Theoretical Neuroscience

?

Theoretical Neuroscience

Neuroscience - understanding the brain:

- How does it ***process sensory information***?
- How does it ***store and combine information*** in a meaningful manner?
- How does it ***generate appropriate behavior***?
- etc...

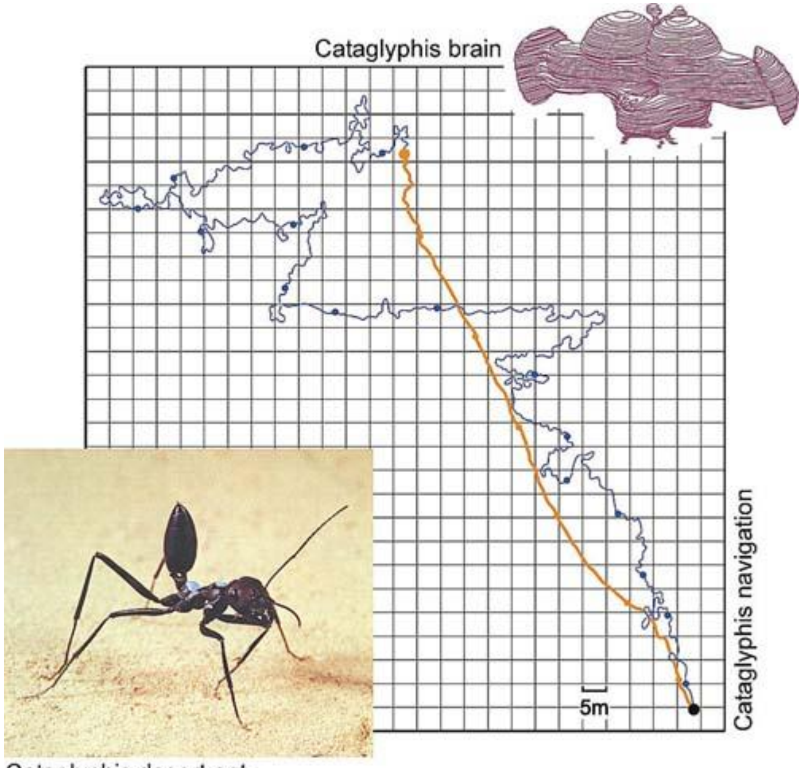
Examples for neural processing:

Visual perception:

Animal/non-animal classification (<150ms, Thorpe et al. 1996)

Spatial navigation & memory:

Path integration in ants (Wehner et al. 2008)



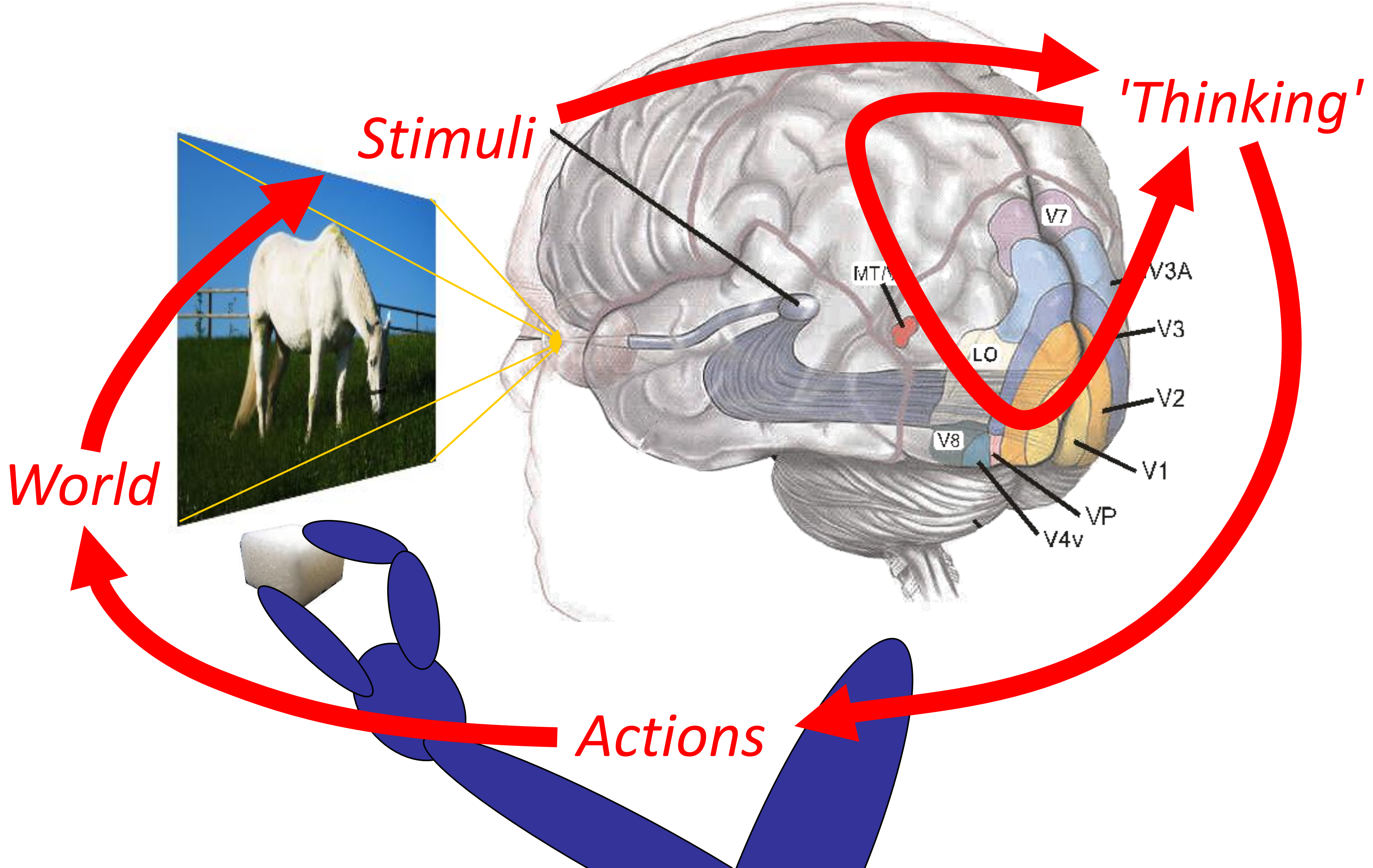
Motor control:

Walking or running on two legs (e.g. Python M. 1970)

Theoretical Neuroscience

Why is understanding the brain so difficult?

The brain is a *non-linear, high-dimensional, recurrently coupled, dynamical* system!



Theoretical Neuroscience

Tools for 'coping' with the brain...

Theoretical Neuroscience

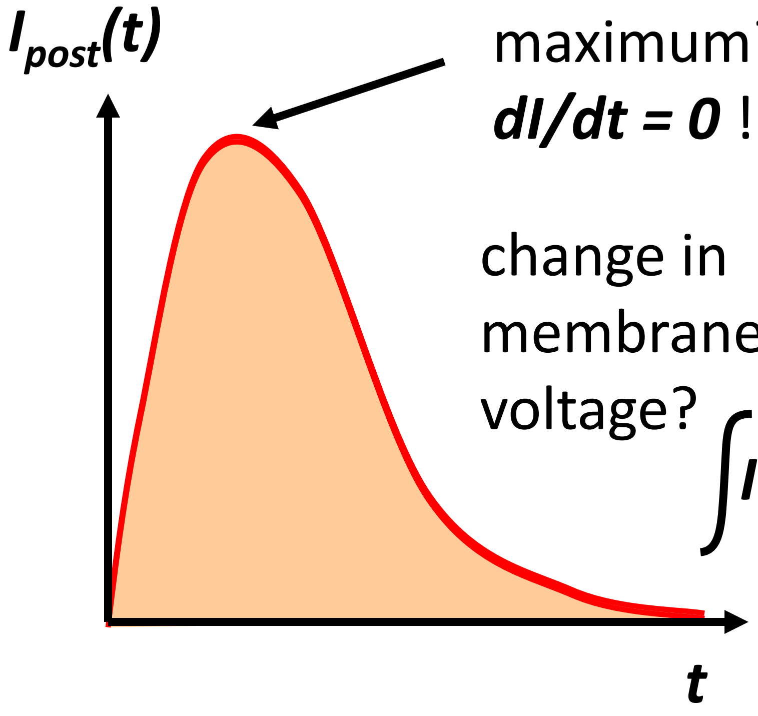
The brain seen as an ***information-processing, dynamical*** system!

1. The Information Processing Perspective:
understand ***what*** the brain is computing

2. The Dynamical Systems Perspective:
understand ***how*** the brain is computing

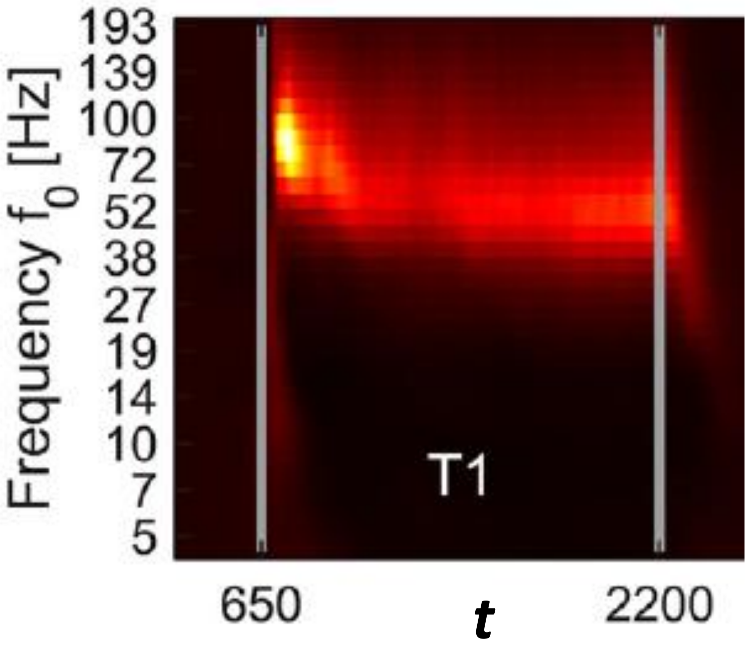
1. Mathematics

Mathematics is the natural language for a quantitative science.



maximum?
$dI/dt = 0$!

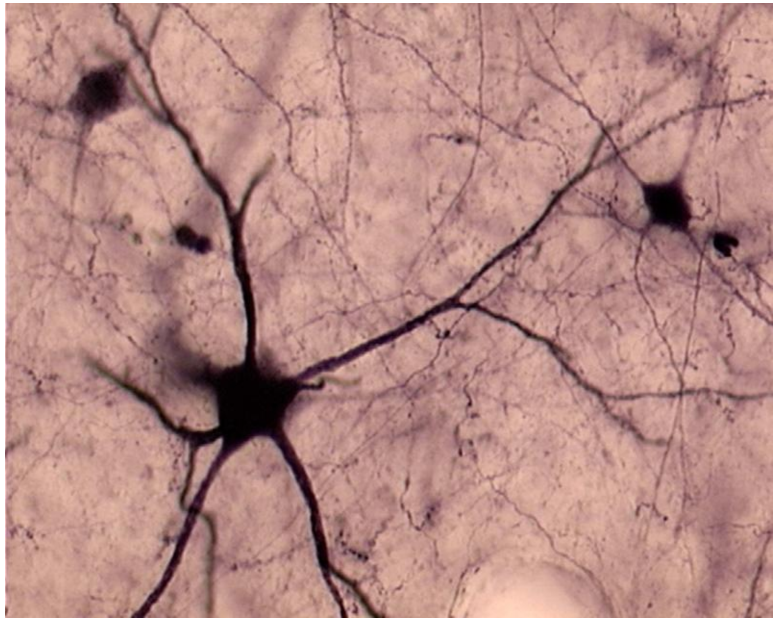
change in membrane voltage?
$\int I(t)\, dt$

