Reciprocal Coupling Effects on Synchronous Neurons

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ILLINOIS STATE UNIVERSITY
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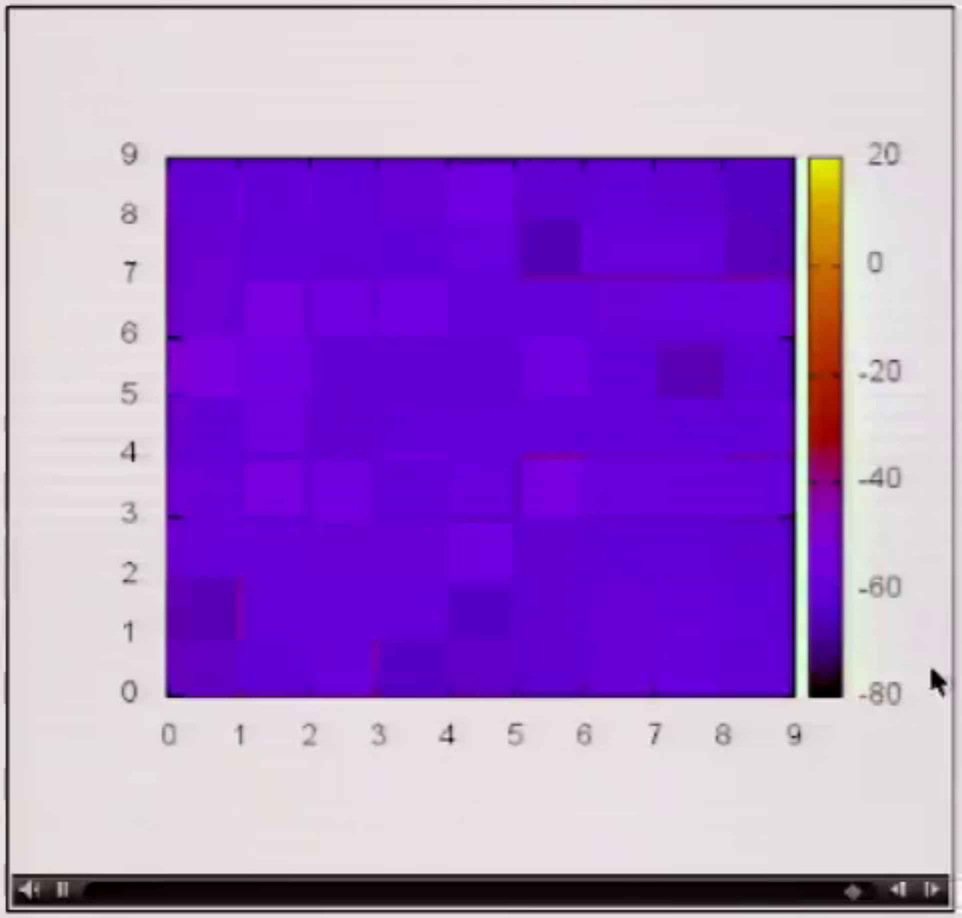
SIAM Conference on
Applications of Dynamical Systems

Preliminaries

Synchronization everywhere:

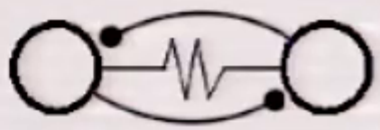
Fireflies flashing, animal populations in connected habitats, suspended bridges, marching bands, synchronized swimming, electronic devices, parallel computing, music, flash photography, metronomes, telecommunication, power grids, heartbeat and breathing, paddling in lobster and shrimp, stomatogastric nervous systems of crustaceans, brain activity (memory, perception, sleep, seizures, Parkinson's, depression, schizophrenia), and much, much more.

100 Coupled Neurons



Pair of Neurons

We are interested in understanding, in the context of synchronization, the effect that connected neurons have on each other.

