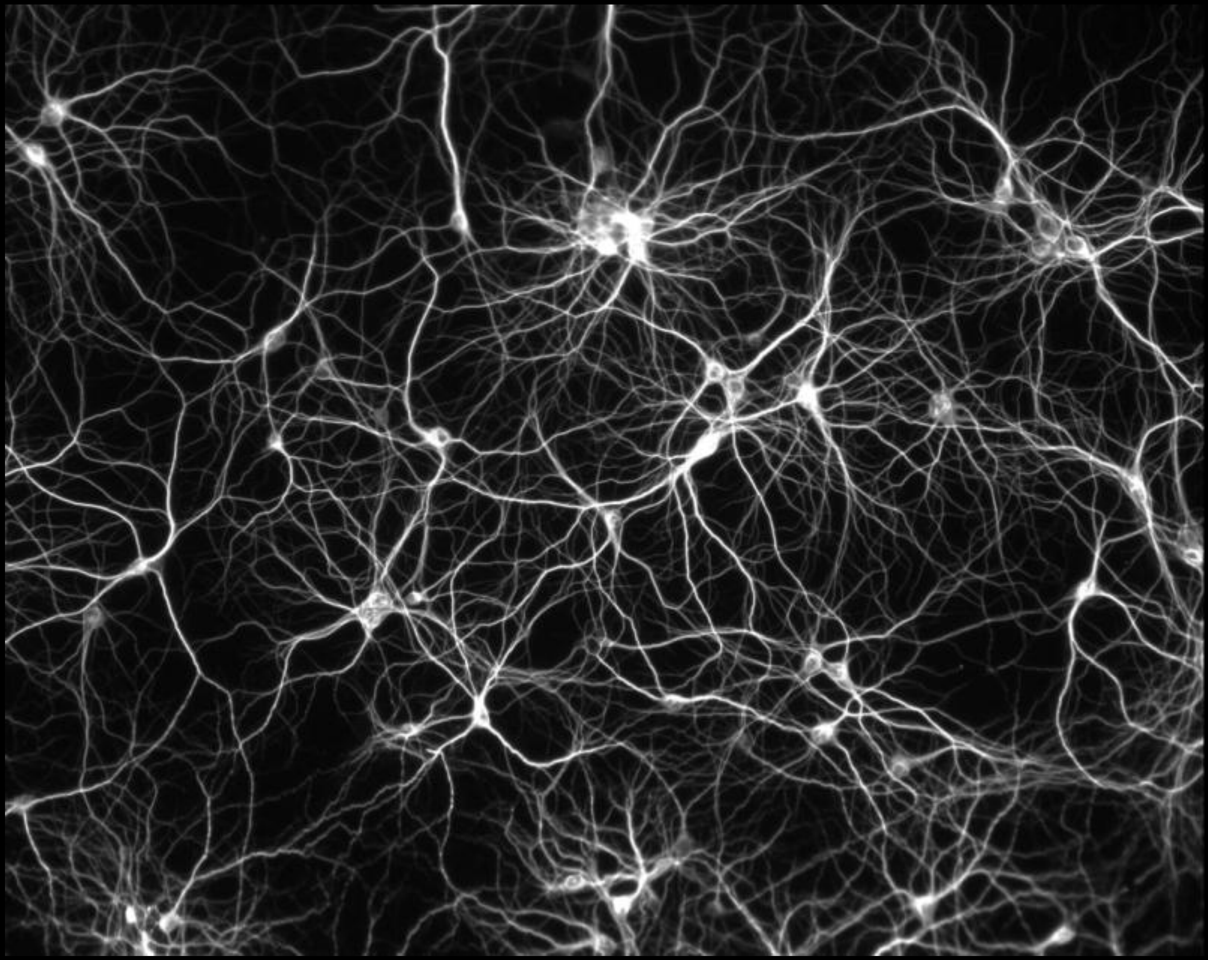
Neural Physics: an overview



Cooper Mellema

Topics

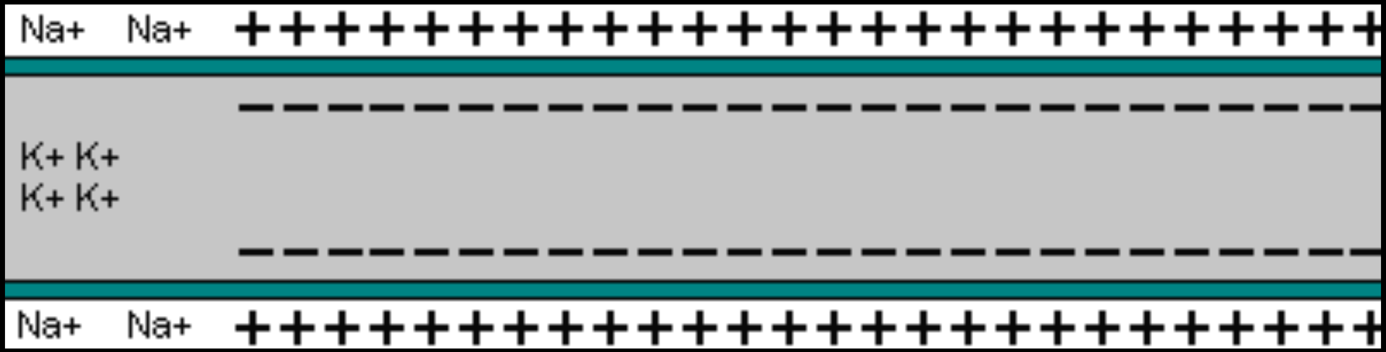
- Electrophisiology
- Channel Biophysics
- Information theory in neural networks

