Manipulation of Spatio-temporal Patterns in Networks of Relaxation Electrochemical Oscillators

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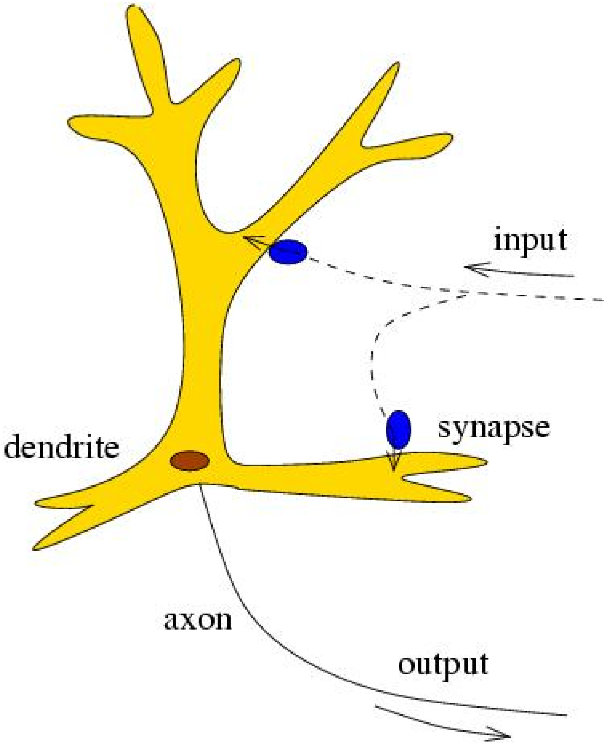
PART I

Electrochemical and Physiological Systems

An Amateur's Approach to Neurophysiology...

Hoppensteadt & Izhikevich, *Weakly Connected Neural Networks* (1997)

- Neurons are *cells* consisting of a *body* (soma), *dendrites* and an *axon* (not all neurons)
- Neurons generate *action potentials* (spikes) which propagate along the axon (not all neurons)
- Neurons *communicate* via action potentials
- Neurons are *functionally polarized* (not always)
- The junctions between the axon of one neuron and the dendrite of another is called *synapse* (chemical or electrical)
- A neuron or synapse can be *excitatory* (facilitates action potentials) or *inhibitory* (impedes action potentials)



Neural Oscillators: Wilson-Cowan Model

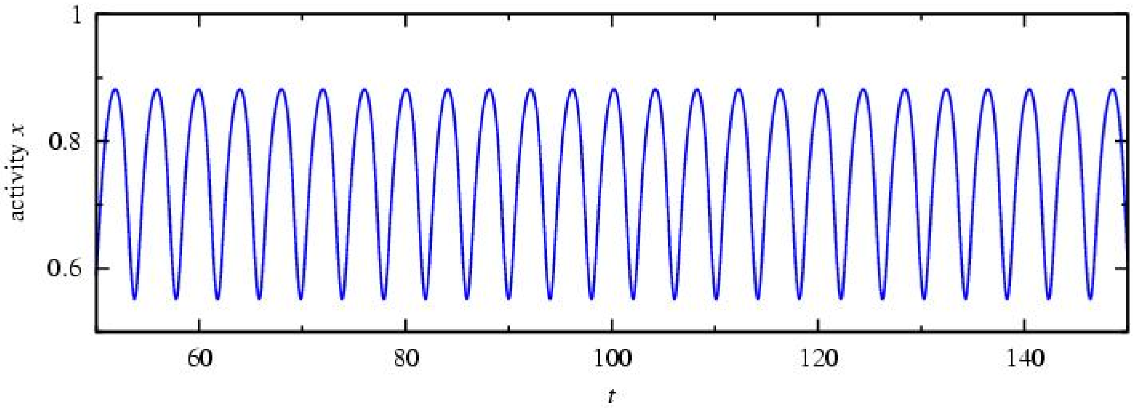
Kybernetik **13** (1973) 55

Consider an interconnected pair of an excitatory and an inhibitory neuron...

