# Synchrony in Neural Systems:

## a very brief, biased, basic view

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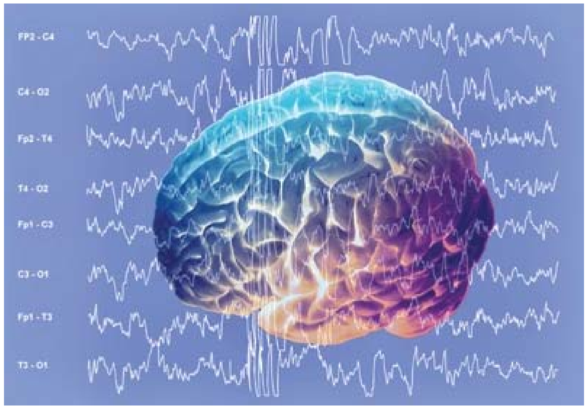
UC Davis

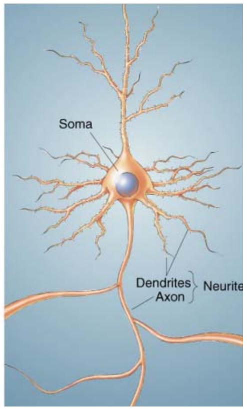
**NIMBIOS Workshop on Synchrony**
**April 11, 2011**

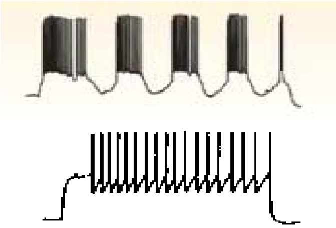


# components of neuronal networks

## neurons

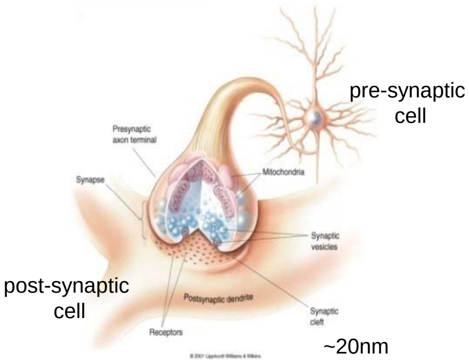
**cell type**
- intrinsic properties (densities of ionic channels, pumps, etc.)
- morphology (geometry)
- noisy, heterogeneous





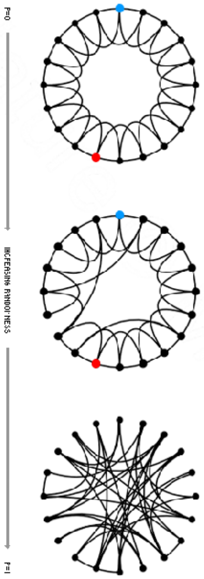
## synapses

**synaptic dynamics**
- excitatory/inhibitory; electrical
- fast/slow
- facilitating/depressing
- noisy, heterogeneous
- delays

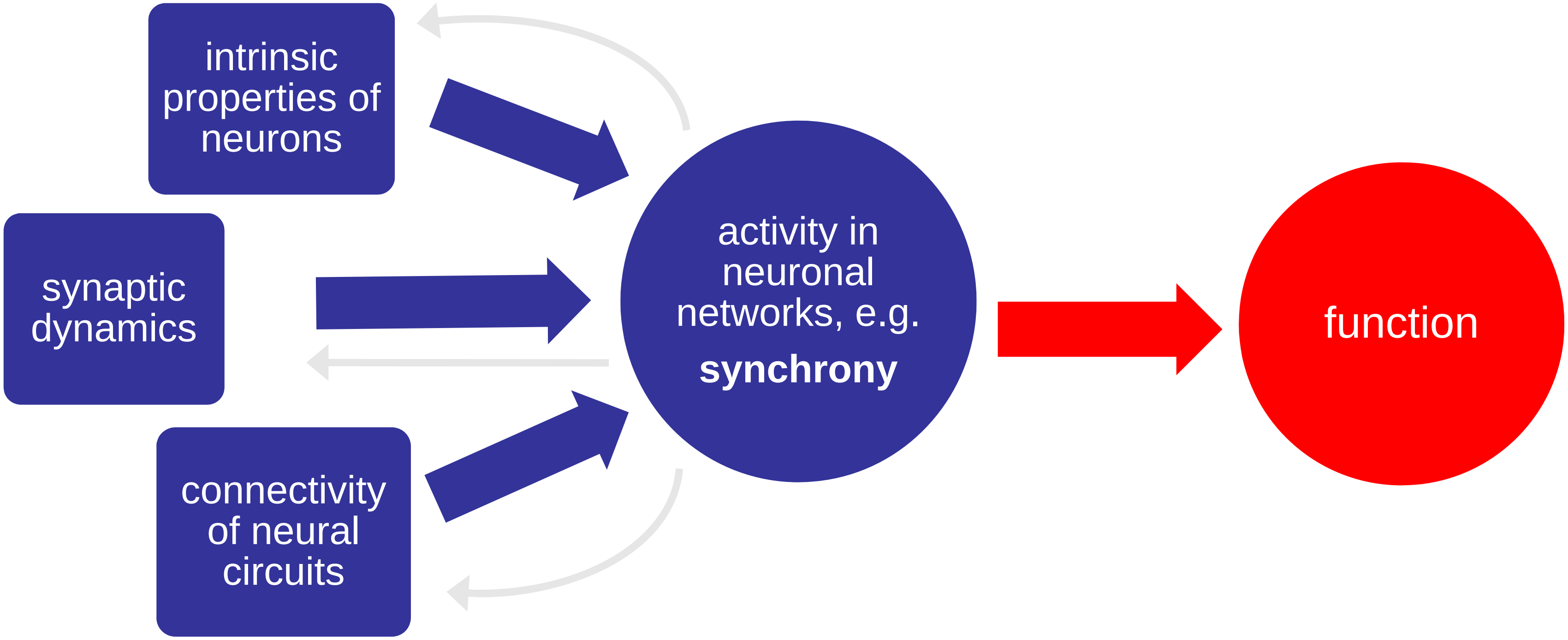


## connectivity

**network topology**
- specific structure
- random; small world, local
- heterogeneous



# a fundamental challenge in neuroscience



intrinsic properties of neurons

synaptic dynamics

connectivity of neural circuits

activity in neuronal networks, e.g.