Brief overview of Electrophisiology

- Describes the electrical properties of neurons and neural tissues
- Neurons are negative compared to the intercellular space
- Signals are transduced as a rolling wave of depolarization
- Neuron can be modeled as an RC circuit with different components of R and C modeled as differential equations

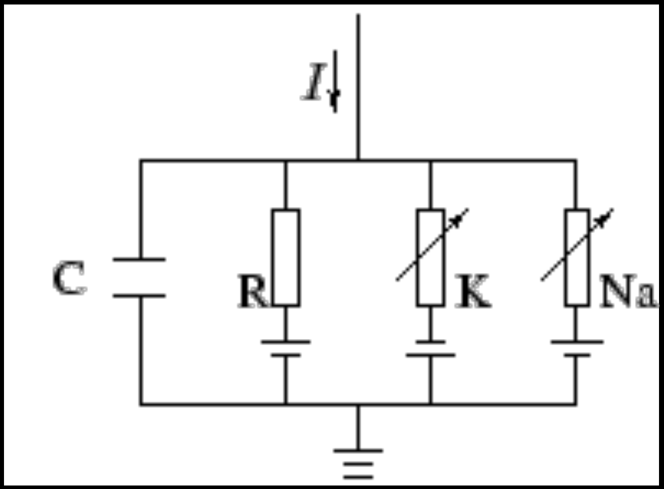
How a neuron fires

- Low sodium inside, low potassium outside
- First, an input opens a number of sodium channels, causing the cell to depolarize
- Sodium channels are gated, and more open with sufficient depolarization, leading to a positive feedback loop of depolarization, then shut off
- Potassium channels open, leading to repolarization



Hodgekin-Huxley Equation

- 4 components: membrane capacitance, sodium resistance, potassium resistance, and resistance of all other channels



- First, we split the current into different components for later

$$I(t) = I_C(t) + \Sigma I_k(t)$$

- Then, we set up a differential equation whose parameters we can measure

$$C\,dV/dt = -\Sigma I_k(t) + I(t)$$

Hodgekin-Huxley 2

- Each component of the current $I_k(t)$ is described by a differential equation in turn:

$$\Sigma I_k = g_{Na}\, m^3 h\, (V - V_{Na}) + g_K\, n^4\, (V - V_K) + g_L\, (\mathrm{V} - E_L)$$

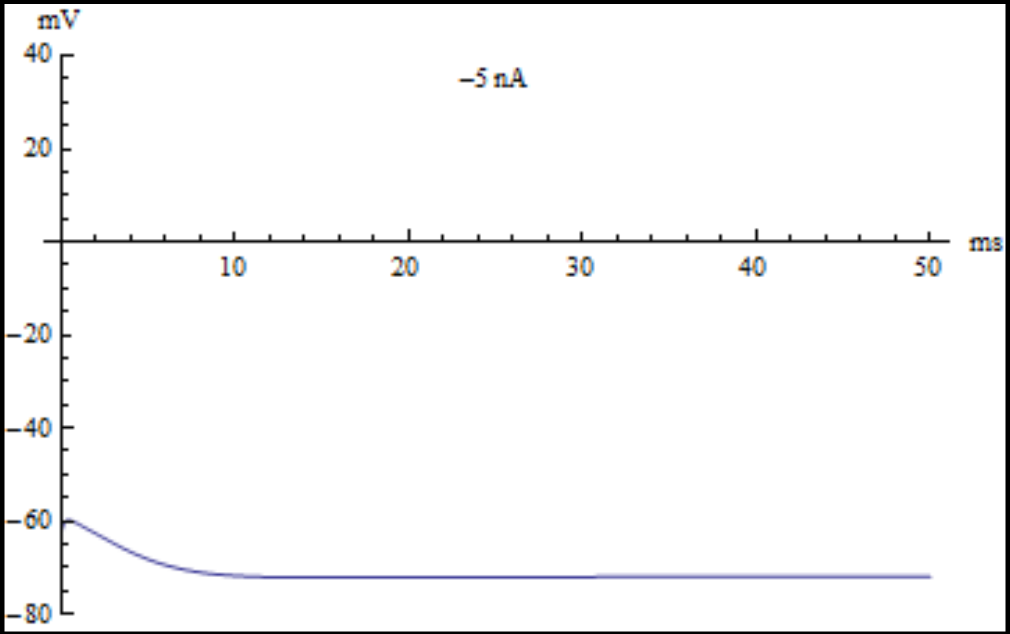
m and h represent the gating of sodium channels, n represents the gating of potassium channels. These are governed by the following equations:

$$dm/dt = \mathrm{f(V)(1-m)-g(V)m}$$

$$dn/dt = \mathrm{f2(V)(1-n)-g2(V)n}$$

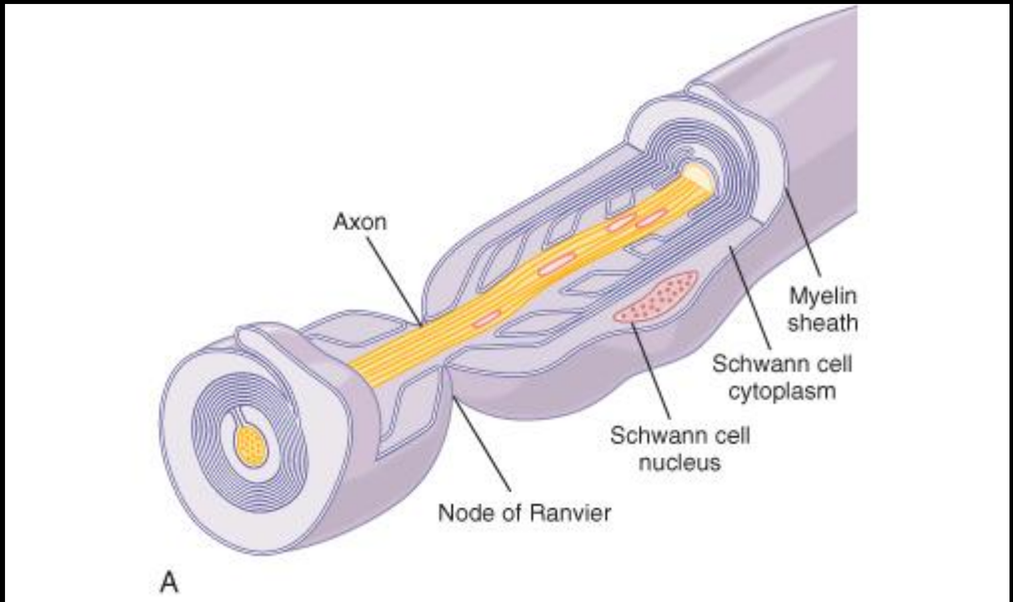
$$dh/dt = \mathrm{f3(V)(1-h)-g3(V)h}$$

Result: Simple spiking model that has a frequency dependent on the input current



Improvements on Hodgekin-Huxley:

- Add in additional channels rather than just “other resistances” (ex: chloride can be important)
- Rewrite equations in terms of both voltage *and* concentration
- Apply electronic cable theory to axons along with periodic myelination
- Many more, must decide what is useful



Example Extension: Rose-Hindmarsh model (from X. Zhao et al.)

$$C dV/dt = -g(V)(V - V_{Na}) - g_R R(V - V_K) - H + I_{ext}$$

$$dR/dt = -1/\tau_R \; [R - R_\infty (V)]$$

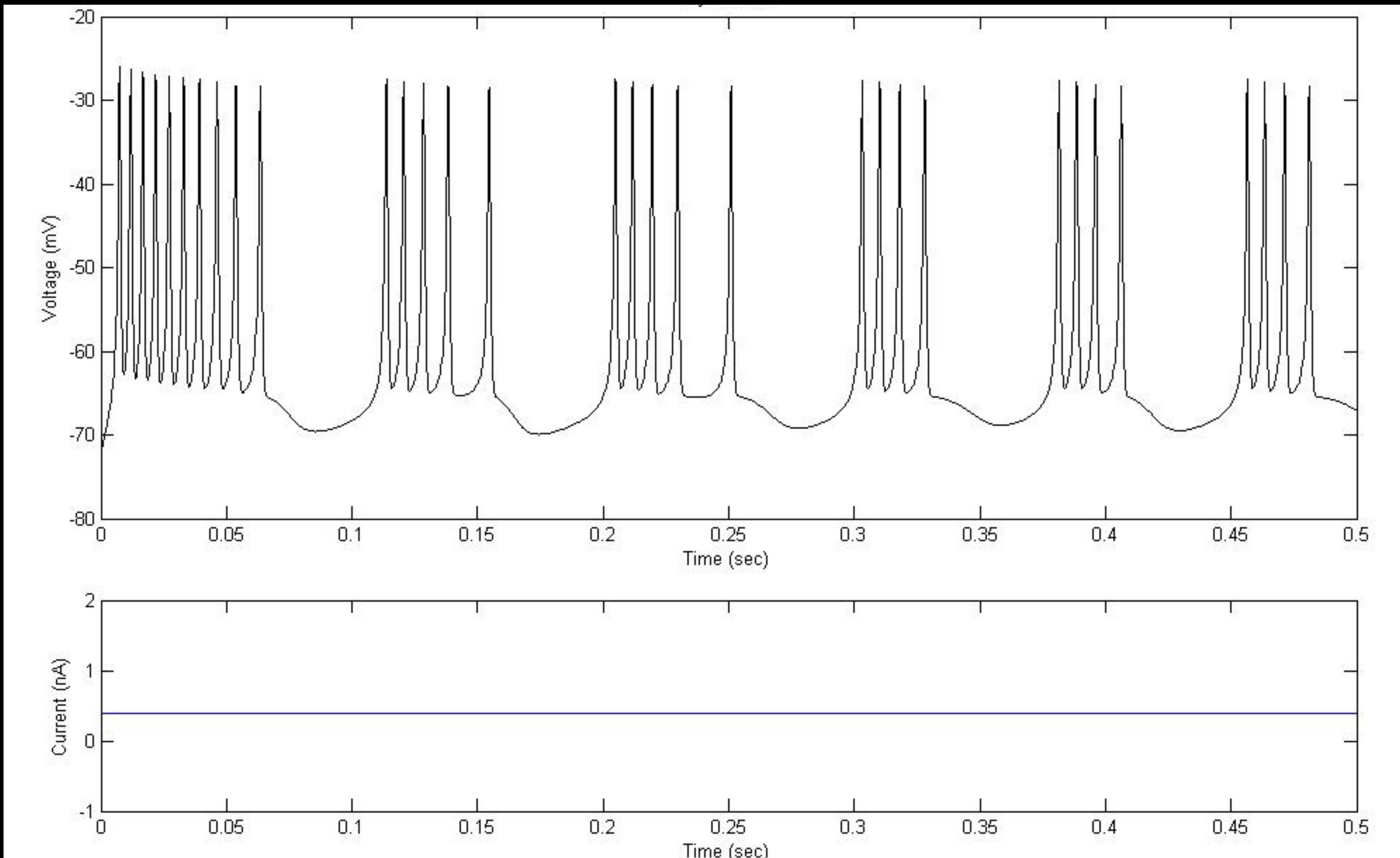
$$dH/dt = -1/\tau_H \; [H - g_H (V - V_H)]$$

