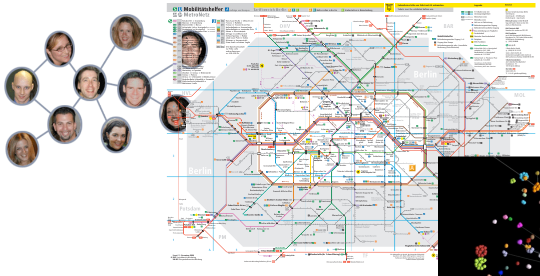
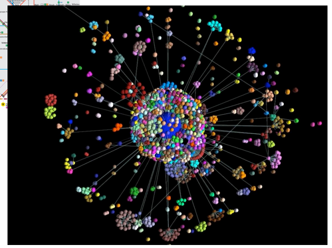
Introduction to neuronal dynamics





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SUMMARY – Day 3

1. Individual neurones:
   - Membranes, channels and excitation
   - Action potential
2. Models of neuronal activity
   - Hodgkin-Huxley
   - Dynamical models
3. Connecting neurons
   - A simple small-world network
   - The cortex – anatomy and topology
   - Multilevel model of the cortex

Order, dissorder and life

- Are these systems …
  - … ordered?
  - … stable?
  - … self-organized?
  - … in equilibrium?

INFORMATION !!

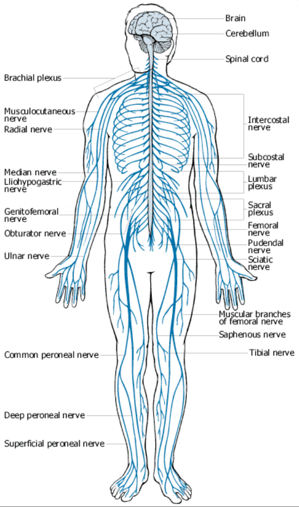
Order, dissorder and life

In the abiotic world, information plays no role, physical interactions just happen driven by ***energy exchange*** between the interacting parts. But for living organisms, information is the very essence of their existence, *to maintain a long-term state of **unstable thermodynamic equilibrium*** with its surrounding, consistently increase its organization and reproduce.

Molecular information

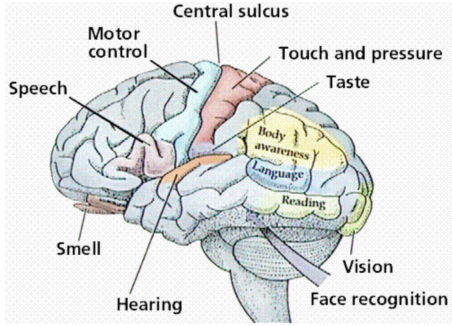
Neural information

The nervous system



- Peripheral nervous system:
  - Collect sensory stimuli
  - Computation, reflexes
- Central Nervous System:
  - Instincts, emotions
  - Memory
  - Cognition

The nervous system

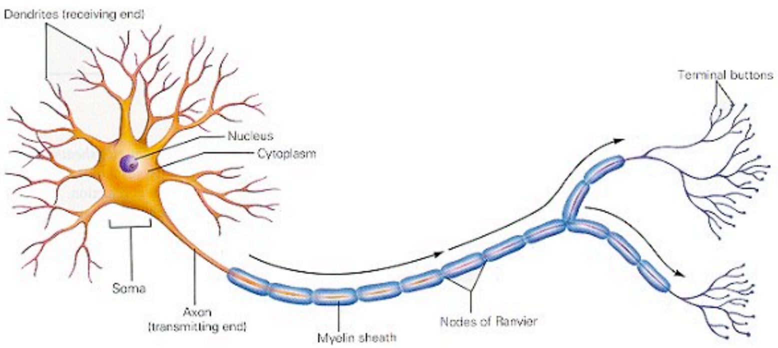


- Integration
- “Reconsider the situation”

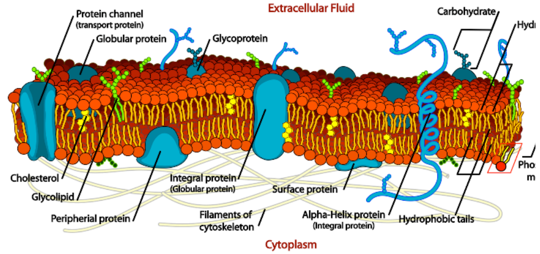
Excitable neurones

The Major Structures of the Neuron

The neuron receives nerve impulses through its dendrites. It then sends the nerve impulses through its axon to the terminal buttons where neurotransmitters are released to stimulate other neurons.



