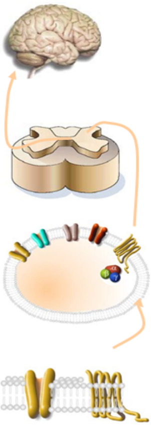
Neural coding and information transmission

Lubomir Kostal
Institute of Physiology CAS, Prague, Czech Republic

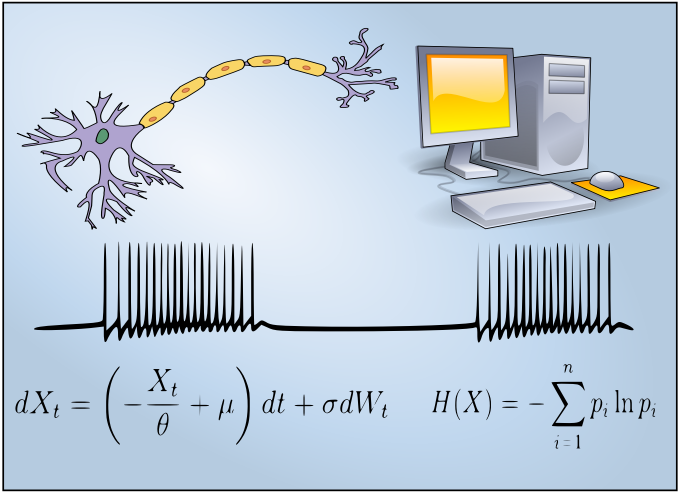
Major Fields of Research within the Institute of Physiology



NEUROPHYSIOLOGY	CARDIOVASCULAR PHYSIOLOGY	METABOLISM
	System level	
- Circadian rhythms - Memory - Epilepsy - Alzheimer's disease - Pain - Population coding	-Central and peripheral blood pressure control - Regulation of embryonic cardiac output - Pathophysiology of heart failure	-Neurohumoral control - Energy expenditure -Glucose homeostasis -Nutritional interventions - Metabolic syndrome - Biomarkers
	Cellular level	
- Spiking activity -Synaptic transmission - Neuromodulation - Nociception - Ionic channels: NMDA, TRP, nicotinic, purinergic -Metabotropic receptors: muscarinic, adrenergic -Secretion of pituitary hormones	-Calcium influx and calcium sensitization in contractility of resistance arteries -Calcium transients and ion channels - Gap junctional coupling -Isolated cardiac myocytes -Cell proliferation in cardiac growth and regeneration	-Intracellular signalling -Mitochondrial (dys)function - Membrane biophysics
	Molecular level	
-Receptor structure-function - Gene and protein expression	-Adrenergic receptor number regulation - Mitochondrial membrane potential -RhoA/Rho kinase pathway in calcium sensitization	-Transport proteins -Reactive oxygen species - Structure of signalling proteins

Department of Computational Neuroscience

Computational Neuroscience Group, IPHYS, Prague



http://comput.biomed.cas.cz

Outline

1. What is *Computational neuroscience*?
2. Neurons are not *perfect*
3. Neurons are not *reliable*
4. Neurons process information *optimally* . . .
   - 4.1 Adapting properties to local conditions
   - 4.2 Energy-efficient coding

- Thanks to: Ryota Kobayashi, Petr Lansky, Philippe Lucas, Jean-Pierre Rospars, Marie Levakova

What is *Computational Neuroscience*?

Computational Neuroscience

"The aim of computational neuroscience is to explain how electrical and chemical signals are used in the brain to represent and process information."

