Microgravity Environment Interpretation Tutorial

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Acronyms and Abbreviations

a - acceleration
β - buoyancy
σ – stress (force per unit area)
F – force
m - mass
A – area
ε – strain (ΔL/L)
L – length
E – Young's Modulus (material property)
τ – shear force
μ – viscosity
dv/*dx* – tangential velocity gradient
g - unit gravity (9.8 m/sec^2)
K_b – Boltzman's constant

<x> - root mean square distance
D – diffusion coefficient
α - diffusivity
t - time
Vsed (or υ) – sedimentation (terminal) velocity
ρ - density
r - radius
j = flux
dc/dx (or ΔC)– concentration gradient
∇y - flux
N_h/N_0 – particle concentration ratio (top:bottom)
ω - angular frequency

Gravitational Influence

First, consider what constitutes a gravity-dependent effect…

Gravity can produce two effects on an object:

- deformation (weight, structural)
and/or
- displacement (motion, transport)

Effects attributed to gravity established as a cascade of events:

- 'physical trigger' (addition or removal of gravity loading)
- increase or removal of a normally occurring mass displacement (solid or liquid) and/or structural deformation (including electrochemical gradients)
- transmitted/biologically propagated signal
- observed (measured) outcome of the system being studied

Reactions are governed by F = ma:

- differences in density between the object and its surroundings (intracellular components and/or extracellular environment)
- inherent structural properties of the object

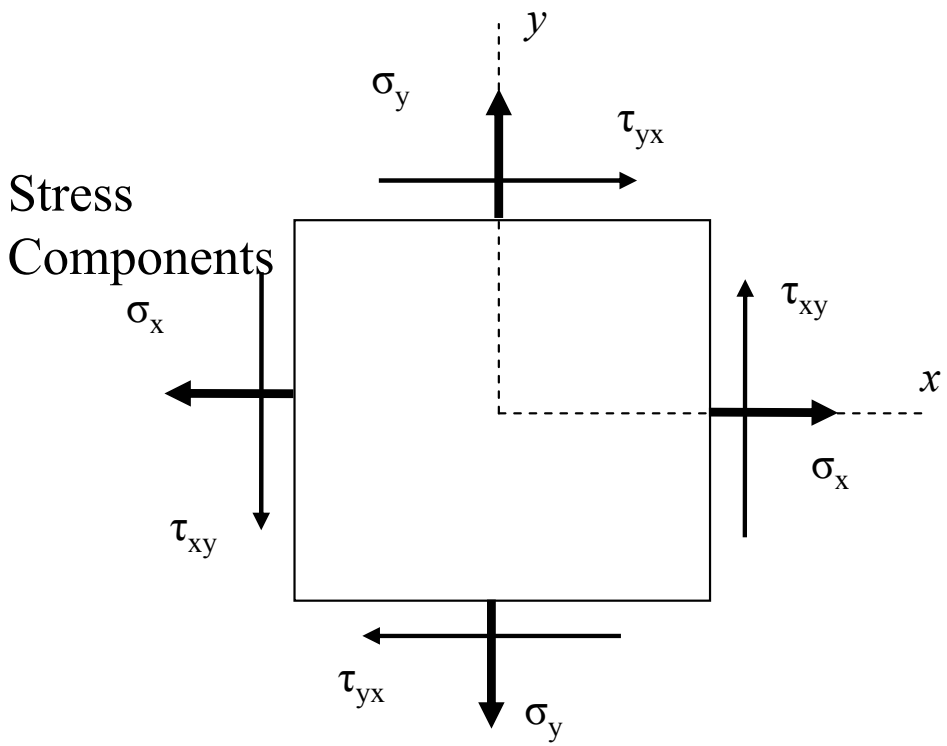
General Relationships Derived from F = ma

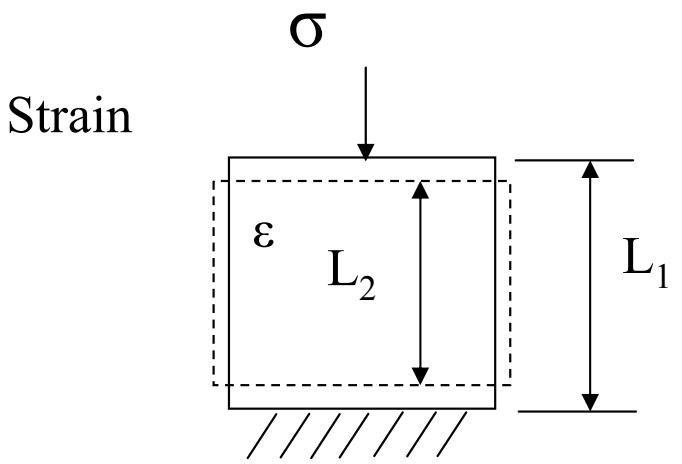
Structural

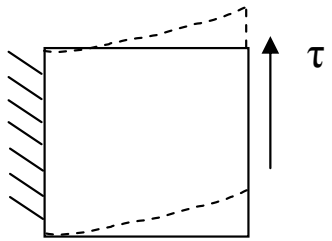
$\sigma = F/A$

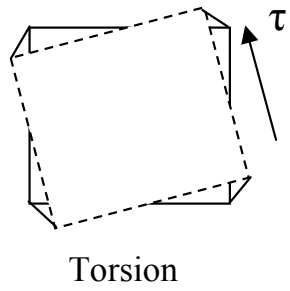
$\varepsilon_a = (L_2 - L_1)/L_1 = \Delta L/L_1$

