Física (Mecânica) dos Meios Contínuos

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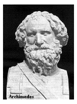
History

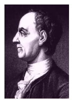
Faces of Fluid Mechanics


Archimedes (C. 287-212 BC)


Newton (1642-1727)


Leibniz (1646-1716)

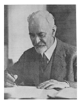

Bernoulli (1667-1748)


Euler (1707-1783)


Navier (1785-1836)


Stokes (1819-1903)


Reynolds (1842-1912)


Prandtl (1875-1953)


Taylor (1886-1975)

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Significance

- Fluids everywhere
  - Weather & climate
  - Vehicles: automobiles, trains, ships, and planes, etc.
  - Environment
  - Physiology and medicine
  - Sports & recreation
  - Many other examples!

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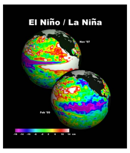
Weather & Climate

Tornadoes

Thunderstorm

Global Climate



Hurricanes

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Vehicles

Aircraft

Surface ships

High-speed rail

Submarines

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Environment

Air pollution

River hydraulics

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Physiology and Medicine

Blood pump

A BVS blood pump

Ventricular assist device

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Sports & Recreation

Water sports

Cycling

Offshore racing

Auto racing

Surfing

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Analytical Fluid Dynamics

- The theory of mathematical physics problem formulation
- Control volume & differential analysis (RTT)
- Exact solutions only exist for simple geometry and conditions
- Approximate solutions for practical applications
  - Linear
  - Empirical relations using EFD data

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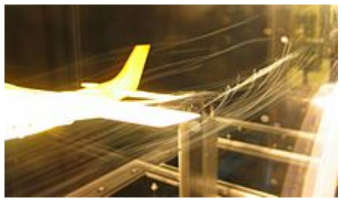
Full and model scales: wind tunnel



- Scales: full-scale and model
- Selection of the model scale: governed by dimensional analysis and similarity

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Computational Fluid Dynamics

- CFD is use of computational methods for solving fluid engineering systems, including modeling (mathematical & Physics) and numerical methods (solvers, finite differences, and grid generations, etc.).
- Rapid growth in CFD technology since advent of computer

ENIAC 1, 1946

IBM WorkStation

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Purpose

- The objective of CFD is to model the continuous fluids with Partial Differential Equations (PDEs) and discretize PDEs into an algebra problem, solve it, validate it and achieve simulation based design instead of "build & test"
- Simulation of physical fluid phenomena that are difficult to be measured by experiments: scale simulations (full-scale ships, airplanes), hazards (explosions,radiations,pollution), physics (weather prediction, planetary boundary layer, stellar evolution).

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Modeling

- Mathematical physics problem formulation of fluid engineering system
- Governing equations: Navier-Stokes equations (momentum), continuity equation, pressure Poisson equation, energy equation, ideal gas law, combustions (chemical reaction equation), multi-phase flows(e.g. Rayleigh equation), and turbulent models (RANS, LES, DES).
- Coordinates: Cartesian, cylindrical and spherical coordinates result in different form of governing equations
- Initial conditions(initial guess of the solution) and Boundary Conditions (no-slip wall, free-surface, zero-gradient, symmetry, velocity/pressure inlet/outlet)
- Flow conditions: Geometry approximation, domain, Reynolds Number, and Mach Number, etc.

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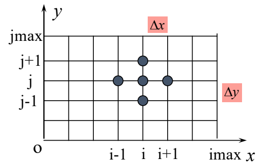
Numerical methods

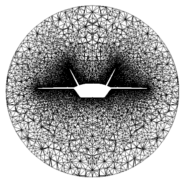
- **Finite difference methods**: using numerical scheme to approximate the exact derivatives in the PDEs

$$\frac{\partial^2 P}{\partial x^2} = \frac{P_{i+1} - 2P_i + P_{i-1}}{\Delta x^2}$$

$$\frac{\partial^2 P}{\partial y^2} = \frac{P_{j+1} - 2P_j + P_{j-1}}{\Delta y^2}$$



- **Finite volume methods**
- **Grid generation:** conformal mapping, algebraic methods and differential equation methods
- **Grid types**: structured, unstructured
- **Solvers**: direct methods (Cramer's rule, Gauss elimination, LU decomposition) and iterative methods (Jacobi, Gauss-Seidel, SOR)



Slice of 3D mesh of a fighter aircraft

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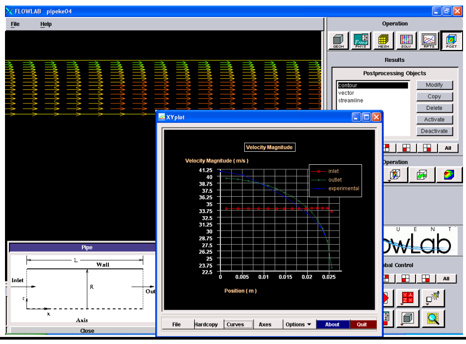
"Hands-on" experience using CFD Interface (pipe template)