$$g(V) = v_0 + v_1 V + v_2 V^2$$

$$R_\infty (V) = 0.17 + r_2 (V - V_4)^2$$

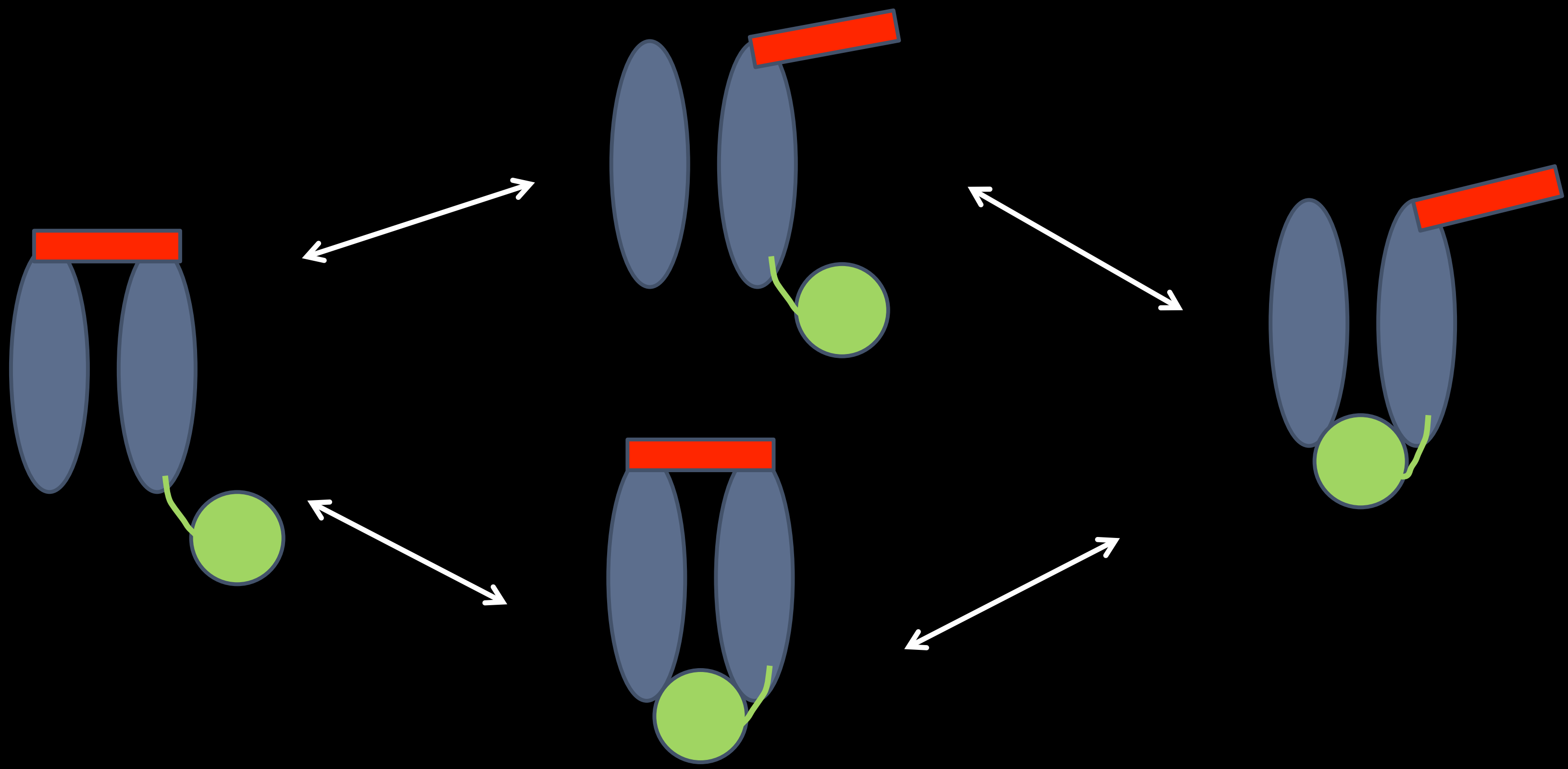
- Specific example of Hodgekin-Huxley with less general solutions

