# Long short-term memory

<https://en.wikipedia.org/wiki/Long_short-term_memory#History>

# summary

**Long short-term memory** (**LSTM**) is an artificial [recurrent neural network](https://en.wikipedia.org/wiki/Recurrent_neural_network) (RNN) architecture[[1]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-lstm1997-1) used in the field of [deep learning](https://en.wikipedia.org/wiki/Deep_learning). Unlike standard [feedforward neural networks](https://en.wikipedia.org/wiki/Feedforward_neural_network), LSTM has feedback connections. It can not only process single data points (such as images), but also entire sequences of data (such as speech or video). For example, LSTM is applicable to tasks such as unsegmented, connected [handwriting recognition](https://en.wikipedia.org/wiki/Handwriting_recognition),[[2]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-2) [speech recognition](https://en.wikipedia.org/wiki/Speech_recognition)[[3]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-sak2014-3)[[4]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-liwu2015-4) and anomaly detection in network traffic or IDSs (intrusion detection systems).

A common LSTM unit is composed of a **cell**, an **input gate**, an **output gate** and a **forget gate**. The cell remembers values over arbitrary time intervals and the three *gates* regulate the flow of information into and out of the cell.

LSTM networks are well-suited to [classifying](https://en.wikipedia.org/wiki/Classification_in_machine_learning), [processing](https://en.wikipedia.org/wiki/Computer_data_processing) and [making predictions](https://en.wikipedia.org/wiki/Predict) based on [time series](https://en.wikipedia.org/wiki/Time_series) data, since there can be lags of unknown duration between important events in a time series. LSTMs were developed to deal with the [vanishing gradient problem](https://en.wikipedia.org/wiki/Vanishing_gradient_problem) that can be encountered when training traditional RNNs. Relative insensitivity to gap length is an advantage of LSTM over RNNs, [hidden Markov models](https://en.wikipedia.org/wiki/Hidden_Markov_models) and other sequence learning methods in numerous applications.[[*citation needed*](https://en.wikipedia.org/wiki/Wikipedia:Citation_needed)]

The advantage of an LSTM cell compared to a common recurrent unit is its cell memory unit. The cell vector has the ability to encapsulate the notion of forgetting part of its previously stored memory, as well as to add part of the new information. To illustrate this, one has to [inspect the equations](https://theaisummer.com/understanding-lstm/#lstm-long-short-term-memory-cells) of the cell and the way it processes sequences under the hood.

## **History[**[**edit**](https://en.wikipedia.org/w/index.php?title=Long_short-term_memory&action=edit&section=1)**]**

**1995**-**1997:** LSTM was proposed by [Sepp Hochreiter](https://en.wikipedia.org/wiki/Sepp_Hochreiter) and [Jürgen Schmidhuber](https://en.wikipedia.org/wiki/J%C3%BCrgen_Schmidhuber).[[5]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-5)[[6]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-6)[[1]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-lstm1997-1) By introducing Constant Error Carousel (CEC) units, LSTM deals with the [vanishing gradient problem](https://en.wikipedia.org/wiki/Vanishing_gradient_problem). The initial version of LSTM block included cells, input and output gates.[[7]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-ASearchSpaceOdyssey-7)

**1999:** [Felix Gers](https://en.wikipedia.org/wiki/Felix_Gers) and his advisor [Jürgen Schmidhuber](https://en.wikipedia.org/wiki/J%C3%BCrgen_Schmidhuber) and Fred Cummins introduced the forget gate (also called “keep gate”) into LSTM architecture,[[8]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-lstm1999-8) enabling the LSTM to reset its own state.[[7]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-ASearchSpaceOdyssey-7)

**2000:** Gers & Schmidhuber & Cummins added peephole connections (connections from the cell to the gates) into the architecture.[[9]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-lstm2000-9) Additionally, the output activation function was omitted.[[7]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-ASearchSpaceOdyssey-7)

**2009:** An LSTM based model won the [ICDAR](https://en.wikipedia.org/wiki/ICDAR) connected handwriting recognition competition. Three such models were submitted by a team lead by [Alex Graves](https://en.wikipedia.org/wiki/Alex_Graves_(computer_scientist)).[[10]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-10) One was the most accurate model in the competition and another was the fastest.[[11]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-11)

**2013:** LSTM networks were a major component of a network that achieved a record 17.7% [phoneme](https://en.wikipedia.org/wiki/Phoneme) error rate on the classic [TIMIT](https://en.wikipedia.org/wiki/TIMIT) natural speech dataset.[[12]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-12)

**2014:** Kyunghyun Cho et al. put forward a simplified variant called [Gated recurrent unit](https://en.wikipedia.org/wiki/Gated_recurrent_unit) (GRU).[[13]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-13)

**2015:** Google started using an LSTM for speech recognition on Google Voice.[[14]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-Beau15-14)[[15]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-GoogleVoiceSearch-15) According to the official blog post, the new model cut transcription errors by 49%. [[16]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-16)

**2016:** Google started using an LSTM to suggest messages in the Allo conversation app.[[17]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-GoogleAllo-17) In the same year, Google released the [Google Neural Machine Translation](https://en.wikipedia.org/wiki/Google_Neural_Machine_Translation) system for Google Translate which used LSTMs to reduce translation errors by 60%.[[18]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-GoogleTranslate-18)[[19]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-WiredGoogleTranslate-19)[[20]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-20)

Apple announced in its [Worldwide Developers Conference](https://en.wikipedia.org/wiki/Apple_Worldwide_Developers_Conference) that it would start using the LSTM for quicktype[[21]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-AppleQuicktype-21)[[22]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-AppleQuicktype2-22)[[23]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-23) in the iPhone and for Siri.[[24]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-AppleSiri-24)[[25]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-25)

Amazon released [Polly](https://en.wikipedia.org/wiki/Amazon_Polly), which generates the voices behind Alexa, using a bidirectional LSTM for the text-to-speech technology.[[26]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-AmazonAlexa-26)

**2017:** Facebook performed some 4.5 billion automatic translations every day using long short-term memory networks.[[27]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-FacebookTranslate-27)

Researchers from [Michigan State University](https://en.wikipedia.org/wiki/Michigan_State_University), [IBM Research](https://en.wikipedia.org/wiki/IBM_Research), and [Cornell University](https://en.wikipedia.org/wiki/Cornell_University) published a study in the Knowledge Discovery and Data Mining (KDD) conference.[[28]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-28)[[29]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-29)[[30]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-30) Their study describes a novel neural network that performs better on certain data sets than the widely used long short-term memory neural network.

