Computing with spike timing and delays

AIMS

- Discuss the problems of the standard models using firing-rates and synaptic weights have encoding both absolute and relative sizes of stimuli.
- Describe the alternative model of using spike timing with respect to an oscillatory potential and delay lines to encode information.
- Discuss the biological plausibility and functional advantages and disadvantages of this model.

READING

- Sejnowski TJ (1995) Pattern recognition - time for a new neural code'. Nature 376 21-22.
- Hopfield J J (1995) `Pattern-recognition computation using action-potential timing for stimulus representation' Nature 376 33-36.

Types of neuronal pattern recognition.

Scale-invariant recognition.

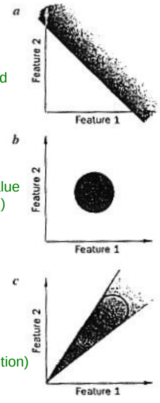
To recognise input pattern of activity $\underline{x}$ as similar to stored pattern $\underline{x}^*$, i.e. $\underline{x} \approx \lambda \underline{x}^*$, you need to encode the scale λ and the pattern (relative sizes of elements) $\underline{x}^*$, e.g. $\underline{x}^* = (2,3,1)$.

Standard neural networks have to normalise inputs to do scale-invariant recognition: losing scale information, plus weak inputs => weak connections => less important.

Linear pattern separation (perceptrons: weighted sum of firing rates & threshold)

Tuning to respond at a given absolute value (radial basis functions)

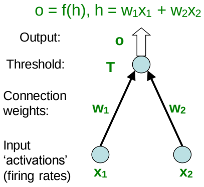
Tuning to respond to given *relative* values (scale-invariant recognition)



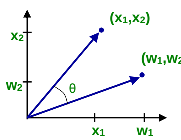
Strength-matching in standard artificial neural networks

Recap: Implications of using the 'weighted sum' of input activations as the 'net input' to the artificial neuron

$o = f(h)$, $h = w_1x_1 + w_2x_2$

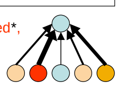


The input activations and the connection weights can be thought of as vectors $\underline{x}$ and $\underline{w}$.
The weighted sum $w_1x_1 + w_2x_2$ is also known as the 'dot product' ($\underline{w}.\underline{x}$) of $\underline{x}$ and $\underline{w}$ and depends on the angle θ between them: $\underline{w}.\underline{x} = |\underline{w}|\,|\underline{x}|\cos(\theta)$



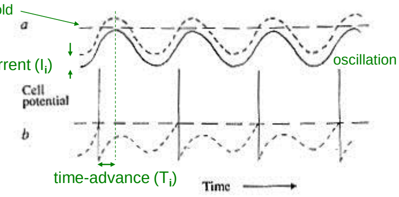
What this means is that..

If the total amounts of input activation & connection weight are limited*, the maximum net input h (& thus output firing rate) occurs when the patterns of input activations and of connection weights **match**.



* e.g. $|\underline{w}| = 1$, $|\underline{x}| = 1$.

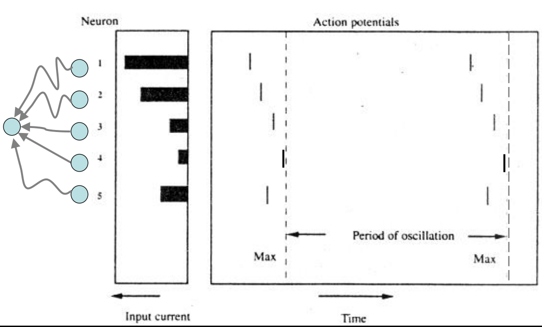
Hopfield's 1995 time-advance coding network



Code pattern $\underline{x}$ in timing of spikes relative to a sub-threshold membrane potential oscillation: i.e. intensities (strengths) of elements of stimuli as a time-advances (not a firing rates).

FIG. 1 *a*, When there is no input current, the subthreshold cell potential oscillation (solid line) never exceeds the firing threshold (horizontal broken line). When an input current is added, the cell potential (neglecting currents which flow during an action potential) will cross threshold, as shown by the broken curve. *b*, The cell potential corresponding to the broken curve in *a*, including the effect of the currents which flow during action potentials, which leave the cell in a depolarized state from which it slowly recovers. The cell potential never again exceeds the threshold for spike generation until the next cycle of the periodic oscillation. Thus the cell fires only on the upward threshold crossings of the broken line in *a*.

