Silicon Neurons

NE-I Class

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Neurons . . . in a nutshell

A quick tutorial

Complexity

- Real Neurons
- Conductance based models
- Integrate and fire models
- Rate based models
  - Sigmoidal units
  - Linear threshold units

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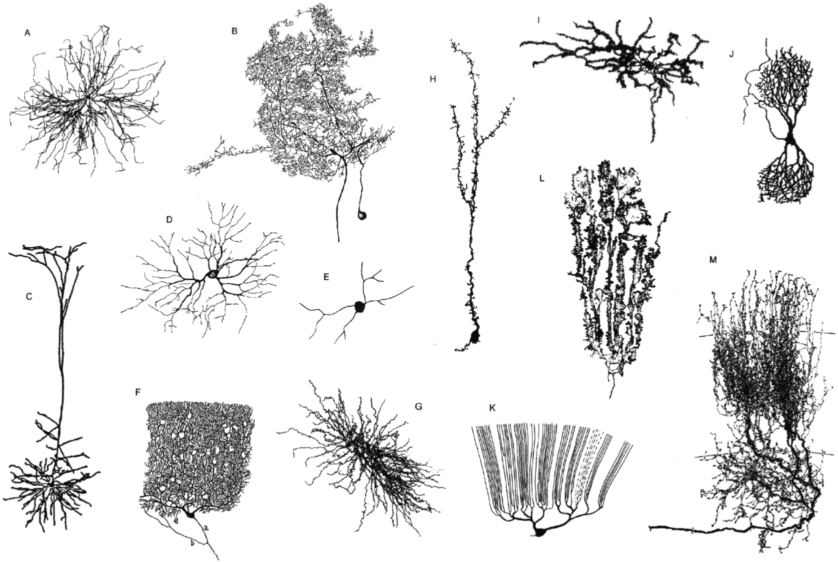
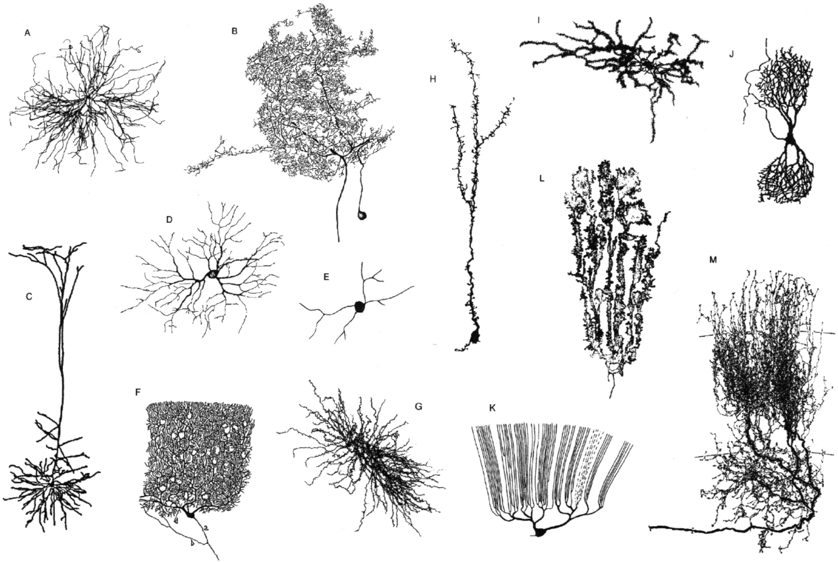
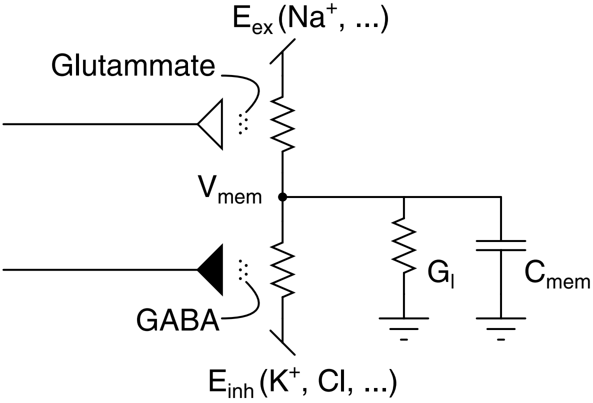
Neurons of the world



Neurons of the world



Equivalent Circuit



If excitatory input currents are relatively small, the neuron behaves exactly like a first order low-pass filter.

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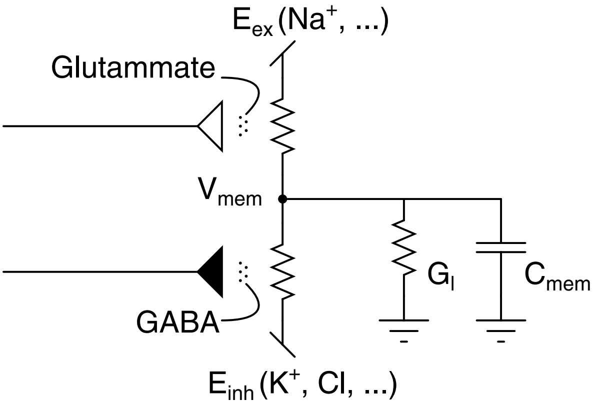

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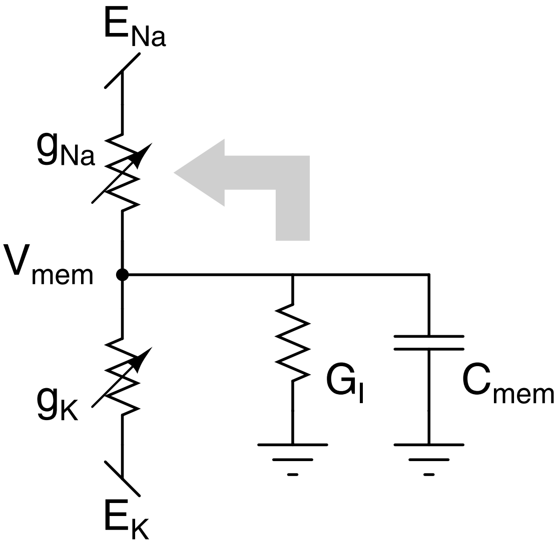
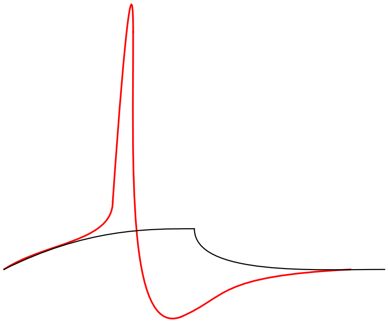
Spike generating mechanism