Cell membranes

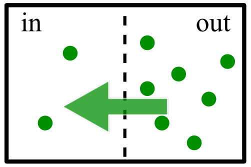


- Cell membranes are composed of *lipid bilayers* that are impermeable to charged particles. Therefore, polarized molecules (e.g. water) and ions can only cross the membrane through special proteins that are highly specialized for a given subtance, called “ion channels.”

Membrane potential

- Single ion (Nernst equation)

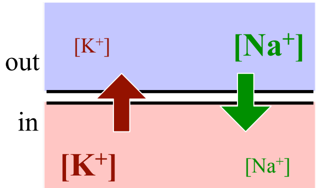
$$E_m = \frac{RT}{F} \ln \left(\frac{[Na^+]_{out}}{[Na^+]_{in}} \right)$$



- Many ions (GHK equation)

$$E_m = \frac{RT}{F} \ln \left(\frac{P_{Na}[Na^+]_{out} + P_K[K^+]_{out} + P_{Cl}[Cl^-]_{in}}{P_{Na}[Na^+]_{in} + P_K[K^+]_{in} + P_{Cl}[Cl^-]_{out}} \right)$$

- Resting potential
  - depends on active pumping!
  - – 70 mV !!!

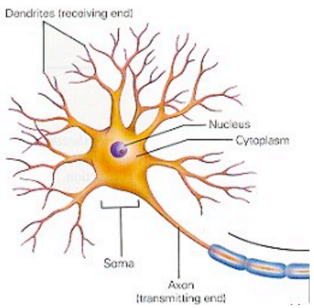


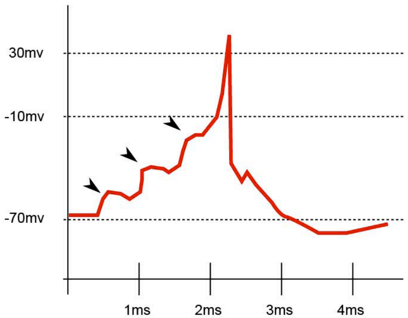
Action potentials

- small depolarization: *the membrane recovers its resting potential*
- large enough depolarization:
  1. K^+ channels open (fast) ⟶ excitation
  2. Na^+ channels open (slow) ⟶ recovery
  3. Refractory period
  4. Propagation of excitation

Spatio-temporal integration

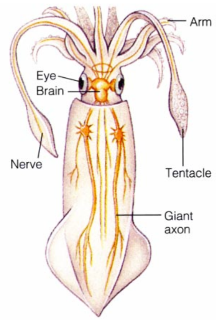
Very rarely, a neuron will fire an AP after single excitation from presynaptic neurons. Typically APs are the consequence of multiple converging inputs.



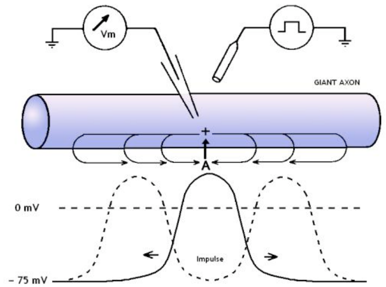


Voltage-clamp experiments

Squid

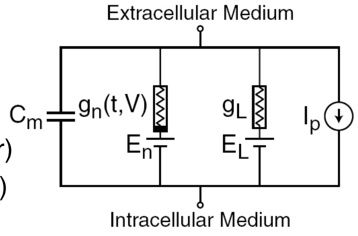


Setting the desired potential



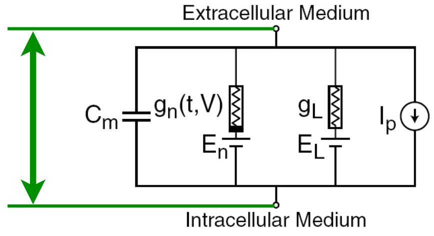
The Hodgkin-Huxley model (1952)

