

# Recurrent Neural Networks and Advanced Architectures for NLP

Giovanni Colavizza

Text Mining  
Amsterdam University College

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# Overview

- 1 Neural Language Models
- 2 Recurrent Neural Networks
- 3 Fancy RNNs

# Neural Language Models

# Recap

With language models, we want to compute:

- The probability of a sequence of words:  $P(w) = P(w_1, w_2, \dots, w_n)$ .
- The probability of a new word given what came before it:  
 $P(w_n | w_1, w_2, \dots, w_{n-1})$ .
- We have also seen n-gram language models which make use of the Markov assumption. For example, a trigram language model would predict the probability of a sequence of words by conditioning on the two previous words at each step:

$$P(w) = P(w_1)P(w_2|w_1)P(w_3|w_1, w_2) \dots P(w_n|w_{n-2}, w_{n-1})$$

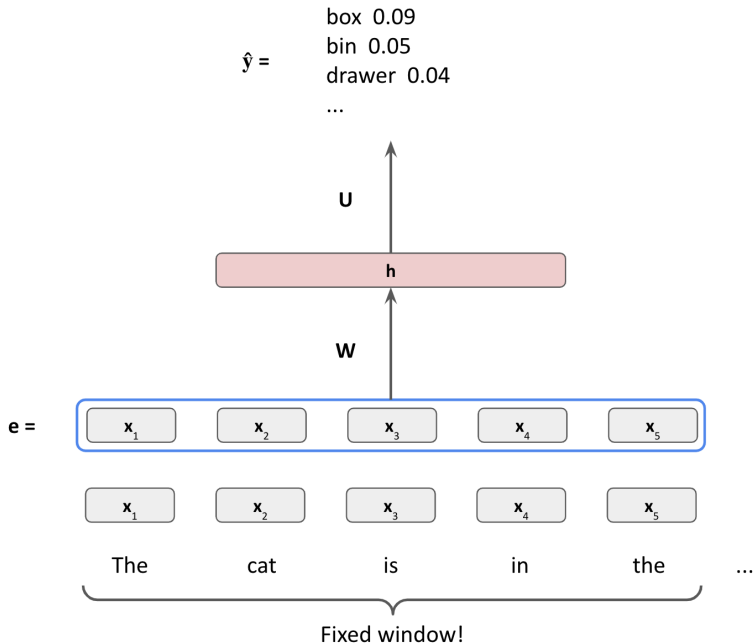
- n-gram language models have some issues, including sparsity and limited use of context.

# A first neural language model

We can start by using word embeddings as features for a **fixed-window neural language model**:

- Given a fixed-window sequence of words represented using their embeddings  $\mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_t$ ;
- we are interested in estimating the probability of the next word  $\hat{p}(\mathbf{x}_{t+1} | \mathbf{x}_1, \mathbf{x}_2, \dots, \mathbf{x}_t)$ .
- We can use the previous words' embeddings as features, concatenate them and feed them to a hidden layer with a non-linearity, and concluding by estimating probabilities with a softmax.

# A first neural language model



# A first neural language model

Where:

- Each  $\mathbf{x}$  is a  $1 \times d$  embedding vector of dimensionality  $d$ .
- $\mathbf{e} = [\mathbf{x}_1; \mathbf{x}_2; \dots; \mathbf{x}_t]$  is the concatenation of the embeddings of the words in the fixed-window preceding  $w_{t+1}$ . Therefore  $\mathbf{e}$  has dimensionality  $1 \times dk$ , where  $k$  is the number of words in the fixed-window.
- $\mathbf{h} = f(\mathbf{W}\mathbf{e}^T)$  is the hidden layer, with  $f$  an appropriate activation function and  $\mathbf{W}$  a weight matrix.  $\mathbf{W}$  has dimensionality  $dk \times h$  and  $\mathbf{h}$  has dimensionality  $1 \times h$ . The dimensionality of the embeddings and the hidden layer are hyperparameters of the model.
- Finally,  $\hat{y} = \text{softmax}(\mathbf{U}\mathbf{h}^T)$  is the predicted next word probability as estimated using a softmax function. Here  $\mathbf{U}$  is another weight matrix of dimensionality  $|V| \times h$ , so that with the softmax we predict a probability distribution over the vocabulary  $V$ .