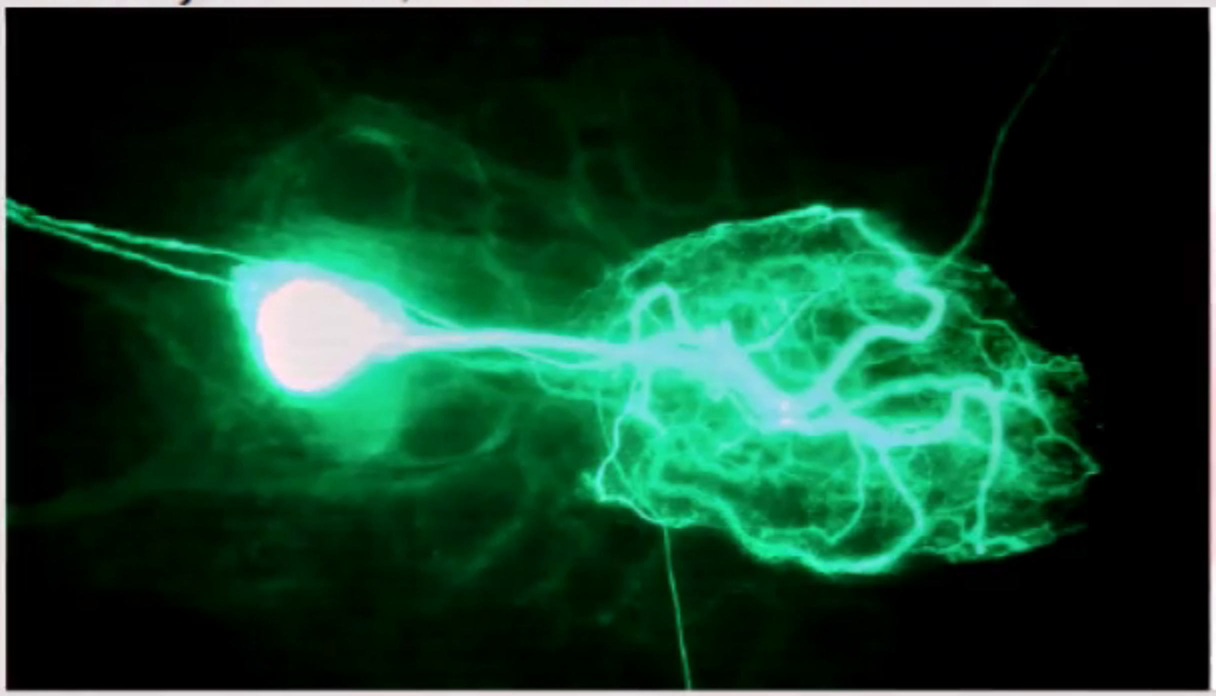


The system we look at consists of two neurons reciprocally coupled, via gap junction and chemical synapse. This pair is present in many neuronal networks, particularly in central pattern generators, and therefore are biologically relevant.

Lets first meet the single neuron.

Single Neuron

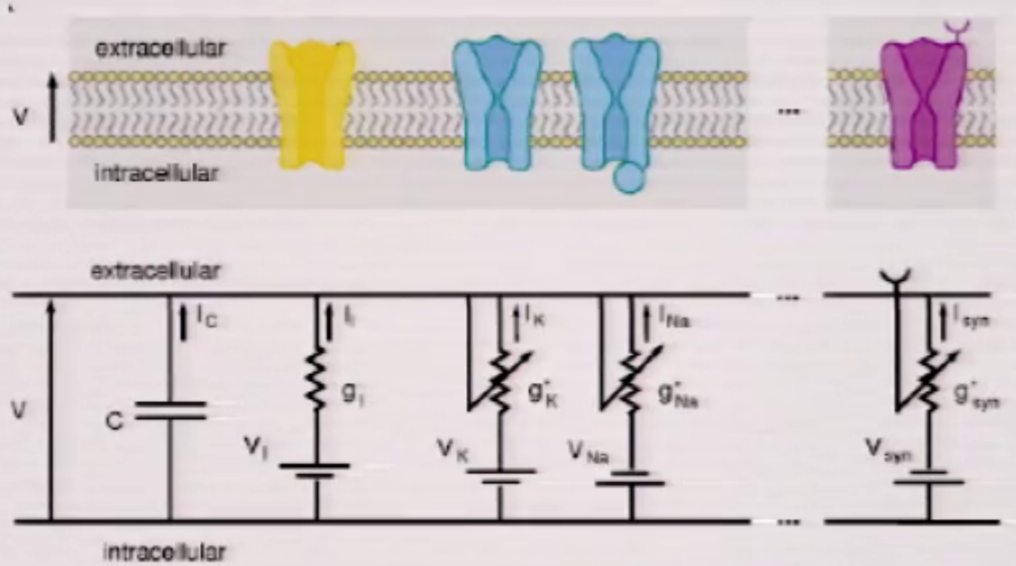
Neurons are electrically excitable cells comprised basically of soma, axon and dendrites.



Single identified neuron in the stomatogastric ganglion of the crab, after being stained with fluorescent dye (The ISU Crab Lab).

Membrane

The electrical excitability of the neuron depends on the structure of its semipermeable membrane, separating the cell interior from the extracellular liquid, and functions as a capacitor. The membrane contains channels which are represented by resistors. Nernst potentials due to the difference in ion concentrations are represented by batteries.