Microsoft reported reaching 94.9% recognition accuracy on the [Switchboard corpus](https://en.wikipedia.org/w/index.php?title=Switchboard_corpus&action=edit&redlink=1), incorporating a vocabulary of 165,000 words. The approach used "dialog session-based long-short-term memory".[[31]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-31)

**2019:** Researchers from the [University of Waterloo](https://en.wikipedia.org/wiki/University_of_Waterloo) proposed a related RNN architecture which represents continuous windows of time. It was derived using the [Legendre polynomials](https://en.wikipedia.org/wiki/Legendre_polynomials) and outperforms the LSTM on some memory-related benchmarks.[[32]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-32)

An LSTM model climbed to third place on the in Large Text Compression Benchmark.[[33]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-33)[[34]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-34)

## **Idea[**[**edit**](https://en.wikipedia.org/w/index.php?title=Long_short-term_memory&action=edit&section=2)**]**

In theory, classic (or "vanilla") [RNNs](https://en.wikipedia.org/wiki/Recurrent_neural_network) can keep track of arbitrary long-term dependencies in the input sequences. The problem with vanilla RNNs is computational (or practical) in nature: when training a vanilla RNN using [back-propagation](https://en.wikipedia.org/wiki/Back-propagation), the gradients which are back-propagated can ["vanish" (that is, they can tend to zero) or "explode" (that is, they can tend to infinity)](https://en.wikipedia.org/wiki/Vanishing_gradient_problem), because of the computations involved in the process, which use [finite-precision numbers](https://en.wikipedia.org/wiki/Round-off_error). RNNs using LSTM units partially solve the [vanishing gradient problem](https://en.wikipedia.org/wiki/Vanishing_gradient_problem), because LSTM units allow gradients to also flow *unchanged*. However, LSTM networks can still suffer from the exploding gradient problem.[[35]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-35)

## **Architecture[**[**edit**](https://en.wikipedia.org/w/index.php?title=Long_short-term_memory&action=edit&section=3)**]**

There are several architectures of LSTM units. A common architecture is composed of a **cell** (the memory part of the LSTM unit) and three "regulators", usually called gates, of the flow of information inside the LSTM unit: an **input gate**, an **output gate** and a **forget gate**. Some variations of the LSTM unit do not have one or more of these gates or maybe have other gates. For example, [gated recurrent units](https://en.wikipedia.org/wiki/Gated_recurrent_unit) (GRUs) do not have an output gate.

Intuitively, the *cell* is responsible for keeping track of the dependencies between the elements in the input sequence. The *input gate* controls the extent to which a new value flows into the cell, the *forget gate* controls the extent to which a value remains in the cell and the *output gate* controls the extent to which the value in the cell is used to compute the output activation of the LSTM unit. The activation function of the LSTM *gates* is often the [logistic sigmoid function](https://en.wikipedia.org/wiki/Logistic_sigmoid_function).

There are connections into and out of the LSTM *gates*, a few of which are recurrent. The weights of these connections, which need to be learned during [training](https://en.wikipedia.org/wiki/Supervised_learning), determine how the gates operate.

## **#others**

## **Training[**[**edit**](https://en.wikipedia.org/w/index.php?title=Long_short-term_memory&action=edit&section=10)**]**

A RNN using LSTM units can be trained in a supervised fashion, on a set of training sequences, using an optimization algorithm, like [gradient descent](https://en.wikipedia.org/wiki/Gradient_descent), combined with [backpropagation through time](https://en.wikipedia.org/wiki/Backpropagation_through_time) to compute the gradients needed during the optimization process, in order to change each weight of the LSTM network in proportion to the derivative of the error (at the output layer of the LSTM network) with respect to corresponding weight.

A problem with using [gradient descent](https://en.wikipedia.org/wiki/Gradient_descent) for standard RNNs is that error gradients [vanish](https://en.wikipedia.org/wiki/Vanishing_gradient_problem) exponentially quickly with the size of the time lag between important events. This is due to {\displaystyle \lim \_{n\to \infty }W^{n}=0} if the [spectral radius](https://en.wikipedia.org/wiki/Spectral_radius) of {\displaystyle W} is smaller than 1.[[40]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-40)[[41]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-gradf-41)

However, with LSTM units, when error values are back-propagated from the output layer, the error remains in the LSTM unit's cell. This "error carousel" continuously feeds error back to each of the LSTM unit's gates, until they learn to cut off the value.

### CTC score function**[**[**edit**](https://en.wikipedia.org/w/index.php?title=Long_short-term_memory&action=edit&section=11)**]**

Many applications use stacks of LSTM RNNs[[42]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-fernandez2007-42) and train them by [connectionist temporal classification (CTC)](https://en.wikipedia.org/wiki/Connectionist_temporal_classification_(CTC))[[43]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-graves2006-43) to find an RNN weight matrix that maximizes the probability of the label sequences in a training set, given the corresponding input sequences. CTC achieves both alignment and recognition.

### Alternatives**[**[**edit**](https://en.wikipedia.org/w/index.php?title=Long_short-term_memory&action=edit&section=12)**]**

Sometimes, it can be advantageous to train (parts of) an LSTM by [neuroevolution](https://en.wikipedia.org/wiki/Neuroevolution)[[44]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-wierstra2005-44) or by policy gradient methods, especially when there is no "teacher" (that is, training labels).

#### Success[[edit](https://en.wikipedia.org/w/index.php?title=Long_short-term_memory&action=edit&section=13)]

There have been several successful stories of training, in a non-supervised fashion, RNNs with LSTM units.

In 2018, [Bill Gates](https://en.wikipedia.org/wiki/Bill_Gates) called it a “huge milestone in advancing artificial intelligence” when bots developed by [OpenAI](https://en.wikipedia.org/wiki/OpenAI) were able to beat humans in the game of Dota 2.[[45]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-OpenAIfive-45) OpenAI Five consists of five independent but coordinated neural networks. Each network is trained by a policy gradient method without supervising teacher and contains a single-layer, 1024-unit Long-Short-Term-Memory that sees the current game state and emits actions through several possible action heads.[[45]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-OpenAIfive-45)

In 2018, [OpenAI](https://en.wikipedia.org/wiki/OpenAI) also trained a similar LSTM by policy gradients to control a human-like robot hand that manipulates physical objects with unprecedented dexterity.[[46]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-OpenAIhand-46)

In 2019, [DeepMind](https://en.wikipedia.org/wiki/DeepMind)'s program AlphaStar used a deep LSTM core to excel at the complex video game [Starcraft II](https://en.wikipedia.org/wiki/Starcraft_II).[[47]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-alphastar-47) This was viewed as significant progress towards Artificial General Intelligence.[[47]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-alphastar-47)

## **Applications[**[**edit**](https://en.wikipedia.org/w/index.php?title=Long_short-term_memory&action=edit&section=14)**]**

Applications of LSTM include:

* [Robot control](https://en.wikipedia.org/wiki/Robot_control)[[48]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-48)
* [Time series prediction](https://en.wikipedia.org/wiki/Time_series_prediction)[[44]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-wierstra2005-44)
* [Speech recognition](https://en.wikipedia.org/wiki/Speech_recognition)[[49]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-49)[[50]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-50)[[51]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-ReferenceA-51)
* Rhythm learning[[37]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-peephole2002-37)
* Music composition[[52]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-52)
* Grammar learning[[53]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-53)[[36]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-peepholeLSTM-36)[[54]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-54)
* [Handwriting recognition](https://en.wikipedia.org/wiki/Handwriting_recognition)[[55]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-55)[[56]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-56)
* Human action recognition[[57]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-57)
* [Sign language translation](https://en.wikipedia.org/wiki/Sign_language)[[58]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-58)
* Protein homology detection[[59]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-59)
* Predicting subcellular localization of proteins[[60]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-60)
* Time series anomaly detection[[61]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-61)
* Several prediction tasks in the area of business process management[[62]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-62)
* Prediction in medical care pathways[[63]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-63)
* [Semantic parsing](https://en.wikipedia.org/wiki/Semantic_parsing)[[64]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-64)
* [Object co-segmentation](https://en.wikipedia.org/wiki/Object_co-segmentation)[[65]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-Wang_Duan_Zhang_Niu_p=1657-65)[[66]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-Duan_Wang_Zhai_Zheng_2018_p.-66)
* Airport passenger management[[67]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-67)
* Short-term [traffic forecast](https://en.wikipedia.org/wiki/Traffic_forecast)[[68]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-68)
* [Drug design](https://en.wikipedia.org/wiki/Drug_design)[[69]](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_note-pmid29095571-69)

