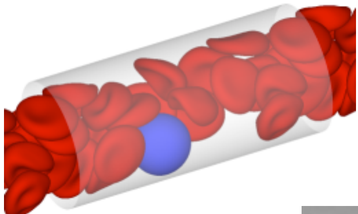
Lecture 1

- Introduction
  - Logistics
  - Why study fluid mechanics?
  - Fluidity and viscosity

> If you don't know where you're going, you might not get there.
> **Yogi Berra** *1925 -*

Why study fluid mechanics?

- *Panta rei.**



$O(10)\ \mu\mathrm{m}$

$O(1)\ \mathrm{mm}$

$O(10)\ \mathrm{cm}$

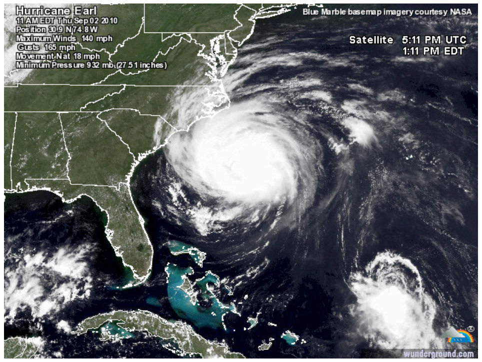
$0(10)\ \mathrm{m}$

*Heraclitus, 535-475 BCE

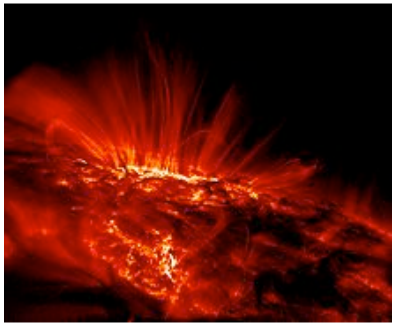
Why study fluid mechanics?

- *Panta rei.*

$0(1)$ km



$0(1000)$ km



$O(10^8)$ km

$O(10^5)$ Parsec

* 1 Parsec = 3 x 10^{16} m

Disciplines (an incomplete list)

- Engineering
  - Fluid machinery, hydraulics, piping
  - Energy systems, combustion, solar thermal
  - Aerodynamics, transportation, and propulsion
  - Chemical processing and materials synthesis
  - Petrochemical and natural resources
  - Pollution and environment
  - …
- Science
  - Climate and meteorology
  - Geophyiscs & planetary sci.
  - Cosmology
  - Biological fluids and processes
  - …

Goals of this class

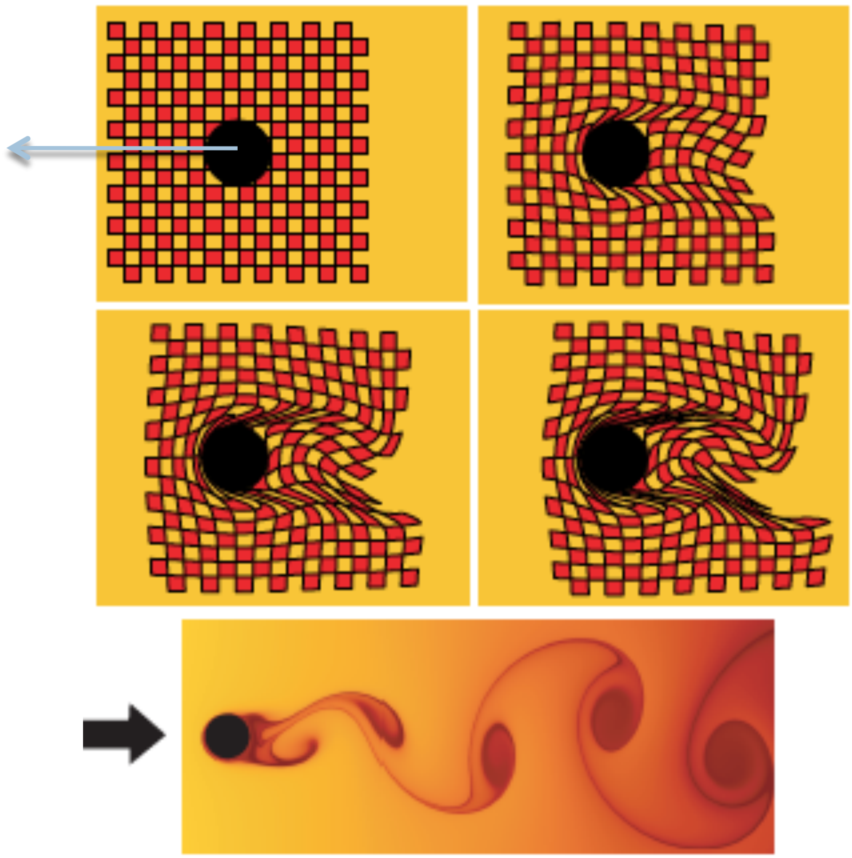
- Understand the fundamental principles (and their mathematical expression) that govern continuum fluid flow
  - Fluid properties
  - Fluid motion and kinematics
  - Forces acting on fluids and Newton's laws
  - Thermodynamics and energy
- Comfortably apply approximations and idealizations
  - Order-of-magnitude estimates
  - Dimensional analysis and scaling
  - Control volume analysis (accounting)
  - Ideal flows (neglect friction)
- Understand how experiments and simulations can be used for scientific and engineering purposes
- Understand how key engineering machines and devices work and how they can be analyzed systematically

