Recurrent Neural Networks

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University of Colorado Boulder
Fall 2022

https://home.cs.colorado.edu/~DrG/Courses/NeuralNetworksAndDeepLearning/AboutCourse.html

Review

- Last week:
  - Problems
  - Applications
  - PASCAL VOC detection challenge: region proposals with CNN features
  - PASCAL VOC semantic segmentation challenge: fully convolutional networks
- Assignments (Canvas):
  - Lab assignment 2 due earlier today
  - Lab assignment 3 due in 1.5 weeks
- Questions?

Today’s Topics

- Deep learning for sequential data
- Recurrent neural networks (RNNs)
- Gated RNNs
- Programming tutorial

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Sequence Definition: Data of Arbitrary Length

e.g., Document

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Bordered with fertile lands, backed with inexhaustible forests of finest timber and immense fields of coal, iron and the precious minerals, the situation of this lake has not failed to attract the attention of every one versed in the ways of business or commerce who has visited the region.

Another such body of fresh water, lying within two miles of a noble ocean roadstead with which it may easily be joined, capable of being converted into anchorage ground for the fleets of the world, does not exist elsewhere; it would seem to have been provided by nature as a complement to our harbor system, which it will make perfect in its every feature.

A Focus of Great Enterprises.

Puget Sound having been for many years marked as the seat of coming great commercial expansion has become, within the last decade, the focus of enterprise looking to the realization of its future. Four great transcontinental railway lines have selected its waters for termini of their systems. Already two of them are establishing ocean steamship lines to Asia and the Oriental islands.

From all parts of the world come fleets of vessels to this island sea to compete for the cargoes which lie close at hand or arrive as freights of railways spanning the continent. The tide of progress in trade and commerce is so rapid as to run ahead of the facilities provided, and such is likely to be the case for years to come. The eyes of the industrial world are set this way.

A cursory glance at the resources of the state show good reasons for faith in its future:

The wheat yield of 1890 was about 20,000,000 bushels; that for the current year is estimated at over 25,000,000 bushels. The capacity of the natural wheat fields of the state is conservatively placed at 200,000,000 bushels per year. Oats, barley, hay, fruits of all kinds, every farm crop, reward the husbandman with prodigious returns.

The lumber cut of the state for 1890 was 1,222,830,042 feet, an increase of 538,647,042 feet over the preceding year; nearly 100 per cent. This does not include the lumber cut into laths, pickets, etc., estimated at 164,185,800 feet.

The coal output of the state for 1890 was 1,349,773 tons; an increase of 438,246 tons, or about 50 per cent for the year.

The coal measures are practically limitless in extent and the business of shipping coal is in its infancy. The amount of coal mined hereafter will be limited only by the demand for it.

Iron ores of the best quality—fit for steel making—cover an immense field. Works for its manufacture are in course of construction at several points.

The precious metals are distributed over a wide area and promise enormous development of wealth. Gold, silver, lead, copper, tin, asbestos, graphite, limestone, marble, granite, sandstone, are to be added to iron and coal. All these combined furnish an opulence of mineral resources rarely encountered in a single field.

A state possessing unrivaled agricultural advantages, and having superadded to these such incomparable wealth in timber and minerals, cannot fail to develop manufacturing interests on a gigantic scale. Such development is already entered upon.

With the completion of the railway systems now speeding to their terminals at this point, the state will have an enjoyment of transportation lines greater and more perfect than any one state has hitherto equipped. She will be prepared to handle with utmost dispatch the traffic which throngs at her gates.

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Great as the outlook for domestic trade may appear, it does not exceed the just scope for foreign commerce.

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Commercial Expansion.

It is not too much to assert that a commercial expansion equal to that now existing at the port of New York is impending for these waters. A far greater shore line than that port has, will be essential for the proper accommodation of the docks and wharves required here for the reason that nearly the entire shipping of the Pacific coast must find harbor facilities at a few ports, embracing Puget Sound, San Francisco and the mouth of the Columbia river; whereas, many good harbors exist on the Atlantic seaboard within easy radius of New York.

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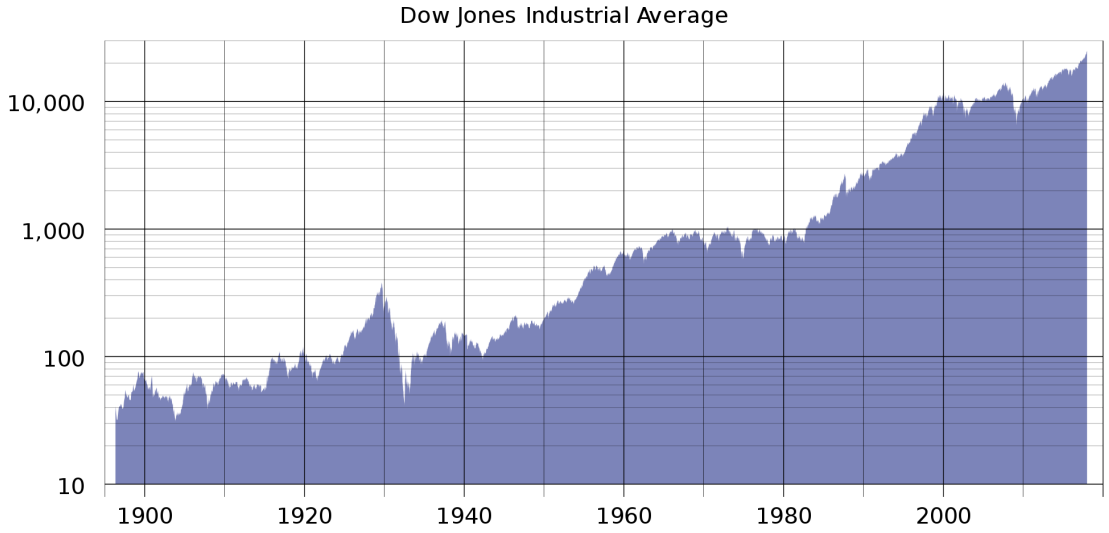

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Properties of Sequences?