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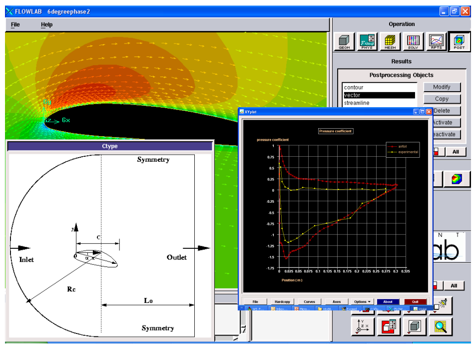
"Hands-on" experience using CFD Interface (airfoil template)



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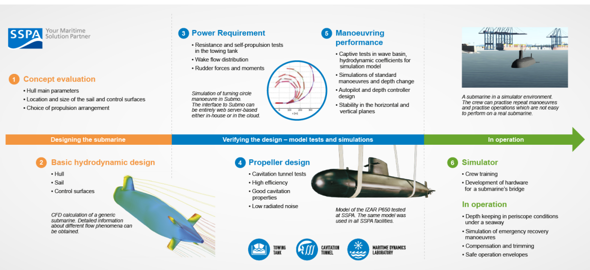
Designing, building and operating a submarine



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Diffusion & Convection

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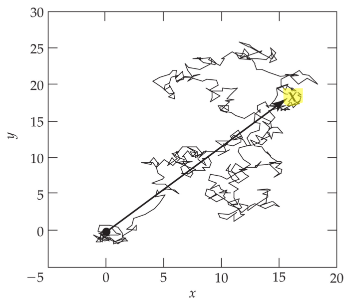
Diffusion: Random walk



Range of Values for the Binary Diffusion Coefficient, D_{ij}, at Room Temperature

Diffusing quantity	Diffusion coefficients ($cm^2\ s^{-1}$)
Gases in gases	0.1 to 0.5
Gases in liquids	1×10^{-7} to 7×10^{-5}
Small molecules in liquids	1×10^{-5}
Proteins in liquids	1×10^{-7} to 7×10^{-7}
Proteins in tissues	1×10^{-7} to 7×10^{-10}
Lipids in lipid membranes	1×10^{-9}
Proteins in lipid membranes	1×10^{-10} to 1×10^{-12}

Range of Values for Viscosity, Density, and Kinematic Viscosity at Room Temperature

	Viscosity, μ ($g\ cm^{-1}\ s^{-1}$)	Density, ρ ($g\ cm^{-3}$)	Kinematic viscosity, $\nu = \mu/\rho$ ($cm^2\ s^{-1}$)
Gases	10^{-4}	0.001	0.1
Liquids			
Water	0.01	1.0	0.01
Glycerol	10	1	10
Blood	0.03	1.2	0.025

Relations between Fluxes and Gradients for Molecular Transport

Molecular transport mechanism	Flux	Gradient	Coefficient of proportionality
Momentum	Shear stress	Velocity	Viscosity
Mass	Mass or molar flux	Concentration[a]	Diffusion coefficient
Energy	Energy	Temperature	Thermal conductivity

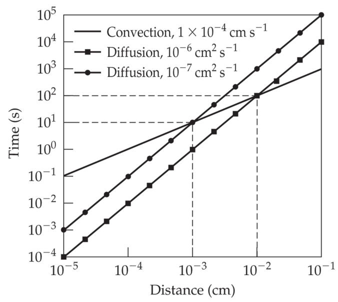
Relative Importance of Diffusion and Convection

Molecule	MW ($g\ mol^{-1}$)	D_{ij} ($cm^2\ s^{-1}$)	Diffusion time, L^2/D_{ij} (s)	Pe $= Lv/D_{ij}$
Oxygen	32	2×10^{-5}	5	0.05
Glucose	180	2×10^{-6}	50	0.50
Insulin	6,000	1×10^{-6}	100	1.0
Antibody	150,000	6×10^{-7}	167	1.67

Particle	Diameter	D_{ij} ($cm^2\ s^{-1}$)	Diffusion time (s)	Pe
Virus	0.1 μm	5×10^{-8}	2,000	20
Bacterium	1 μm	5×10^{-9}	20,000	200
Cell	10 μm	5×10^{-10}	200,000	2,000

Note: For L = 100 μm, and if v = 1 μm s^{-1}, the time for convection is always equal to L/v = 100 s for all molecules and particles.

