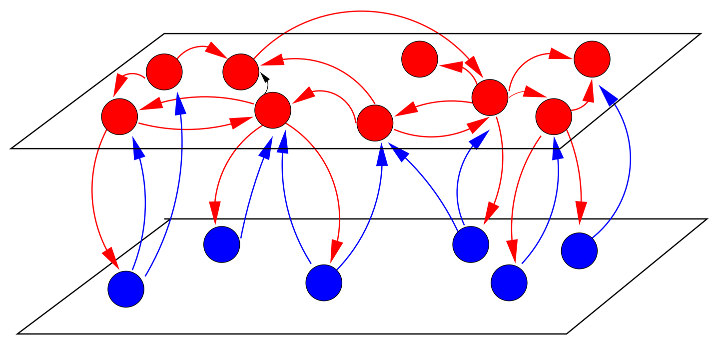
INSTITUT NATIONAL DE RECHERCHE EN INFORMATIQUE ET EN AUTOMATIQUE — INRIA

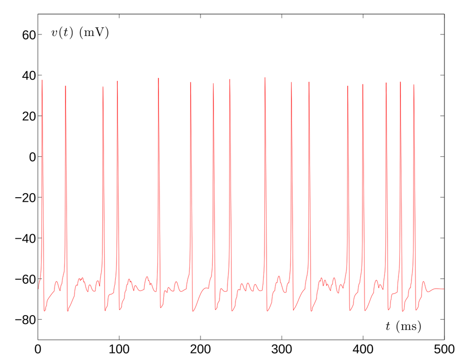
Spiking Neural Networks

1 Introduction

- Computational and mathematical modeling of neural systems
- Goal: understanding of the information contents of neural signals by modeling the nervous system at different scales, from single cells to neural networks.



Excitatory-inhibitory neural network



Spiking activity of a neuron

- Numerical schemes for the simulation of neurons and neural networks.
- Analysis of the dynamics of neurons and neural networks.

2 Models

Integrate-and-fire models. The neuron is described by his membrane potential v obeying the nonlinear differential equation

$$\frac{dv}{dt} = f(v) + I + I_{syn}(t)$$

and the reset condition

$$v(t) = \vartheta \Rightarrow v(t) = v_r \text{ and } t^f = t$$

- I is an external current, ϑ a threshold, v_r a reset potential and t^f is the so-called firing time or spike timing.
- I_{syn} is the synaptic current generated by the activity of presynaptic neurons,

$$I_{syn}(t) = \sum_j w_{ij} \sum_f \alpha(t - t_j^f)$$

where α is a pulse-coupling function, for instance $\alpha(t) = \delta(t)$ (instantaneous coupling), $\alpha(t) = \exp(-t/\tau)$ (exponential coupling) or $\alpha(t) = g(t)(v - E_s)$ (conductance-based current) where g is a conductance and E_s a reversal potential.

Detailed neuron models. More details models account for numerous ion channels and include a spike-description. Reduction of these models to two dimensions can be expressed as

$$\frac{dv}{dt} = f(v, u) + I + I_{syn}(t)$$
$$\frac{du}{dt} = g(v, u)$$

Population models. Time-dependent firing rate models are commonly described by

$$\tau\frac{dr}{dt} = -r * F(Wr + h)$$

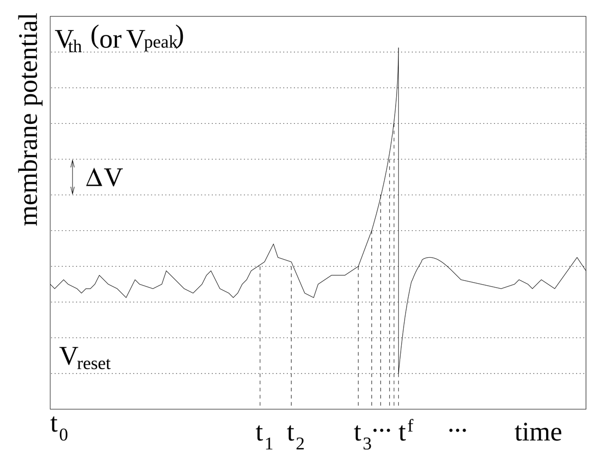
where r is the firing rate vector, τ the relaxation time, W the matrix of the synaptic weights and F is a sigmoid-like activation function, for instance $F(X) = H(X - \Theta)$ where H is the Heaviside function and Θ a threshold.

3 Numerical Schemes

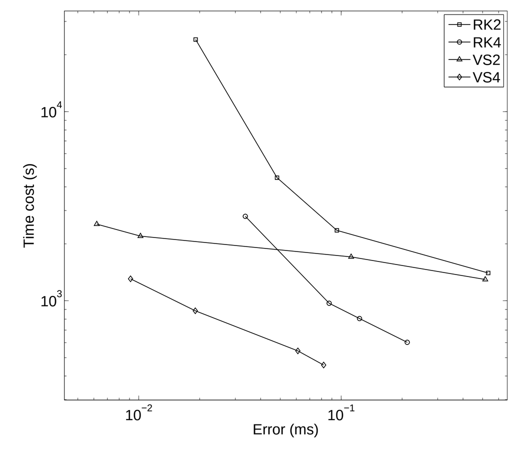
Due to discontinuities, traditional time-stepping schemes fail to compute the spike timings accurately.