Result: bursting pattern

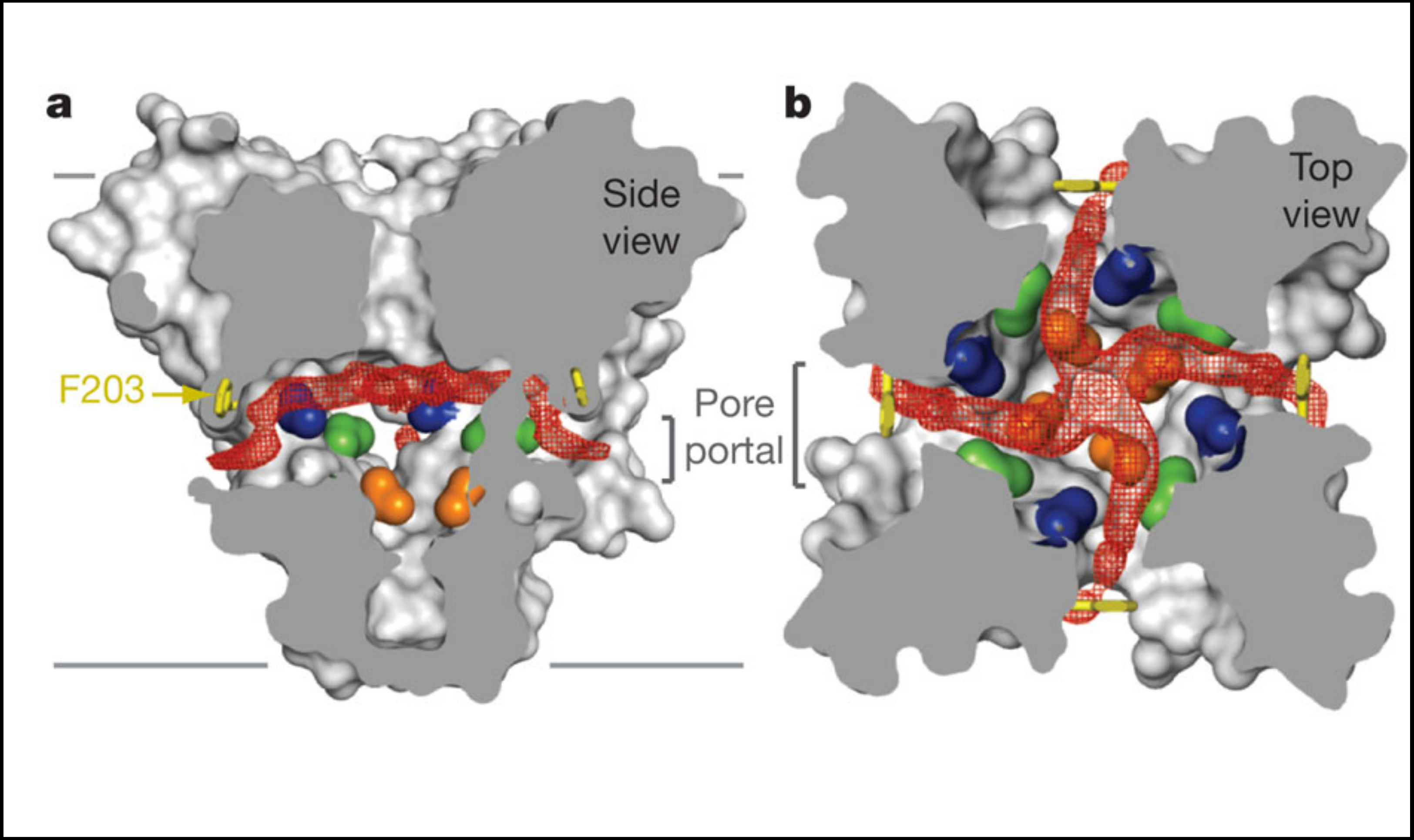


Single Channel biophysics

- Sodium channel has 2 gates, and therefore 4 states, probability to go between states governed by voltage and temp: statistical mechanics approach