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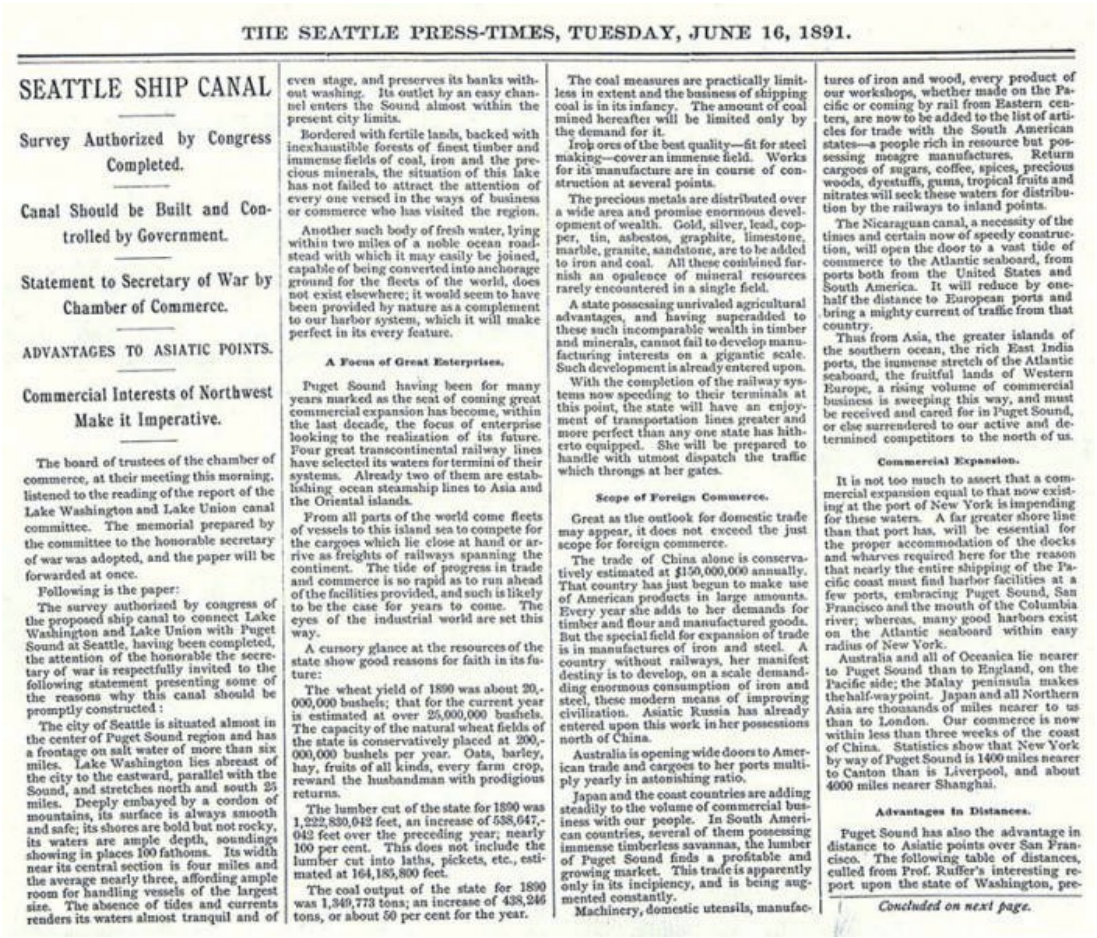

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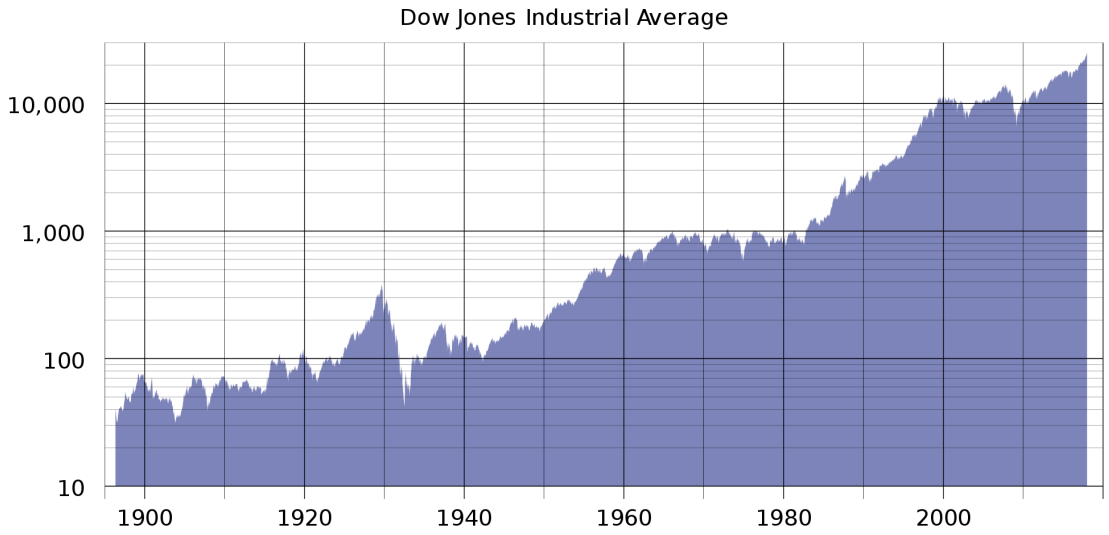
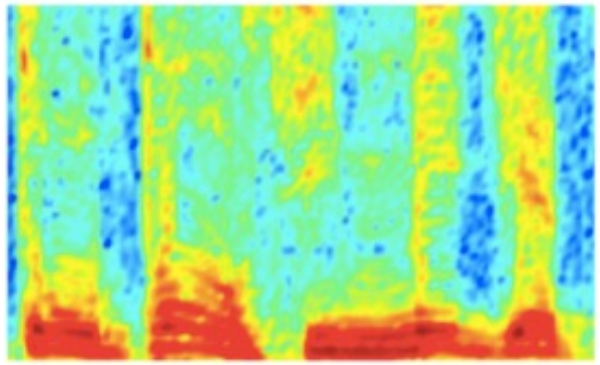


e.g., sentences, audio samples, brain waves, radio waves, air temperature

Sequence Sources

* Elements of a sequence occur in a certain order
* Elements depend on each other

AUDIO



Audio Spectrogram

IMAGES

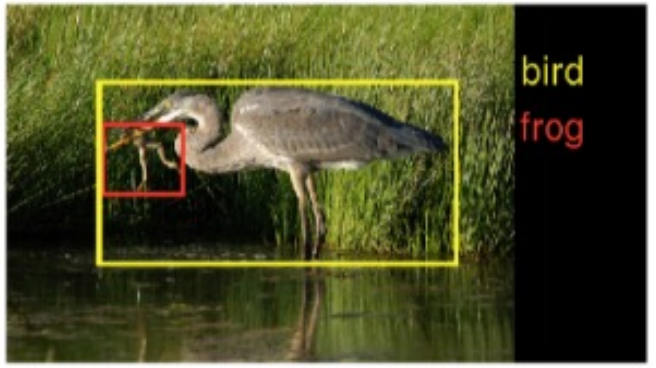


Image pixels

TEXT

0	0	0	0.2	0	0.7	0	0	0	...	...