T. Sejnowski *et al.*: Computational Neuroscience, *Science*, 1988

Cybernetics: Or Control and Communication in the Animal and the Machine

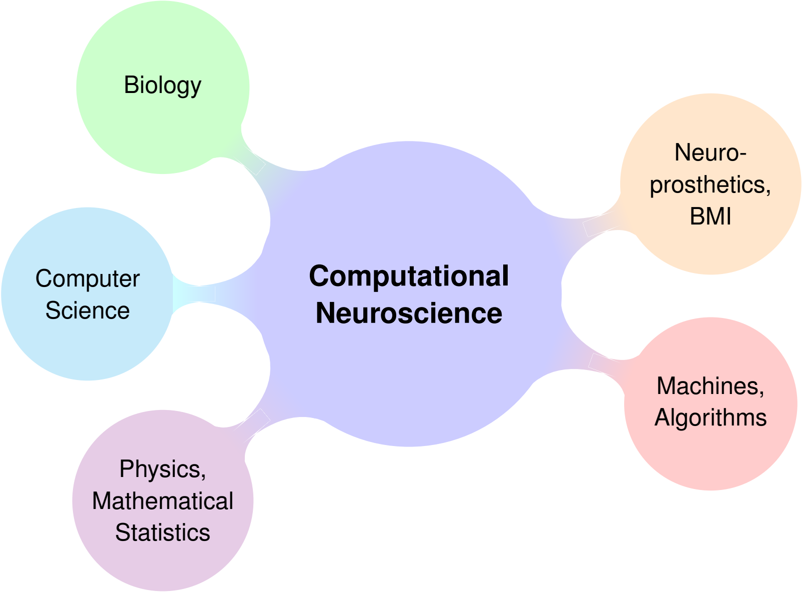
Norbert Wiener, 1948

Why? – Progress in *neuroscience* (from molecules to fMRI)
– Progress in *computing power*

But... How the nervous system enables us to *see, remember, plan?*

"What are the algorithms used in the brain?"

Multidisciplinarity (by definition) . . . . . . *Fundamental Research* + Applications



Computational neuroscience

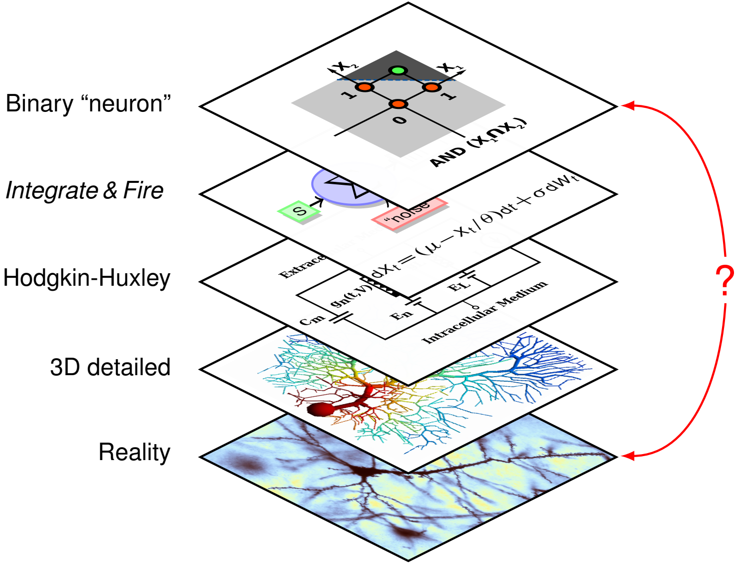
- Effective theories (quantitative description)
- Since 1980's: dramatic increase (journals, conferences, labs, ...)

1. Models of neurons (networks, systems)
2. Coding, information processing and transmission

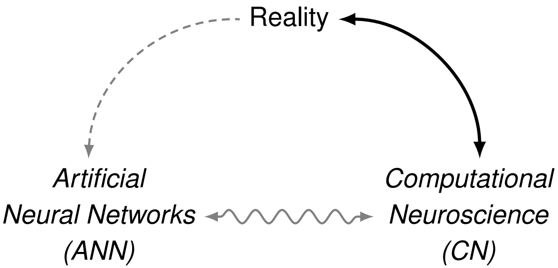
- Sensory neurons: stimulus coding ⇒ artificial systems
- Applications: technology (HW, algorithms), *bio-inspired computing*

- Comput. Neuroscience *vs.* Artificial Neuronal Networks

Neuronal models



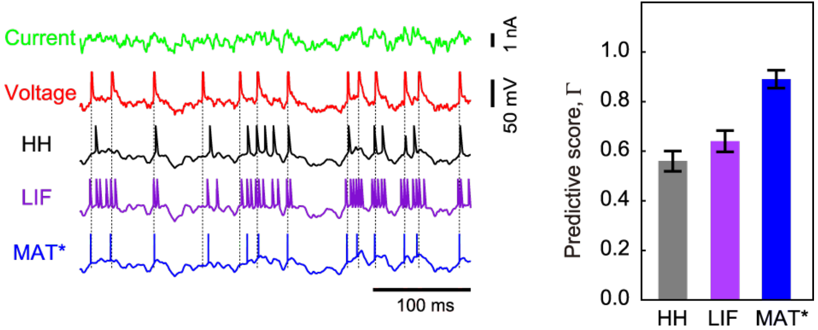
Comput. Neuroscience *vs.* Artificial Neural Networks



- *Computational Neuroscience*: linked to biological reality
- Biological details: sometimes unexpected and fundamentally new points of view

Spike prediction: how “good” are neuronal models?