$E = \sigma_a / \varepsilon_a$









General Relationships Derived from F = ma

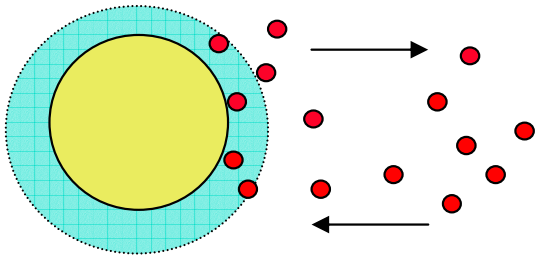
Transport

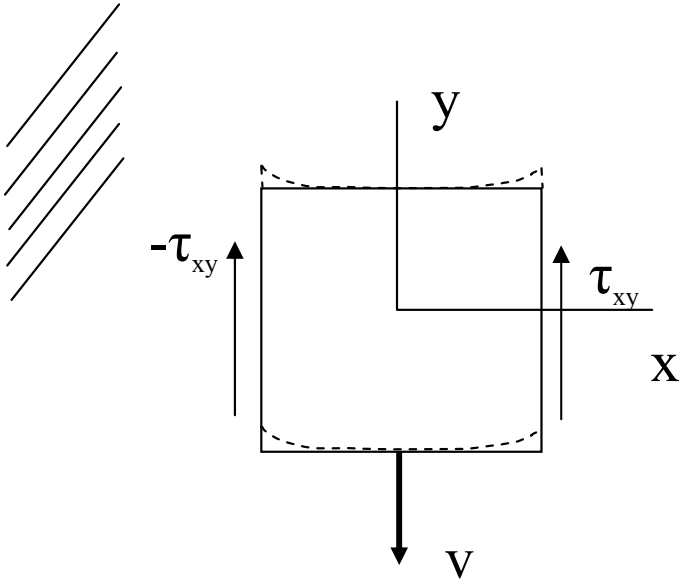
$$V_{sed} = 2/9\ (\rho_{particle} - \rho_{fluid})\ (g/\mu)\ r^2$$

$$\tau_{xy} = \mu\ dv/dx$$

$$\langle x \rangle^2 = 2Dt$$

$$-j_1 = D\ dc_1/dx$$

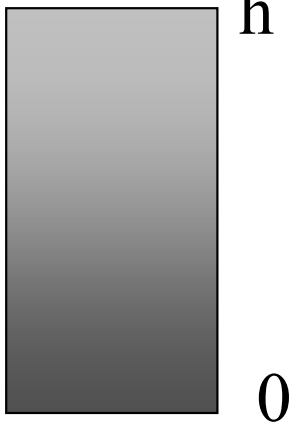


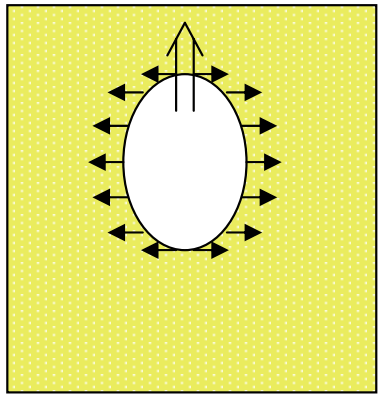


$$\nabla y_i = \sum_{j=1}^{n-1} y_i\ y_j / D_{ij}\ (V_j - V_i)$$

$$N_h/N_0 = e^{-[(V\Delta\rho\ g\ h)/K_b\ T)]}$$

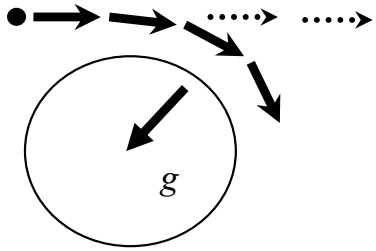
Buoyancy = $f(g\ \beta\ \Delta C)$





Accelerated vs. Constant Velocity Motion

Freefall in a Vacuum



Terminal Velocity
in a Viscous Medium

Linear
Acceleration
$\upsilon = \upsilon_0 + at$

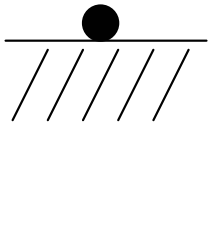
Centripetal
Acceleration
ω = Constant

Non-accelerated
υ = Constant

Physical Effects at the Cellular Level

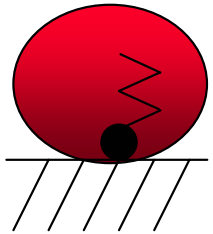
Weight

$\nu = 0$

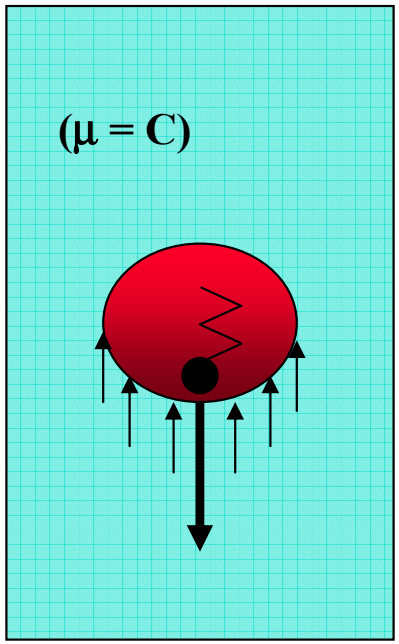


No motion

Weight & Deformation



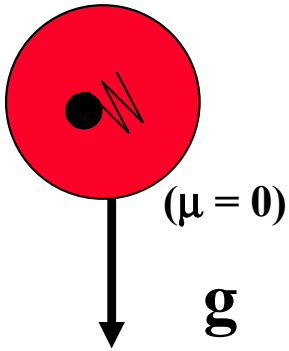
Weight, Deformation and Motion



ν = Constant

Terminal Velocity
(no accelerated motion)

Freefall
(no resistance)



Weightless

Accelerated Motion

"Indirect Effects of Gravity at the Cellular Level"
-- Cascade of Cause and Effect Events

→ Physical

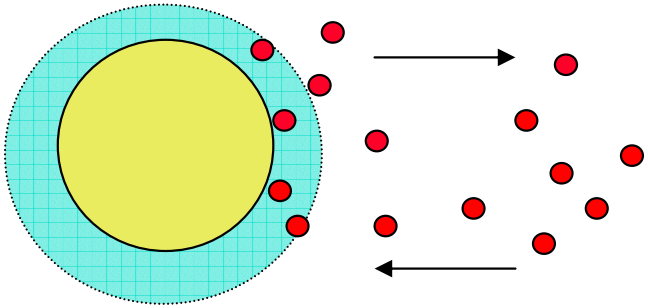
→ Chemical

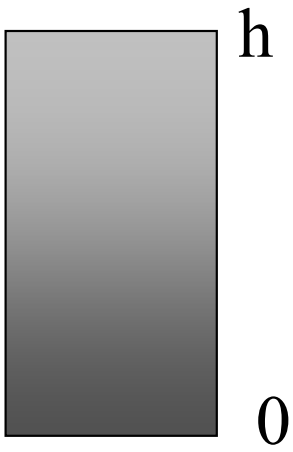
→ Biological

Concentration of Byproducts Around a Cell

Cell Surface → Boundary Layer → Bulk Fluid

What are the components of interest, what are the forces acting on them and which are gravity-dependent?