Hodgkin & Huxley, *J Neurophy* (1939)

Huber-Braun Model Equations

a) Membrane potential V:

$$C\frac{dV}{dt} = -I_\ell - I_d - I_r - I_{sd} - I_{sr} - I_{syn}$$

where C is the membrane capacitance, and the main currents are $I_d = \rho g_d a_{d\infty}(V - V_d)$ and $I_i = \rho g_i a_i(V - V_i)$ with $i = r, sd, sr$. The synaptic current is I_{syn}, and $I_\ell = g_\ell(V - V_\ell)$ is the leakage current.

b) Activation functions a_i with $i = r, sd$:

$$\frac{da_i}{dt} = \phi\frac{(a_{i\infty} - a_i)}{\tau_i}$$

where ϕ considers thermal effects, $a_{i\infty}$ are activation function in the continuous state, and τ_i are time constants;

c) Activation function a_{sr}:

$$\frac{da_{sr}}{dt} = \phi\frac{(-\eta I_{sd} - k a_{sr})}{\tau_{sr}}$$

where η and k are related to ions Ca^{2+}, *etc.*

Feudel *et al.*, *Chaos* (2000)

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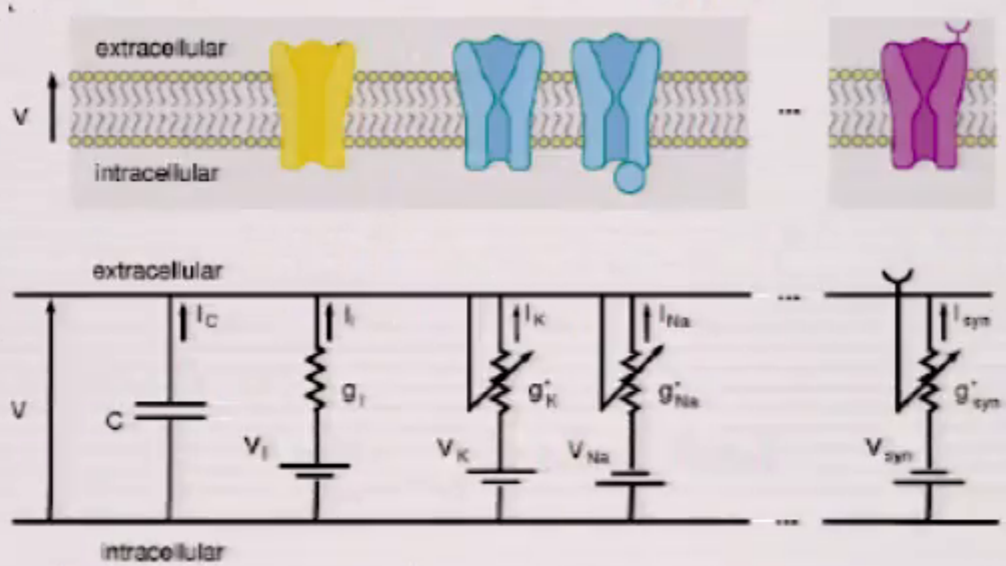