## **See also[**[**edit**](https://en.wikipedia.org/w/index.php?title=Long_short-term_memory&action=edit&section=15)**]**

* [Recurrent neural network](https://en.wikipedia.org/wiki/Recurrent_neural_network)
* [Deep learning](https://en.wikipedia.org/wiki/Deep_learning)
* [Gated recurrent unit](https://en.wikipedia.org/wiki/Gated_recurrent_unit)
* [Differentiable neural computer](https://en.wikipedia.org/wiki/Differentiable_neural_computer)
* [Long-term potentiation](https://en.wikipedia.org/wiki/Long-term_potentiation)
* [Prefrontal cortex basal ganglia working memory](https://en.wikipedia.org/wiki/Prefrontal_cortex_basal_ganglia_working_memory)
* [Time series](https://en.wikipedia.org/wiki/Time_series)
* [Seq2seq](https://en.wikipedia.org/wiki/Seq2seq)
* [Highway network](https://en.wikipedia.org/wiki/Highway_network)

## **References[**[**edit**](https://en.wikipedia.org/w/index.php?title=Long_short-term_memory&action=edit&section=16)**]**

* 1. ^ [Jump up to:***a***](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-lstm1997_1-0) [***b***](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-lstm1997_1-1) [***c***](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-lstm1997_1-2) [*Sepp Hochreiter*](https://en.wikipedia.org/wiki/Sepp_Hochreiter); [*Jürgen Schmidhuber*](https://en.wikipedia.org/wiki/J%C3%BCrgen_Schmidhuber) (1997). [*"Long short-term memory"*](https://www.researchgate.net/publication/13853244). [*Neural Computation*](https://en.wikipedia.org/wiki/Neural_Computation_(journal)). **9** (8): 1735–1780. [*doi*](https://en.wikipedia.org/wiki/Doi_(identifier)):[*10.1162/neco.1997.9.8.1735*](https://doi.org/10.1162%2Fneco.1997.9.8.1735). [*PMID*](https://en.wikipedia.org/wiki/PMID_(identifier)) [*9377276*](https://pubmed.ncbi.nlm.nih.gov/9377276). [*S2CID*](https://en.wikipedia.org/wiki/S2CID_(identifier)) [*1915014*](https://api.semanticscholar.org/CorpusID:1915014).
  2. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-2) Graves, A.; Liwicki, M.; Fernandez, S.; Bertolami, R.; Bunke, H.; [*Schmidhuber, J.*](https://en.wikipedia.org/wiki/J%C3%BCrgen_Schmidhuber) (2009). [*"A Novel Connectionist System for Improved Unconstrained Handwriting Recognition"*](http://www.idsia.ch/~juergen/tpami_2008.pdf) *(PDF)*. IEEE Transactions on Pattern Analysis and Machine Intelligence. **31** (5): 855–868. [*CiteSeerX*](https://en.wikipedia.org/wiki/CiteSeerX_(identifier)) [*10.1.1.139.4502*](https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.139.4502). [*doi*](https://en.wikipedia.org/wiki/Doi_(identifier)):[*10.1109/tpami.2008.137*](https://doi.org/10.1109%2Ftpami.2008.137). [*PMID*](https://en.wikipedia.org/wiki/PMID_(identifier)) [*19299860*](https://pubmed.ncbi.nlm.nih.gov/19299860). [*S2CID*](https://en.wikipedia.org/wiki/S2CID_(identifier)) [*14635907*](https://api.semanticscholar.org/CorpusID:14635907).
  3. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-sak2014_3-0) Sak, Hasim; Senior, Andrew; Beaufays, Francoise (2014). [*"Long Short-Term Memory recurrent neural network architectures for large scale acoustic modeling"*](https://web.archive.org/web/20180424203806/https:/static.googleusercontent.com/media/research.google.com/en/pubs/archive/43905.pdf) *(PDF)*. Archived from [*the original*](https://static.googleusercontent.com/media/research.google.com/en/pubs/archive/43905.pdf) *(PDF)* on 2018-04-24.
  4. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-liwu2015_4-0) Li, Xiangang; Wu, Xihong (2014-10-15). "Constructing Long Short-Term Memory based Deep Recurrent Neural Networks for Large Vocabulary Speech Recognition". [*arXiv*](https://en.wikipedia.org/wiki/ArXiv_(identifier)):[*1410.4281*](https://arxiv.org/abs/1410.4281) [[*cs.CL*](https://arxiv.org/archive/cs.CL)].
  5. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-5) [*Sepp Hochreiter*](https://en.wikipedia.org/wiki/Sepp_Hochreiter); [*Jürgen Schmidhuber*](https://en.wikipedia.org/wiki/J%C3%BCrgen_Schmidhuber) (21 August 1995), [*Long Short Term Memory*](ftp://ftp.idsia.ch/pub/juergen/fki-207-95.ps.gz), [Wikidata](https://en.wikipedia.org/wiki/WDQ_(identifier)) [Q98967430](https://www.wikidata.org/wiki/Q98967430)
  6. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-6) [*Sepp Hochreiter*](https://en.wikipedia.org/wiki/Sepp_Hochreiter); [*Jürgen Schmidhuber*](https://en.wikipedia.org/wiki/J%C3%BCrgen_Schmidhuber) (1997), [*"LSTM can Solve Hard Long Time Lag Problems"*](https://papers.nips.cc/paper/1215-lstm-can-solve-hard-long-time-lag-problems.pdf) *(PDF)*, Advances in Neural Information Processing Systems 9, [*Advances in Neural Information Processing Systems*](https://en.wikipedia.org/wiki/Advances_in_Neural_Information_Processing_Systems), [Wikidata](https://en.wikipedia.org/wiki/WDQ_(identifier)) [Q77698282](https://www.wikidata.org/wiki/Q77698282)
  7. ^ [Jump up to:***a***](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-ASearchSpaceOdyssey_7-0) [***b***](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-ASearchSpaceOdyssey_7-1) [***c***](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-ASearchSpaceOdyssey_7-2) [***d***](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-ASearchSpaceOdyssey_7-3) Klaus Greff; Rupesh Kumar Srivastava; Jan Koutník; Bas R. Steunebrink; Jürgen Schmidhuber (2015). "LSTM: A Search Space Odyssey". IEEE Transactions on Neural Networks and Learning Systems. **28** (10): 2222–2232. [*arXiv*](https://en.wikipedia.org/wiki/ArXiv_(identifier)):[*1503.04069*](https://arxiv.org/abs/1503.04069). [*Bibcode*](https://en.wikipedia.org/wiki/Bibcode_(identifier)):[*2015arXiv150304069G*](https://ui.adsabs.harvard.edu/abs/2015arXiv150304069G). [*doi*](https://en.wikipedia.org/wiki/Doi_(identifier)):[*10.1109/TNNLS.2016.2582924*](https://doi.org/10.1109%2FTNNLS.2016.2582924). [*PMID*](https://en.wikipedia.org/wiki/PMID_(identifier)) [*27411231*](https://pubmed.ncbi.nlm.nih.gov/27411231). [*S2CID*](https://en.wikipedia.org/wiki/S2CID_(identifier)) [*3356463*](https://api.semanticscholar.org/CorpusID:3356463).
  8. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-lstm1999_8-0) Gers, F.A. (1999). "Learning to forget: Continual prediction with LSTM". 9th International Conference on Artificial Neural Networks: ICANN '99. **1999**. pp. 850–855. [*doi*](https://en.wikipedia.org/wiki/Doi_(identifier)):[*10.1049/cp:19991218*](https://doi.org/10.1049%2Fcp%3A19991218). [*ISBN*](https://en.wikipedia.org/wiki/ISBN_(identifier)) [*0-85296-721-7*](https://en.wikipedia.org/wiki/Special:BookSources/0-85296-721-7).
  9. ^ [Jump up to:***a***](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-lstm2000_9-0) [***b***](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-lstm2000_9-1) Felix A. Gers; Jürgen Schmidhuber; Fred Cummins (2000). "Learning to Forget: Continual Prediction with LSTM". [*Neural Computation*](https://en.wikipedia.org/wiki/Neural_Computation_(journal)). **12** (10): 2451–2471. [*CiteSeerX*](https://en.wikipedia.org/wiki/CiteSeerX_(identifier)) [*10.1.1.55.5709*](https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.55.5709). [*doi*](https://en.wikipedia.org/wiki/Doi_(identifier)):[*10.1162/089976600300015015*](https://doi.org/10.1162%2F089976600300015015). [*PMID*](https://en.wikipedia.org/wiki/PMID_(identifier)) [*11032042*](https://pubmed.ncbi.nlm.nih.gov/11032042). [*S2CID*](https://en.wikipedia.org/wiki/S2CID_(identifier)) [*11598600*](https://api.semanticscholar.org/CorpusID:11598600).