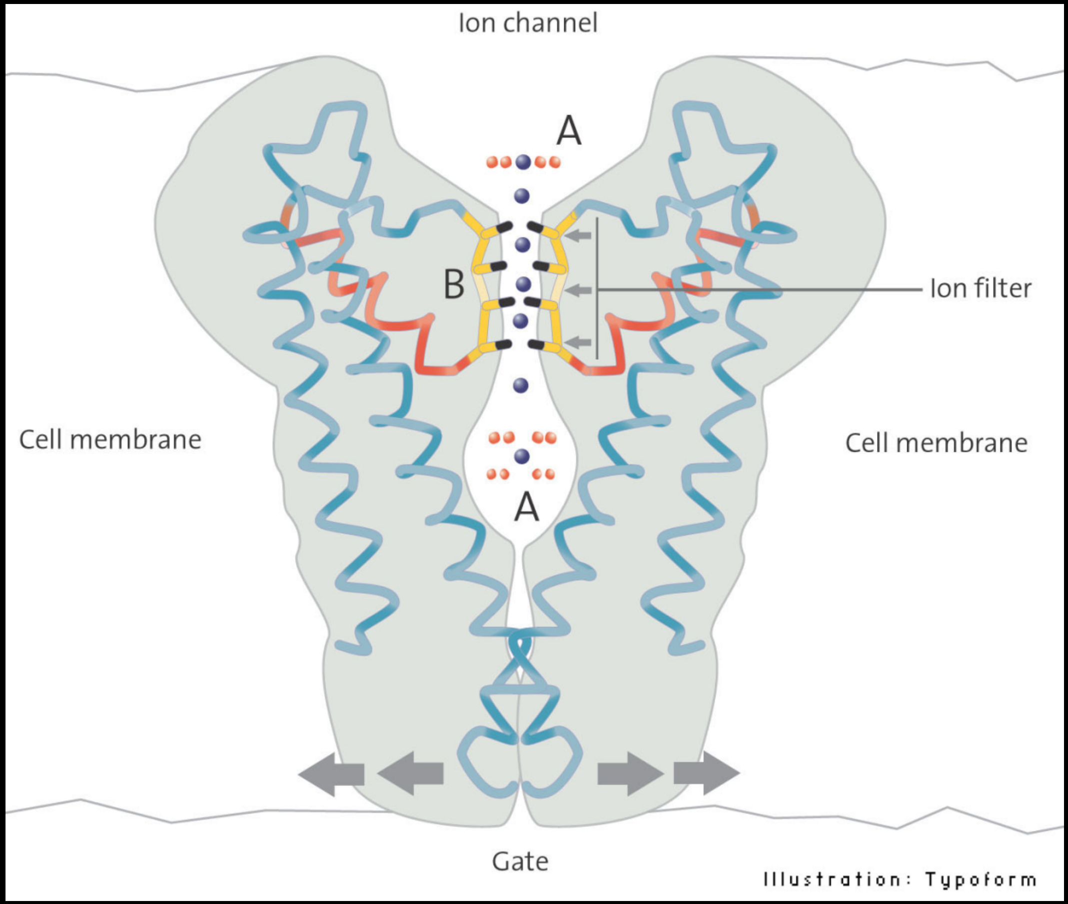


Actual structure

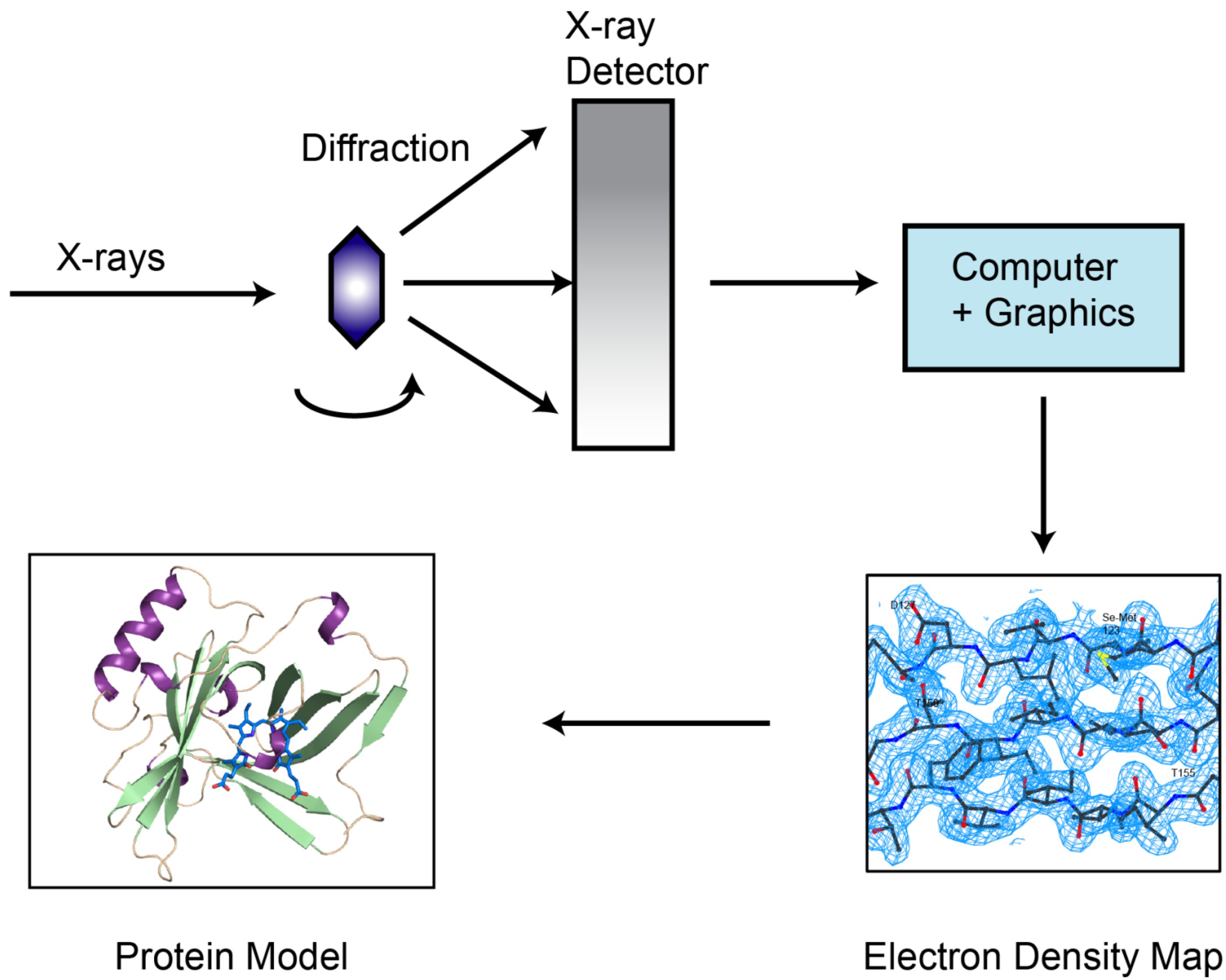


Mechanism of Sodium Channel Activity

- Inner "neck" is positively charged
- With a change in voltage, neck twists open or closed
- Sodium let through by size exclusion, governed primarily by hydration energy