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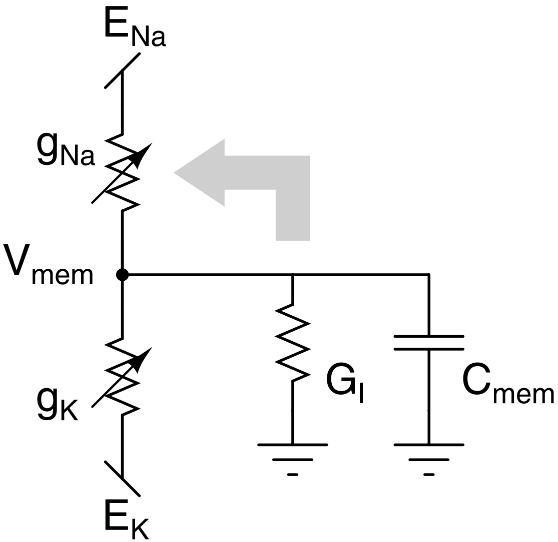
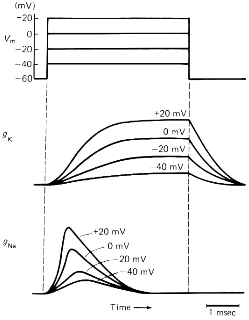
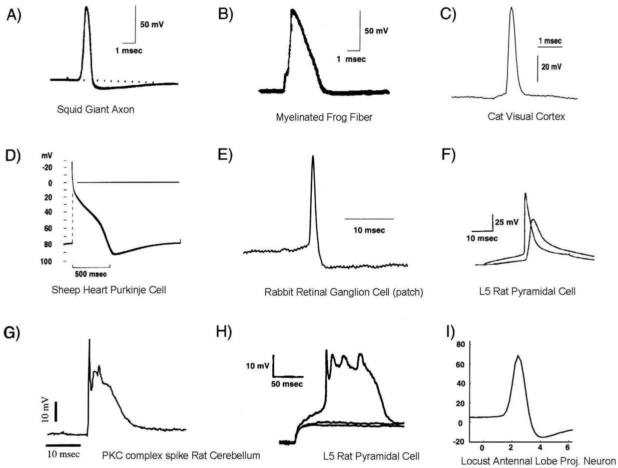
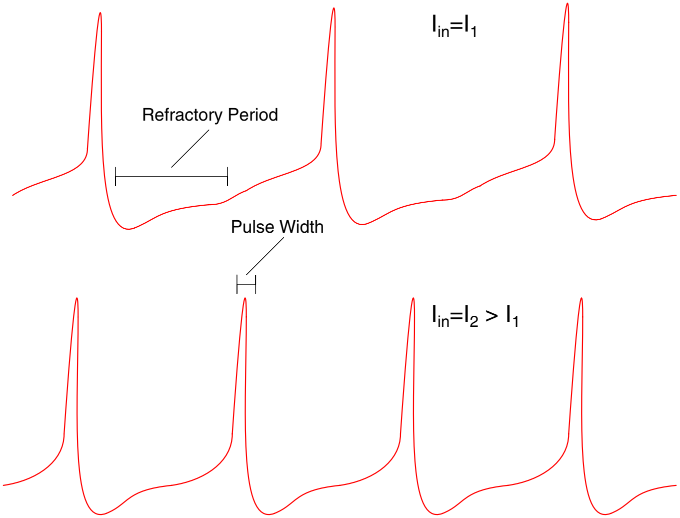




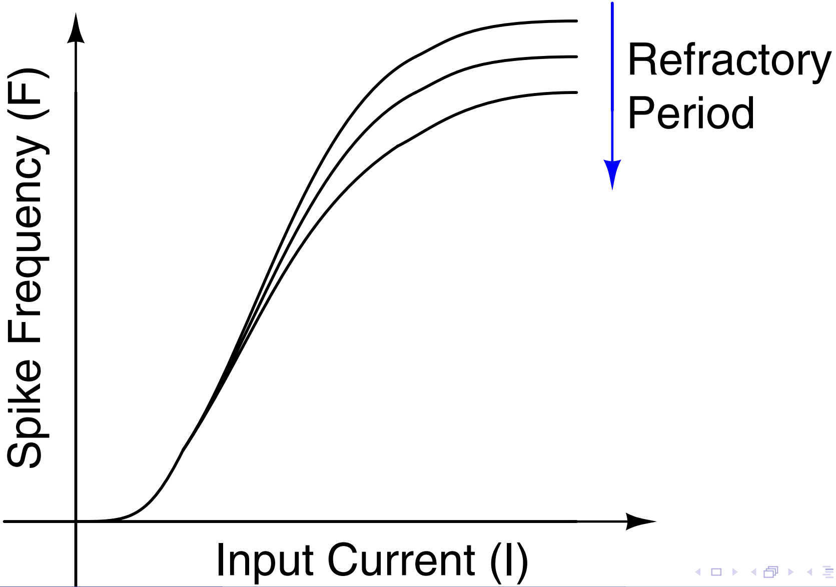
Action potentials of the world



Spike properties



The F-I curve



Hardware implementations of spiking neurons

The first artificial neuron model was proposed in the 1943 by McCulloch and Pitts. Hardware implementations of this model date almost back to the same period.

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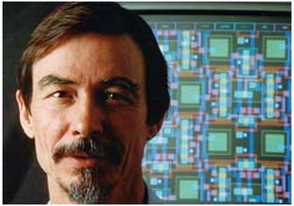
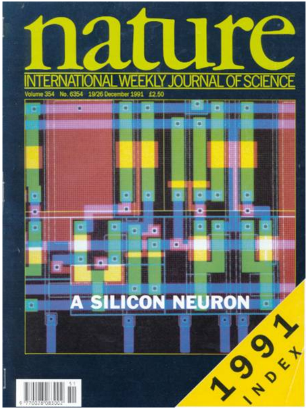


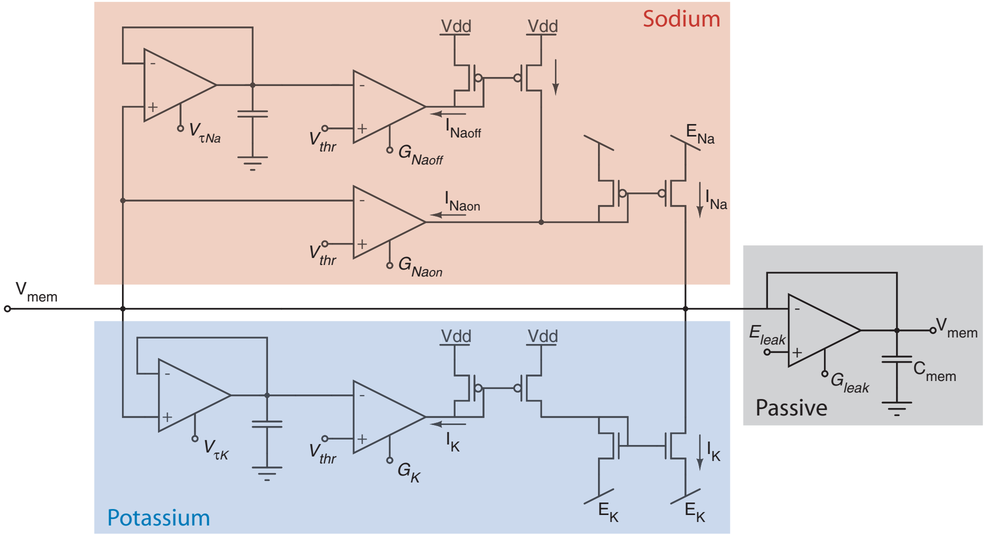
One of the most influential circuits that implements an *integrate and fire* (I&F) model of a neuron was the Axon-Hillock Circuit, proposed by Carver Mead in the late 1980s.