$$\dot{x} = -x + S(\rho_{\mathrm{x}} + ax - by) \tag{1}$$

$$\dot{y} = -y + S(\rho_{\mathrm{y}} + cx - dy) \tag{2}$$

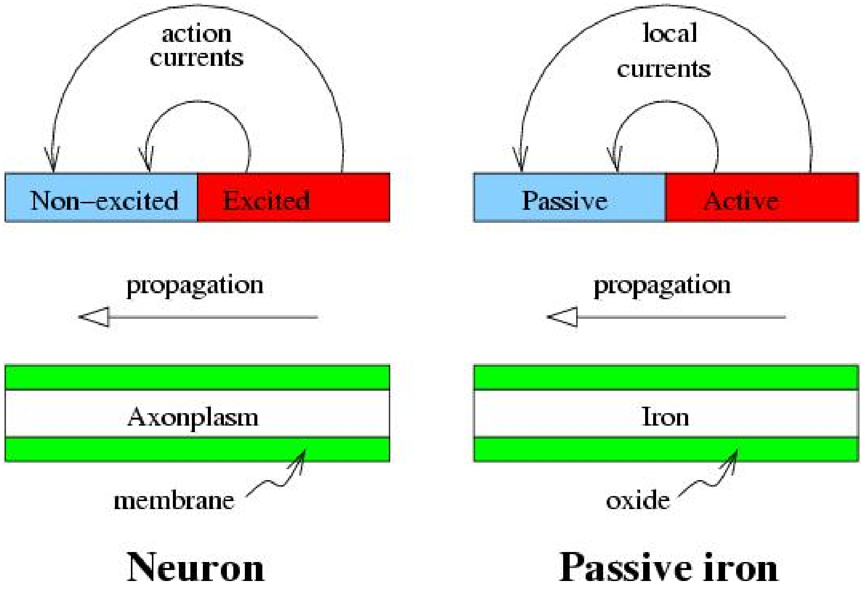
where, $S = \frac{1}{1+e^{-x}}$ and x, y the "activities" of each neuron.



$\rho_{\mathrm{x}} = 0.5$, $\rho_{\mathrm{y}} = -8$, $a = 10$, $b = 10$, $c = 10$, $d = -2$.

Ostwald model: From Neurons to Electrochemistry

Z. Phys. Chem. **35** (1900) 333, *Prog. Biophys. Chem.* **6** (1956) 171.



- The electrochemical interface is a membrane permeable to some of the components but not to others (V.G. Levich, *Physicochemical Hydrodynamics*, 1962).
- One of the oscillatory variables is electrical in nature (*Angew. Chem.* **17** (1978) 1).
- Non-excited (silent/passive) electrodes can activate when coupled with active electrodes (*J. Gen. Physiol.* **3** (1920) 107, *J. Gen. Physiol.* **7** (1925) 473).

Electrochemical Rhythmic Activity

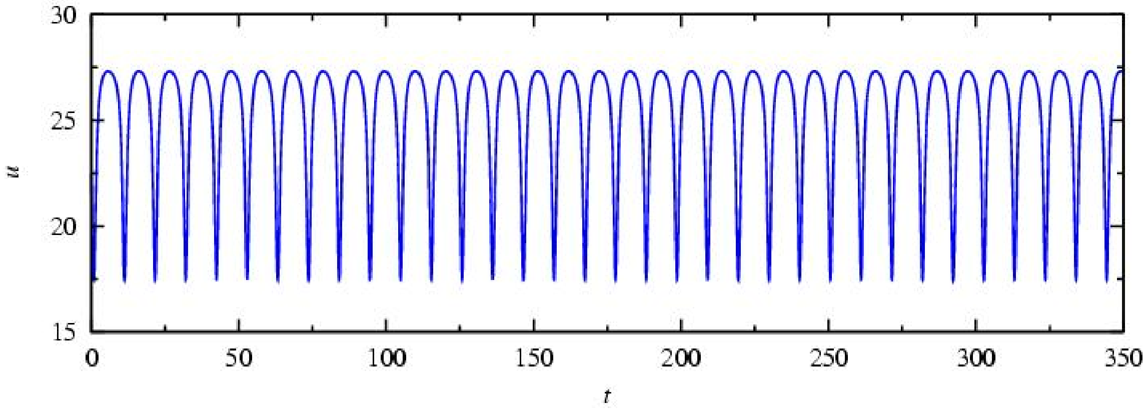
Chem. Phys. Lett. **347** (2001) 133.

Consider an electrochemical interface where ions are produced due an electrochemical *reaction* and transported due *diffusion* and *migration*, (or watch the movie)

$$\varepsilon \dot{u} = \sigma(v-u) - f(u,c), \tag{3}$$

$$\dot{c} = 1 - c - \sigma(v-u) + \alpha f(u,c), \tag{4}$$

where , $f(u,c) = c(a_1 u + a_2 u^2 + a_3 u^3)$.

