stress is proportional to strain
  - Fluid: deforms continuously under applied shear. Stress is proportional to strain rate

Solid

$$\tau = \frac{F}{A} \propto \alpha$$



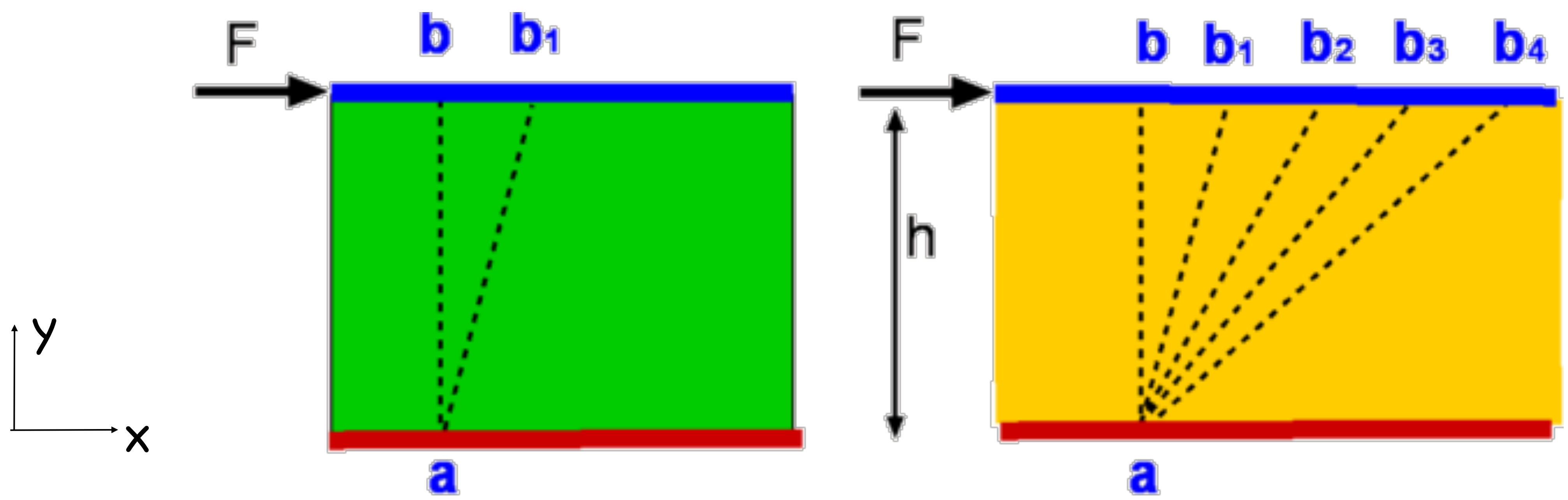


Fluid

$$\tau = \frac{F}{A} \propto \eta \frac{V}{h}$$

Strain as a measure of Deformation

To understand deformation due to shear, picture two flat plates with a fixed spacing, h, between them:



a) Solid filled between plates　　b) Fluid filled between plates

- Fluids are qualitatively different from solids in their response to a shear stress. Ordinary fluids such as air and water have no intrinsic configuration, and hence fluids do not develop a restoring force that can provide a static balance to a shear stress.

- When the shear stress is held steady, and assuming that the geometry does not interfere, the shear deformation rate, may also be steady or have a meaningful time-average.

Strain as a measure of Deformation

A strain measure for simple shear can be obtained by dividing the displacement of the moving plate, Δx, by the distance between the plates:

$$\gamma = \frac{\Delta x}{h} \simeq \frac{dx}{dy}$$

Shear strain

The shear rate, or rate of shearing strain, is the rate of change of shear strain with time:

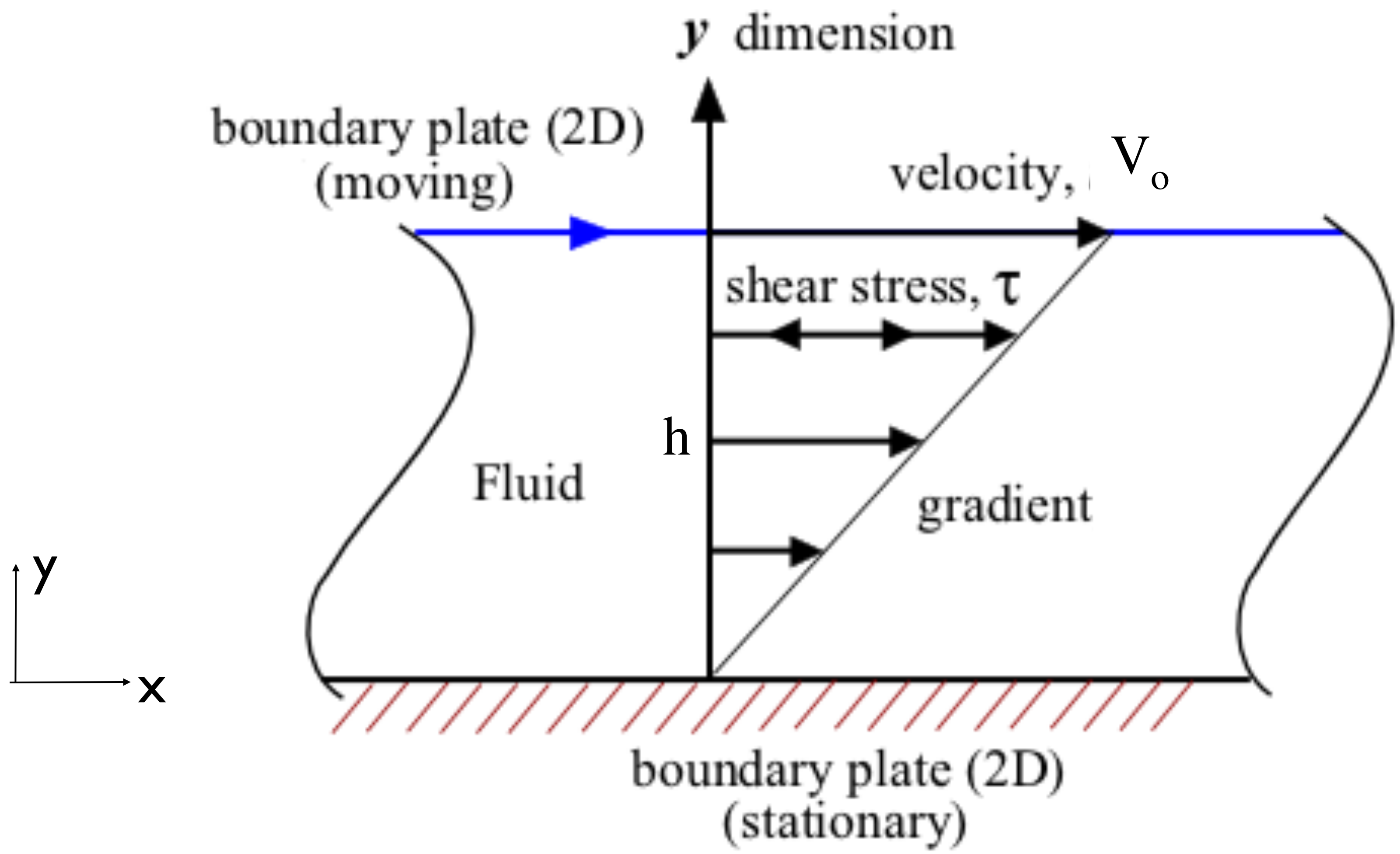
$$\dot{\gamma} = \frac{d\gamma}{dt} = \frac{d}{dt}\left(\frac{dx}{dy}\right) = \frac{d}{dy}\left(\frac{dx}{dt}\right)$$

$$\dot{\gamma} = \frac{dv}{dy}$$

Shear strain rate

Viscosity is a property that represents the internal resistance of a fluid to flow