Using Dimensionless Relationships

Biot (Bi) - film transport to intraparticle diffusion rate
Damköhler (Da) - max reaction rate to max transport rate
Sherwood (Sh) - total mass transport to diffusion only
Schmidt (Sc) - momentum to diffusion
Grashof (Gr) - buoyancy to viscous resistance
Reynolds (Re) - momentum to drag
Prandtl (Pr) – convection regime, momentum to thermal (free to forced)

Peclet (Pe) - convection to diffusion = (Re) (Pr)

$Pe = (v\ L) / \alpha$
where v = velocity, L = characteristic length, α = diffusivity

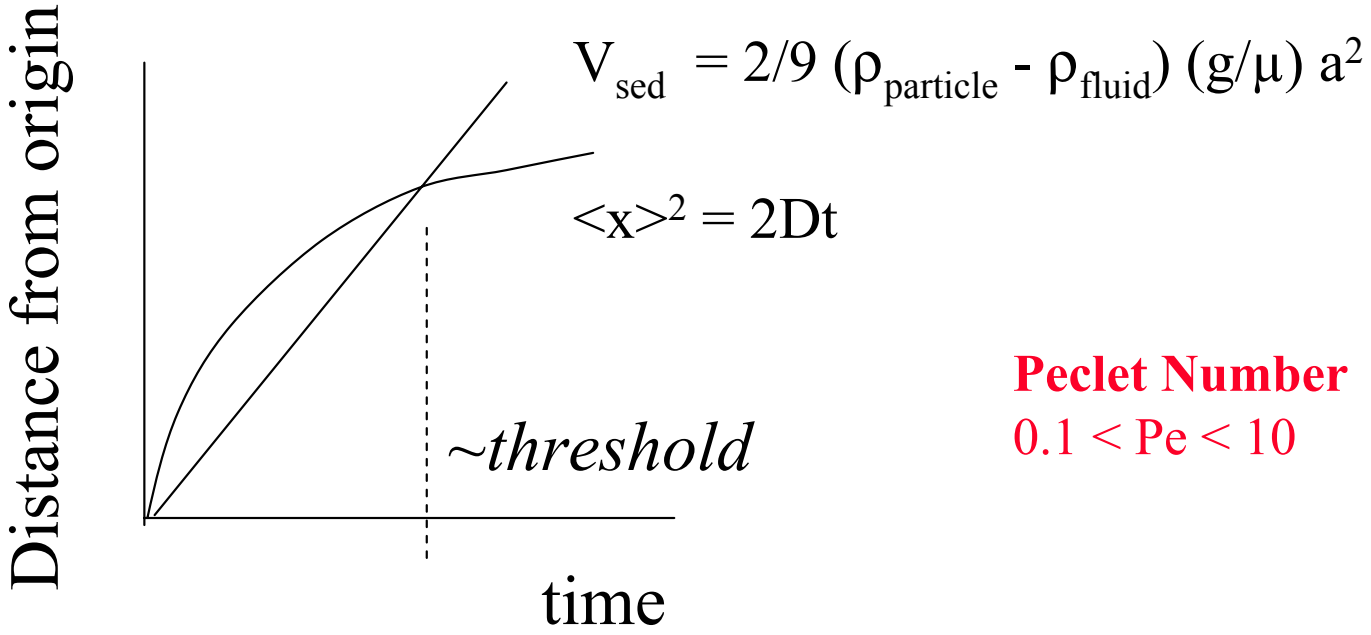
if $Pe > 10$ → convection dominant
if $Pe < 0.1$ → diffusion dominant

Forcing Functions on cell movement

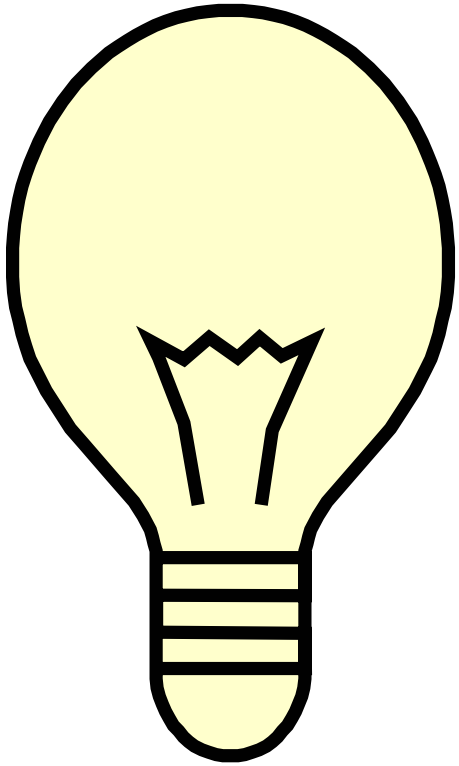
Bacteria fall into a "gray zone"

1 μm < Bacteria < 10 μm

Particles < 1 micron – diffusion dominated
Particles > 10 microns – sedimentation dominated



Peclet Number
$0.1 < Pe < 10$



Is a Lightbulb Gravity Dependent?