Alternative strategies have been developed :

- Event-driven schemes: Timings of spike are calculated exactly
- Voltage-stepping schemes: Implicit activity-dependent time discretization.



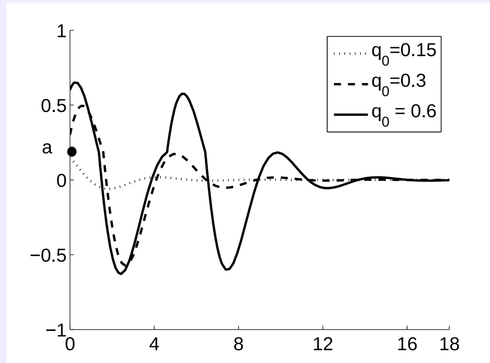
Voltage-stepping scheme (VS)



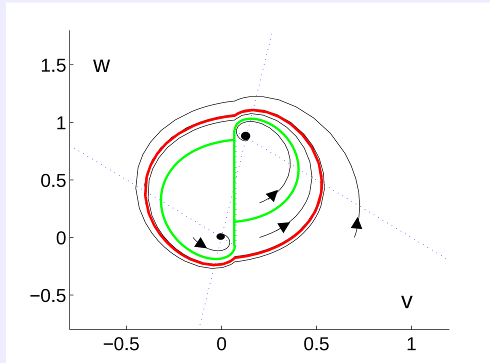
Comparative efficiency

4 Neural Dynamics

- Excitability and oscillations - Piecewise linear approximation

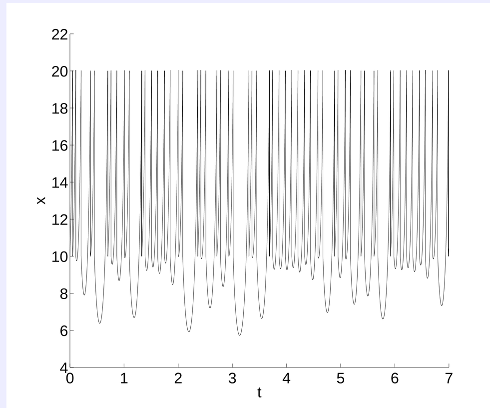


Neural Excitability

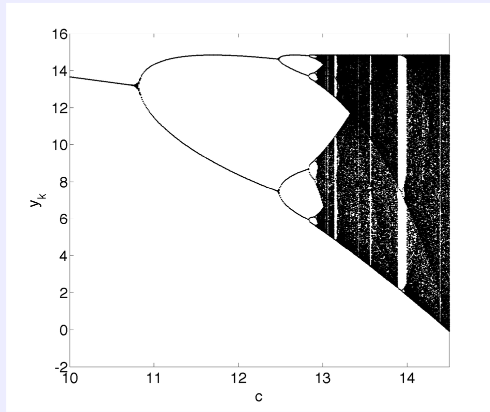


Multistability in the phase plane

- Bifurcations and Chaos



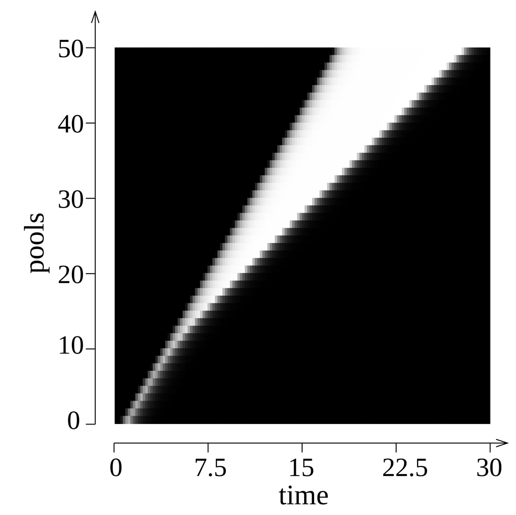
Chaotic solution



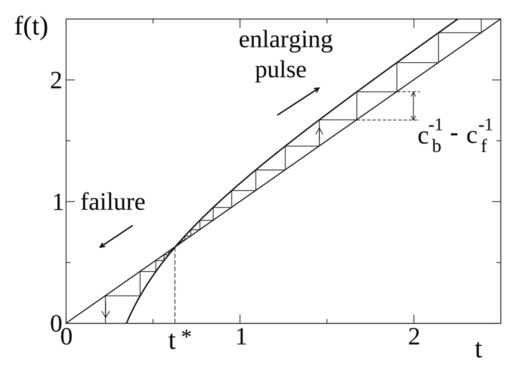
Bifurcation diagram

5 Network Dynamics

- Synchronization
- Propagation of synaptically generated traveling waves. Propagation of pulse in an excitatory-inhibitory network.



Enlarging pulse propagation



Iterative map that governs the propagation

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