

Forget to remember Remember to forget

VLC = $\int \int \int$ Vision
Learning of VaLid
Control

Long Short Term Memories and Gated Recurrent Units

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Some of the images and animations used here were originally designed by Adam Prügel-Bennett.

Recap: An RNN is just a recursive function invocation

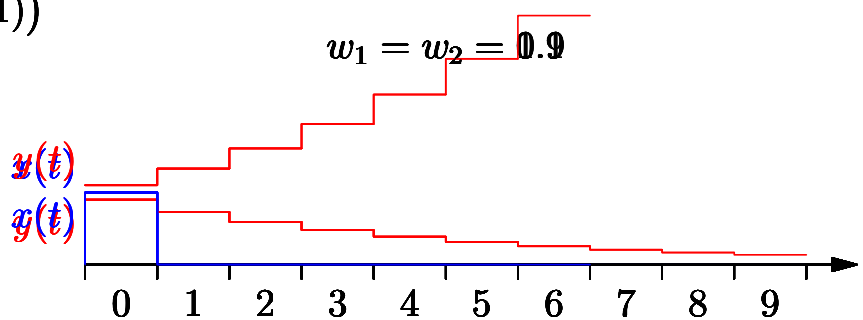
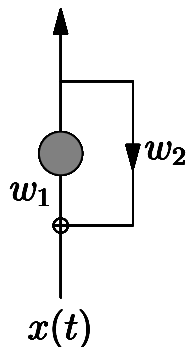
- $\mathbf{y}(t) = \mathbf{f}(\mathbf{x}(t), \mathbf{c}(t) | \mathbf{W}_f)$
- and the state $\mathbf{c}(t) = \mathbf{g}(\mathbf{x}(t), \mathbf{c}(t-1) | \mathbf{W}_g)$
- If the output $\mathbf{y}(t)$ depends on the input $\mathbf{x}(t-2)$, then prediction will be

$$\mathbf{f}(\mathbf{x}(t), \mathbf{g}(\mathbf{x}(t), \mathbf{g}(\mathbf{x}(t-1), \mathbf{g}(\mathbf{x}(t-2), \mathbf{c}(t-2) | \mathbf{W}_g) | \mathbf{W}_g) | \mathbf{W}_g) | \mathbf{W}_f)$$

- it should be clear that the gradients of this with respect to the weights can be found with the chain rule
- The back-propagated error will involve applying \mathbf{f} multiple times
- Each time the error will get multiplied by some factor a
- If $\mathbf{y}(t)$ depends on the input $\mathbf{x}(t-\tau)$ then the back-propagated signal will be proportional to $a^{\tau-1}$
- This either vanishes or explodes when τ becomes large

