Cellular Electrodynamics

Santiago Ramón y Cajal (1852-1934)

Instructor:

Prof. Christopher Bergevin (cberge@yorku.ca)

Website:

http://www.yorku.ca/cberge/4080W2020.html

York University

Winter 2020

BPHS 4080   Lecture 1

Reference/Acknowledgement:

- TF Weiss (Cellular Biophysics)
- D Freeman

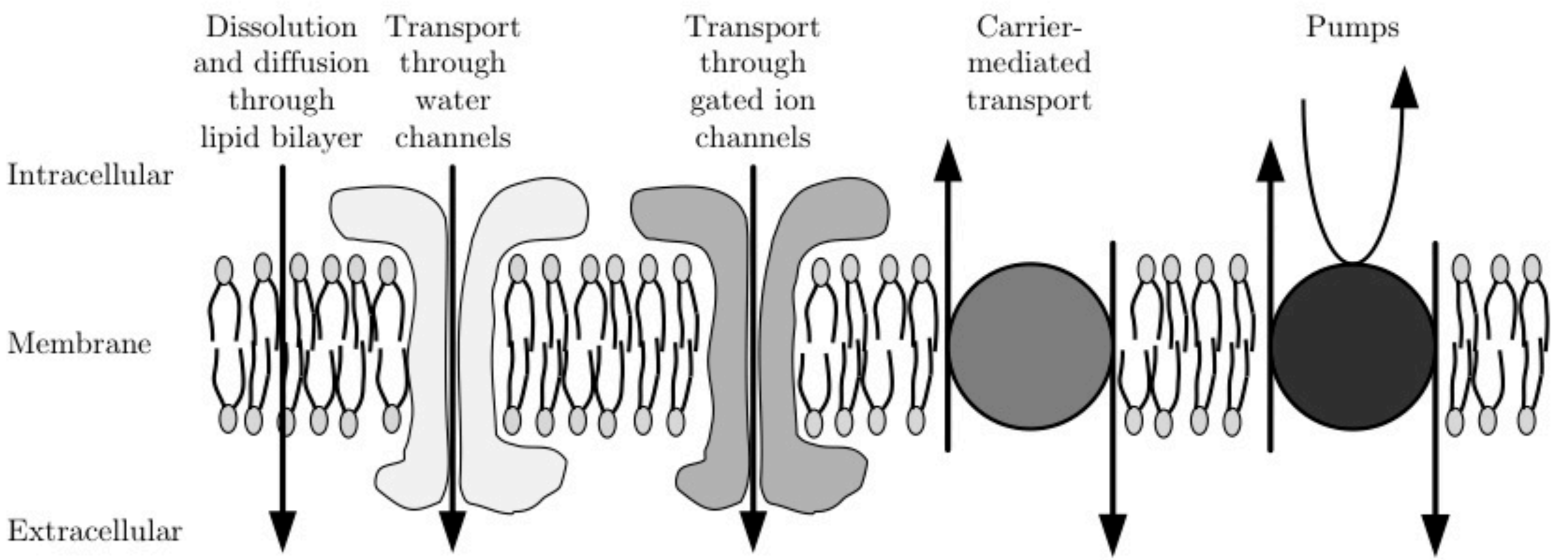

Figure 2.19

Weiss (1996)

MIT Technology Review

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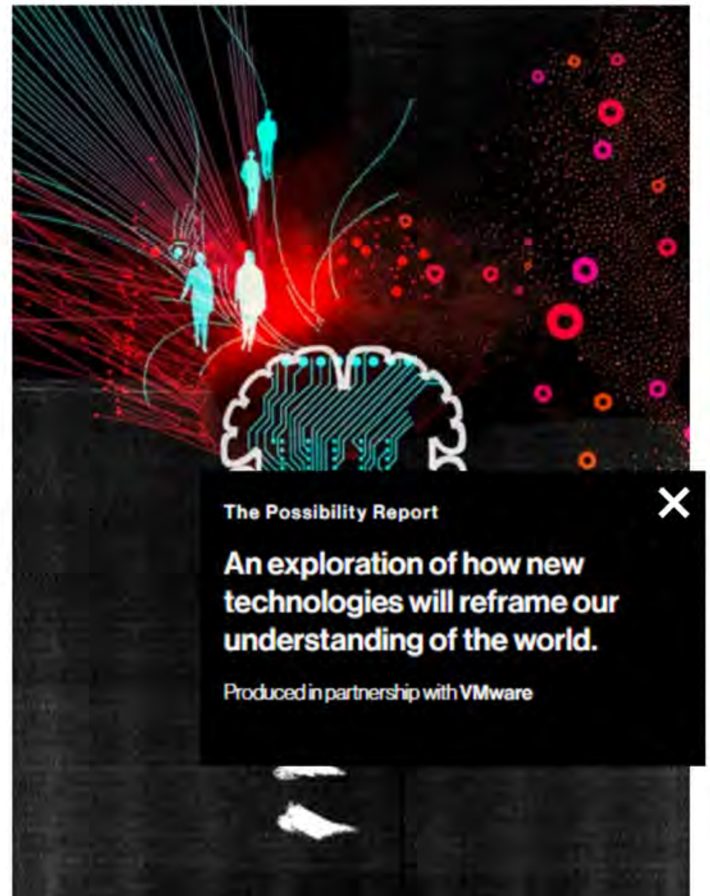
Deep Learning

With massive amounts of computational power, machines can now recognize objects and translate speech in real time. Artificial intelligence is finally getting smart.

by Robert D. Hof



https://www.technologyreview.com/s/513696/deep-learning/

A Primer On Deep Learning

Forbes Agency Council

PR, media strategy, creative & advertising execs share trends & tips **FULL BIO**

POST WRITTEN BY

Jeremy Fain

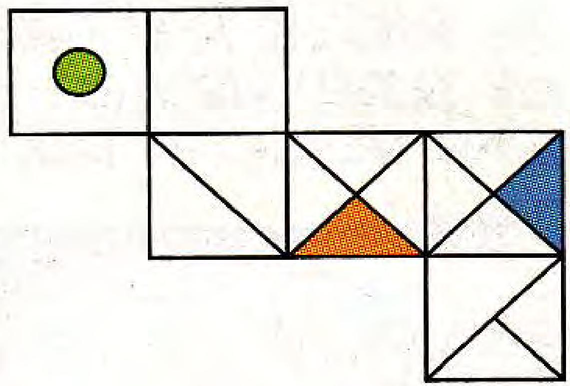
Jeremy Fain is the CEO and co-founder of Cognitiv, the first neural network technology.

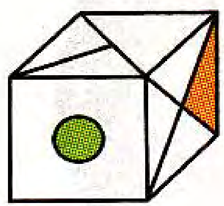
The term "artificial intelligence" (AI) has been around since the 1950s, but there has long existed a yawning gap between what people thought AI to be and what was actually possible. Since the 1960s, much of what has been considered to be AI has been a form of machine learning. However, despite the leaps and bounds in technology since the term was first introduced, the accomplishments of machine learning have often fallen short of public expectations (think the robots in *The Jetsons*).

Fortunately, after a half-century of research, that gap between our expectations and reality is finally closing, thanks to deep learning, a more advanced type of machine learning that's capable of generating human-like insight. Here, I will give an introduction to deep learning and explore the potential of this groundbreaking new field.

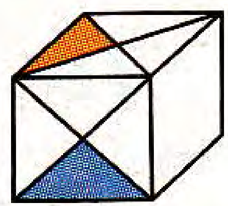
https://www.forbes.com/sites/forbesagencycouncil/2017/12/18/a-primer-on-deep-learning/#439c595d5e9b

Which of the six boxes below cannot be made from this unfolded box? (There may be more than one.)