Conductance-based models of spiking neurons



In 1991 Misha Mahowald and Rodney Douglas proposed a conductance-based silicon neuron and showed that it had properties remarkably similar to those of real cortical neurons.

Conductance based Si-Neurons



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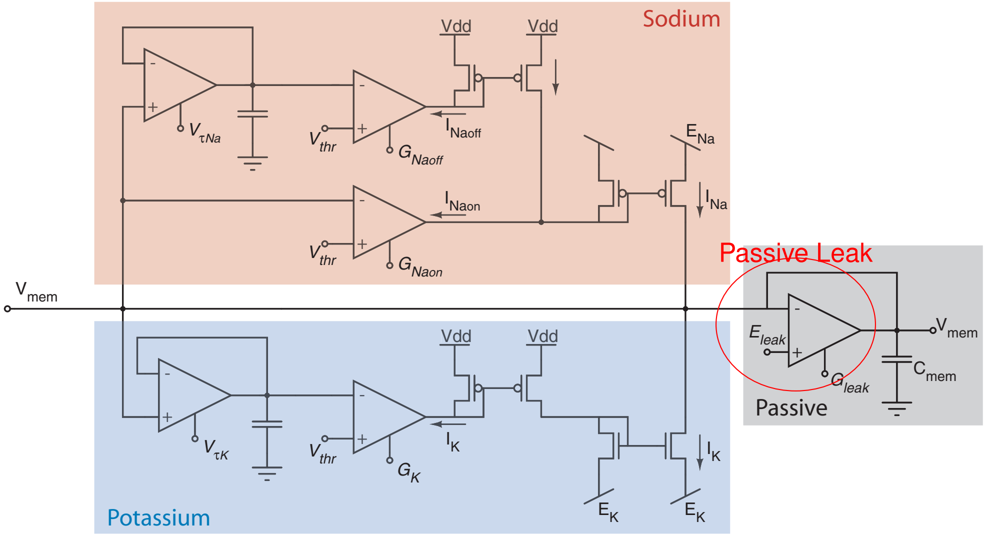

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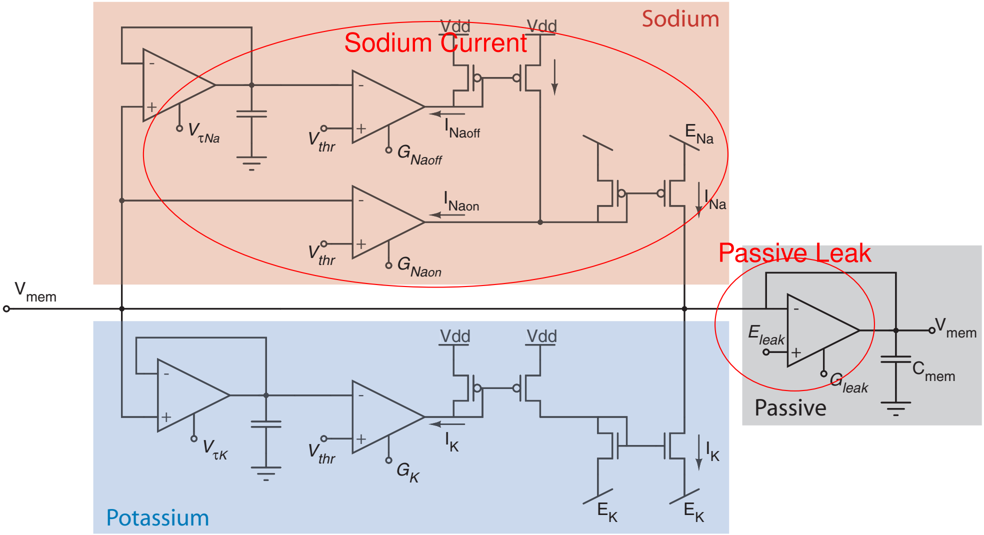

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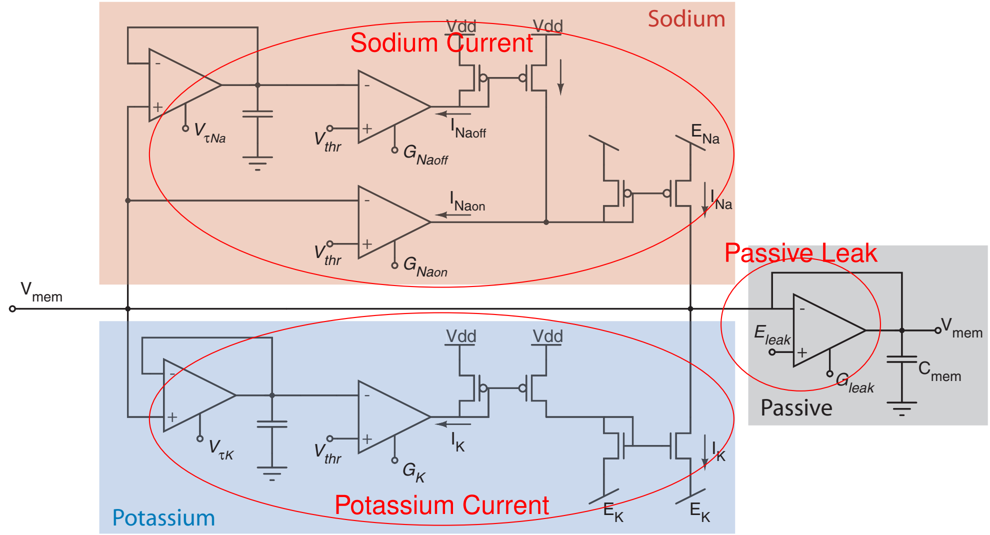