# A first neural language model

This model is interesting, yet unfortunately:

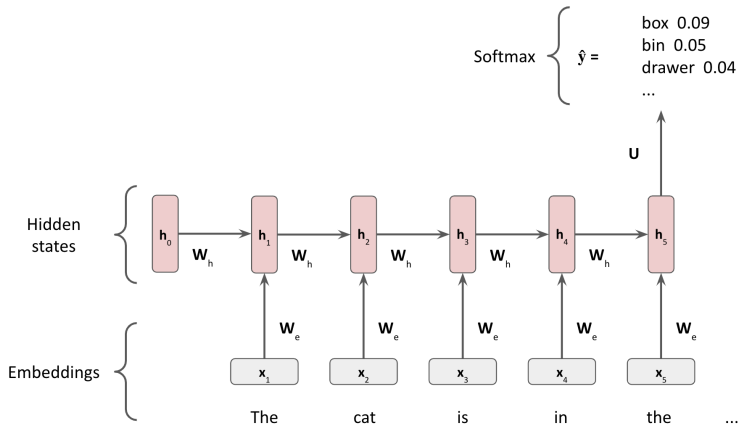
- it does not solve the use of a broader context with flexible word windows;
- larger windows would mean more parameters so scale is also an issue;
- and it does not make an efficient use of parameters and shared weights.

Can we do better? Yes, with **Recurrent Neural Networks**.



# Recurrent Neural Networks

# Recurrent architecture

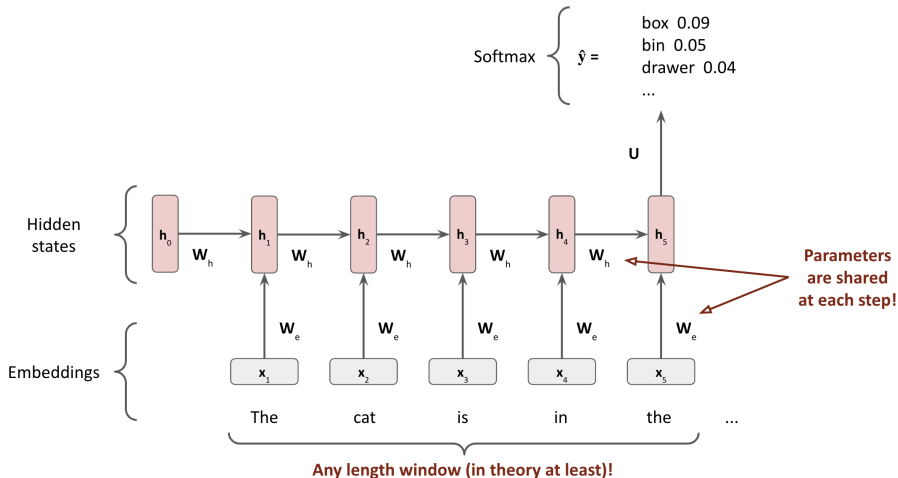


# Recurrent architecture

Where:

- Each  $\mathbf{x}$  is a  $1 \times d$  embedding vector of dimensionality  $d$ .
- $\mathbf{h}_t = f(\mathbf{W}_h \mathbf{h}_{t-1}^T + \mathbf{W}_e \mathbf{x}_t^T)$  is the hidden layer, with  $f$  an appropriate activation function,  $\mathbf{W}_e$  and  $\mathbf{W}_h$  weight matrices.  $\mathbf{W}_h$  has dimensionality  $h \times h$ ,  $\mathbf{W}_e$  has dimensionality  $h \times d$ , and  $\mathbf{h}$  has dimensionality  $1 \times h$ .  $\mathbf{h}_0$  is the initial hidden layer. The dimensionality of the embeddings and the hidden layer are hyperparameters of the model.
- Finally,  $\hat{y} = \text{softmax}(\mathbf{U} \mathbf{h}^T)$  is the predicted next word probability as estimated using a softmax function. Here  $\mathbf{U}$  is another weight matrix of dimensionality  $|V| \times h$ , so that with the softmax we predict a probability distribution over the vocabulary  $V$ .

# Recurrent architecture



# Why RNNs?

RNNs are a big step forward re. our previous concerns:

- Can process inputs on any length and use previous context of any length (in theory);
- model size does not depend on window size ( $W$  matrices remain of the same dimension);
- weights are shared across time steps.