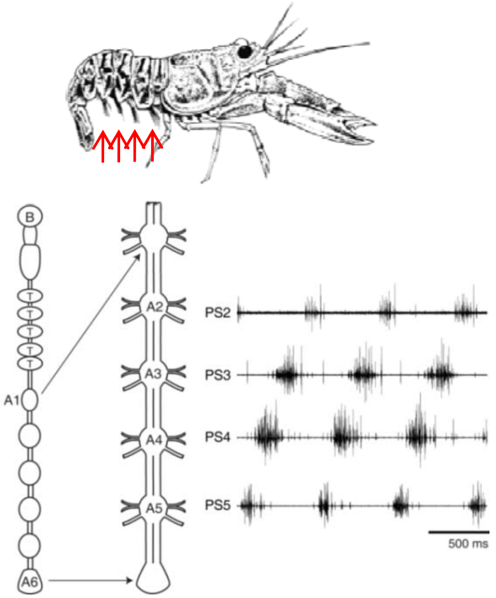
**synchrony**

function

# why could “*synchrony*” be important for function in neural systems?

**1. coordination of overt behavior:** locomotion, breathing, chewing, etc.

**example: crayfish swimming**

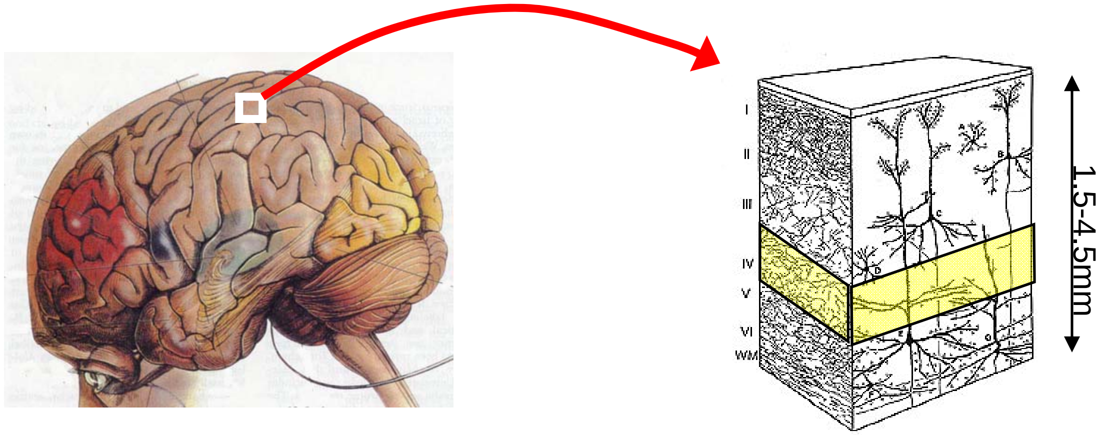


B. Mulloney et al

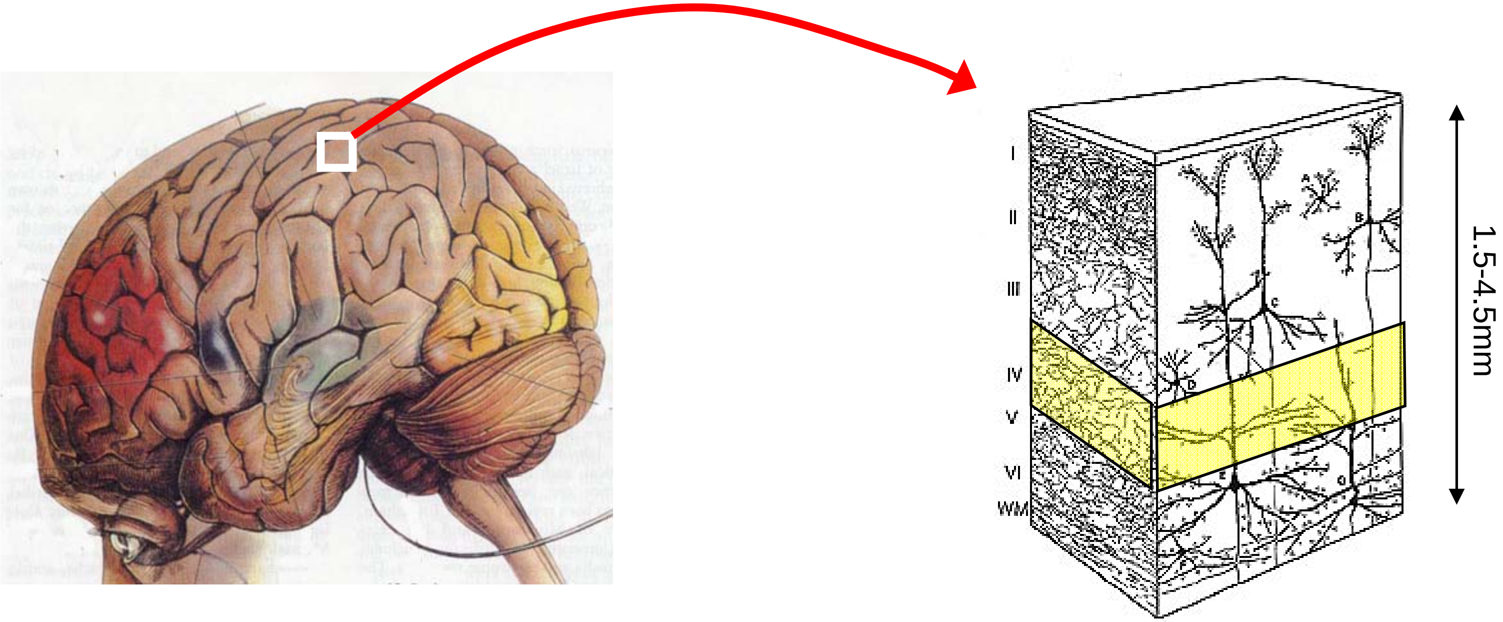
shrimp swimming

# why could “*synchrony*” be important for function in neural systems?

1. **coordination of overt behavior:** locomotion, breathing, chewing, etc.
2. **cognition, information processing (e.g. in the cortex) …?**



Should we expect synchrony in the cortex?