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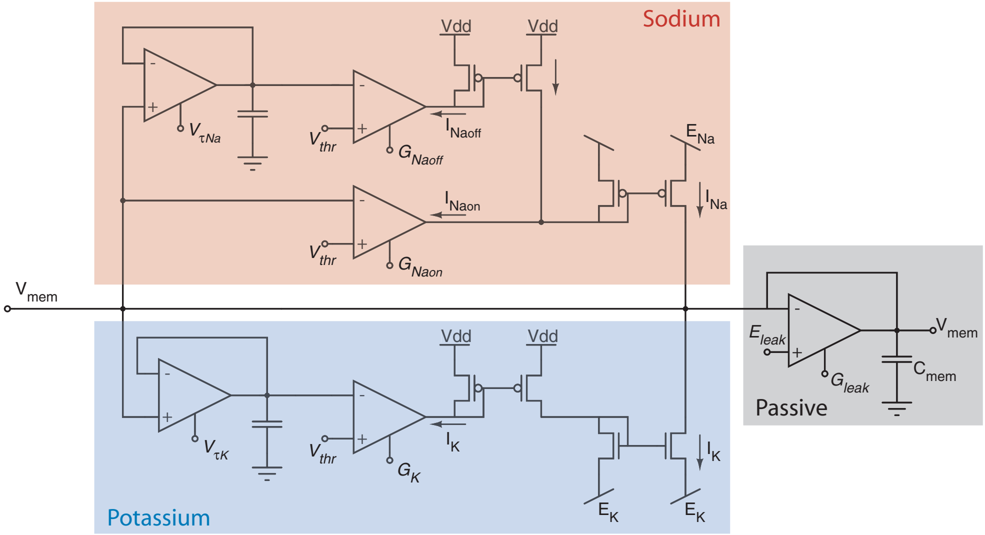
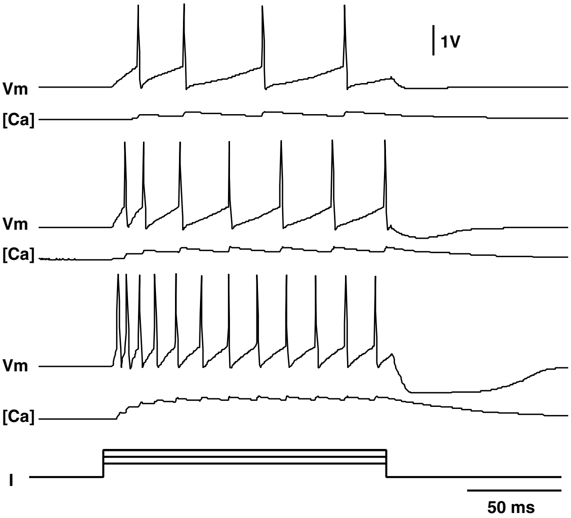


Conductance based Si-Neurons

Silicon neuron's measurements



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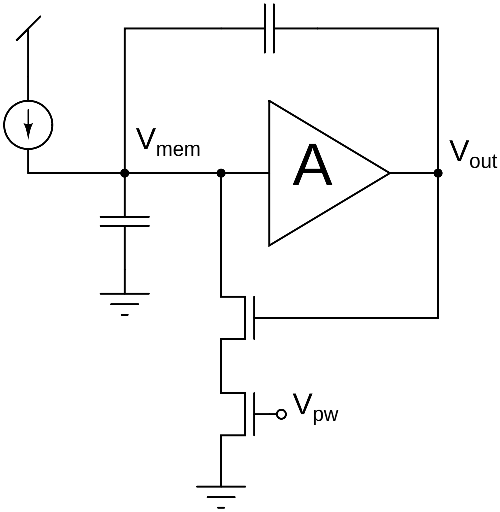

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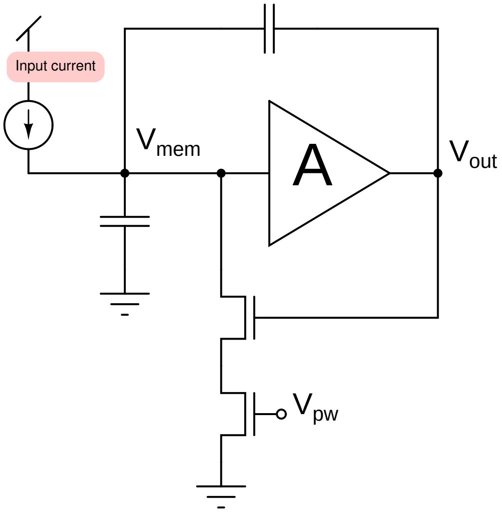

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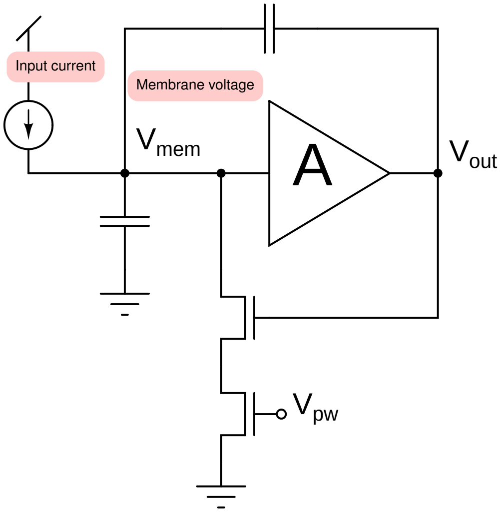

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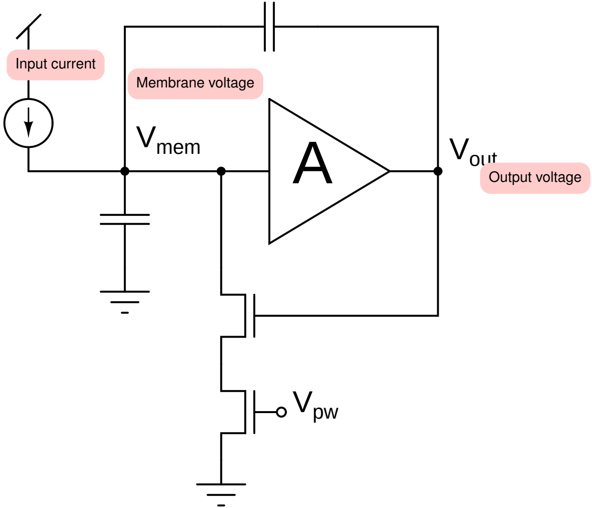

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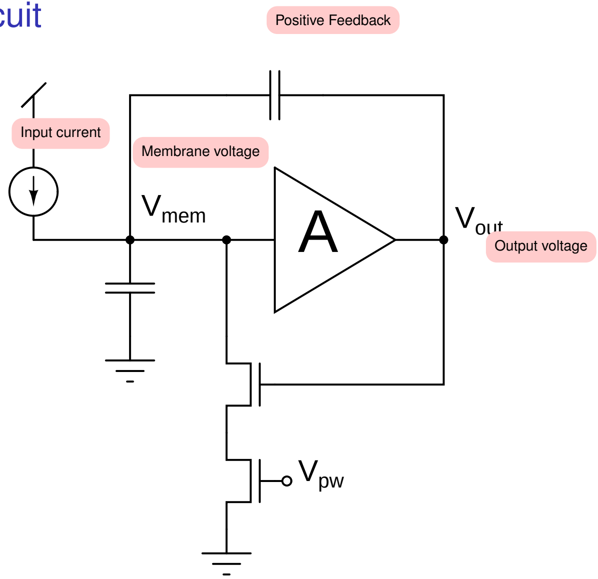

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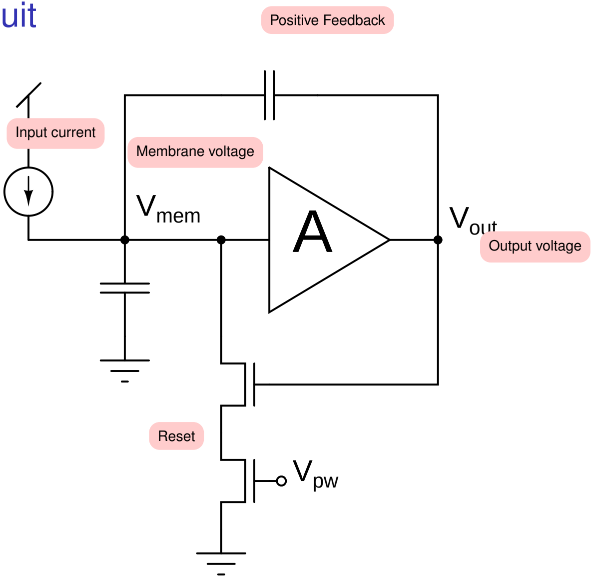