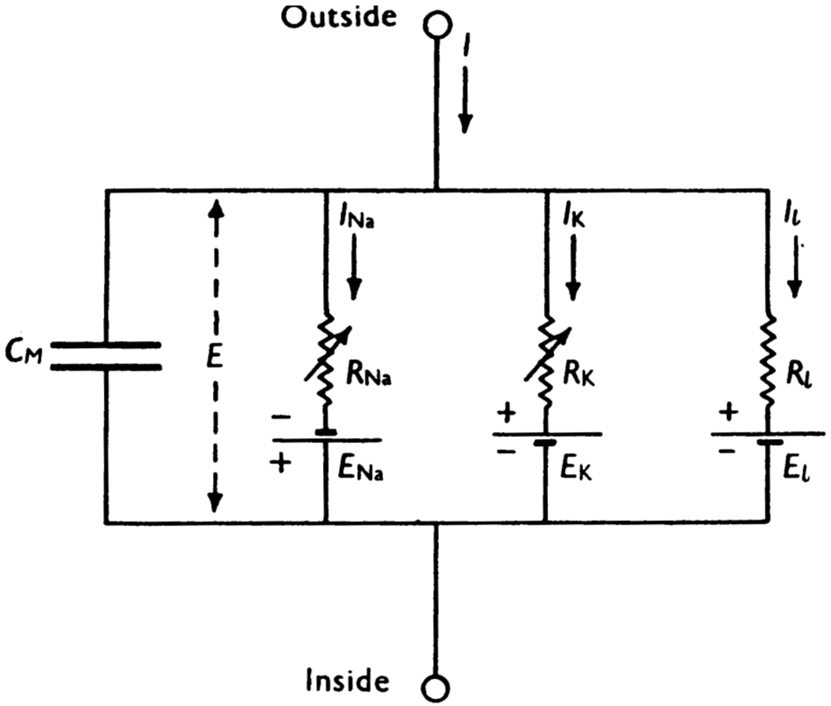


Fourier/Wavelet transform

2. Physics

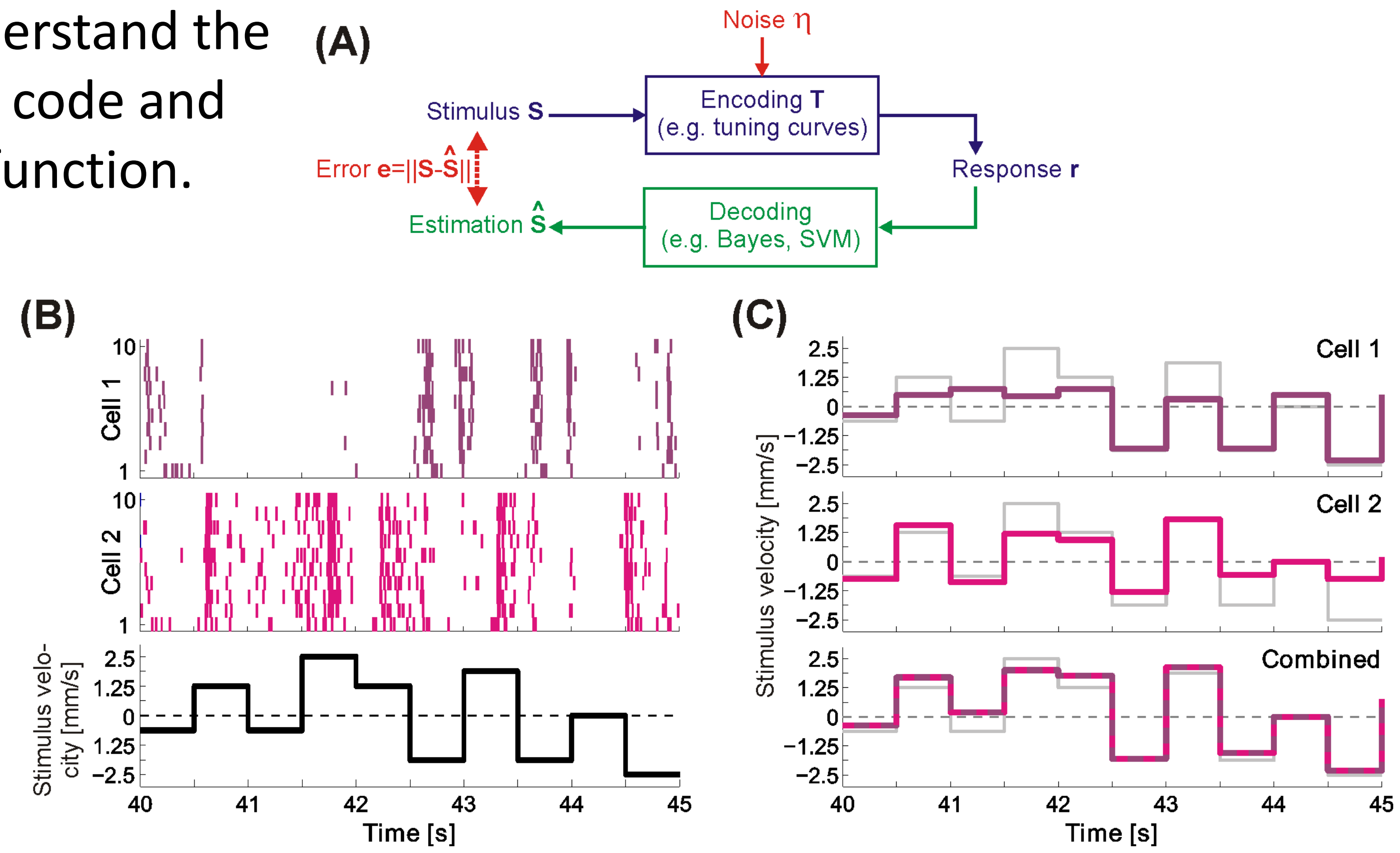
Concepts from Physics are especially useful to describe dynamical phenomena in the brain, e.g.:
the neuron as an ***electrical circuit***





3. Statistics & Information Theory

...provide a gateway to understand the neural code and brain function.



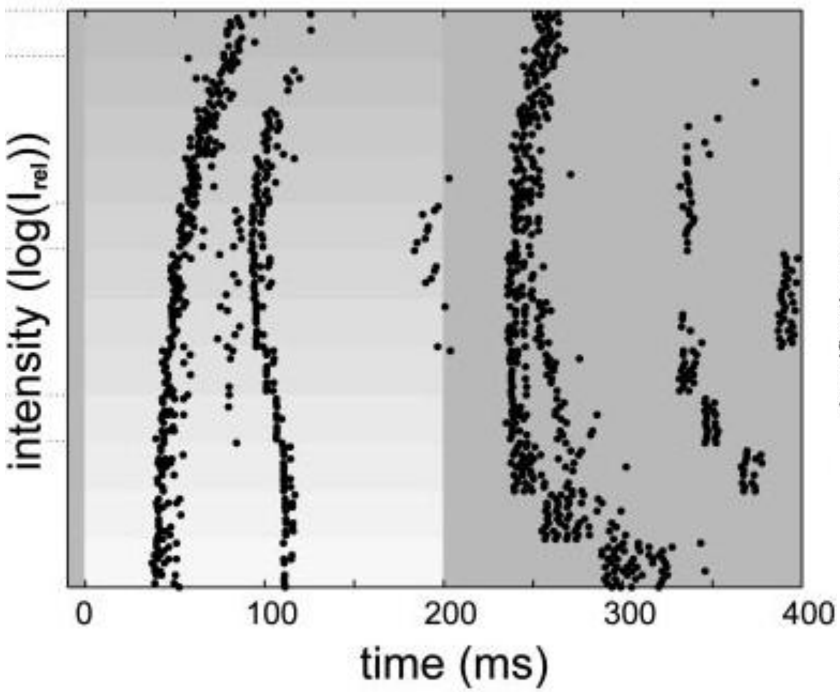
3. Statistics & Information Theory

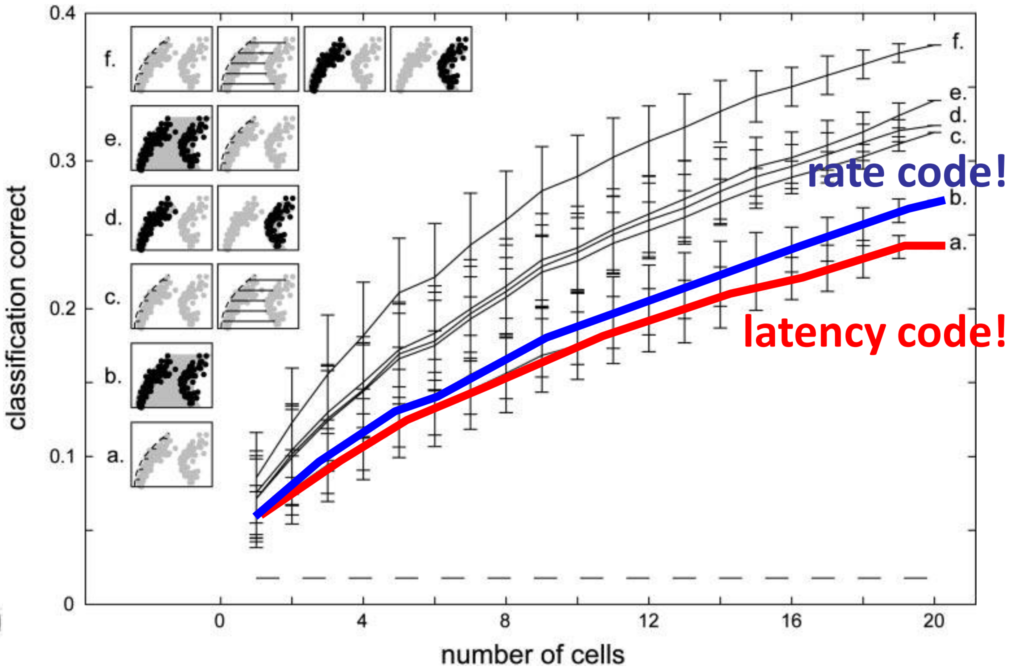
An application: Brain prostheses (Brain-Computer-Interfaces)

Theoretical Neuroscience

What can we achieve?

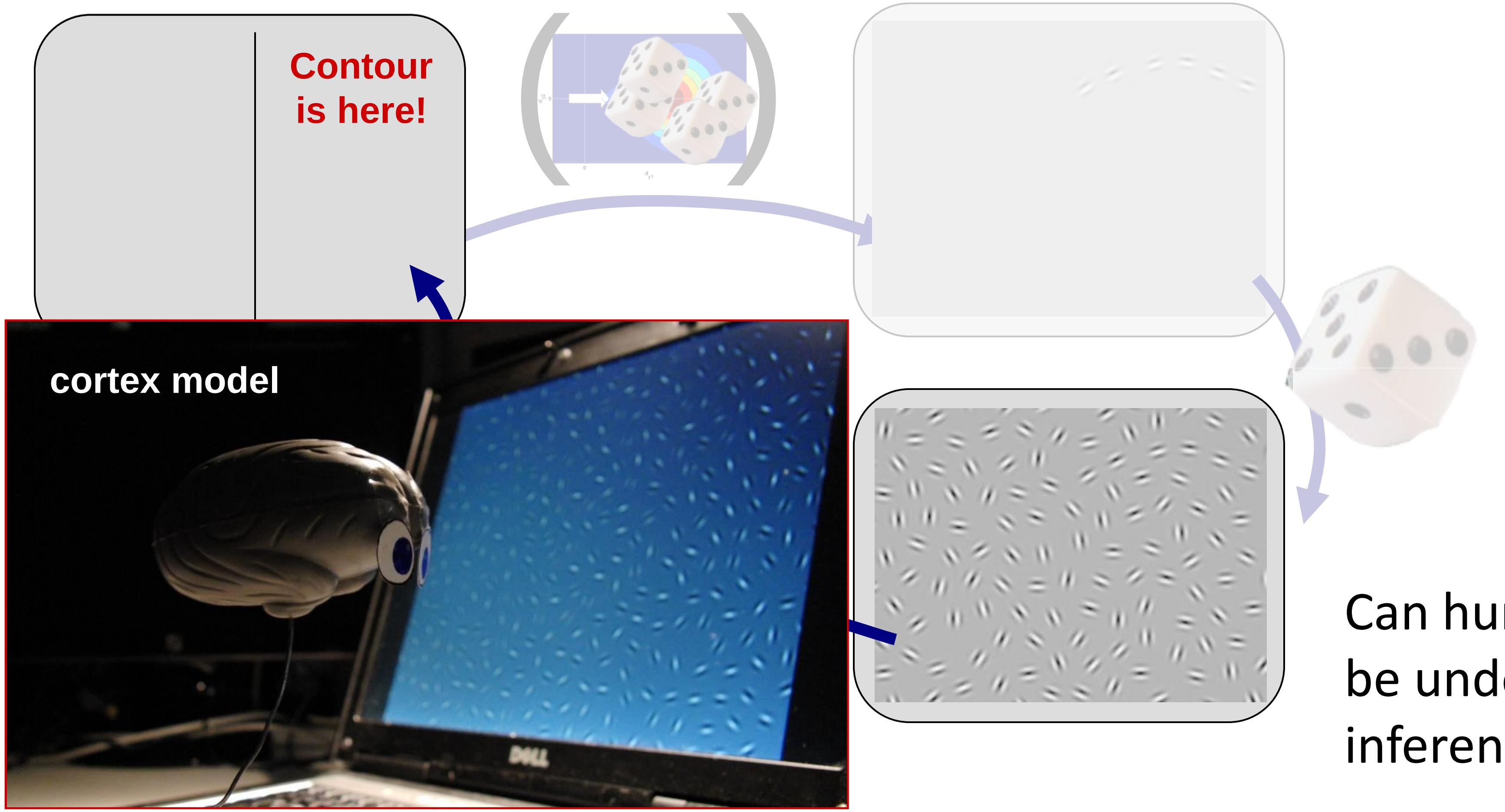
1. Quantitative access to brain function





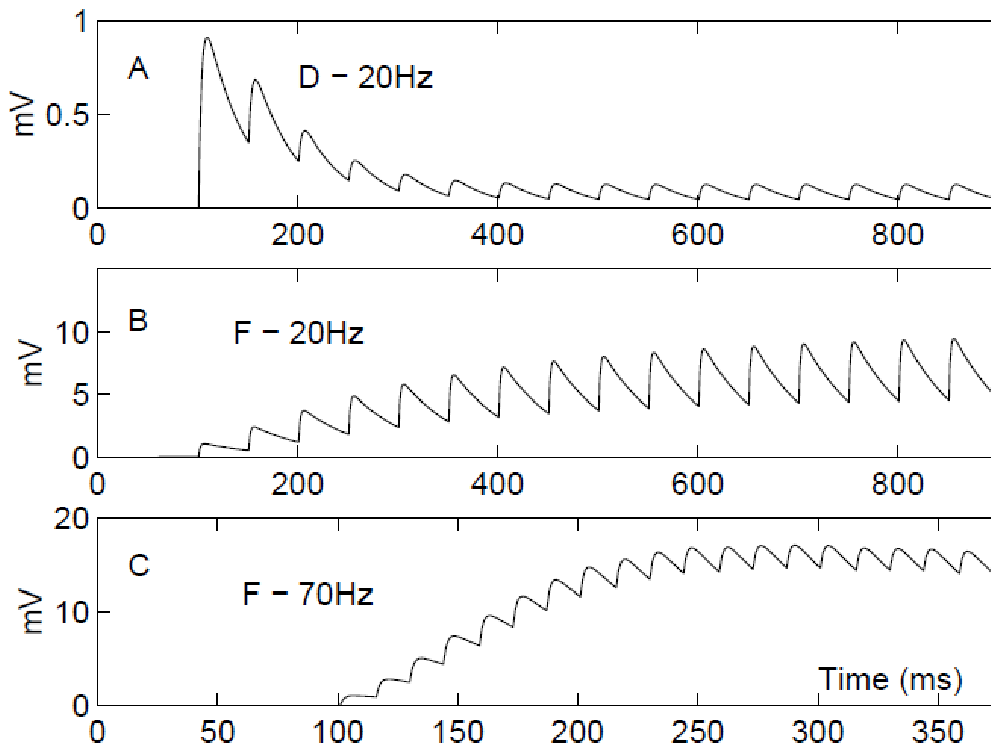
Do neurons (RGC's) use a rate-code or a latency code?