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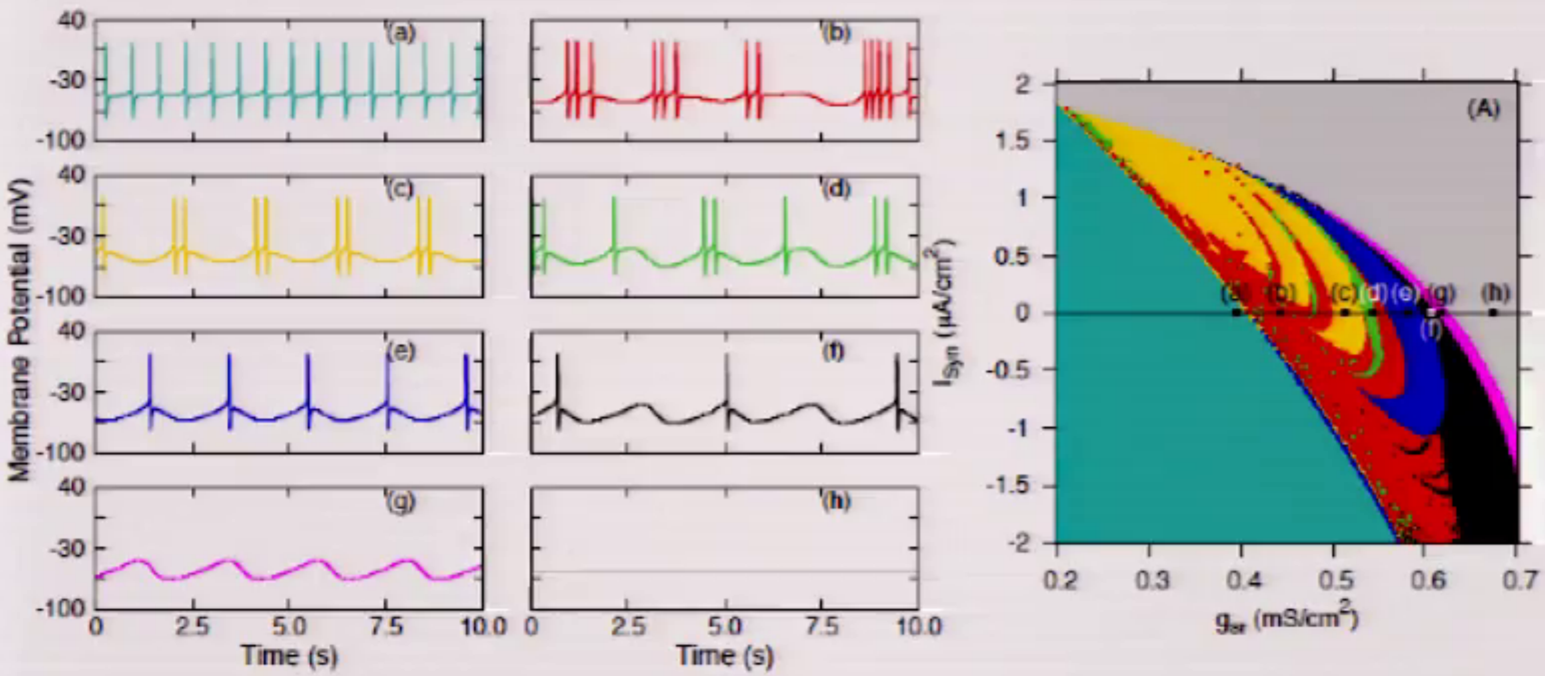
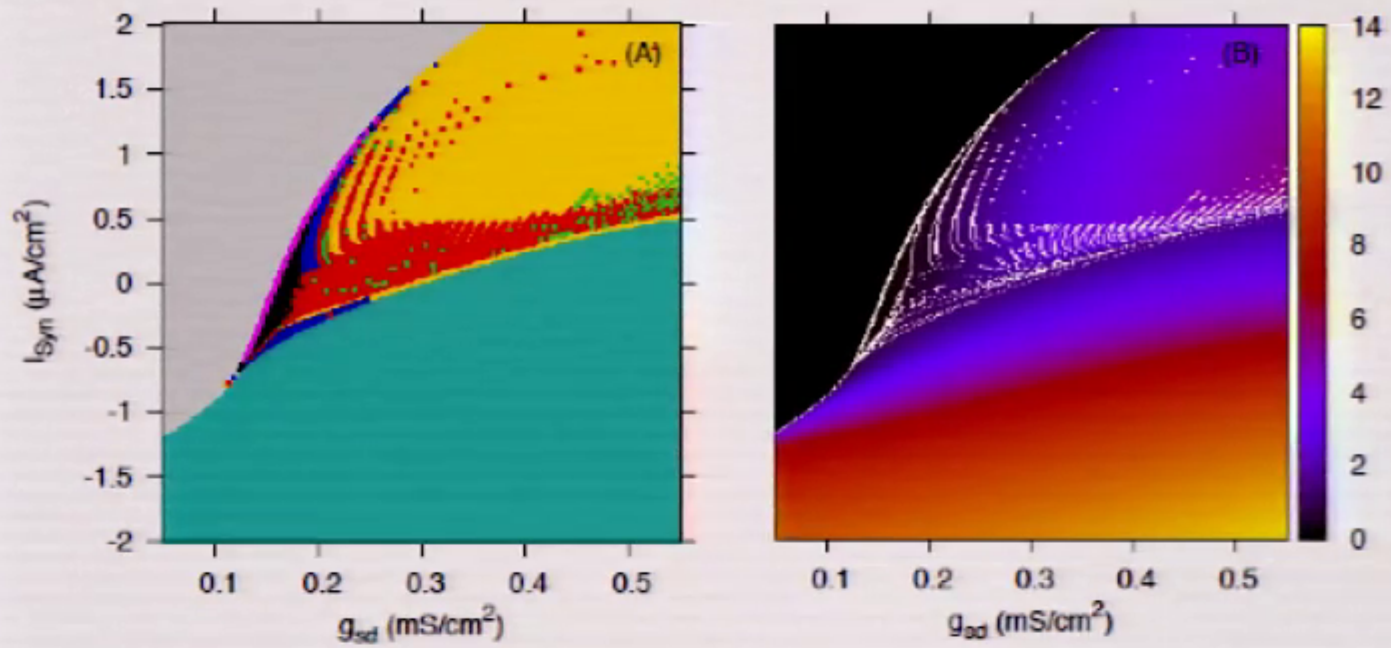
Spiking Patterns