  10. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-10) Graves, A.; Liwicki, M.; Fernández, S.; Bertolami, R.; Bunke, H.; Schmidhuber, J. (May 2009). "A Novel Connectionist System for Unconstrained Handwriting Recognition". IEEE Transactions on Pattern Analysis and Machine Intelligence. **31** (5): 855–868. [*CiteSeerX*](https://en.wikipedia.org/wiki/CiteSeerX_(identifier)) [*10.1.1.139.4502*](https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.139.4502). [*doi*](https://en.wikipedia.org/wiki/Doi_(identifier)):[*10.1109/tpami.2008.137*](https://doi.org/10.1109%2Ftpami.2008.137). [*ISSN*](https://en.wikipedia.org/wiki/ISSN_(identifier)) [*0162-8828*](https://www.worldcat.org/issn/0162-8828). [*PMID*](https://en.wikipedia.org/wiki/PMID_(identifier)) [*19299860*](https://pubmed.ncbi.nlm.nih.gov/19299860). [*S2CID*](https://en.wikipedia.org/wiki/S2CID_(identifier)) [*14635907*](https://api.semanticscholar.org/CorpusID:14635907).
  11. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-11) Märgner, Volker; Abed, Haikal El (July 2009). "ICDAR 2009 Arabic Handwriting Recognition Competition". 2009 10th International Conference on Document Analysis and Recognition: 1383–1387. [*doi*](https://en.wikipedia.org/wiki/Doi_(identifier)):[*10.1109/ICDAR.2009.256*](https://doi.org/10.1109%2FICDAR.2009.256). [*ISBN*](https://en.wikipedia.org/wiki/ISBN_(identifier)) [*978-1-4244-4500-4*](https://en.wikipedia.org/wiki/Special:BookSources/978-1-4244-4500-4). [*S2CID*](https://en.wikipedia.org/wiki/S2CID_(identifier)) [*52851337*](https://api.semanticscholar.org/CorpusID:52851337).
  12. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-12) Graves, Alex; Mohamed, Abdel-rahman; Hinton, Geoffrey (2013-03-22). "Speech Recognition with Deep Recurrent Neural Networks". [*arXiv*](https://en.wikipedia.org/wiki/ArXiv_(identifier)):[*1303.5778*](https://arxiv.org/abs/1303.5778) [[*cs.NE*](https://arxiv.org/archive/cs.NE)].
  13. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-13) Cho, Kyunghyun; van Merrienboer, Bart; Gulcehre, Caglar; Bahdanau, Dzmitry; Bougares, Fethi; Schwenk, Holger; Bengio, Yoshua (2014). "Learning Phrase Representations using RNN Encoder-Decoder for Statistical Machine Translation". [*arXiv*](https://en.wikipedia.org/wiki/ArXiv_(identifier)):[*1406.1078*](https://arxiv.org/abs/1406.1078) [[*cs.CL*](https://arxiv.org/archive/cs.CL)].
  14. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-Beau15_14-0) Beaufays, Françoise (August 11, 2015). [*"The neural networks behind Google Voice transcription"*](http://googleresearch.blogspot.co.at/2015/08/the-neural-networks-behind-google-voice.html). Research Blog*. Retrieved 2017-06-27*.
  15. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-GoogleVoiceSearch_15-0) Sak, Haşim; Senior, Andrew; Rao, Kanishka; Beaufays, Françoise; Schalkwyk, Johan (September 24, 2015). [*"Google voice search: faster and more accurate"*](http://googleresearch.blogspot.co.uk/2015/09/google-voice-search-faster-and-more.html). Research Blog*. Retrieved 2017-06-27*.
  16. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-16) [*"Neon prescription... or rather, New transcription for Google Voice"*](https://googleblog.blogspot.com/2015/07/neon-prescription-or-rather-new.html). Official Google Blog*. Retrieved 2020-04-25*.
  17. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-GoogleAllo_17-0) Khaitan, Pranav (May 18, 2016). [*"Chat Smarter with Allo"*](http://googleresearch.blogspot.co.at/2016/05/chat-smarter-with-allo.html). Research Blog*. Retrieved 2017-06-27*.
  18. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-GoogleTranslate_18-0) Wu, Yonghui; Schuster, Mike; Chen, Zhifeng; Le, Quoc V.; Norouzi, Mohammad; Macherey, Wolfgang; Krikun, Maxim; Cao, Yuan; Gao, Qin (2016-09-26). "Google's Neural Machine Translation System: Bridging the Gap between Human and Machine Translation". [*arXiv*](https://en.wikipedia.org/wiki/ArXiv_(identifier)):[*1609.08144*](https://arxiv.org/abs/1609.08144) [[*cs.CL*](https://arxiv.org/archive/cs.CL)].
  19. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-WiredGoogleTranslate_19-0) Metz, Cade (September 27, 2016). [*"An Infusion of AI Makes Google Translate More Powerful Than Ever | WIRED"*](https://www.wired.com/2016/09/google-claims-ai-breakthrough-machine-translation/). Wired*. Retrieved 2017-06-27*.
  20. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-20) [*"A Neural Network for Machine Translation, at Production Scale"*](http://ai.googleblog.com/2016/09/a-neural-network-for-machine.html). Google AI Blog*. Retrieved 2020-04-25*.
  21. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-AppleQuicktype_21-0) Efrati, Amir (June 13, 2016). [*"Apple's Machines Can Learn Too"*](https://www.theinformation.com/apples-machines-can-learn-too). The Information*. Retrieved 2017-06-27*.
  22. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-AppleQuicktype2_22-0) Ranger, Steve (June 14, 2016). [*"iPhone, AI and big data: Here's how Apple plans to protect your privacy | ZDNet"*](https://www.zdnet.com/article/ai-big-data-and-the-iphone-heres-how-apple-plans-to-protect-your-privacy). ZDNet*. Retrieved 2017-06-27*.
  23. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-23) [*"Can Global Semantic Context Improve Neural Language Models? - Apple"*](https://machinelearning.apple.com/2018/09/27/can-global-semantic-context-improve-neural-language-models.html). Apple Machine Learning Journal*. Retrieved 2020-04-30*.
  24. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-AppleSiri_24-0) Smith, Chris (2016-06-13). [*"iOS 10: Siri now works in third-party apps, comes with extra AI features"*](http://bgr.com/2016/06/13/ios-10-siri-third-party-apps/). BGR*. Retrieved 2017-06-27*.
  25. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-25) Capes, Tim; Coles, Paul; Conkie, Alistair; Golipour, Ladan; Hadjitarkhani, Abie; Hu, Qiong; Huddleston, Nancy; Hunt, Melvyn; Li, Jiangchuan; Neeracher, Matthias; Prahallad, Kishore (2017-08-20). [*"Siri On-Device Deep Learning-Guided Unit Selection Text-to-Speech System"*](http://www.isca-speech.org/archive/Interspeech_2017/abstracts/1798.html). Interspeech 2017. ISCA: 4011–4015. [*doi*](https://en.wikipedia.org/wiki/Doi_(identifier)):[*10.21437/Interspeech.2017-1798*](https://doi.org/10.21437%2FInterspeech.2017-1798).
  26. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-AmazonAlexa_26-0) Vogels, Werner (30 November 2016). [*"Bringing the Magic of Amazon AI and Alexa to Apps on AWS. – All Things Distributed"*](http://www.allthingsdistributed.com/2016/11/amazon-ai-and-alexa-for-all-aws-apps.html). www.allthingsdistributed.com*. Retrieved 2017-06-27*.
