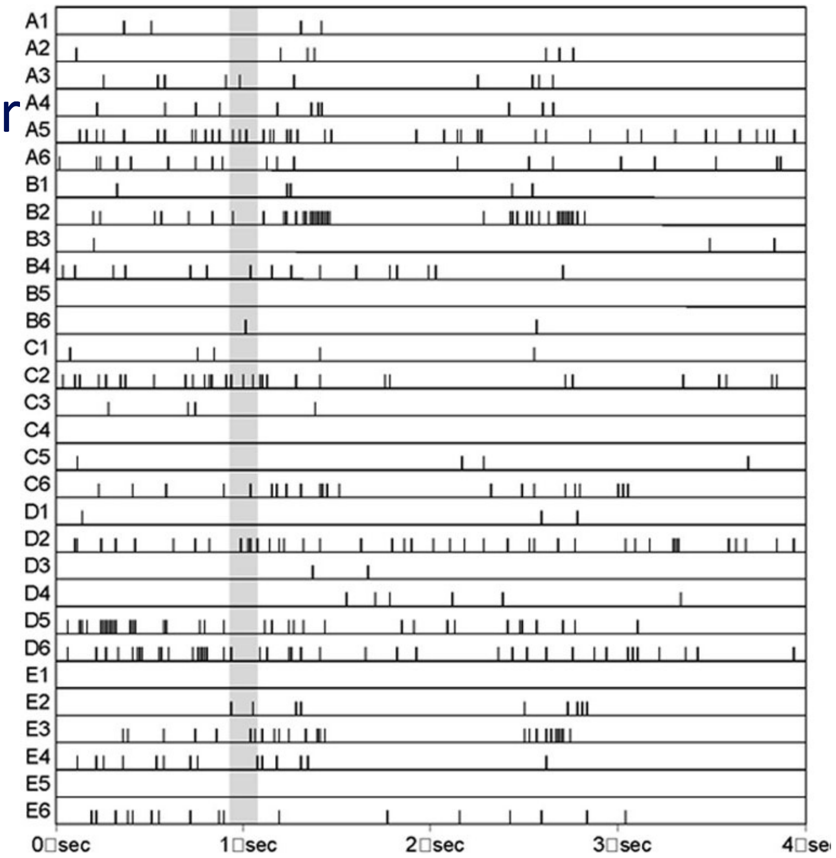
Spiking Neurons

Spike Train

- Action potentials convey information through their timing or frequency
- Spikes ← Abstraction from action potential:
  - ignore the brief duration of an action potential.
  - ignore the shape and amplitudes
  - Just keep track on when neurons are fired.
- High-dimensional time series
  - the number (frequency) and timing of spikes matter