Postnova *et al.*, *Biosystems* (2006)

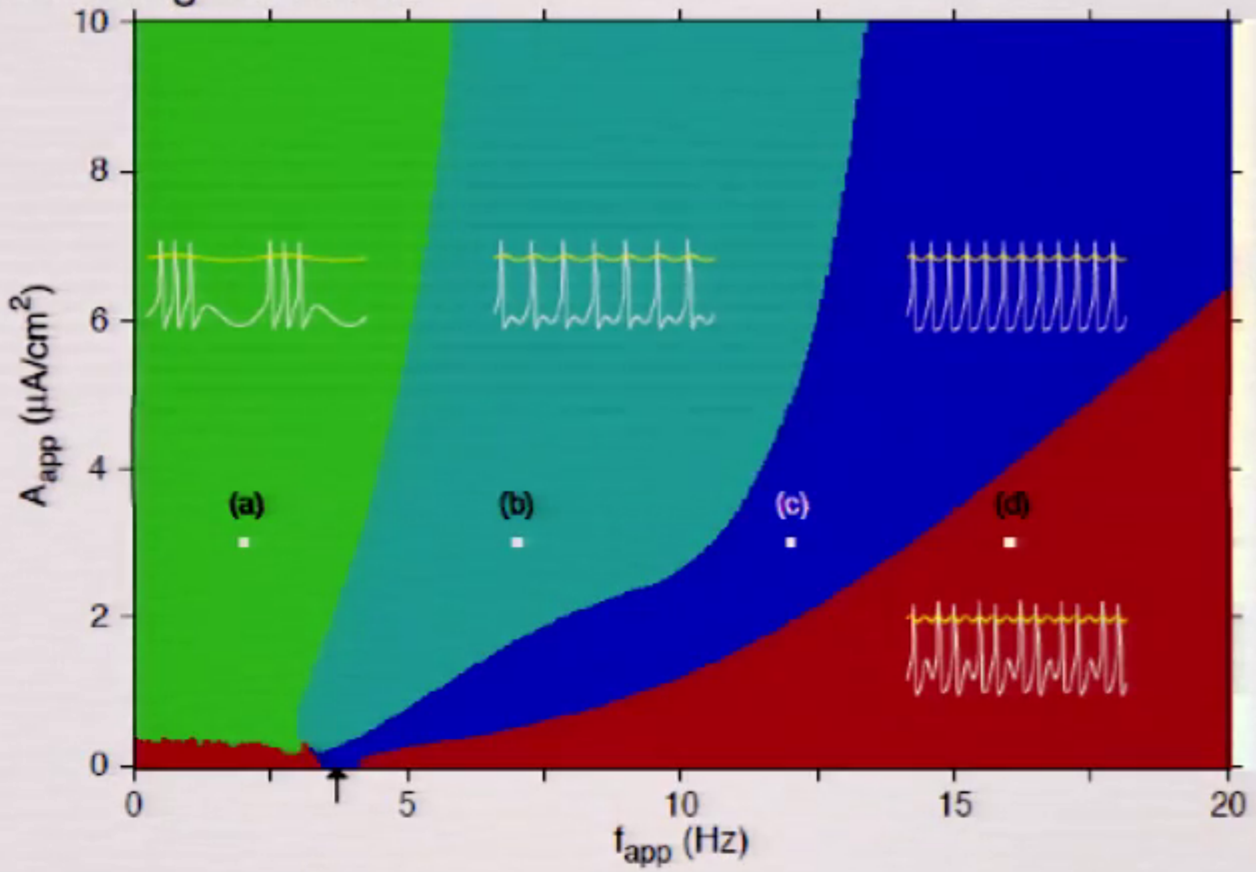
Firing Frequency

Single neuron color map for firing patterns and corresponding firing rates as a function of the synaptic input I_{syn} and the conductance g_{sd}.