Simple Shear Flow

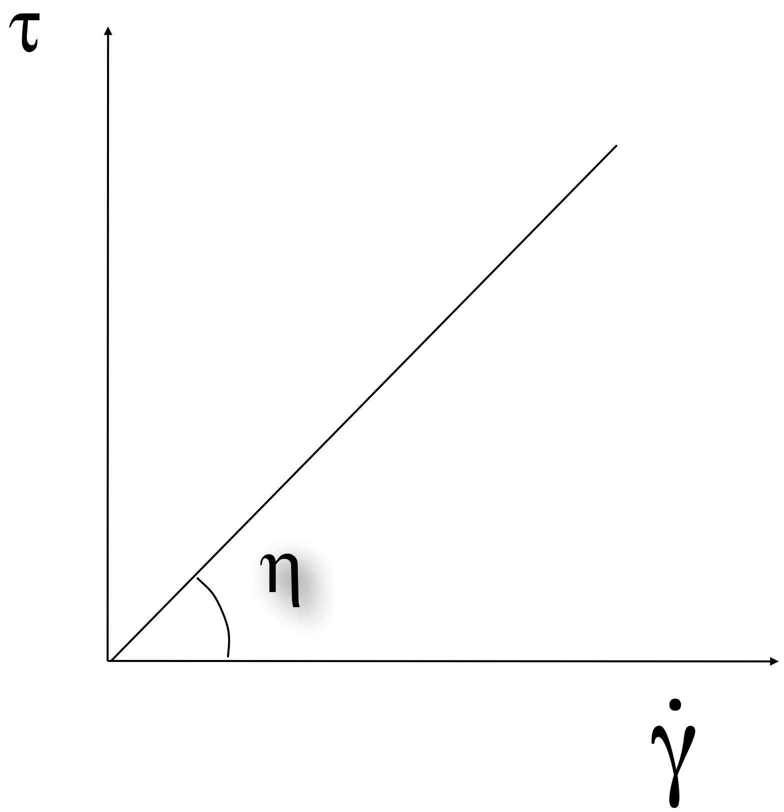


The velocity profile is a straight line: the velocity varies uniformly from 0 to V_0

$$\dot{\gamma} = \frac{dv}{dy} = \frac{V_0}{h}$$

Newton's Law of Viscosity

Newtonian fluids:
Shearing stress is linearly related to the rate of shearing strain.



This is called a "flow curve"
The proportionality constant is the viscosity

Newton's law of viscosity

$$\tau = \eta \frac{dv}{dx} = \eta \frac{d\gamma}{dt}$$

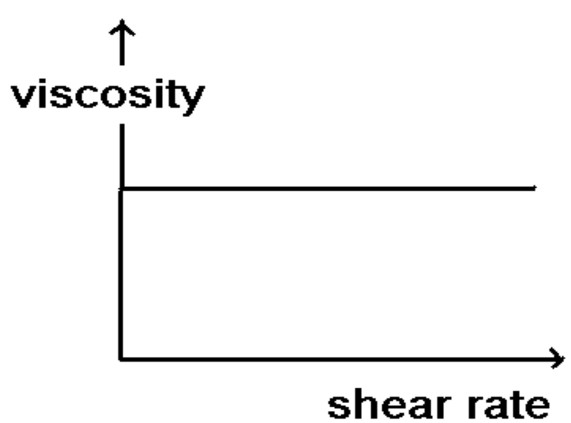
Newtonian Fluids

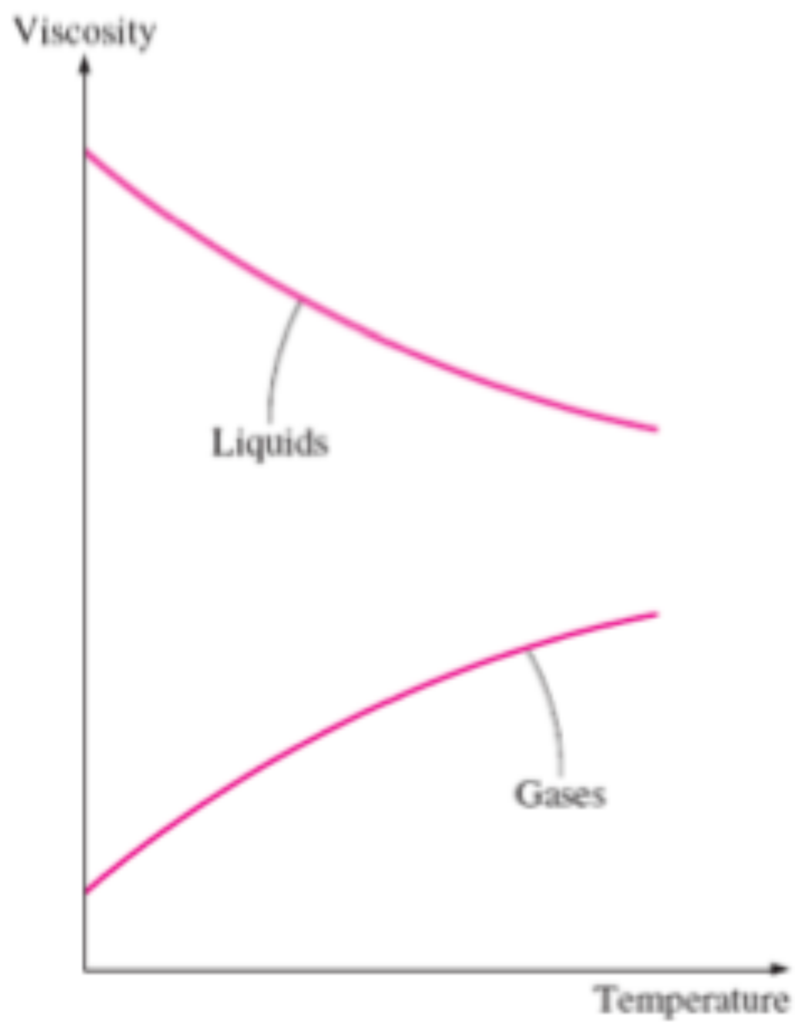
Viscosity of Newtonian fluids depends only on temperature and pressure, e.g.:

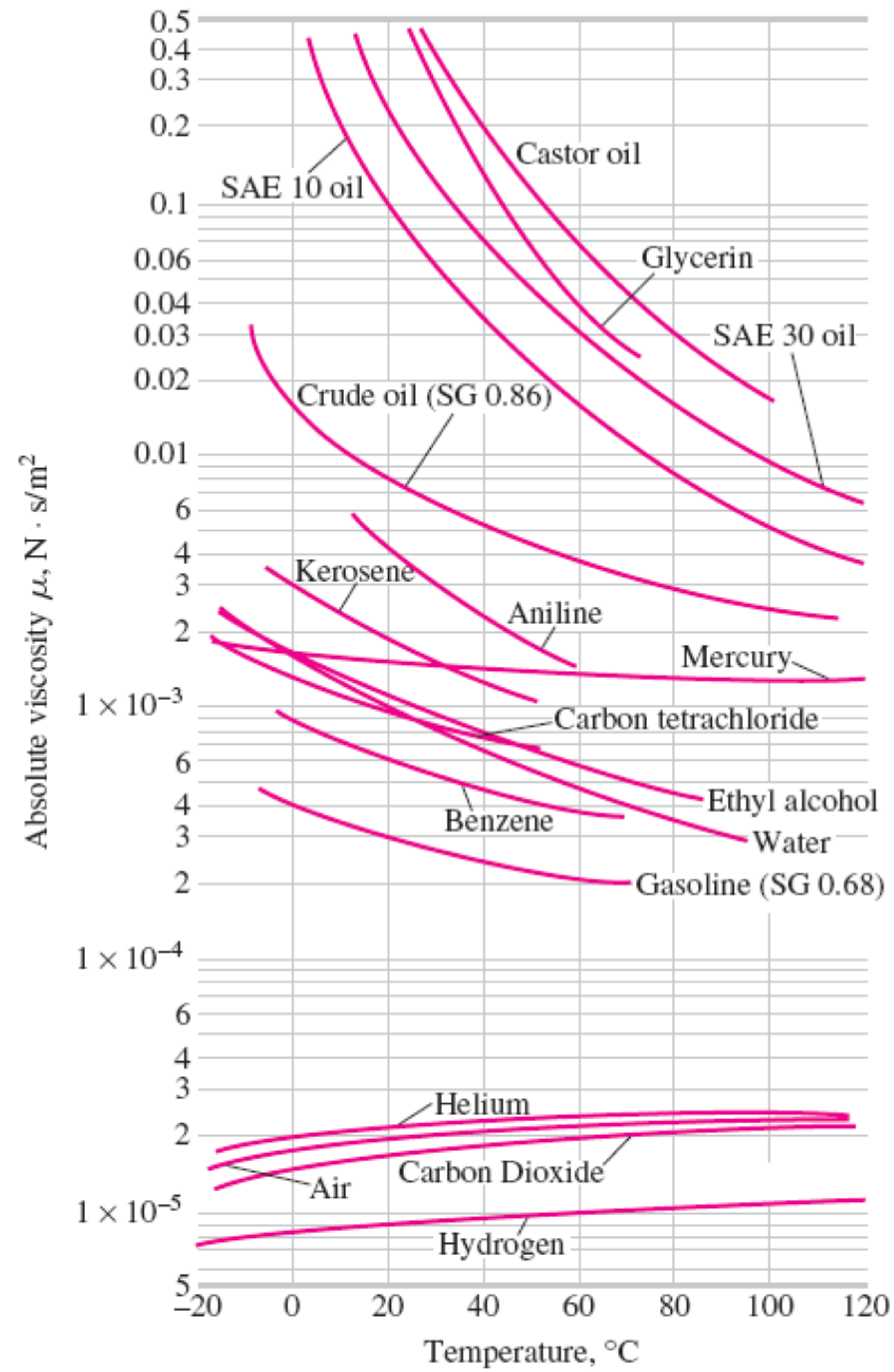
$$\eta(T,P) = \eta_0 e^{\left[\frac{\Delta E}{R}\left(\frac{T_0 - T}{T_0 T}\right)\right]} e^{\beta(P - P_0)}$$