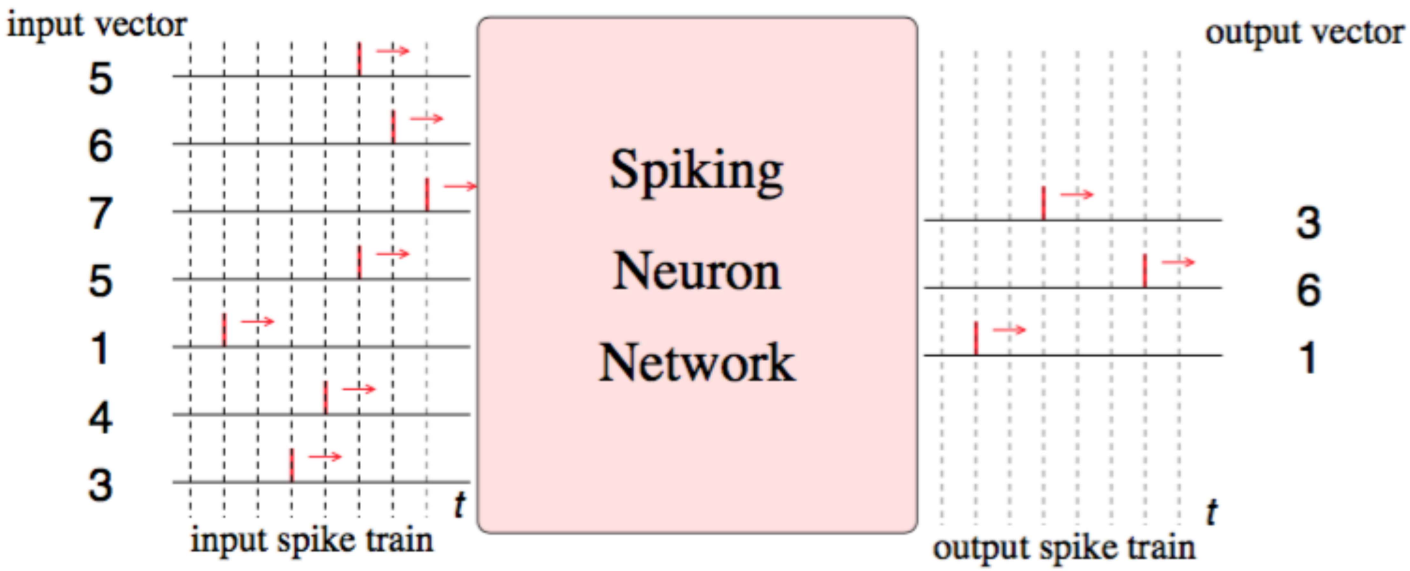


Spike trains from 30 neurons in the visual cortex of a monkey.

Towards SNN

- In the traditional model, neuron ‘fires’ at each iteration in the most cases.
- In the traditional model, the output is real-valued; no coding scheme considered.
- The investigations in neuroscience suggest that the information is transmitted and processed as spike trains in the brain.
- It is possible to make ANN much more biological plausible?

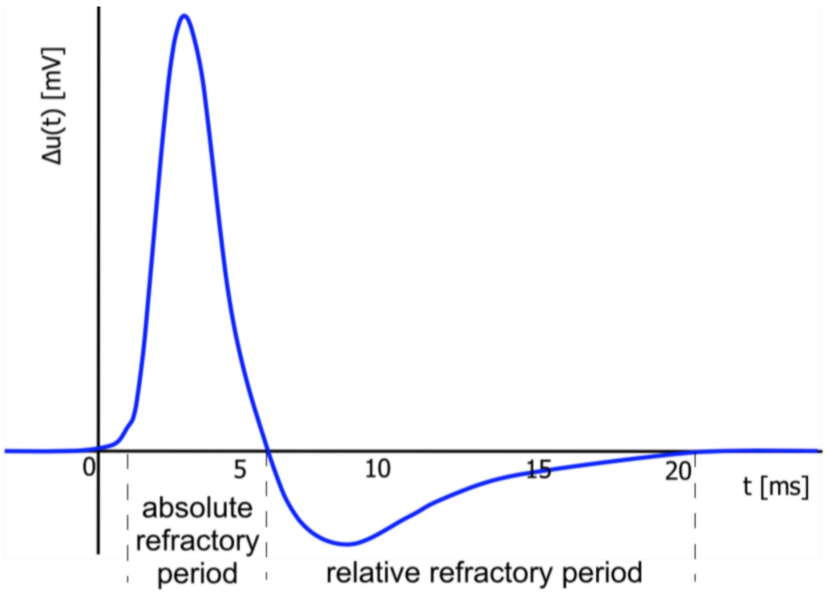
From ANN to SNN



Encoding: An integer value is encoded as the 'time-to-first-spike'

