Constituents of blood
- constituents - plasma 55%, erythrocytes (red blood cells) 45%
- also - leukocytes (white blood cells 7 - 22 µm, various types) and platelets (2- 4 µm)

Red blood cells
- biconcave disk shape when unstressed
- thin membrane - lipid bilayer with protein skeleton
- contents - concentrated hemoglobin solution, no nucleus in mammals
- very flexible, very different shapes in flow
- can aggregate (humans, many other species) forming rouleaux and networks of rouleaux

Viscosity of blood
- can test viscosity of fluids using a viscometer
- types of viscometer: coaxial (Couette), cone and plate, tube
- shear rate and stress are approximately uniform in coaxial (Couette) and cone and plate viscometers
- compute shear rate γ by dividing velocity difference by width of gap - unit s⁻¹
- compute shear stress τ from force required to drive flow
- apparent viscosity given by \( \mu = \frac{\tau}{\gamma} \)
- shear rate is not uniform in tube viscometer - apparent viscosity is estimated using Poiseuille's law

Experimental results
- relative apparent viscosity = (apparent viscosity)/(suspending medium viscosity)
- apparent viscosity varies strongly with shear rate
- deformability reduces viscosity at high shear rates
  - rbcs accommodate to the flow
  - at low shear rates rbcs don't deform much
• aggregation increases apparent viscosity at low shear rates
  - rbcs stick together, inhibiting flow
  - at high shear rates, aggregates are broken up
• in normally flowing vessels, shear rates are generally 100 s\(^{-1}\) or more, almost constant viscosity
• in regions of low flow, viscosity may be much higher

Blood flow in narrow tubes
• experiments in glass tubes down to 100 \(\mu\text{m}\) diameter - Fahraeus and Lindqvist, 1931
• recall Poiseuille's law \[ Q = \frac{\pi \Delta p d^4}{128 L \mu} \] rearrange to give \[ \mu_{\text{app}} = \frac{\pi \Delta p d^4}{128 L Q} \]
• apparent viscosity falls with decreasing diameter - Fahraeus-Lindqvist effect
• main explanation - a layer of reduced red blood cell concentration near tube wall

Two-layer model for blood flow in narrow tubes
• assume a plasma layer at the wall with viscosity \(\mu_0\)

• assume a central region with viscosity \(\mu_c\)
• as before, \(\tau = r \Delta p / 2L\)
• define $\lambda = (\text{radius of core})/(\text{tube radius})$

• velocity profile - blunted

• analysis
  - use $du/dr = \tau/\mu$, integrate for both regions
  - match velocities at interface, non-slip at wall
  - integrate velocity to get flow rate
  - find apparent viscosity $\mu_{\text{app}} = \frac{\mu_0}{1 - \lambda^4 (1 - \mu_0 / \mu_c)}$

• good fit to experimental data for glass tubes down to 30 µm diameter, assuming $\mu_c/\mu_0 = 3$
  and width of plasma layer = 1.8 µm

• a generalization of the "stacked-coins" model