Word, context, or document vectors

https://www.tensorflow.org/tutorials/representation/word2vec

Sequence Applications: One-to-Many

- **Input**: fixed-size
- **Output**: sequence
- e.g., image captioning

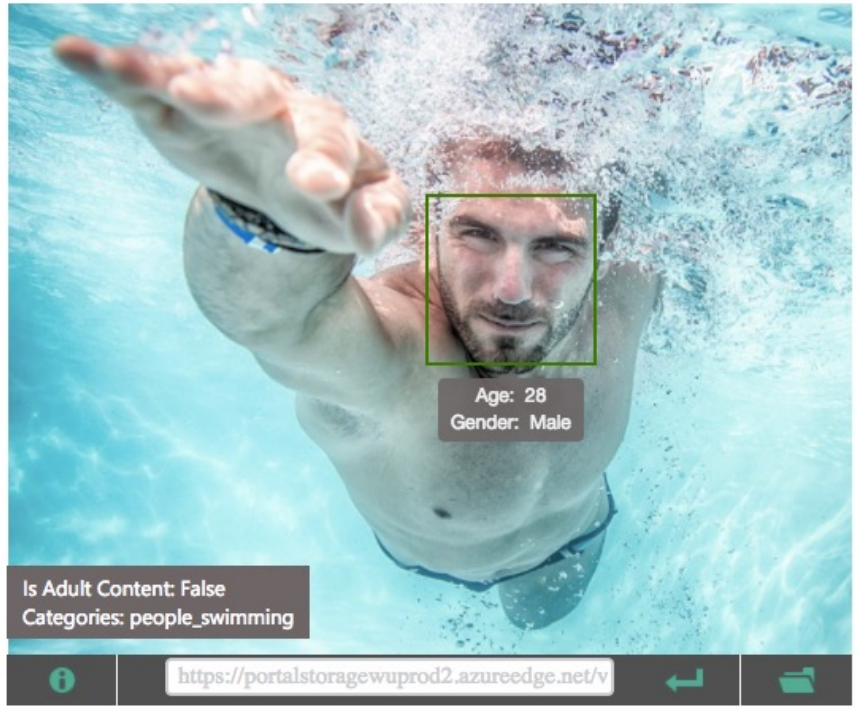


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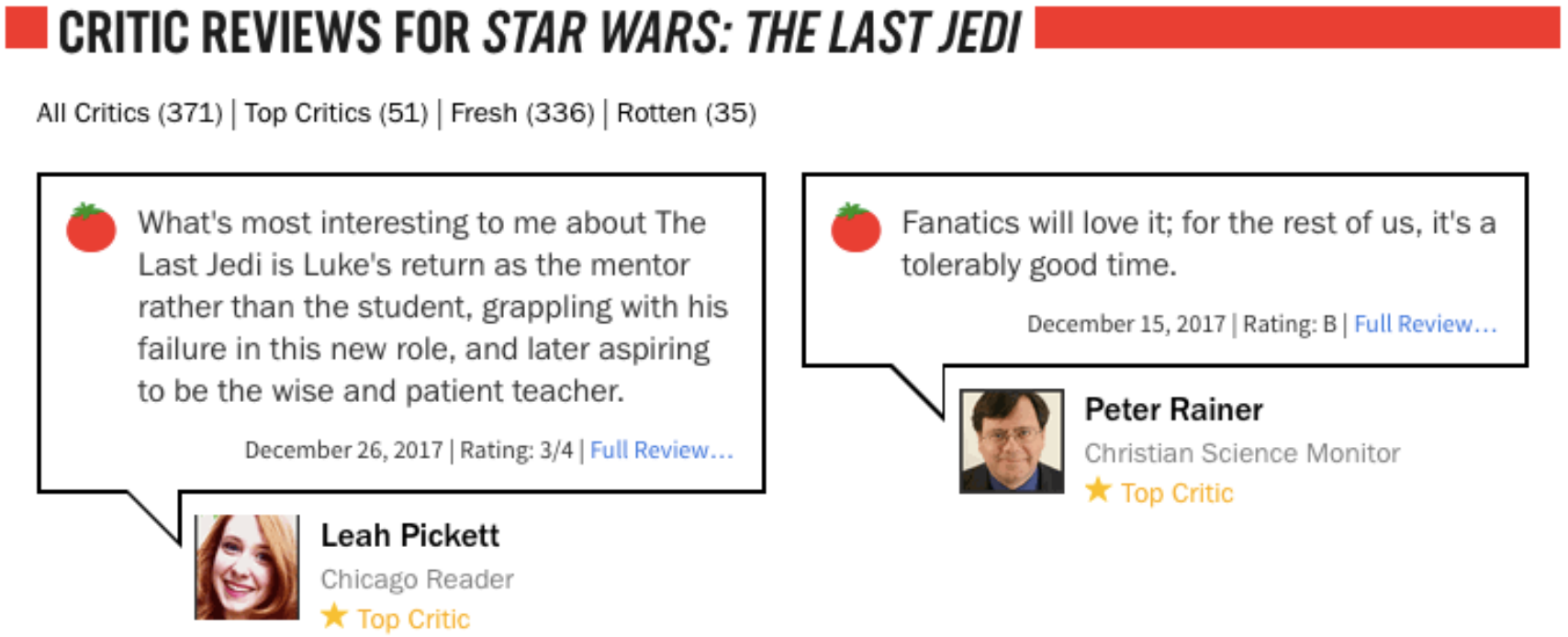
Image Dimensions	1500 x 1155
Clip Art Type	0 Non-clipart
Line Drawing Type	0 Non-LineDrawing
Black & White Image	False

