Simple Model of Spiking Neurons

Paper by Eugene M. Izhikevich, 2003

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What was Izhikevich working with?

Hodgkin-Huxley Model

A description of ion channel voltage-dependence and cell membrane potential drop due to ion exchange.

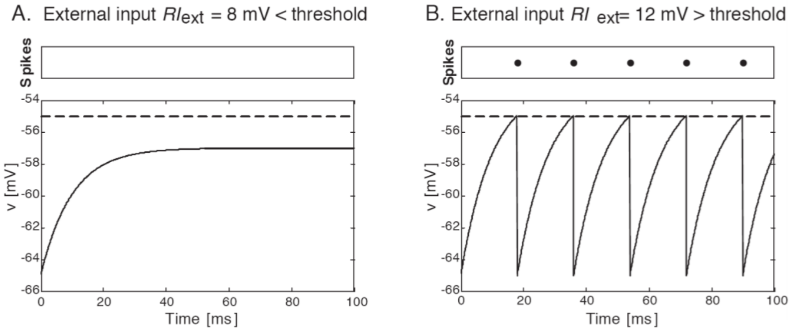
$$C \cdot \frac{dV}{dt} = -g_K n^4 \cdot (V - E_K) - g_{Na} m^3 h \cdot (V - E_{Na}) - g_L \cdot (V - E_L) + I(t)$$

Biophysically accurate, plausible

Computationally prohibitive, simulates a handful of neurons

Integrate-and-Fire Model

A differential equation to describe: 1) the development of membrane potential and 2) spiking mechanism at threshold.



Computationally efficient in real time

Unrealistically simple

How does Izhikevich produce a model that is:

1) Computationally Simple

2) Capable of producing rich firing patterns of cortical neurons

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A New Model

Hodgkin-Huxley neuronal models were reduced by bifurcation methodologies.

Resulted in a two-dimensional system of differential equations:

$$v' = 0.04v^2 + 5v + 140 - u + I$$
$$u' = a(bv - u)$$

Bifurcation theory = studying qualitative changes that occur when parameter values are modified.

Dependent on dimensionless variables (*v* and *u*) and parameters (*a*, *b*, *c*, and *d*).

Variables

$$v' = 0.04v^2 + 5v + 140 - u + I$$
$$u' = a(bv - u)$$

‘ = d/dt, or change over time.

v = membrane potential of the neuron

u = membrane recovery available

(activation of K+ ionic currents and inactivation of Na+ ionic currents - providing negative feedback to *v*)

Parameters

a = the time scale of recovery variable *u*
= smaller *a* means slower recovery

b = the sensitivity of *u* to subthreshold fluctuations of membrane potential *v*
= greater *b* means lower-threshold spiking dynamics

c = the after-spike reset value of *v* (by high-threshold K+ conductances)

d = the after-spike reset of *u* (by slow high-threshold Na+ and K+ conductances)

Variables

$$v' = 0.04v^2 + 5v + 140 - u + I$$
$$u' = a(bv - u)$$

$$\text{if } v \geq 30 \text{ mV}, \text{ then } \begin{cases} v \leftarrow c \\ u \leftarrow u + d. \end{cases}$$

v = membrane potential of the neuron

u = membrane recovery available

(activation of K+ ionic currents and inactivation of Na+ ionic currents - providing negative feedback to *v*)

Parameters

a = the time scale of recovery variable *u*
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Now, parameters may be modified to produce different types of neuronal dynamics!

Different Types of Dynamics

Excitatory Neurons Thalamo
Cortical

- RS (Regular Spiking) Resonator
- IB (Intrinsically Bursting)
- CH (Chattering)