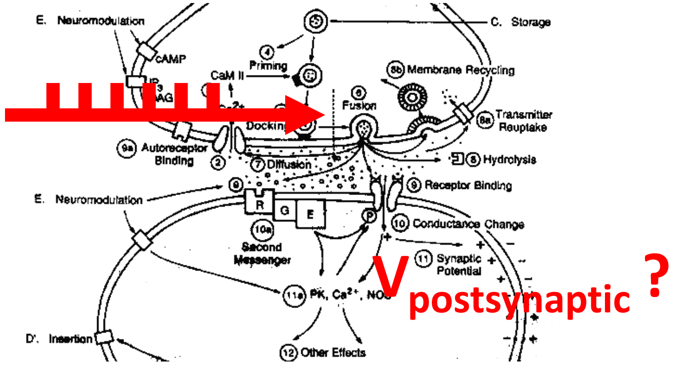
2. Formalizing and testing theories



Can human contour integration be understood as probabilistic inference in a generative model?

3. Developing unified theories



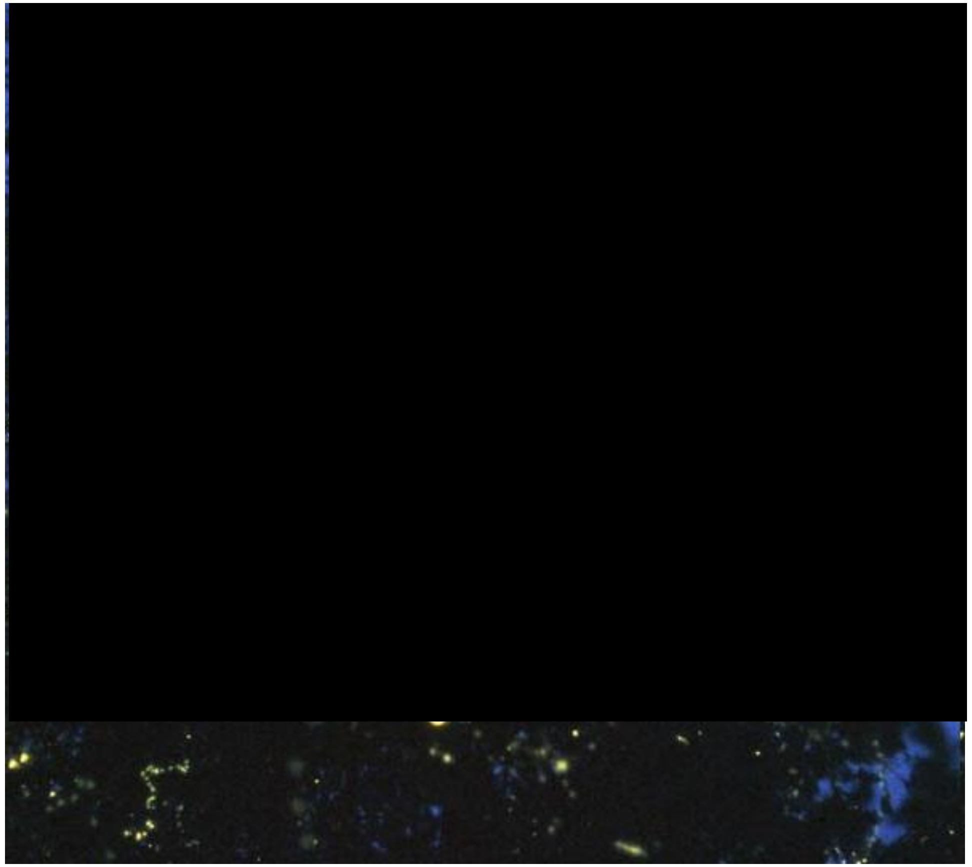


$$\frac{dx}{dt} = \frac{z}{\tau_{rec}} - U_{SE}x\delta(t - t_{sp})$$
$$\frac{dy}{dt} = -\frac{y}{\tau_{in}} + U_{SE}x\delta(t - t_{sp})$$
$$\frac{dz}{dt} = \frac{y}{\tau_{in}} - \frac{z}{\tau_{rec}}$$

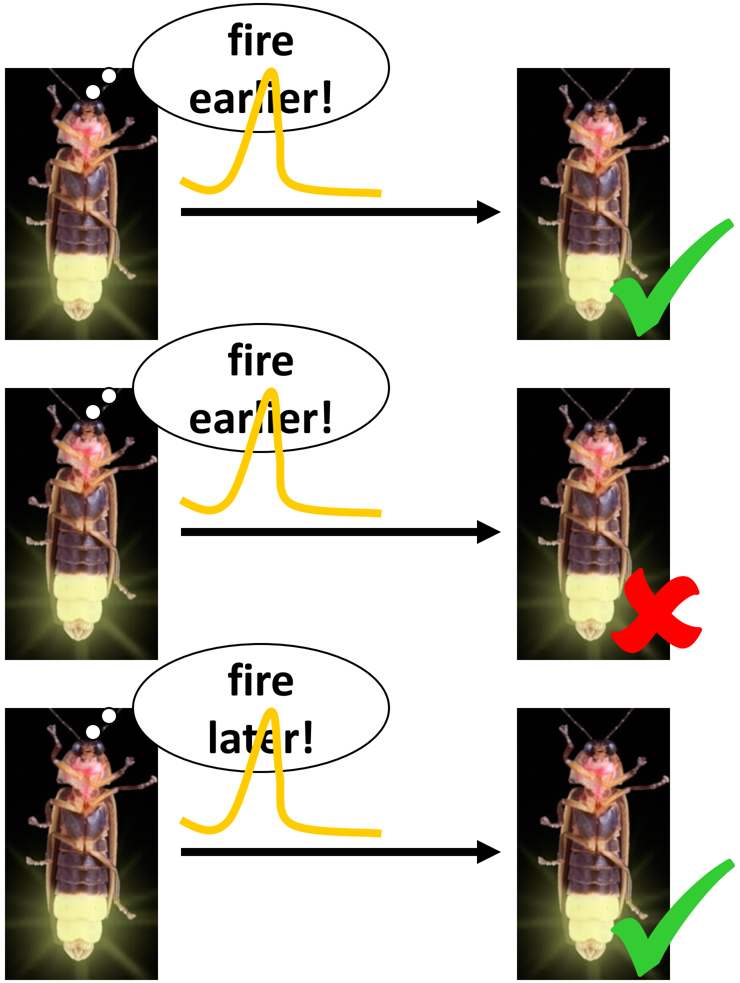
No! Unifying model!

Synapses show an abundant variety of different behaviours:
are they all different?

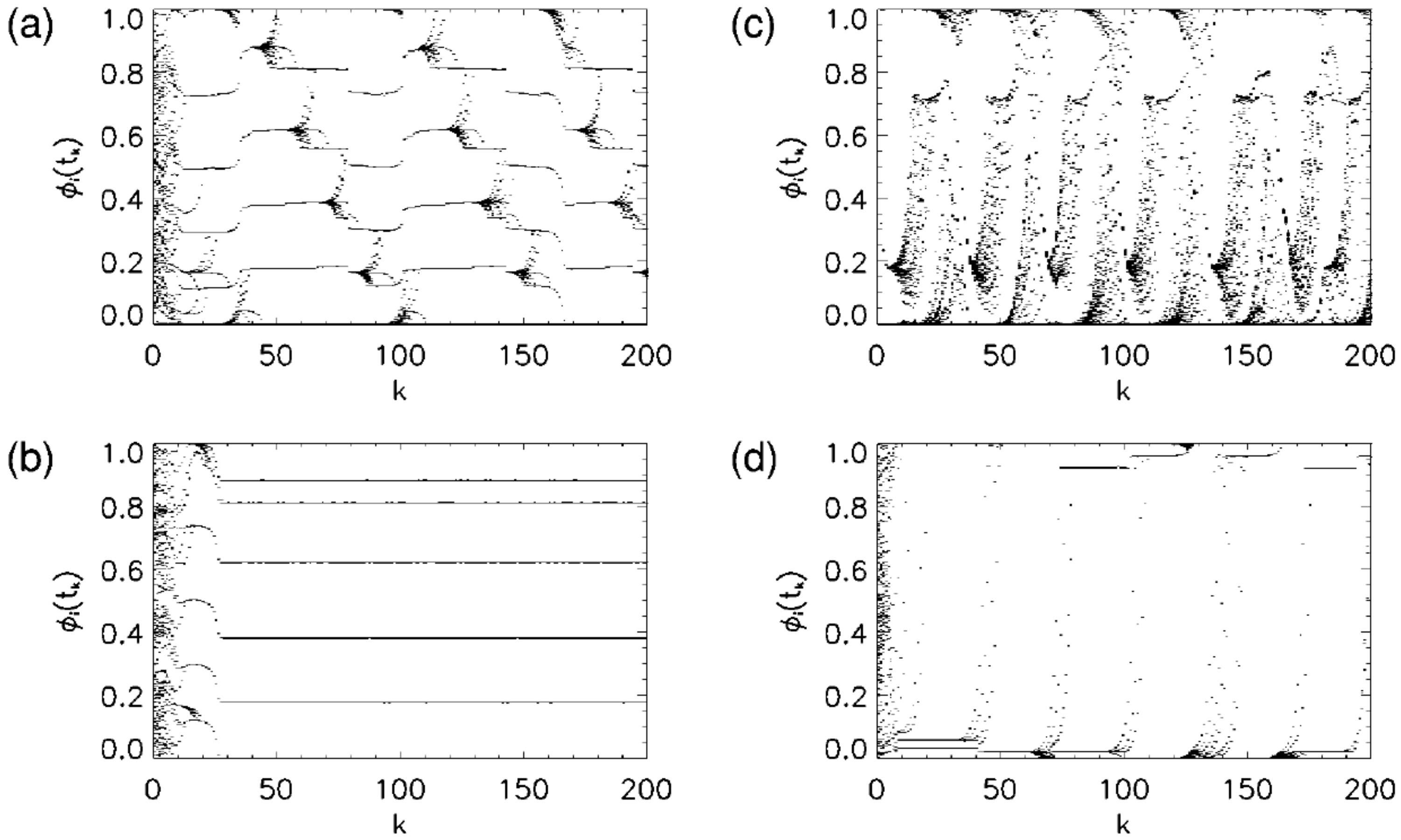
4. Uncover and analyze fundamental mechanisms



similar to neurons in networks,
fireflies in Malaysia synchronize
their light pulses... why?



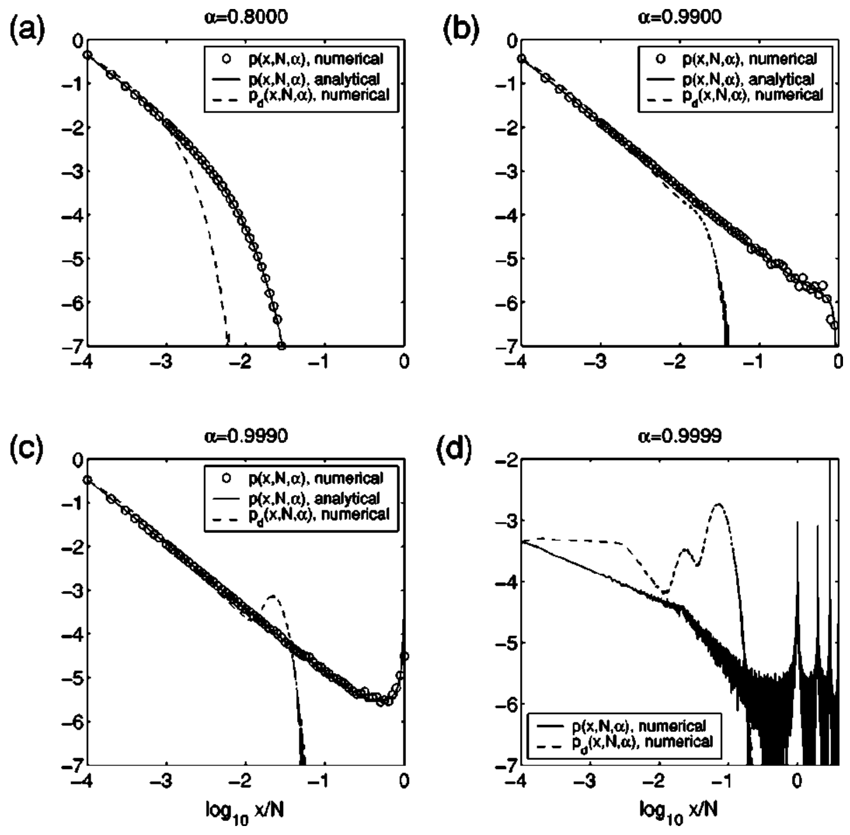
...and neurons do it, too, and according to the same mechanisms!



