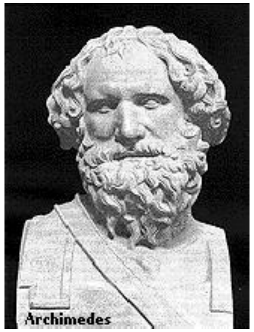
Física (Mecânica) dos Meios Contínuos

Margarida Telo da Gama

Rodrigo Coelho

History

Faces of Fluid Mechanics



Archimedes
(C. 287-212 BC)

Newton
(1642-1727)

Leibniz
(1646-1716)

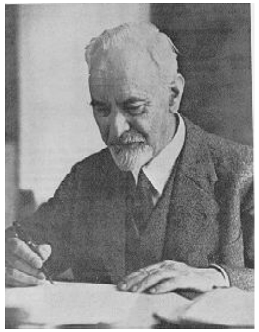
Bernoulli
(1667-1748)

Euler
(1707-1783)

Navier
(1785-1836)

Stokes
(1819-1903)

Reynolds
(1842-1912)



Prandtl
(1875-1953)

Taylor
(1886-1975)

Significance

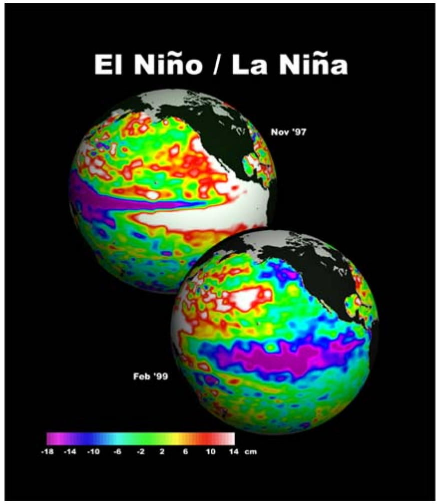
- Fluids everywhere
  - Weather & climate
  - Vehicles: automobiles, trains, ships, and planes, etc.
  - Environment
  - Physiology and medicine
  - Sports & recreation
  - Many other examples!