Ryota Kobayashi: *Quantitative Neuron Modeling* (2007, 2008, 2009)

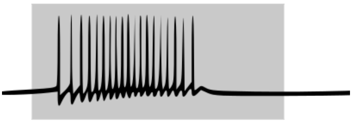


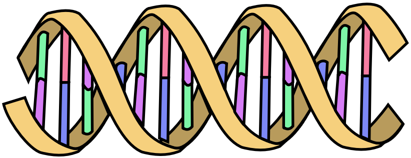
(Rat motor cortex)

Kobayashi et al., *Front. Comput. Neurosci.* (2009)

Jolivet et al., *J. Neurosci. Methods* (2008); Gerstner & Naud, *Science* (2009)

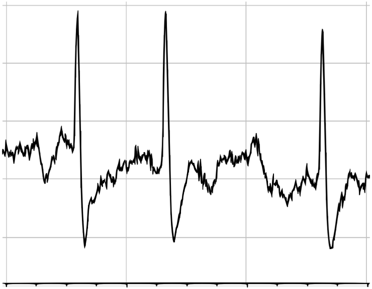
- Computational Neuroscience: models + “explanation”
- Last three decades: increased interest (HBP, . . .)
- Comparison: *genetic code*?
- Benefits $\times$ theoretically challenging
- New “algorithms” and signal-processing approaches? (*energetic efficiency, robustness, . . .*)



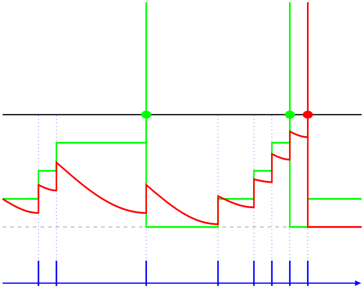


’Perfect’ neurons

Membrane potential: perfect *vs.* leaky model



Experimental data

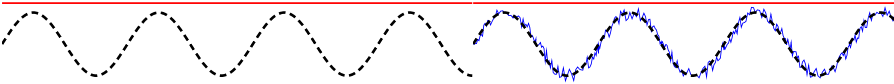


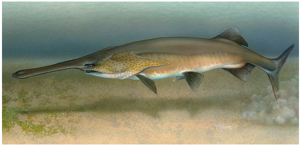
Formal (idealized) model

- Leakage: just an “imperfection”?
- Sub-threshold *vs.* supra-threshold regimes
- New possibilities: stochastic resonance, . . .

“Beneficial” role of noise – signal thresholding

Stochastic resonance

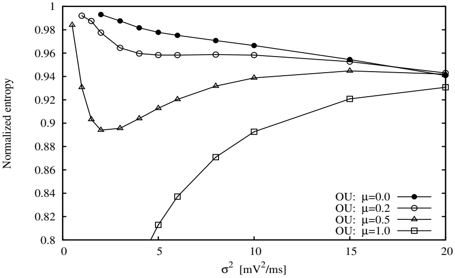




Russel et al., *Nature* (1999)

Greenwood et al., *Phys. Rev. Lett.* (2000)

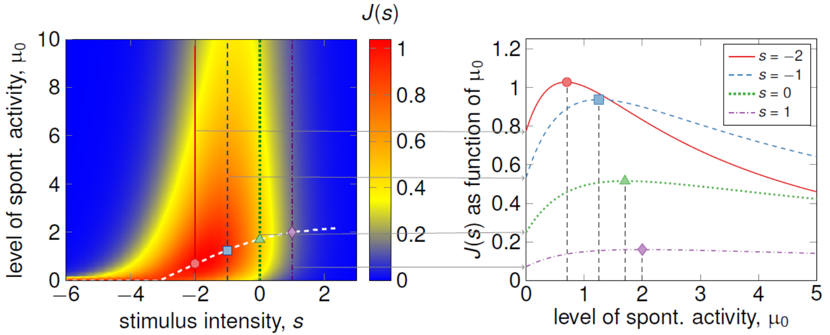
- Review: McDonnell & Ward, *Nat. Rev. Neurosci.* (2011)
- Resonance-like effects: *sub-* a *supra- threshold*, *coherence*, *spiking-rate*, . . .
- Generally: stochastic *vs.* deterministic