Nevertheless, RNNs can be slow and won't really remember information from many steps back.

# Training RNNs

How can we train RNNs?

- Predict the next word at each step, and calculate the loss accordingly.
- The loss at step  $t$  is the usual **cross-entropy** (now on multiple classes), calculated for the word to be predicted at  $t + 1$ :

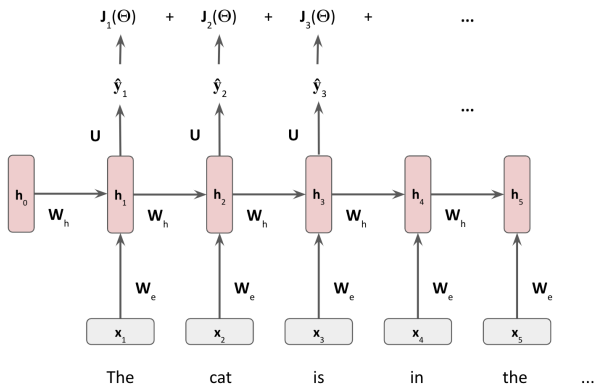
$$\mathcal{L}_t(\mathbf{W}) = - \sum_{x \in V} y_x \log(\hat{y}_x) = -\log(\hat{y}_{x_{t+1}})$$

- The overall loss is the average of the sum of the losses, calculated at each step:

$$\mathcal{L}(\mathbf{W}) = \frac{1}{T} \sum_{t=1}^T \mathcal{L}_t(\mathbf{W}) = \frac{1}{T} \sum_{t=1}^T -\log(\hat{y}_{x_{t+1}})$$

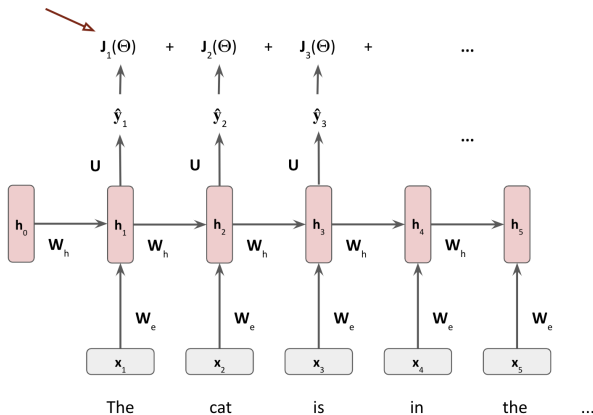
- Optimization can be done via SGD (backpropagation). Since the parameters  $\mathbf{W}$  are used repeatedly, this is sometimes called **backpropagation through time**.

# Training RNNs



# Training RNNs

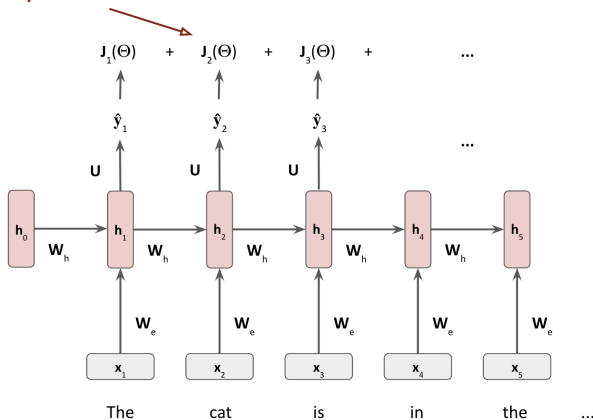
Negative log  
probability for "cat"





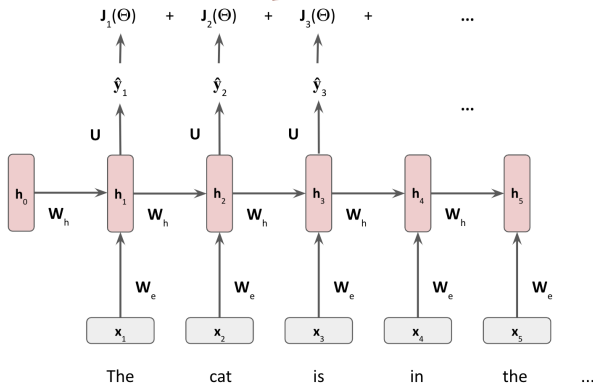
# Training RNNs

Negative log  
probability for "is"