[Ernst, Geisel and Pawelzik, Physical Review E 1998]

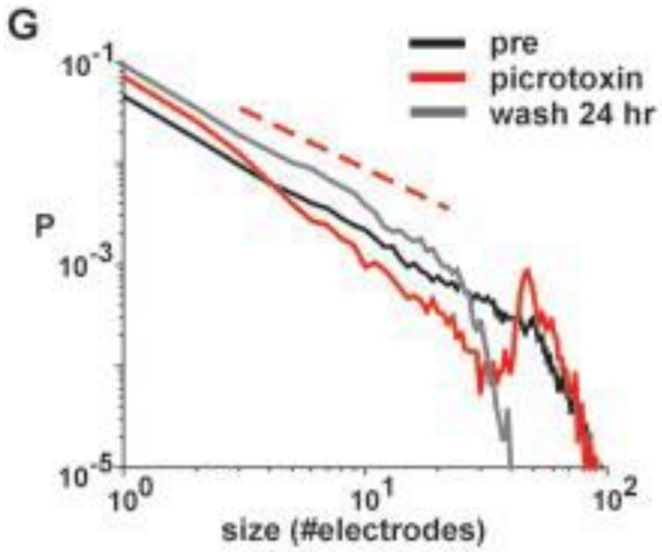
5. Provide critical predictions

Theory



[Eurich, Herrmann, and Ernst 2002]

Experiment



[Beggs and Plenz 2003]

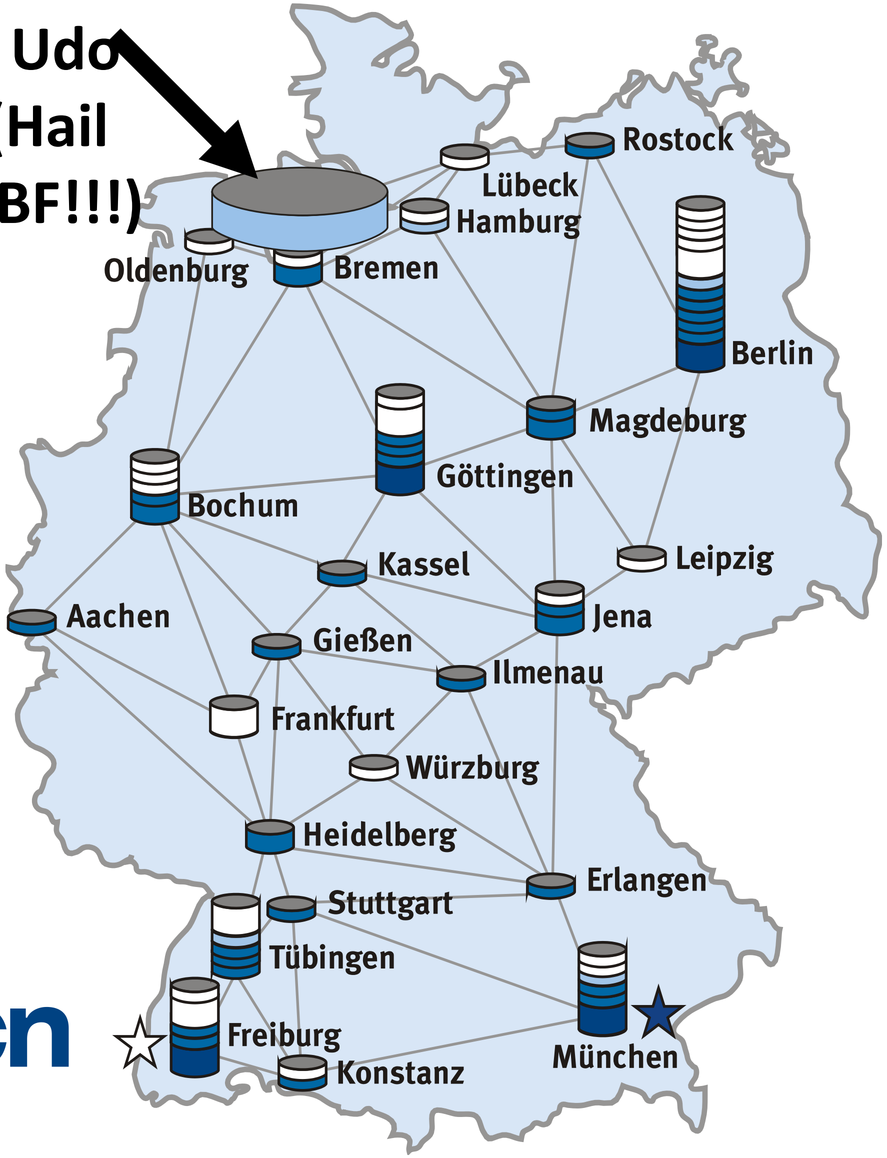
Computational Neuroscience

...an Interdisciplinary Challenge!

(examples from Bremen University
coming in this lecture...)

The Bernstein National Network for Computational Neuroscience

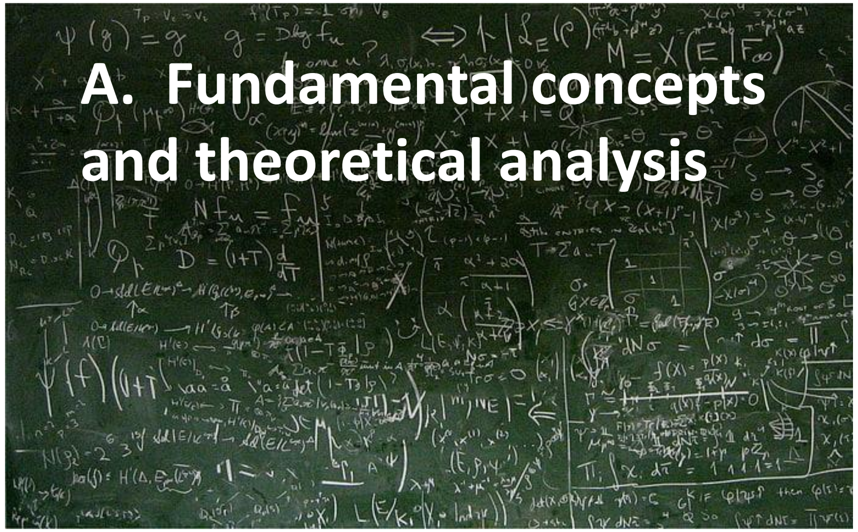
Bernstein Award Udo Ernst (Hail the BMBF!!!)



It's not an ivory tower – there are even more experimentalists involved than weird theoreticians!

Theoretical Neuroscience

The Plan...

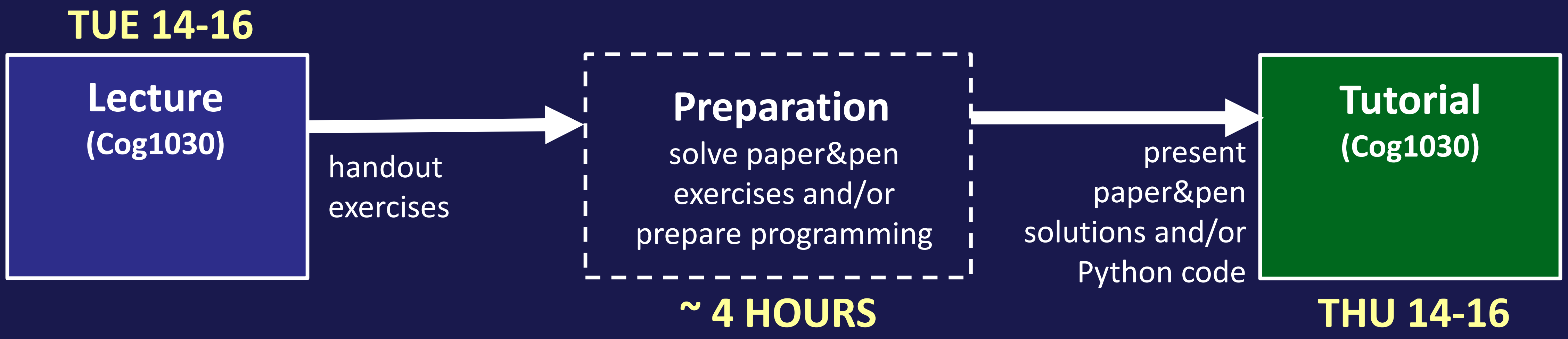


- Spikes and rates (delta functions)
- Correlations
- Receptive fields
- Differential equations
- Statistical properties of neural signals
- Encoding and decoding, Loss functions → Sami!

- Receiver-Operator characteristics → Sami!
- Bayesian inference → Sami!
- Reverse correlation and Spike-triggered average
- Auto- and Cross-correlation
- Fourier analysis → Sami!
- Wavelet analysis → Sami!

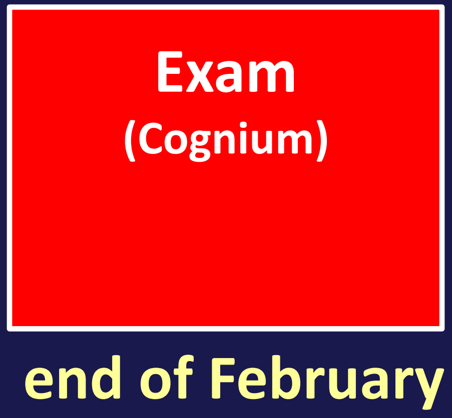
- Integrate-and-fire neuron, Hodgkin-Huxley
- Linear-Nonlinear Poisson/Generalized Linear Model
- Perceptrons and deeper networks
- Recurrent networks and population dynamics

Organization



Literature:

- Gerstner, Kistler, Naud and Paninski, *Neuronal Dynamics*,
Online Book: https://neuronaldynamics.epfl.ch/
- Dayan & Abbott, *Theoretical Neuroscience*, MIT Press
- Gonick & Smith, *The Cartoon Guide to Statistics*, Collins
- Hertz, Krogh and Palmer, *Introduction To The Theory Of Neural Computation*, Westview Press



Repository!

...one step back:
Brain research – Why?

Fundamental questions unsolved:

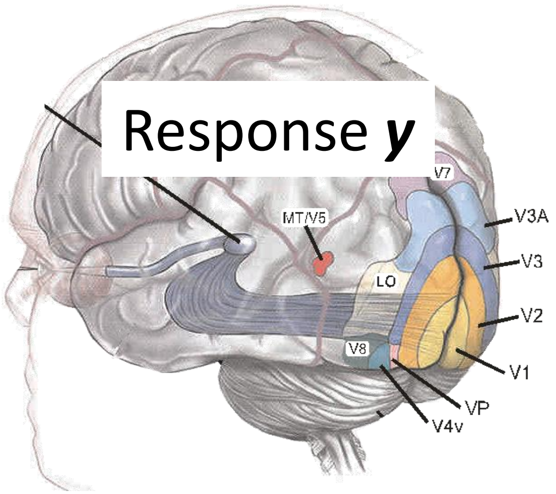
- Perception
- Memory
- Behaviour
- Consciousness

Large (potential) benefits for application:

- Machine Learning
- Neurology+Psychiatry
- Brain-Computer Interfaces
- Assistance Systems (e.g. health care, traffic, ...)

'Formalizing' brain research...

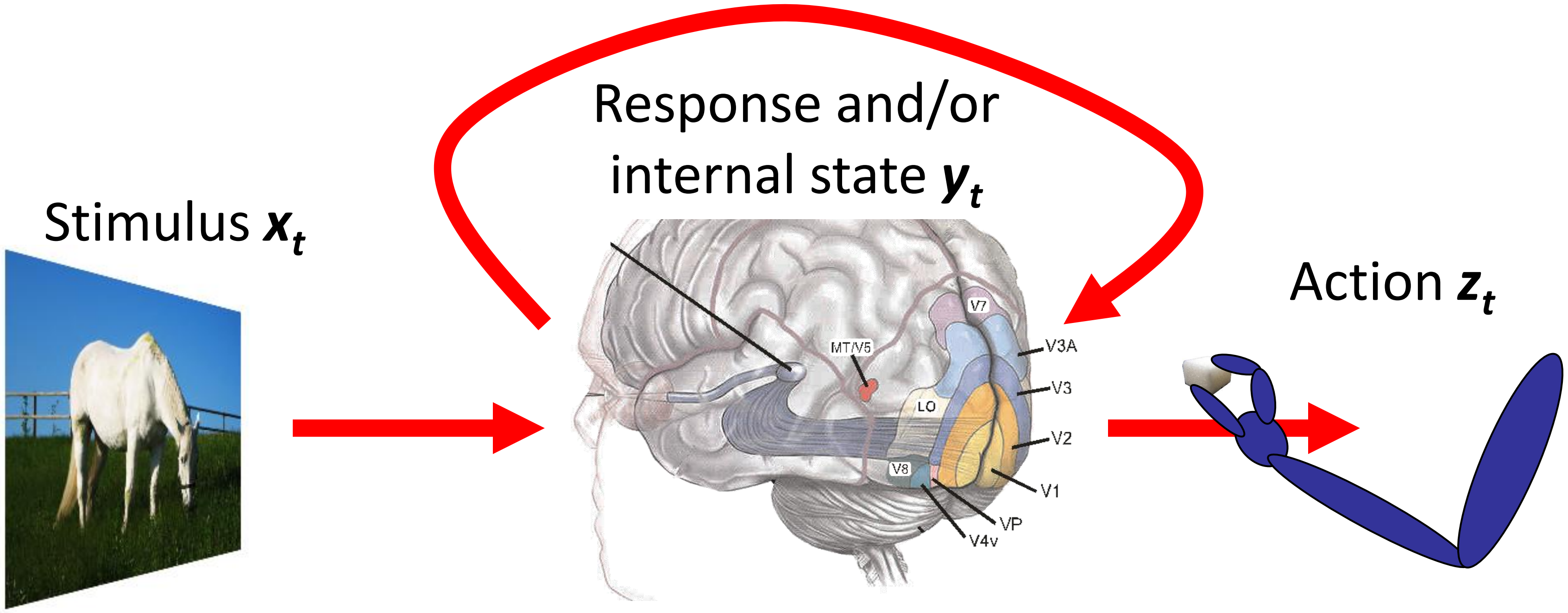
Stimulus ***x***



$$y = f(x)$$

Mapping

'Formalizing' brain research...



$$y_t = f(x_t\,,\, y_{t-1})$$

$$z_t = g(y_t)$$

Dynamical System

closing the loop...