Captions: https://www.microsoft.com/cognitive-services/en-us/computer-vision-api

Sequence Applications: Many-to-One

- **Input**: sequence
- **Output**: fixed-size
- e.g., sentiment analysis (hate? love?, etc)



https://www.rottentomatoes.com/m/star_wars_the_last_jedi

Sequence Applications: Many-to-Many

- **Input**: sequence
- **Output**: sequence
- e.g., language translation

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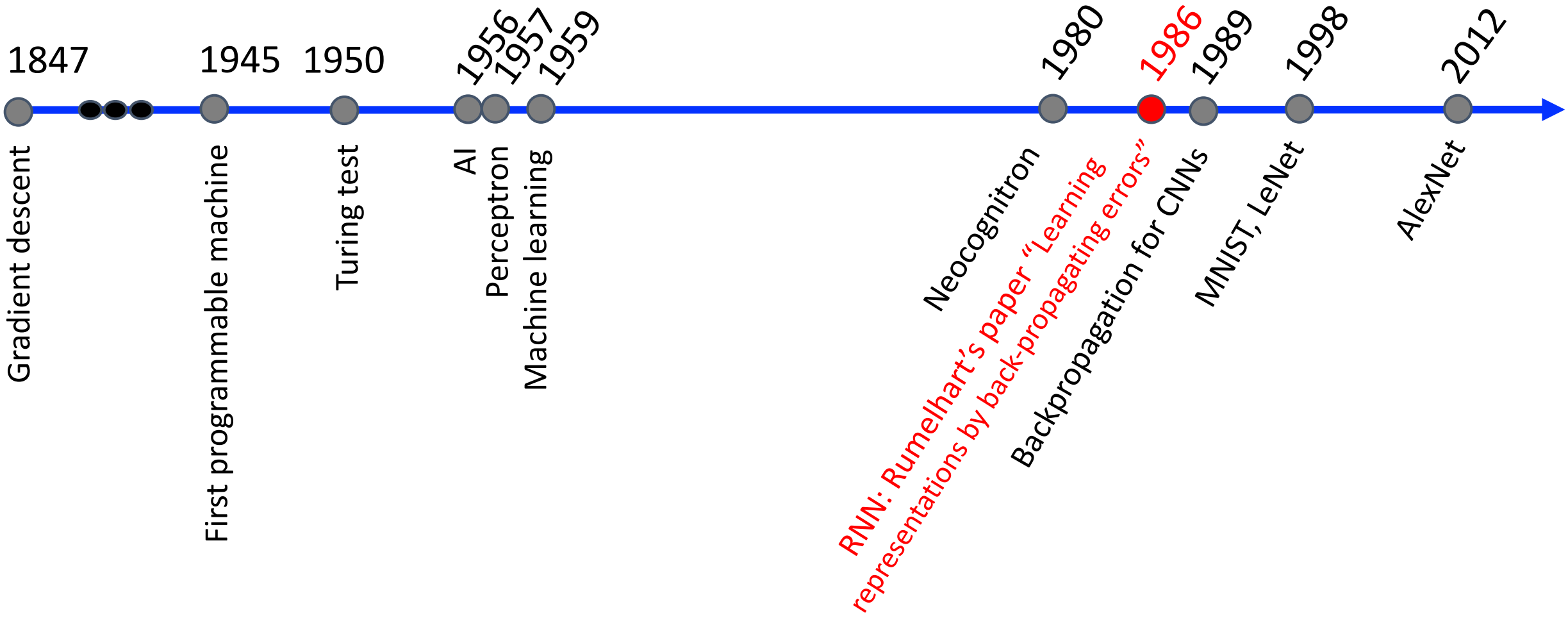
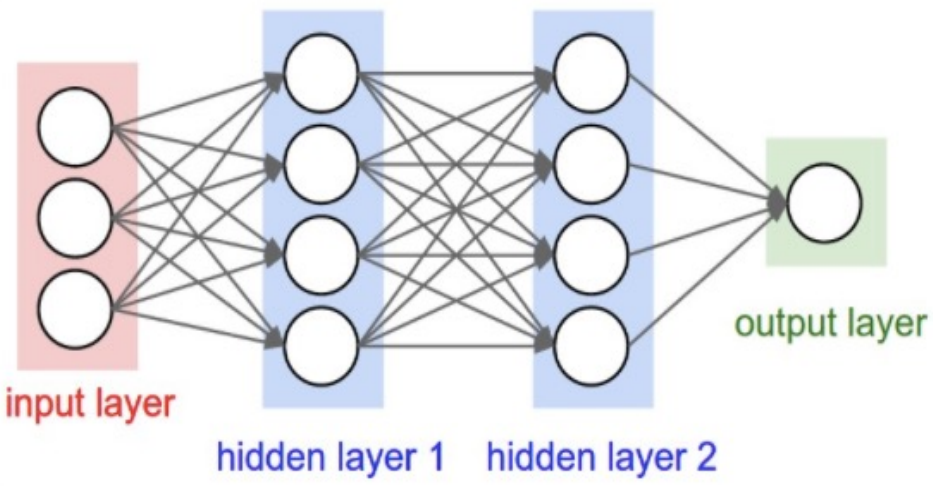
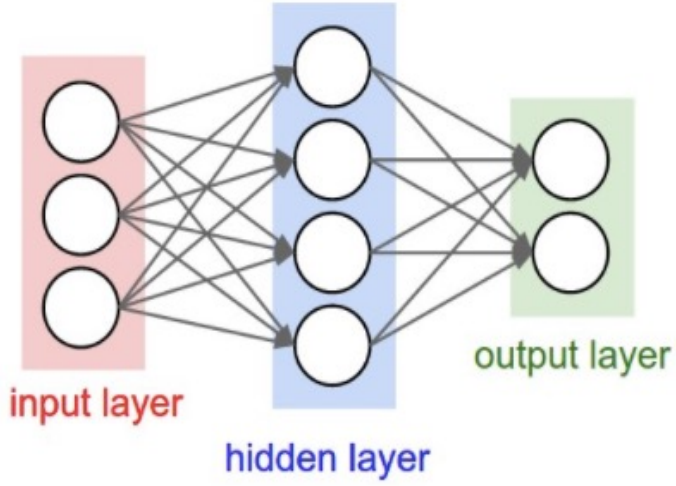
Historical Context



Recall: Feedforward Neural Networks





Problem: many model parameters

Problem: inputs/output sizes are fixed

Problem: no memory of past since weights learned independently

Each layer serves as input to the next layer with no loops

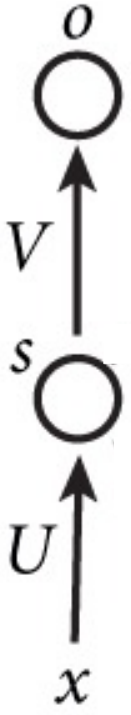
Figure Source: http://cs231n.github.io/neural-networks-1/

Recurrent Neural Networks (RNNs)