# Training RNNs

Negative log  
probability for "in"



## Recall perplexity?

A second look at perplexity:

- We defined it as the inverse probability of the corpus, normalized by the number of words. For a corpus composed of  $n$  words:

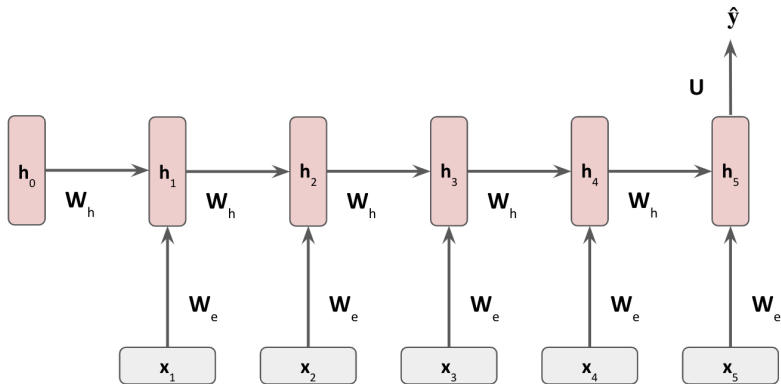
$$PP = P(w_1, w_2, \dots, w_n)^{-\frac{1}{n}} = \prod_{i=1}^n \left( \frac{1}{P(w_i | w_1, \dots, w_{i-1})} \right)^{\frac{1}{n}}$$

- It is actually equal to the exponential of the cross-entropy loss:

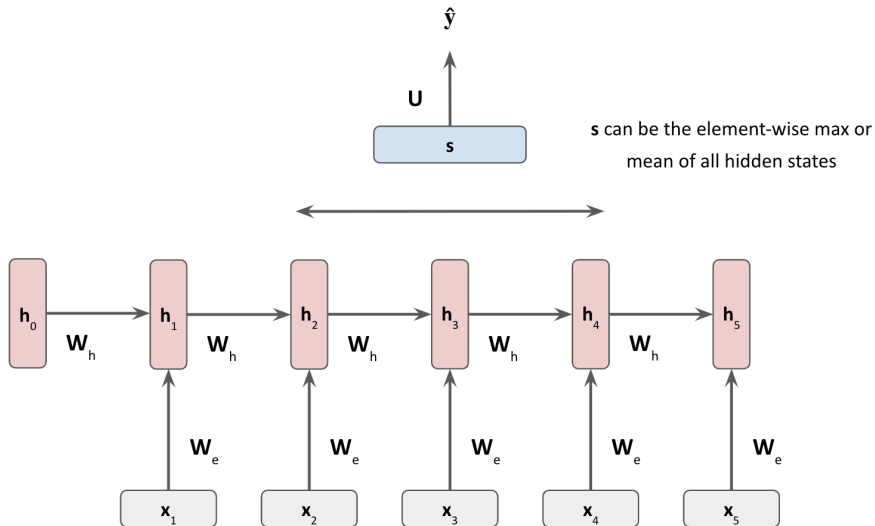
$$PP = \prod_{i=1}^n \left( \frac{1}{\hat{y}_{x_{i+1}}} \right)^{\frac{1}{n}} = \exp \left( \frac{1}{n} \sum_{i=1}^n -\log(\hat{y}_{x_{i+1}}) \right) = \exp(\mathcal{L})$$

- So *lower perplexity == lower loss == higher data likelihood*.