Where:
η_0 is viscosity at T_0 and P_0
(reference temperature and pressure)
ΔE: activation energy for flow
R: gas constant
β: material property [m^2/N]

Most common fluids such as water, air, gasoline, and oils are Newtonian fluids.
Blood and liquid plastics are example of non-Newtonian fluids.
Note that viscosity is independent of the rate of deformation for Newtonian fluids.







The viscosity of liquids decreases and the viscosity of gases increases with temperature. (dynamic & kinematics viscosity)

Coefficient of Dynamic Viscosity (absolute viscosity)

The Coefficient of Dynamic Viscosity, η , is defined as the shear force, per unit area (measurement of the fluid's internal resistance to flow), (or shear stress), required to drag one layer of fluid with unit velocity past another layer a unit distance away (velocity gradient or shear rate).

$$\eta = \tau \Big/ \frac{du}{dy} = \frac{Force}{Area} \Big/ \frac{Velocity}{Distance} = \frac{Force \times Time}{Area} = \frac{Mass}{Length \times Time}$$

Units: Newton seconds per square meter, Nsm^{-2} or Kilograms per meter per second, $kgm^{-1}s^{-1}$, *Pa s* .

Although note that η is often expressed in *Poise*, P , where 10 P = 1 $kgm^{-1}s^{-1}$

Coefficient of Kinematic Viscosity

Kinematic Viscosity, *ν*, is defined as the ratio of dynamic viscosity to mass density.

$$\upsilon = \frac{\eta}{\rho}$$

Units: square meters per second, m^2/s

Although note that *ν* is often expressed in *Stokes*, St , where 1 Stoke = 0.0001m^2/s

Fluid	μ, kg/(m · s)†	Ratio $\mu/\mu(H_2)$	ρ, kg/m^3	ν m^2/s†	Ratio $\nu/\nu(Hg)$
Hydrogen	8.8 E–6	1.0	0.084	1.05 E–4	920
Air	1.8 E–5	2.1	1.20	1.51 E–5	130
Gasoline	2.9 E–4	33	680	4.22 E–7	3.7
Water	1.0 E–3	114	998	1.01 E–6	8.7
Ethyl alcohol	1.2 E–3	135	789	1.52 E–6	13
Mercury	1.5 E–3	170	13,580	1.16 E–7	1.0
SAE 30 oil	0.29	33,000	891	3.25 E–4	2,850
Glycerin	1.5	170,000	1,264	1.18 E–3	10,300