A



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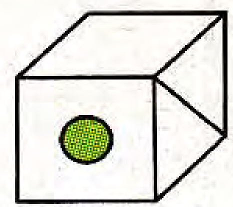

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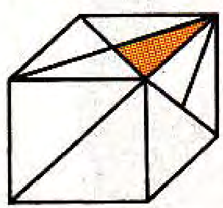
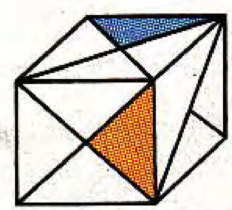
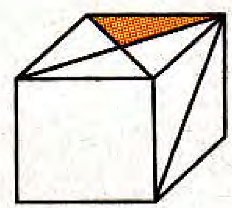


D



E



F

- What helps prevent disaster here? What sort of ‘signals’ convey the relevant info?
- What are the basic biological mechanisms at work here?
- What are the basic physical mechanisms at work here?

http://www.superstock.com/

Neurons

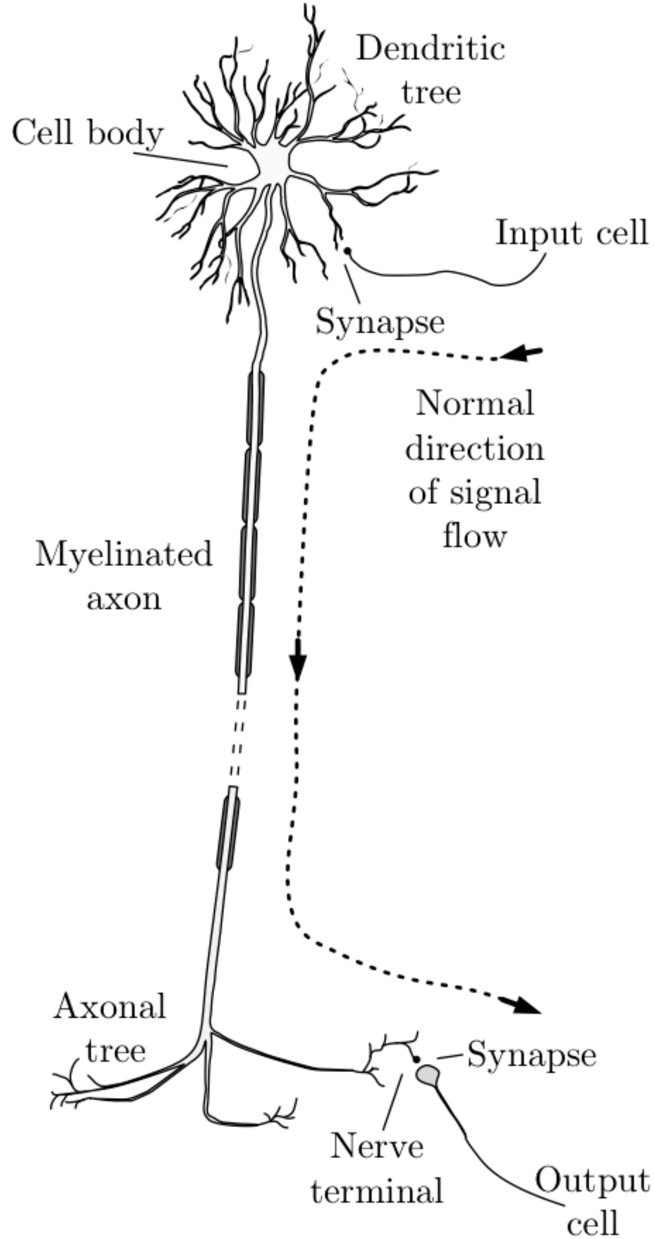


Figure 1.22

Weiss (1996)

BIOPHYSICS @ YORK

redefine THE POSSIBLE.

UNIVERSITÉ
UNIVERSITY

York University
BPHS 4080: Cellular Electrodynamics (3 credits)
Winter 2020

Time & Location
Lecture: MWF 1:30-2:30 (SC 304)

Instructor: Christopher Bergevin
Office: Petrie 240
Email: cberge@yorku.ca
Office Hours: Check course website (or email for appt.)

Course Website:
`http://www.yorku.ca/cberge/4080W2020.html`

Textbook:
Cellular Biophysics, vol. I & II, TF Weiss (*MIT Press*)*.

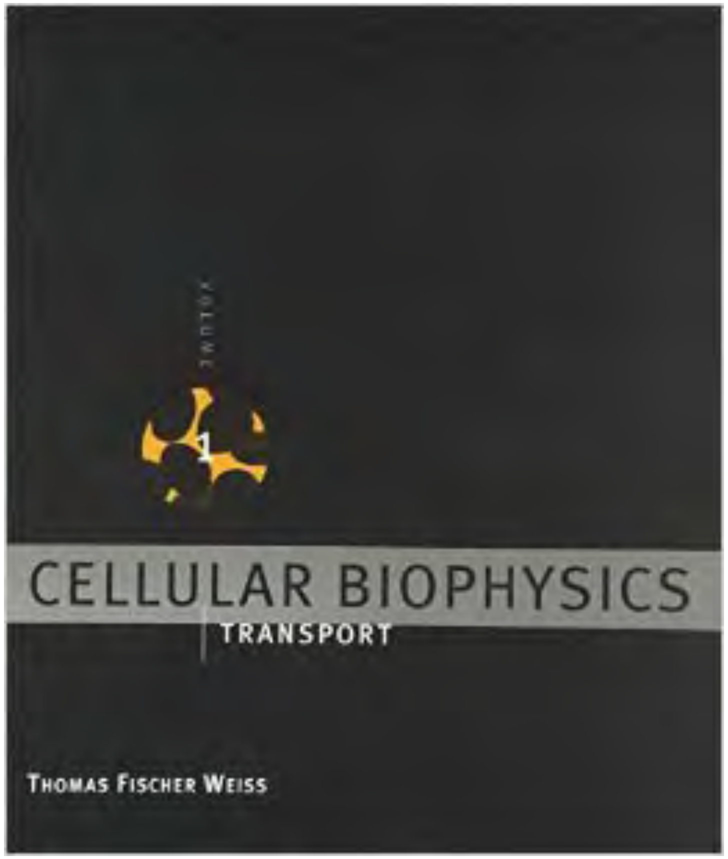
Prerequisites: SC/BPHS 2090 2.00; SC/PHYS 2020 3.00; SC/PHYS 2060 3.00

Course Theme/Topics: This course will generally focus on the topic of cellular transport to examine the interplay between physics and the life sciences. Topics will include (but are not limited to):

- Diffusion
- Osmosis
- Carrier-mediated transport
- Ion channels
- Modeling cell membranes using electric circuit analogs
- Action potentials (e.g., Hodgkin Huxley model)
- Nonlinear dynamics
- Synapses, Neural systems

http://www.yorku.ca/cberge/4080W2020.html

→ This is the course website and will be the main "go to" place for all course-related info (e.g., syllabus, slides, chapters for reading, exam info, etc…)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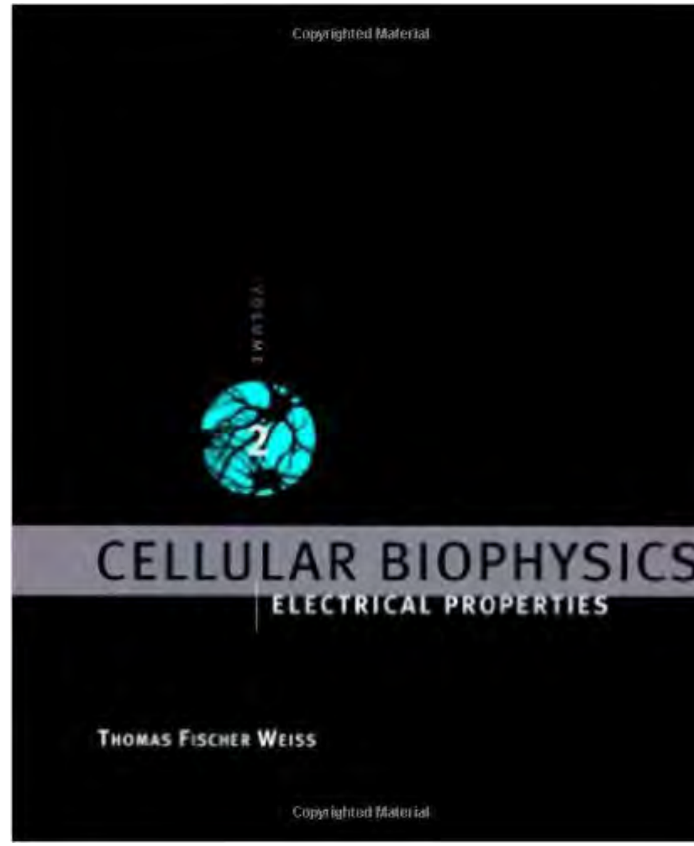
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BPHS 4080 Overview

- Diffusion
- Cell membranes
- Osmosis
- Carrier-mediated transport
- Electrical responses of cells
- Electro-diffusion, Resting potential
- Ion pumps
- Core-conductor model