- Main idea: use hidden state to capture information about the past

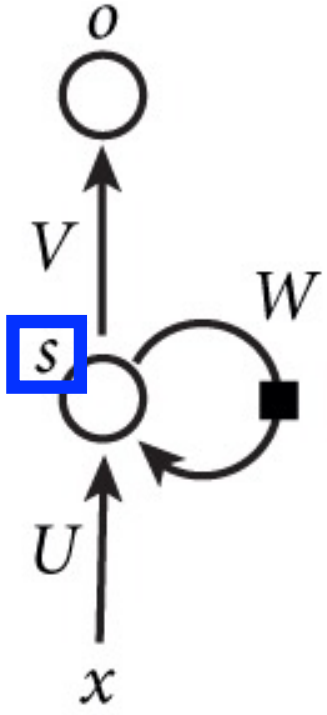
Feedforward Network

Each layer receives input from the previous layer with no loops



Recurrent Network

Each layer receives input from the previous layer and the output from the previous time step (i.e., time-delayed connections)



http://www.wildml.com/2015/09/recurrent-neural-networks-tutorial-part-1-introduction-to-rnns/

Recurrent Neural Networks (RNNs)

- Main idea: use hidden state to capture information about the past

Recurrent: same function is applied to previous result

Model parameters

$$s_t = f_m(s_{t-1}, x_t)$$

New state — Old state — Input at time step

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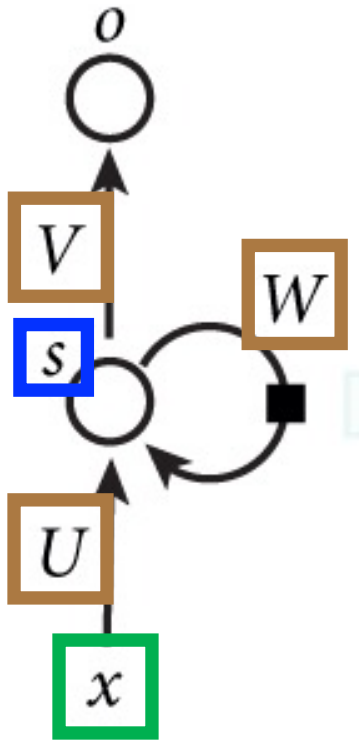

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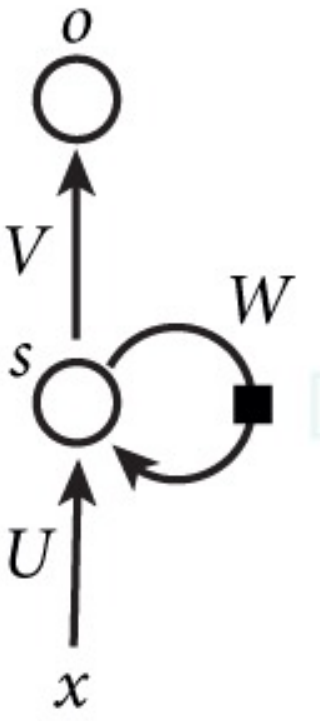
RNN: Time Step 1

- Main idea: use hidden state to capture information about the past



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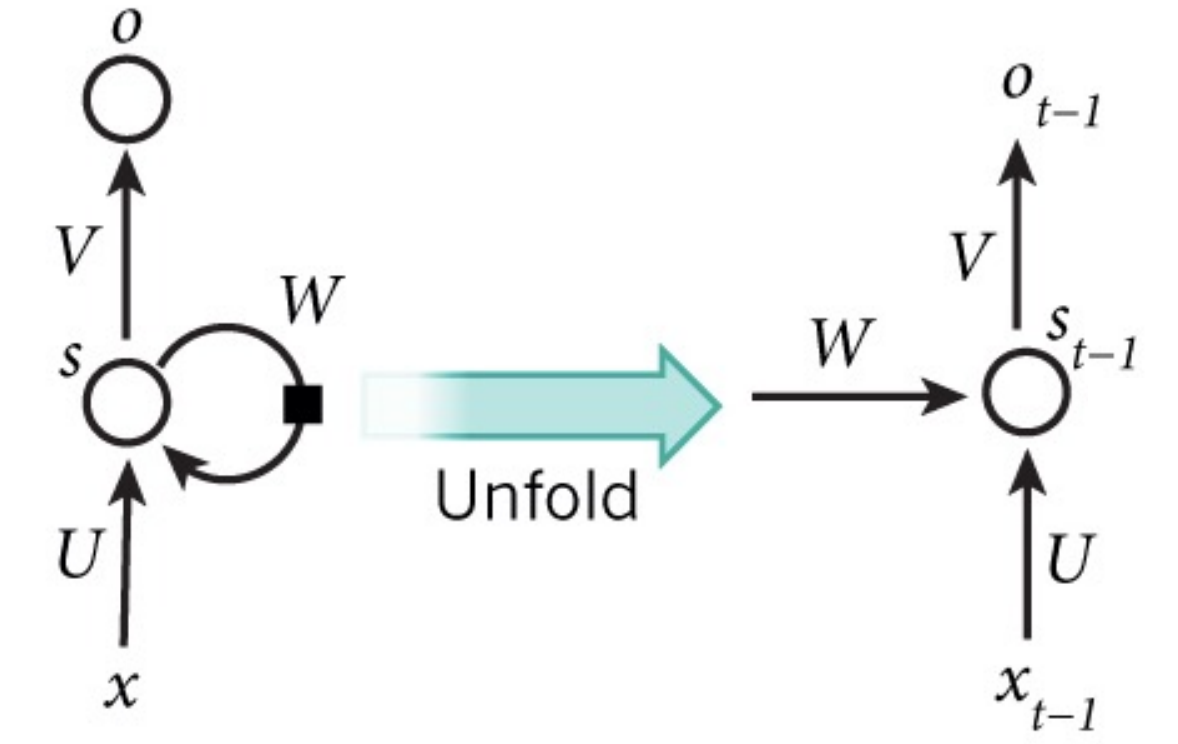