What is a fluid?

- Solids: *Elasticity*.
  - Molecules are densely packed and organized
  - *Elasticity*: materials are deformed under static and dynamic forces, but "spring back" to the original configuration when forces are removed.
  - May reach a static (unchanging) configuration under body forces (gravity) and both normal and tangential (shearing) surface forces
- Fluids: *Fluidity*.
  - Molecules are less densely packed and disorganized
  - *Fluidity:* materials deform continuously and permanently under applied shearing forces.
  - Fluids may be static under body forces and normal surface forces (pressure) provided these are exactly balanced.

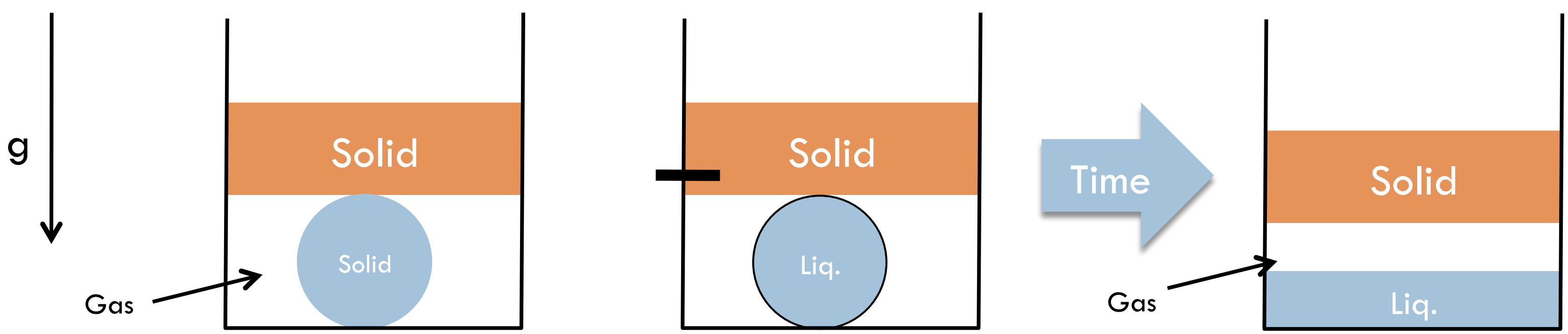
What is a fluid? (2)

- Visualization of continuous and permanent deformation



What is a fluid? (3)

- Fluids: materials that deform continuously and permanently under applied shearing forces
- Consequence: At rest, fluids take the shape of their container, except possibly at interfaces between materials that are everywhere normal to gravity (such that at rest there is no shearing force)