  27. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-FacebookTranslate_27-0) Ong, Thuy (4 August 2017). [*"Facebook's translations are now powered completely by AI"*](https://www.theverge.com/2017/8/4/16093872/facebook-ai-translations-artificial-intelligence). www.allthingsdistributed.com*. Retrieved 2019-02-15*.
  28. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-28) [*"Patient Subtyping via Time-Aware LSTM Networks"*](http://biometrics.cse.msu.edu/Publications/MachineLearning/Baytasetal_PatientSubtypingViaTimeAwareLSTMNetworks.pdf) *(PDF)*. msu.edu*. Retrieved 21 Nov 2018*.
  29. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-29) [*"Patient Subtyping via Time-Aware LSTM Networks"*](http://www.kdd.org/kdd2017/papers/view/patient-subtyping-via-time-aware-lstm-networks). Kdd.org*. Retrieved 24 May 2018*.
  30. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-30) [*"SIGKDD"*](http://www.kdd.org/). Kdd.org*. Retrieved 24 May 2018*.
  31. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-31) Haridy, Rich (August 21, 2017). [*"Microsoft's speech recognition system is now as good as a human"*](http://newatlas.com/microsoft-speech-recognition-equals-humans/50999). newatlas.com*. Retrieved 2017-08-27*.
  32. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-32) Voelker, Aaron R.; Kajić, Ivana; Eliasmith, Chris (2019). [*Legendre Memory Units: Continuous-Time Representation in Recurrent Neural Networks*](http://compneuro.uwaterloo.ca/files/publications/voelker.2019.lmu.pdf) *(PDF)*. [*Advances in Neural Information Processing Systems*](https://neurips.cc/).
  33. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-33) [*"The Large Text Compression Benchmark"*](http://www.mattmahoney.net/dc/text.html#1218)*. Retrieved 2017-01-13*.
  34. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-34) Fabrice Bellard (2019), "[Lossless Data Compression with Neural Networks](https://bellard.org/nncp/nncp.pdf)"
  35. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-35) bro, n. [*"Why can RNNs with LSTM units also suffer from "exploding gradients"?"*](https://stats.stackexchange.com/q/320919/82135). Cross Validated*. Retrieved 25 December 2018*.
  36. ^ [Jump up to:***a***](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-peepholeLSTM_36-0) [***b***](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-peepholeLSTM_36-1) [***c***](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-peepholeLSTM_36-2) Gers, F. A.; Schmidhuber, J. (2001). [*"LSTM Recurrent Networks Learn Simple Context Free and Context Sensitive Languages"*](ftp://ftp.idsia.ch/pub/juergen/L-IEEE.pdf) *(PDF)*. IEEE Transactions on Neural Networks. **12** (6): 1333–1340. [*doi*](https://en.wikipedia.org/wiki/Doi_(identifier)):[*10.1109/72.963769*](https://doi.org/10.1109%2F72.963769). [*PMID*](https://en.wikipedia.org/wiki/PMID_(identifier)) [*18249962*](https://pubmed.ncbi.nlm.nih.gov/18249962).
  37. ^ [Jump up to:***a***](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-peephole2002_37-0) [***b***](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-peephole2002_37-1) [***c***](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-peephole2002_37-2) Gers, F.; Schraudolph, N.; Schmidhuber, J. (2002). [*"Learning precise timing with LSTM recurrent networks"*](http://www.jmlr.org/papers/volume3/gers02a/gers02a.pdf)*(PDF)*. Journal of Machine Learning Research. **3**: 115–143.
  38. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-38) Gers, F. A.; Schmidhuber, E. (November 2001). [*"LSTM recurrent networks learn simple context-free and context-sensitive languages"*](ftp://ftp.idsia.ch/pub/juergen/L-IEEE.pdf) *(PDF)*. IEEE Transactions on Neural Networks. **12** (6): 1333–1340. [*doi*](https://en.wikipedia.org/wiki/Doi_(identifier)):[*10.1109/72.963769*](https://doi.org/10.1109%2F72.963769). [*ISSN*](https://en.wikipedia.org/wiki/ISSN_(identifier)) [*1045-9227*](https://www.worldcat.org/issn/1045-9227). [*PMID*](https://en.wikipedia.org/wiki/PMID_(identifier)) [*18249962*](https://pubmed.ncbi.nlm.nih.gov/18249962).
  39. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-39) Xingjian Shi; Zhourong Chen; Hao Wang; Dit-Yan Yeung; Wai-kin Wong; Wang-chun Woo (2015). "Convolutional LSTM Network: A Machine Learning Approach for Precipitation Nowcasting". Proceedings of the 28th International Conference on Neural Information Processing Systems: 802–810. [*arXiv*](https://en.wikipedia.org/wiki/ArXiv_(identifier)):[*1506.04214*](https://arxiv.org/abs/1506.04214). [*Bibcode*](https://en.wikipedia.org/wiki/Bibcode_(identifier)):[*2015arXiv150604214S*](https://ui.adsabs.harvard.edu/abs/2015arXiv150604214S).
  40. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-40) S. Hochreiter. Untersuchungen zu dynamischen neuronalen Netzen. Diploma thesis, Institut f. Informatik, Technische Univ. Munich, 1991.
  41. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-gradf_41-0) Hochreiter, S.; Bengio, Y.; Frasconi, P.; Schmidhuber, J. (2001). [*"Gradient Flow in Recurrent Nets: the Difficulty of Learning Long-Term Dependencies (PDF Download Available)"*](https://www.researchgate.net/publication/2839938). In Kremer and, S. C.; Kolen, J. F. (eds.). A Field Guide to Dynamical Recurrent Neural Networks. IEEE Press.
  42. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-fernandez2007_42-0) Fernández, Santiago; Graves, Alex; Schmidhuber, Jürgen (2007). "Sequence labelling in structured domains with hierarchical recurrent neural networks". Proc. 20th Int. Joint Conf. On Artificial Intelligence, Ijcai 2007: 774–779. [*CiteSeerX*](https://en.wikipedia.org/wiki/CiteSeerX_(identifier)) [*10.1.1.79.1887*](https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.79.1887).
  43. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-graves2006_43-0) Graves, Alex; Fernández, Santiago; Gomez, Faustino (2006). "Connectionist temporal classification: Labelling unsegmented sequence data with recurrent neural networks". In Proceedings of the International Conference on Machine Learning, ICML 2006: 369–376. [*CiteSeerX*](https://en.wikipedia.org/wiki/CiteSeerX_(identifier)) [*10.1.1.75.6306*](https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.75.6306).
  44. ^ [Jump up to:***a***](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-wierstra2005_44-0) [***b***](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-wierstra2005_44-1) Wierstra, Daan; Schmidhuber, J.; Gomez, F. J. (2005). [*"Evolino: Hybrid Neuroevolution/Optimal Linear Search for Sequence Learning"*](https://www.academia.edu/5830256). Proceedings of the 19th International Joint Conference on Artificial Intelligence (IJCAI), Edinburgh: 853–858.
  45. ^ [Jump up to:***a***](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-OpenAIfive_45-0) [***b***](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-OpenAIfive_45-1) Rodriguez, Jesus (July 2, 2018). [*"The Science Behind OpenAI Five that just Produced One of the Greatest Breakthrough in the History of AI"*](https://towardsdatascience.com/the-science-behind-openai-five-that-just-produced-one-of-the-greatest-breakthrough-in-the-history-b045bcdc2b69). Towards Data Science*. Retrieved 2019-01-15*.