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RNN: Time Step 2

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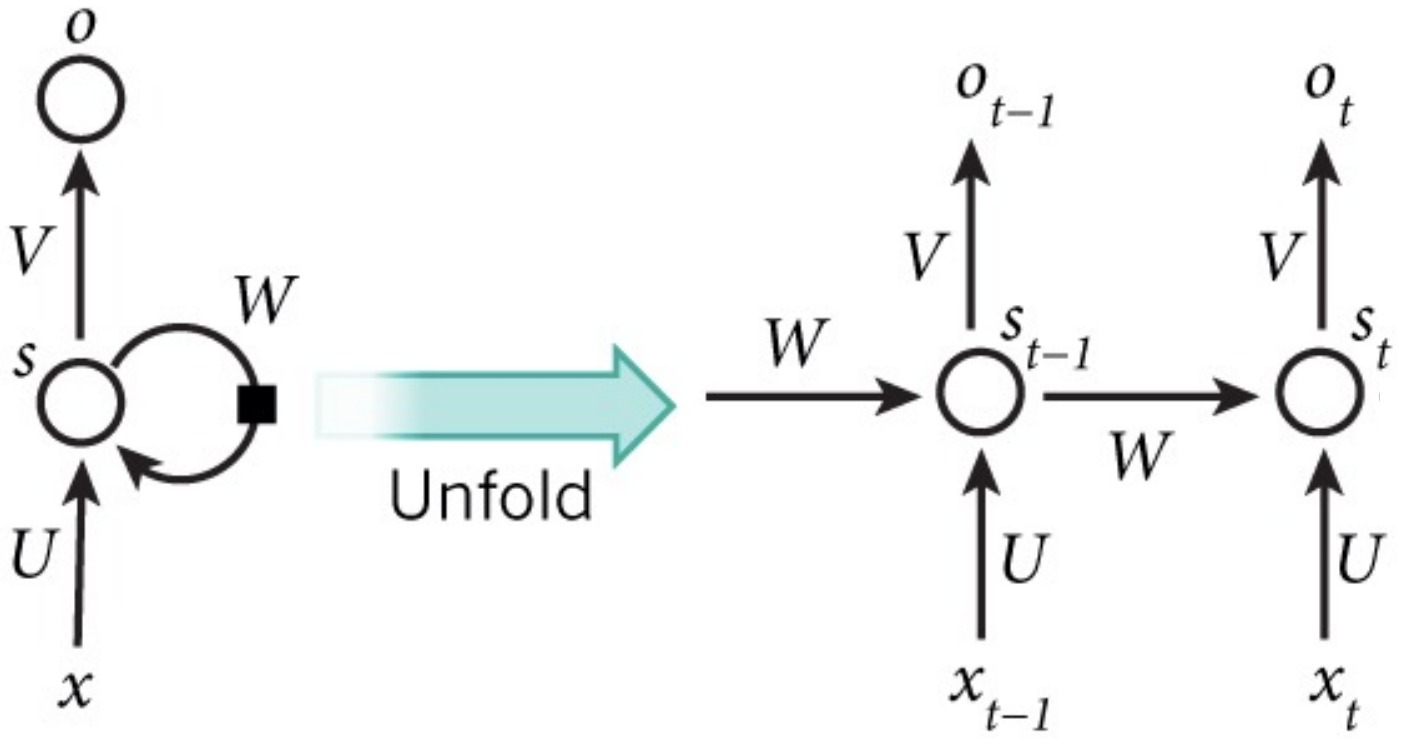

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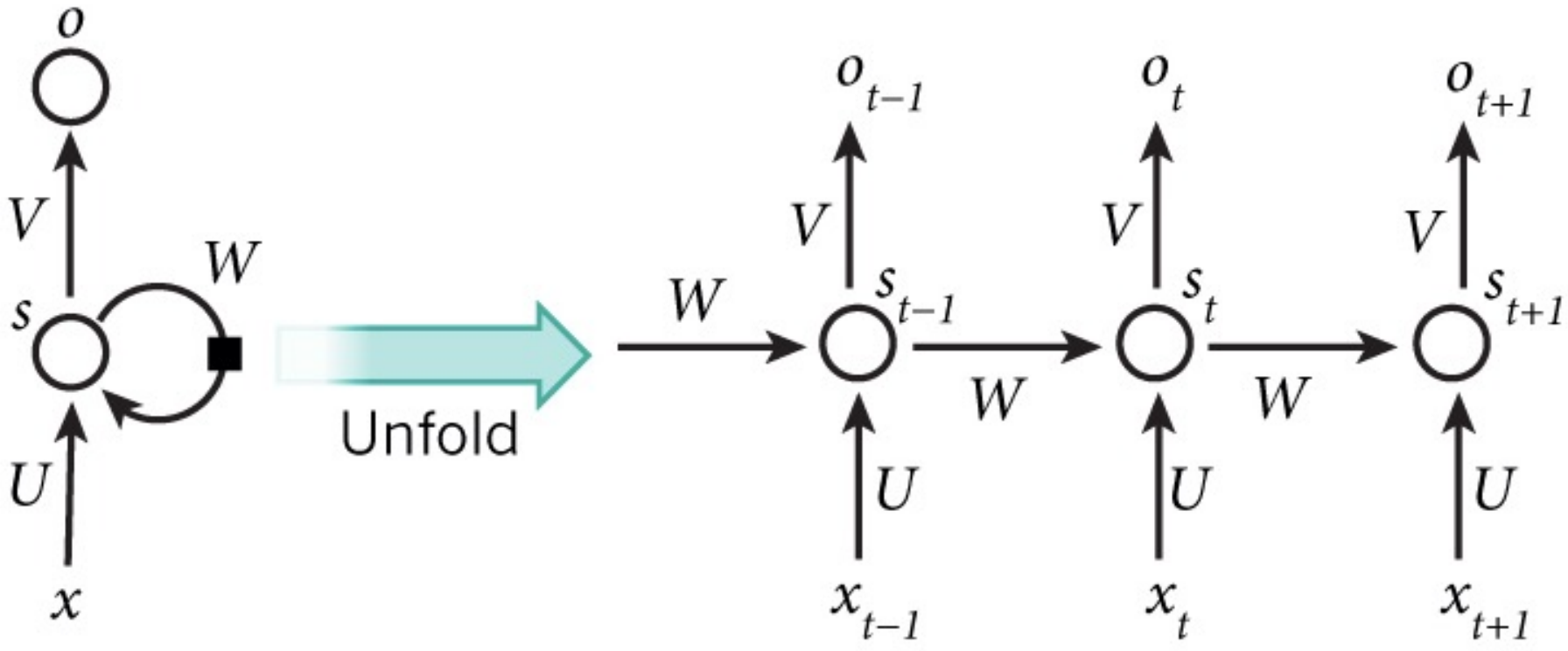