Vanishing and Exploding Gradients

$$y(t) = w_1 (x(t) + w_2 y(t-1))$$



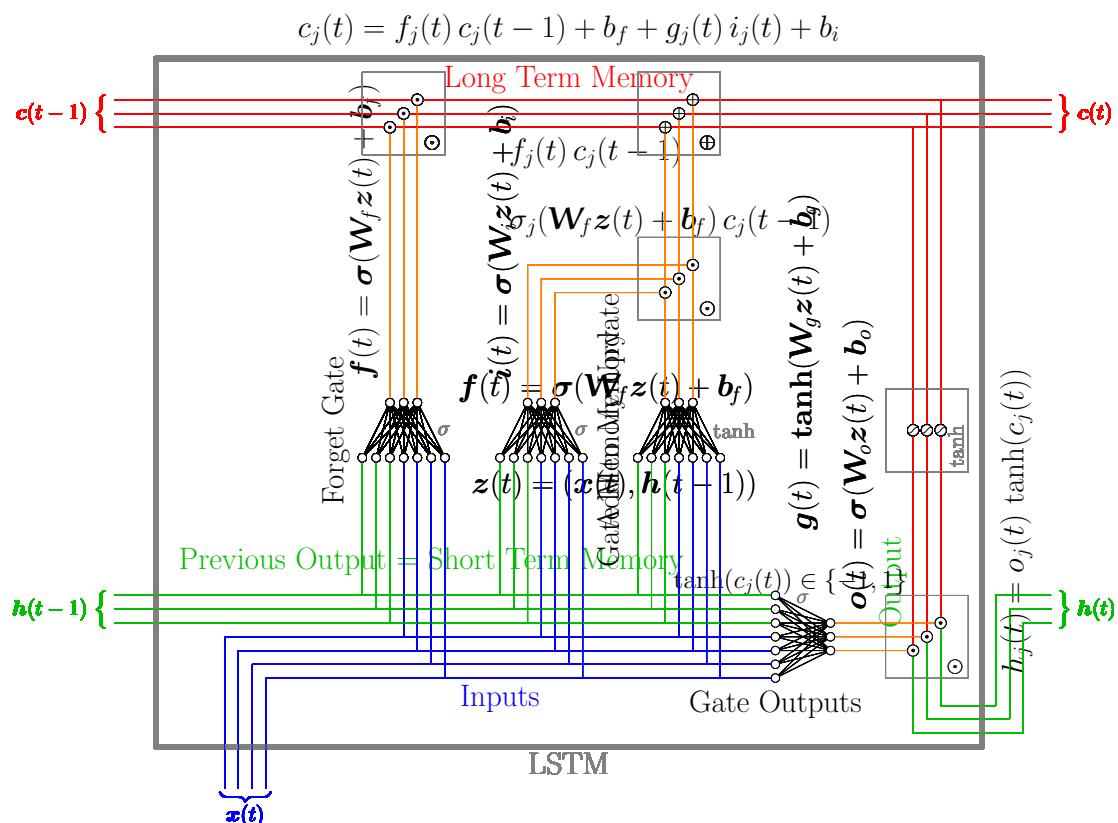
LSTM Architecture

- The LSTM (long-short term memory) was designed to solve this problem
- Key ideas: to retain a 'long-term memory' requires

$$c(t) = c(t - 1)$$

- Sometimes we have to forget and sometimes we have to change a memory
- To do this we should use 'gates' that saturate at 0 and 1
- Sigmoid functions naturally saturate at 0 and 1

LSTM Architecture



Update Equations

Initially, for $t = 1$, $\mathbf{h}(0) = \mathbf{0}$

- Inputs $\mathbf{z}(t) = (\mathbf{x}(t), \mathbf{h}(t-1))$
- Network updates (\mathbf{W}_* and \mathbf{b}_* are the learnable parameters)

$$\begin{aligned} \mathbf{f}(t) &= \sigma(\mathbf{W}_f \mathbf{z}(t) + \mathbf{b}_f) & \mathbf{i}(t) &= \sigma(\mathbf{W}_i \mathbf{z}(t) + \mathbf{b}_i) \\ \mathbf{g}(t) &= \tanh(\mathbf{W}_g \mathbf{z}(t) + \mathbf{b}_g) & \mathbf{o}(t) &= \sigma(\mathbf{W}_o \mathbf{z}(t) + \mathbf{b}_o) \end{aligned}$$

- Long-term memory update

$$\mathbf{c}(t) = \mathbf{f}(t) \odot \mathbf{c}(t-1) + \mathbf{g}(t) \odot \mathbf{i}(t)$$