- Membrane potential, V_m
- Lipid bilayer, C_m
- Voltage-gated channels (nonlinear)
  - $g_n(t,V)$ and E_n (Nernst potential)
- Leak channels (linear)
  - g_L and E_L
- Active pumps, I_p



The Hodgkin-Huxley model (1952)

$$\dot{V}_m = -\frac{1}{C_m}\left(\sum_i I_i\right)$$



- Ionic currents $I_i(V_m,t) = (V_m - E_i)g_i$
  - leak conductance $g_L = const.$
  - voltage gated $g_n(V_m,t) = \bar{g}_n \phi^\alpha \chi^\beta$

channel activation and innactivation, experimentaly estimated

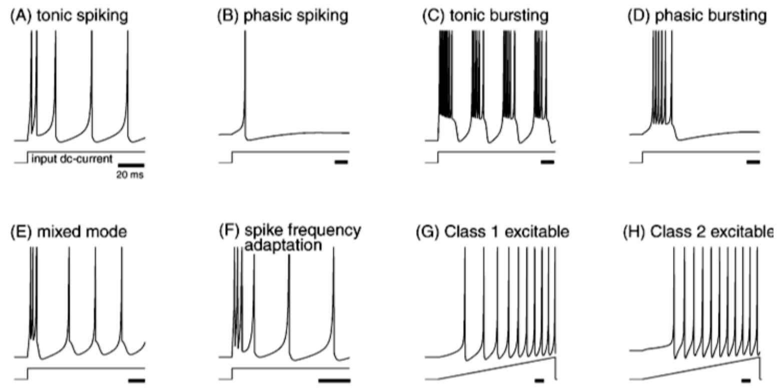
The Hodgkin-Huxley model (1952)

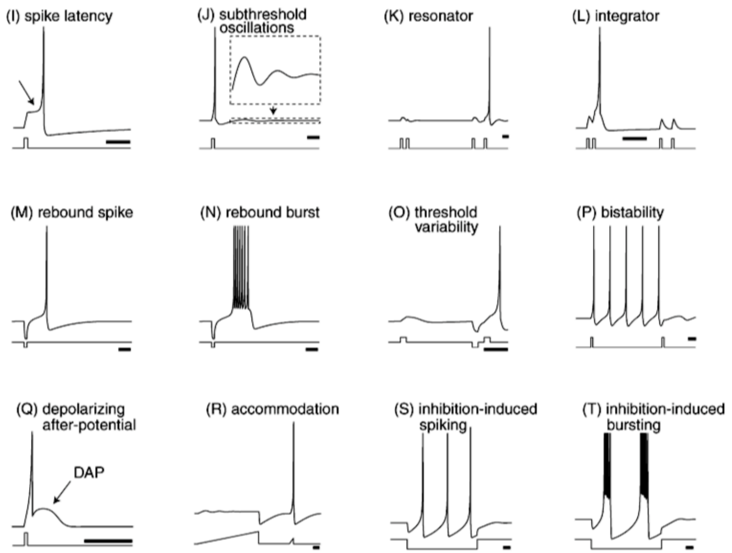
- Biologically realistic
- Reproduces all known neuron electrical behaviours
- Predicted the existence of ion channels !!
- Nobel prize 1962 (!?),

but …

- very complicated
- very slow for computation
- is *not* the model of a neuron!