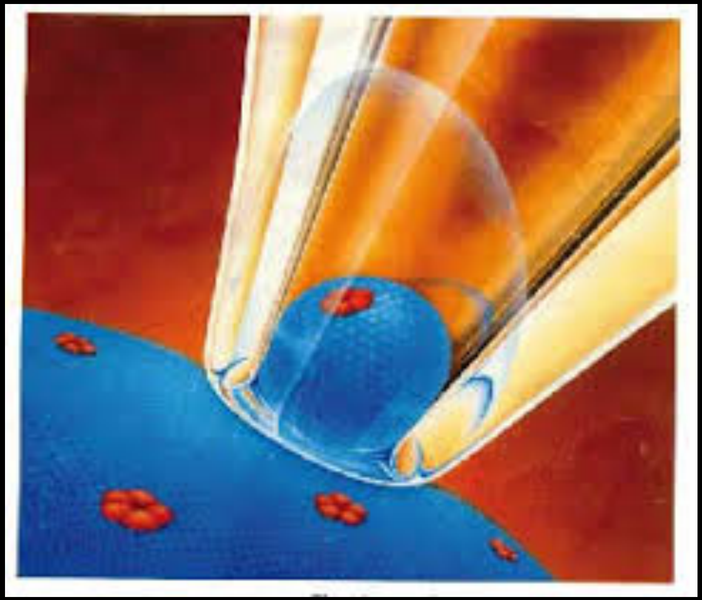


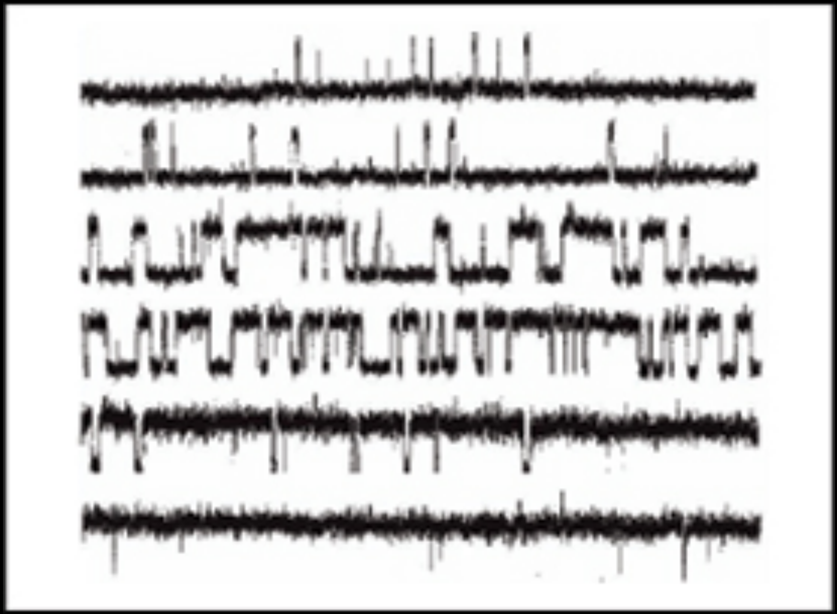
Overview of the X-ray Crystallographic Method



Patch Clamp

- Allows for determinations of single channel behavior





Information theory

- Need to be able to quantify information able to be encoded by the brain
- Multiple approaches: I am going to cover the method where “information” is a change in entropy and look at a specific example from Urban and Padmanabhan (2010)
- Individual neurons vary within a network, and highly heterogeneous neurons can encode up to 2 times more information than a purely homogeneous system
- This means that intrinsic diversity is important for neuronal coding, and not just biological imprecision

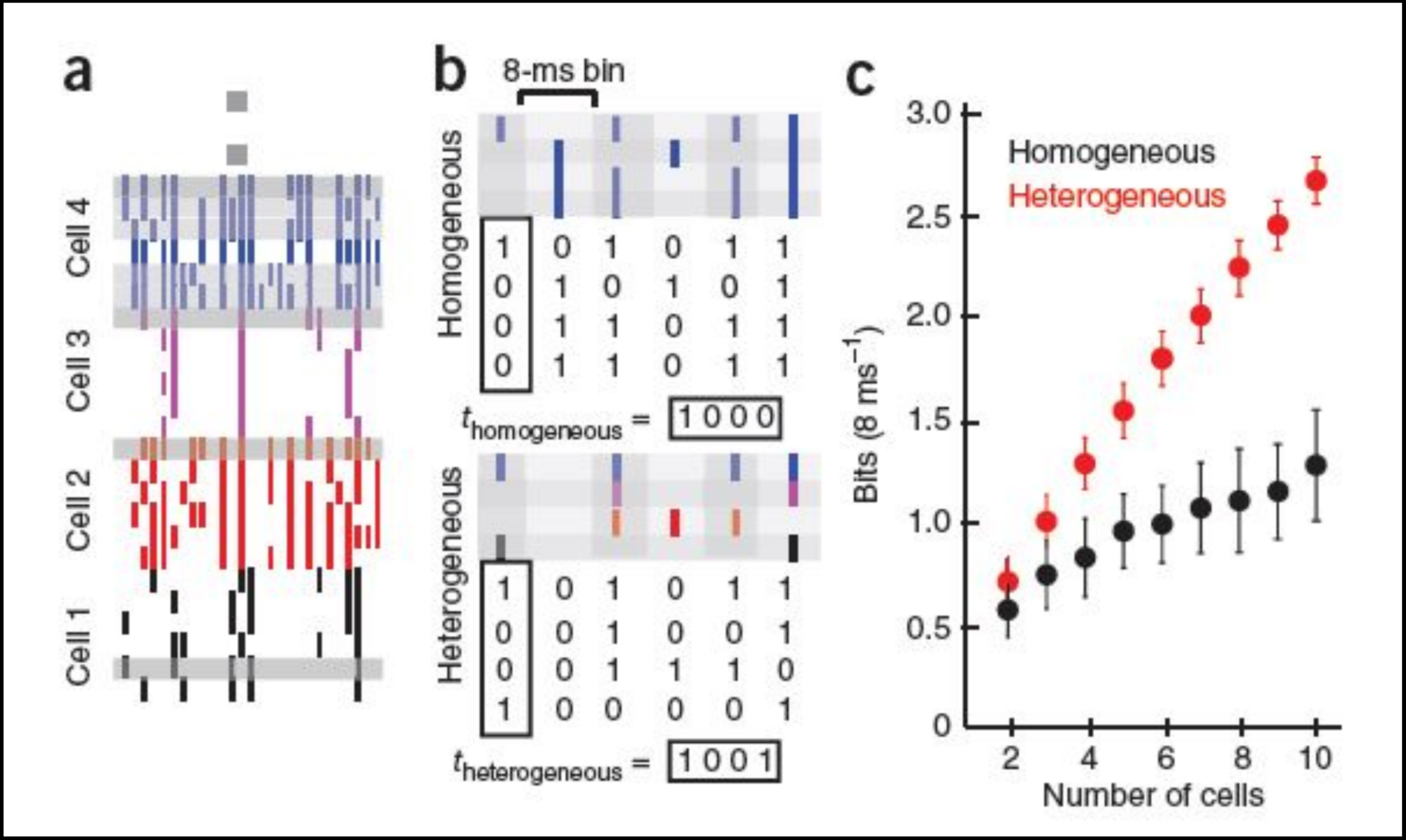
Quantifying "Information"

- Using the statistical definition of entropy,

$$S=-A\sum_{n}P(n)*\ln[P(n)]$$

- P(n) is the probability of a certain "word" of 0's and 1's based on the distribution of 0's and 1's generated.
- Information here is defined as entropy minus a noise factor