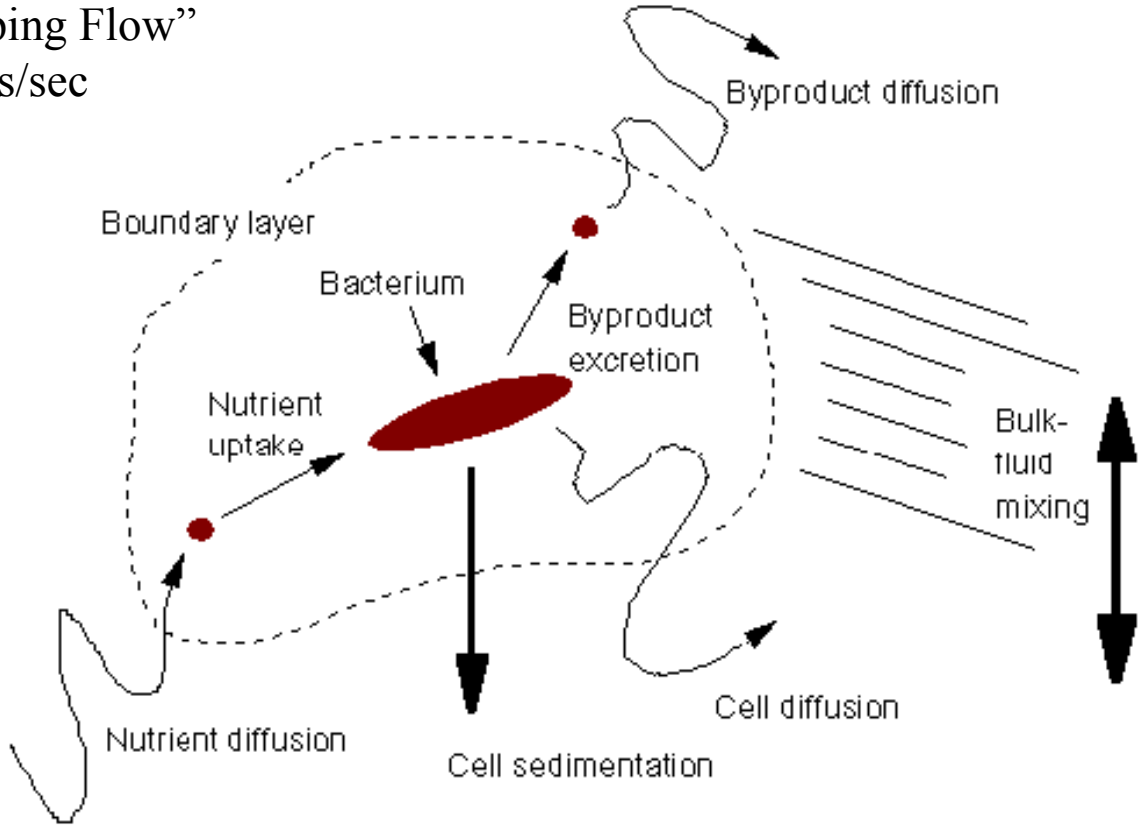
Sub-micron Mass Transfer Phenomena

Free Body Diagram

Navier-Stokes "Creeping Flow"

V_{term} ~ 0.06 microns/sec

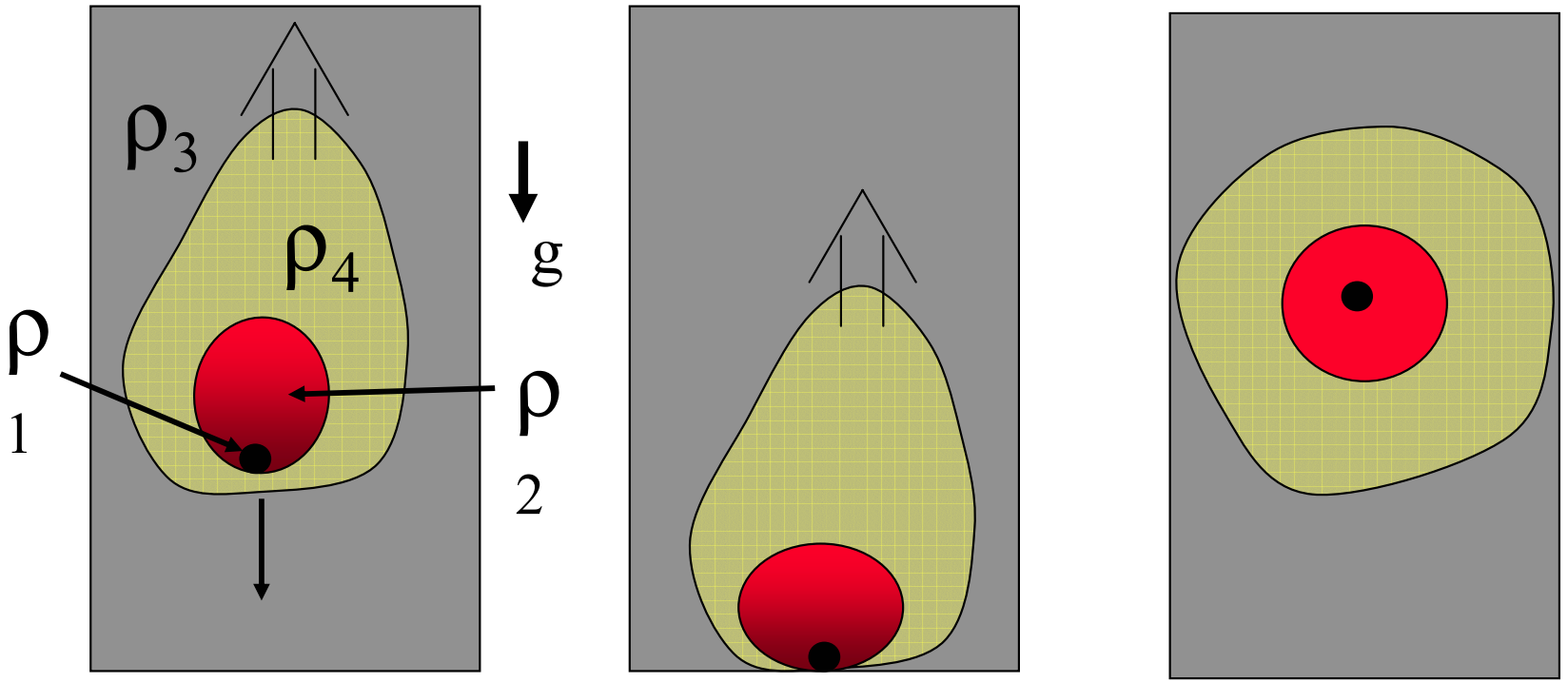
Re ~ 10^{-7}



Klaus et al. (1997) *Microbiol*. 143 (2): 449-455
Klaus (1998) *TIBTECH* 16 (9): 369-373