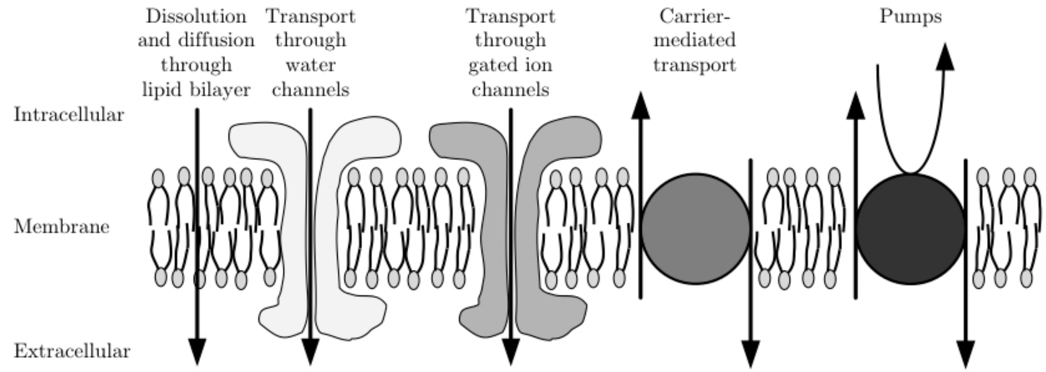

Figure 2.19

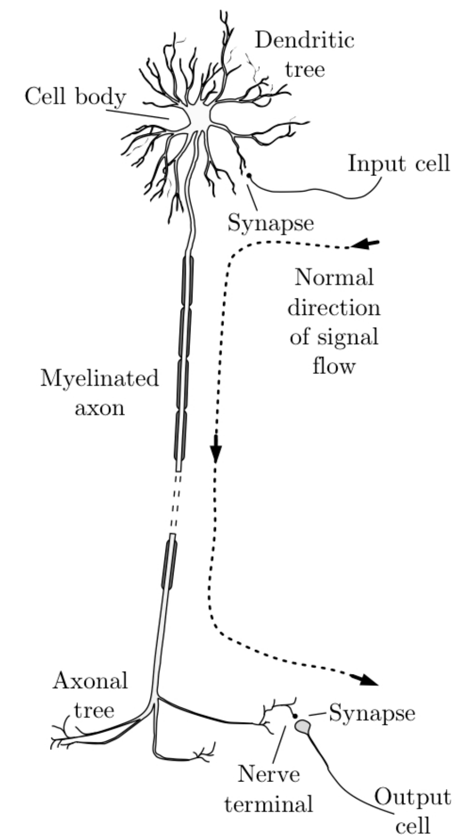

Figure 1.22

BPHS 4080 Overview (cont)

- Cable model
- Hodgkin-Huxley
- Myelination, saltatory conduction
- Ion channels

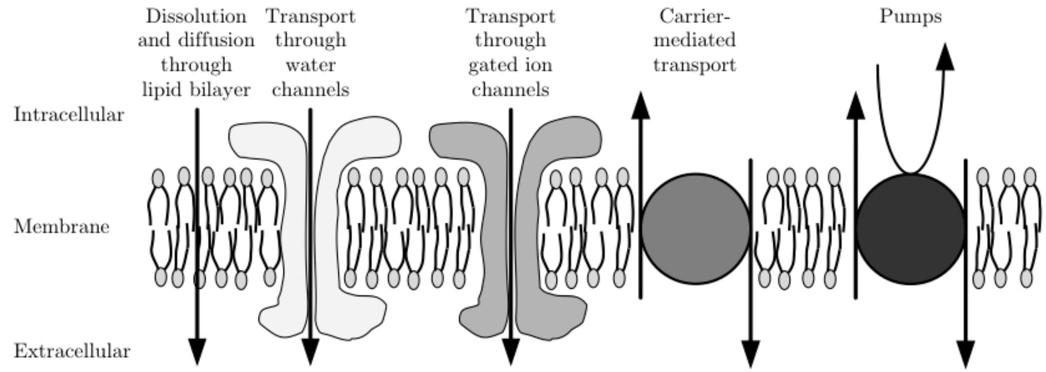

Figure 2.19

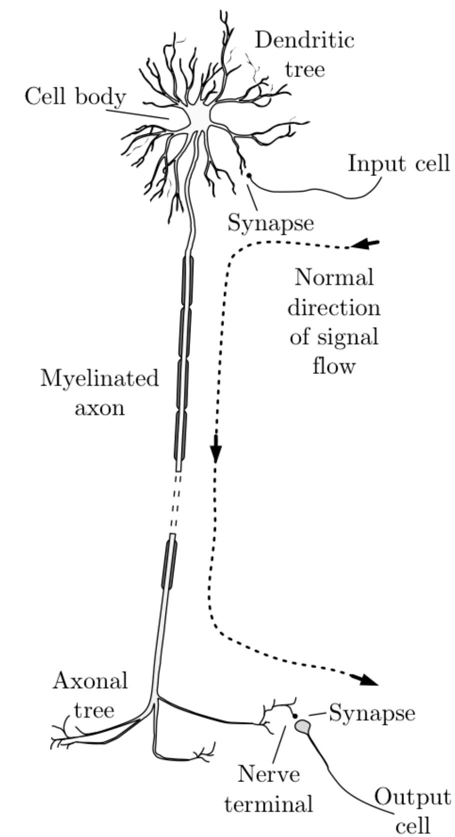

Figure 1.22

4080 Summary: Hodgkin-Huxley Equations

$$\frac{1}{2\pi a(r_o + r_i)} \frac{\partial^2 V_m}{\partial z^2} = C_m \frac{\partial V_m}{\partial t} + G_K(V_m, t)\,(V_m - V_K) + G_{Na}(V_m, t)\,(V_m - V_{Na}) + G_L(V_m - V_L)$$

$$G_K(V_m, t) = \overline{G}_K n^4(V_m, t)$$

$$G_{Na}(V_m, t) = \overline{G}_{Na} m^3(V_m, t) h(V_m, t)$$

$$n(V_m, t) + \tau_n(V_m)\frac{dn(V_m, t)}{dt} = n_\infty(V_m)$$

$$m(V_m, t) + \tau_m(V_m)\frac{dm(V_m, t)}{dt} = m_\infty(V_m)$$

$$h(V_m, t) + \tau_h(V_m)\frac{dh(V_m, t)}{dt} = h_\infty(V_m)$$

$$\tau_x \frac{dx}{dt} + x = x_\infty \qquad \frac{dx}{dt} = \alpha_x(1 - x) - \beta_x x$$

$$x_\infty = \alpha_x/(\alpha_x + \beta_x) \text{ and } \tau_x = 1/(\alpha_x + \beta_x)$$

$$\alpha_m = \frac{-0.1(V_m + 35)}{e^{-0.1(V_m+35)} - 1},$$

$$\beta_m = 4e^{-(V_m+60)/18},$$

$$\alpha_h = 0.07e^{-0.05(V_m+60)},$$

$$\beta_h = \frac{1}{1 + e^{-0.1(V_m+30)}},$$

$$\alpha_n = \frac{-0.01(V_m + 50)}{e^{-0.1(V_m+50)} - 1},$$

$$\beta_n = 0.125e^{-0.0125(V_m+60)},$$

Nernst Equilibrium Potential

$$V_n = \frac{RT}{z_n F} \ln \frac{c_n(d)}{c_n(0)} = \frac{RT}{z_n F} \ln \frac{c_n^o}{c_n^i}$$

$$G_n = \frac{1}{\int_o^d \frac{dx}{u_n z_n^2 F^2 c_n(x)}} \geq 0$$

Weiss (1996)