Elements of Neural Dynamics

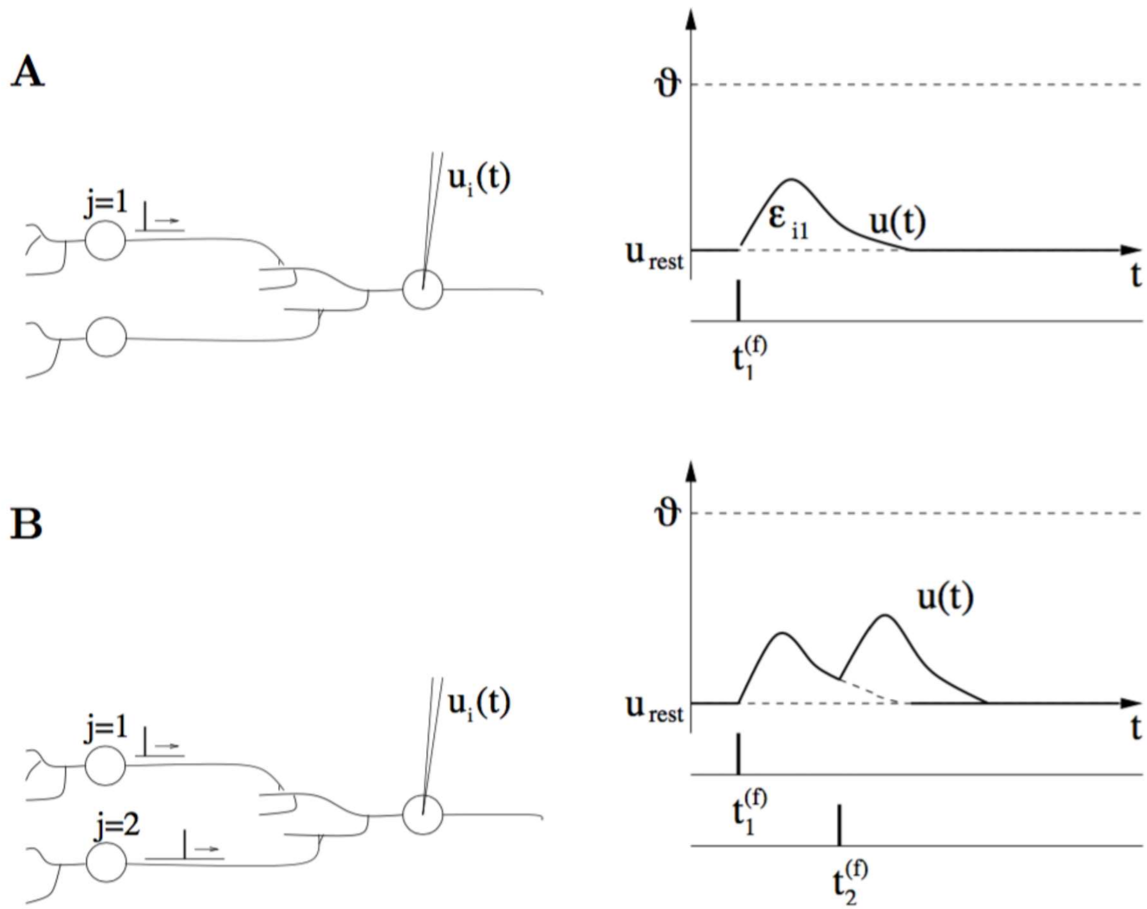
- Absolute refractory period
  - Minimal temporal distance between two spikes
- Relative refractory period
  - where it is difficult, but not impossible to excite an action potential.
- Negative Spike-after-potential



Dynamics of spike firing

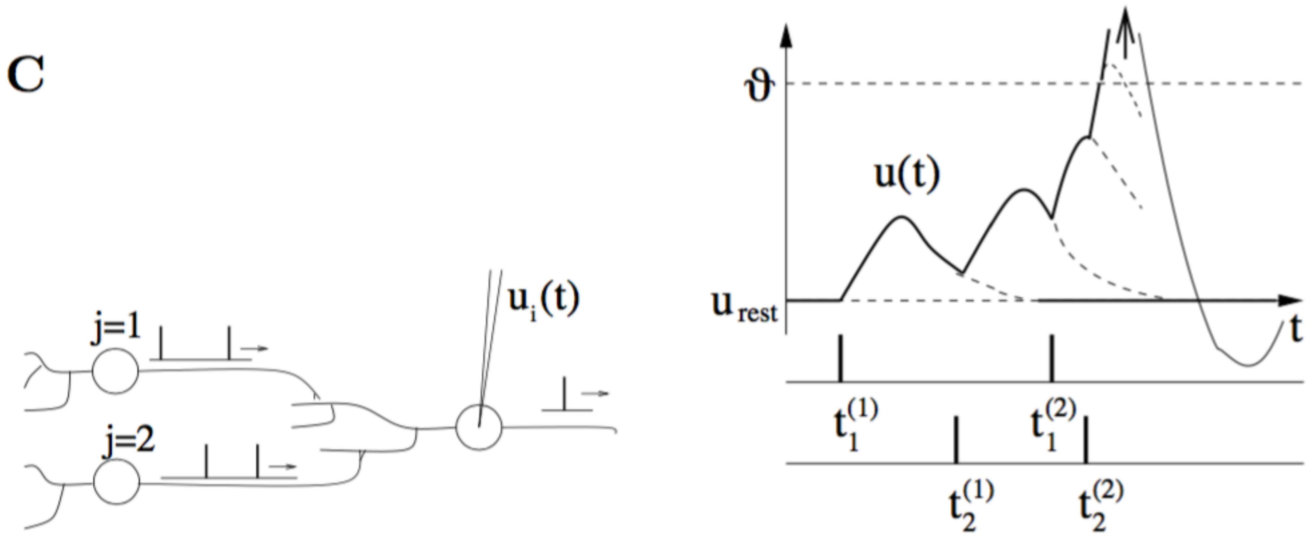
Elements of Neural Dynamics

- Postsynaptic potential (PSP)
  - Transient impact of incoming spikes
- Attenuate over time
- Additive in this model