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RNN: And So On…

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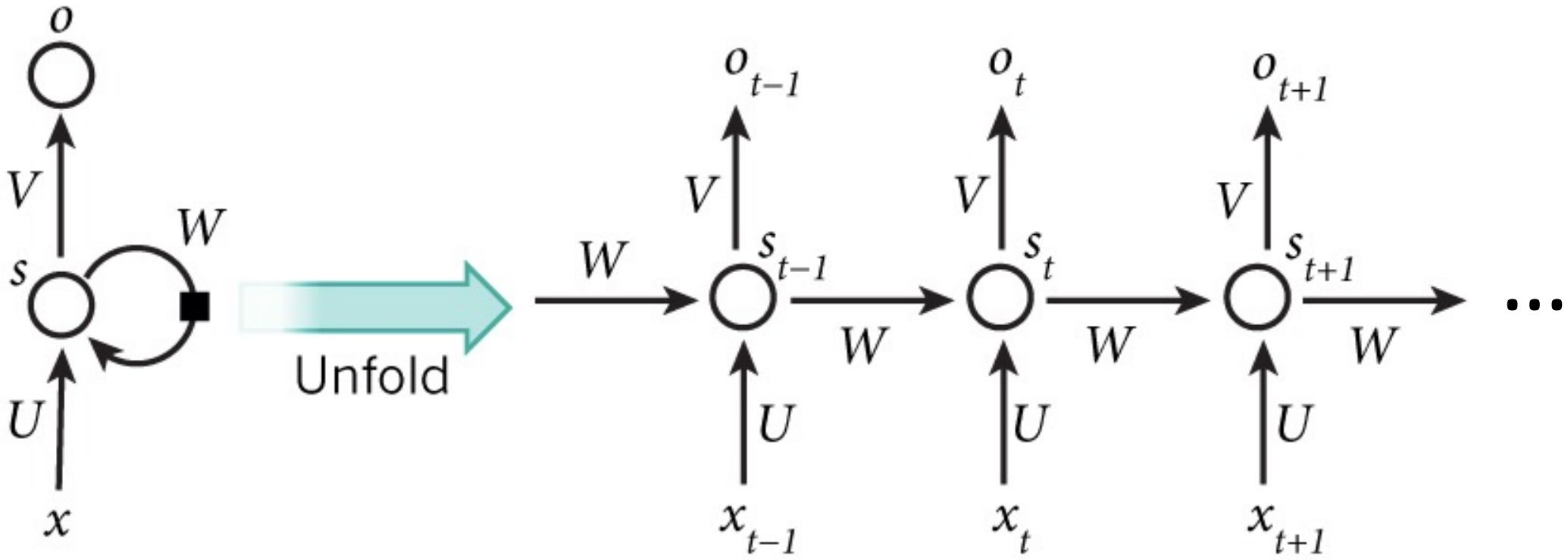

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RNN: Model Parameters and Inputs

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Recurrence formula applied at every time step:

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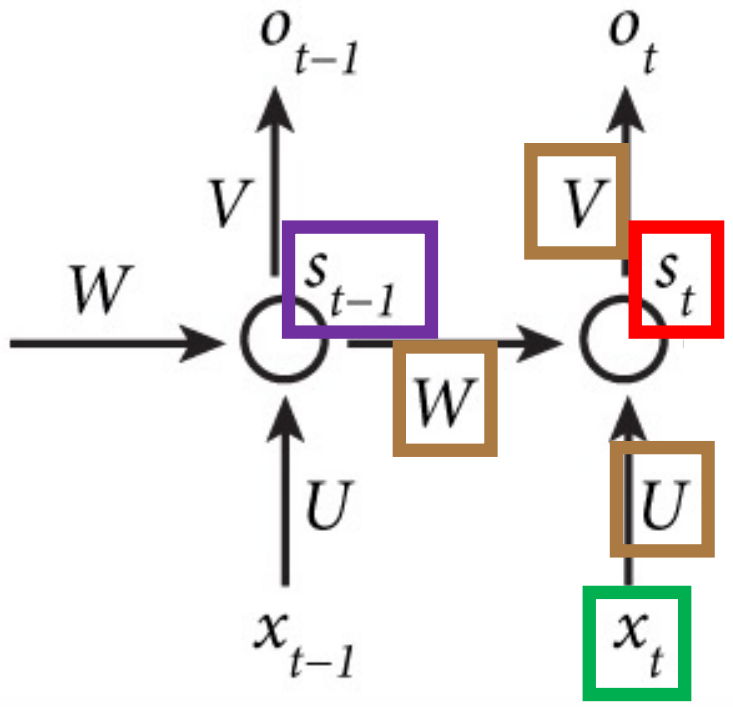
New state | Old state | Input at time step



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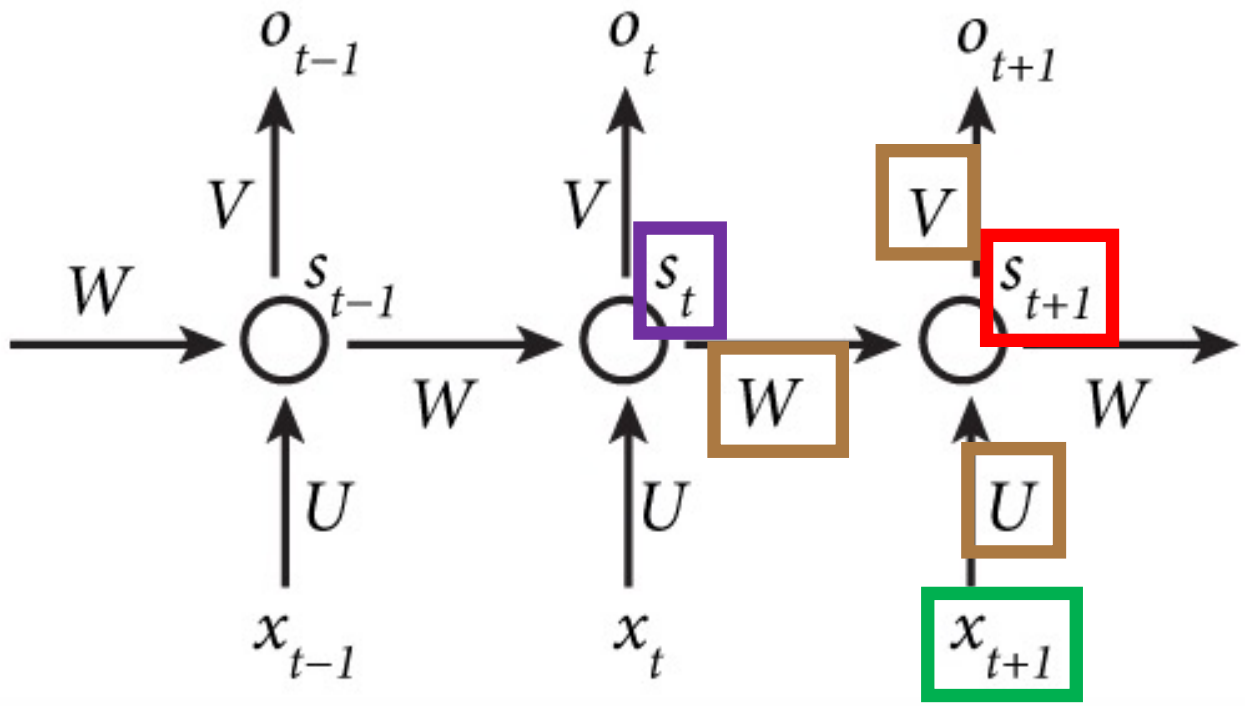