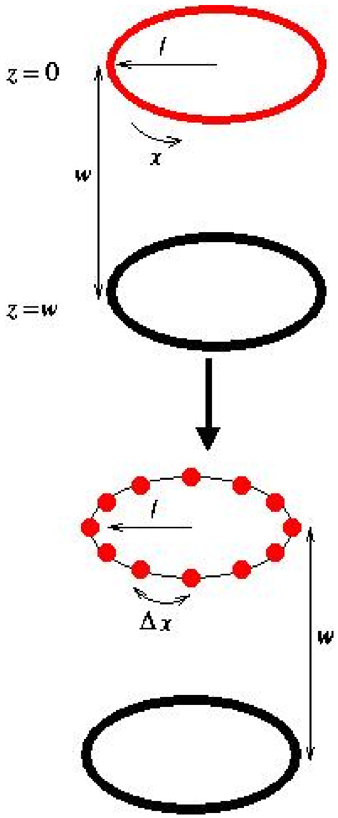


$\sigma = 0.1$, $\varepsilon = 0.055$, $\alpha = 0.1$, $V = 29.27$ and $a_1 = 1.125$, $a_2 = -0.075$, $a_3 = 0.00125$.

PART II

Networks of Excitatory Electrochemical Oscillators

Ring Networks: Formulation



Continuous case:

$$\frac{\partial c_m}{\partial t} = D_m \nabla^2 c_m + n_m F \gamma_m \nabla (c_m \nabla \Phi), \tag{5}$$

with boundary conditions,

$$j_{\mathrm{F},m} + j_{\mathrm{C},m} = -D_m \frac{\partial c_m}{\partial z}\Big|_{z=0} - n_m F \gamma_m c_m \frac{\partial \Phi}{\partial z}\Big|_{z=0}, \tag{6}$$

$$c_m(x, y, z = w, \tau) = c_{\mathrm{b},m}, \tag{7}$$

$$\Phi(x, y, z = w, t) = 0, \tag{8}$$

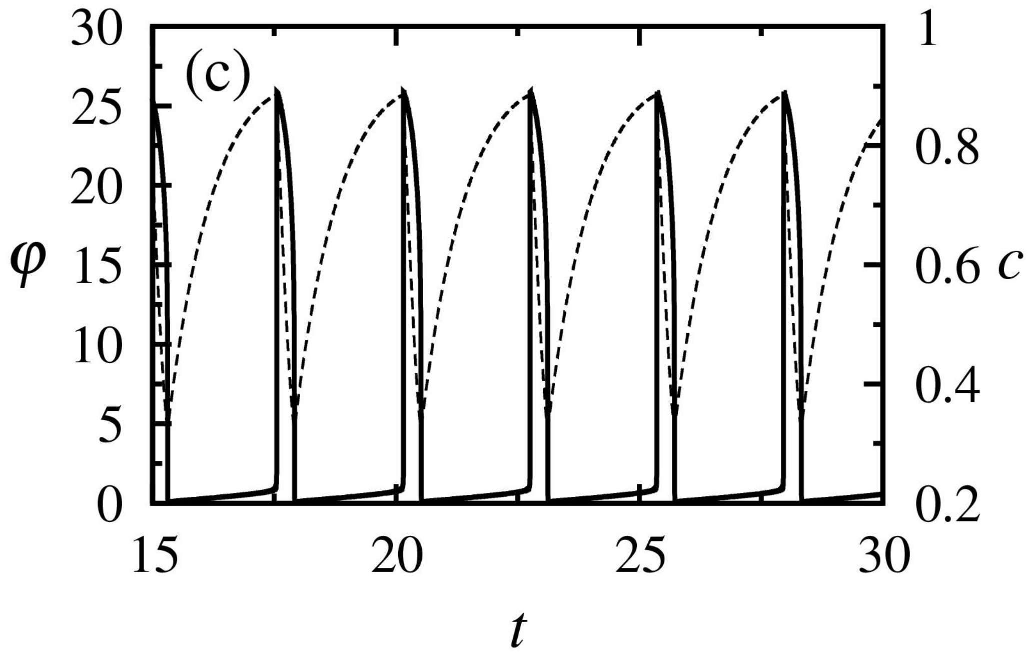
Discrete case:

$$\varepsilon \frac{du^{(k)}}{dt} = \frac{\sigma}{\beta}(v - u^{(k)}) - i_{\mathrm{F}}(u^{(k)}, c^{(k)}) + \frac{\sigma\beta}{3h} \sum_{\substack{m=[k-1] \\ m \neq k}}^{[k+1]} (u^{(m)} - u^{(k)}), \tag{9}$$

$$\frac{dc^{(k)}}{dt} = 1 - c^{(k)} - \frac{t_c \sigma}{\beta}(v - u^{(k)}) + j_{\mathrm{F}}(u^{(k)}, c^{(k)}). \tag{10}$$