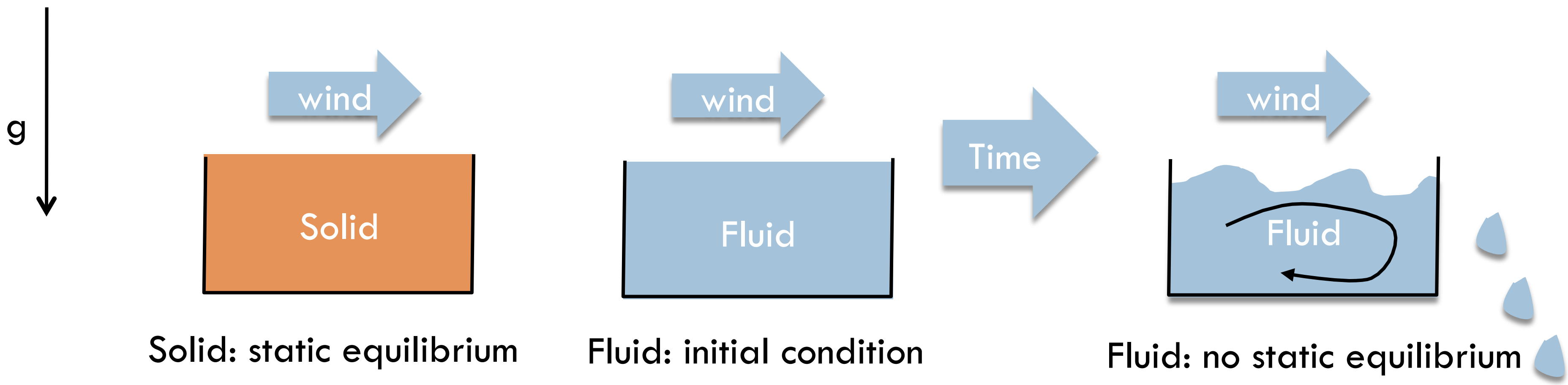
Solid: static equilibrium

Fluid: initial condition,
Pin removed and balloon bursts

Fluid: static equilibrium

What is a fluid? (4)

- Example: wind (air) over water



Solid: static equilibrium

Fluid: initial condition

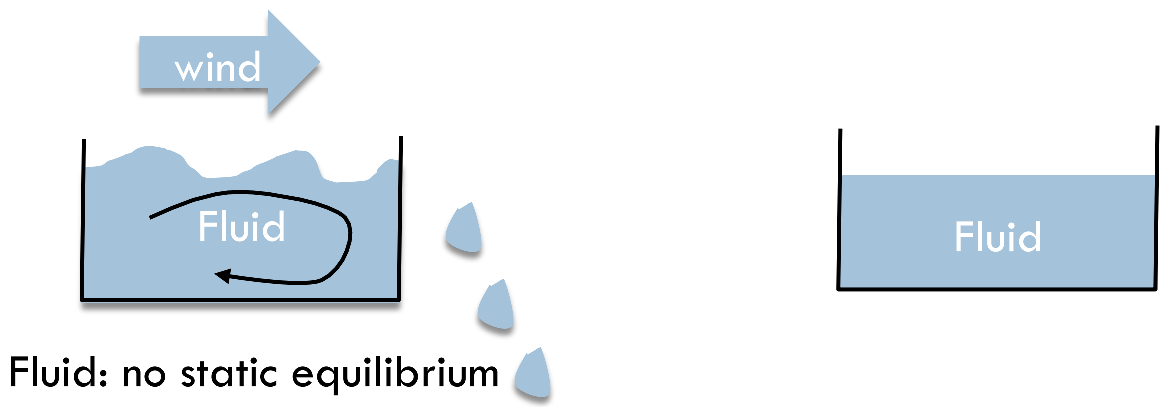
Fluid: no static equilibrium

Properties of a fluid

- "Property" refers to a measurable or inferable quantity associated with the thermodynamic state of a material or its response to externally imposed forces, heat, and change in composition
- Thermodynamic state quantities (state variables) such as pressure, temperature, density, enthalpy, coefficient of thermal expansion, and so on, are independent of these externalities
  - For a pure substance, two state variables uniquely determine all others.
  - Example: the density of a fluid at a given temperature and pressure is the same whether the fluid is being sheared or not
- Other kinds of properties are associated with response of a material to forces, heat, and change in composition
  - Viscosity, thermal conductivity, mass diffusivity
  - In some cases, these are generic to the material (only a function of the thermodynamic state), while in others these properties can depend on (for example) the rate at which something is done to the material