Diffusion and convection times



Reynolds number

The Reynolds number is the ratio of inertial forces to viscous forces within a fluid which is subjected to relative internal movement due to different fluid velocities.

$$Re = \frac{\rho V L}{\eta}$$

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Peclet number

The Peclet number is the ratio of the rate of advection of a physical quantity by the flow to the rate of diffusion of the same quantity driven by an appropriate gradient.

$$Pe = \frac{VL}{D}$$

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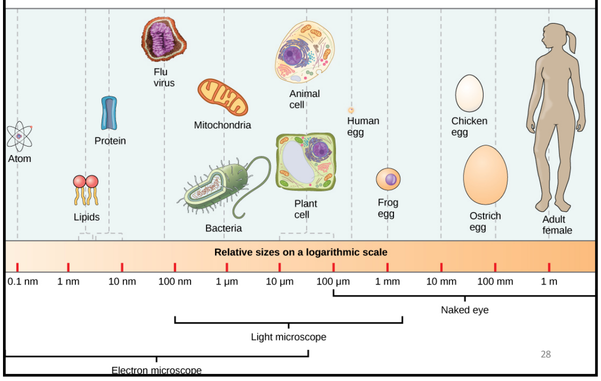
Scales of living systems



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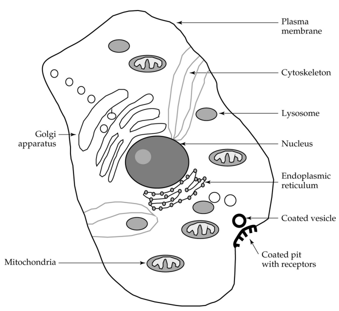
Mammalian eukaryotic cell & organelles.



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Examples of Organs and Organ Systems with Transport Functions

Organ or organ system	Transport functions
Respiratory system	Delivery of oxygen from the lungs to the blood and transport of carbon dioxide in the opposite direction
Cardiovascular system	Transport of oxygen within red blood cells
	Removal of carbon dioxide
	Delivery of antibodies and cells of immune system to sites of infection
	Thrombosis and hemostasis
Gastrointestinal tract	Digestion and absorption of nutrients
Liver	Carbohydrate storage and release
	Cholesterol metabolism and lipoprotein synthesis and metabolism
	Synthesis of plasma and transport proteins (e.g., albumin, transferring)
	Synthesis and export of molecules for tissue energy metabolism
	Urea synthesis
	Metabolism of toxins
Kidneys	Filtration of plasma
	Removal of urea and waste products
	Water reabsorption
	Maintenance of plasma volume and blood pH

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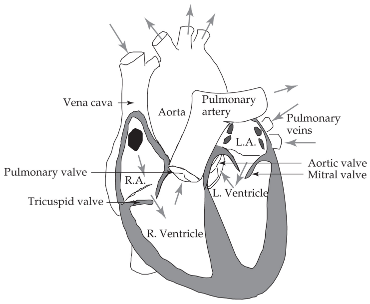
Diagram of the heart showing valves, veins and arteries



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Distribution of Blood Volume	
Region	Total (%)
Small veins and venules	45–53
Large veins	15
Lungs	10–12
Heart	8–11
Systemic arteries	10–12
Capillaries	4–5

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Blood Flow Distribution during Rest and Heavy Exercise

	Rest		Heavy exercise	
Region	L min^{-1}	Percent of cardiac output	L min^{-1}	Percent of cardiac output
Digestive system	1.40	24	0.30	1
Renal	1.10	19	0.90	4
Brain	0.75	13	0.75	3
Heart	0.25	4	1.00	4
Skeletal muscle	1.20	21	22.00	85.5
Skin	0.50	9	0.60	2
Others	0.60	10	0.10	0.5
Cardiac output	5.80	100	25.65	100.0

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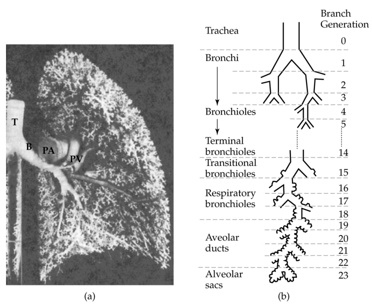
Schematic of the airways in the lung



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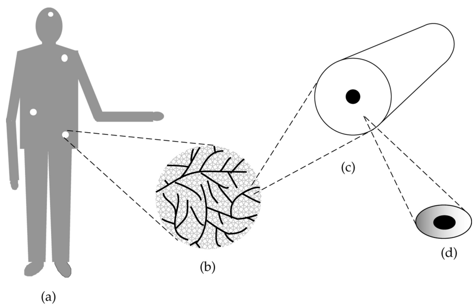

Drug delivery to tumor cells at four levels: (a) the body (~1 m), (b) the tissue (~1 cm), (c) the microvessel (~0.01 cm), and (d) the cell (~10 µm).

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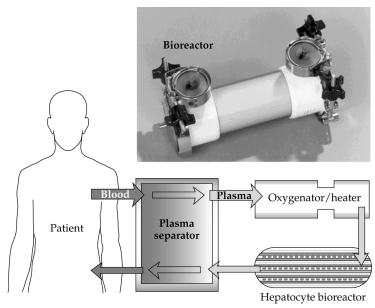
Flow for extracorporeal artificial liver.



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