Information Transfer



Overcoming Noise and Chaotic behavior:

- Neurons are incredibly noisy, and sorting information from noise is incredibly difficult
- Solutions:
  - Matrix algebra analysis of overdetermined systems
  - Dimensional reduction techniques, such as PCA (principal component analysis)
  - Smoothing and filtering data

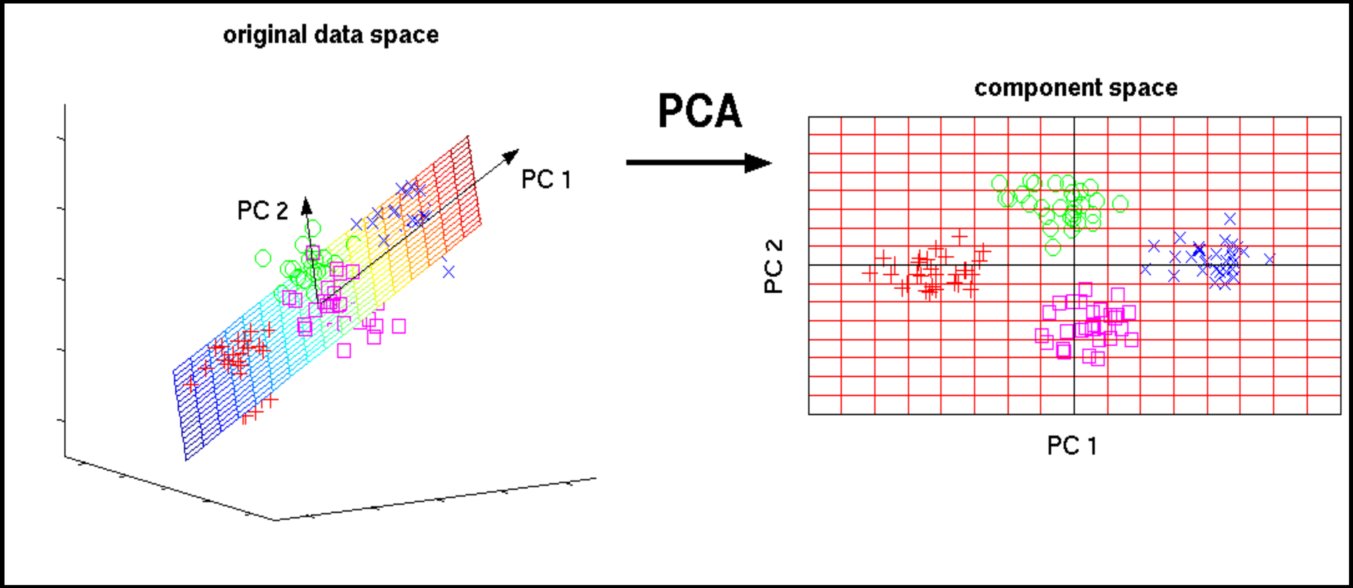
Overdetermined Systems

- Problem when trying to decode neuronal systems and modeling them
- Far more solutions than unknowns, sometimes orders of magnitude more solutions than unknowns
- Approximate solution (ordinary least squares) for **A**x=**b**:

find Min. of $||\mathbf{Ax}-\mathbf{b}||$

given by $\mathbf{x} = (\mathbf{A}^t\mathbf{A})^{-1}\mathbf{A}^t\mathbf{b}$

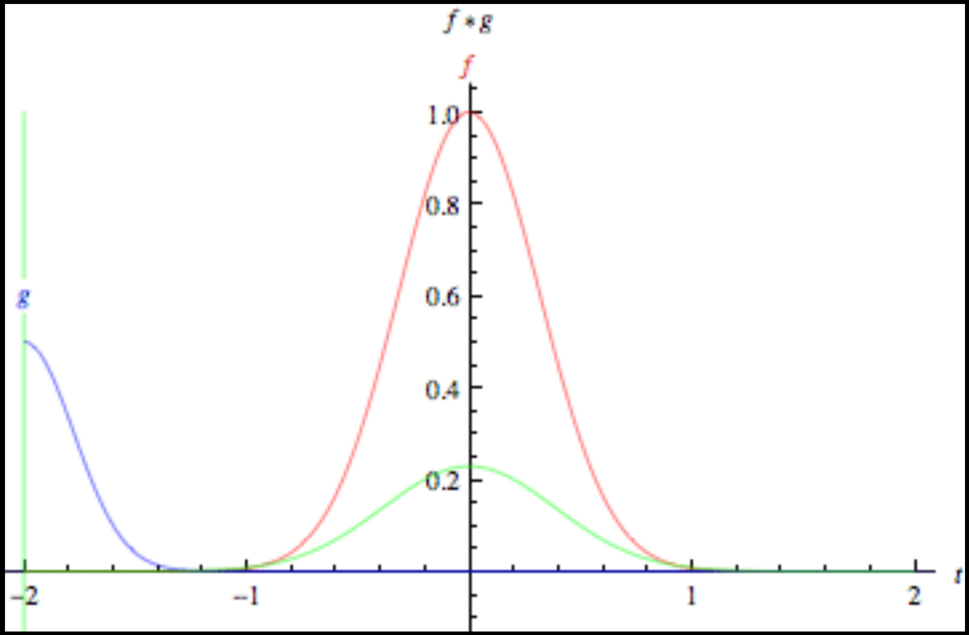
PCA: Principal Component Analysis



- Repeatedly project a high dimensional space onto a lower dimensional space while maximizing the variance
- Principal components are eigenvectors of covariance matrix, these are our basis vectors

Smoothing and Filtering

- In practice, much of the calculations and computations are simpler if you smooth the data
- Basic filters can do anything from averaging windows of data to convoluting Gaussians with data



Questions