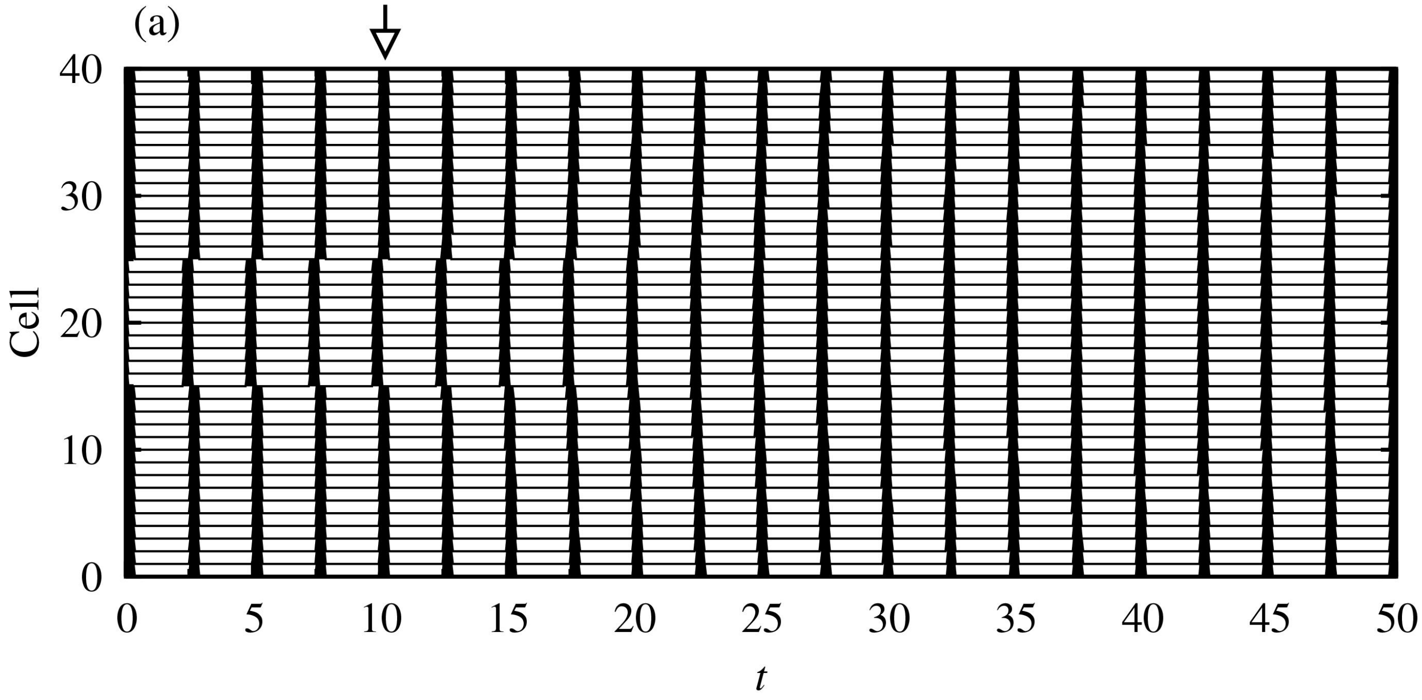
Oscillations of a Single Cell

Relaxation oscillations of the potential φ



Phase Compensation

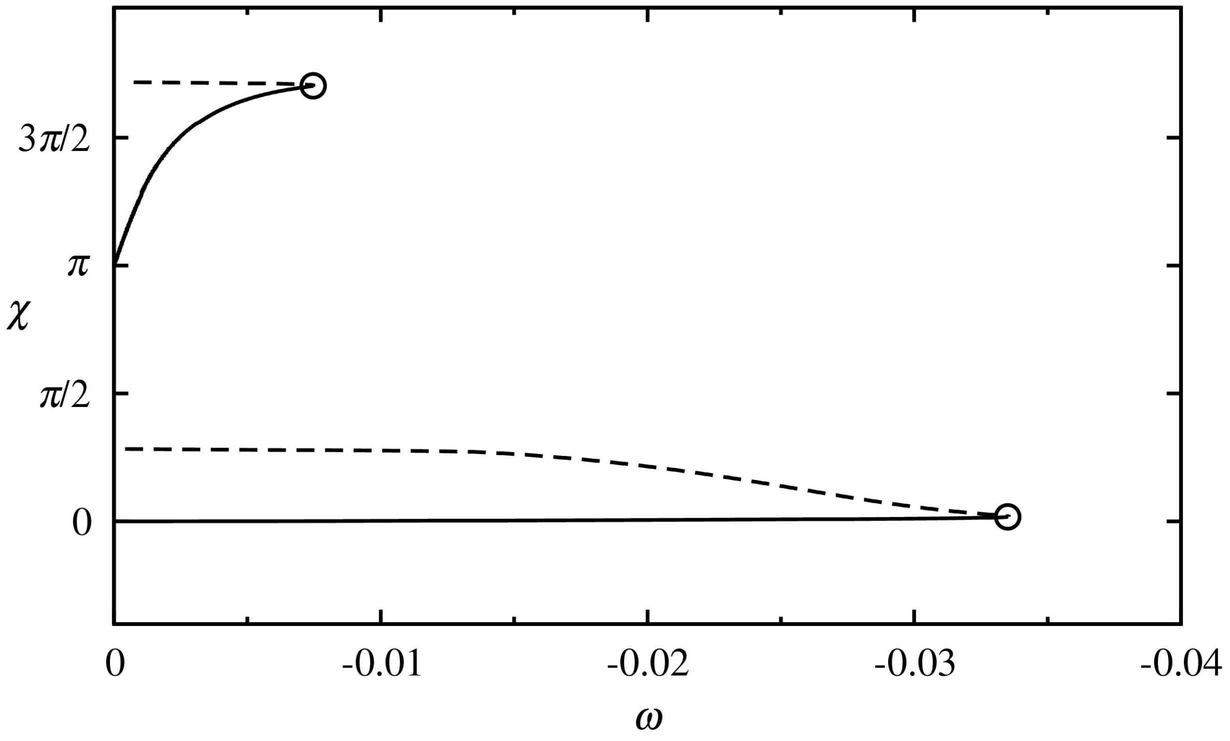
Group $\{16\text{-}25\}$ oscillates with 0.2π phase difference from the rest of the cells. At $t = 10$ coupling is effective