Cell Cultures Induce Complex Gravity-Dependent Environmental Interactions

Falling (1g) Attached (1g) Weightless

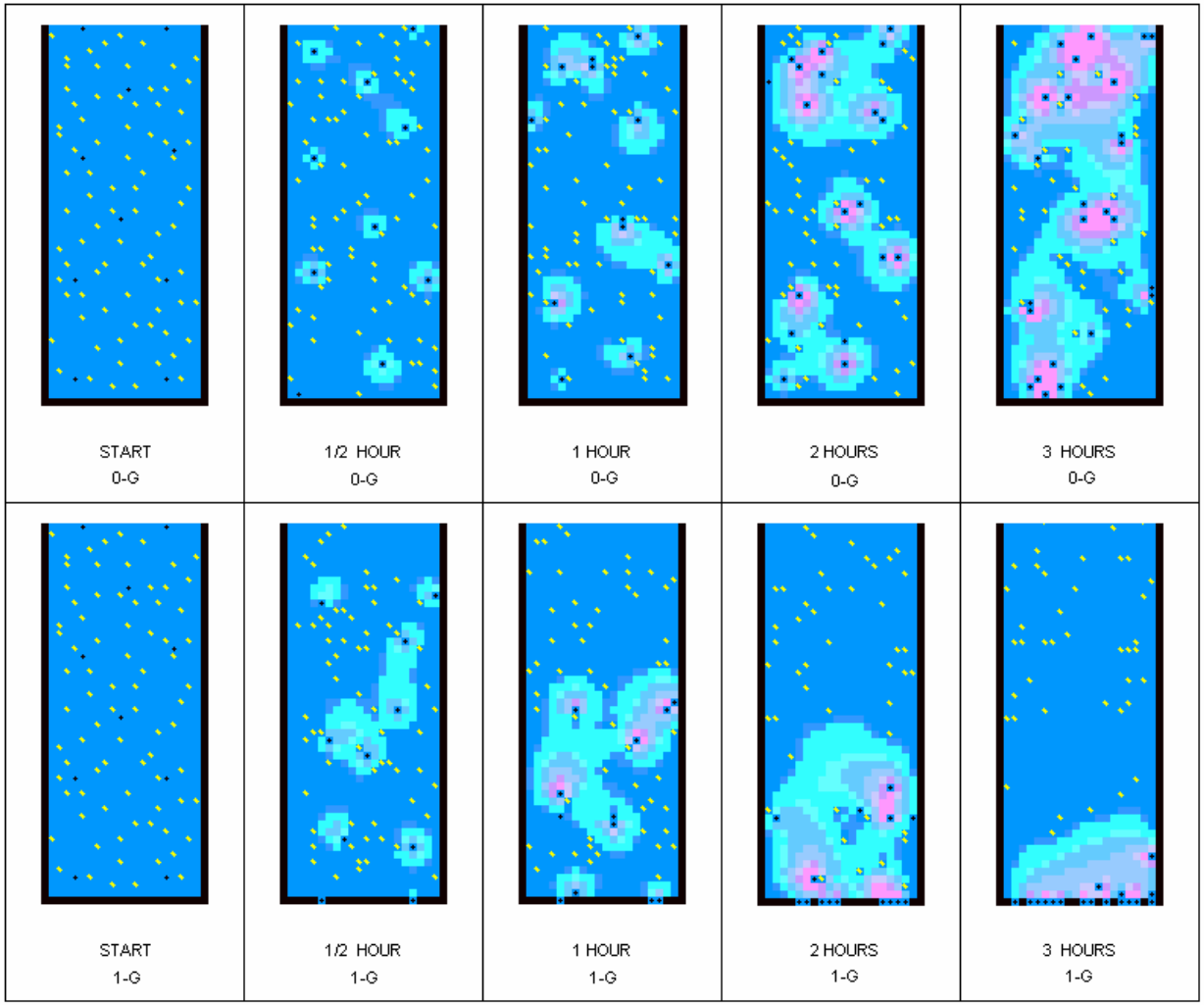


$\rho_1 > \rho_2 > \rho_3 > \rho_4$

+ mechanical stress/strain factors
+ fluid shear effects

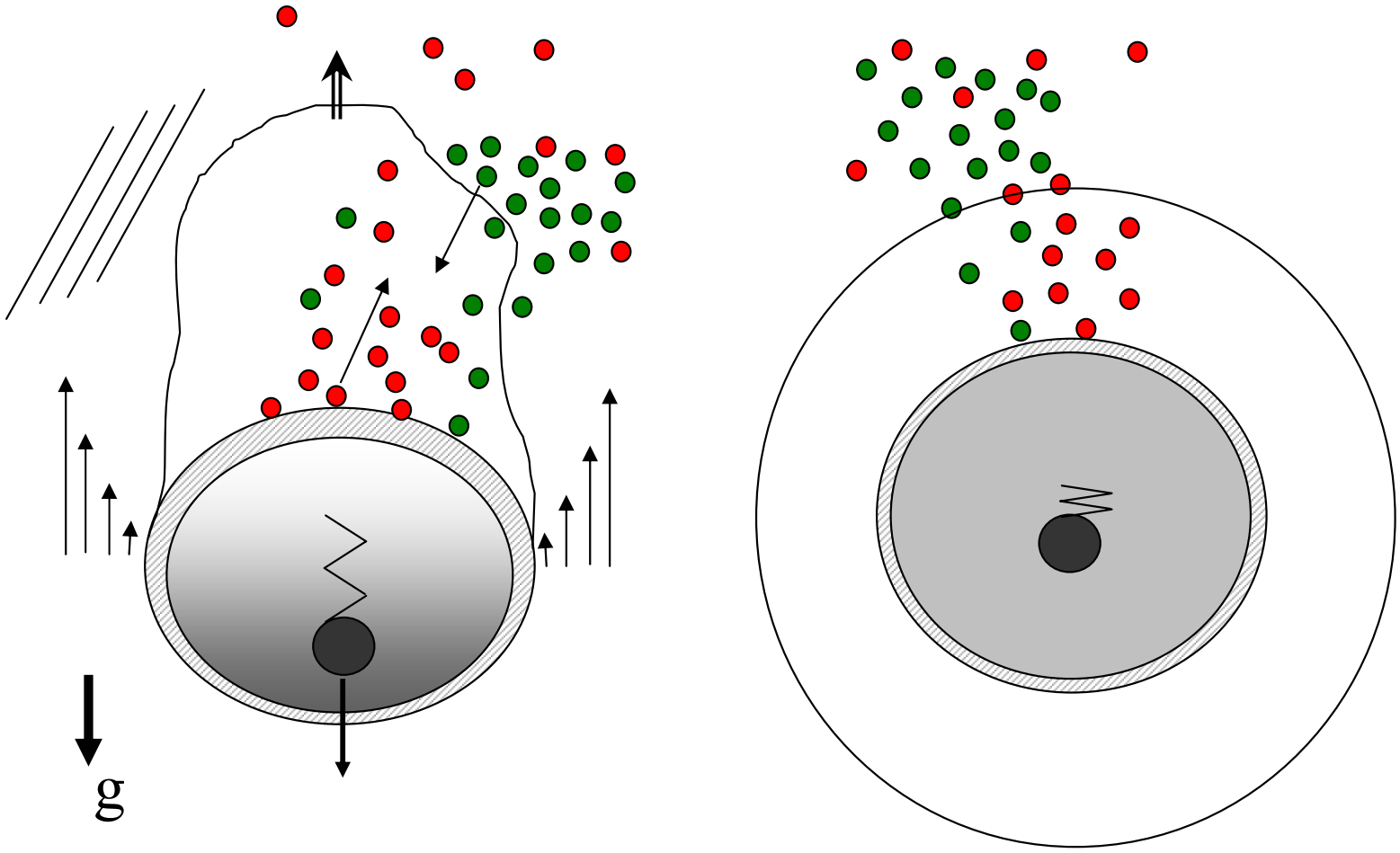
Klaus (2001)