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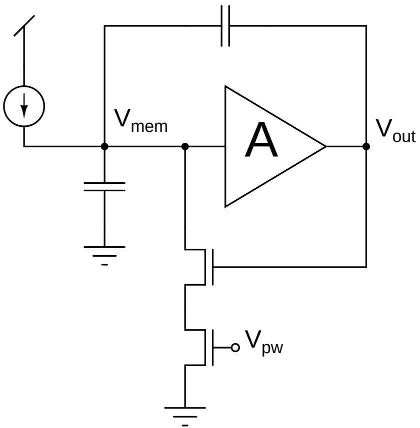
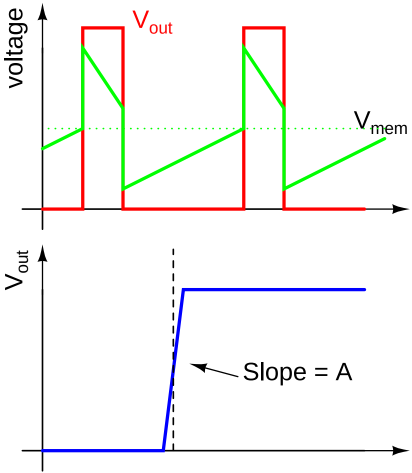




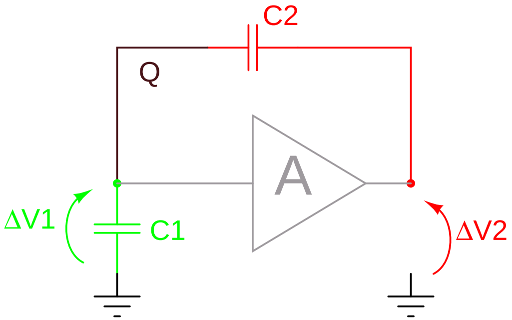
Capacitive Divider

Given the change $\Delta V2$, what is $\Delta V1$?

$$Q = C_1 V_1 + C_2(V_1 - V_2) = \text{constant}$$

$$C_1 \Delta V_1 + C_2(\Delta V_1 - \Delta V_2) = 0$$

$$\Delta V_1 = \frac{C_2}{C1 + C2} \Delta V_2$$



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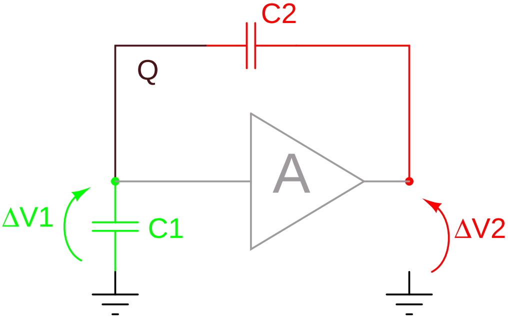

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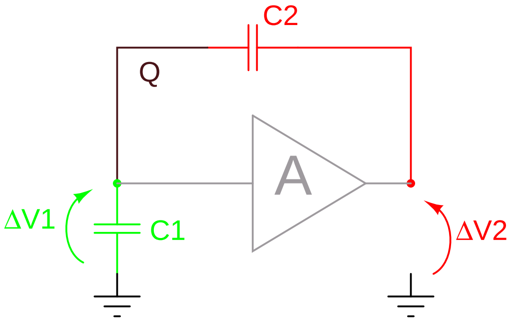

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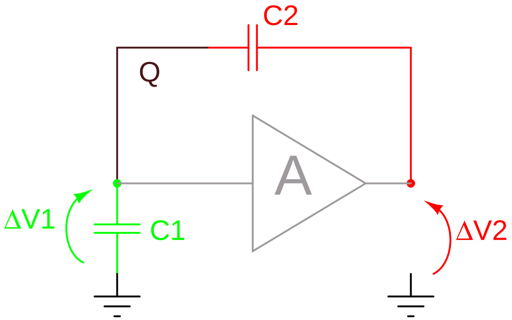
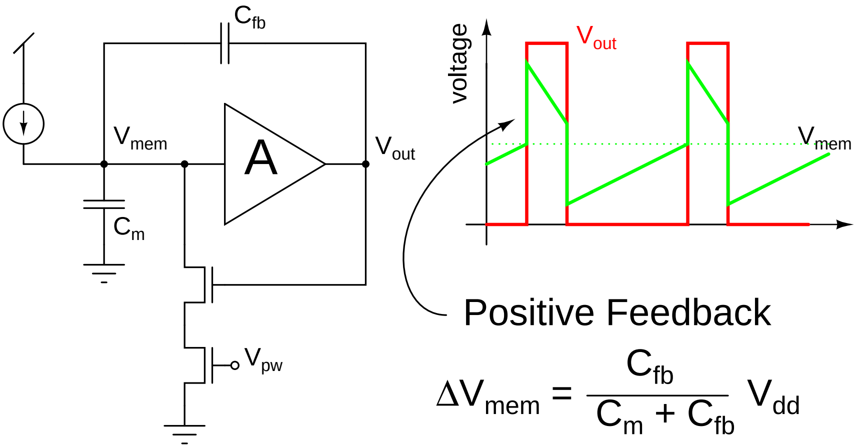


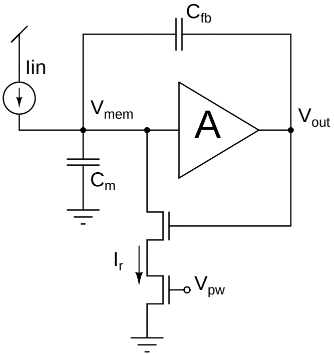
Positive Feedback

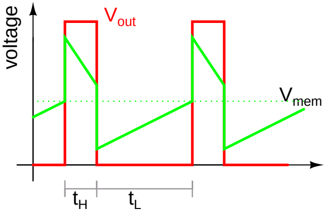


Positive Feedback

$$\Delta V_{mem} = \frac{C_{fb}}{C_m + C_{fb}} V_{dd}$$

Axon-Hillock Circuit Dynamics





$$t_L = \frac{C_{fb} + C_m}{I_{in}} \Delta V_{mem} = \frac{C_{fb}}{I_{in}} V_{dd}$$

$$t_H = \frac{C_{fb} + C_m}{I_r - I_{in}} \Delta V_{mem} = \frac{C_{fb}}{I_r - I_{in}} V_{dd}$$

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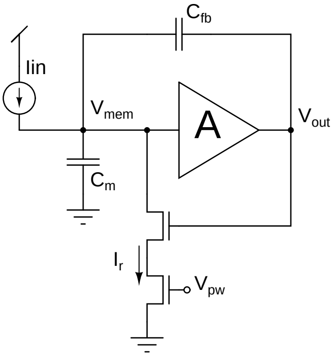