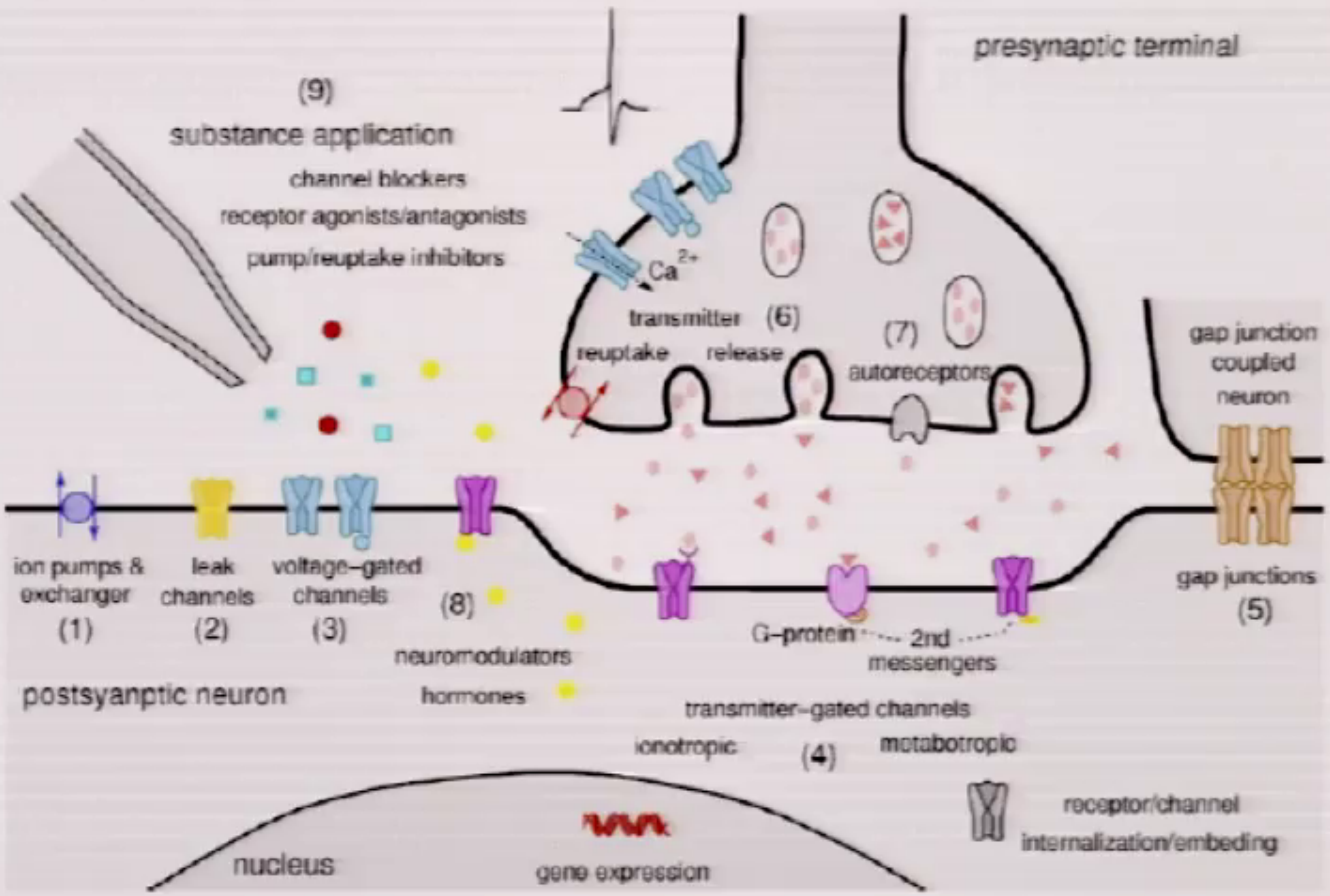


Modulation

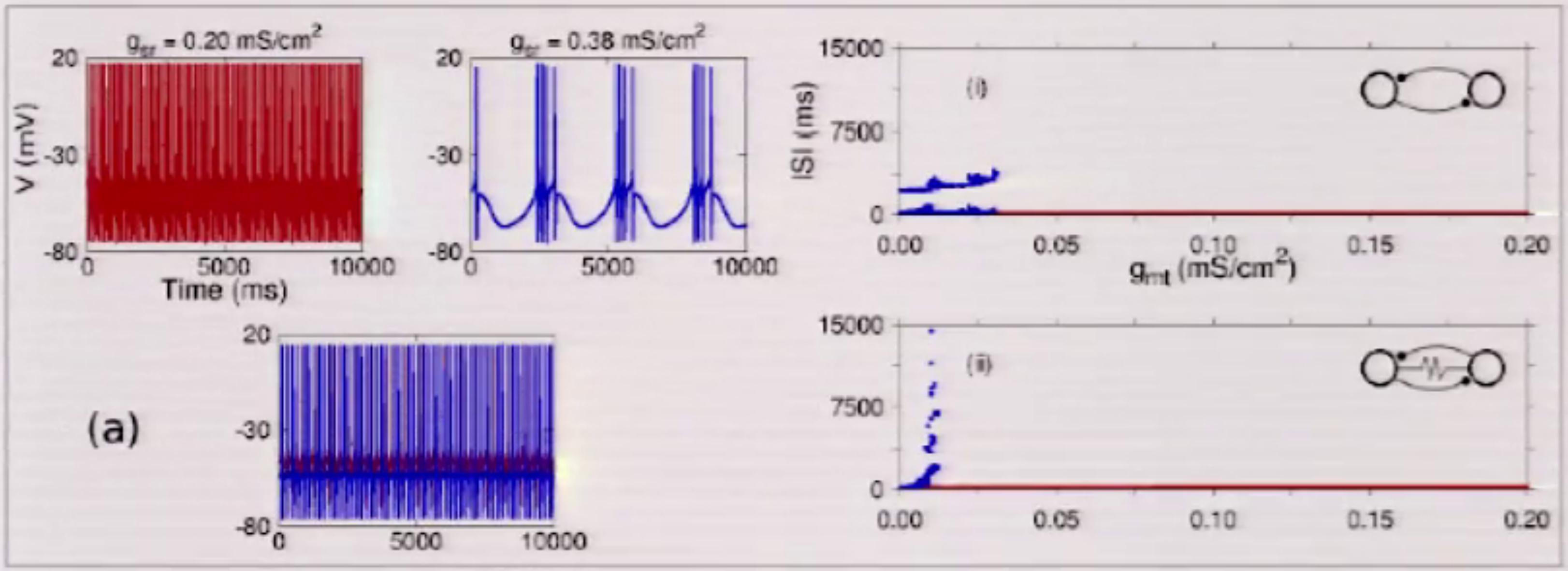
Single tonic neuron forced by a sinusoidal function responds in different ways depending upon the amplitude and the frequency of the forcing function.