Noise reduction information processor for the in-phase state.

Period Compensation

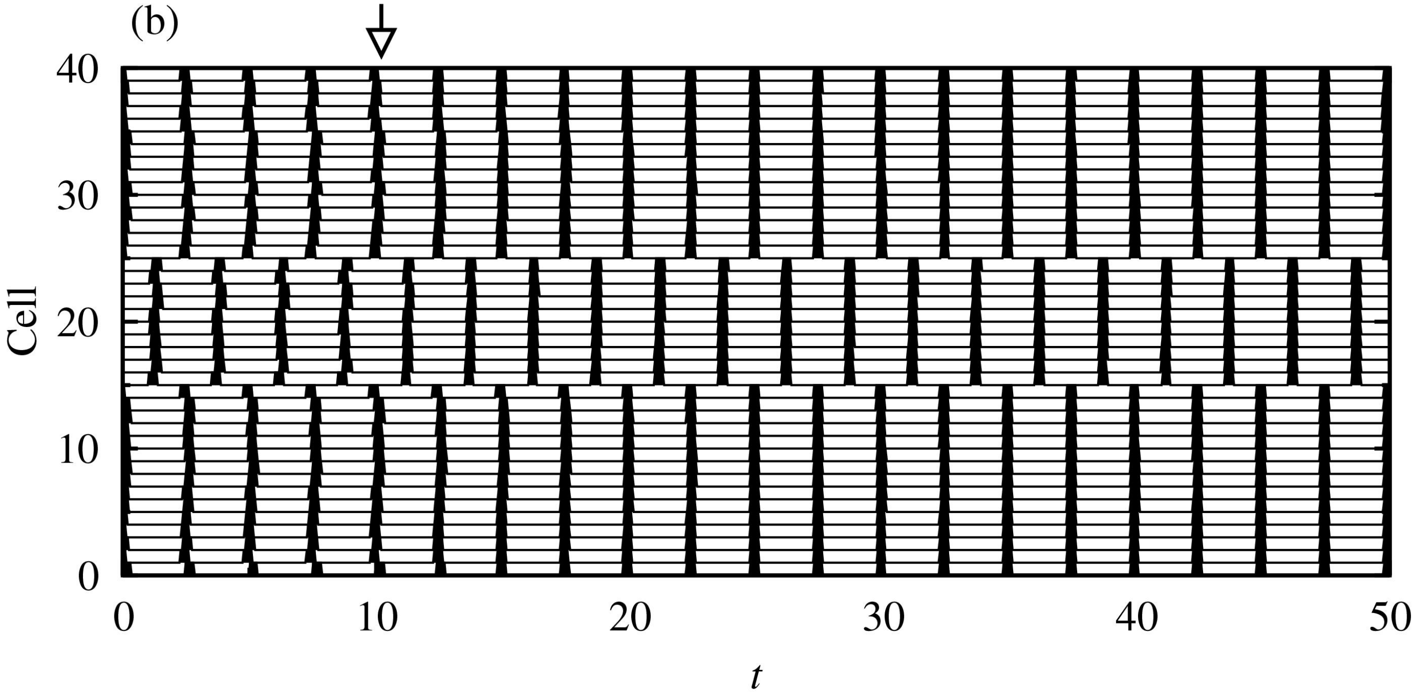
Relaxation oscillators also eliminate period differences. For small ω, non-identical oscillators synchronize rapidly in-phase



The in-phase state $(\chi = 0)$ remains over a wide range of period differences, ω.