Perspectives

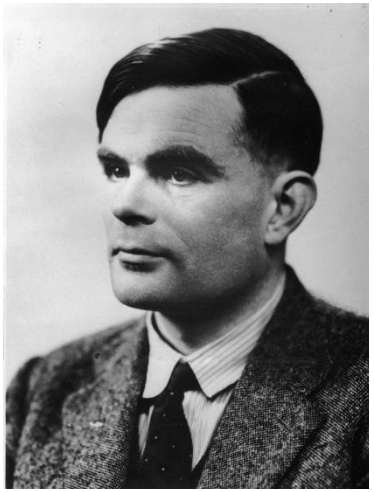
Computer Sciences

[Church, Turing, Tarski, von Neumann]:

this is computation!

$$y_t = f(x_t , y_{t-1})$$

e.g: How much information do these spikes convey about the stimulus?



Physics

[Galilei, Newton, Cauchy...]:

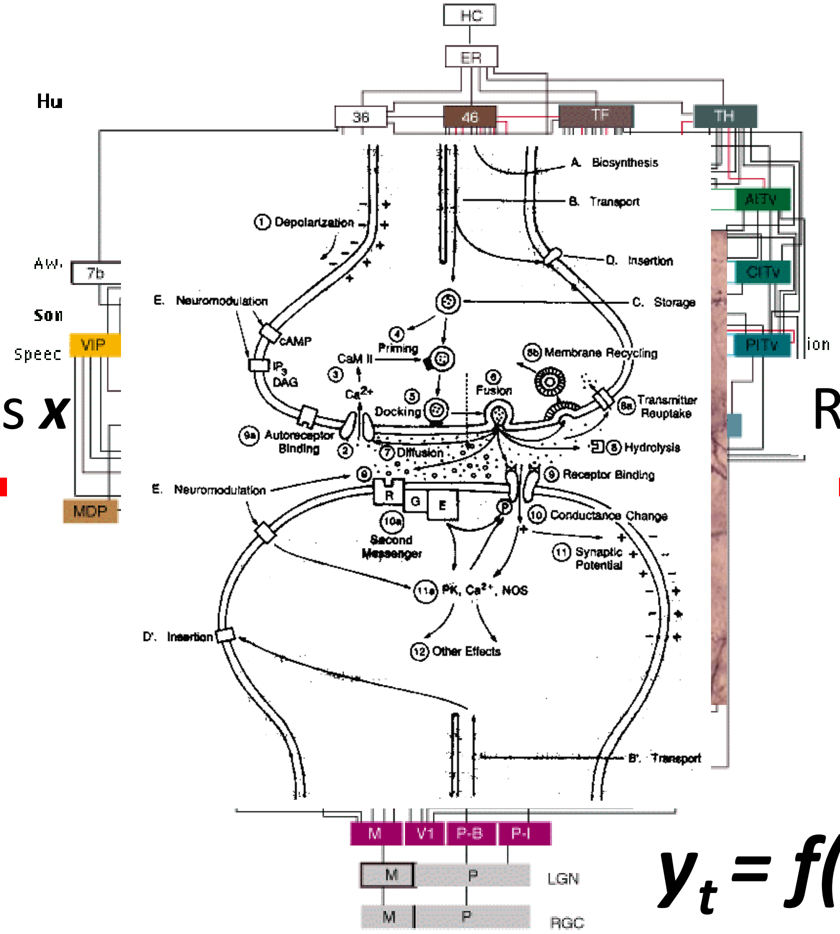
this is a dynamical system!

$$dy/dt = f(x(t) , y(t), t)$$

e.g.: How is an action potential generated?

A useful concept on all length scales...

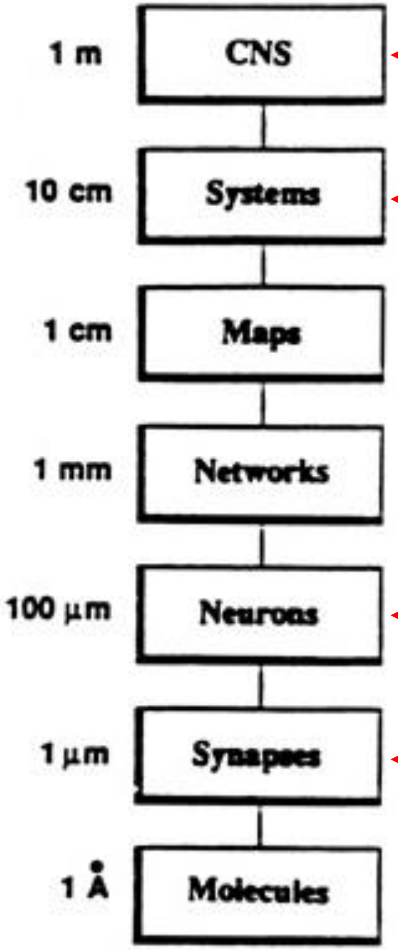
Stimulus $\boldsymbol{x}$



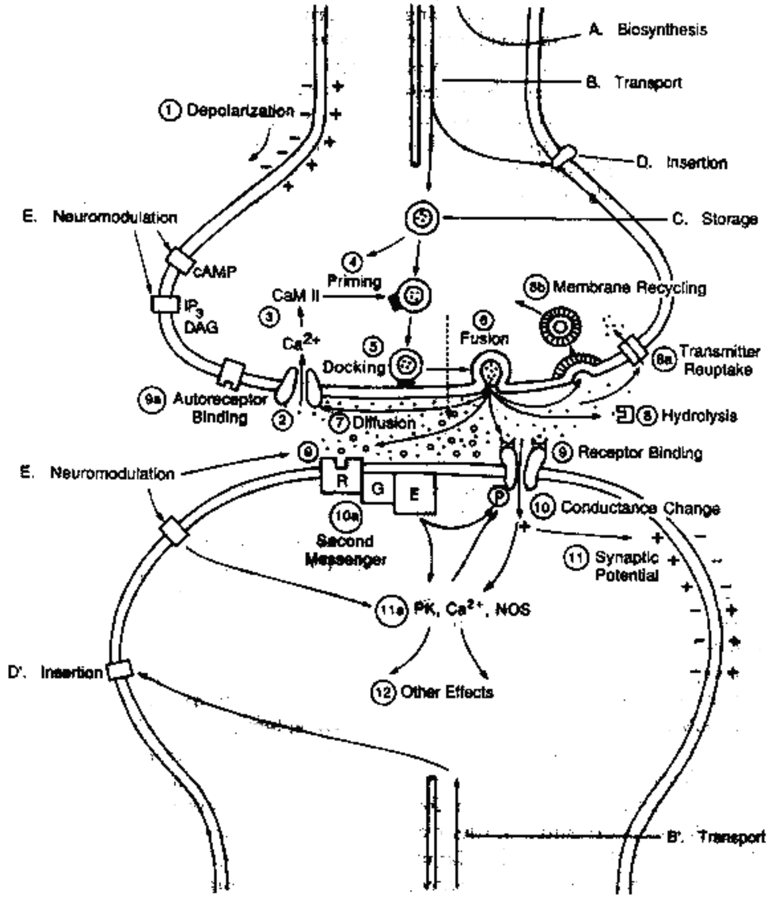
Response $\boldsymbol{y}$

$$y_t = f(x_t, y_{t-1})$$

Dynamical System



...and on all time scales!



Vesicle release:
~ 1 ms

Dynamic synapses (depression/facilitation):
~ 10 - 1000 ms

Short-term synaptic plasticity:
~ 1 - 1000 s

Synaptic tagging and capture:
~ days – months

Computational Neuroscience I:

Today: a teaser!

The workhorse of neural modelling: **The Integrate-and-fire Neuron!**

Computational Neuroscience I

a) **A simple neuron model: Integrate-and-fire** (intro differential equations, numerical solutions)

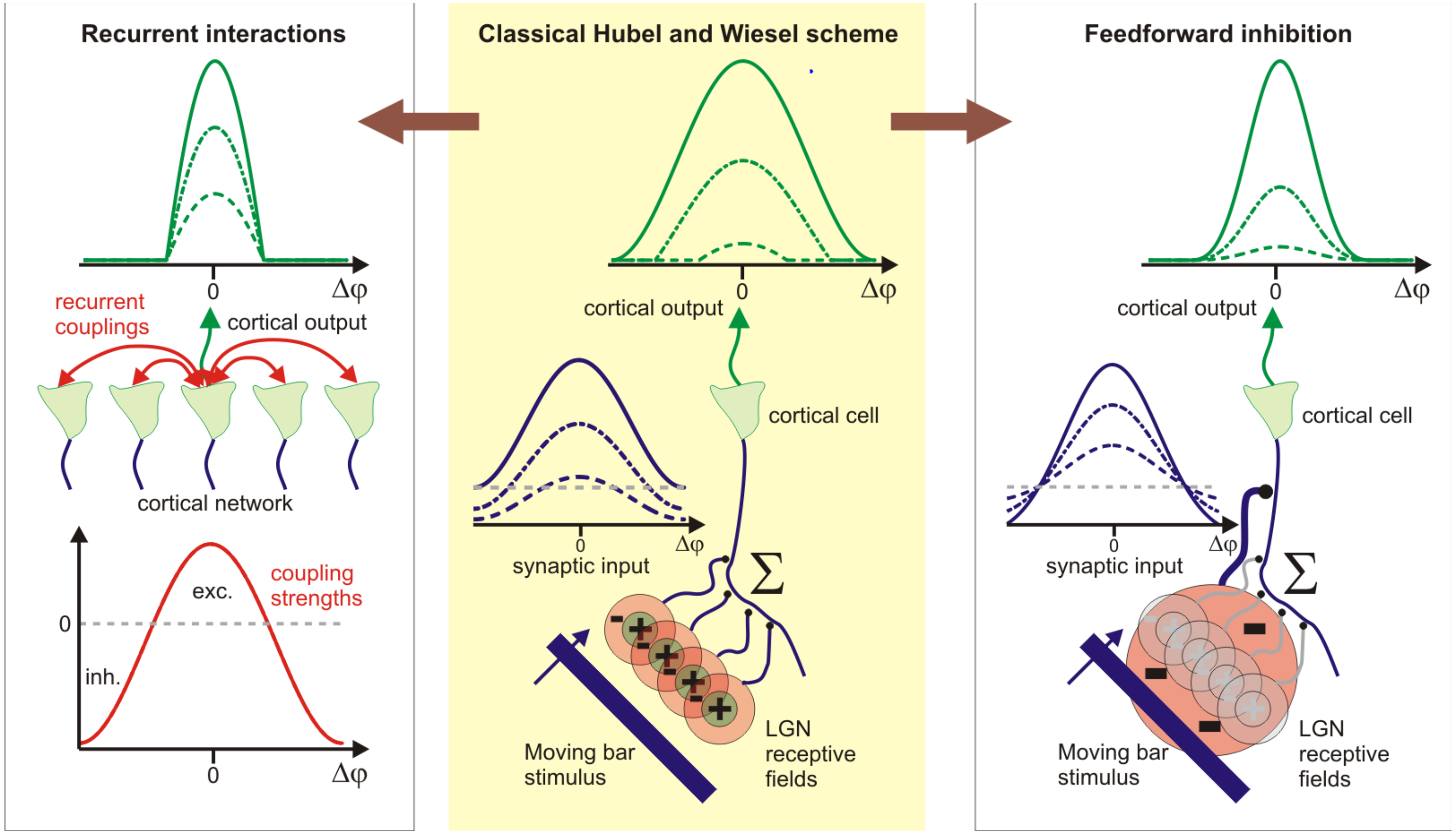
b) **Spike statistics** (delta-functions, spike trains and rates, correlations and variability, Poisson+Bernoulli+Gauss)

c) **Generalized linear models and reverse correlation** (receptive fields, stimulus-response characteristics, convolutions, spike-triggered average)

d) **Discrimination and decoding** (ROC analysis, Bayesian estimation, loss functions and estimation)

e) **Spectral analysis** (complex numbers, Fourier analysis, Wavelet transformation, power spectra)