  46. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-OpenAIhand_46-0) [*"Learning Dexterity"*](https://blog.openai.com/learning-dexterity/). OpenAI Blog. July 30, 2018*. Retrieved 2019-01-15*.
  47. ^ [Jump up to:***a***](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-alphastar_47-0) [***b***](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-alphastar_47-1) Stanford, Stacy (January 25, 2019). [*"DeepMind's AI, AlphaStar Showcases Significant Progress Towards AGI"*](https://medium.com/mlmemoirs/deepminds-ai-alphastar-showcases-significant-progress-towards-agi-93810c94fbe9). Medium ML Memoirs*. Retrieved 2019-01-15*.
  48. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-48) Mayer, H.; Gomez, F.; Wierstra, D.; Nagy, I.; Knoll, A.; Schmidhuber, J. (October 2006). A System for Robotic Heart Surgery that Learns to Tie Knots Using Recurrent Neural Networks. 2006 IEEE/RSJ International Conference on Intelligent Robots and Systems. pp. 543–548. [*CiteSeerX*](https://en.wikipedia.org/wiki/CiteSeerX_(identifier)) [*10.1.1.218.3399*](https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.218.3399). [*doi*](https://en.wikipedia.org/wiki/Doi_(identifier)):[*10.1109/IROS.2006.282190*](https://doi.org/10.1109%2FIROS.2006.282190). [*ISBN*](https://en.wikipedia.org/wiki/ISBN_(identifier)) [*978-1-4244-0258-8*](https://en.wikipedia.org/wiki/Special:BookSources/978-1-4244-0258-8). [*S2CID*](https://en.wikipedia.org/wiki/S2CID_(identifier)) [*12284900*](https://api.semanticscholar.org/CorpusID:12284900).
  49. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-49) Graves, A.; Schmidhuber, J. (2005). "Framewise phoneme classification with bidirectional LSTM and other neural network architectures". Neural Networks. **18** (5–6): 602–610. [*CiteSeerX*](https://en.wikipedia.org/wiki/CiteSeerX_(identifier)) [*10.1.1.331.5800*](https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.331.5800). [*doi*](https://en.wikipedia.org/wiki/Doi_(identifier)):[*10.1016/j.neunet.2005.06.042*](https://doi.org/10.1016%2Fj.neunet.2005.06.042). [*PMID*](https://en.wikipedia.org/wiki/PMID_(identifier)) [*16112549*](https://pubmed.ncbi.nlm.nih.gov/16112549).
  50. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-50) Fernández, Santiago; Graves, Alex; Schmidhuber, Jürgen (2007). [*An Application of Recurrent Neural Networks to Discriminative Keyword Spotting*](http://dl.acm.org/citation.cfm?id=1778066.1778092). Proceedings of the 17th International Conference on Artificial Neural Networks. ICANN'07. Berlin, Heidelberg: Springer-Verlag. pp. 220–229. [*ISBN*](https://en.wikipedia.org/wiki/ISBN_(identifier)) [*978-3540746935*](https://en.wikipedia.org/wiki/Special:BookSources/978-3540746935).
  51. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-ReferenceA_51-0) Graves, Alex; Mohamed, Abdel-rahman; Hinton, Geoffrey (2013). "Speech Recognition with Deep Recurrent Neural Networks". Acoustics, Speech and Signal Processing (ICASSP), 2013 IEEE International Conference on: 6645–6649. [*arXiv*](https://en.wikipedia.org/wiki/ArXiv_(identifier)):[*1303.5778*](https://arxiv.org/abs/1303.5778). [*doi*](https://en.wikipedia.org/wiki/Doi_(identifier)):[*10.1109/ICASSP.2013.6638947*](https://doi.org/10.1109%2FICASSP.2013.6638947). [*ISBN*](https://en.wikipedia.org/wiki/ISBN_(identifier)) [*978-1-4799-0356-6*](https://en.wikipedia.org/wiki/Special:BookSources/978-1-4799-0356-6). [*S2CID*](https://en.wikipedia.org/wiki/S2CID_(identifier)) [*206741496*](https://api.semanticscholar.org/CorpusID:206741496).
  52. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-52) Eck, Douglas; Schmidhuber, Jürgen (2002-08-28). Learning the Long-Term Structure of the Blues. Artificial Neural Networks — ICANN 2002. Lecture Notes in Computer Science. **2415**. Springer, Berlin, Heidelberg. pp. 284–289. [*CiteSeerX*](https://en.wikipedia.org/wiki/CiteSeerX_(identifier)) [*10.1.1.116.3620*](https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.116.3620). [*doi*](https://en.wikipedia.org/wiki/Doi_(identifier)):[*10.1007/3-540-46084-5\_47*](https://doi.org/10.1007%2F3-540-46084-5_47). [*ISBN*](https://en.wikipedia.org/wiki/ISBN_(identifier)) [*978-3540460848*](https://en.wikipedia.org/wiki/Special:BookSources/978-3540460848).
  53. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-53) Schmidhuber, J.; Gers, F.; Eck, D.; Schmidhuber, J.; Gers, F. (2002). "Learning nonregular languages: A comparison of simple recurrent networks and LSTM". Neural Computation. **14** (9): 2039–2041. [*CiteSeerX*](https://en.wikipedia.org/wiki/CiteSeerX_(identifier)) [*10.1.1.11.7369*](https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.11.7369). [*doi*](https://en.wikipedia.org/wiki/Doi_(identifier)):[*10.1162/089976602320263980*](https://doi.org/10.1162%2F089976602320263980). [*PMID*](https://en.wikipedia.org/wiki/PMID_(identifier)) [*12184841*](https://pubmed.ncbi.nlm.nih.gov/12184841). [*S2CID*](https://en.wikipedia.org/wiki/S2CID_(identifier)) [*30459046*](https://api.semanticscholar.org/CorpusID:30459046).
  54. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-54) Perez-Ortiz, J. A.; Gers, F. A.; Eck, D.; Schmidhuber, J. (2003). "Kalman filters improve LSTM network performance in problems unsolvable by traditional recurrent nets". Neural Networks. **16** (2): 241–250. [*CiteSeerX*](https://en.wikipedia.org/wiki/CiteSeerX_(identifier)) [*10.1.1.381.1992*](https://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.381.1992). [*doi*](https://en.wikipedia.org/wiki/Doi_(identifier)):[*10.1016/s0893-6080(02)00219-8*](https://doi.org/10.1016%2Fs0893-6080%2802%2900219-8). [*PMID*](https://en.wikipedia.org/wiki/PMID_(identifier)) [*12628609*](https://pubmed.ncbi.nlm.nih.gov/12628609).
  55. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-55) A. Graves, J. Schmidhuber. Offline Handwriting Recognition with Multidimensional Recurrent Neural Networks. Advances in Neural Information Processing Systems 22, NIPS'22, pp 545–552, Vancouver, MIT Press, 2009.
  56. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-56) Graves, Alex; Fernández, Santiago; Liwicki, Marcus; Bunke, Horst; Schmidhuber, Jürgen (2007). [*Unconstrained Online Handwriting Recognition with Recurrent Neural Networks*](http://dl.acm.org/citation.cfm?id=2981562.2981635). Proceedings of the 20th International Conference on Neural Information Processing Systems. NIPS'07. USA: Curran Associates Inc. pp. 577–584. [*ISBN*](https://en.wikipedia.org/wiki/ISBN_(identifier)) [*9781605603520*](https://en.wikipedia.org/wiki/Special:BookSources/9781605603520).
  57. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-57) M. Baccouche, F. Mamalet, C Wolf, C. Garcia, A. Baskurt. Sequential Deep Learning for Human Action Recognition. 2nd International Workshop on Human Behavior Understanding (HBU), A.A. Salah, B. Lepri ed. Amsterdam, Netherlands. pp. 29–39. Lecture Notes in Computer Science 7065. Springer. 2011