**Should we expect synchrony in the cortex?**

# EEG: “brain waves”: behavioral correlates, function/dysfunction

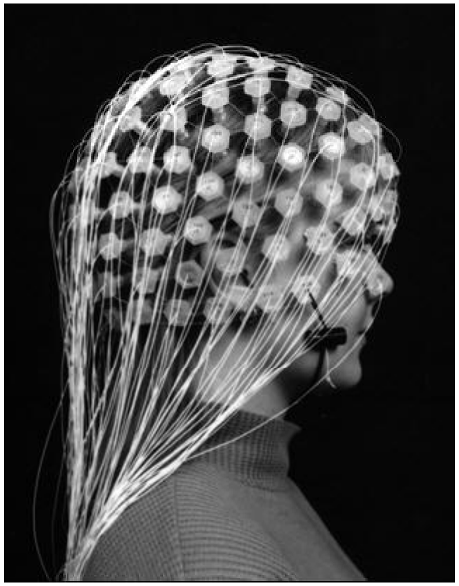
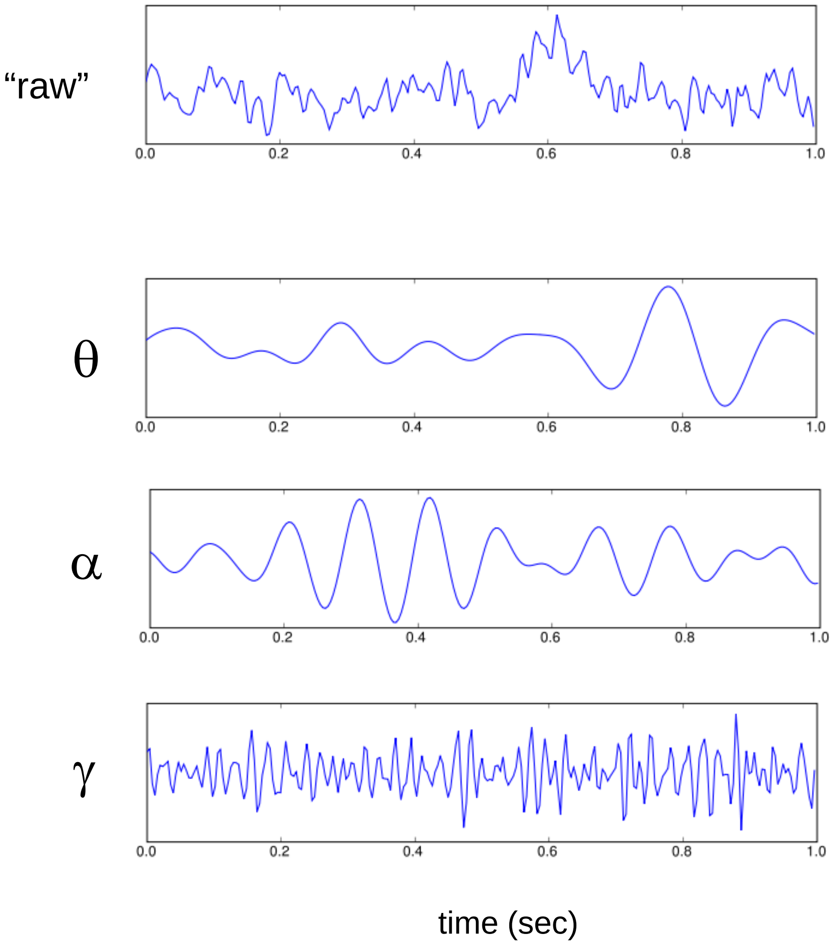
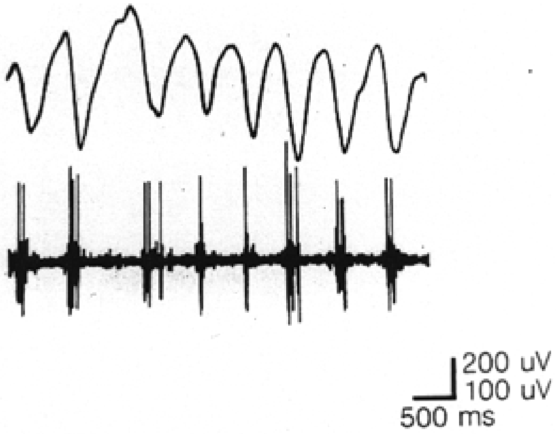


Figure 1: A geodesic net with 128 electrodes making scalp contact with a salinated sponge material is shown (Courtesy Electrical Geodesics, Inc). This is one of several kinds of EEG recording methods. Reproduced from Nunez (2002).

EEG recordings



# large-scale cortical oscillations arise from synchronous activity in neuronal networks



Gray and Singer (1989) Proc. Nat. Acad. Sci. 86: 1698-1702.

*in vivo* $\gamma$-band (30-70 Hz) cortical oscillations.

## how can we gain insight into the functions and dysfunctions related to neuronal synchrony?

1. Develop appropriate/meaningful ways of measuring/quantifying synchrony.
2. Identify mechanisms underlying synchronization – both from the dynamical and biophysical standpoints.

# 1. measuring correlations/levels of synchrony

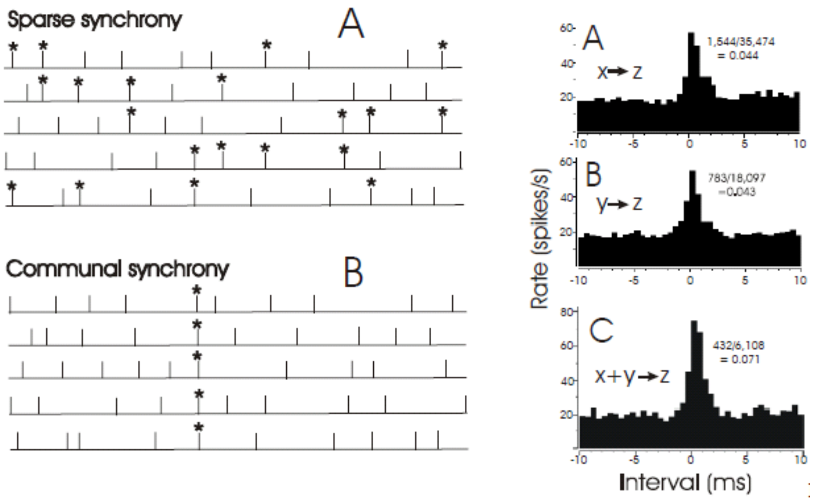
i. limited spatio-temporal data.

ii. measuring phase

iii. spike-train data (embeds “discrete” spikes in continuous time)

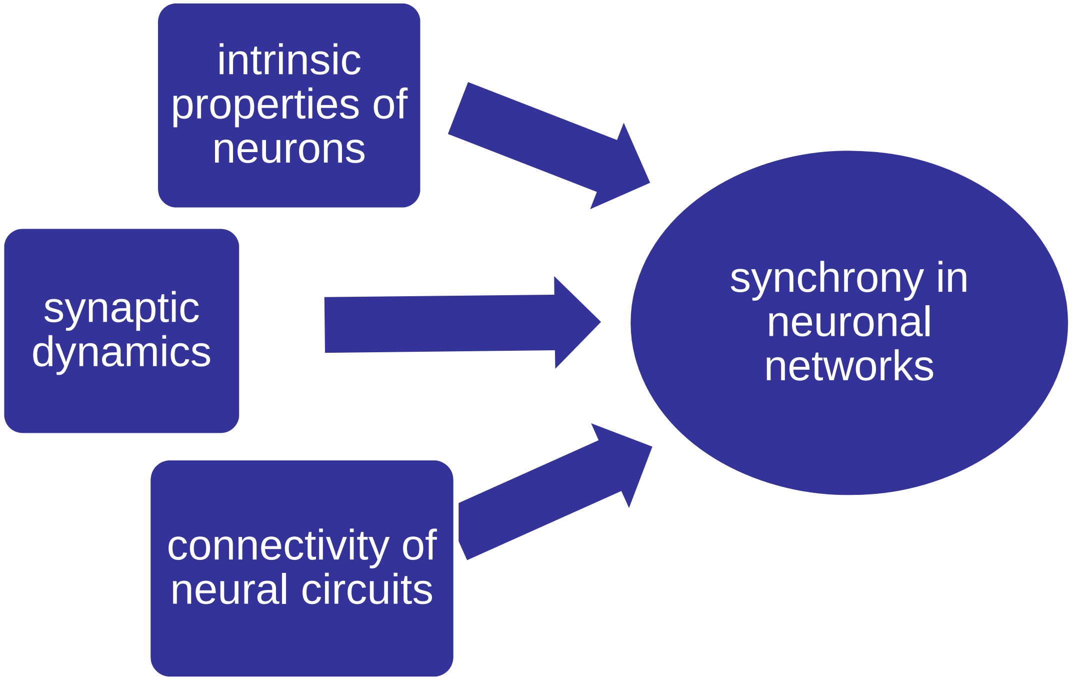
iv. appropriate assessment of chance correlations.

v. higher order correlations (temporally and spatially)



Swadlow, et al.