Elements of Neural Dynamics

- A spike is generated if the cumulated membrane potential reaches the threshold from below.
- Generalization of threshold unit



Spike Response Model

- Modeling the membrane potential over time $u(t)$:
  - accumulation of PSP + internal membrane potential
  - $\hat{t}$: the last firing time
  - $t_i^{(f)}$: the presynaptic neuron fires at $t_i^{(1)}, t_i^{(2)}, \dots, t_i^{(f)}$

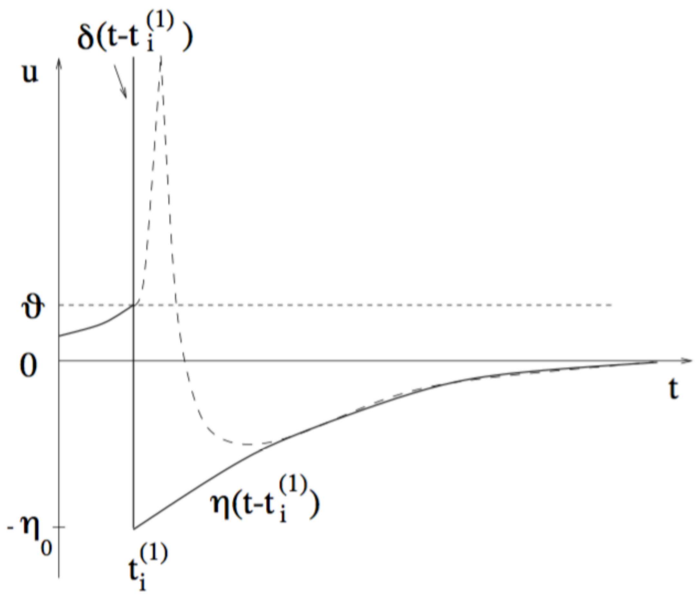
$$u(t) = \underbrace{\eta\,(t - \hat{t})}_{action\ potential} + \underbrace{\sum_i w_i \sum_f \epsilon_i(t - t_i^{(f)})}_{Input}$$

- Kernel function:
  - Spike emission $\eta(t)$ and
  - postsynaptic potential $\epsilon(t)$
- Generalization of threshold unit
- Synaptic plasticity → weights

Spike Response Model

- Common Kernel form:
  - $\eta(t)$:

$$\eta(t - t_i^{(f)}) = \begin{cases} 1/\Delta t & \text{for } 0 < t - t_i^{(f)} < \Delta t \\ -\eta_0 \exp\left(-\frac{t - t_i^{(f)}}{\tau}\right) & \text{for } \Delta t < t - t_i^{(f)} \end{cases}$$