  58. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-58) Huang, Jie; Zhou, Wengang; Zhang, Qilin; Li, Houqiang; Li, Weiping (2018-01-30). "Video-based Sign Language Recognition without Temporal Segmentation". [*arXiv*](https://en.wikipedia.org/wiki/ArXiv_(identifier)):[*1801.10111*](https://arxiv.org/abs/1801.10111) [[*cs.CV*](https://arxiv.org/archive/cs.CV)].
  59. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-59) Hochreiter, S.; Heusel, M.; Obermayer, K. (2007). [*"Fast model-based protein homology detection without alignment"*](https://doi.org/10.1093%2Fbioinformatics%2Fbtm247). Bioinformatics. **23** (14): 1728–1736. [*doi*](https://en.wikipedia.org/wiki/Doi_(identifier)):[*10.1093/bioinformatics/btm247*](https://doi.org/10.1093%2Fbioinformatics%2Fbtm247). [*PMID*](https://en.wikipedia.org/wiki/PMID_(identifier)) [*17488755*](https://pubmed.ncbi.nlm.nih.gov/17488755).
  60. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-60) Thireou, T.; Reczko, M. (2007). [*"Bidirectional Long Short-Term Memory Networks for predicting the subcellular localization of eukaryotic proteins"*](https://www.semanticscholar.org/paper/2985b87fc977d8a893da6086b2a18298b9650d96). IEEE/ACM Transactions on Computational Biology and Bioinformatics. **4** (3): 441–446. [*doi*](https://en.wikipedia.org/wiki/Doi_(identifier)):[*10.1109/tcbb.2007.1015*](https://doi.org/10.1109%2Ftcbb.2007.1015). [*PMID*](https://en.wikipedia.org/wiki/PMID_(identifier)) [*17666763*](https://pubmed.ncbi.nlm.nih.gov/17666763). [*S2CID*](https://en.wikipedia.org/wiki/S2CID_(identifier)) [*11787259*](https://api.semanticscholar.org/CorpusID:11787259).
  61. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-61) Malhotra, Pankaj; Vig, Lovekesh; Shroff, Gautam; Agarwal, Puneet (April 2015). [*"Long Short Term Memory Networks for Anomaly Detection in Time Series"*](https://www.elen.ucl.ac.be/Proceedings/esann/esannpdf/es2015-56.pdf) *(PDF)*. European Symposium on Artificial Neural Networks, Computational Intelligence and Machine Learning — ESANN 2015.
  62. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-62) Tax, N.; Verenich, I.; La Rosa, M.; Dumas, M. (2017). Predictive Business Process Monitoring with LSTM neural networks. Proceedings of the International Conference on Advanced Information Systems Engineering (CAiSE). Lecture Notes in Computer Science. **10253**. pp. 477–492. [*arXiv*](https://en.wikipedia.org/wiki/ArXiv_(identifier)):[*1612.02130*](https://arxiv.org/abs/1612.02130). [*doi*](https://en.wikipedia.org/wiki/Doi_(identifier)):[*10.1007/978-3-319-59536-8\_30*](https://doi.org/10.1007%2F978-3-319-59536-8_30). [*ISBN*](https://en.wikipedia.org/wiki/ISBN_(identifier)) [*978-3-319-59535-1*](https://en.wikipedia.org/wiki/Special:BookSources/978-3-319-59535-1). [*S2CID*](https://en.wikipedia.org/wiki/S2CID_(identifier)) [*2192354*](https://api.semanticscholar.org/CorpusID:2192354).
  63. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-63) Choi, E.; Bahadori, M.T.; Schuetz, E.; Stewart, W.; Sun, J. (2016). [*"Doctor AI: Predicting Clinical Events via Recurrent Neural Networks"*](http://proceedings.mlr.press/v56/Choi16.html). Proceedings of the 1st Machine Learning for Healthcare Conference. **56**: 301–318. [*arXiv*](https://en.wikipedia.org/wiki/ArXiv_(identifier)):[*1511.05942*](https://arxiv.org/abs/1511.05942). [*Bibcode*](https://en.wikipedia.org/wiki/Bibcode_(identifier)):[*2015arXiv151105942C*](https://ui.adsabs.harvard.edu/abs/2015arXiv151105942C). [*PMC*](https://en.wikipedia.org/wiki/PMC_(identifier)) [*5341604*](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5341604). [*PMID*](https://en.wikipedia.org/wiki/PMID_(identifier)) [*28286600*](https://pubmed.ncbi.nlm.nih.gov/28286600).
  64. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-64) Jia, Robin; Liang, Percy (2016-06-11). ["Data Recombination for Neural Semantic Parsing"](https://arxiv.org/abs/1606.03622). *arXiv:1606.03622 [cs]*.
  65. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-Wang_Duan_Zhang_Niu_p=1657_65-0) Wang, Le; Duan, Xuhuan; Zhang, Qilin; Niu, Zhenxing; Hua, Gang; Zheng, Nanning (2018-05-22). [*"Segment-Tube: Spatio-Temporal Action Localization in Untrimmed Videos with Per-Frame Segmentation"*](https://qilin-zhang.github.io/_pages/pdfs/Segment-Tube_Spatio-Temporal_Action_Localization_in_Untrimmed_Videos_with_Per-Frame_Segmentation.pdf) *(PDF)*. Sensors. **18** (5): 1657. [*doi*](https://en.wikipedia.org/wiki/Doi_(identifier)):[*10.3390/s18051657*](https://doi.org/10.3390%2Fs18051657). [*ISSN*](https://en.wikipedia.org/wiki/ISSN_(identifier)) [*1424-8220*](https://www.worldcat.org/issn/1424-8220). [*PMC*](https://en.wikipedia.org/wiki/PMC_(identifier)) [*5982167*](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5982167). [*PMID*](https://en.wikipedia.org/wiki/PMID_(identifier)) [*29789447*](https://pubmed.ncbi.nlm.nih.gov/29789447).
  66. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-Duan_Wang_Zhai_Zheng_2018_p._66-0) Duan, Xuhuan; Wang, Le; Zhai, Changbo; Zheng, Nanning; Zhang, Qilin; Niu, Zhenxing; Hua, Gang (2018). Joint Spatio-Temporal Action Localization in Untrimmed Videos with Per-Frame Segmentation. 25th IEEE International Conference on Image Processing (ICIP). [*doi*](https://en.wikipedia.org/wiki/Doi_(identifier)):[*10.1109/icip.2018.8451692*](https://doi.org/10.1109%2Ficip.2018.8451692). [*ISBN*](https://en.wikipedia.org/wiki/ISBN_(identifier)) [*978-1-4799-7061-2*](https://en.wikipedia.org/wiki/Special:BookSources/978-1-4799-7061-2).
  67. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-67) Orsini, F.; Gastaldi, M.; Mantecchini, L.; Rossi, R. (2019). Neural networks trained with WiFi traces to predict airport passenger behavior. 6th International Conference on Models and Technologies for Intelligent Transportation Systems. Krakow: IEEE. [*arXiv*](https://en.wikipedia.org/wiki/ArXiv_(identifier)):[*1910.14026*](https://arxiv.org/abs/1910.14026). [*doi*](https://en.wikipedia.org/wiki/Doi_(identifier)):[*10.1109/MTITS.2019.8883365*](https://doi.org/10.1109%2FMTITS.2019.8883365). 8883365.
  68. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-68) Zhao, Z.; Chen, W.; Wu, X.; Chen, P.C.Y.; Liu, J. (2017). "LSTM network: A deep learning approach for Short-term traffic forecast". IET Intelligent Transport Systems. **11** (2): 68–75. [*doi*](https://en.wikipedia.org/wiki/Doi_(identifier)):[*10.1049/iet-its.2016.0208*](https://doi.org/10.1049%2Fiet-its.2016.0208).
  69. [**^**](https://en.wikipedia.org/wiki/Long_short-term_memory#cite_ref-pmid29095571_69-0) Gupta A, Müller AT, Huisman BJH, Fuchs JA, Schneider P, Schneider G (2018). [*"Generative Recurrent Networks for De Novo Drug Design"*](https://www.ncbi.nlm.nih.gov/entrez/eutils/elink.fcgi?dbfrom=pubmed&tool=sumsearch.org/cite&retmode=ref&cmd=prlinks&id=29095571). Mol Inform. **37** (1–2). [*doi*](https://en.wikipedia.org/wiki/Doi_(identifier)):[*10.1002/minf.201700111*](https://doi.org/10.1002%2Fminf.201700111). [*PMC*](https://en.wikipedia.org/wiki/PMC_(identifier)) [*5836943*](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5836943). [*PMID*](https://en.wikipedia.org/wiki/PMID_(identifier)) [*29095571*](https://pubmed.ncbi.nlm.nih.gov/29095571).