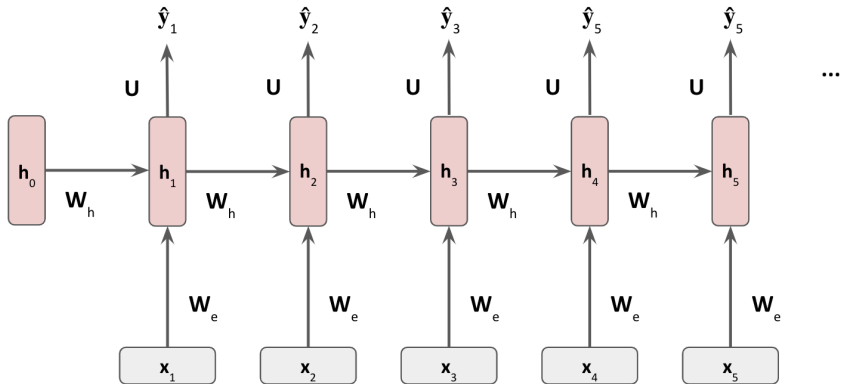
## RNN flavors: Many to one



## RNN flavors: Many to one



## RNN flavors: Many to many

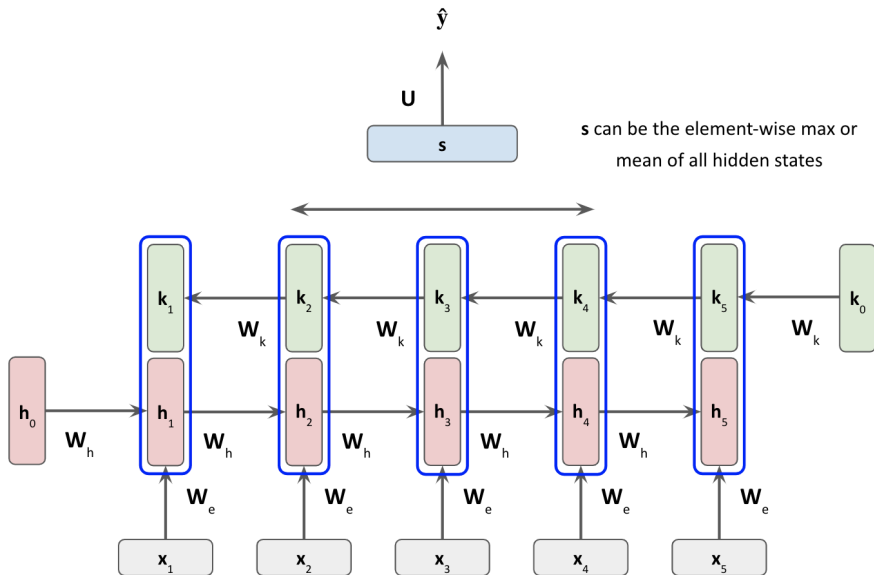


# Notes

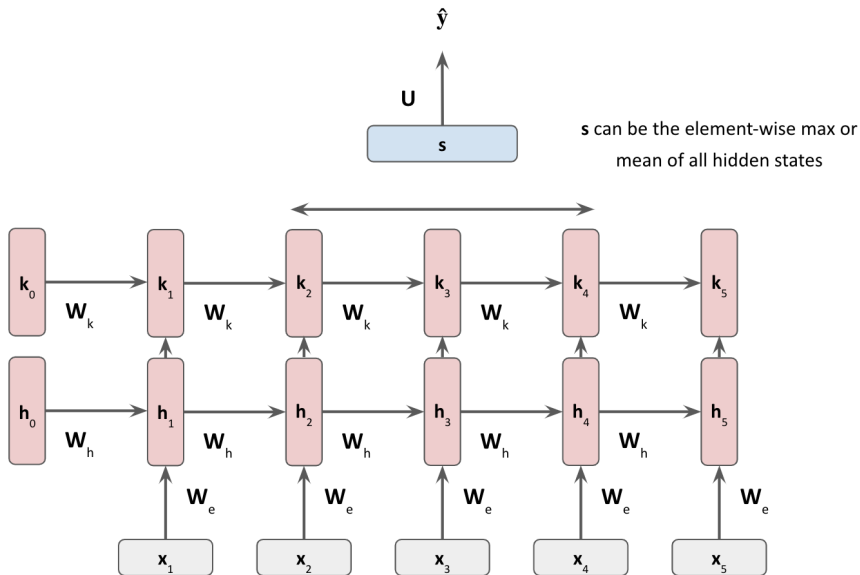
## Fancy RNNs



# Bi-RNNs

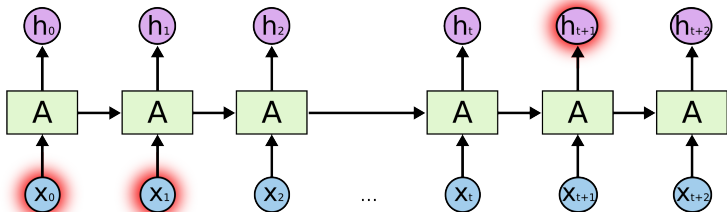


# Multilayer RNNs



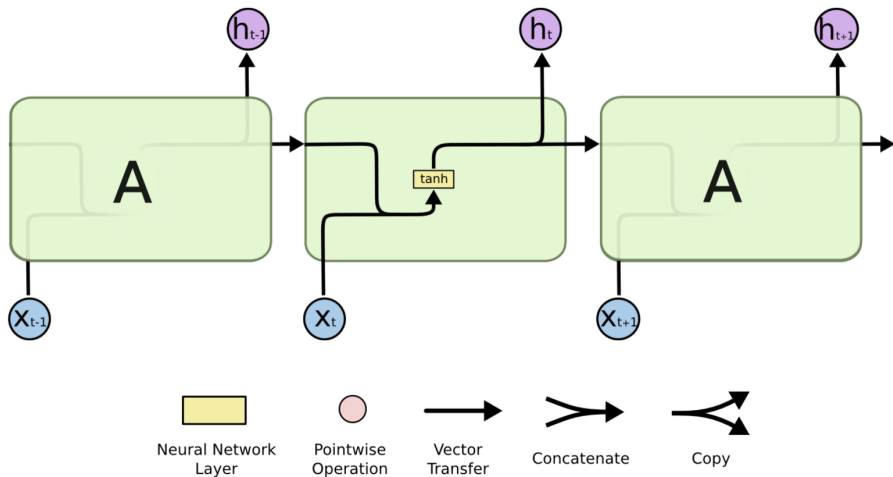
# Vanishing Gradients

- RNNs have a crucial issue: **vanishing and exploding gradients**.