Spike Response Model

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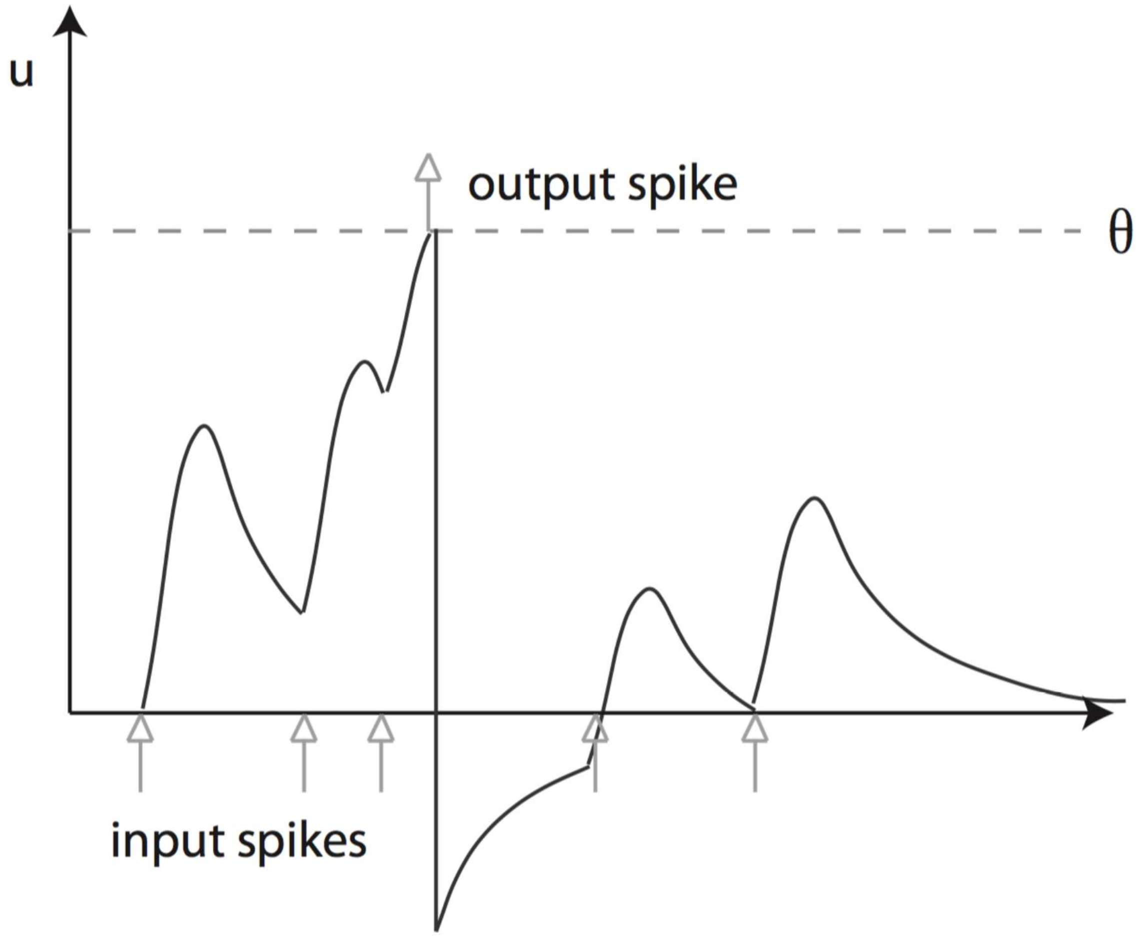
$$u(t) = \eta\,(t - \hat{t}) + \sum_i w_i \sum_f \epsilon_i(t - t_i^{(f)})$$

- When to fire? Reaches the threshold from below

$$u(t) = v \ \bigwedge \frac{du(t)}{dt} > 0 \xrightarrow{\text{yields}} spike\ at\ time\ t$$

Spike Response Model



Other models…

- Hodgkin-Huxley Model

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

$$\tau_n\frac{dn}{dt} = -[n-n_0(u)], \quad \tau_m\frac{dm}{dt} = -[m-m_0(u)], \quad \tau_h\frac{dh}{dt} = -[h-h_0(u)]$$

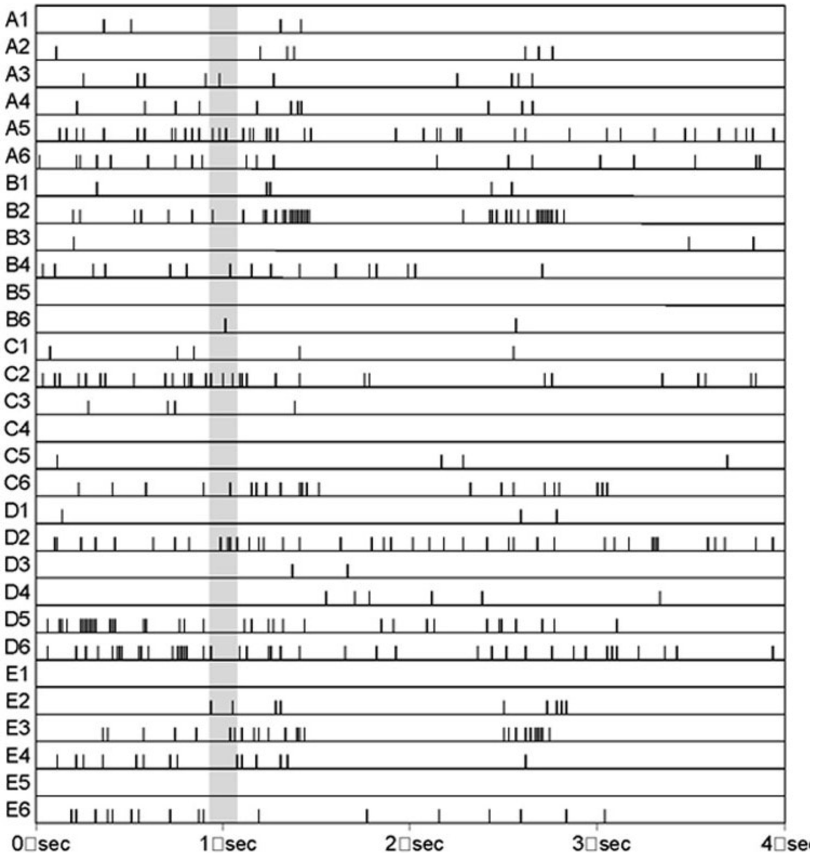
  - Derived from dynamics in electrical circuits
  - Match the biological data reasonably well
  - Complexity is quite high