Weather & Climate

Tornadoes

Thunderstorm

Global Climate



Hurricanes

Vehicles

Aircraft

Surface ships

High-speed rail

Submarines

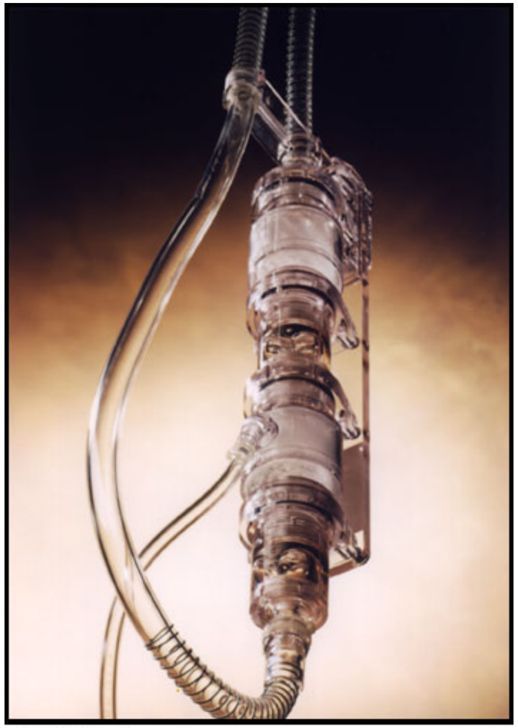
Environment

Air pollution

River hydraulics

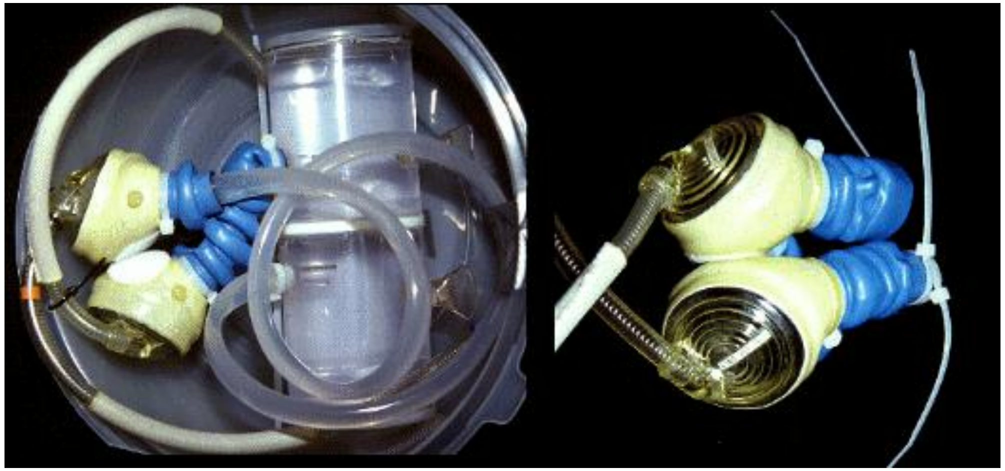
Physiology and Medicine

Blood pump



A BVS blood pump

Ventricular assist device



Sports & Recreation

Water sports

Cycling

Offshore racing

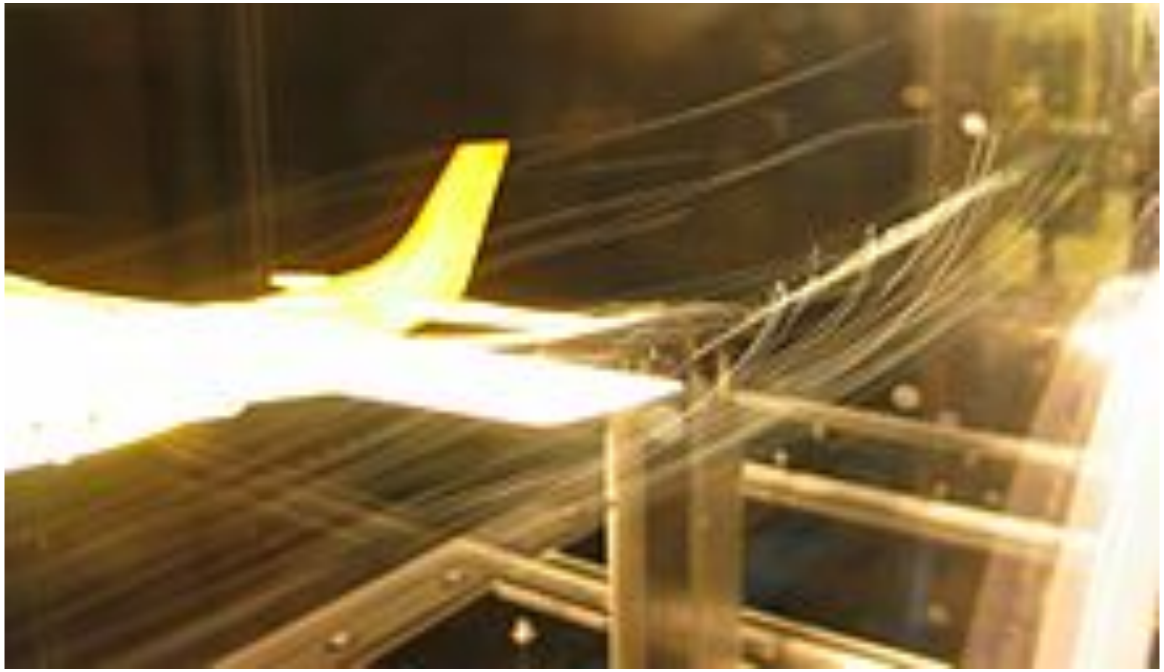
Auto racing

Surfing

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

Full and model scales: wind tunnel



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

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

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).

Modeling

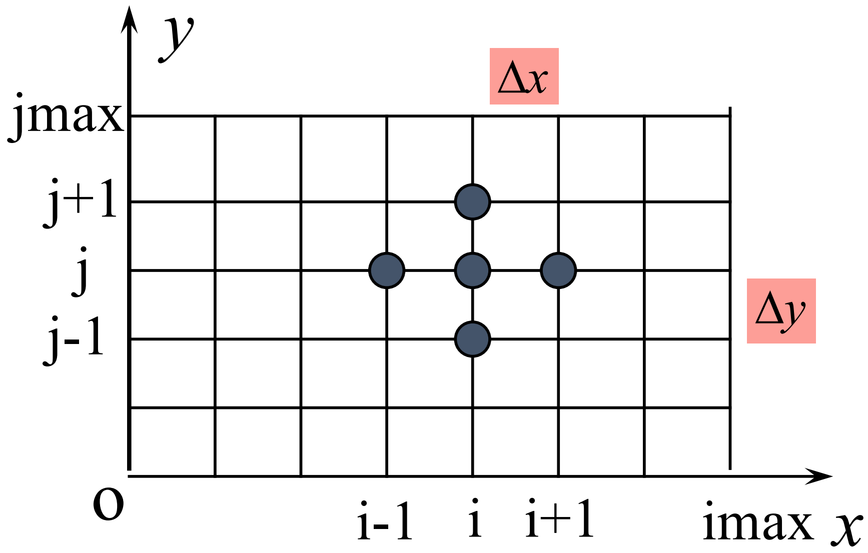
- Mathematical physics problem formulation of fluid engineering system
- Governing equations: Navier-Stokes equations (momentum), continuity equation, pressure Poisson equation, energy equation, ideal gas law, combustions (chemical reaction equation), multi-phase flows(e.g. Rayleigh equation), and turbulent 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.

Numerical methods

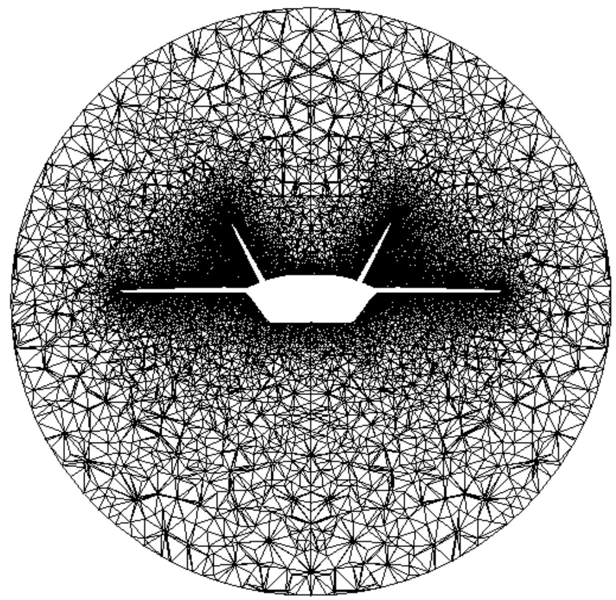
- **Finite difference methods**: using numerical scheme to approximate the exact derivatives in the PDEs