## **External links[**[**edit**](https://en.wikipedia.org/w/index.php?title=Long_short-term_memory&action=edit&section=17)**]**

* [Recurrent Neural Networks](http://www.idsia.ch/~juergen/rnn.html) with over 30 LSTM papers by [Jürgen Schmidhuber](https://en.wikipedia.org/wiki/J%C3%BCrgen_Schmidhuber)'s group at [IDSIA](https://en.wikipedia.org/wiki/IDSIA)
* Gers, Felix (2001). [*"Long Short-Term Memory in Recurrent Neural Networks"*](http://www.felixgers.de/papers/phd.pdf) *(PDF)*. PhD thesis.
* Gers, Felix A.; Schraudolph, Nicol N.; Schmidhuber, Jürgen (Aug 2002). [*"Learning precise timing with LSTM recurrent networks"*](http://www.jmlr.org/papers/volume3/gers02a/gers02a.pdf) *(PDF)*. Journal of Machine Learning Research. **3**: 115–143.
* Abidogun, Olusola Adeniyi (2005). [*Data Mining, Fraud Detection and Mobile Telecommunications: Call Pattern Analysis with Unsupervised Neural Networks*](http://etd.uwc.ac.za/xmlui/handle/11394/249). Master's Thesis (Thesis). University of the Western Cape. [*hdl*](https://en.wikipedia.org/wiki/Hdl_(identifier)):[*11394/249*](https://hdl.handle.net/11394%2F249). [*Archived*](https://web.archive.org/web/20120522234026/http:/etd.uwc.ac.za/usrfiles/modules/etd/docs/etd_init_3937_1174040706.pdf) *(PDF)* from the original on May 22, 2012.
  + [original](http://etd.uwc.ac.za/bitstream/handle/11394/249/Abidogun_MSC_2005.pdf) with two chapters devoted to explaining recurrent neural networks, especially LSTM.
* Monner, Derek D.; Reggia, James A. (2010). [*"A generalized LSTM-like training algorithm for second-order recurrent neural networks"*](http://www.cs.umd.edu/~dmonner/papers/nn2012.pdf) *(PDF)*. Neural Networks. **25** (1): 70–83. [*doi*](https://en.wikipedia.org/wiki/Doi_(identifier)):[*10.1016/j.neunet.2011.07.003*](https://doi.org/10.1016%2Fj.neunet.2011.07.003). [*PMC*](https://en.wikipedia.org/wiki/PMC_(identifier)) [*3217173*](https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3217173). [*PMID*](https://en.wikipedia.org/wiki/PMID_(identifier)) [*21803542*](https://pubmed.ncbi.nlm.nih.gov/21803542). High-performing extension of LSTM that has been simplified to a single node type and can train arbitrary architectures
* Dolphin, R. [*"LSTM Networks - A Detailed Explanation"*](https://towardsdatascience.com/lstm-networks-a-detailed-explanation-8fae6aefc7f9). Article.
* Herta, Christian. [*"How to implement LSTM in Python with Theano"*](http://christianherta.de/lehre/dataScience/machineLearning/neuralNetworks/LSTM.html). Tutorial.
* Analyze the equation and build your own custom LSTM cell in Python. [Tutorial](https://theaisummer.com/understanding-lstm/)