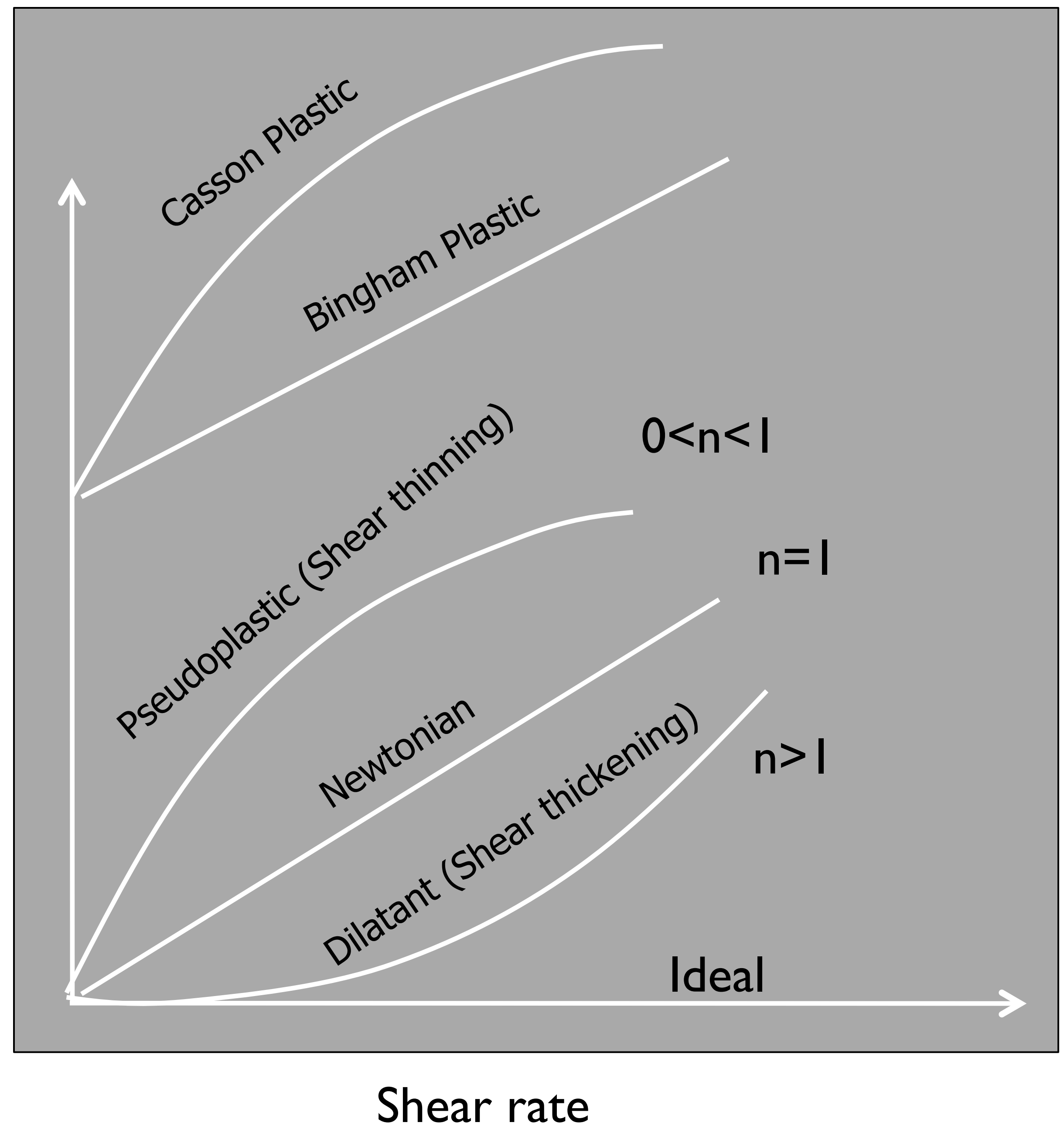
†1 kg/(m · s) = 0.0209 slug/(ft · s); 1 m^2/s = 10.76 ft^2/s.

Model parameters for different fluids

- The structure of some polymers, especially filled polymers or concentrated suspensions can be sufficiently rigid that it permits the material to withstand a certain level of deforming stress without flowing. The maximum stress that can be sustained without flow is called the "yield stress" and this type of behavior is called "plasticity"