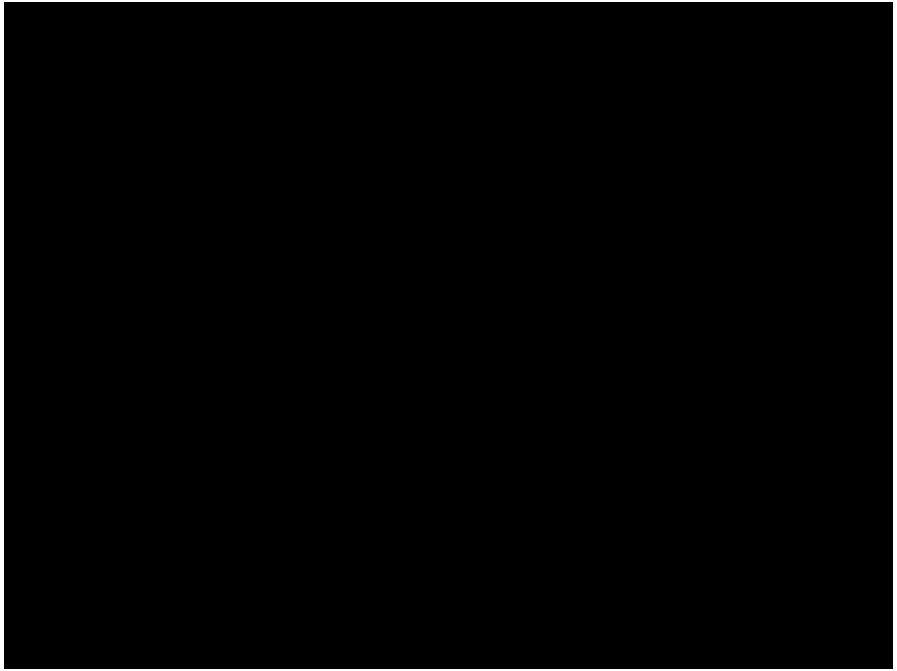
Inhibitory Neurons

- FS (Fast Spiking)
- LTS (Low-threshold Spiking)

Regular Spiking (RS)

- Excitatory - most common type of neurons

- Fires first spikes with short interspike period and then period increases - **spike frequency adaptation**

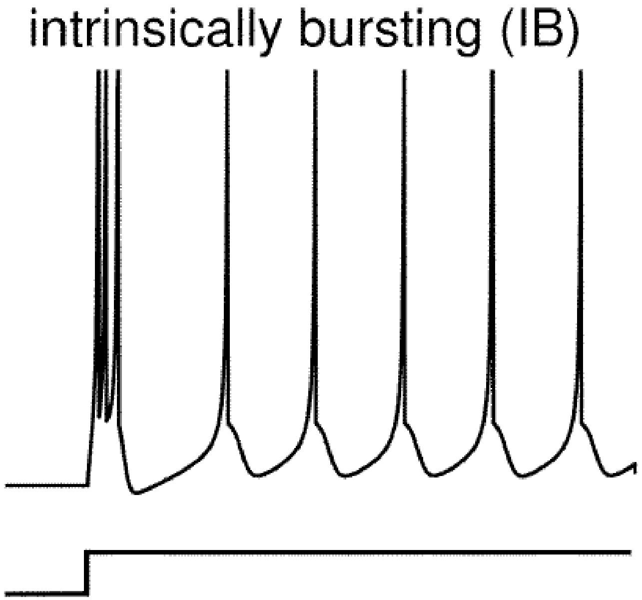


Intrinsically Bursting (IB)

- Neurons fire a stereotypical burst of spikes followed by repetitive single spikes