- Both occur when we backpropagate through time with multiplying several times by  $W$ . If  $W$ 's parameters are small, gradients can vanish to zero. If they are large, they can explode.
- This is an issue as it does not allow to model far away context (vanishing) or to properly converge (exploding).
- Solutions:
  - 1 Exploding: **gradient clipping**.
  - 2 Vanishing: **Long Short-Term Memory** networks.



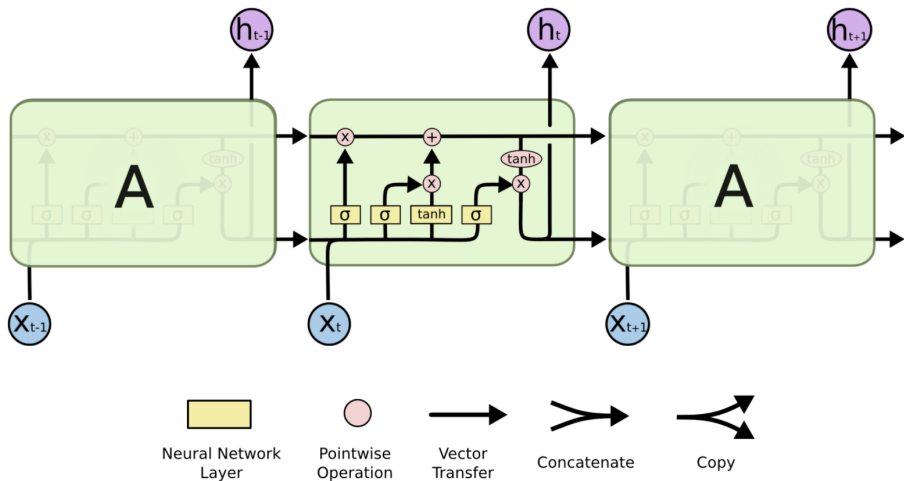
Credit: <https://colah.github.io/posts/2015-08-Understanding-LSTMs>