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

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

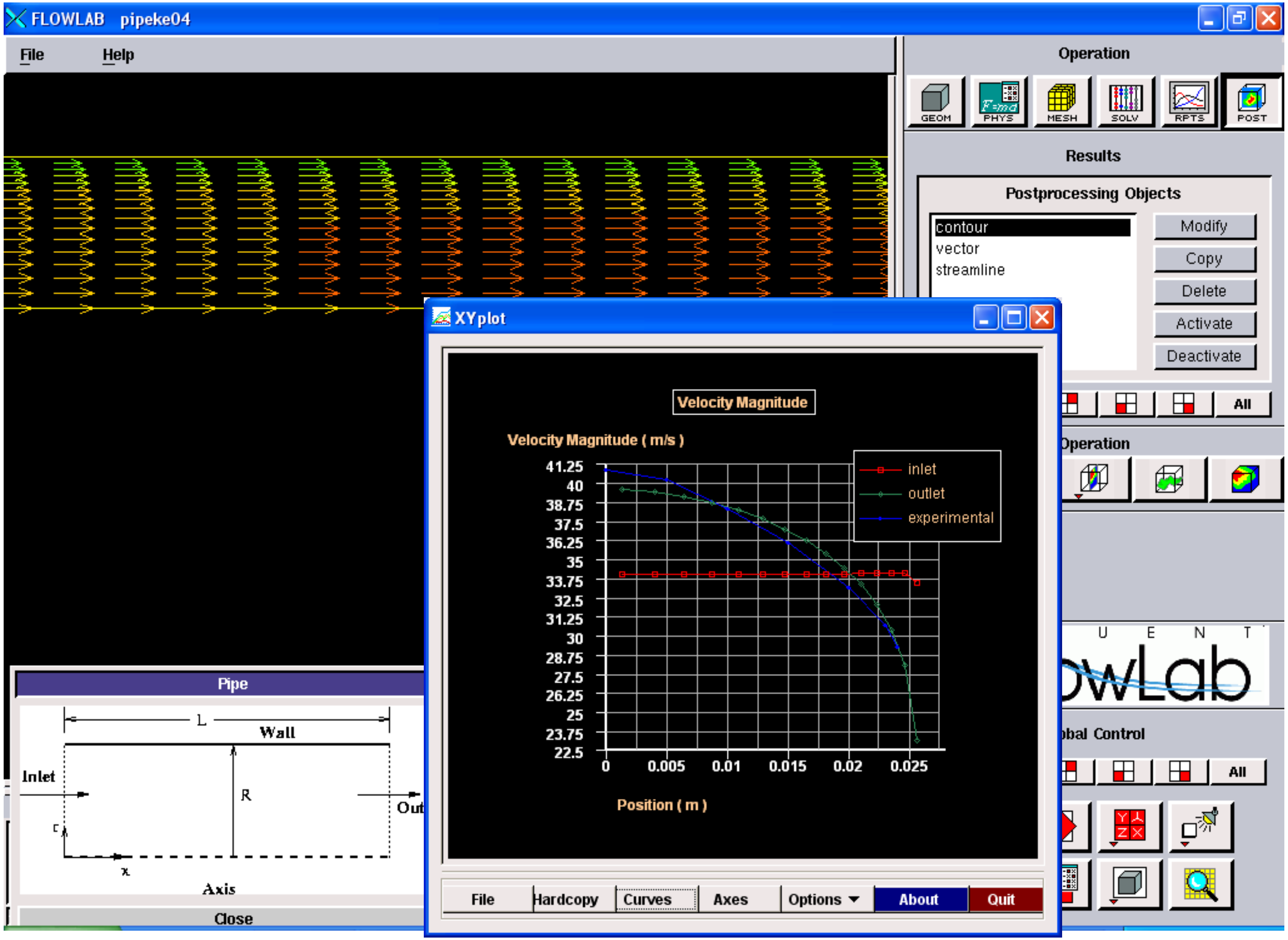


- **Finite volume methods**
- **Grid generation:** conformal mapping, algebraic methods and differential equation methods
- **Grid types**: structured, unstructured
- **Solvers**: direct methods (Cramer's rule, Gauss elimination, LU decomposition) and iterative methods (Jacobi, Gauss-Seidel, SOR)

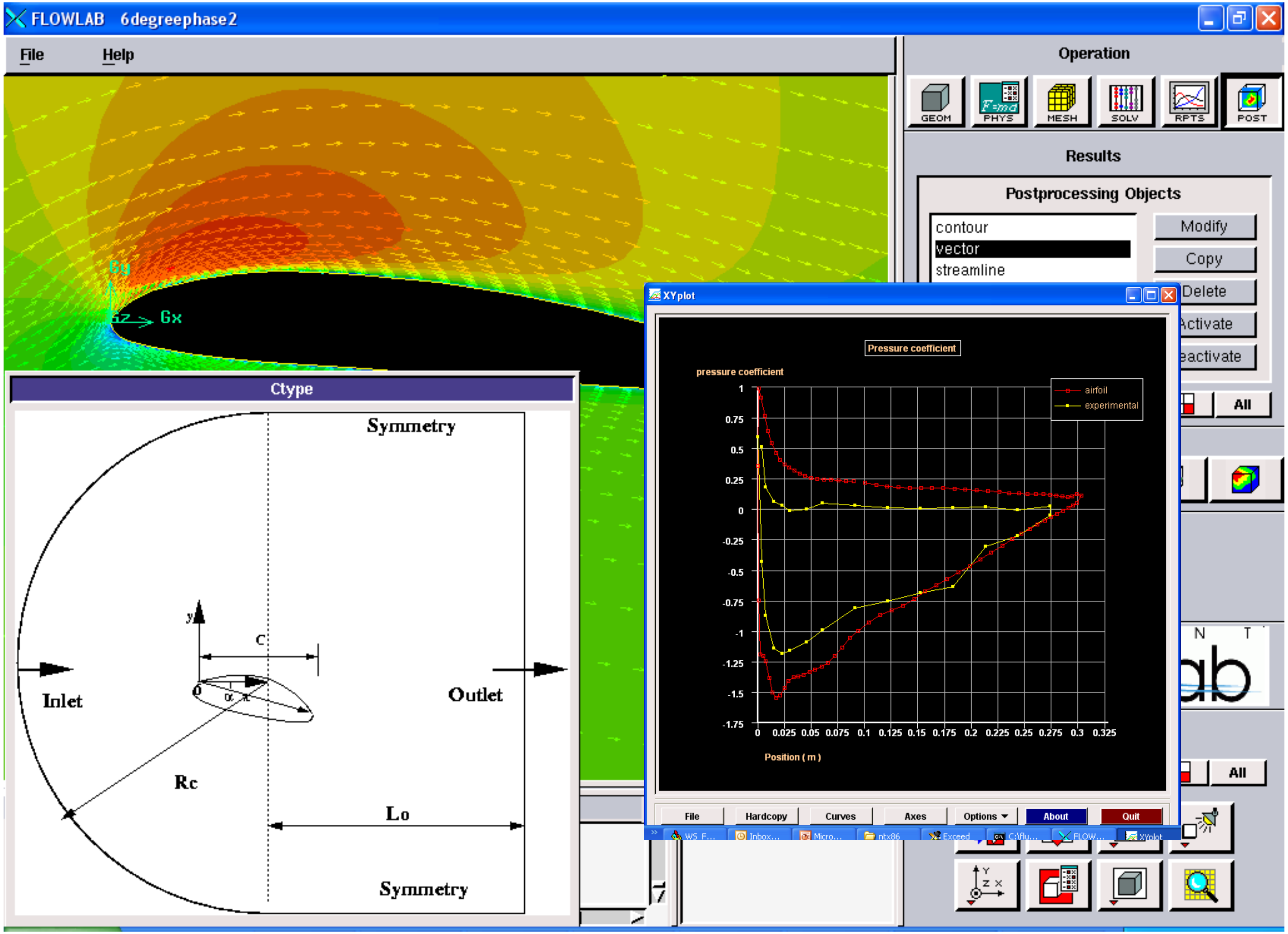


Slice of 3D mesh of a fighter aircraft

“Hands-on” experience using CFD Interface (pipe template)