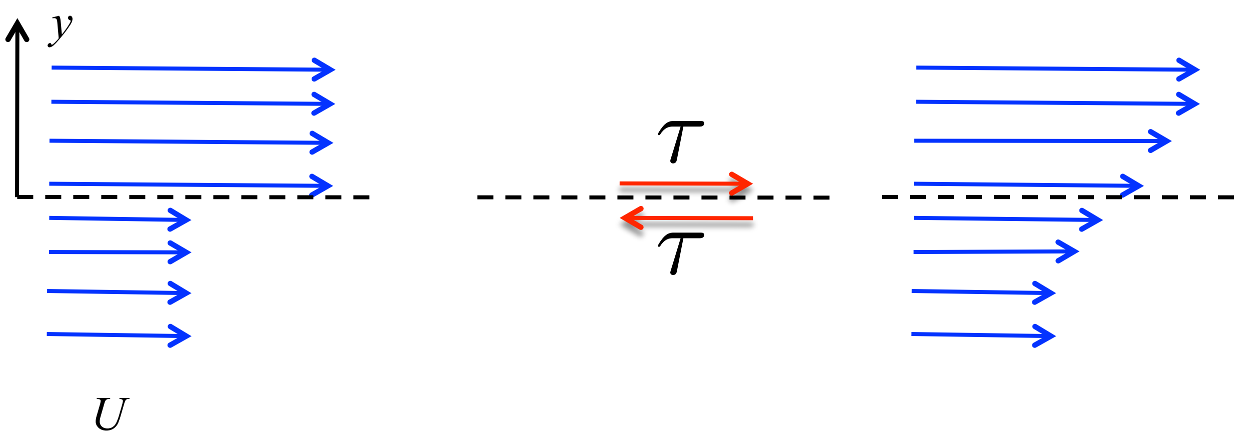
Viscosity

- What happens if we remove the wind in the last example?
- Perpetual motion?



Viscosity (2)

- Viscosity (friction) is a resistance to deformation
- It results in a force (stress) that between regions of high velocity to regions of lower velocity.
- The stress goes to zero when there is no spatial nonuniformity of the motion
- Solids: stress ~ strain
- Fluids: stress ~ rate of strain



$$\tau \sim \frac{\Delta U}{\Delta y}$$

$$\tau = \mu \frac{dU}{dy}$$

Note: this formula is a special case of a more general one we will derive later

Viscosity (3)

- Viscosity μ
  - force per unit area (stress) / (change in velocity / length)
- Density (mass/unit volume): ρ

$$[\rho] = [M/L^3]$$

$$[\mu] = \frac{[ML/T^2][L]}{[L^2]/[L/T]} = [\frac{M}{LT}] = [\rho L^2/T]$$

- Units of viscosity
  - SI: kg/m/s;
  - cgs: 1 Poise* = 1 g/cm/s = 0.1 kg/m/s

Viscosity (4)

- Kinematic viscosity: often more useful (and simpler units!)

$$\nu = \frac{\mu}{\rho} \qquad [\nu] = [L^2/T]$$

Classification of fluids

- For the simplest (*Newtonian*) fluids, viscosity is a property of the fluid, *independent the magnitude, direction, and duration of motion*
- Material properties can depend on the thermodynamic state

$$\mu = \mu\left(T, p\right)$$

{ Or any other two indep. state variables }

- Viscosity does not vary appreciably with pressure at normal T & P.

$$\mu \approx \mu(T)$$

- Viscosity generally increases with T for gases and decreases with T for liquids

Classification of fluids (2)

- Some Newtonian Fluids
  - Air (gases and mixtures of gases)
  - Water
  - Glycerin
  - Kerosine
  - Octane
  - Mercury
  - Motor oil
  - …