- c = -55 mV d = 4

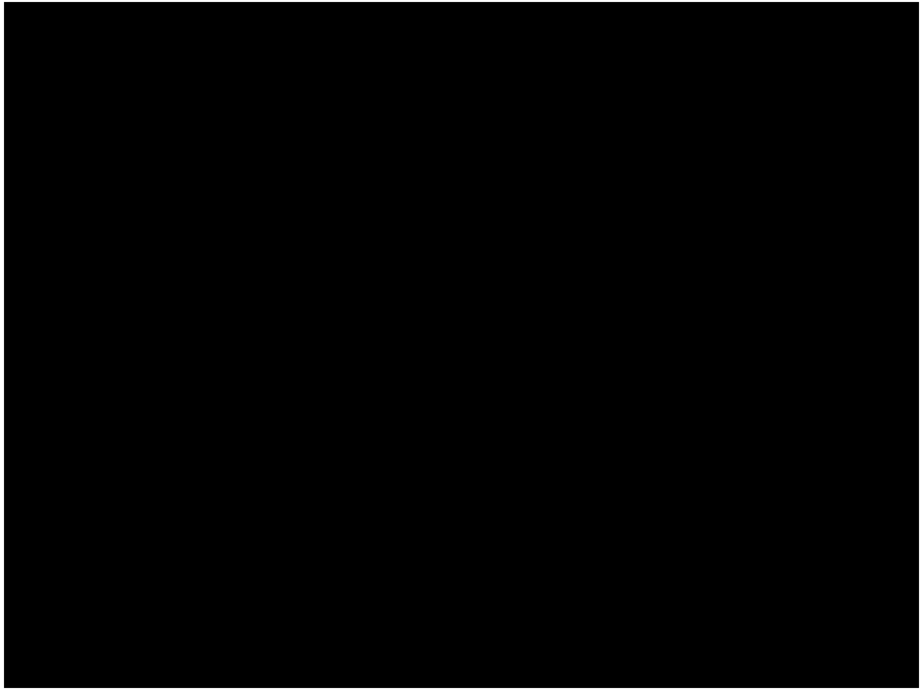
- During initial burst variable u builds up and eventually switches the dynamics from bursting to spiking.



Chattering (CH)

- Neurons can fire stereotypical bursts of closely spaced spikes.

- C = -50mV   d = 2

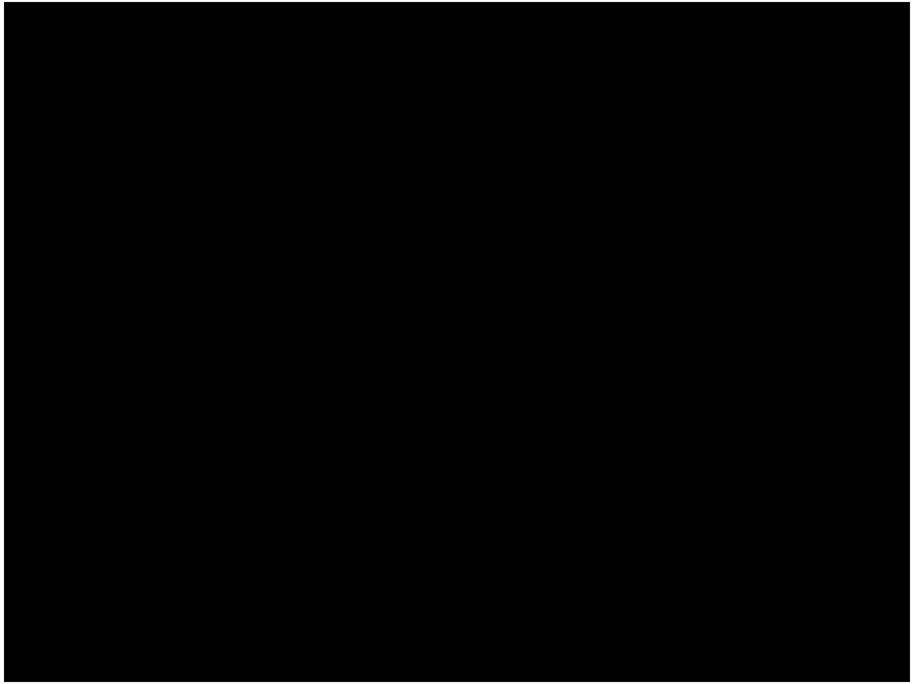


Fast Spiking (FS)

- Inhibitory

- Neurons can fire periodic trains of action potentials with extremely high frequency practically without any adaptation(slowing down)