- Output $\mathbf{h}(t) = \mathbf{o}(t) \odot \tanh(\mathbf{c}(t))$

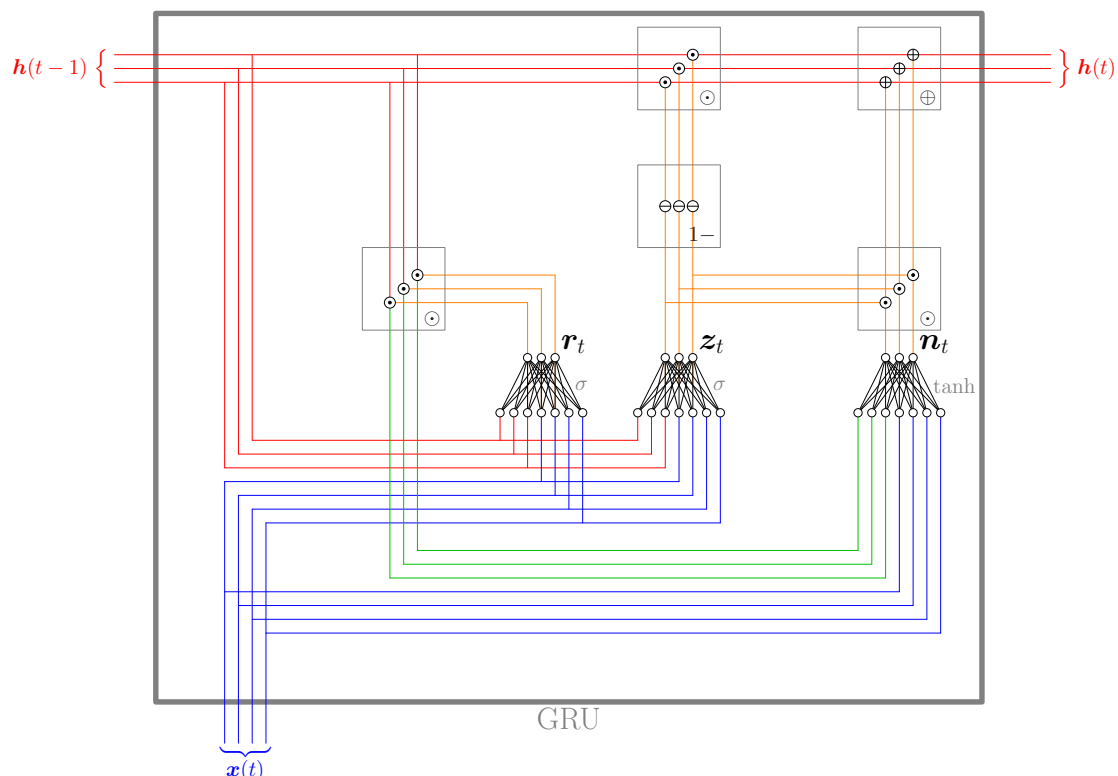
Training LSTMs

- We can train an LSTM by unwrapping it in time.
- Note that it involves four dense layers with sigmoidal (or tanh) outputs.
- This means that typically it is very slow to train.
- There are a few variants of LSTMs, but all are very similar. The most popular is probably the Gated Recurrent Unit (GRU).

- LSTMs have been used to win many competitions in speech and handwriting recognition.
- Major technology companies including Google, Apple, and Microsoft are using LSTMs as fundamental components in products.
- Google used LSTM for speech recognition on the smartphone, for Google Translate.
- Apple uses LSTM for the "Quicktype" function on the iPhone and for Siri.
- Amazon uses LSTM for Amazon Alexa.
- In 2017, Facebook performed some 4.5 billion automatic translations every day using long short-term memory networks¹.

¹https://en.wikipedia.org/wiki/Long_short-term_memory

Gated Recurrent Unit (GRU)



Gated Recurrent Unit (GRU)

- $\mathbf{x}(t)$: input vector
- $\mathbf{h}(t)$: output vector (and 'hidden state')
- $\mathbf{r}(t)$: reset gate vector
- $\mathbf{z}(t)$: update gate vector
- $\mathbf{n}(t)$: new state vector (before update is applied)
- \mathbf{W} and \mathbf{b} : parameter matrices and biases

Gated Recurrent Unit (GRU)

Initially, for $t = 1$, $\mathbf{h}(0) = \mathbf{0}$

$$\mathbf{z}(t) = \sigma(\mathbf{W}_z(\mathbf{x}(t), \mathbf{h}(t-1)) + \mathbf{b}_z)$$

$$\mathbf{r}(t) = \sigma(\mathbf{W}_r(\mathbf{x}(t), \mathbf{h}(t-1)) + \mathbf{b}_r)$$

$$\mathbf{n}(t) = \tanh(\mathbf{W}_n(\mathbf{x}(t), \mathbf{r}(t) \odot \mathbf{h}(t-1)) + \mathbf{b}_n)$$

$$\mathbf{h}(t) = (1 - \mathbf{z}(t)) \odot \mathbf{h}(t-1) + \mathbf{z}(t) \odot \mathbf{n}(t)$$

Most implementations follow the original paper and swap $(1 - \mathbf{z}(t))$ and $(\mathbf{z}(t))$ in the $\mathbf{h}(t)$ update; this doesn't change the operation of the network, but does change the interpretation of the update gate, as the gate would have to produce a 0 when an update was to occur, and a 1 when no update is to happen (which is somewhat counter-intuitive)!

- GRUs have two gates (reset and update) whereas LSTM has three gates (input/output/forget)
- GRU performance on par with LSTM but computationally more efficient (less operations & weights).
- In general, if you have a very large dataset then LSTMs will likely perform slightly better.
- GRUs are a good choice for smaller datasets.