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



Designing, building and operating a submarine

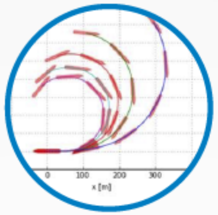
SSPA Your Maritime Solution Partner

1 Concept evaluation

- Hull main parameters
- Location and size of the sail and control surfaces
- Choice of propulsion arrangement

3 Power Requirement

- Resistance and self-propulsion tests in the towing tank
- Wake flow distribution
- Rudder forces and moments



Simulation of turning circle manoeuvre in Submo. The interface to Submo can be entirely web server-based either in-house or in the cloud.

5 Manoeuvring performance

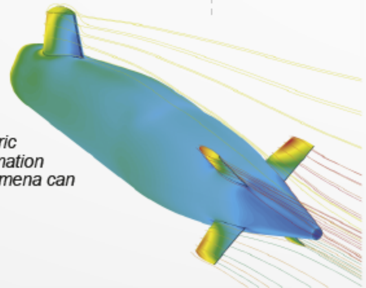
- Captive tests in wave basin, hydrodynamic coefficients for simulation model
- Simulations of standard manoeuvres and depth change
- Autopilot and depth controller design
- Stability in the horizontal and vertical planes

A submarine in a simulator environment. The crew can practise repeat manoeuvres and practise operations which are not easy to perform on a real submarine.

Designing the submarine → **Verifying the design – model tests and simulations** → **In operation**

2 Basic hydrodynamic design

- Hull
- Sail
- Control surfaces



CFD calculation of a generic submarine. Detailed information about different flow phenomena can be obtained.

4 Propeller design

- Cavitation tunnel tests
- High efficiency
- Good cavitation properties
- Low radiated noise

Model of the IZAR P650 tested at SSPA. The same model was used in all SSPA facilities.

TOWING TANK | CAVITATION TUNNEL | MARITIME DYNAMICS LABORATORY

6 Simulator

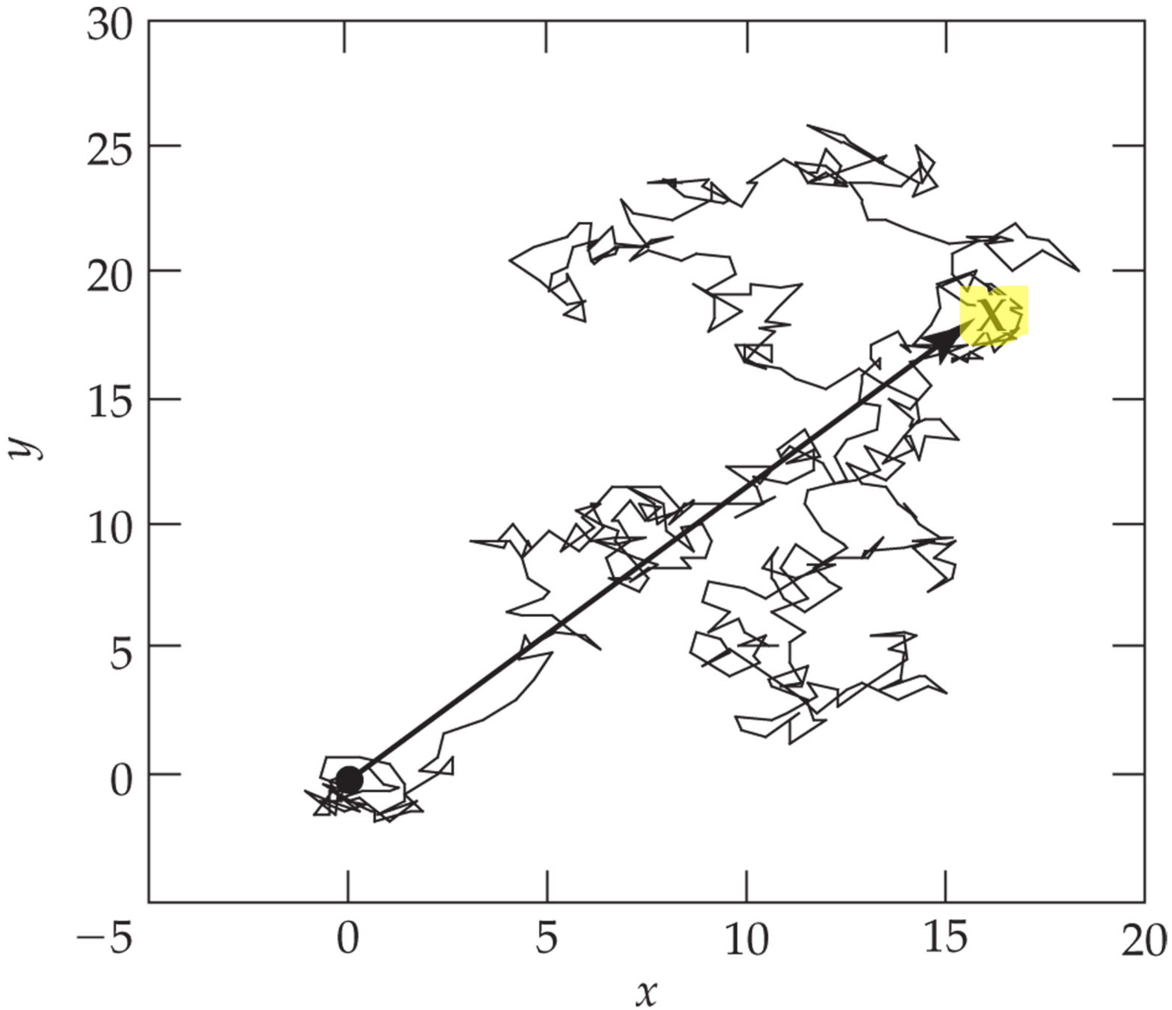
- Crew training
- Development of hardware for a submarine's bridge