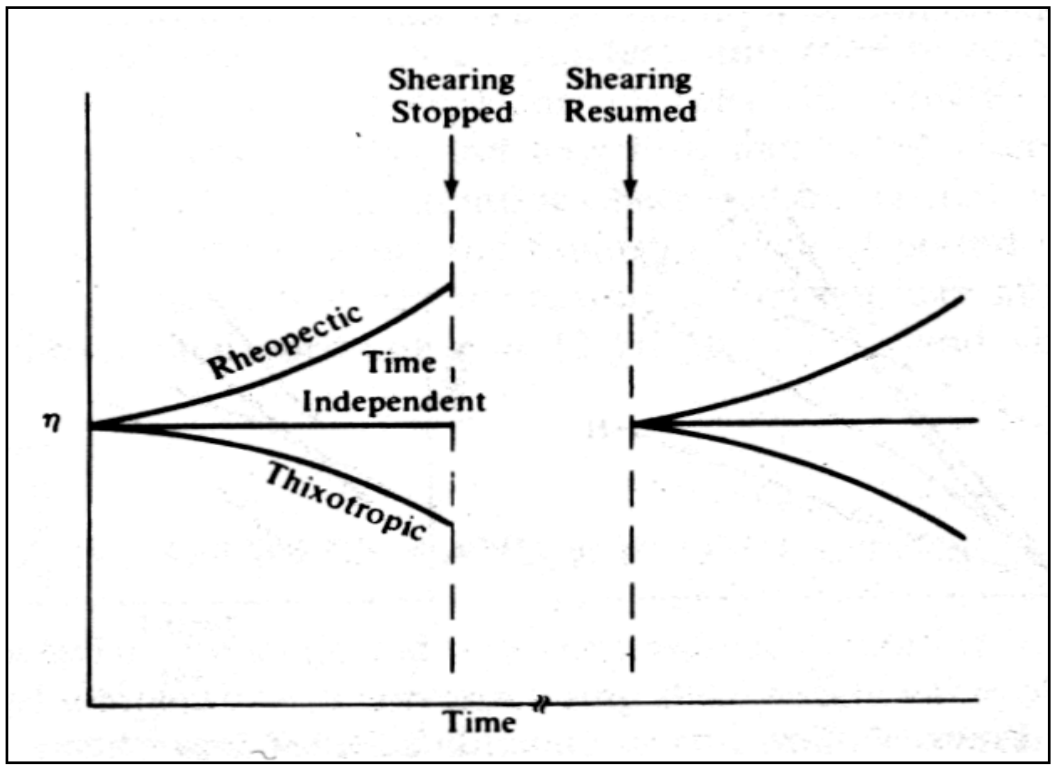
When stress is less than yield stress, material does not flow. It behaves like a solid

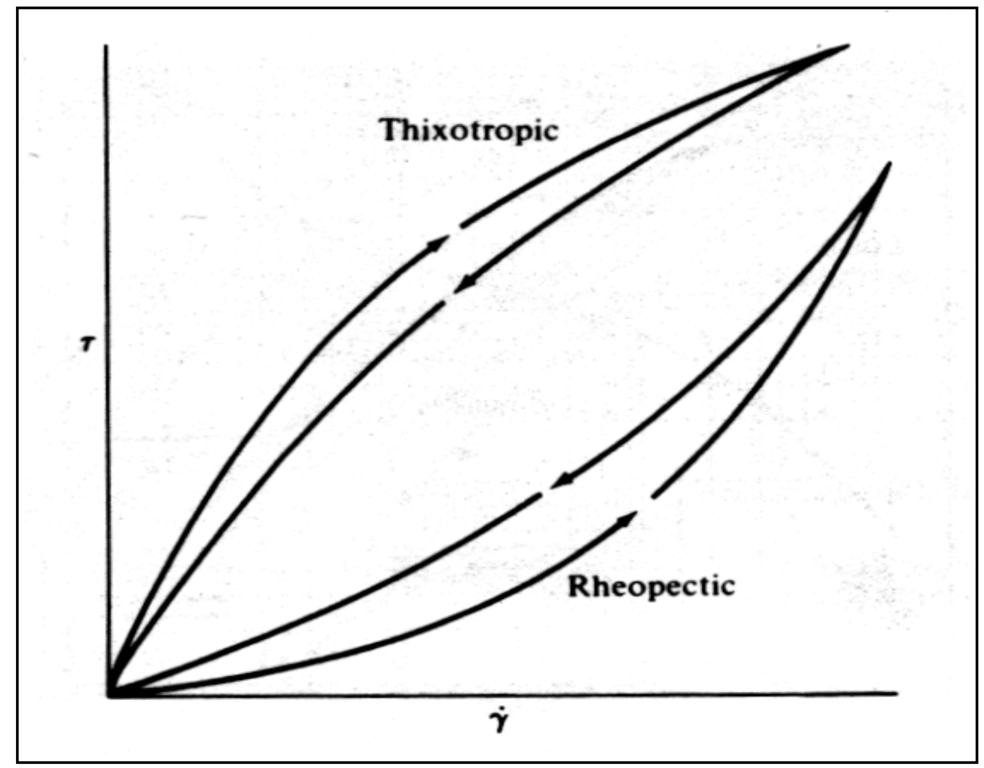
$$\tau = \tau_0 + K\left(\frac{d\gamma}{dt}\right)^n$$



Time-Dependent Behavior

- Apart from shear dependency, some fluids also exhibit reversible time-dependent properties.
- The viscosity of a "thixotropic" fluid decreases with time, implying a progressive breakdown of structure.
- The opposite behavior is observed for a "rheopectic" fluid.