# 2. identify mechanisms underlying synchrony



intrinsic properties of neurons

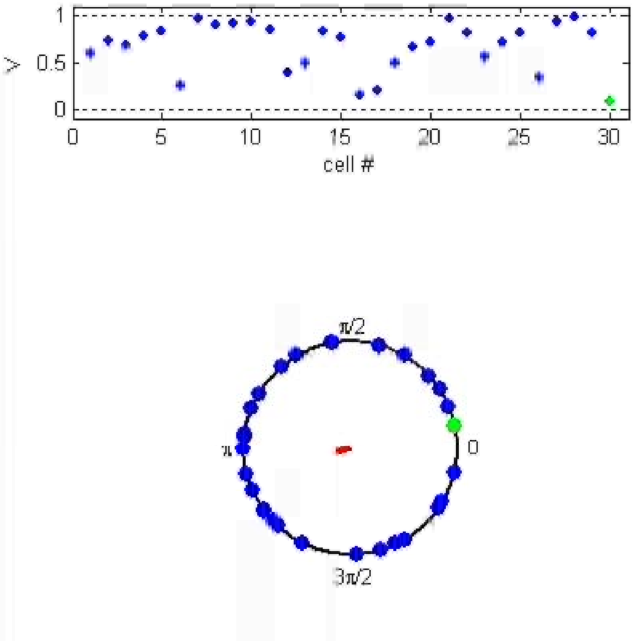
synaptic dynamics

connectivity of neural circuits

synchrony in neuronal networks

# [mechanism A] synchrony in *networks of neuronal oscillators*

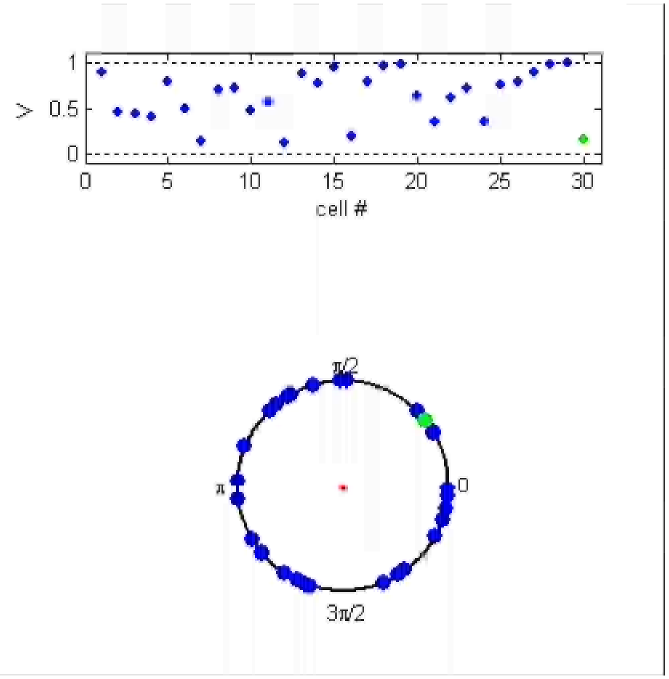
“fast” excitatory synapses



**synchrony**

**movie:**
**LIFfastEsynch.avi**

“slow” excitatory synapse



**asynchrony**

**movie:**
**LIFslowEasynch.avi**

# [mechanism A] synchrony in networks of neuronal oscillators

**Some basic mathematical frameworks:**

**1. phase models (e.g. Kuramoto model)**

$$\frac{d\theta_j}{dt} = \omega_j + H_j(\theta_1, \ldots, \theta_N), \quad j = 1, \ldots, N$$

$$= \omega_j + \sum_{k=1}^{N} w_{kj} H(\theta_k - \theta_j) \qquad \theta_j \in [0,1)$$

## [mechanism A] synchrony in networks of neuronal oscillators

**Some basic mathematical frameworks:**

**2. theory of weak coupling** (Malkin, Neu, Kuramoto, Ermentrout-Kopell, …)

$$\frac{d\theta_j}{dt} = \omega_j + \sum_{k=1}^{N} w_{kj}\,\frac{1}{T}\int_0^T Z(\tilde{t} + \phi_j T)\,\tilde{I}_{syn}\Big(V_o\big(\tilde{t} + \phi_k T\big)\Big)d\tilde{t}\,, \qquad j = 1,\ldots,N$$

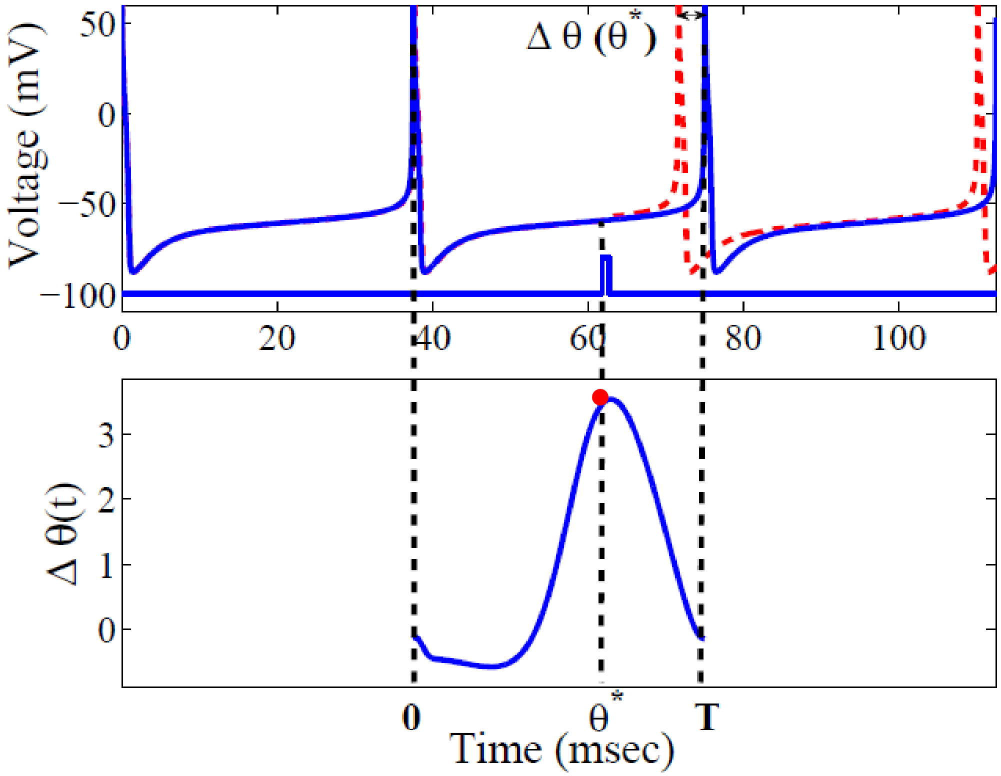
$$= \omega_j + \sum_{k=1}^{N} w_{kj} H(\theta_k - \theta_j)$$