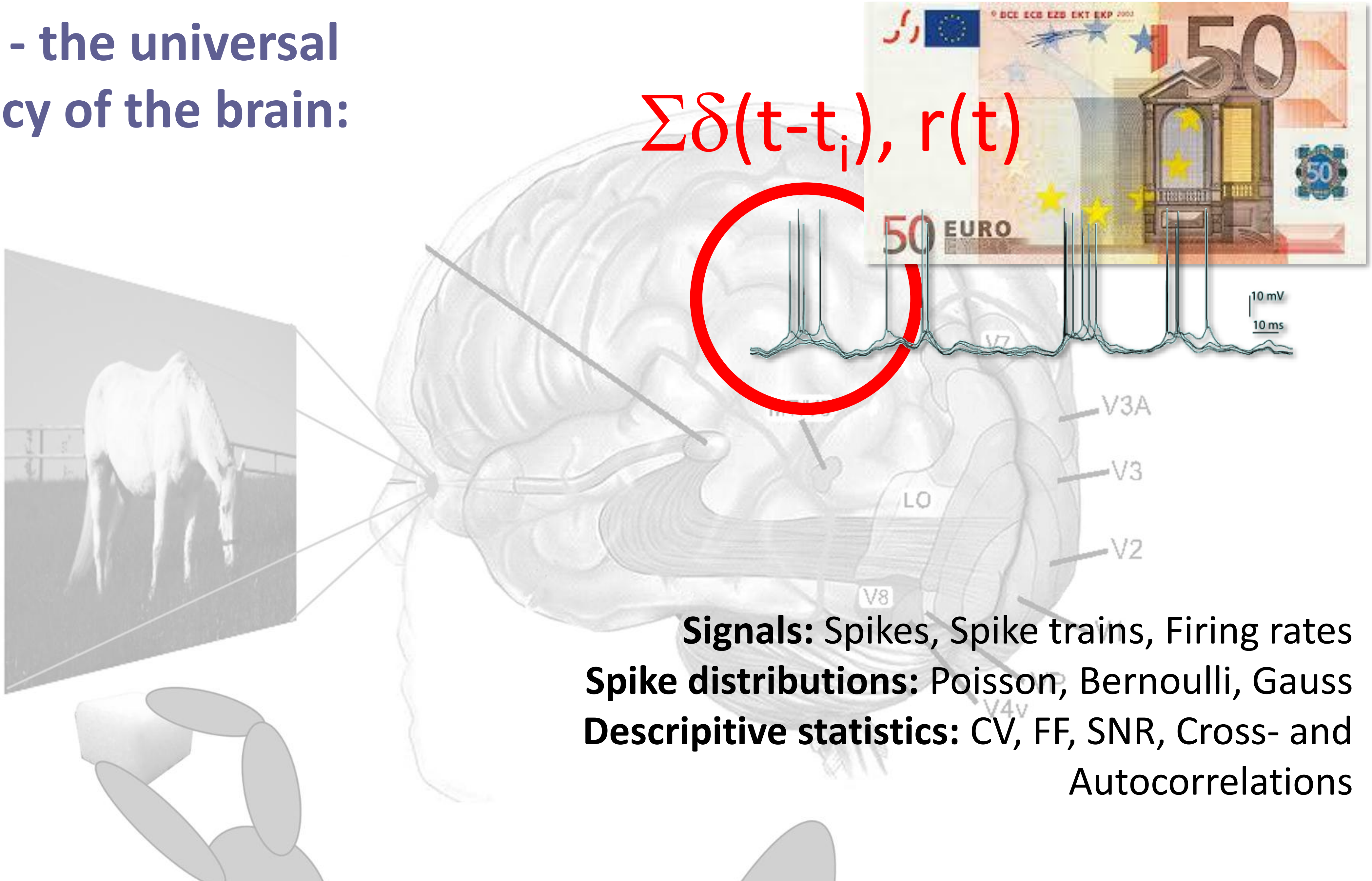
4. Formalizing and testing theories



Orientation preference in visual cortex: an on-going puzzle...

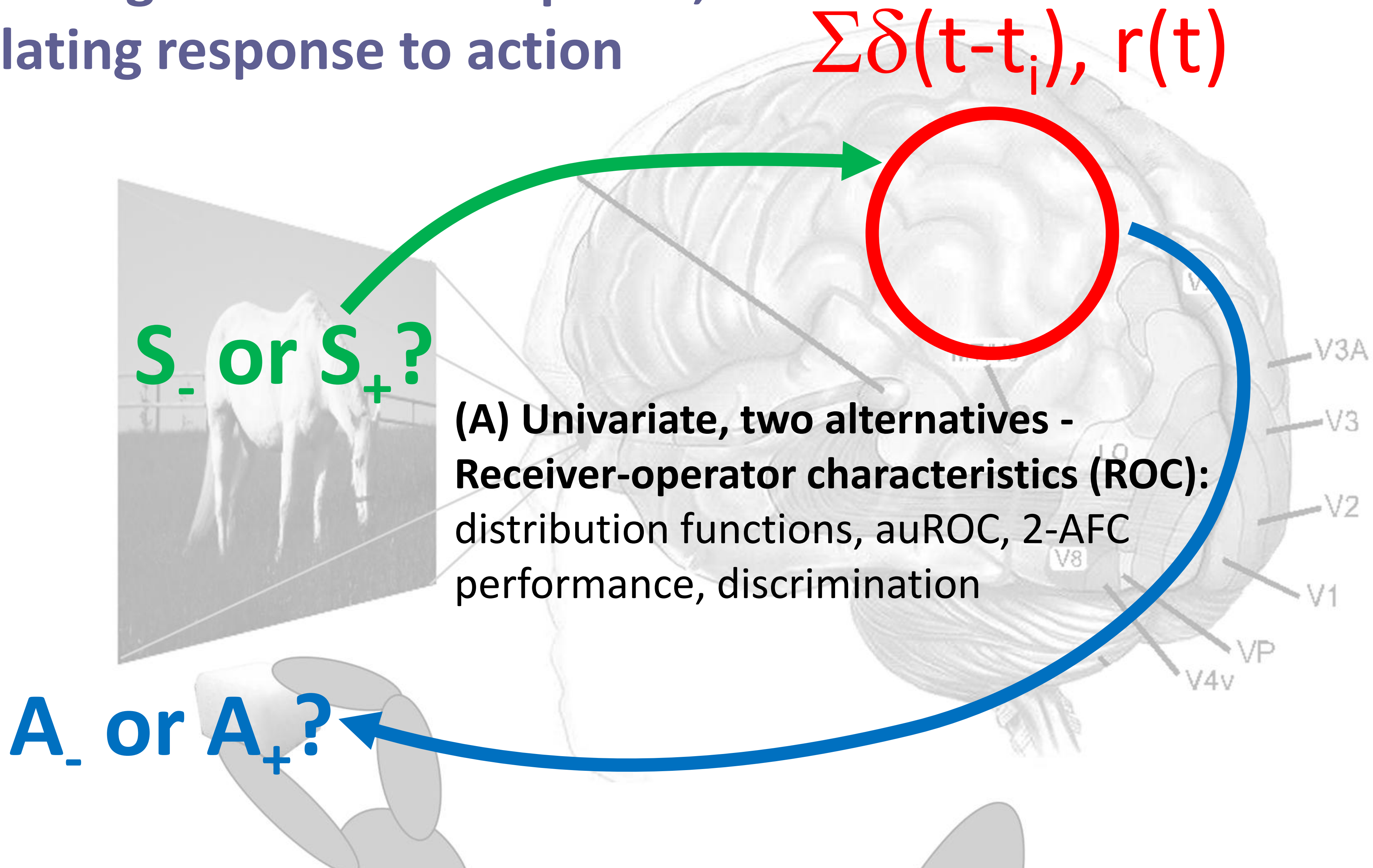
Spikes - the universal currency of the brain:

$\Sigma\delta(t-t_i), r(t)$



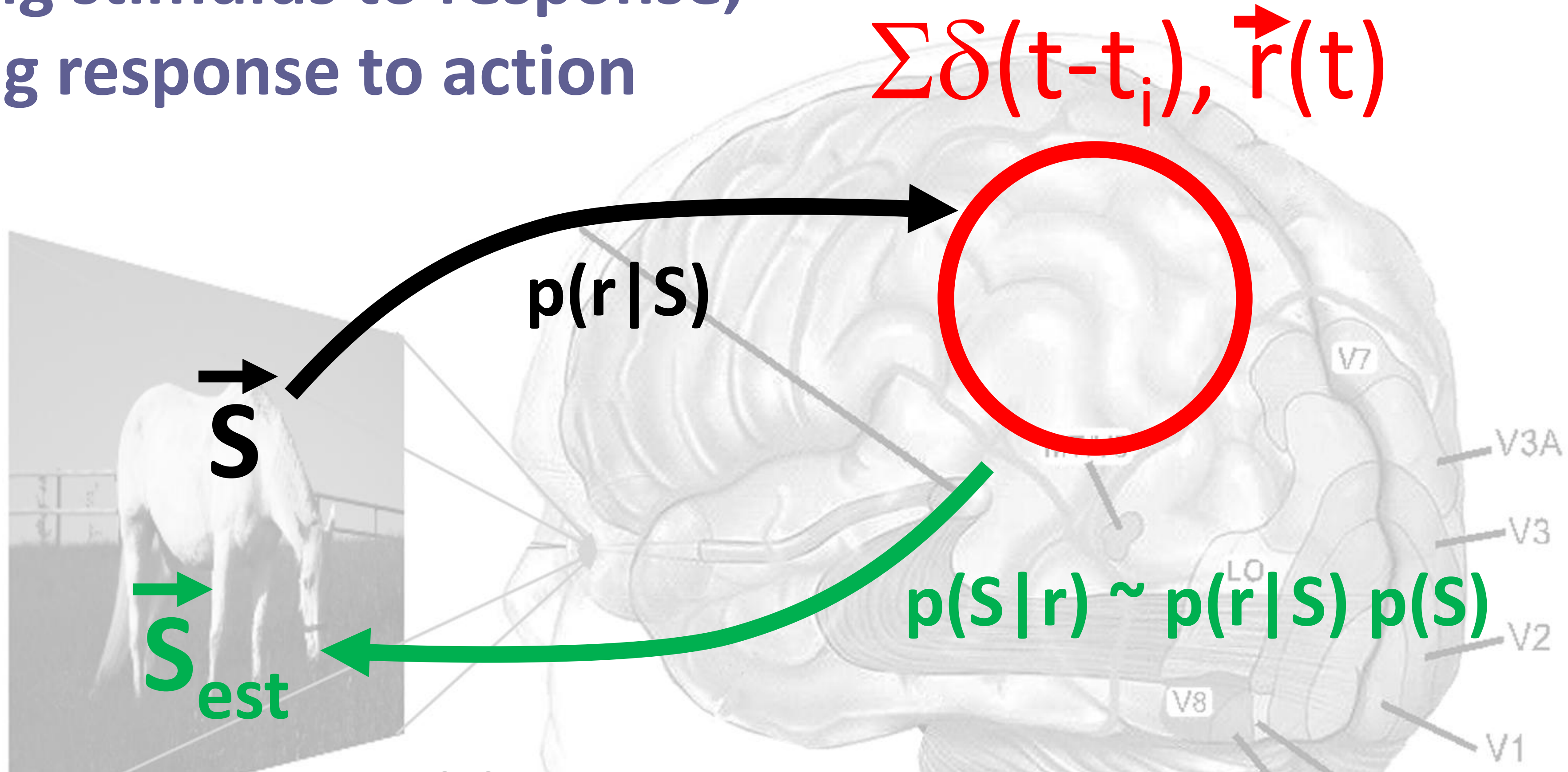
Signals: Spikes, Spike trains, Firing rates
Spike distributions: Poisson, Bernoulli, Gauss
Descripitive statistics: CV, FF, SNR, Cross- and Autocorrelations

Relating stimulus to response, relating response to action



(A) Univariate, two alternatives - Receiver-operator characteristics (ROC):
distribution functions, auROC, 2-AFC performance, discrimination

