

## 5. Sequence modeling with recurrent neural networks

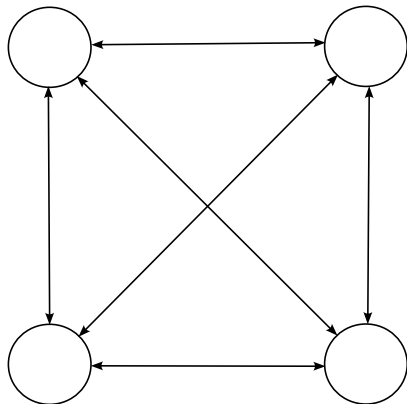
### 5.1. Structure of the Elman Recursive Neural Network

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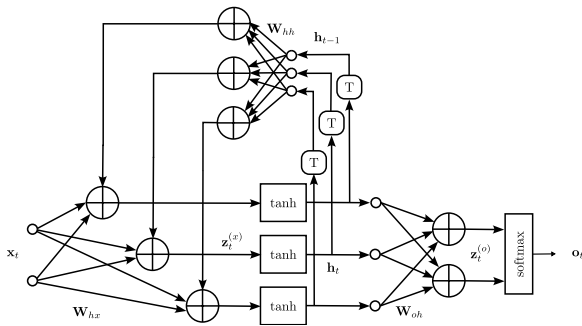
# The Hopfield network



- Introduced in 1982 by John Hopfield.
- Structure previously introduced by W. A. Little in 1974.
- First to include the idea of recurrence.
- Used in optimization as the classic travelling salesman problem.
- Continuous state versions exist.

# Structure of the Elman RNN

## State equations



$$\begin{aligned} \mathbf{z}_t^{(x)} &= \mathbf{W}_{hx}^\top \mathbf{x}_t + \mathbf{W}_{hh}^\top \mathbf{h}_{t-1} + \mathbf{b}_h \\ \mathbf{z}_t^{(o)} &= \mathbf{W}_{oh}^\top \mathbf{h}_t + \mathbf{b}_o \\ \mathbf{h}_t &= \tanh(\mathbf{z}_t^{(x)}) \\ \mathbf{o}_t &= \mathbf{o}(\mathbf{z}_t^{(o)}) = \text{softmax}(\mathbf{z}_t^{(o)}) \end{aligned} \tag{1}$$

# Structure of the Elman RNN

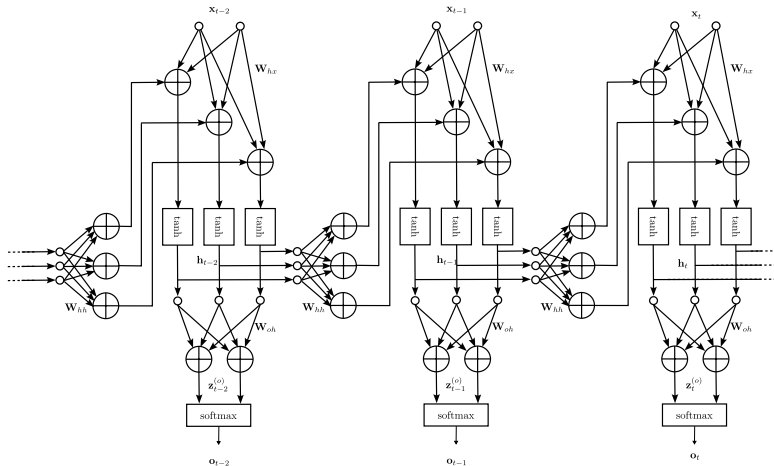
## State equations

Introduced by J. L. Elman in 1990, which follows a similar structure by M. I. Jordan, 1986.

- The input matrix  $\mathbf{W}_{HX}$  extracts features from the input sample.
- The output matrix  $\mathbf{W}_{oh}$  transforms the hidden state into an output response, through a softmax activation.
- The hidden state matrix  $\mathbf{W}_{hh}$  performs the feedback. It must store the dependencies between the past inputs and the present output.
- the hidden state itself is a summary of the past samples.
- The network is an infinite impulse response structure.

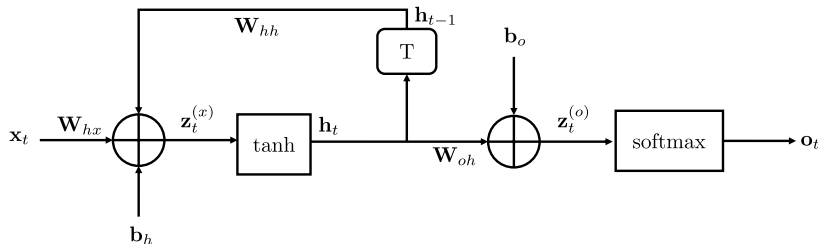
# Structure of the Elman RNN

## The Elman RNN unfolded



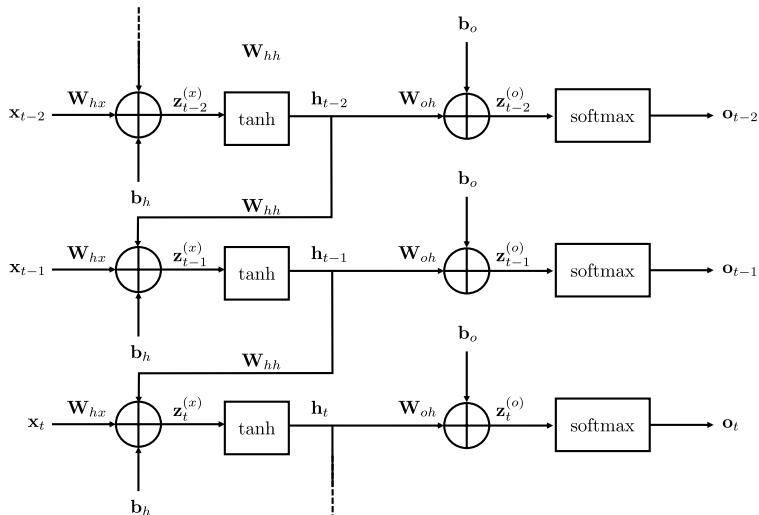
# Structure of the Elman RNN

A more compact view of the RNN



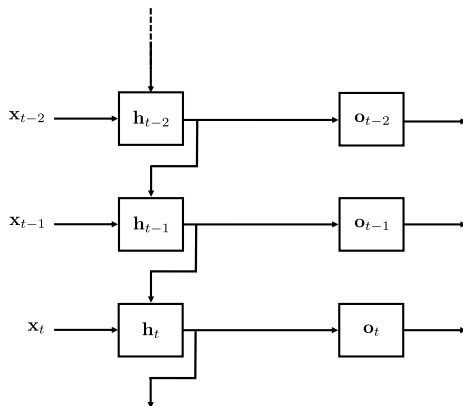
# Structure of the Elman RNN

Unfolded compact representation of the RNN



# Structure of the Elman RNN

Unfolded even more compact representation



- Input  $\mathbf{x}_t$  is transformed with  $\mathbf{W}_{hx}$ ,
- Hidden state  $\mathbf{h}_{t-1}$  is transformed with  $\mathbf{W}_{hh}$  and bias  $\mathbf{b}_h$ .
- The output of this box, transformed with a tanh, is  $\mathbf{h}_t$ .