**iPRC**

**synaptic current**

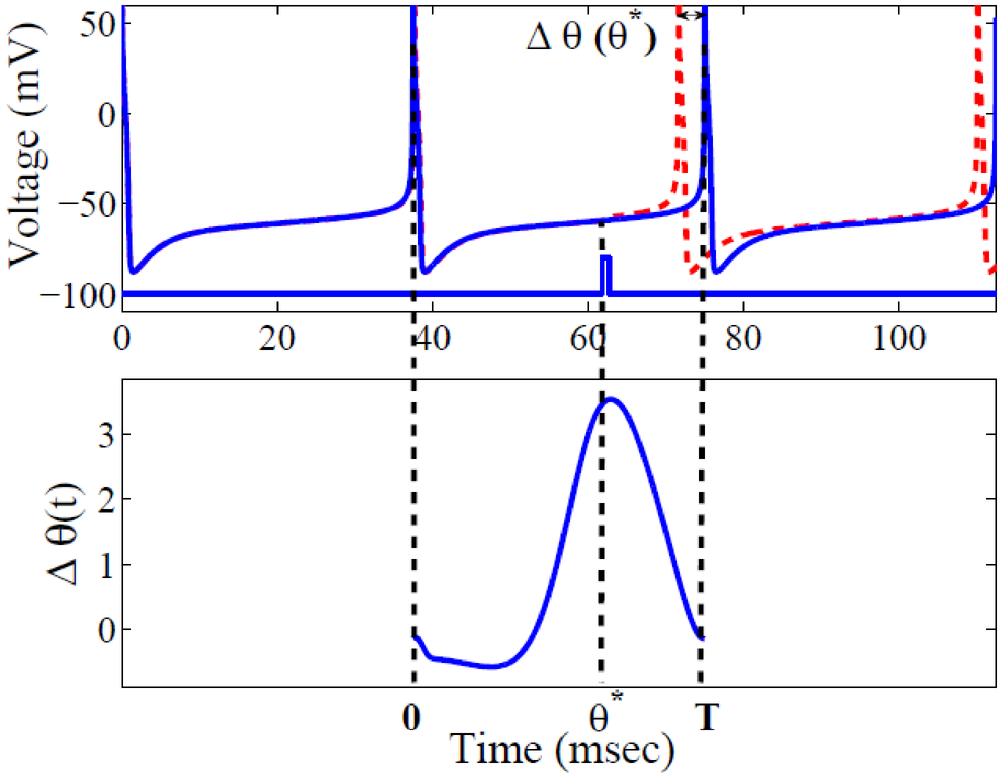
# **phase response curve (PRC)** $\Delta\theta(\theta)$

quantifies the phase shifts in response to ***small,* brief (δ-function)** input at different phases in the oscillation.



# infinitesimal phase response curve (iPRC) $\mathcal{Z}(\theta)$

the PRC **normalized by the stimulus "amplitude" (**i.e. total charge delivered).



## [mechanism A] synchrony in networks of neuronal oscillators

**Some mathematical frameworks:**

**2. spike-time response curve (STRC) maps**

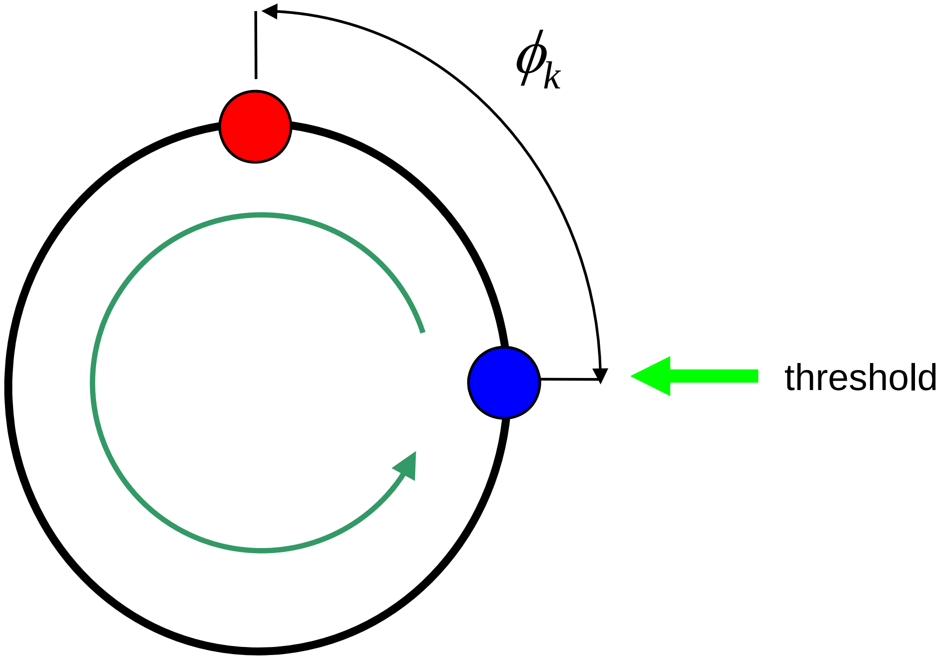
$$\phi_{k+1} = \phi_k + \Delta\theta(1-\phi_k) + \Delta\theta(\phi_k + \Delta\theta(1-\phi_k))$$

$\phi_k =$ phase difference between pair of coupled neurons when neuron 1 fires for the *k*th time.

$\Delta\theta(\theta) =$ phase response curve for neuron for a given stimulus..

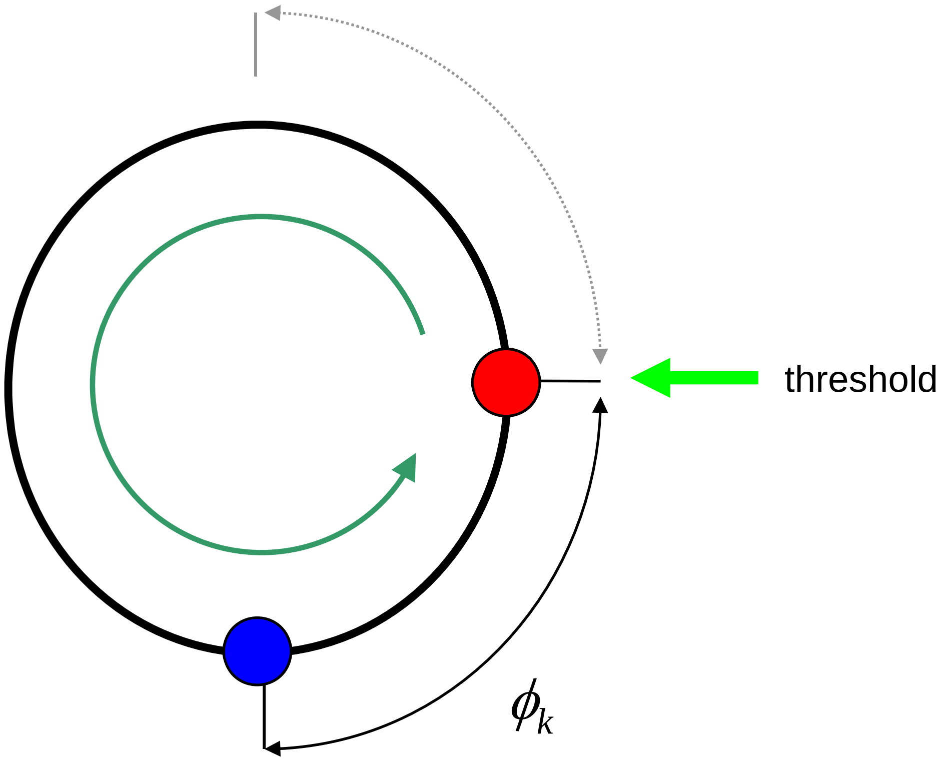
## pair of coupled cells: reduction to 1-D map

blue cell has just been reset after crossing threshold.