Kostal et al., *Netw. Comput.Neural Syst.* (2007)

Noise-aided signal enhacement in neural systems

- Multiple 'positive' roles of noise/imperfections in *signal* processing

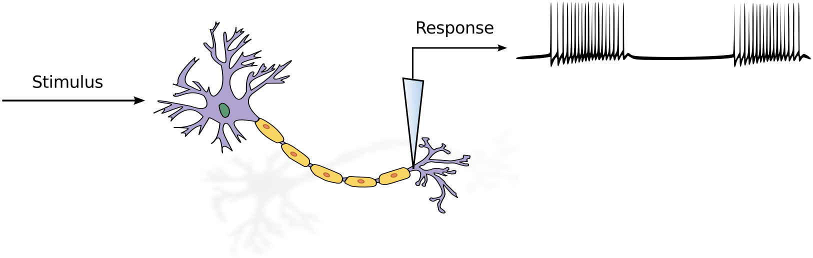


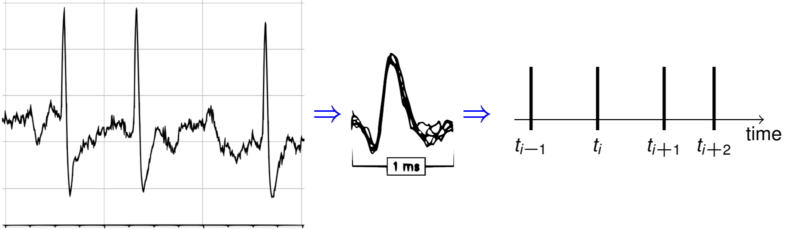
Levakova *et al.*, *Neural Comput.* (2016)

- Spontaneous activity *stabilizes* the membrane potential (not related to sub-threshold intensities or leakage)

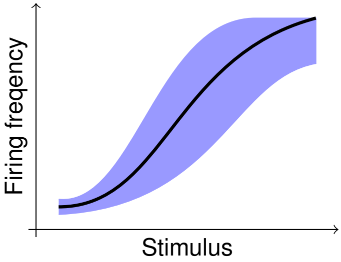
’Reliability’ of neuronal response

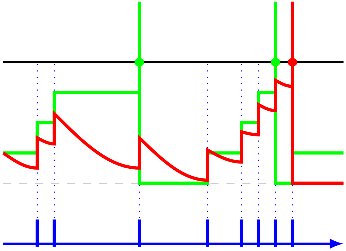
Neuronal code: basic assumptions





Frequency *vs.* temporal coding

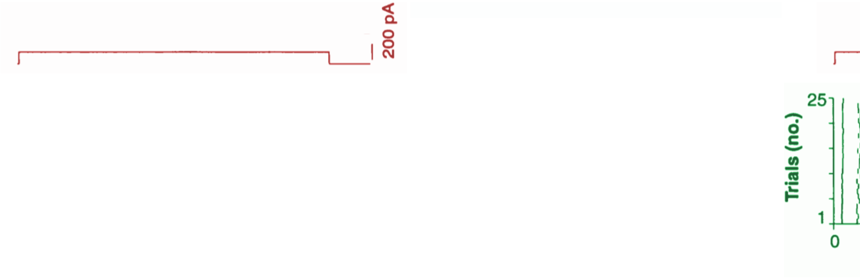




1. Frequency: Adrian (1926), number of pulses (AP) per unit time
2. Temporal: Perkel & Bullock (1968), intervals between APs,

- *Variability, noise*: Stein et al., *Nat. Rev. Neurosci.* 2005

Reliability of neuronal response



Mainen and Sejnowski, *Science* (1995)

1. Encoding of *elementary* (simple) *vs. complex* stimuli
   - rate-level, dose-response, tuning *curves*
   - bottom-up approach?
2. "*Convenient*" *vs. natural* stimulation
   - parameterization (dimensionality, Gaussian processes)
   - experimental setup (*e.g.,* insect olfaction)