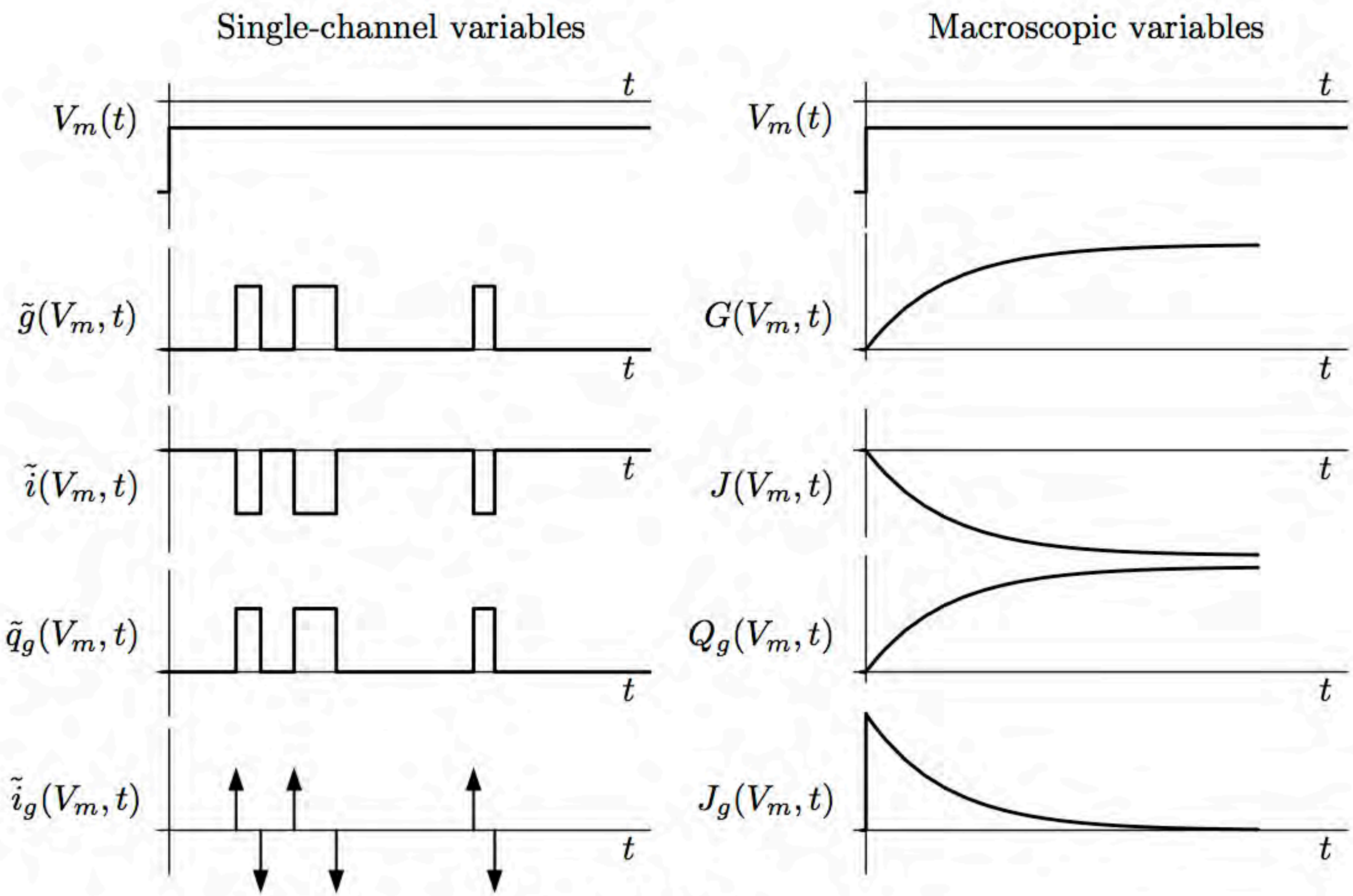

Figure 6.52

Biophysically, this figure encapsulates numerous key ideas....

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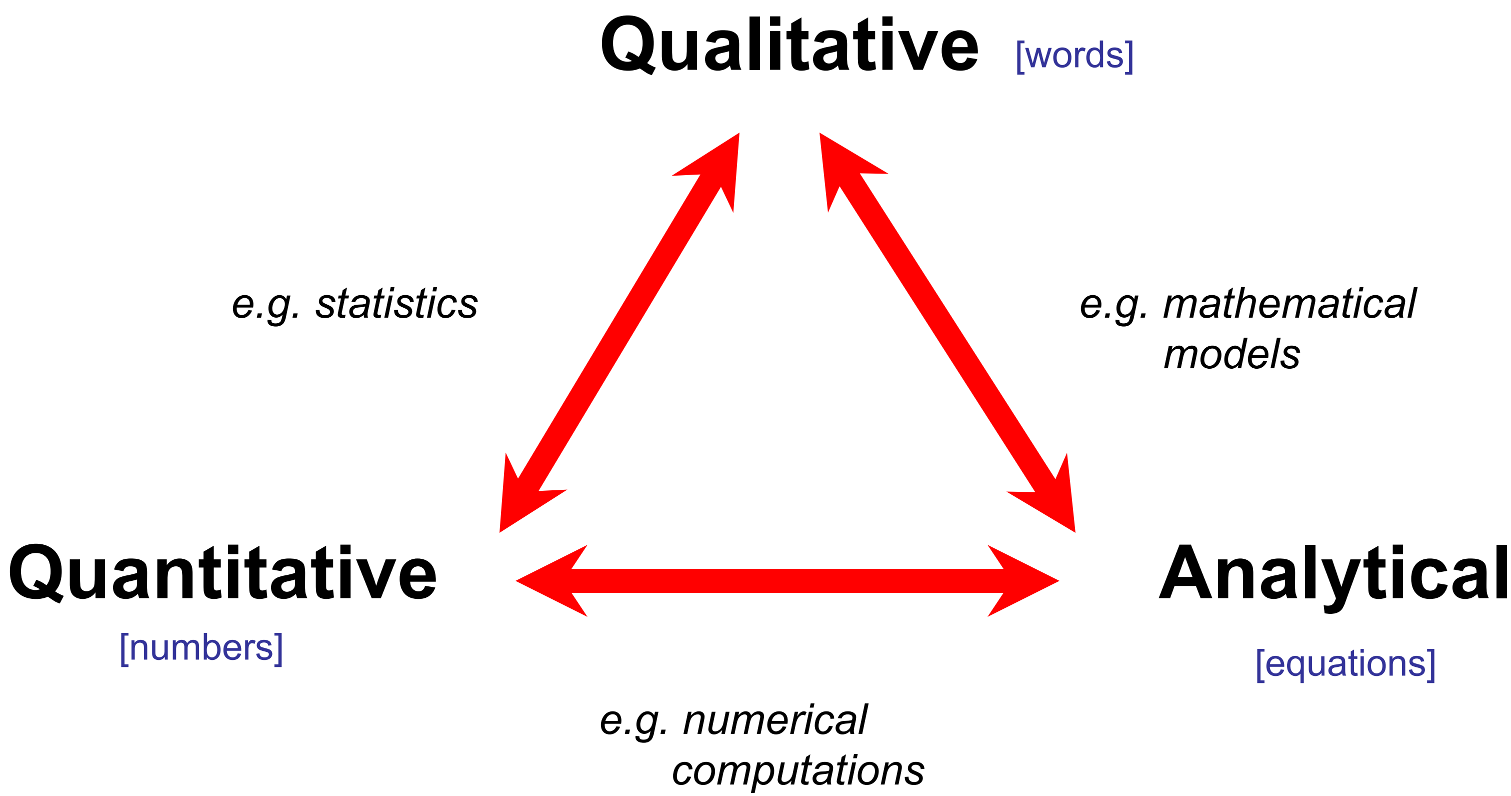
Describing biological/physiological systems



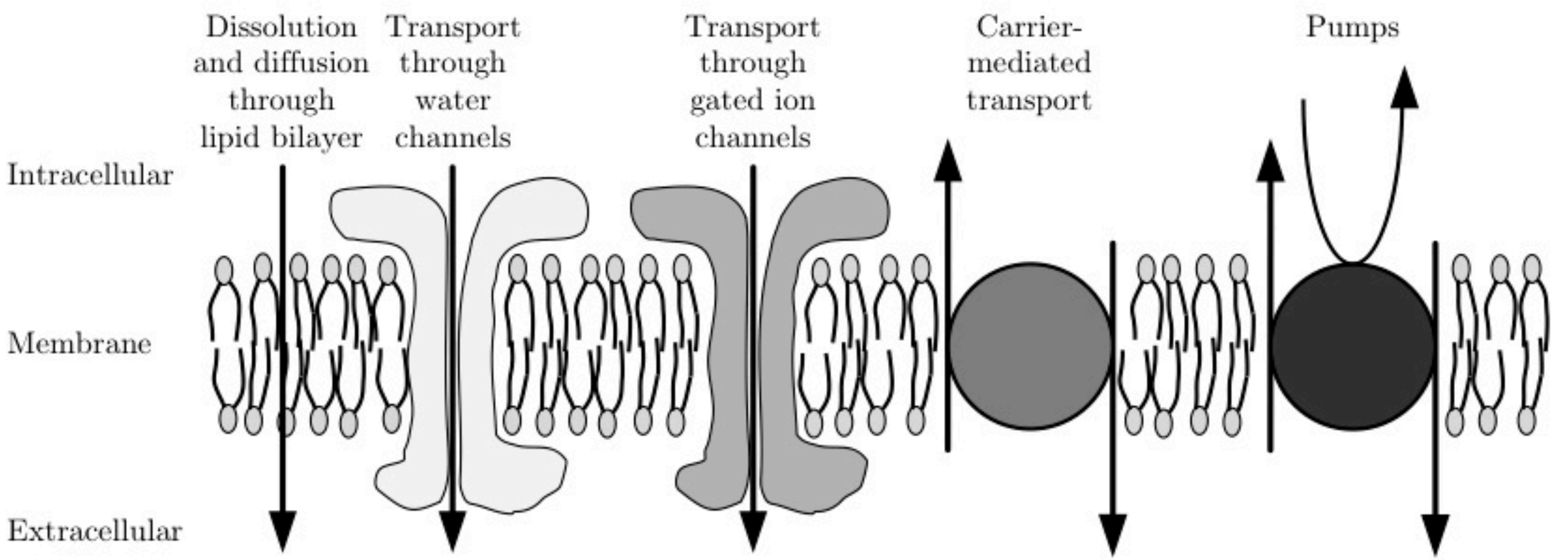
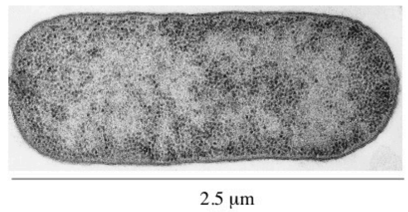