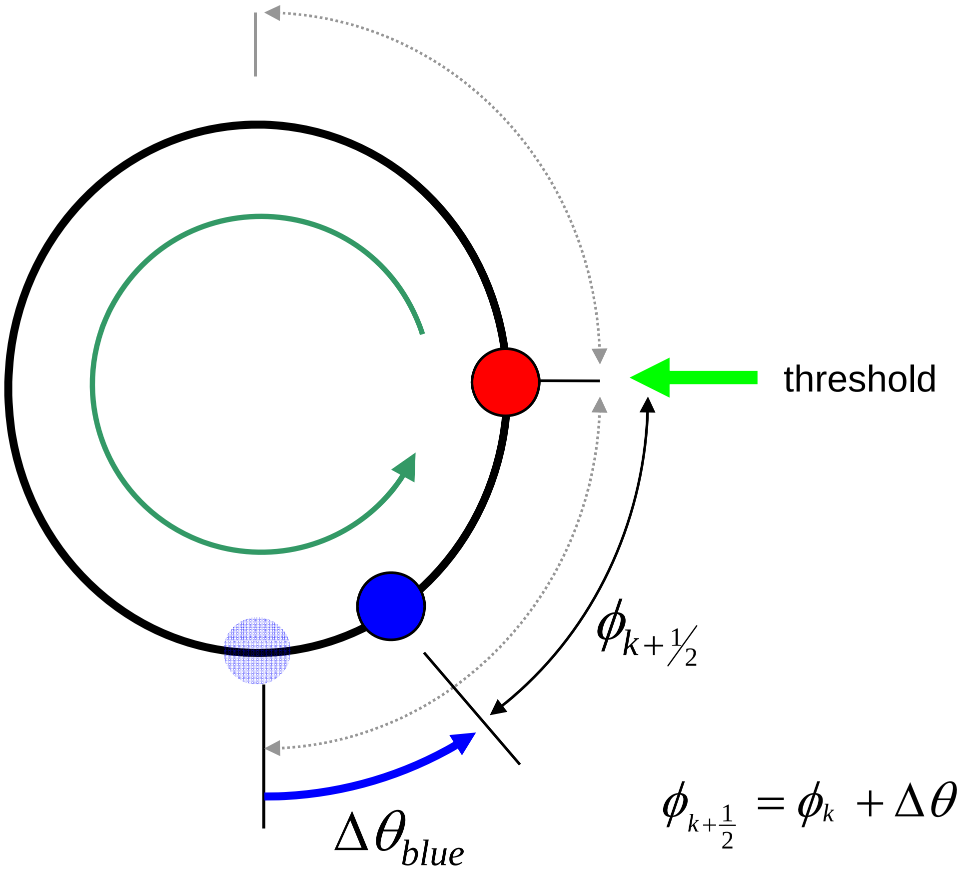
## pair of coupled cells: reduction to 1-D map

red cell hits threshold.



# pair of coupled cells: reduction to 1-D map

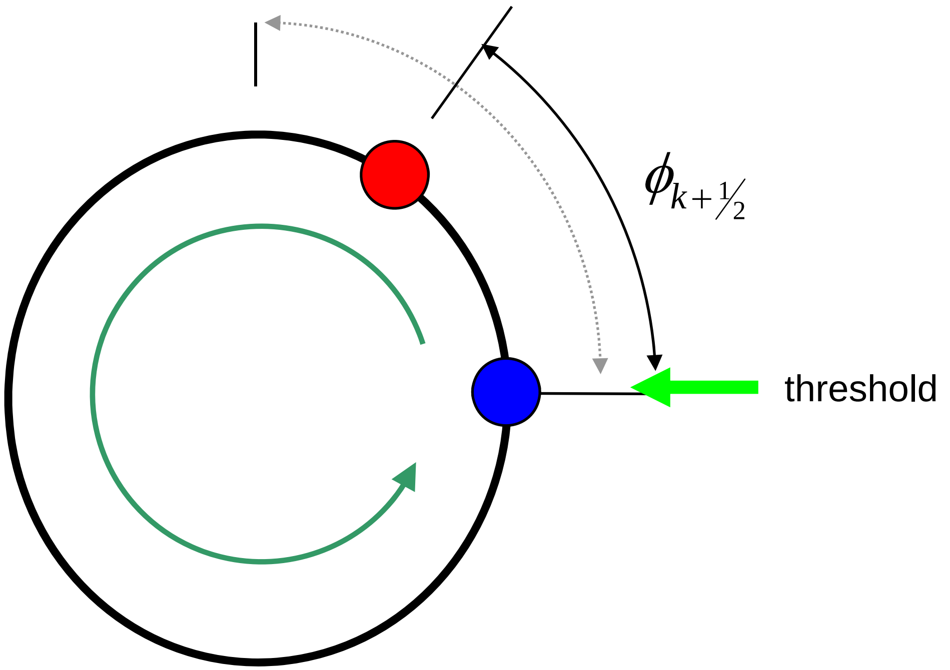
blue cell is phase advanced by synaptic input
from red cell; red cell is reset.



$$\phi_{k+\frac{1}{2}} = \phi_k + \Delta\theta(1-\phi_k)$$

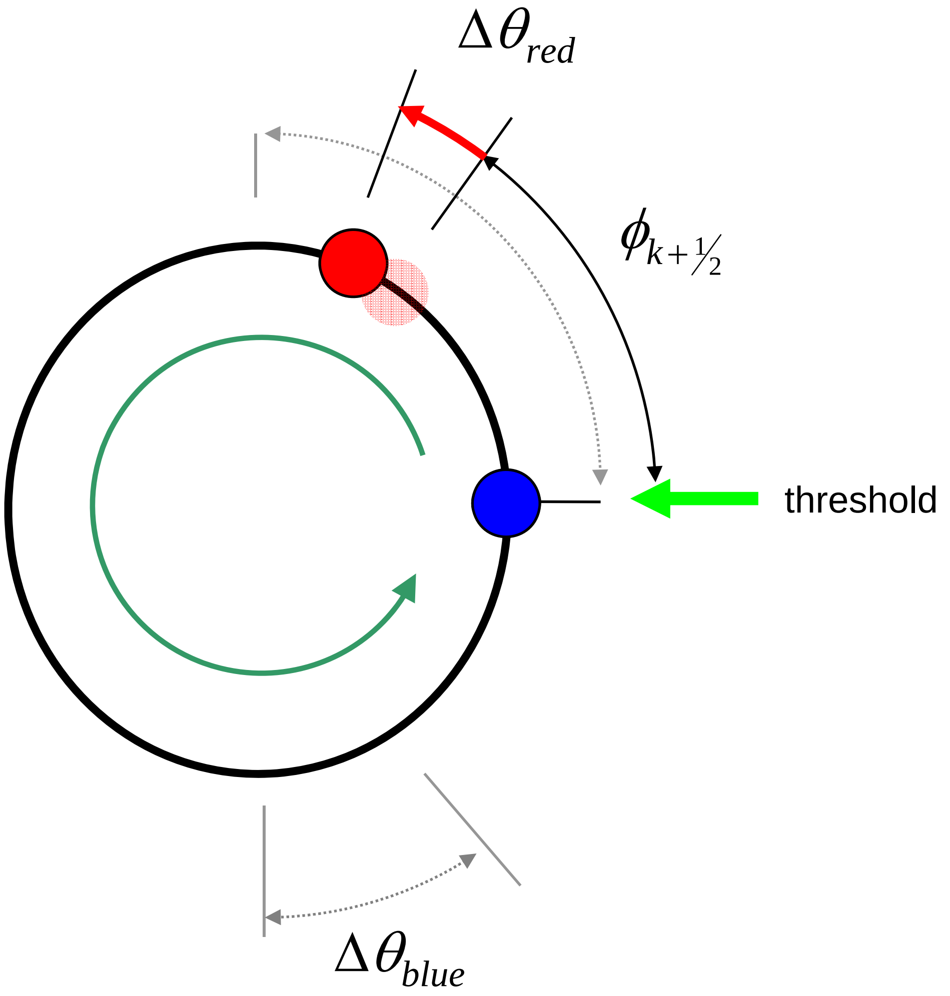
# pair of coupled cells: reduction to 1-D map

blue cell hits threshold.