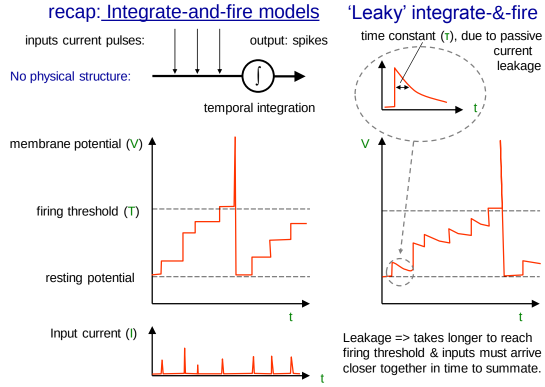
Achieve recognition by using transmission delays to match the times of spikes in the stored pattern $\underline{x}^*$ (output unit does 'coincidence detection').



Coincidence detection and current leakage

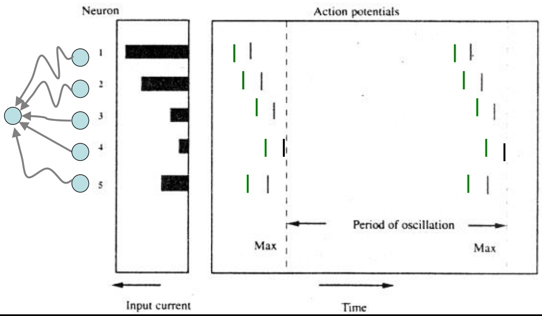
recap: Integrate-and-fire models

'Leaky' integrate-&-fire

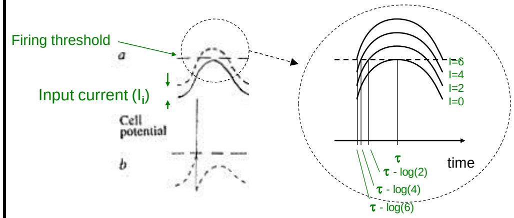


Leakage => takes longer to reach firing threshold & inputs must arrive closer together in time to summate.

If amount of time advance (T_i) is proportional to $\log(x_i)$ (e.g. input current I=log(intensity) in the retina), then the network will do scale-invariant recognition: $\log(2x_i)= \log(2) + \log(x_i)$. Doubling inputs does not change relative times & scale is not lost (it is the overall time advance).



In a range of small currents, a roughly sinusoidal membrane potential oscillation could produce something like a log coding of stimulus intensity



Can also code output, i.e. strength of recognized input, as a time advance.

Decomposition of task (different aspects of recognition) and recombination of can be done on most-confident-first (greatest overall strength) basis – as long as the oscillation is synchronised across system (e.g. EEG rhythms in olfactory bulb; hippocampus).

Provides alternative to standard models of input values = activation (firing rates) and processing using variable connection strengths. Here input values = time advance, processing via delay-lines. Can do scale-invariant recognition, as much of human recognition is (e.g. odors, voices, patterns in general).

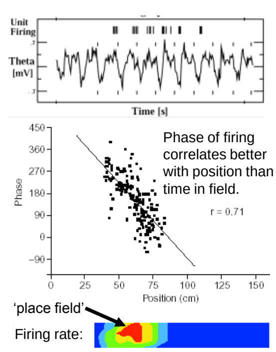
Disadvantages: need long delays (implausible in myelinated axons – but not olfactory bulb). There is no learning rule for setting the delays (or means of changing them!). Possible model is to assume a wide range of pre-existing delays and select those that lead to recognition.

But recent evidence suggests that most axons are only partially myelinated and that myelination is an active process that is required for learning..

McKenzie et al (2014) Motor skill learning requires active central myelination. *Science* 346: 318-22.

Evidence for temporal coding: The theta-phase of place cell firing

Firing phase precesses from *late* to *early* as the rat runs through the place field:



O'Keefe & Recce, 1993