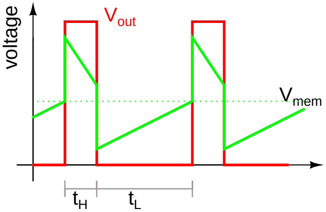

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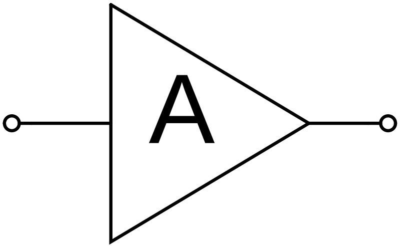
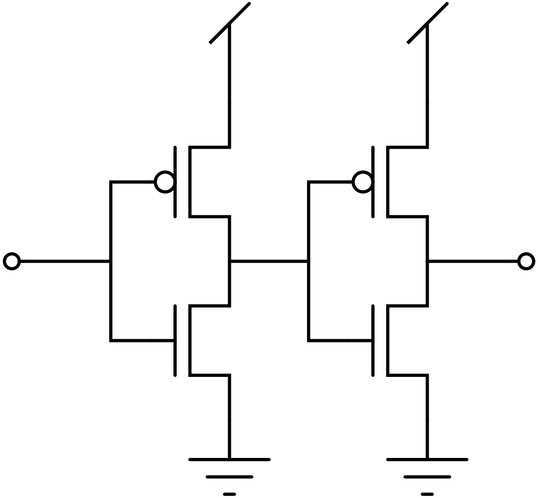
Frequency $\propto I_{in}$

Pulse width $\propto 1 / I_r$ for $I_r \gg I_{in}$

Gain

How to make voltage gain





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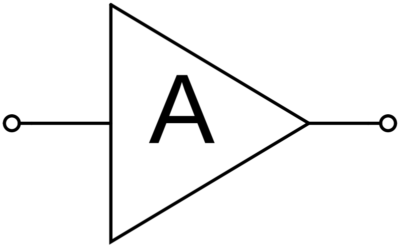
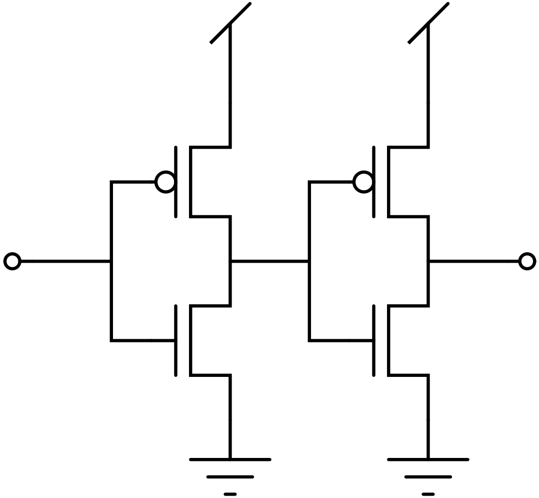
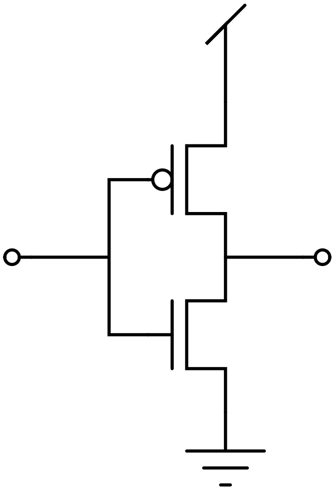




Power Dissipation

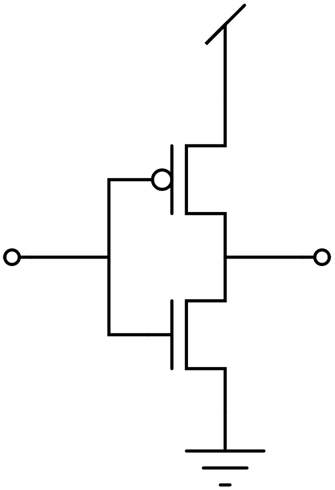


The Axon-Hillock circuit is very compact and allows for implementations of dense arrays of silicon neurons

BUT

it has a major drawback:

Power Dissipation



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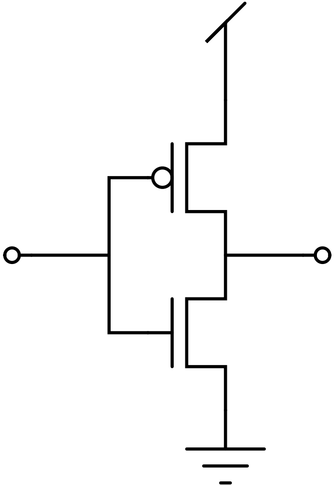

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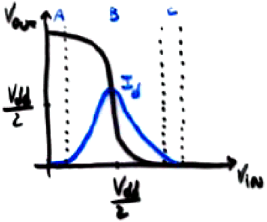
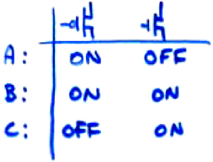
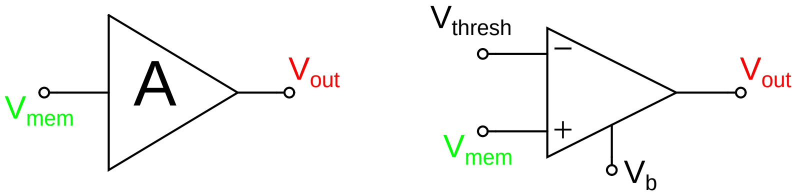
During the time when an inverter switches, a large amount of current flows from V_{dd} to *Gnd*.



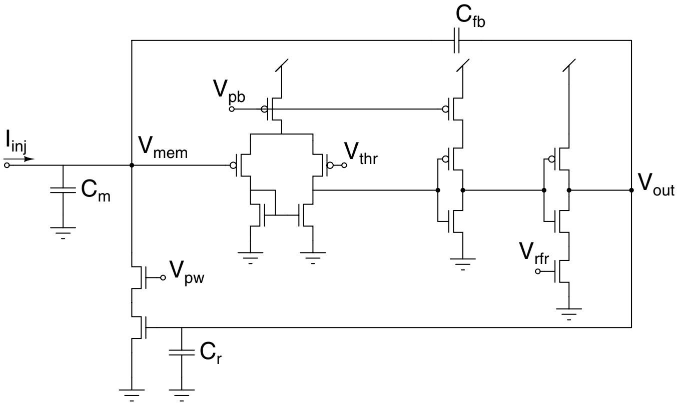


Gain

Another way to make gain

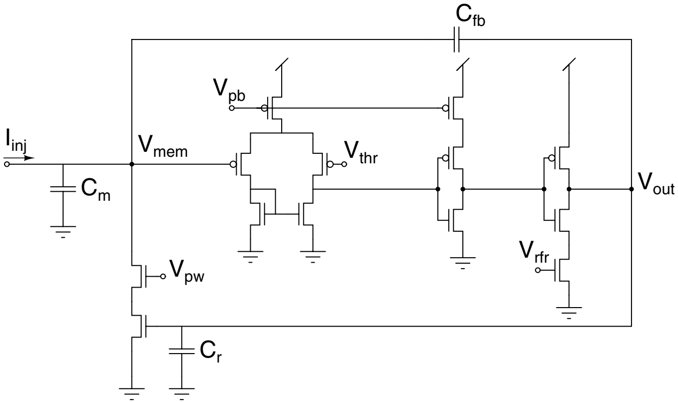


A more elaborate I&F circuit



This circuit is low-power, has an explicit voltage threshold, and models the refractory period of real spikes.