- Integrate-and-fire model
  - Derived from Hodgkin-Huxley model
  - More computational tractable

Neural Coding

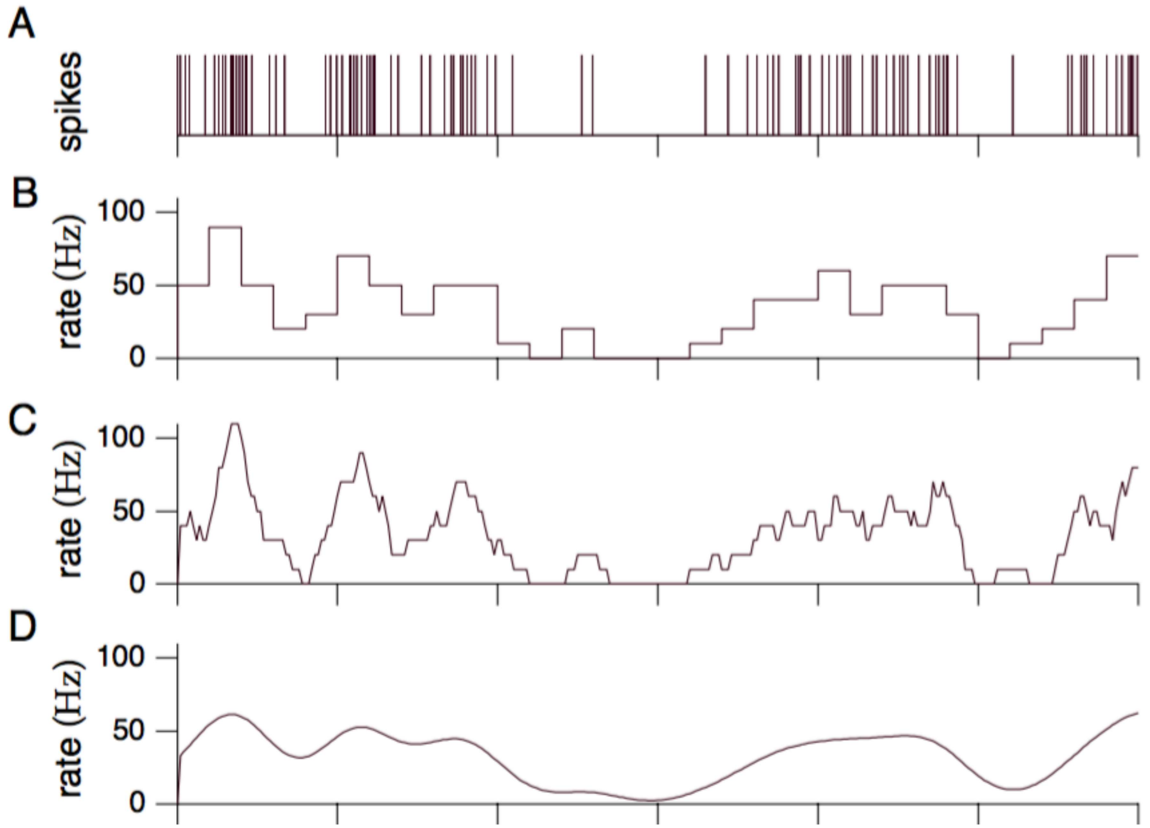
Neural coding

- How can we interpret spike trains?
  - Rate coding → average firing rate
  - Temporal coding → temporal patterns in spike trains
  - Population coding → joint patterns of a collection of neurons
  - …