Relating stimulus to response, relating response to action



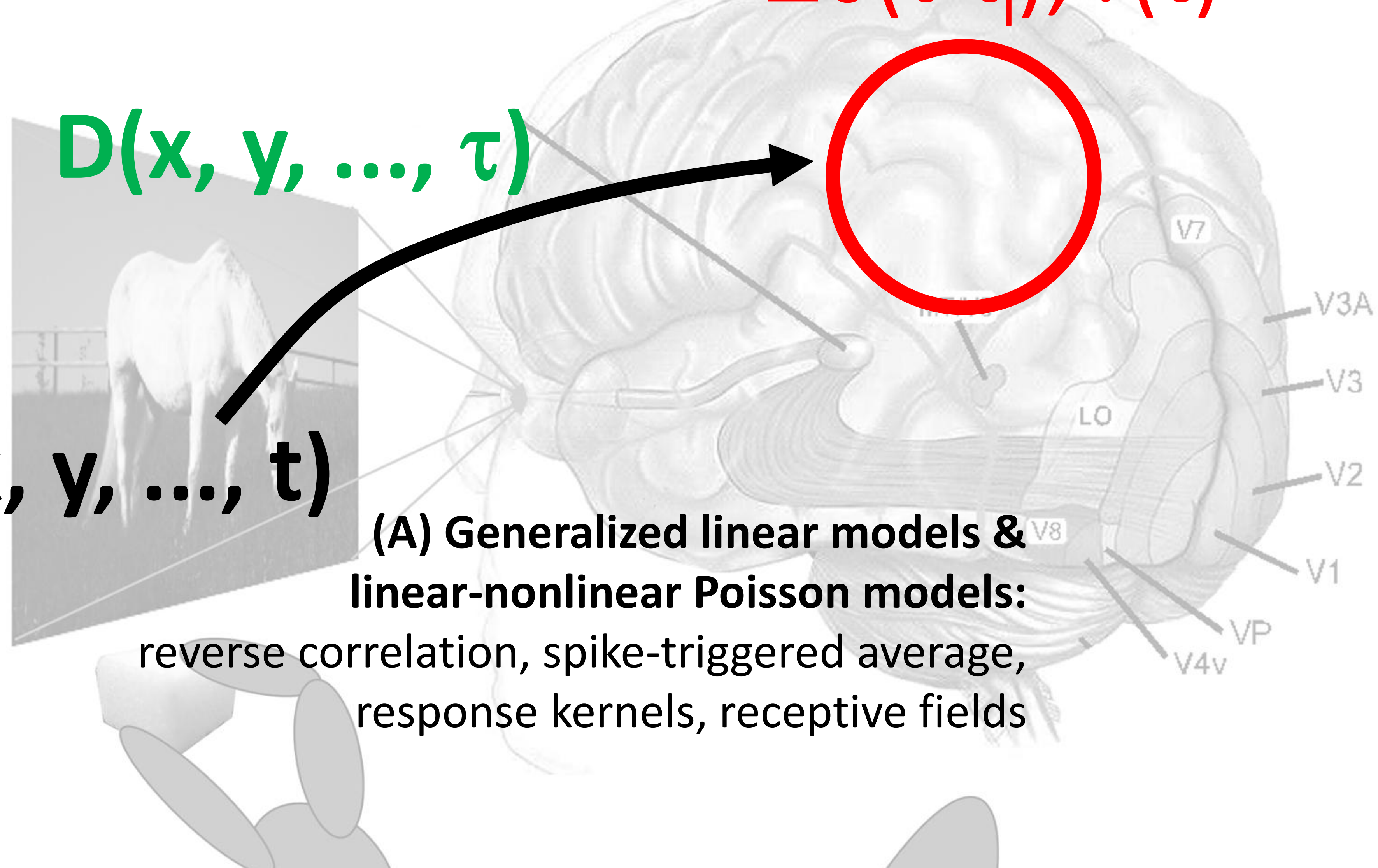
(B) Multivariate estimation - Bayesian inference:
loss functions, estimators, maximum likelihood & maximum a posteriori estimation

Modelling neural responses to dynamical stimuli

$\Sigma\delta(t-t_i)$, $r(t)$

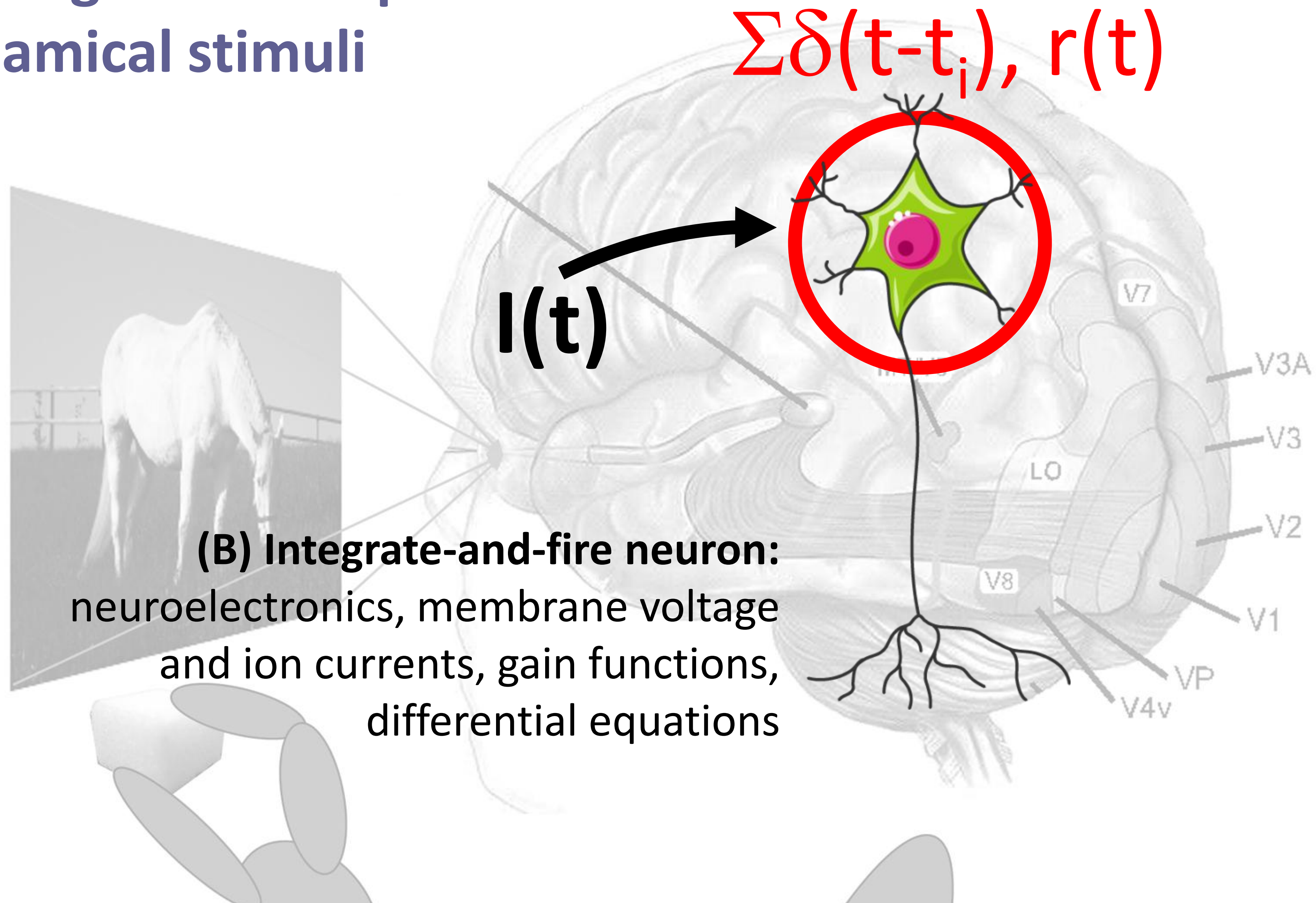
$D(x, y, \ldots, \tau)$

$S(x, y, \ldots, t)$



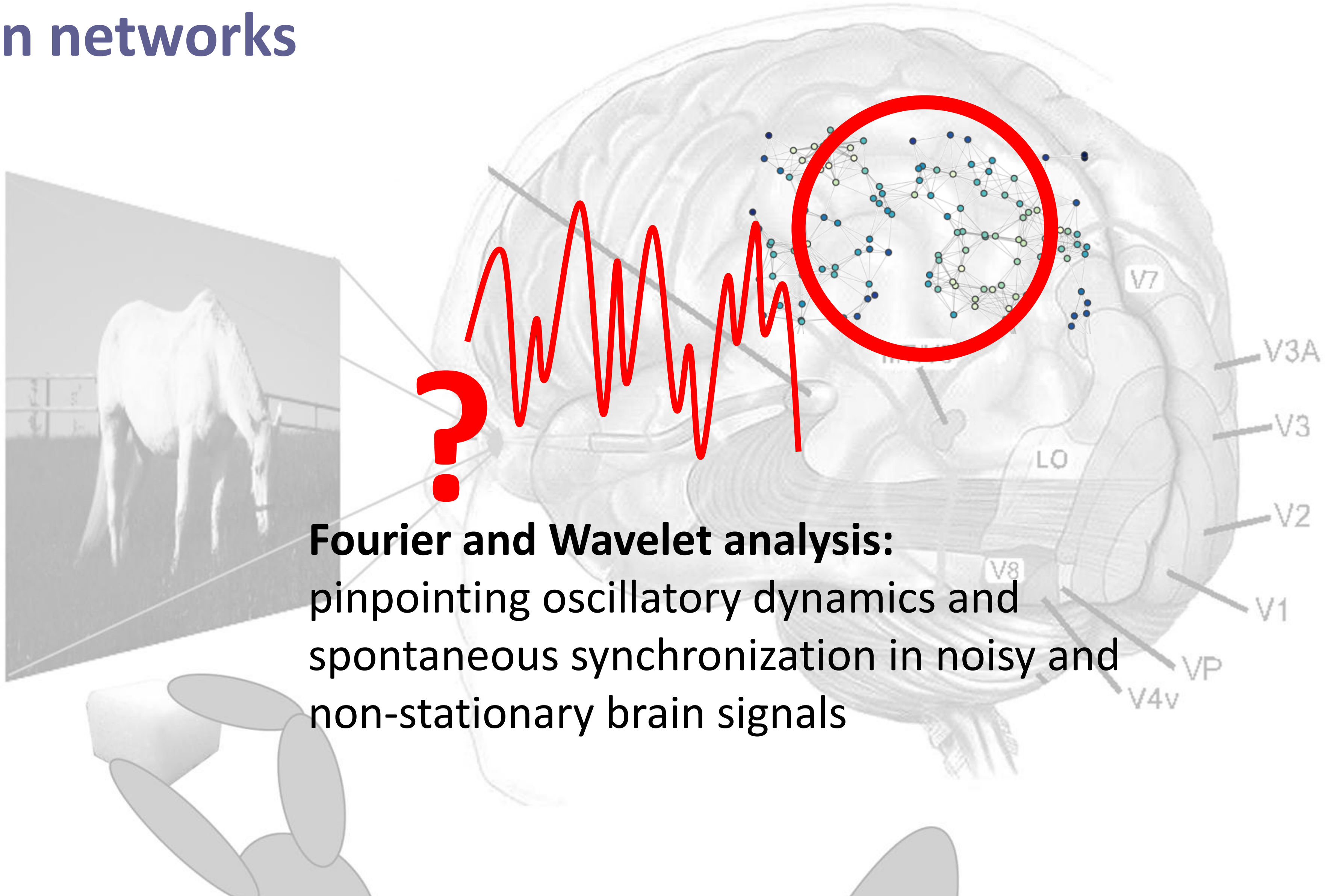
(A) Generalized linear models & linear-nonlinear Poisson models:
reverse correlation, spike-triggered average, response kernels, receptive fields

Modelling neural responses to dynamical stimuli



(B) Integrate-and-fire neuron:
neuroelectronics, membrane voltage and ion currents, gain functions, differential equations

Towards collective dynamics of brain networks



Fourier and Wavelet analysis:
pinpointing oscillatory dynamics and spontaneous synchronization in noisy and non-stationary brain signals

Computational Neuroscience II (summer term)

a) **Neurons, Populations and Networks** (mean-field dynamics, synaptic interactions, collective phenomena, synchronization and pattern formation, network structures...)

b) **Learning and Memory** (attractor networks, Hopfield model, memory capacity, short-term synaptic plasticity, spike-timing dependent plasticity...)

c) **Computation, Representation and Classification** (perceptron, MLPs, backpropagation, self-organization, Kohonen, cortical maps, place cells, machine learning...)

Mathematical, Physical and Statistical Concepts

a) Basics:

- functions, inverse functions
- linearity, monotonicity
- derivatives and integrals
- extremal values
- delta-distribution

Mathematical, Physical and Statistical Concepts

b) Probabilities and Elementary Statistics:

- random variables
- central limit theorem, (conditional) probabilities
- probability distributions (normal, Poisson, Bernoulli, ...)
- moments, cumulative distributions
- Bayes' rule
- risk functions
- estimators (ML, MAP)

Mathematical, Physical and Statistical Concepts

c) Linear Algebra:

- vectors
- vector operations
- matrix multiplication

Mathematical, Physical and Statistical Concepts

d) Differential Equations:

- definitions
- DEQs of one variable
- DEQs of two variables
- solving DEQs
- linear system theory: fixed points, limit cycles, stability analysis, pattern formation...