Fractured Synchrony

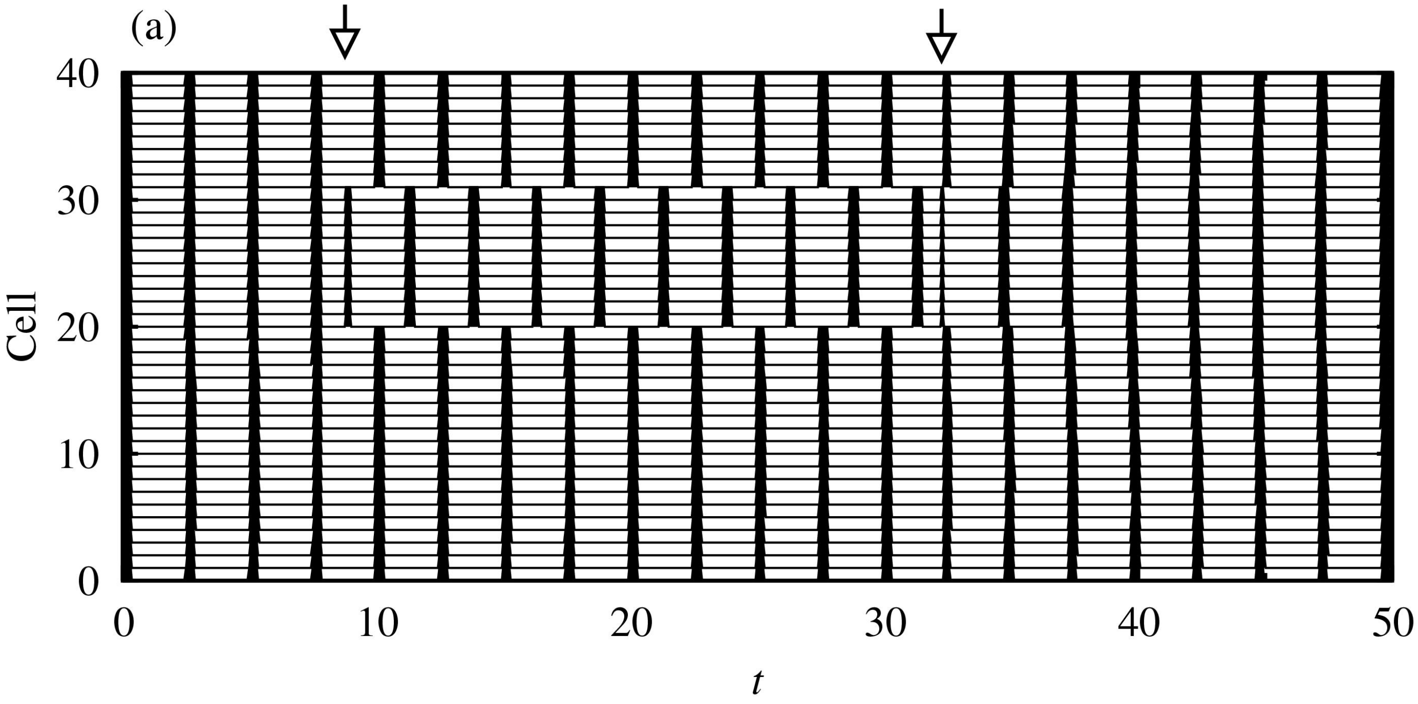
Group $\{16\text{-}25\}$ oscillates with almost π phase difference from the rest of the cells. At $t = 10$ coupling is effective



Noise reduction information processor for the anti-phase state. How about the non-relaxation case?

Effect of Perturbations: Coding and Correcting

A perturbation on the in-phase state induces anti-phase synchrony. Group {20-30} is perturbed at $t = 20$ and $t = 32.25$.