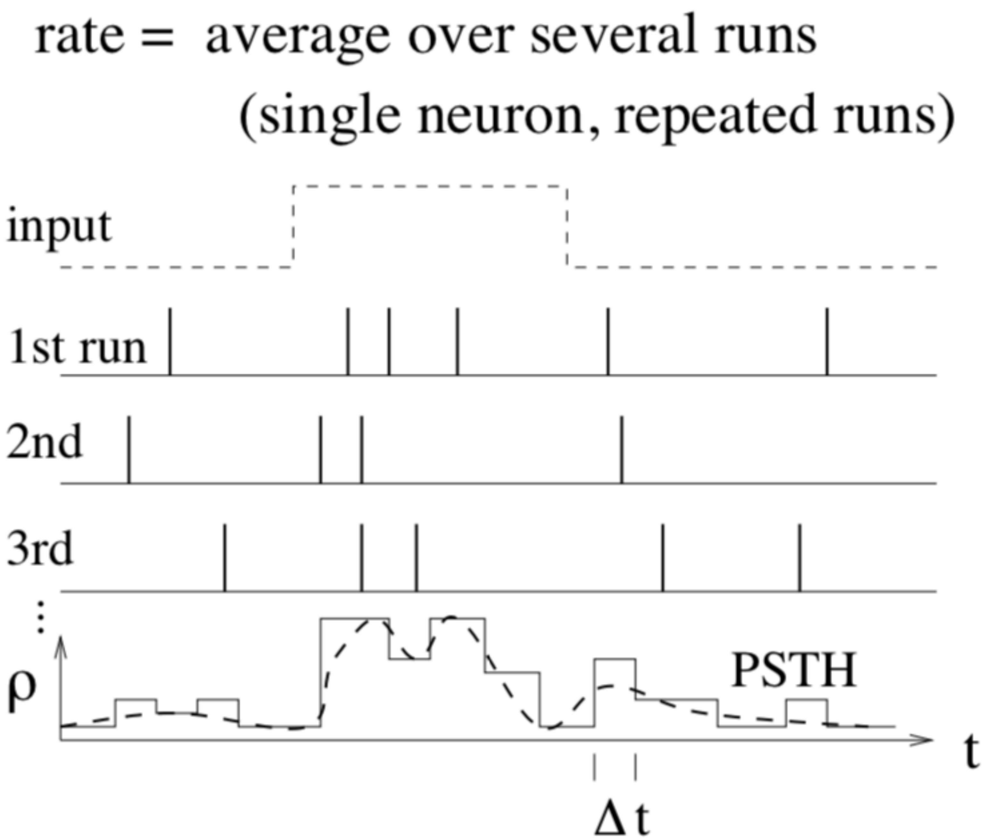


Spike-Rate coding: Spike Count

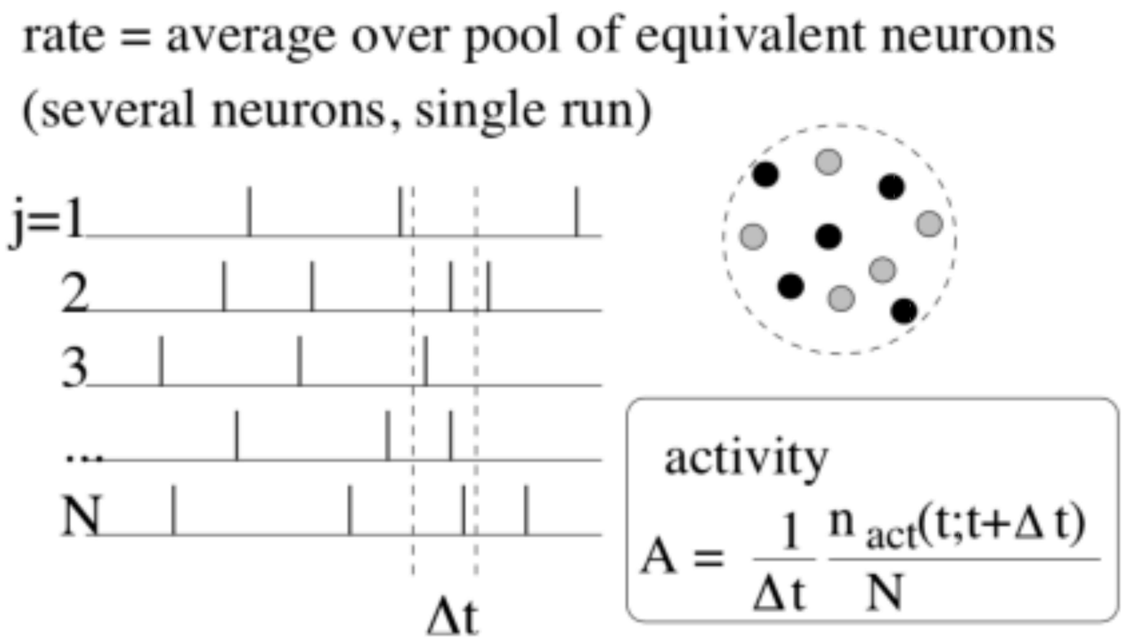
B: discrete-time binning; C: Moving average; D: Gaussian window