Finite Element Model – "Dynamic" Visualization

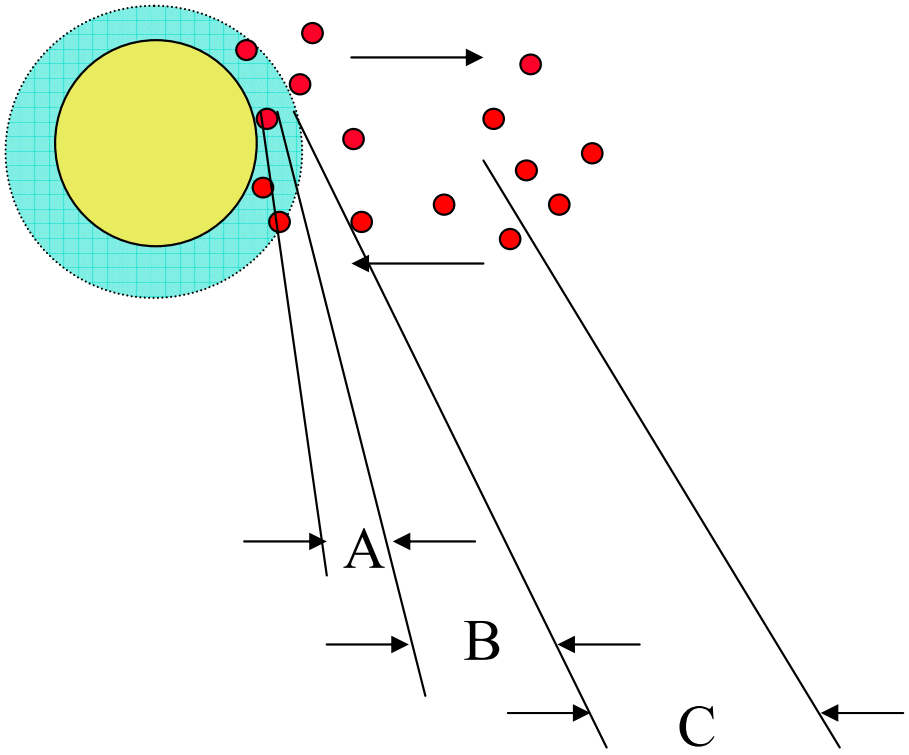


Lanning (1998) UROP

Discrete Transport Illustration



Spatial vs. Temporal Dependent Transport Regimes

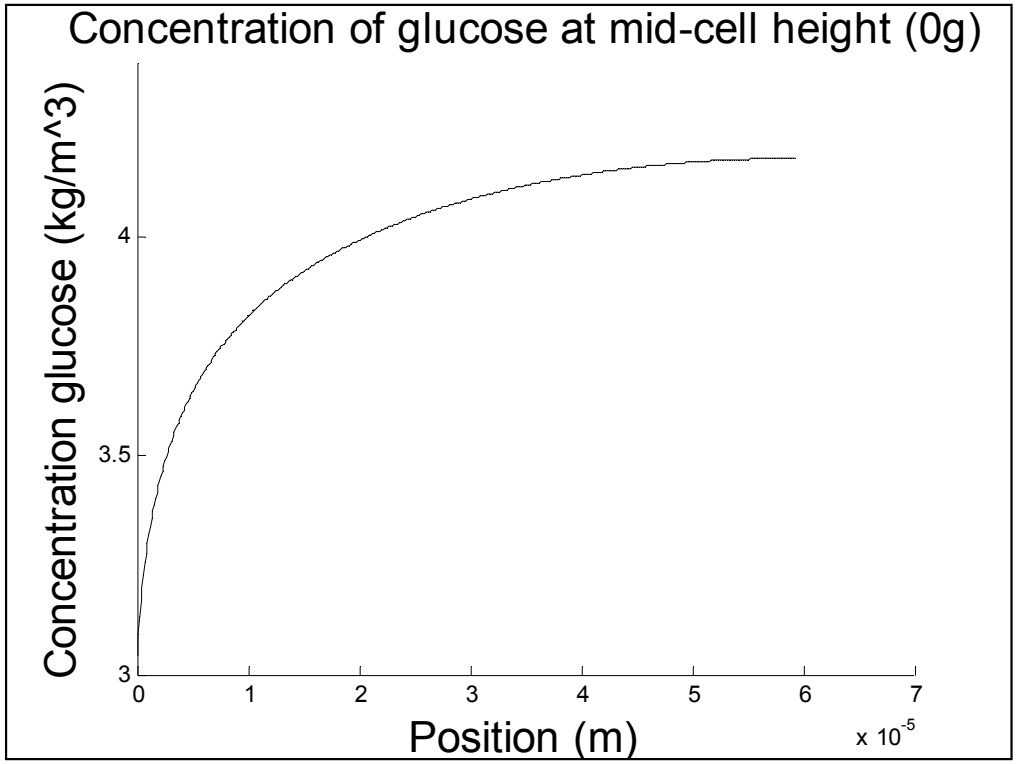


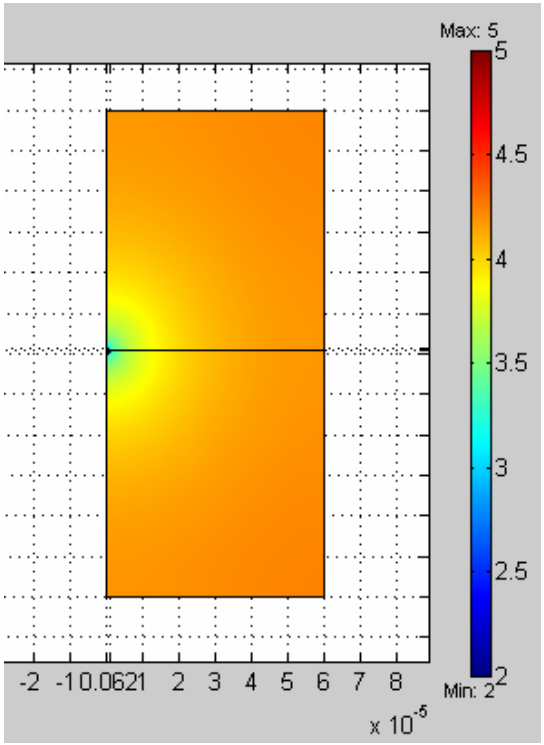
A. Spatial (*discrete*)
- Cell Surface Factors
- Production/Consumption Rates
- Osmosis