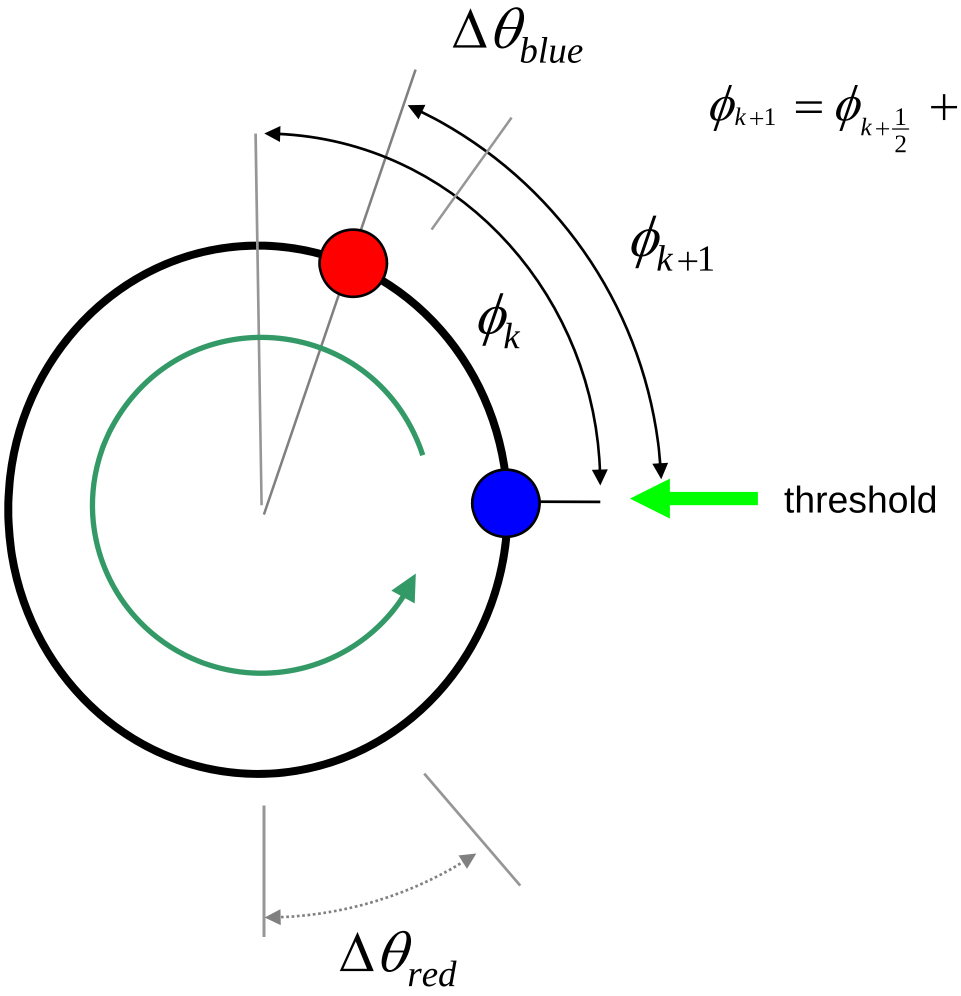


# pair of coupled cells: reduction to 1-D map

red cell is phase advanced by synaptic input from blue cell; blue cell is reset.



# pair of coupled cells: reduction to 1-D map



$$\phi_{k+1} = \phi_{k+\frac{1}{2}} + \Delta\theta(\phi_{k+\frac{1}{2}})$$

# pair of coupled cells: reduction to 1-D map

(similar to Strogatz and Mirillo, 1990)

$$\phi_{k+\frac{1}{2}} = \phi_k + \Delta\theta(1-\phi_k)$$

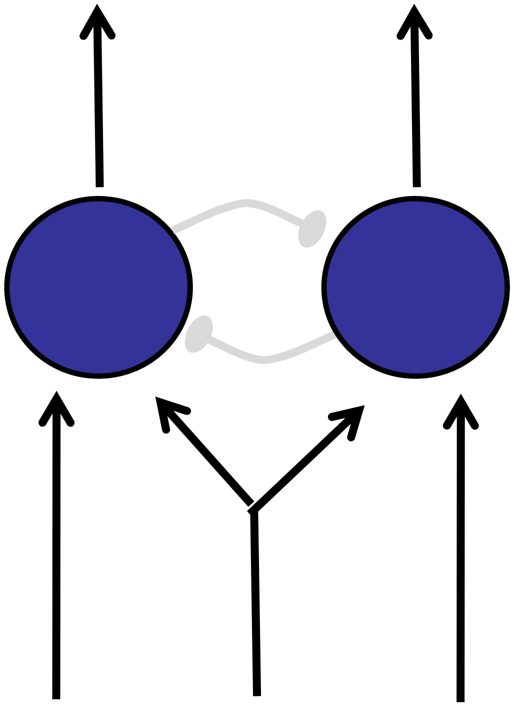
$$\phi_{k+1} = \phi_{k+\frac{1}{2}} + \Delta\theta(\phi_{k+\frac{1}{2}})$$

↓

$$\phi_{k+1} = \phi_k + \Delta\theta(1-\phi_k) + \Delta\theta(\phi_k + \Delta\theta(1-\phi_k))$$