Figure 2.19

Weiss (1996)

Ex. Eating a potato

Escherichia Coli (E. Coli)



Culture Medium

NH_4Cl	1.0 g
$MgSO_4$	0.13 g
KH_2PO_4	3.0 g
Na_2HPO_4	6.0 g
Glucose	4.0 g
Water	1.0 L

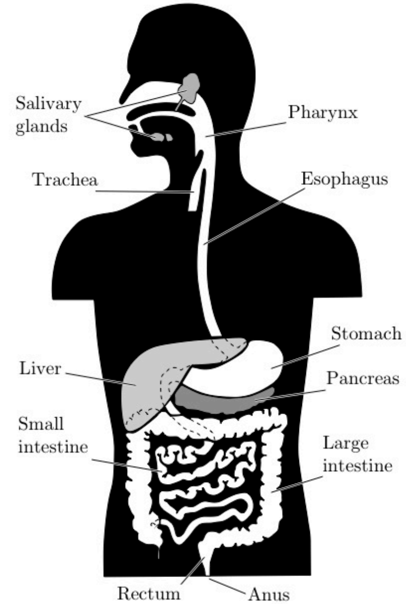
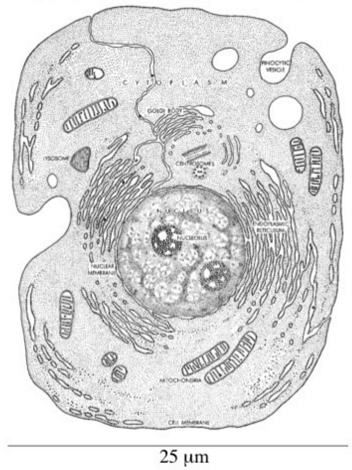


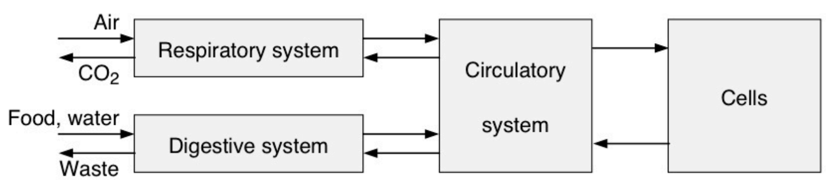
Figure 2.2

Generic Eukaryotic Animal Cell



Culture Medium

Essential Amino Acids (a dozen)
Vitamins (eight)
Salts (Na^+, K^+, Ca^{2+}, Mg^{2+}, Cl^-, PO_4^{3-}, HCO_3^-)
Glucose
Serum



Inputs to Organism
- air
- water
- food
  - carbohydrates
  - fats
  - proteins

Inputs to Cells
- oxygen
- water
- ions
- building block molecules
  - sugars
  - lipids
  - amino acids

Weiss (1996)

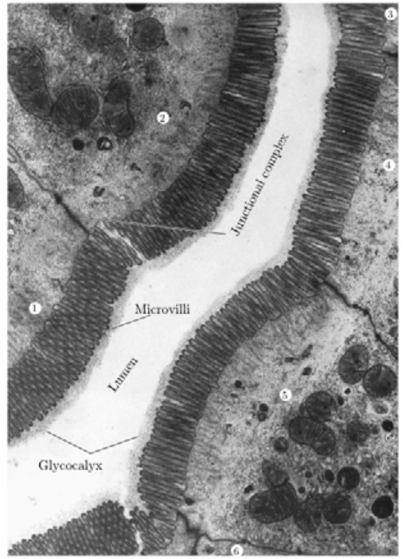


Figure 2.8

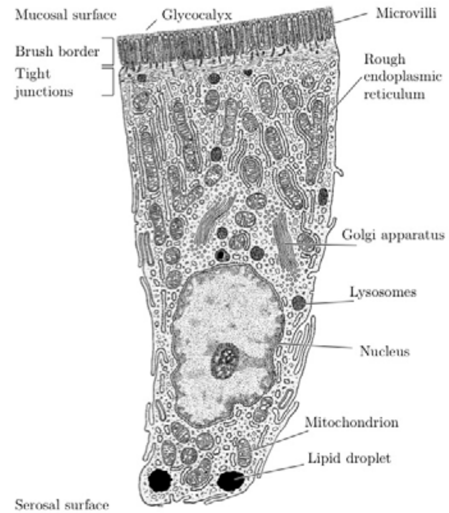


Figure 2.9

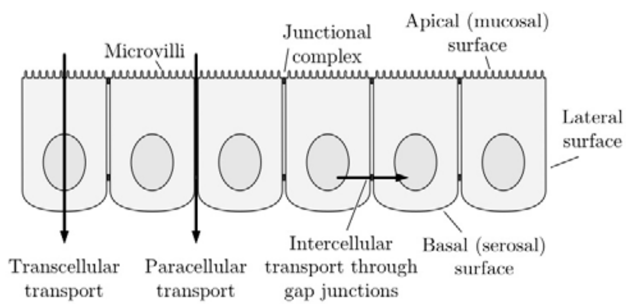


Figure 2.13

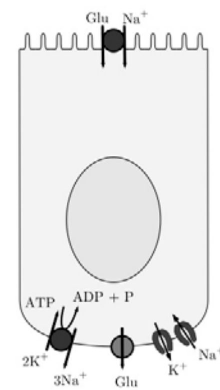


Figure 2.15

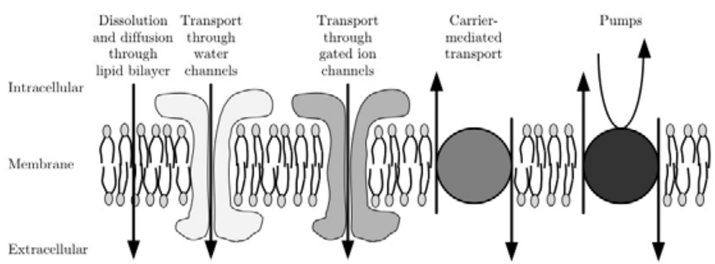


Figure 2.19

Weiss (1996)

Functions of more than one variable

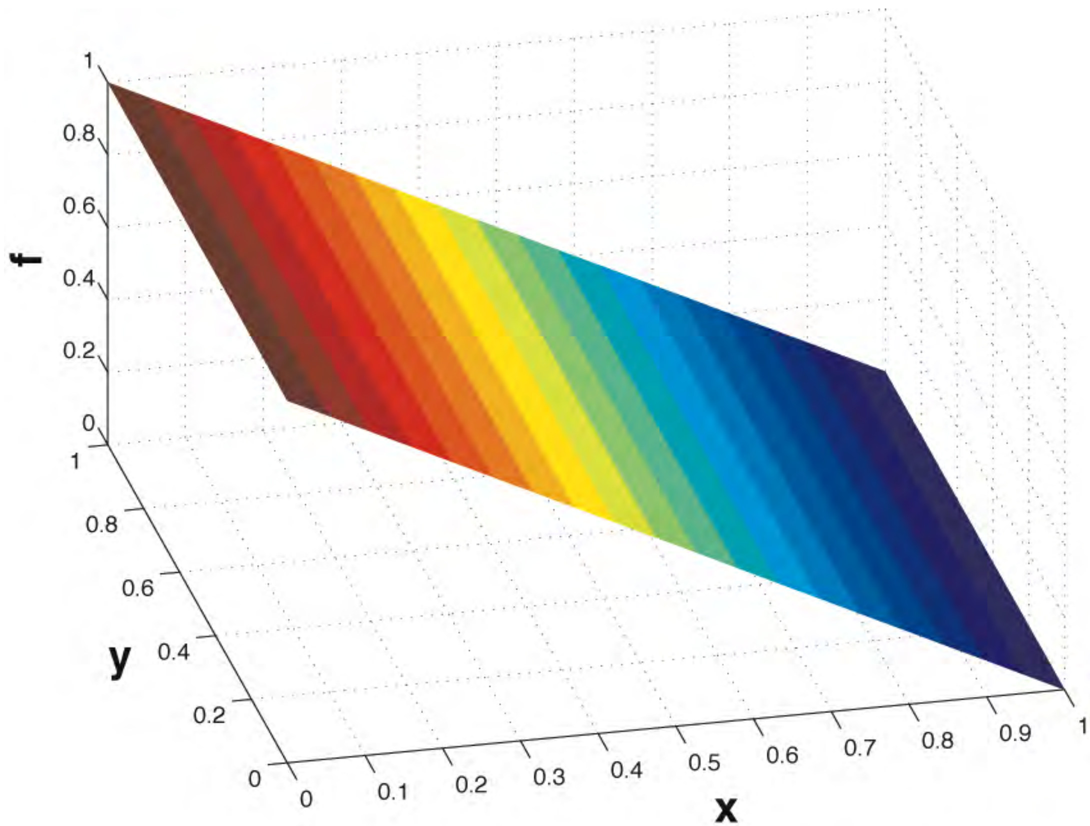
$\Rightarrow$ will be important for the various types of systems we will be describing analytically in the course