- Electrostatic Forces

B. Temporal/Spatial
- Boundary Layer Transport
- Gradient Driven Diffusion
- Molecular Collisions

C. Temporal (*continuum*)
- Random Diffusion
- Gradient Driven Diffusion
- Convection
- Stirring / Mixing

Numerical Modeling

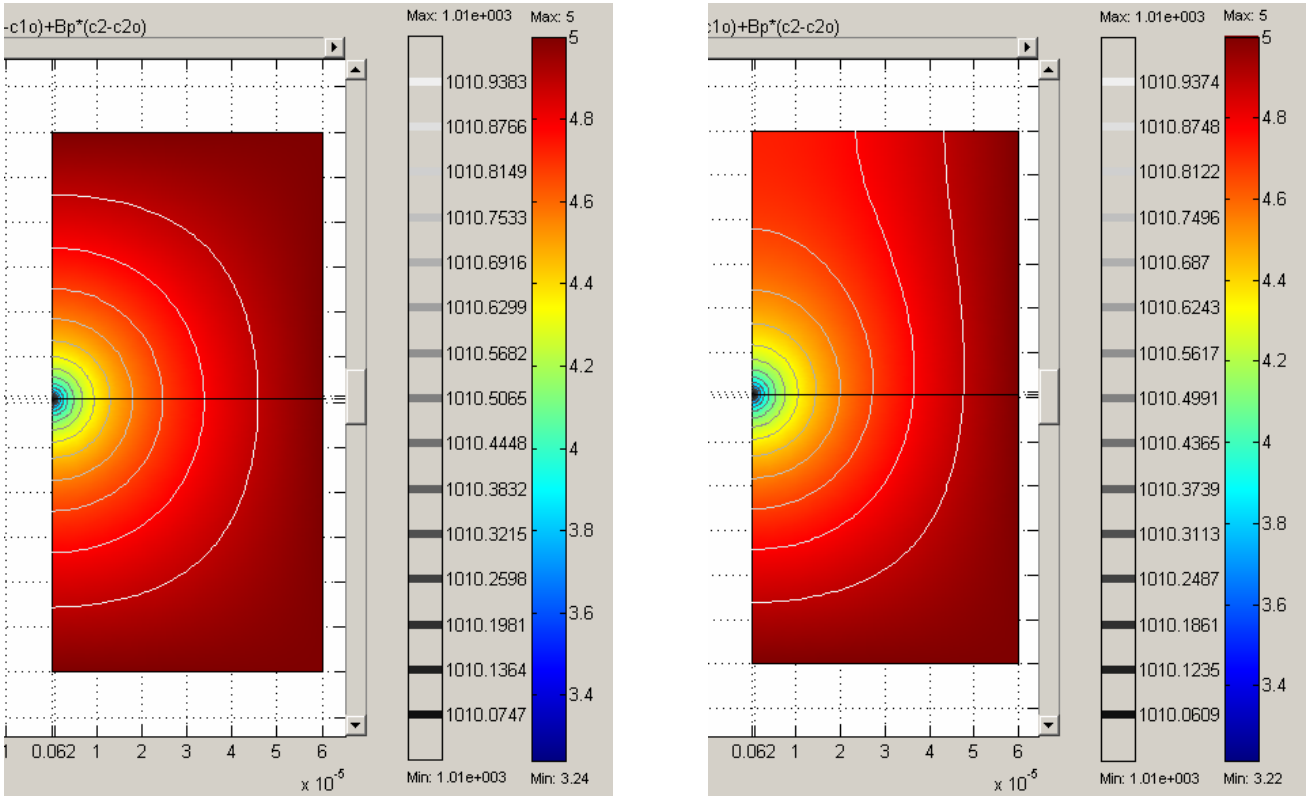




2D, axi-symmetric model of glucose gradient (kg/m^3) around growing bacterial cell, 0g.