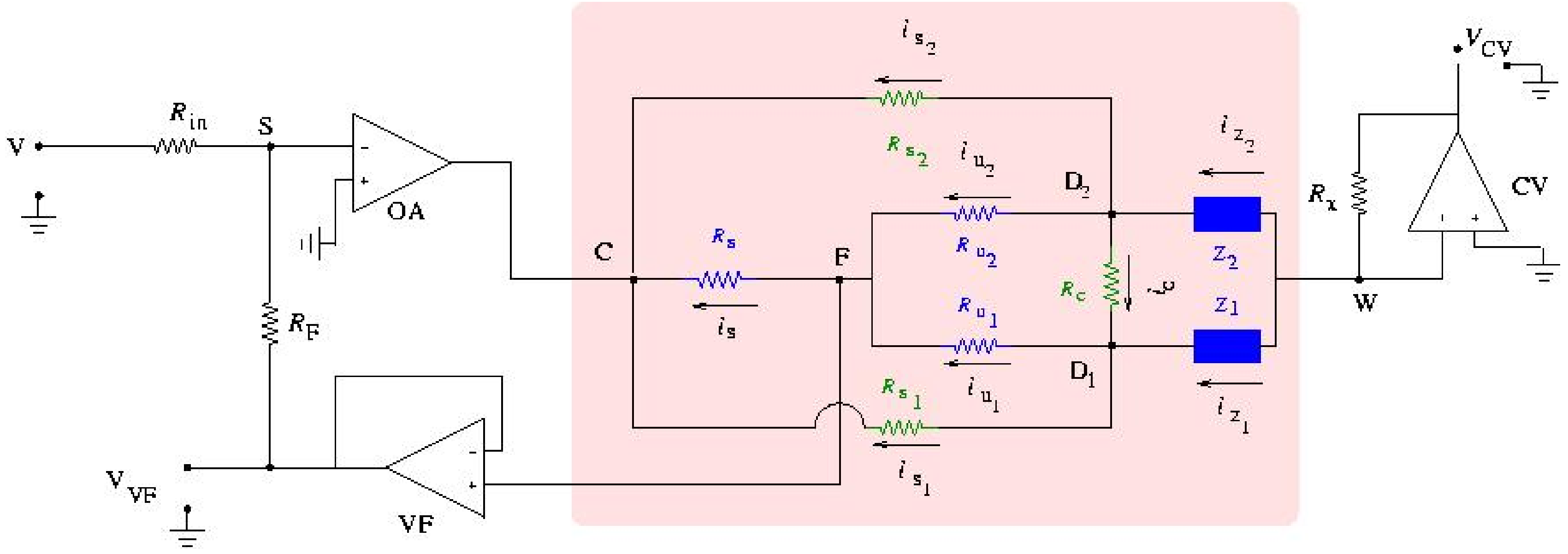


Coded information can be corrected also by perturbing a single cell.

PART III

From Excitation to Inhibition

Coupled Electrode Pairs: Formulation



If the reference electrode is a *point*, F, then we consider the "escape" currents, i_{s_1} and i_{s_2} flowing towards the counter C, without passing from F.

Coupled Electrode Pairs: The Model

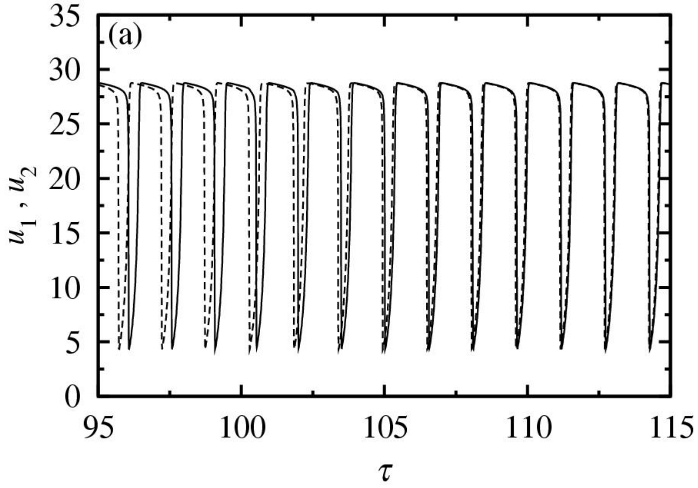
$$C_k\frac{dU_k}{dt} = \frac{V-U_k}{R_{\mathrm{u}_k}} - i_{\mathrm{e}_k}(U_k, c_k) + \frac{V-U_k}{R_{\mathrm{s}_k}} + \frac{R_\mathrm{s}}{R_{\mathrm{s}_k}}\sum_{m=1}^{2}\frac{V-U_m}{R_{\mathrm{u}m}} - \sum_{m=1}^{2}(-1)^{m+k}\frac{U_m}{R_\mathrm{c}}, \tag{11}$$

$$\frac{dc_k}{dt} = \frac{2D_k}{\delta_k^2}(c_{k,\mathrm{b}} - c_k) - \frac{2}{\delta_k F A_k}\frac{V-U_k}{R_{\mathrm{u}_k}} + \frac{2}{\delta_k F A_k} i_{\mathrm{q}_k}(U_k, c_k), \tag{12}$$

The connection can be tuned by varying R_s.