e.g. concentration of a solute in a solution (c) depends upon both spatial location (x) and time (t)

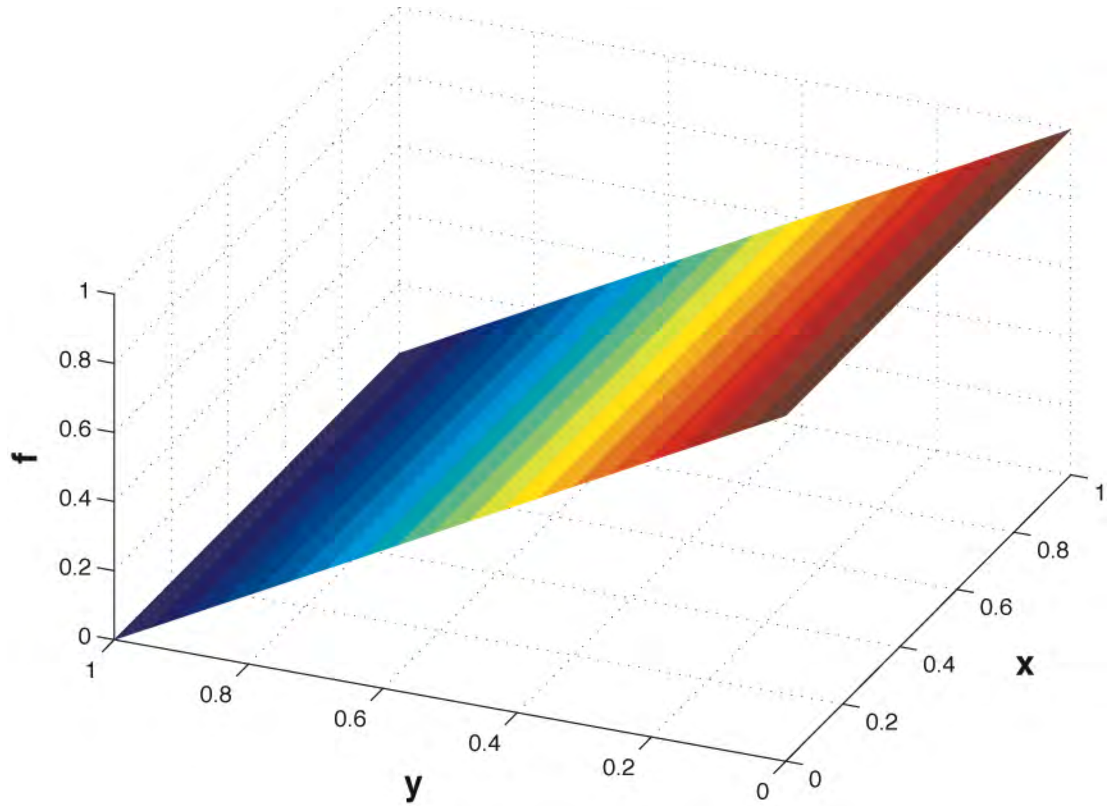
$$f = f(x, y)$$

f - dependent variable

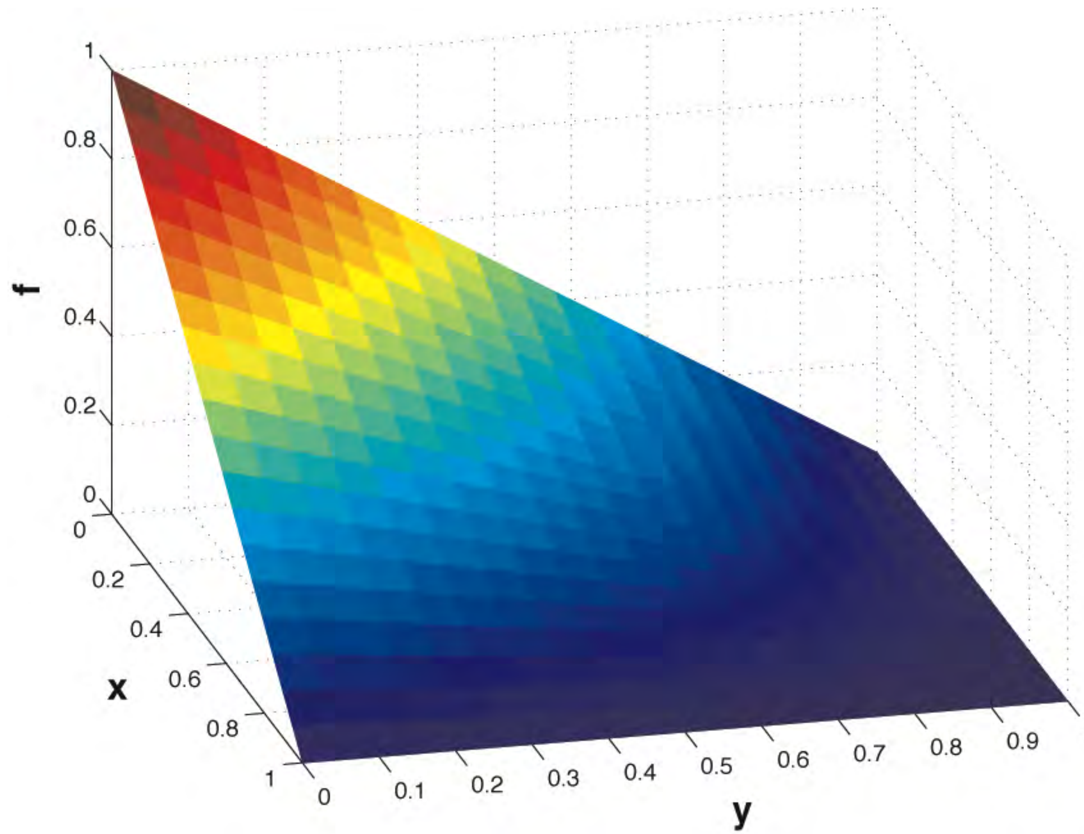
x, y - independent variables



$$f(x, y) = (1 - x) = f(x)$$



$$f(x, y) = (1 - y) = f(y)$$



<u>Biological Context</u>

f - reaction rate $[mol/s]$

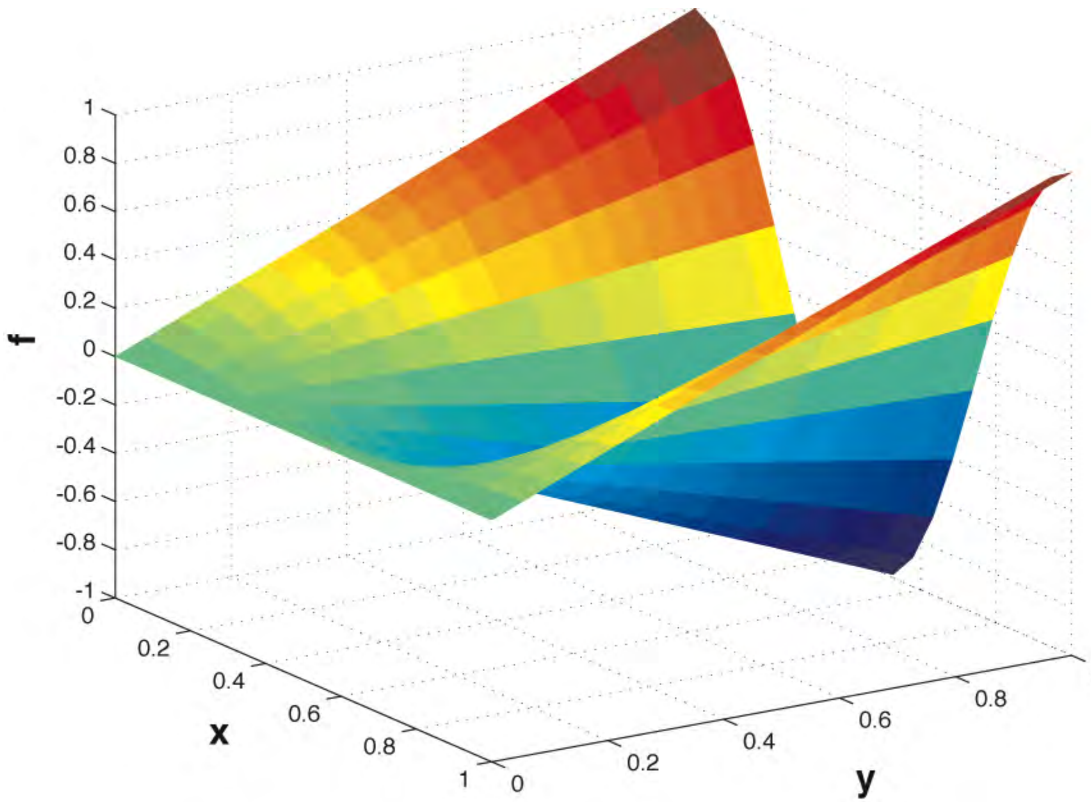
x, y - concentration of inhibitor agents $[mol]$

$$\cancel{f(x,y) = (1-y)(1-x)}$$

$$f(x,y) = k(1-x)(1-y)$$

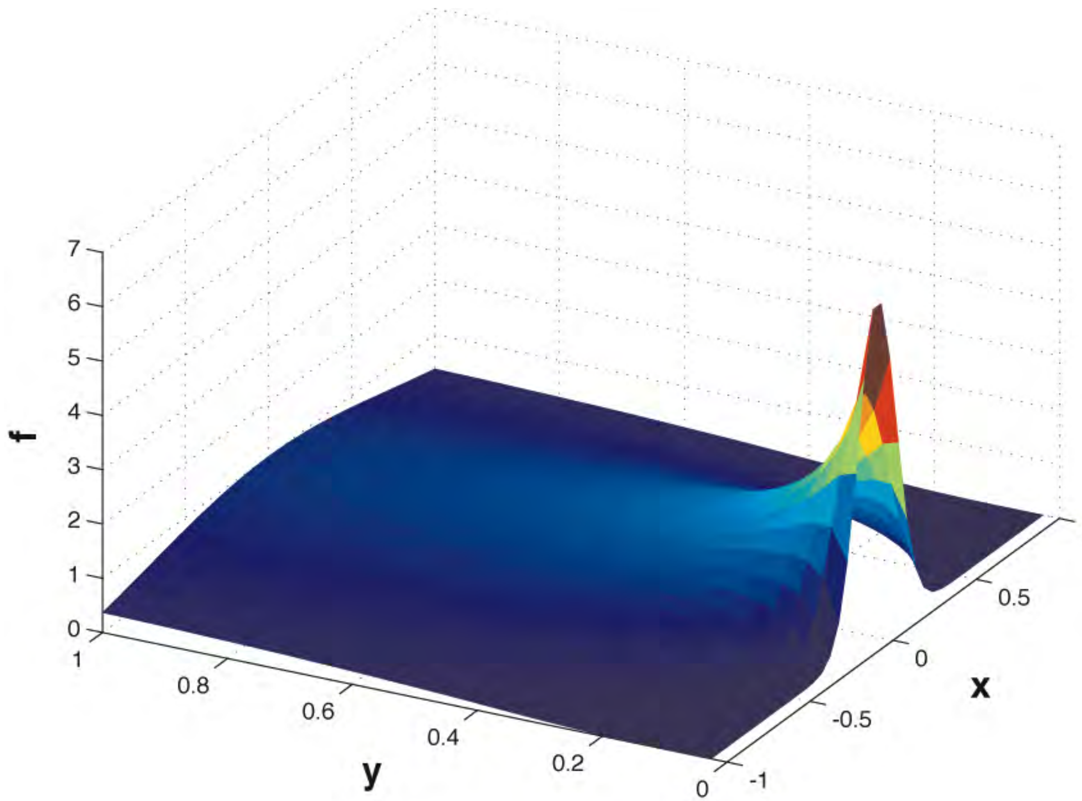
don't forget about units!

$$[k] = \frac{1}{mol \cdot s}$$



$$f(x,y) = y\cos(2\pi x)$$

can you think of an example of what the various variables might represent?



$$f(x,y) = \frac{1}{\sqrt{y}} e^{-x^2/y}$$

solution to
diffusion equation
(or *heat eqn.*)

Differentiation of functions of more than one variable

Derivative (definition) for a function of a single variable

$$\frac{dg(x)}{dx} = \lim_{\Delta x \to 0} \frac{g(x + \Delta x) - g(x)}{\Delta x}$$

For multi-variable function, keep one variable constant

$$\frac{\partial f(x,y)}{\partial x} = \lim_{\Delta x \to 0} \frac{f(x + \Delta x, y) - f(x,y)}{\Delta x}$$

note difference in notation

y is effectively held constant here

Differentiation of functions of more than one variable

Can also take partial deriv.
with respect to partial deriv.

$$\frac{\partial}{\partial y}\left(\frac{\partial f}{\partial x}\right)$$

Simplified notation