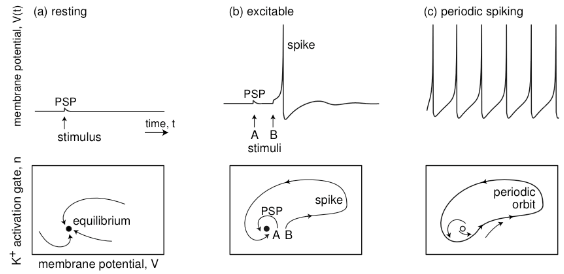
Neuron dynamics





Dynamical models

For simulation purposes, do we really need ***realistic*** *models of neuronal activity?*



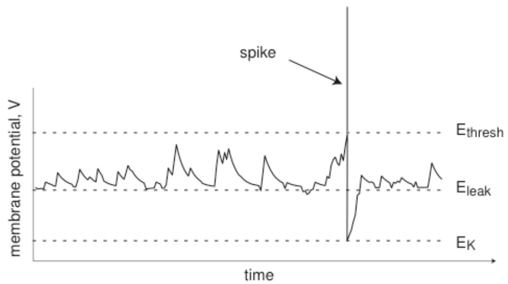
- Ingredients for excitability:
  - threshold
  - interplay between *fast* and *slow* dynamics

Neuronal models

- Integrate and fire (1-dimensional)

$$C\dot{V} = I - g_{leak}(V - E_{leak})$$

$$\dot{v} = b - v, \quad \text{if } v = 1: \; v \to 0$$

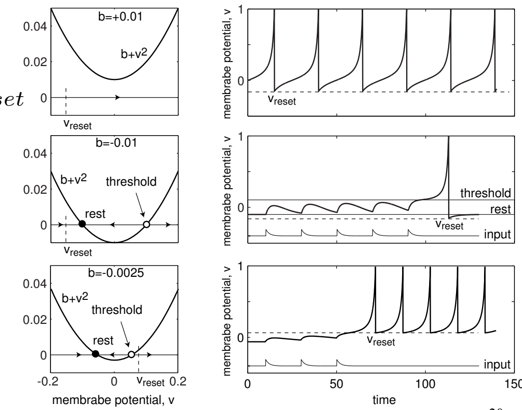


Neuronal models

- Quadratic integrate and fire

$$\dot{v} = b + v^2,$$

$$\text{if } v = v_{peak}: \; v \longrightarrow v_{reset}$$



Neuronal models

- FitzHugh-Nagumo model (2-D)

$$\dot{V} = V(a - V)(V - 1) - w + I$$

$$\dot{w} = bV - cw \longrightarrow \text{recovery variable}$$

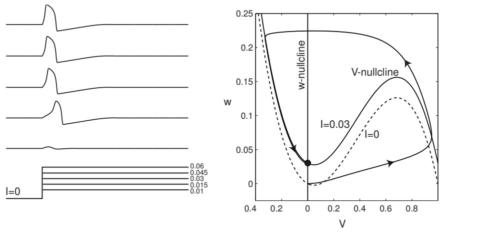
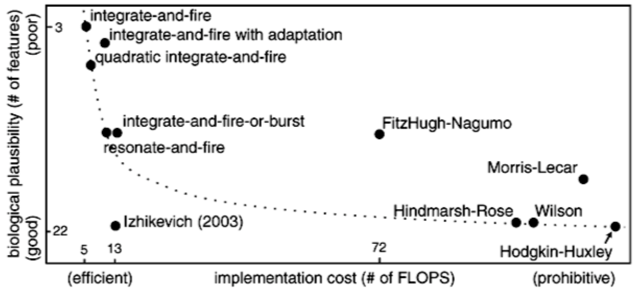


Figure 7.7: Class 3 excitability in FitzHugh-Nagumo model (4.11, 4.12) with $a = 0.1, b = 0.01, c = 0$. The model fires a single spike for any pulse of current.

Performance vs realism



More information …

- Wikipedia
  - Action potential, Hodgkin-Huxley model
- Interactive animation
  - http://outreach.mcb.harvard.edu/animations/actionpotential.swf
- Papers
  - E. M. Izhikevich "*Which model to use for cortical spiking neurons?*" IEEE trans. Neural Nets **15**(5) (2004)