Synapse

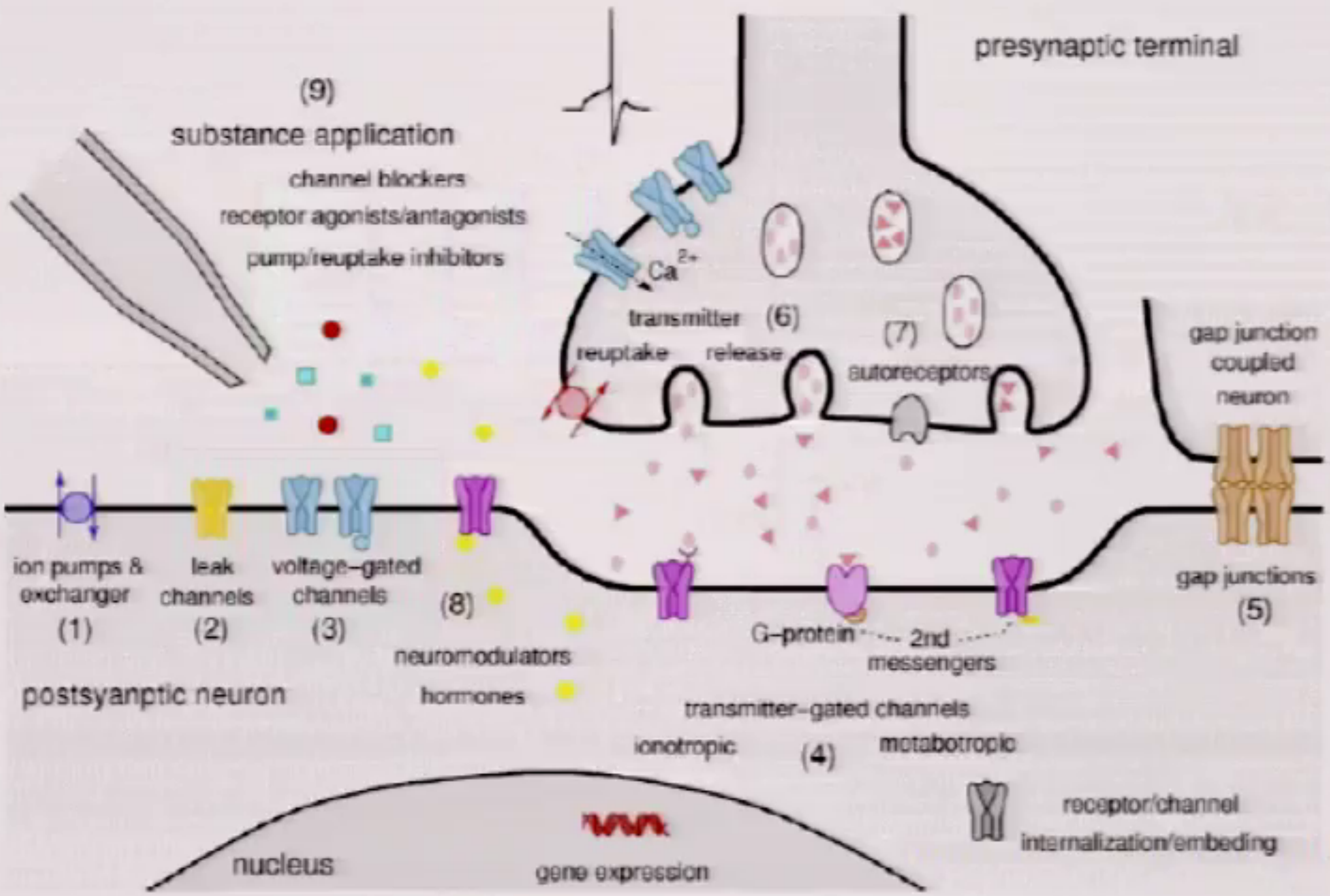

presynaptic terminal
(9)
substance application
channel blockers
receptor agonists/antagonists
pump/reuptake inhibitors
Ca^{2+}
transmitter (6)
reuptake
release
(7)
autoreceptors
gap junction
coupled
neuron
ion pumps &
exchanger
(1)
leak
channels
(2)
voltage-gated
channels
(3)
(8)
neuromodulators
hormones
postsyanptic neuron
G-protein
2nd
messengers
gap junctions
(5)
transmitter-gated channels
ionotropic
(4)
metabotropic
receptor/channel
internalization/embeding
nucleus
gene expression

Two Coupled Neurons



Rosa *et al.*, *Biosystems* (2015)

Synapse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presynaptic spike

$$C\frac{dV_{pre}}{dt} = -\sum I_v$$

⇩

transmitter release

$$c_{release} = \frac{c_{spike}}{1 + exp(-s_{syn}(V_{pre} - V_{spike}))}$$

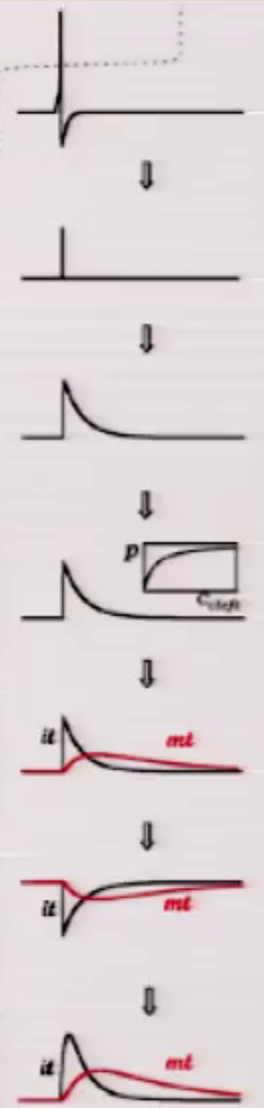
⇩

transmitter concentration

$$\frac{dc_{cleft}}{dt} = \frac{c_{release}}{\tau_{accum}} - \frac{c_{cleft}}{\tau_{elim}}$$

ionotropic (a) ⇩ | ⇩ *metabotropic (b)*

ionotropic (a)	metabotropic (b)
receptors activation $p_{it} = \frac{r_{it} c_{cleft}}{c_{it} + c_{cleft}}$	**receptors activation** $p_{mt} = \frac{r_{mt} c_{cleft}}{c_{mt} + c_{cleft}}$
⇩	⇩
current activation $a_{it} = p_{it}$	**current activation** $\frac{da_{mt}}{dt} = \frac{p_{mt}}{\tau_{act}} - \frac{a_{mt}}{\tau_{inact}}$
⇩	⇩
postsynaptic current $I_{post_{it}} = g_{it} a_{it} (V_{post} - E_{it})$	**postsynaptic current** $I_{post_{mt}} = g_{mt} a_{mt} (V_{post} - E_{mt})$
⇩	⇩
postsynaptic potential $C\frac{dV_{post_{it}}}{dt} = -\sum I_v - I_{post_{it}}$	**postsynaptic potential** $C\frac{dV_{post_{mt}}}{dt} = -\sum I_v - I_{post_{mt}}$



Summary

1. Synchronization is everywhere, prominently in neurological systems.
2. We study synchronization (or lack of) in a pair of neurons reciprocally coupled via gap junction and chemical synapse.
3. The neuron model equations we use possess a rich dynamics, are physiologically meaningful and capable of generating a wide range of spiking patterns and frequencies.
4. The neuronal pair of interest here is of biological relevance, and in the cases we have studied for inhibitory coupling, strong enough coupling knocks down the slower neuron.

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