$$\frac{\partial}{\partial y}\left(\frac{\partial f}{\partial x}\right) = \frac{\partial}{\partial y}(f_x) = (f_x)_y = f_{xy}$$

Differentiation of functions of more than one variable

Examples:

ex.1 $$\frac{\partial z}{\partial x} \quad \text{for} \quad z(x,y) = (xy)^{1/2}$$

$$\boxed{\frac{\partial z}{\partial x} = \frac{1}{2}\; y^{1/2}\; x^{-1/2}}$$

ex.2 $$\frac{\partial}{\partial b}\left(\frac{\partial \phi}{\partial a}\right) \quad \text{for} \quad \phi(a,b) = ab^2 + 3a^2e^b$$

Notation: $\frac{\partial}{\partial b}\left(\frac{\partial \phi}{\partial a}\right) = \frac{\partial}{\partial b}(\phi_a) = (\phi_a)_b = \phi_{ab}$

$$\boxed{\frac{\partial}{\partial b}\left(\frac{\partial \phi}{\partial a}\right) = 2b + 6ae^b}$$

First find ϕ_a (assume b is constant): $\phi_a = b^2 + 6ae^b$

Now differentiate with respect to b : $\phi_{ab} = \frac{\partial}{\partial b}(\phi_a) = 2b + 6ae^b$

Note: In this case $\phi_{ab} = \phi_{ba}$ which is true for continuous functions (i.e. order of differentiation doesn't matter

Differential equations

ODE ('ordinary'): considers a function of one variable and how it changes with respect to that variable

ex.

$$\frac{dc}{dt} = kc \qquad \text{where} \quad c = c(t) \text{ and } k = \text{ const.}$$

PDE ('partial'): considers a function of more than one variable and how its various partial derivatives are related

ex.

$$\frac{\partial c}{\partial t} = D\frac{\partial^2 c}{\partial x^2} \qquad \text{where} \quad c = c(x,t) \text{ and } D = \text{ const.}$$