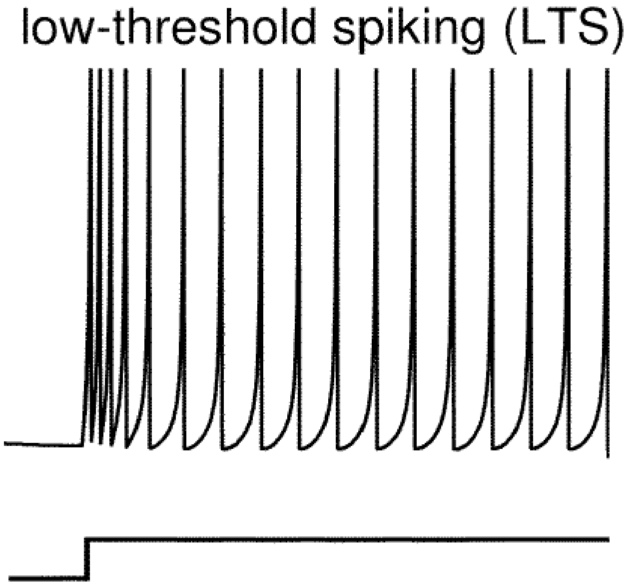
- A = 0.1 (fast recovery)



Low Threshold Spiking (LTS)

- Inhibitory

- These neurons have low firing thresholds,which is accounted for by b = 0.25 in the model

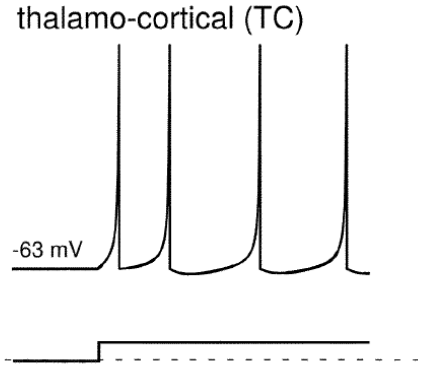


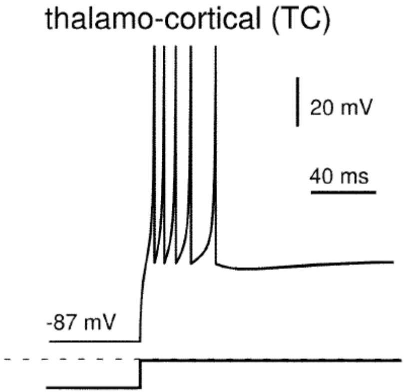
Thalamo-Cortical

- Two firing regimes

- When at rest and then depolarized they exhibit tonic firing

- If a negative current is delivered - membrane potential is hyperpolarized - neurons fire a rebound burst of actional potential