Classification of fluids (3)

http://en.wikipedia.org/wiki/Pitch_drop_experiment

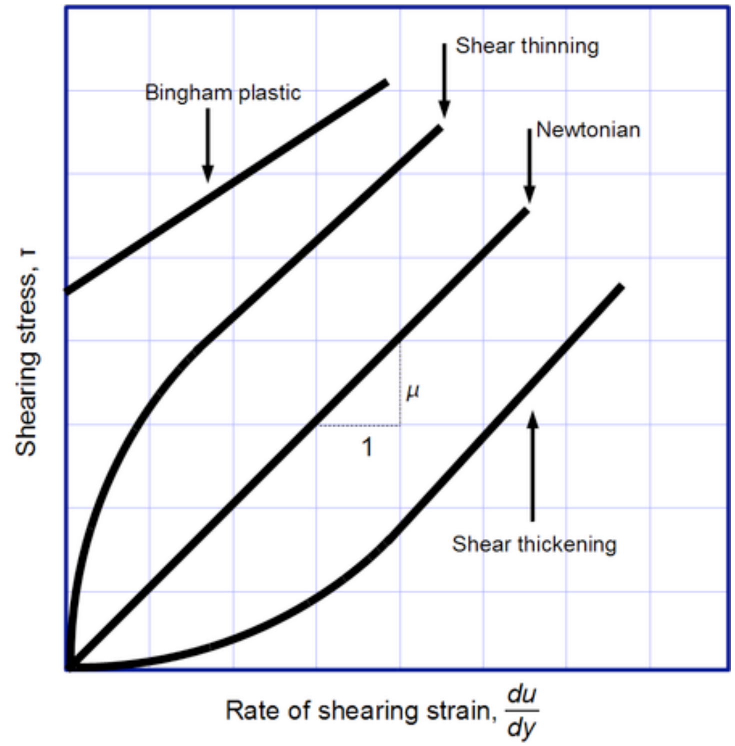
- Viscosity of some Newtonian fluids @ STP

Fluid	Density (kg/m3)	Viscosity (kg/m/s)	Kin. Viscosity (m^2/s)	Kin. Viscosity REL water
Hydrogen	0.089	9.0×10^{-6}	1.0×10^{-4}	112.0
Air (g)	1.2	1.7×10^{-5}	1.4×10^{-5}	15.7
Water (l)	998.	8.9×10^{-4}	8.9×10^{-7}	1
Mercury (l)	13500.	1.5×10^{-3}	1.1×10^{-7}	0.123
Corn syrup	1380.	1.4	1.0×10^{-3}	1.1×10^{3}
Tar pitch *	~1000	2.3×10^{8}	2.2×10^{5}	2.5×10^{11}

* Non-Newtonian

Classification of fluids (4)

- Non Newtonian Fluids
  - Usually materials with complex microscopic structure
    - Suspensions of microscopic particles or droplets (emulsions)
    - Solutions of large molecules (polymers)
- Viscosity changes with shearing rate
  - Shear thinning
  - Shear thickening
  - http://www.youtube.com/watch?v=5GWhOLorDtw
- Viscosity depends on direction of applied stress (non-isotropic)
  - Polymer solutions
- Viscosity changes with duration of stress (time history)
- Viscosity changes with applied magnetic or electric fields



Classification of fluids (5)

- Multi-component (and/or multiphase) fluids
  - Sometimes, we can view multi-component materials as a single fluid
  - Granular flow (sand in an hourglass, debris flow)
  - Liquids with "small" gas bubbles
  - Particulate flows (in liquids and gases)
  - More complex behavior than Newtonian (and even non-Newtonian) fluids