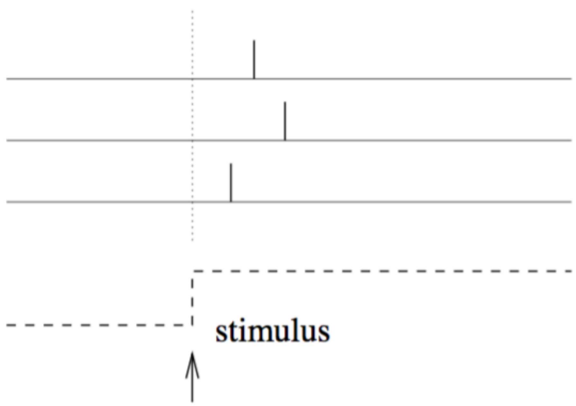
Spike-Rate coding: Spike Density

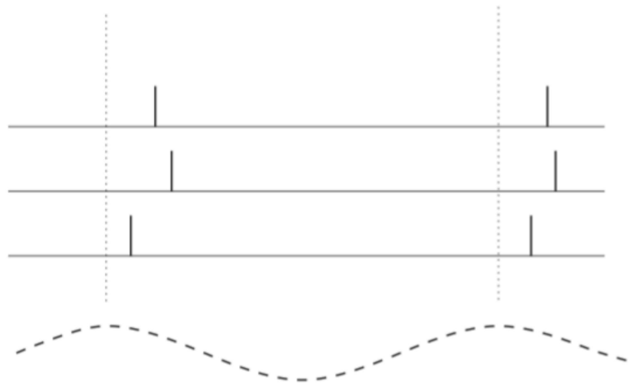


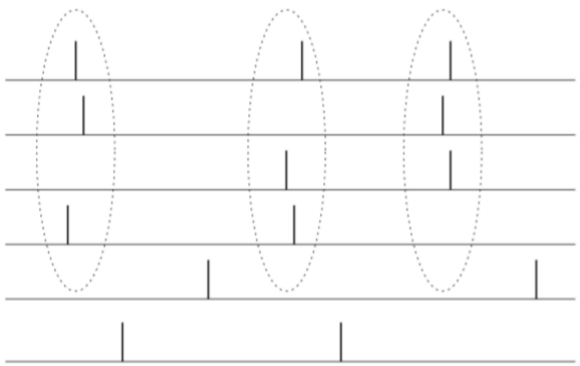
Spike-Rate coding: Population Activity



Temporal coding





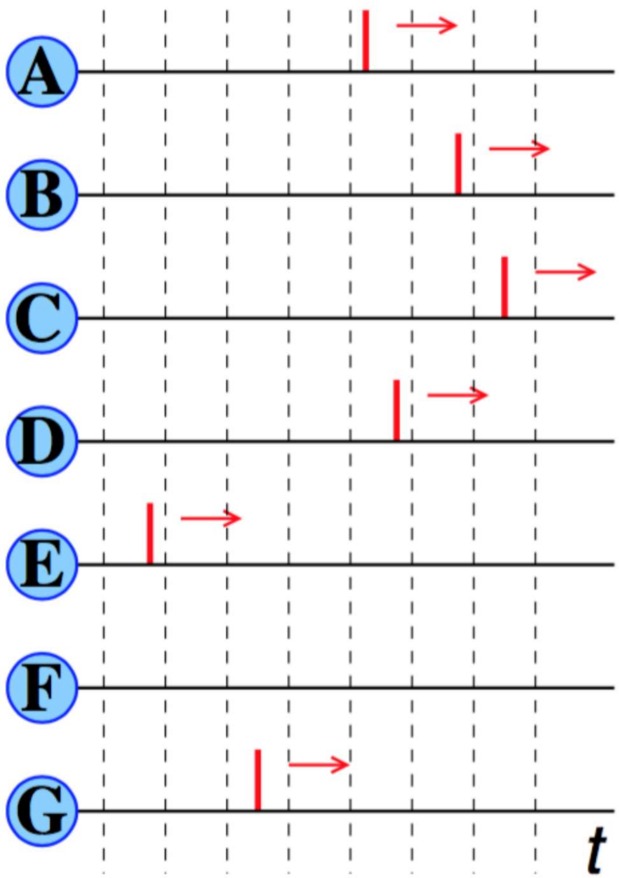


Time-to-first spike

Phase

Temporal correlation

Neural coding



count	latency	rank
1	5	3
1	6	5
1	7	6
1	5	4
1	1	1
0	–	–
1	3	2