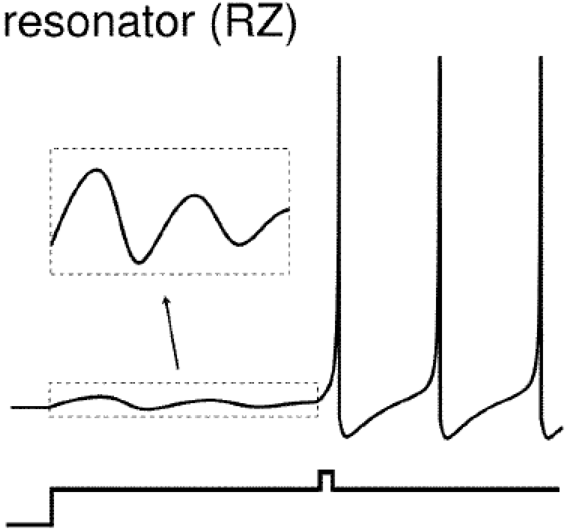
Resonator

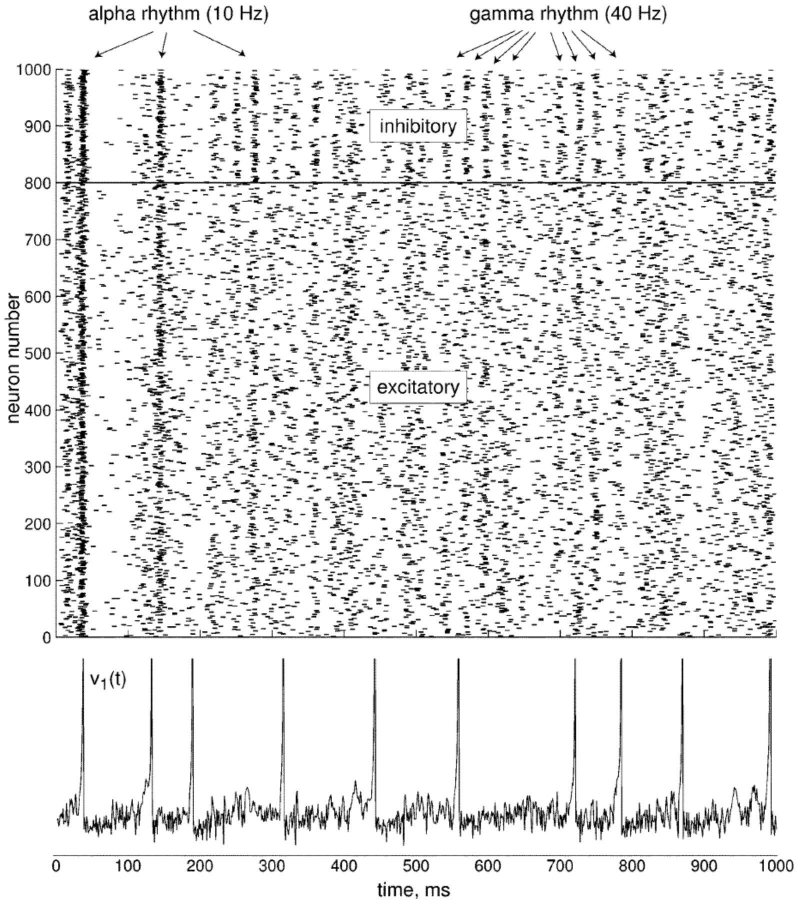
- Neurons have damped or sustained subthreshold oscillations

- a = 0:1 and b = 0:26.

- Bistability of resting and repetitive spiking states

→ The neuron can be switched between the states by an appropriately timed brief stimuli.





Pulse-Coupled Implementation

Model used to simulate network of 10,000 spiking cortical neurons with 1,000,000 synaptic connections in real time.

Heterogeneity of neurons accomplished by random distribution of RS and FS cells.

- RS to model all excitatory.
- FS to model all inhibitory.
- Biased towards RS.

Cortical-like asynchronous dynamics + occasional synchronous firings.

Neurons self-organized into assemblies, collective rhythmic behaviour (like cortex).

“There is no longer a contradiction between biological plausibility and computational efficiency of model neural networks”

In short, Izhikevich was able to produce a model that:

1) Reproduced the rich behaviour of biological neurons, such as spiking - bursting - frequency adaptation - etc.
2) Consisted of only two equations and one nonlinear term, making it simple enough for mass real-time computation.
3) Could be accurately used to model networks of spiking neurons with collective dynamics as if it were an actual mammalian cortex.

Significance

- Took the best attributes of two previous neuronal models and created a new, better one.
- Allowed for simulation of thalamo-cortical networks (thousands of spiking neurons) in real time.
- Paved way for future brain and neuron models:
  - Izhikevich, E. M. (2010). Hybrid spiking models.
  - Izhikevich, E. M., & Edelman, G. M. (2008). Large-scale model of mammalian thalamocortical systems.
  - Szatmáry, B., & Izhikevich, E. M. (2010). Spike-timing theory of working memory.

Limitations

- Great foundation - what's next?
  - Thousands of neurons

    ↓

    Billions
  - Modeling abnormal circumstances (damage, disease, etc.)

Questions?

References

Blohm, G. (2018). NSCI401: Introduction to Modelling in Neuroscience, week 1 notes [Powerpoint slides].

Cano, G., & Dilão, R. (2017). Intermittency in the Hodgkin-Huxley model. *Journal of computational neuroscience*, *43*(2), 115-125.

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Naud, R., Marcille, N., Clopath, C., & Gerstner, W. (2008). Firing patterns in the adaptive exponential integrate-and-fire model. *Biological cybernetics*, *99*(4-5), 335.