Mathematical, Physical and Statistical Concepts

e) Complex Numbers and the Fourier Transformation:

- definitions
- rules for computing with complex numbers
- fourier transformation
- spectral power

Computational Neuroscience I

a) Neural Signals and Signal Analysis:

- spike trains & firing rates
- local field potentials
- Poisson and Bernoulli processes
- autocorrelation, cross-correlation

Computational Neuroscience I

b) Neuronal Response Properties:

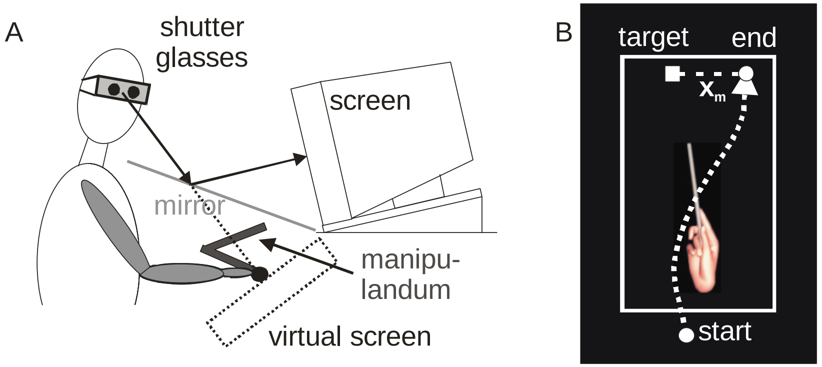
- tuning curves
- receptive fields
- spike-triggered averages
- reverse correlation
- GLMs – generalized linear models

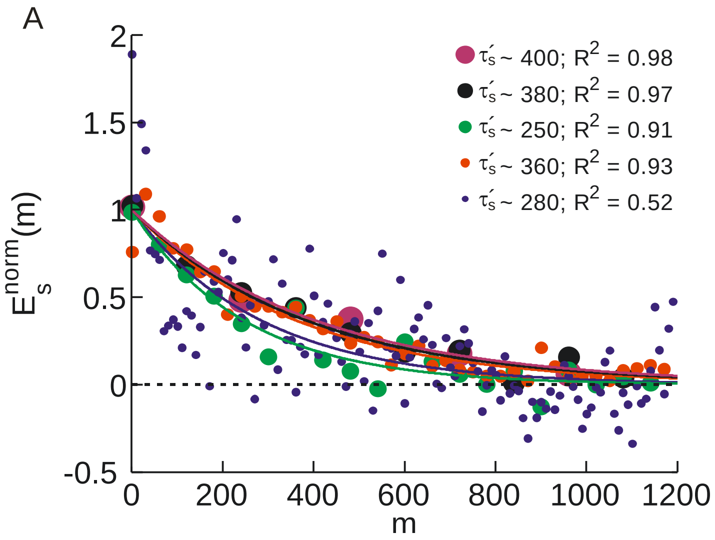
Computational Neuroscience I

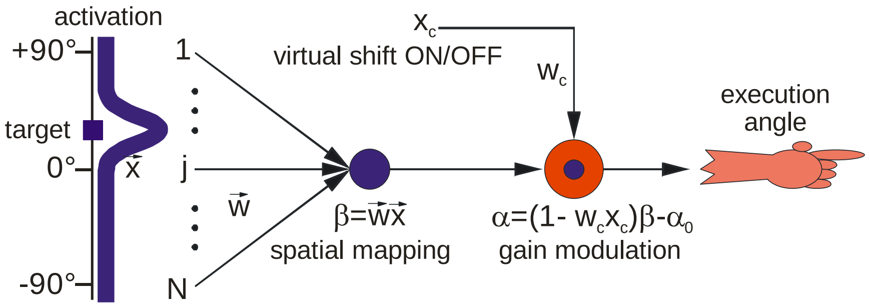
c) Encoding and Decoding:

- single neuron encoding and decoding
- discrimination, likelihood ratio
- receiver-operator characteristics (ROC)
- population encoding and decoding

Psychophysics and Modelling

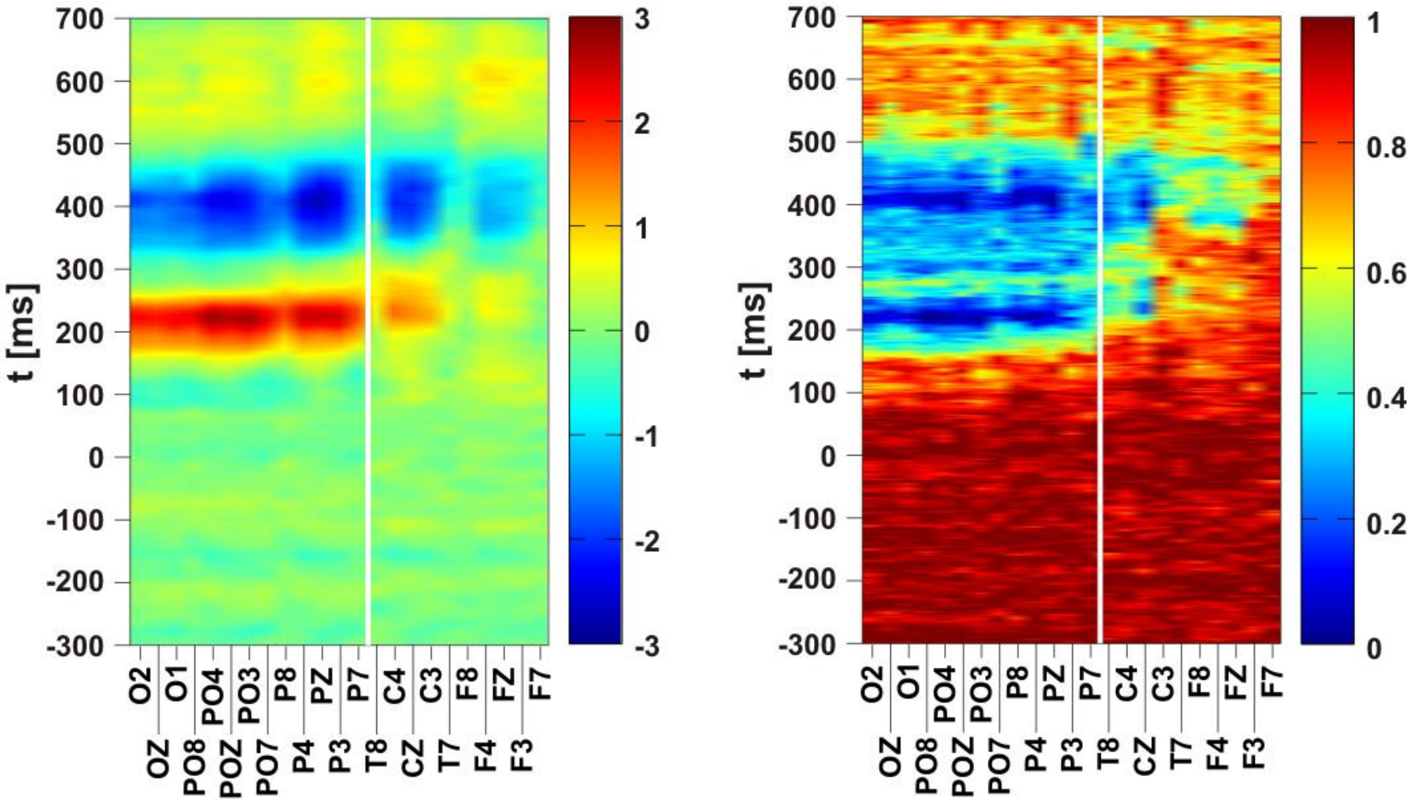






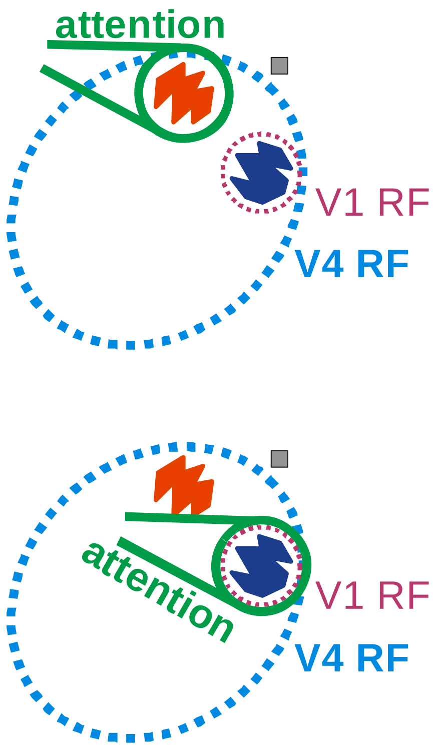
EEG Recordings and statistical analysis

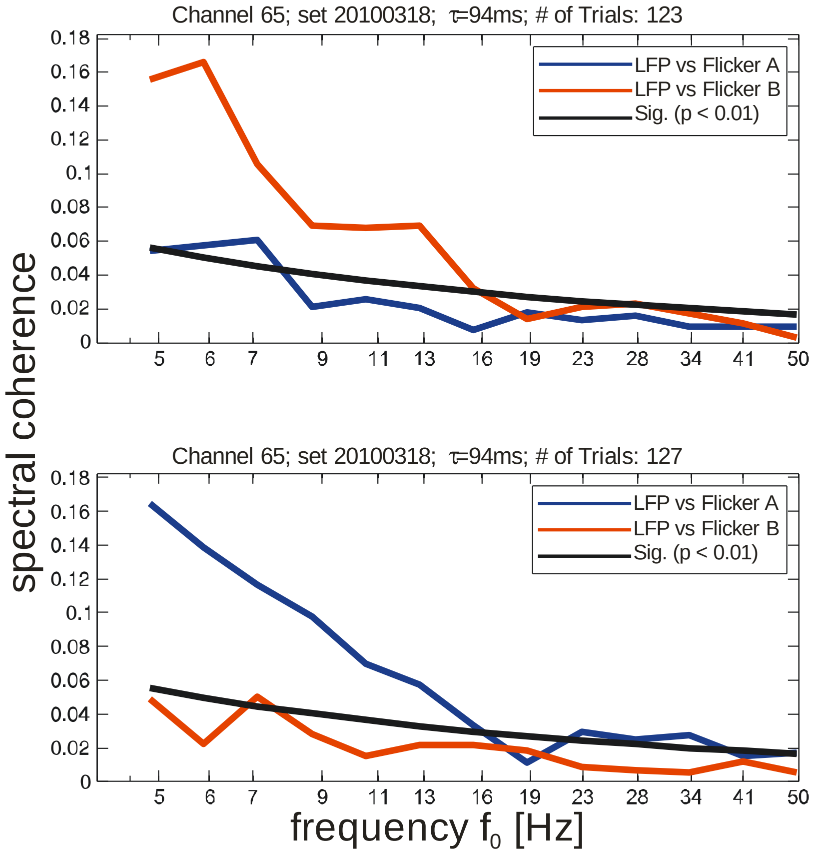
(A) (B)



Are differences in EEG traces statistically significant?

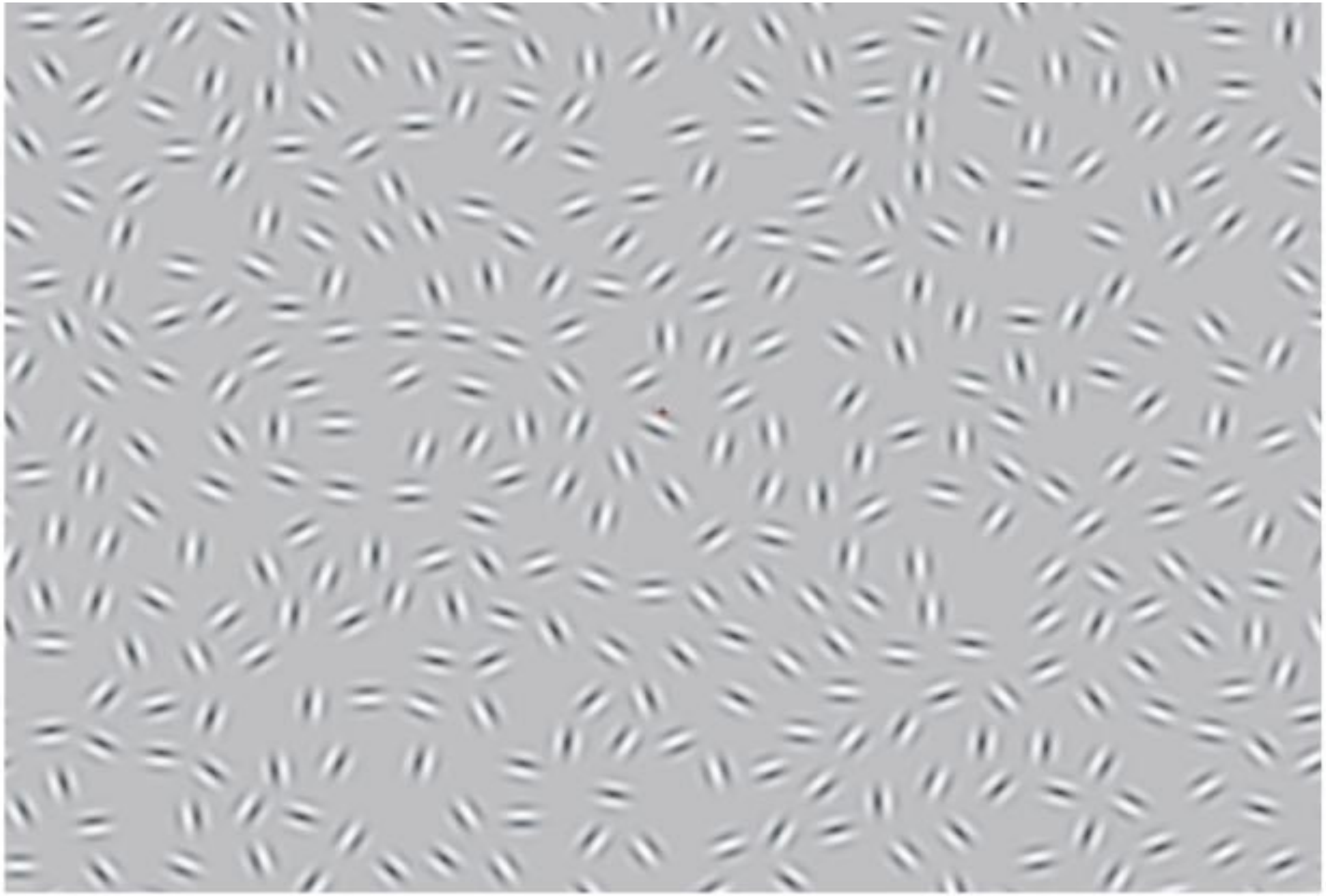
Information routing in cortical networks





Quantifying the gating of visual signals by attention.

Contour integration



Computational Neuroscience II

e) Learning and Memory:

- Hopfield model, attractor networks, memory capacity
- synapses: facilitation and depression, short-term plasticity, spike-timing-dependent plasticity, learning rules (Hebb and Co.)

Computational Neuroscience II

f) Function & Structure – the Computational Brain

- computation and classification
  (multilayer perceptrons, backpropagation, SVMs)
- cortical maps and pattern formation
  (Kohonen-SOMs, place cells, etc.)

population dynamics (Wilson-Cowan models)