In operation

- Depth keeping in periscope conditions under a seaway
- Simulation of emergency recovery manoeuvres
- Compensation and trimming
- Safe operation envelopes

Diffusion & Convection

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

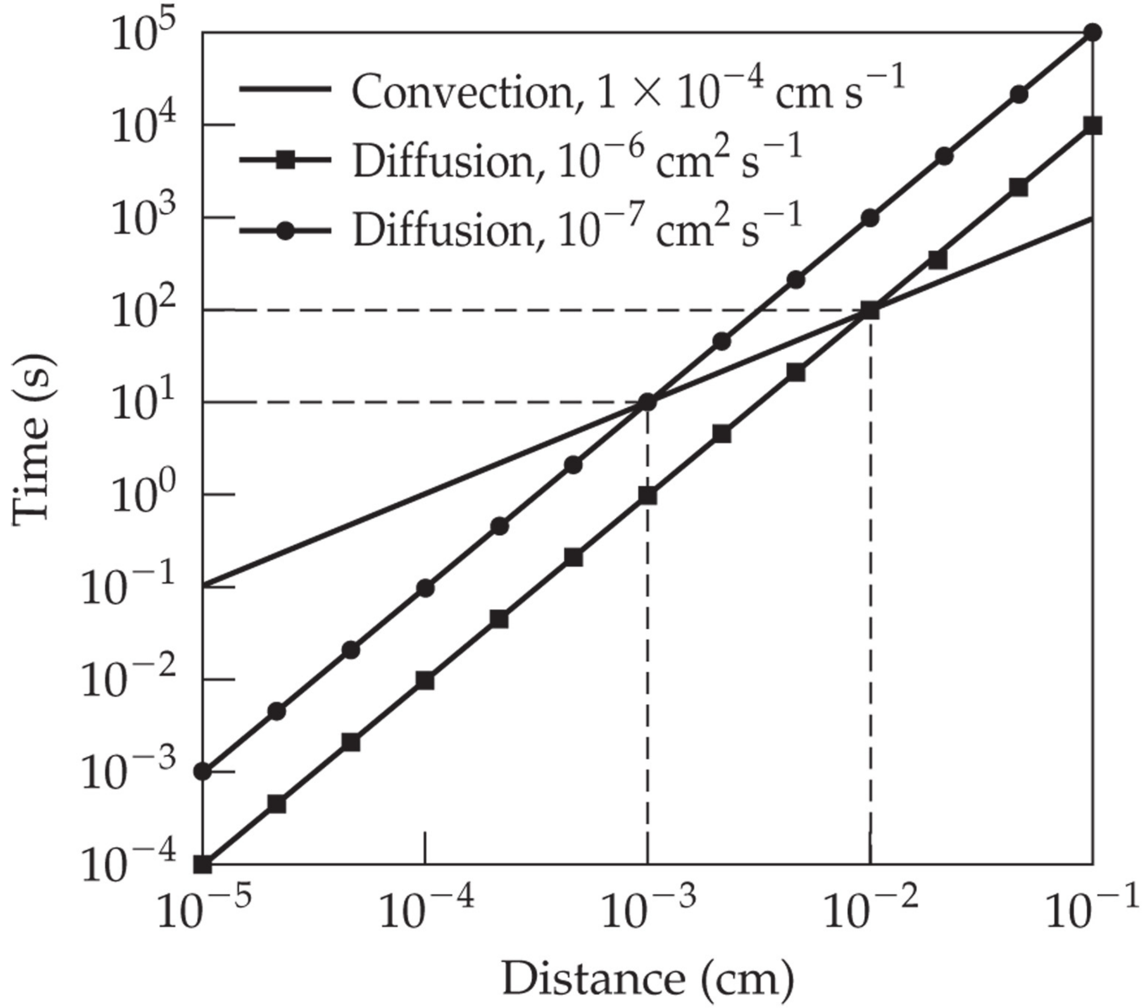
Molecular transport mechanism	Flux	Gradient	Coefficient of proportionality
Momentum	Shear stress	Velocity	Viscosity
Mass	Mass or molar flux	Concentration[a]	Diffusion coefficient
Energy	Energy	Temperature	Thermal conductivity

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.