A more elaborate I&F circuit



- V_{thr} sets the spiking voltage threshold
- V_{rfr} sets the refractory period length
- V_{pw} sets the pulse width

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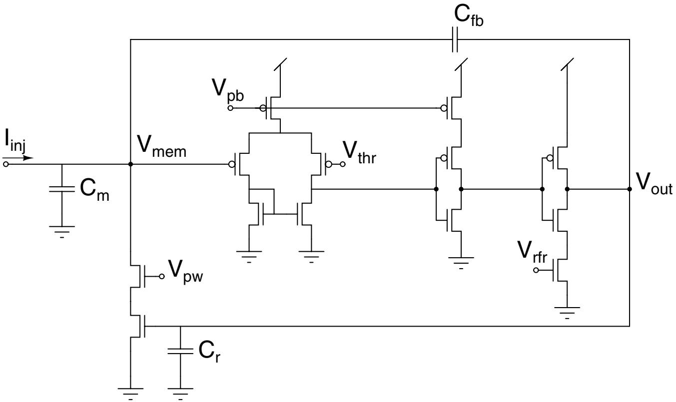

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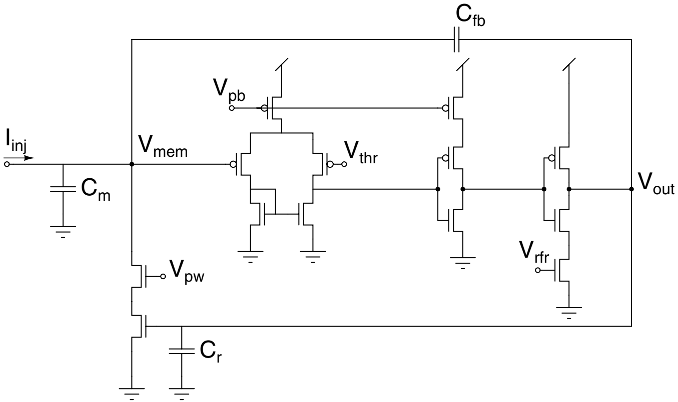

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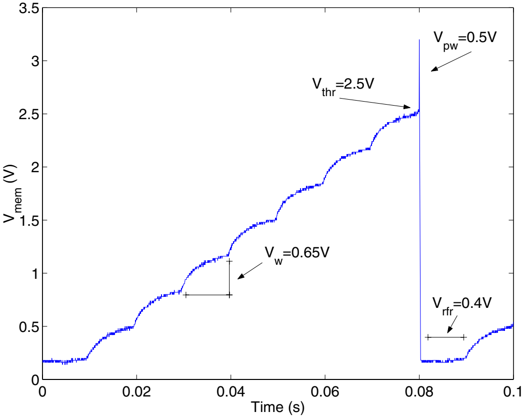
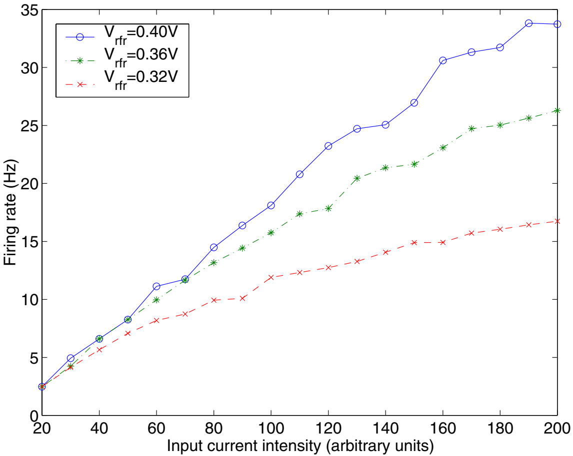
I&F circuit output

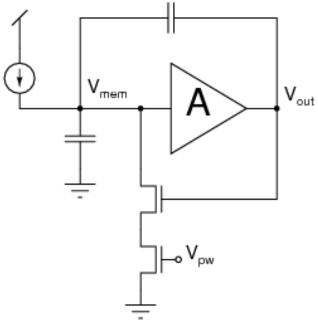




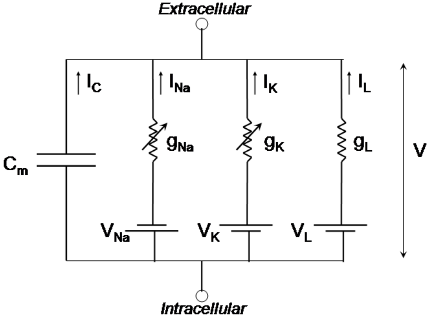
Conductance-based models

Integrate and Fire vs Hodgkin-Huxley

Traditionally there have been two main classes of neuron models:



Integrate and fire (I-C)



Conductance-based (R-C)

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But recently proposed models bridge the gap between the two:

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J Neurophysiol 92: 959–976, 2004;
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Generalized Integrate-and-Fire Models of Neuronal Activity Approximate Spike Trains of a Detailed Model to a High Degree of Accuracy

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First published December 5, 2007; doi:10.1152/jn.01107.2007.

Dynamic *I-V* Curves Are Reliable Predictors of Naturalistic Pyramidal-Neuron Voltage Traces

Laurent Badel,[1] Sandrine Lefort,[2] Romain Brette,[3] Carl C. H. Petersen,[2] Wulfram Gerstner,[1] and Magnus J. E. Richardson[1,4]

Conductance-based models

Integrate and Fire vs Hodgkin-Huxley

But recently proposed models bridge the gap between the two:

J Neurophysiol 92: 959–976, 2004;
10.1152/jn.00190.2004.

Generalized Integrate-and-Fire Models of Neuronal Activity Approximate Spike Trains of a Detailed Model to a High Degree of Accuracy

Renaud Jolivet,[1,*] Timothy J. Lewis,[2,*] and Wulfram Gerstner[1,*]

J Neurophysiol 99: 656–666, 2008.
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DOI 10.1007/s00422-008-0259-4

ORIGINAL PAPER

Biological Cybernetics

Extracting non-linear integrate-and-fire models from experimental data using dynamic *I–V* curves

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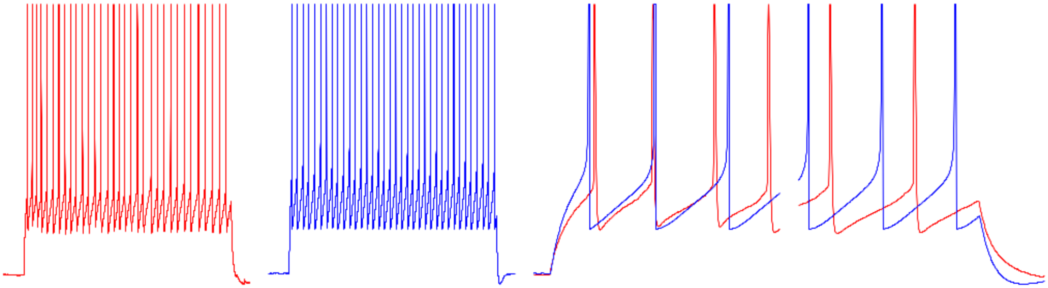
Generalized Integrate and Fire models can account for a very large set of behaviors captured by far more complicated Hodgkin-Huxley models.

$$\frac{d}{dt} u_{mem} = \frac{i_{in}}{C_{mem}} + F(u_{mem})$$

where $F(u_{mem})$ is a non-linear function of $u_{mem}(t)$.