* shape of Z determines phase-locking dynamics

# **[mechanism B] correlated/common input into oscillating or excitable cells** (i.e., the neural Moran effect)

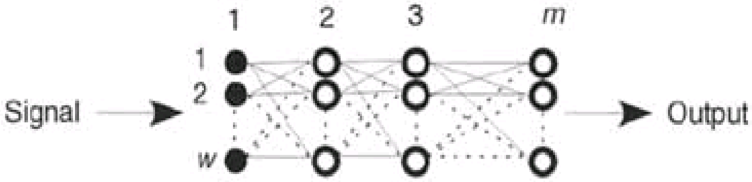


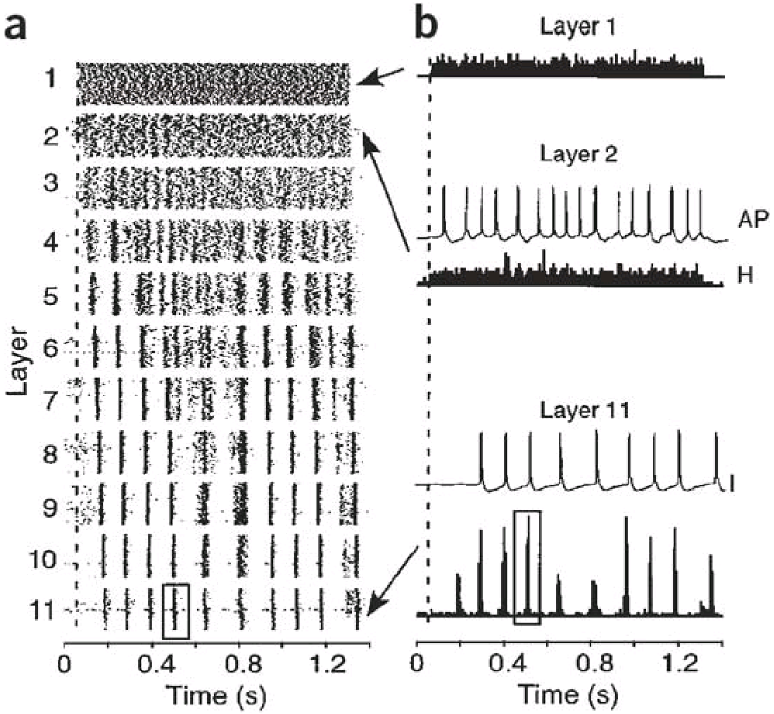
output

… possible network coupling too

input

# [mechanism C] self-organized activity in networks of excitable neurons: feed-forward networks



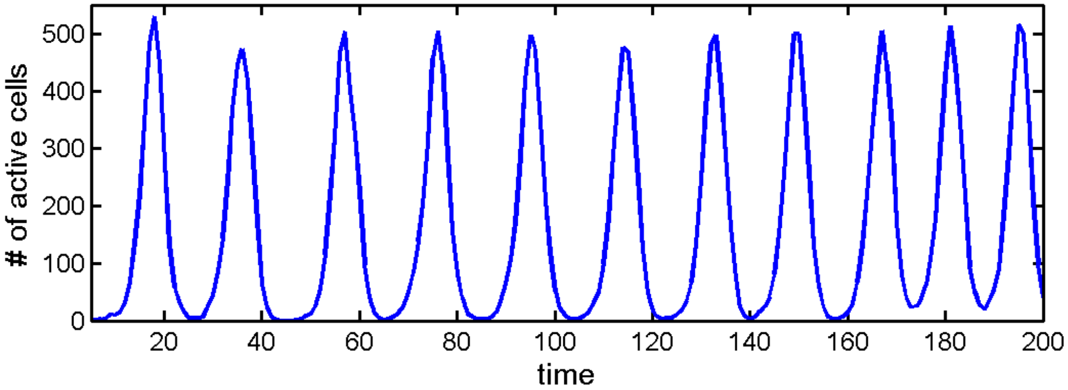


e.g. AD Reyes, *Nature Neurosci* 2003

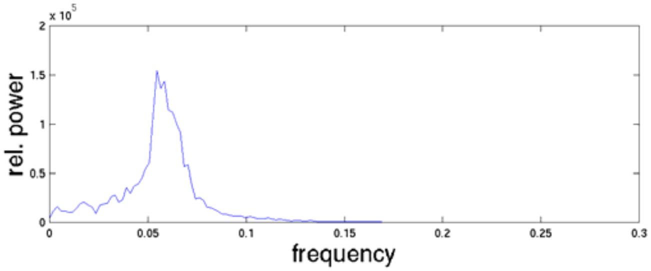
# [mechanism C] self-organized activity in networks of excitable neurons: random networks

## (i) Topological target patterns

units: excitable dynamics with low level of random spontaneous activation (Poisson process);
network connectivity: sparse (Erdos-Renyi) random network; strong bidirectional coupling.



$\lambda$=0.0001, 75x50 network, $r_c$=50, c=0.37

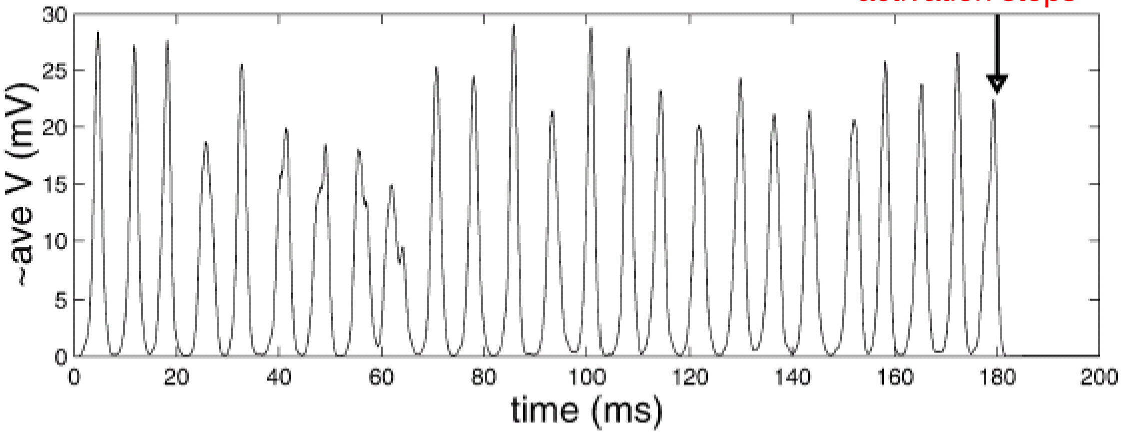


**movie: topotargetoscill.avi**

e.g. Lewis & Rinzel, *Network: Comput. Neural Syst.* 2000

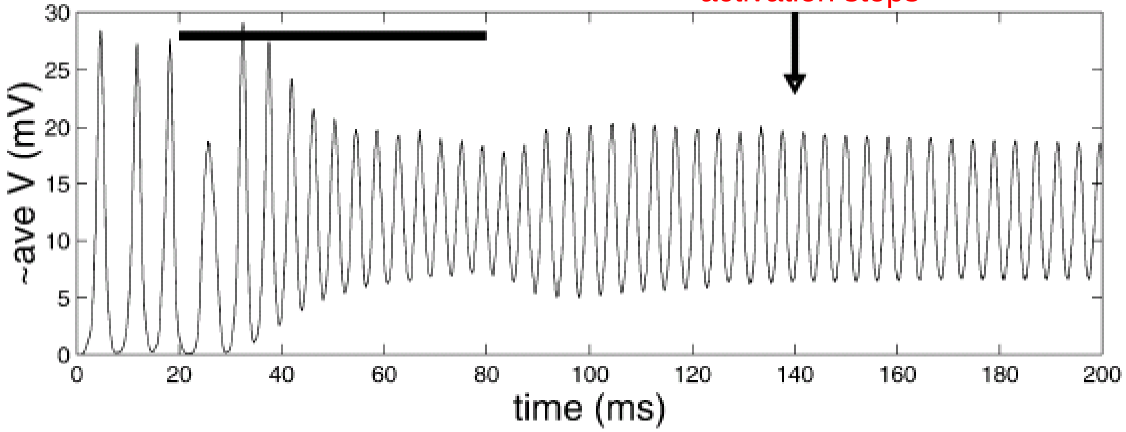
# [mechanism C] self-organized rhythms in networks of excitable neurons

spontaneous random activation stops



**(i) *topological* target patterns waves**

spontaneous random activation stops



**(ii) reentrant waves**

e.g. Lewis & Rinzel, *Neuroomput.* 2001

# Conclusions / Discussions / Open questions