Optimal information processing and adaptation

Efficient coding hypothesis

Horace B. Barlow, 1961

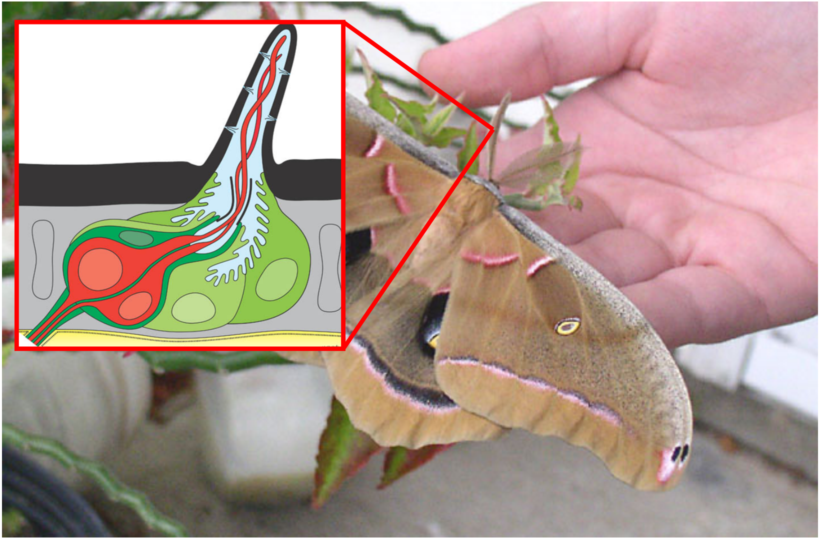
Neurons are adapted, through both evolutionary and developmental processes, to the *statistical characteristics* of their *natural* stimulus.

Methods: *information theory*, estimation theory, . . .

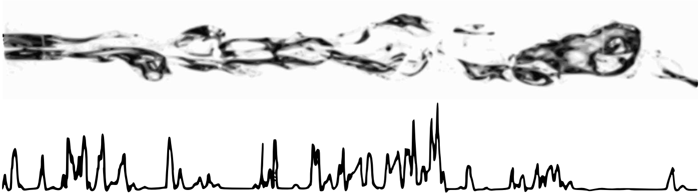
- Optimality conditions, *infomax* (Linsker 1987)
- Retinal neurons (Laughlin 1981, Laughlin *et al.* 1996)
- “Scale” of neuronal performance (Rieke *et al.*, 1996)

Extensions: metabolic cost, decoding feasibility, realistic models, . . .

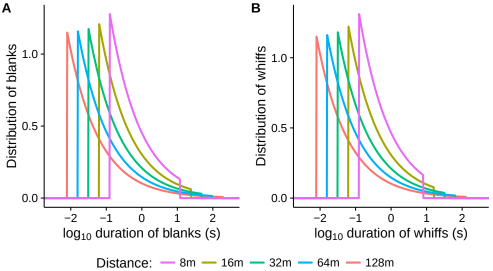
Antherea polyphemus (♂)



Pheromone plume structure



Kostal *et al.*, *PLoS Comput. Biol.* (2008)

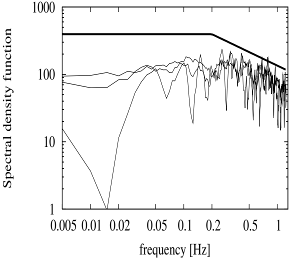


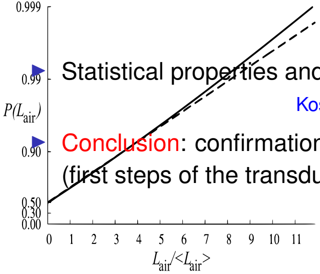
Celani *et al.*, *Phys. Rev. X* (2014); Levakova *et al.*, *PLoS Comput. Biol.* (2018)

- Complicated spatio-temporal structure: turbulent.

Predicted “optimal” stimulus properties

Characteristics	Predicted values	Experimental values
Concentration CDF	exponential	exponential
Spectra	≈flat to 0.2 Hz, —2/3 slope after	≈flat to 0.1 or 0.5 Hz —2/3 slope to 1 Hz
Intermittency	20 %	10 — 40 % 10 — 20 %
Tot. mean L_{air}	1.0×10^{-4} μM	–
Tot. std. dev. of L_{air}	3.0×10^{-4} μM	–
Peak value of L_{air}	3.8×10^{-3} μM	–
Peak/mean ratio	37	$>$ 20 30 — 150
Peak/std.dev. ratio	13	$>$ 3





- Statistical properties and temporal dynamics

  Kostal, Lansky& Rospars, *Neurocomputing* (2007); *AIP* (2008)

- Conclusion: confirmation of the *efficient coding* hypothesis (first steps of the transduction cascade – *bottleneck*)

Kostal et al., *PLoS Comput. Biol.* (2008)

Neuronal coding accuracy and the stimulus distribution

Optimal stimulation (peak coding accuracy):

– stochastic models
Lansky & Greenwood, *Neural Comput.* (2005); ...