ODE review

Solving an ODE: find $c(t)$ for $$\frac{dc}{dt} = kc$$

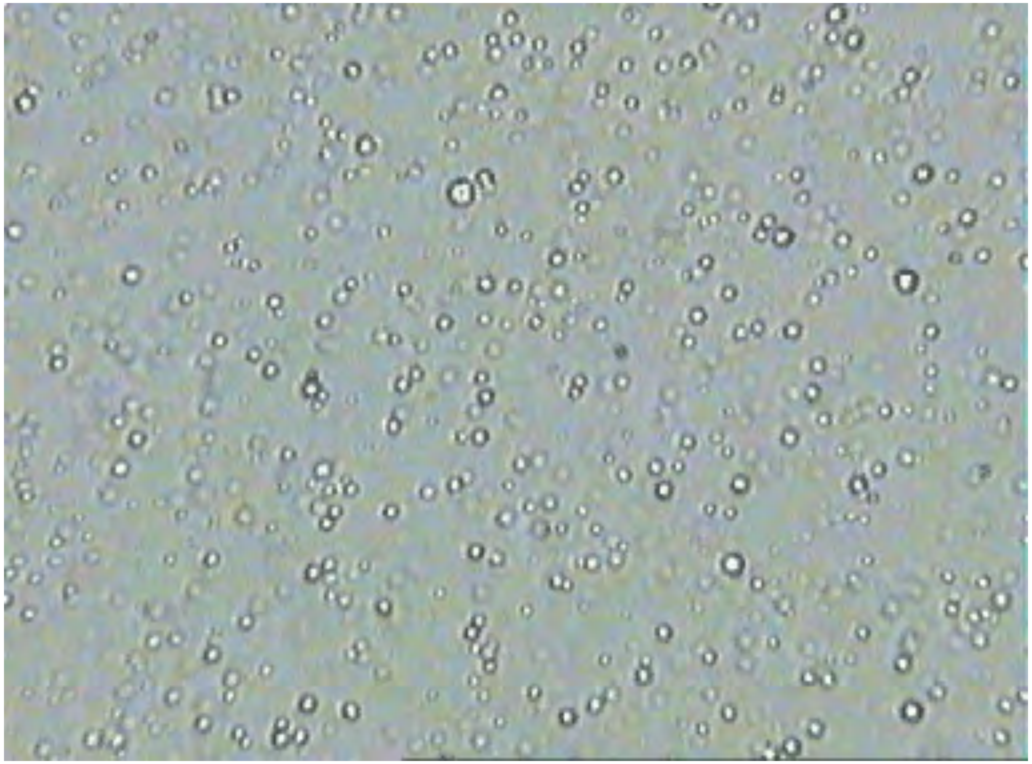
1. Separate variables and integrate $$\int \frac{dc}{c} = \int k \ dt$$

$$\Rightarrow c(t) = Ae^{kt}$$

2. Use an initial condition to find a unique solution. Suppose we have $c(1/k) = \frac{\ln\left(e^{e}\right)}{3}$

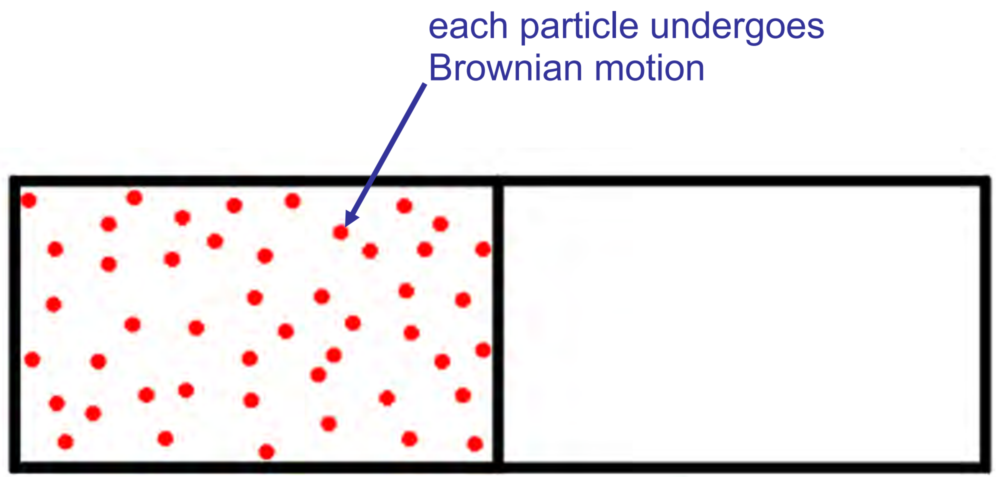
$$\boxed{c(t) = \frac{e^{kt}}{3}}$$

Brownian motion



http://www.microscopy-uk.org.uk/dww/home/hombrown.htm

Diffusion

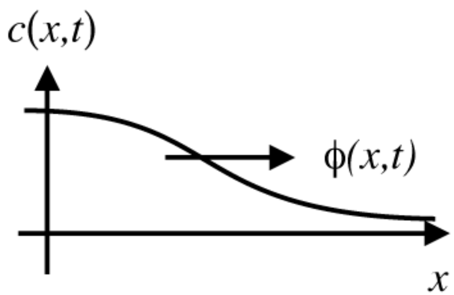


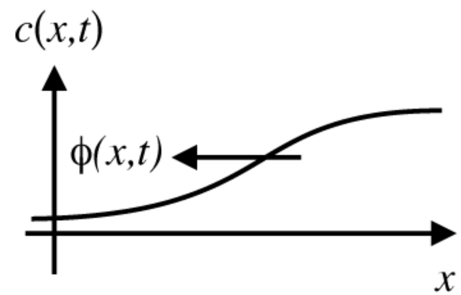
http://en.wikipedia.org/wiki/Image:Entropie.png

Diffusion (1-D)

- Thomas Graham (Scottish chemist, ~1828-1833)

[pioneered the concept of dialysis]



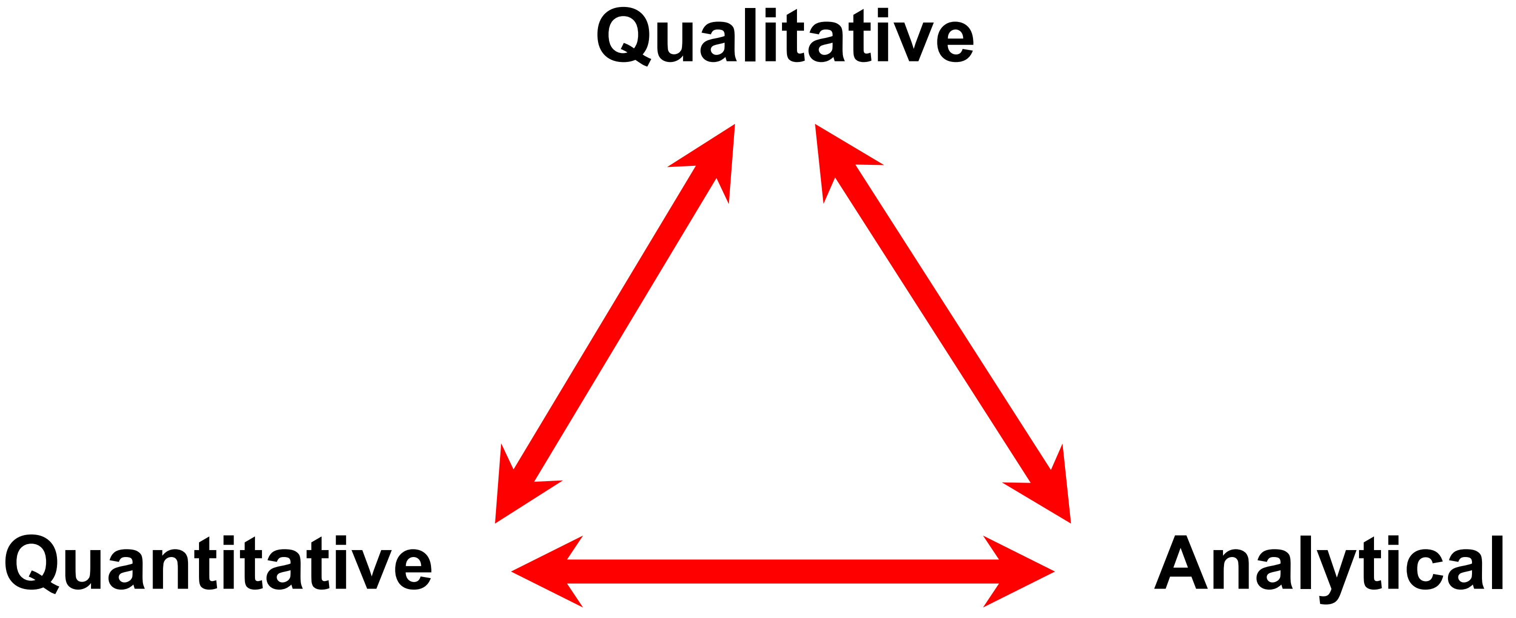


- Adolf Fick (German physiologist, ~1855)

[actually was the first to successfully put a contact lens on a person in 1888!]

“ A few years ago, Graham published an extensive investigation on the diffusion of salts in water, in which he more especially compared the diffusibility of different salts. It appears to me a matter of regret, however, that in such an exceedingly valuable and extensive investigation, the development of a fundamental law, for the operation of diffusion in a single element of space, was neglected, and I have therefore endeavoured to supply this omission.”

- A. Fick (1855)


Qualitative
Quantitative
Analytical