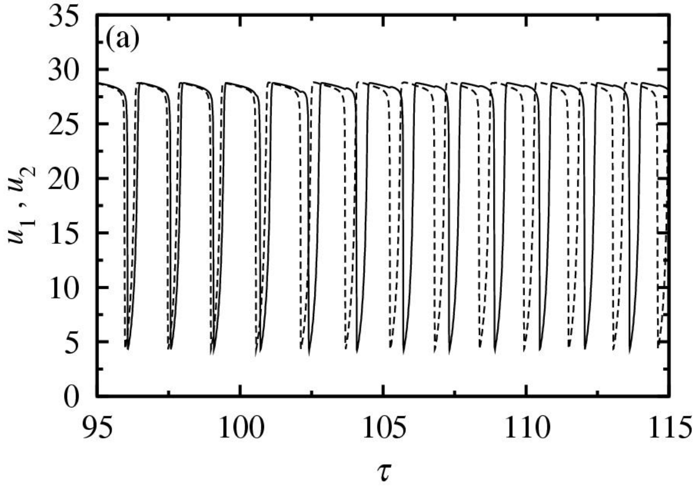
Coupling in the Oscillatory Regime

In-phase synchrony



$R_\mathrm{s} = 40$

Out-of-phase synchrony



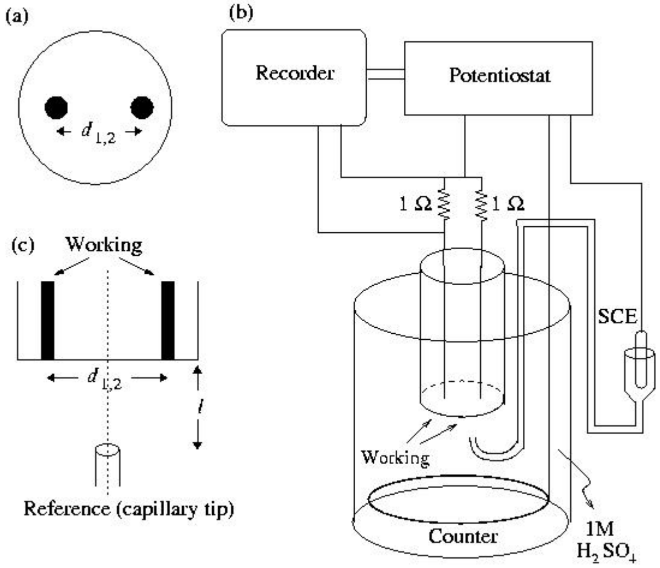
$R_\mathrm{s} = 60$

The transition can be seen in the phase space. For $t < 20$ inhibitory coupling ($R_\mathrm{s} = 60$) and for $t > 20$ excitatory coupling ($R_\mathrm{s} = 40$)

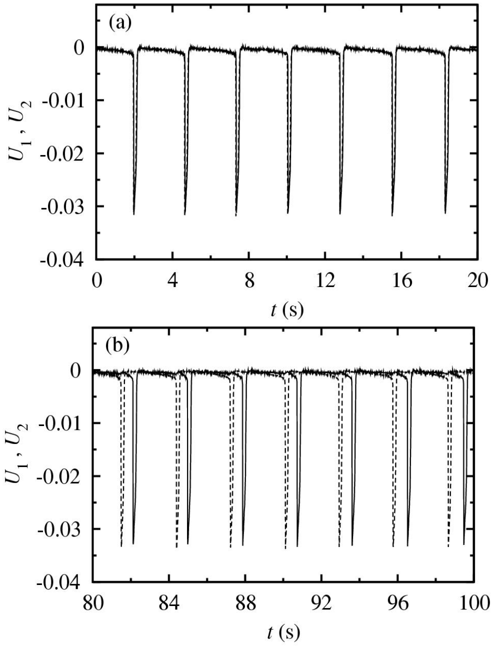
Experimental Realization

The transition from excitation to inhibition was realized experimentally by varying the position of the *reference* electrode

Experimental setup



Transitions for $l = 10$ and $l = 2$ mm



PART IV

Conclusions

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Conclusions and Open Topics

- Coupled relaxation electrochemical oscillators synchronize *rapidly* in-phase
- Relaxation electrochemical networks compensate phase and period differences
- Specific spatio-temporal patterns can be induced by appropriate perturbations
- Perturbations can *erase* and *correct* the spatio-temporal patterns
- The action of the connections (excitatory or inhibitory) can be tuned by varying the position of the reference
- Electrochemical networks can perform some primitive information manipulation tasks

Special thanks to:

Y. Miyakita (experiments, calculations, ideas), S. Nakabayashi (original idea, support, discussions), M. Pagitsas (theoretical support, formulation), G. Chryssoulakis (support) and

The Greek Secretariat of Research and Technology and the Op. P. “Com”

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