Model neurons

The adaptive exponential I&F neuron model



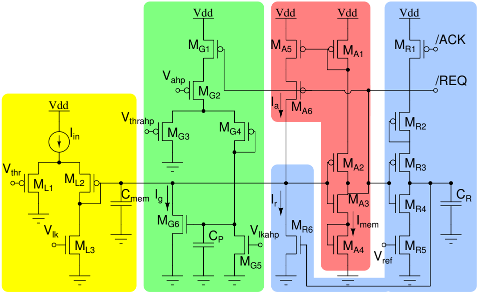
$$C\frac{d}{dt}V + g_L(V - E_L) = I - w + f(V)$$

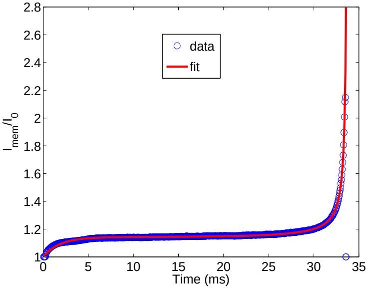
$$\tau_w\frac{d}{dt}w + w = a(V - E_L)$$

[Brette and Gerstner, 2005]

Silicon neurons

The low power I&F neuron





$$\tau \frac{d}{dt} I_{mem} + I_{mem} \approx \frac{I_{th} I_{in}}{I_\tau} - I_g + f(I_{mem})$$

$$\tau_{ahp} \frac{d}{dt} I_g + I_g = \frac{I_{thr} I_{ahp}}{I_{\tau_{ahp}}}$$

[Indiveri et al., 2010] [Brette and Gerstner, 2005]

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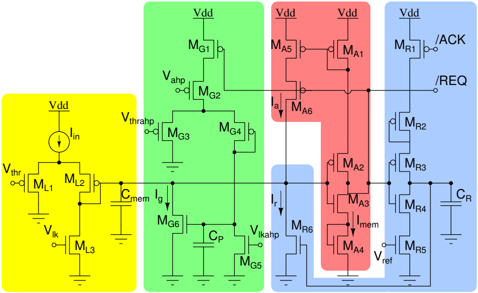

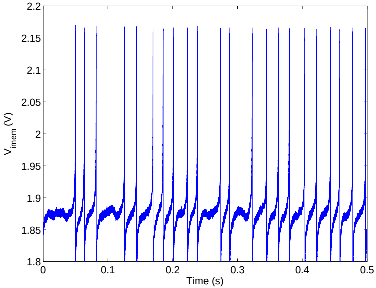

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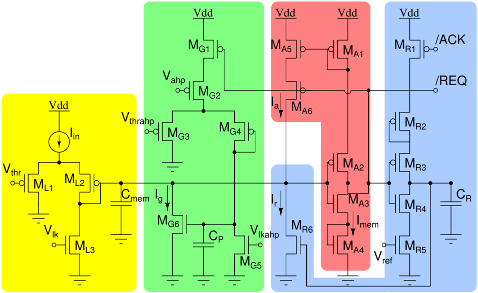

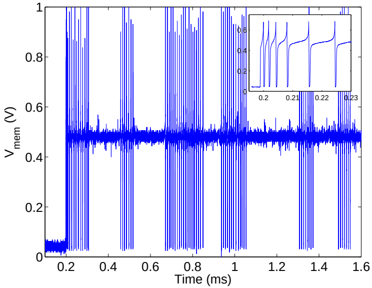

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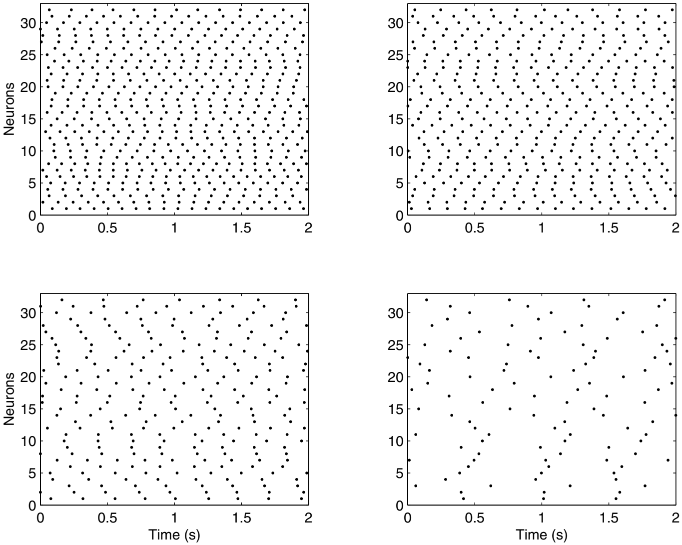
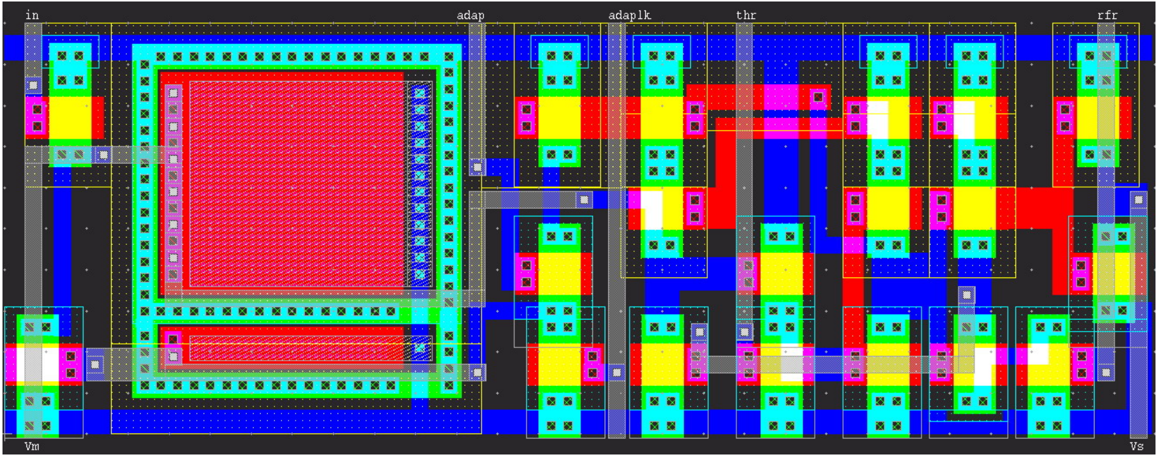
An ultra low-power array of I&F circuits



Silicon neuron layout



Applications

- Basic research
- Neuromorphic Sensors
- Multi-chip sensor-actuator systems
- Computation ?

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