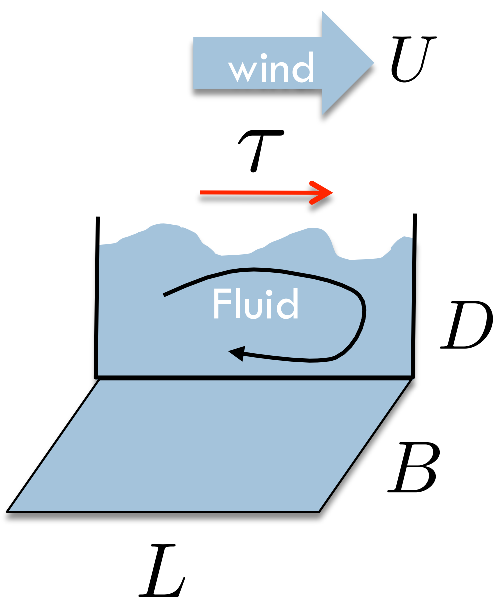
The Reynolds number

- Nature doesn't care about the (arbitrary) units with which we choose to describe material properties
- We want all our analysis to apply to the broadest class of problems possible
- We want to have to conduct as few experiments or prototypes as possible

- The viscous stress should be compared to some other force per unit area to determine 'how viscous' the behavior
- How this is done depends on the particular situation (we should always define "a" Reynolds number, not necessarily "the" Reynolds number)

Back to example

- Suppose wind stops at some time. How long until fluid motion in the tank ceases?



Mass * accel = force

$$\rho D L B \frac{\Delta U}{\Delta t} \sim \tau L B$$

$$\tau \sim \mu \frac{\Delta U}{D}$$

$$\Delta t \sim \frac{D^2 \rho}{\mu}$$

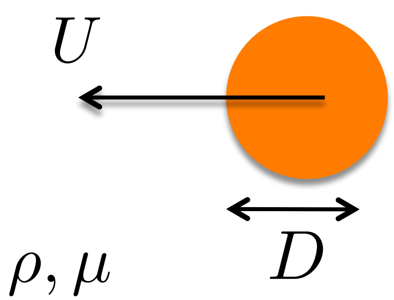
$$\Delta t \frac{U}{D} \sim \frac{\rho U D}{\mu} = \frac{U D}{\nu} = \mathrm{Re}$$

Reynolds number (2)

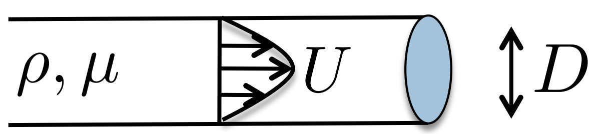
- Generically, the ratio of 'inertial force' to viscous force

$$\mathrm{Re} = \frac{\rho U D}{\mu} = \frac{UD}{\nu}$$

External flow: sphere dragged through fluid



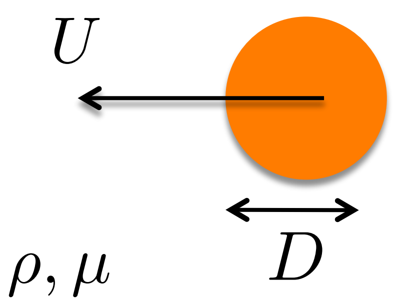
Internal flow in round pipe



Reynolds number (3)

- For example, the force acting on a sphere dragged through the fluid, when suitably scaled*, will be the same regardless of the specific fluid, provided Re is the same

$$\mathrm{Re} = \frac{UD}{\nu}$$



Fluid	Kin. Viscosity (m^2/s)	Diameter (m)	Velocity (m/s)	Reynolds number
Air	1.4×10^{-5}	1×10^{-5}	1.4	1
Corn syrup	1.0×10^{-3}	1×10^{-2}	0.1	1

By convention, the force is scaled as: $C_D = \dfrac{F_D}{\frac{1}{2}\rho U^2 \frac{\pi D^2}{4}} = \mathrm{fun}\,(\mathrm{Re})$

*…and with additional caveats we will discuss next lecture!

Summary

- Fluids are materials that deform continuously and permanently under applied shearing forces
- Viscosity leads to a surface force (stress) between adjacent parcels of fluid moving with different velocities
  - due to momentum transfer between molecules
  - tends to diffuse (smear, lessen) velocity differences over time
- The Reynolds number is an important nondimensional parameter that tells us how important viscosity is
  - Ratio of "inertial force" (i.e. acceleration) to viscous force
  - Controls how quickly (or 'efficiently') viscosity acts to diffuse momentum compared to an imposed rate of change of momentum (inertia)