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

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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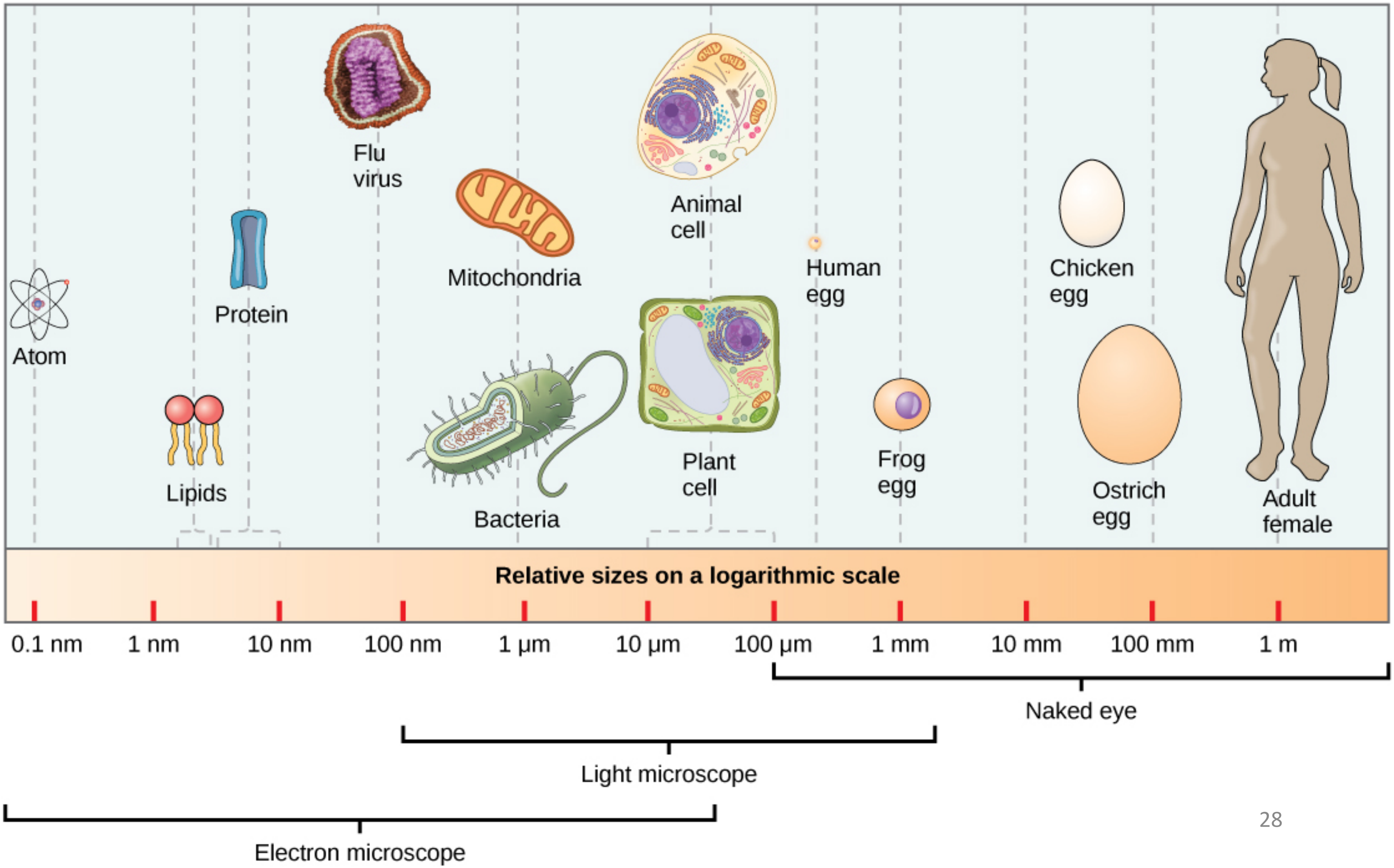
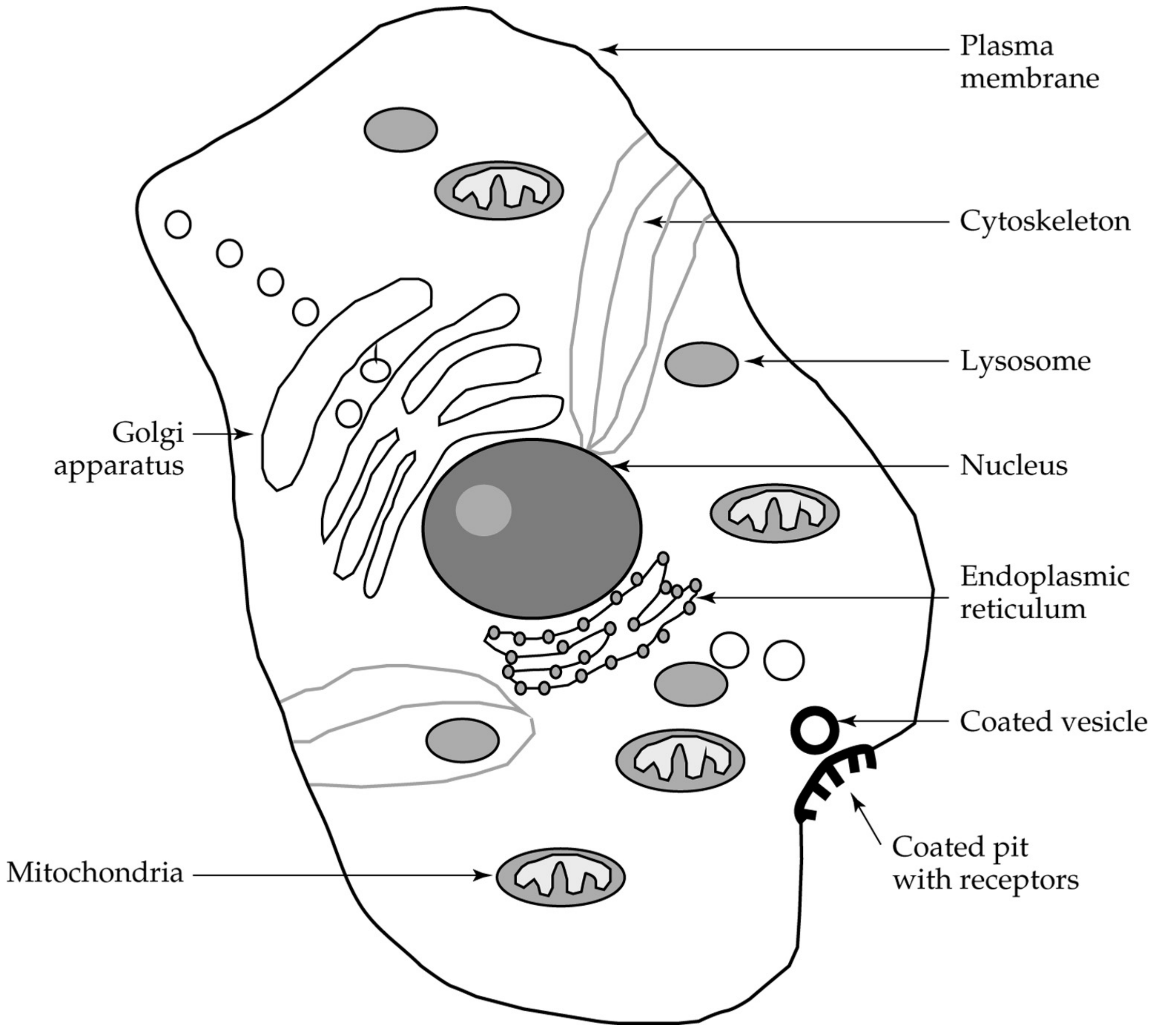
Scales of living systems