## A different view on RNNs



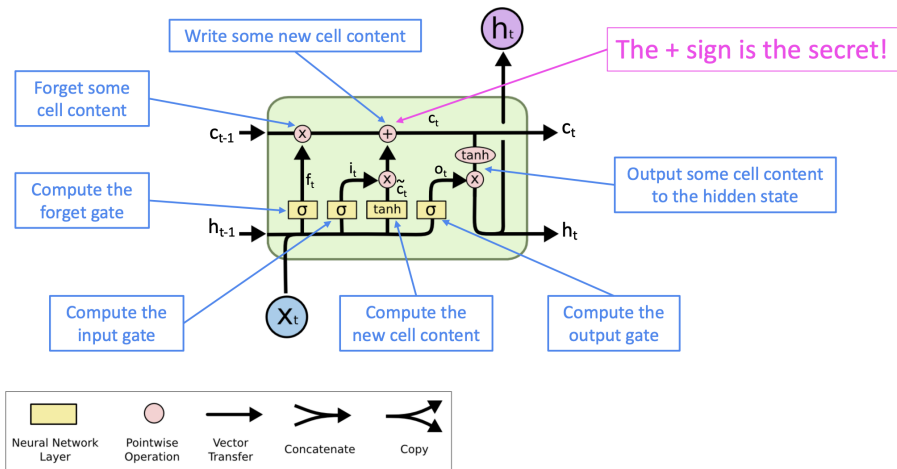
Credit: <https://colah.github.io/posts/2015-08-Understanding-LSTMs>

# LSTMs



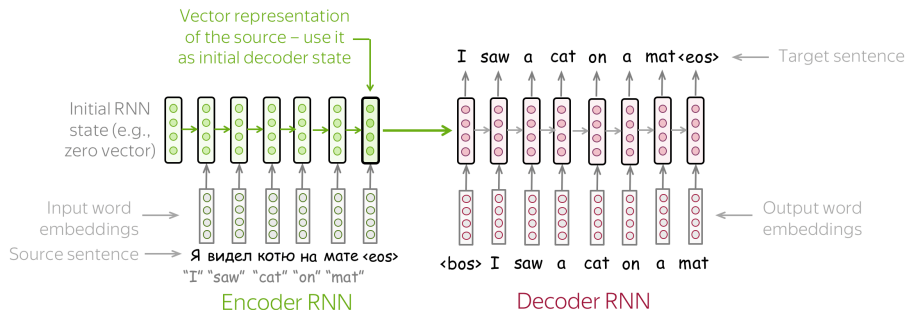
Credit: <https://colah.github.io/posts/2015-08-Understanding-LSTMs>

# LSTMs



*Credit: Stanford CS224N*

# Ses2Seq



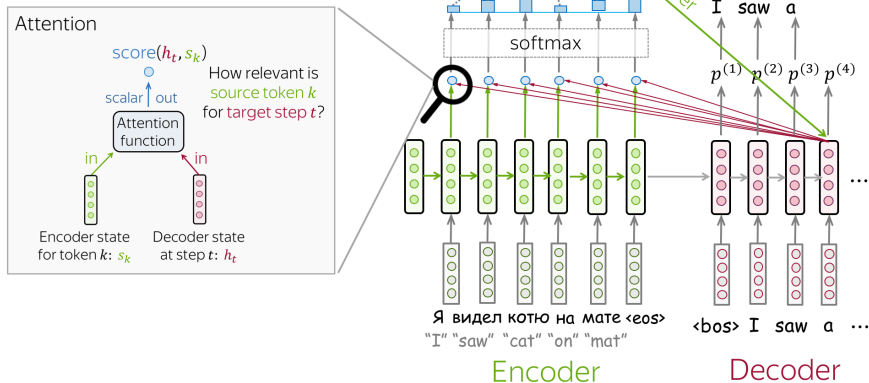
Credit: Lena Voita [https://lena-voita.github.io/nlp\\_course.html](https://lena-voita.github.io/nlp_course.html)

# Attention

Attention output: weighted sum of encoder states with attention weights

Attention weights: distribution over source tokens

A model can learn to “pay attention” to the most relevant source tokens for each step



Credit: Lena Voita [https://lena-voita.github.io/nlp\\_course.html](https://lena-voita.github.io/nlp_course.html)



## What's next

- The most recent advances in neural networks for NLP come from the shift from recurrent architectures to using **attention-based architectures**.
- For your reading assignments, you will explore **transformers** (which combine attention with other ideas from neural networks literature) and **BERT** (which is a neural language model making use of transformers).
- While there is much more to it, in this way you will have a window into contemporary models for NLP.

The next part of the course turns to other topics instead: Web scraping and APIs, recommender systems, corpus annotation, sentiment analysis and clustering with topic modelling, ethics.

# Notes