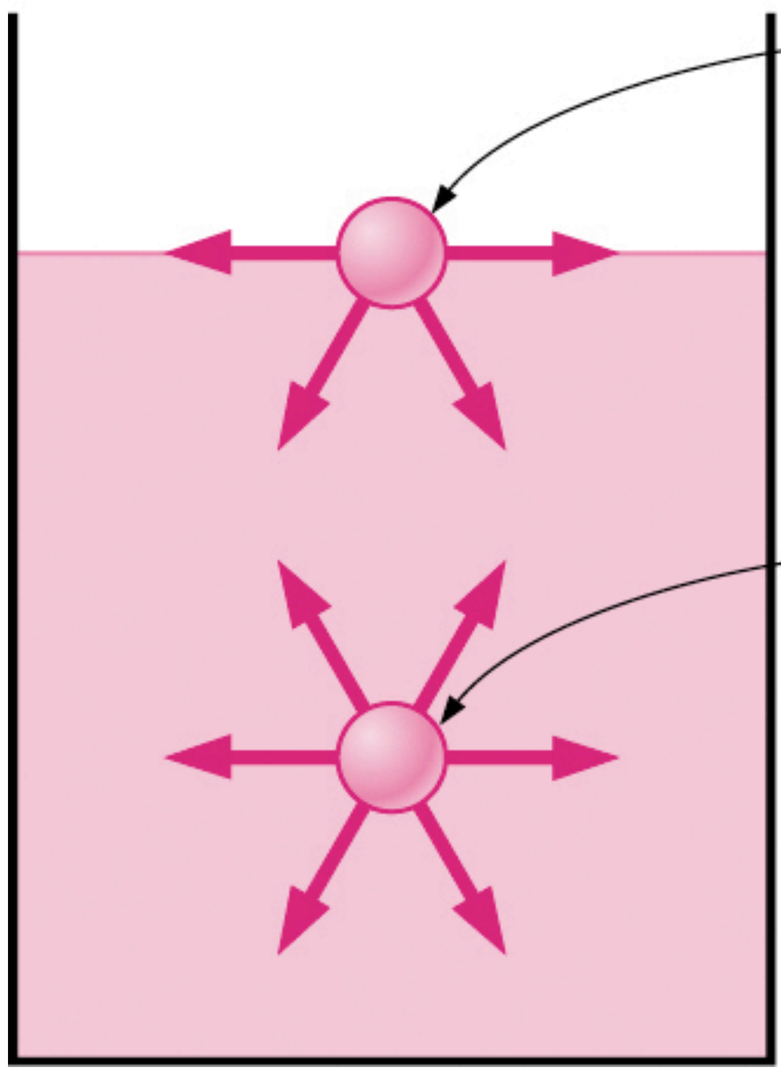




Some thixotropic fluids return to a gel state almost instantly, such as ketchup, and are better called pseudoplastic fluids. An incorrect example often used to demonstrate rheopecty is ooblek which is a very viscous, white fluid. It is a cheap and simple demonstrator, which can be picked up by hand as a semi-solid, but flows easily when not under pressure. However, cornstarch in water is actually a dilatant fluid, since it does not show the time-dependent, shear-induced change required in order to be labeled rheopectic. These terms are often and easily confused since the terms are rarely used; a true rheopectic fluid would when shaken be liquid at first, becoming thicker as shaking continued.

https://ewoldt.mechanical.illinois.edu/the-zoo/

Surface Tension



- Liquid droplets behave like small spherical balloons filled with liquid, and the surface of the liquid acts like a stretched elastic membrane under tension.
- The pulling force that causes this is
  - due to the attractive forces between molecules
  - called surface tension σ_s.
- Attractive force on surface molecule is not symmetric.
- Repulsive forces from interior molecules causes the liquid to minimize its surface area and attain a spherical shape.