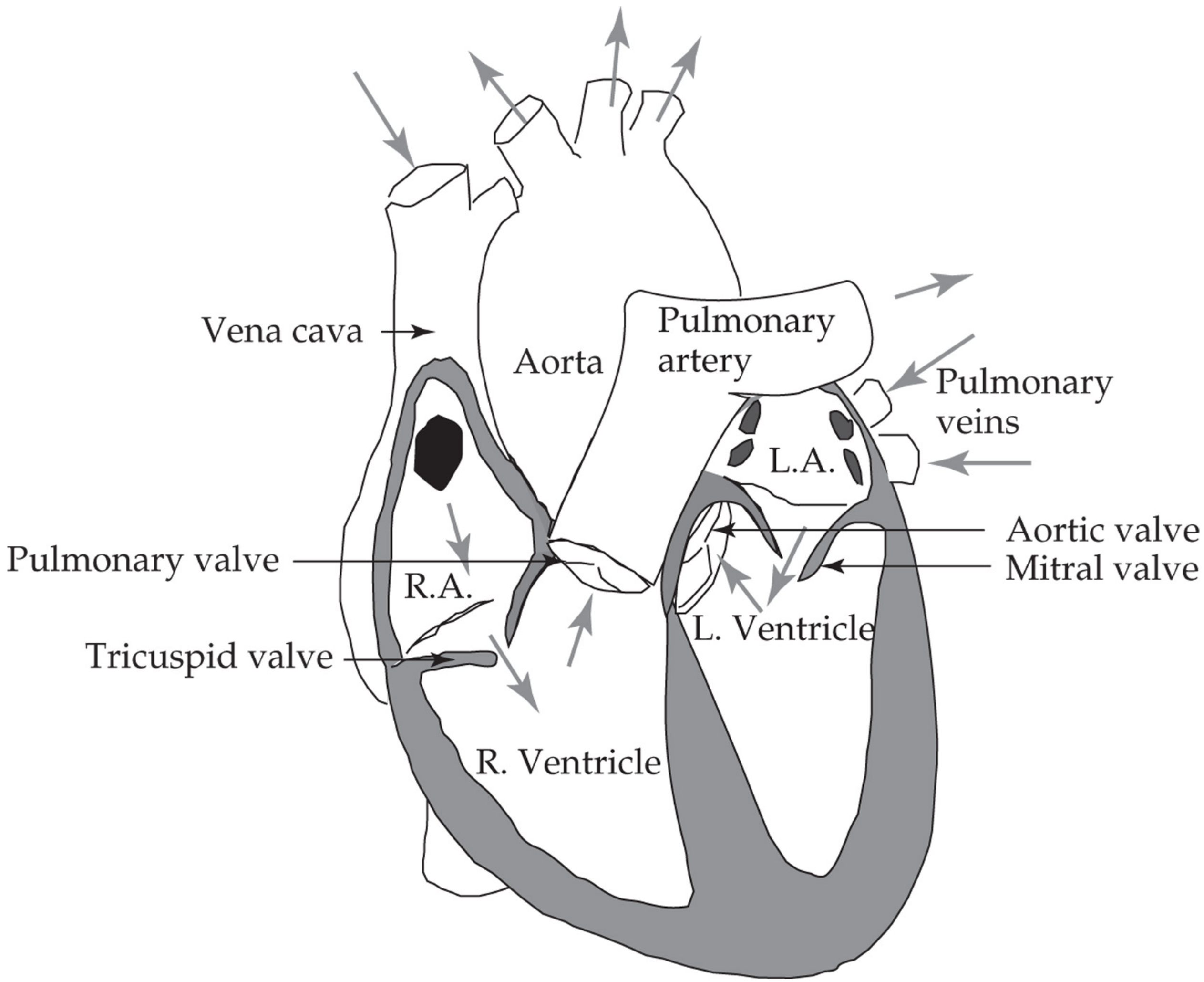
Mammalian eukaryotic cell & organelles.



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

Diagram of the heart showing valves, veins and arteries

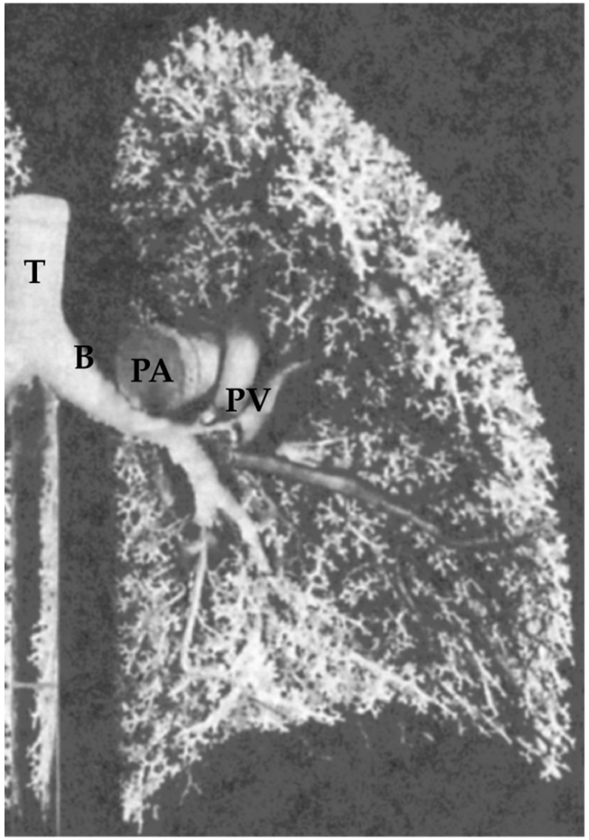


Distribution of Blood Volume	
Region	Total (%)
Small veins and venules	45–53
Large veins	15
Lungs	10–12
Heart	8–11
Systemic arteries	10–12
Capillaries	4–5