Benoit, NASA GSRP (NGT3-52386)

Numerical Modeling



Modeled effects of gravity on extracellular (glucose) transport (0g left, 1g right)

Benoit, NASA GSRP (NGT3-52386)

Potential Factors Affecting Extracellular Concentration Gradient and Cellular Stress/Strain Deformation

Cell movement – sedimentation, diffusion, motility
Accumulation on container bottom
Stirring
Nutrient consumption rate
Byproduct production rate
Byproduct dispersion – diffusion, collective buoyancy
Uptake flux / interference (molecular collisions)
Boundary layer phenomena (gradient diffusion)
Cell Surface phenomena (attraction/repulsion)

Physical Effects in Higher Organisms

Plants respond to:

Gravitropism (a.k.a geotropism) - response to gravity
Phototropism - light
Hydrotropism - water
Thigmotropism - touch
Pneumotropism - pressure
Electrotropism - electricity
Magnetotropism – magnetism

Weightlessness

Structural unloading
Lack of hydrostatic pressure

Environmental factors

Nutrient / water delivery
Airflow
Lighting

Radiation

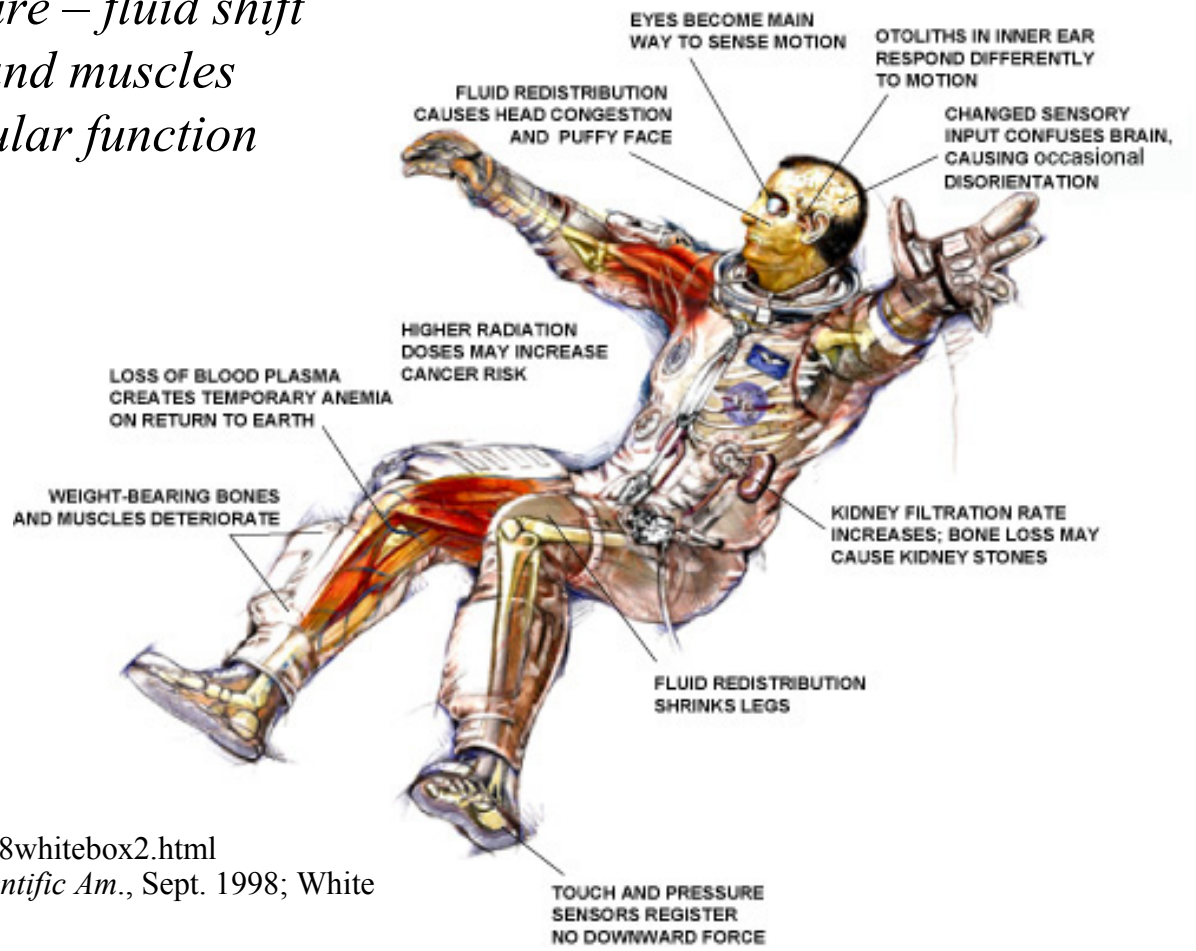
Mammals / Humans

Weightlessness

Lack of body hydrostatic pressure – fluid shift
Structural unloading of bones and muscles
Loss of tactility / altered vestibular function

Radiation

(& Psychological Stress)



http://www.sciam.com/1998/0998issue/0998whitebox2.html
'Weightlessness and the Human Body' *Scientific Am.*, Sept. 1998; White

Summary

1. **Characterize the physical aspects of the biological system**
2. **Identify all forces acting on the system (g-dependent and –independent)**
3. **Draw a Free Body Diagram (intra- and extracellular components)**
4. **Correlate observed biological responses to specific physical factors**
5. **Isolate cause-and-effect gravity-dependent and independent relationships**
6. **Establish a cascade chain of events (beginning with the gravity trigger and ending with the observed biological response)**

altered-g → 1 → 2 → 3… → observation