– auditory system
Jenison & Reale, *Netw. Comput. Neural Syst.* (2003)

Stimulus probability *vs.* coding accuracy:
(*efficient coding hypothesis*)

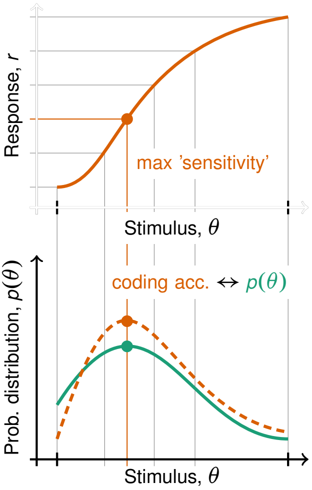
– sound intensity
Dean *et al.*, *Nat. Neurosci.* (2005); Watkins & Barbour, *Nat. Neurosci., Cereb. Cortex.* (2008, 2011), ...

– interaural level differences
Dahmen *et al.*, *Neuron* (2010)

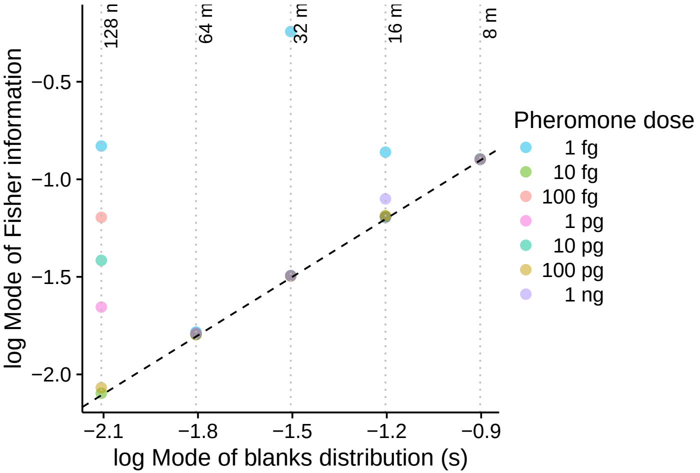
– interaural time differences
Maier *et al.*, *J. Neurophysiol.* (2012)

– primary visual cortex
Durant *et al.*, *J. Opt. Soc. Am. A* (2007)

– somatosensory cortex
Garcia-Lazaro *et al.*, *Eur. J. Neurosci.* (2007)

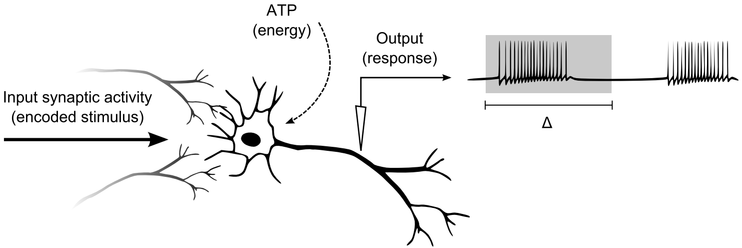


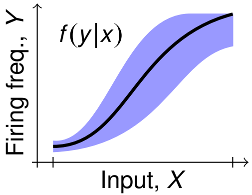
Adaptation of peak coding accuracy



Mechanisms of adaptation?

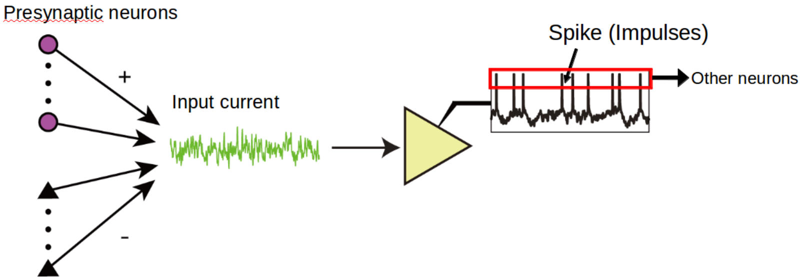
Energy-efficient neural coding?