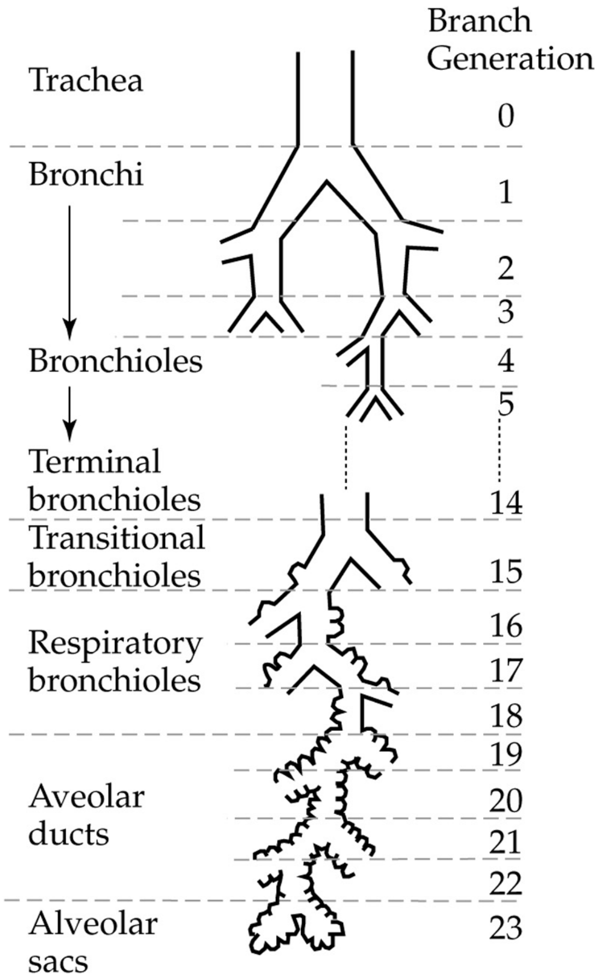
Blood Flow Distribution during Rest and Heavy Exercise

	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

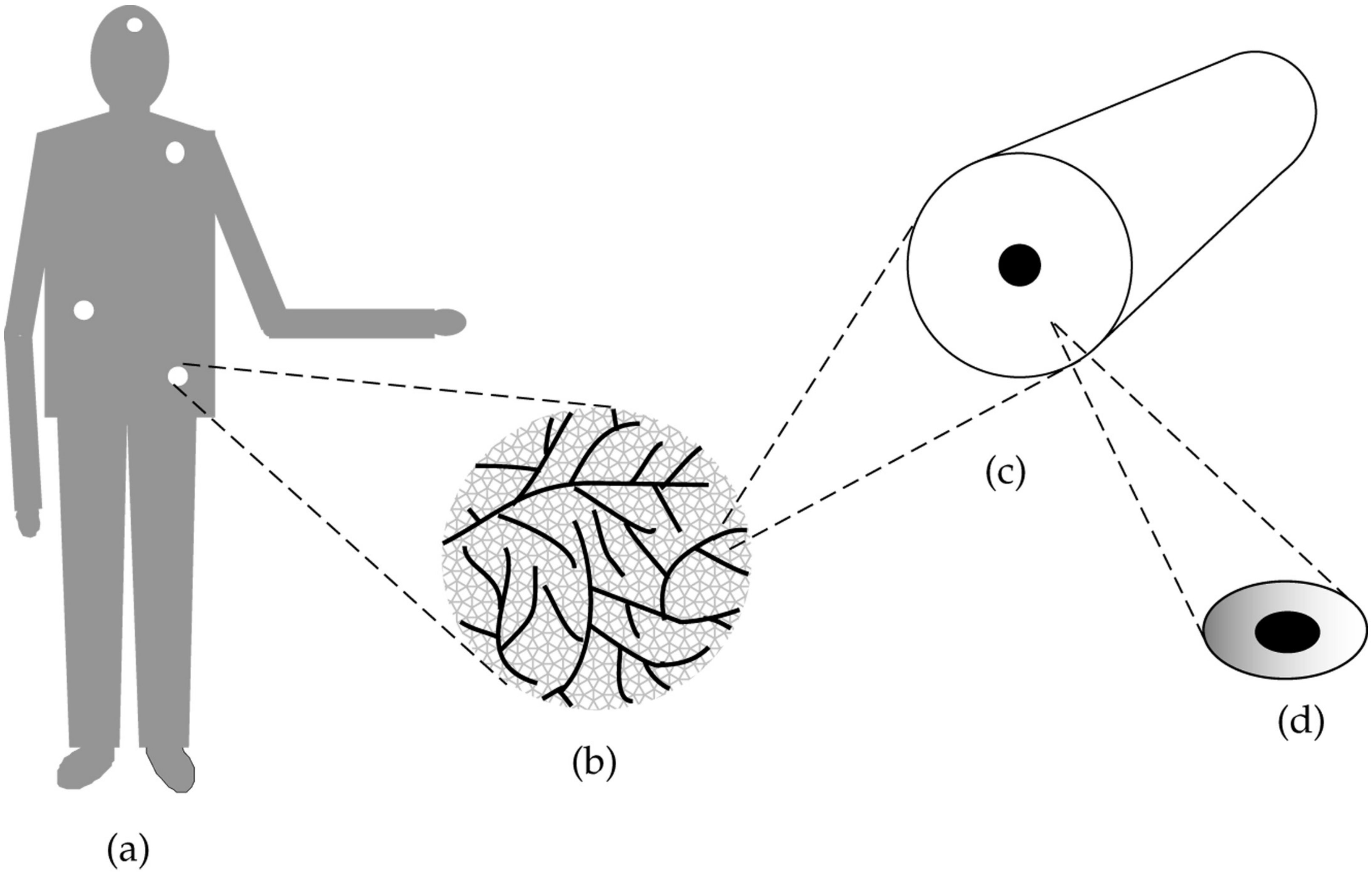
Schematic of the airways in the lung



(a)



(b)



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).

Flow for extracorporeal artificial liver.