- Input (exc. conductance, X) – Output (response, Y)
  - Rate coding: $\#$APs in Δ
  - Temporal coding, . . .
  - Model parameters, type of stimulation, . . .
- Model: $f(y|x)$✔ but $p(x)$**?**
- Efficiency: **Energy** $\times$ **Information** $\times$ **. . .**

Investigated neuronal model (*cortical excitatory*)



- Extended Hodgkin-Huxley + *point-conductance* (*stochasticity*)
  - Adaptation (I_M)
  - Balanced input, $\lambda_E \propto \lambda_I$
  - Excitatory and inhibitory conductances, $\langle g_{E,I} \rangle \propto \lambda_{E,I}$
  - Effective reversal potential: V_r (Miura *et al.*, 2007)
- Input, $x \equiv \langle g_E \rangle$: mean excitatory conductance (input parameter)
- Output, $y \equiv \#\text{APs}/\Delta$: firing rate

Metabolic cost of neuronal activity & efficiency

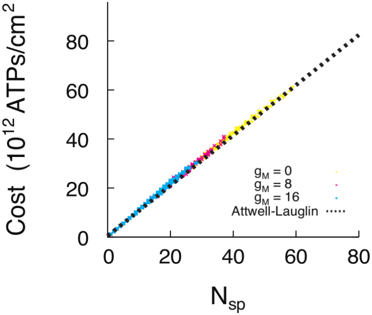
- *Empirical* metabolic cost given $X = x$ (Attwell & Laughlin, 2001)

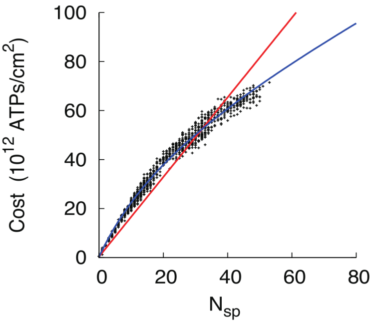
$$w(x) = \kappa \times \big(\langle \#\text{APs in } \Delta\rangle \,|\, x\big) + \beta\,\Delta$$

$[\kappa = 7.1 \times 10^8$ ATPm, $\beta = 4.4 \times 10^8$ ATPm/s$]$

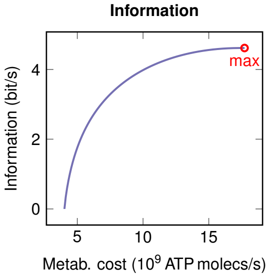
- *Theoretical* (model) cost: only small corrections (RK)✔

- Excitatory *vs.* inhibitory neurons

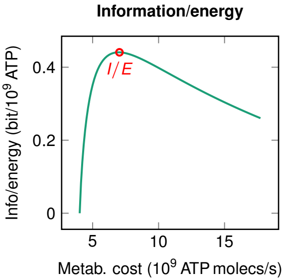




Information transfer *vs.* energy



Information $\times$ Energy:
– infomax (max): traditional point of view
– *constrained* information: metabolic cost
(*Brain Res.* (2012); *Biol. Cybern.* (2013); ...
... *Math. Biosci. Eng.* (2016)

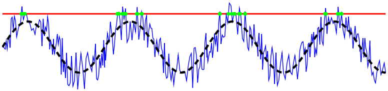


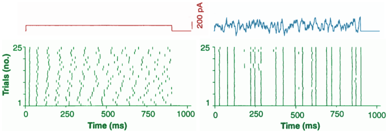
Information-energy efficiency:
– optimal ratio: information/energy
– infomax is *not* efficient

Predictions:
– existence of optima: *universal* and *global*
– different regimes $\Rightarrow$ statistical characteristics/parameters of neuronal activity

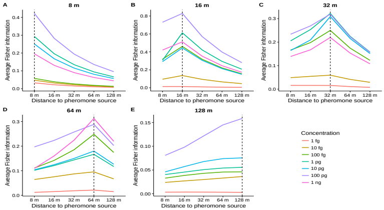
Summary: The take-home message

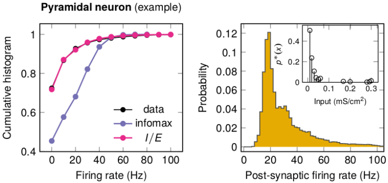
- Neurons *vs.* computers: same problems solved differently





- Fundamental optimality conditions: neurons appear to be close ...





How *exactly* does the neural code work?