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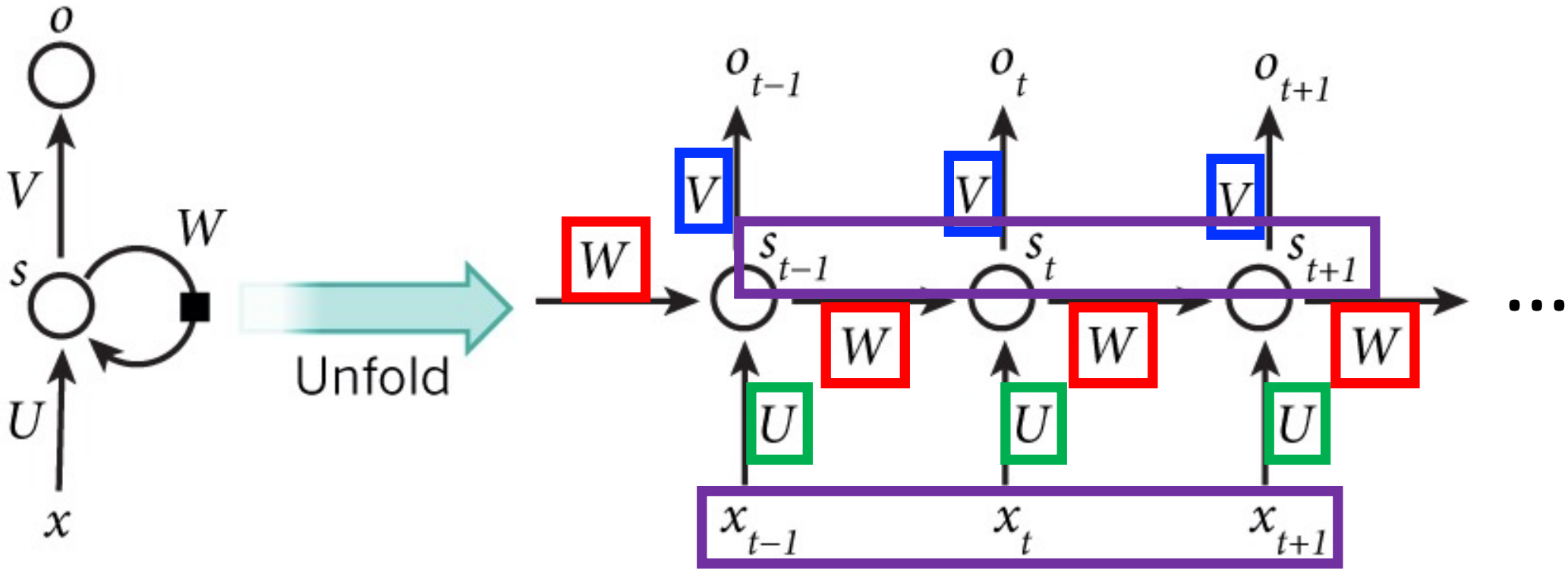
RNN: Model Parameters and Inputs

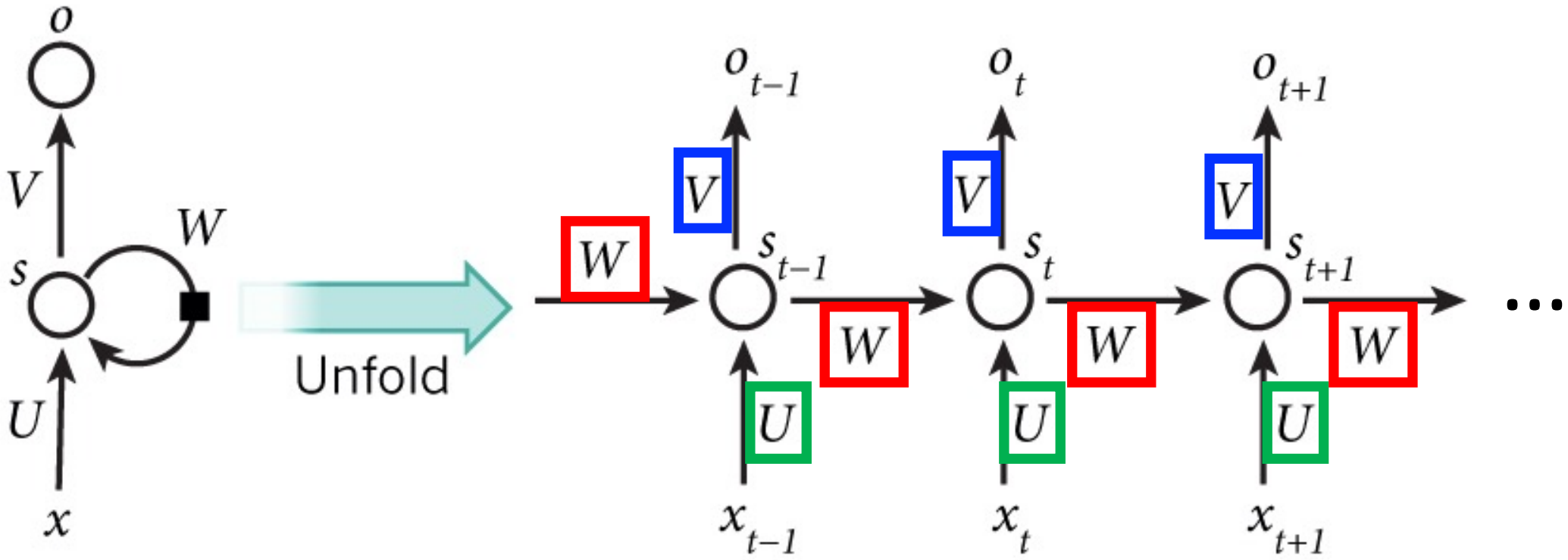
- All layers share the same model parameters (U, V, W)
  - What is different between the layers?



http://www.wildml.com/2015/09/recurrent-neural-networks-tutorial-part-1-introduction-to-rnns/

RNN: Model Parameters and Inputs

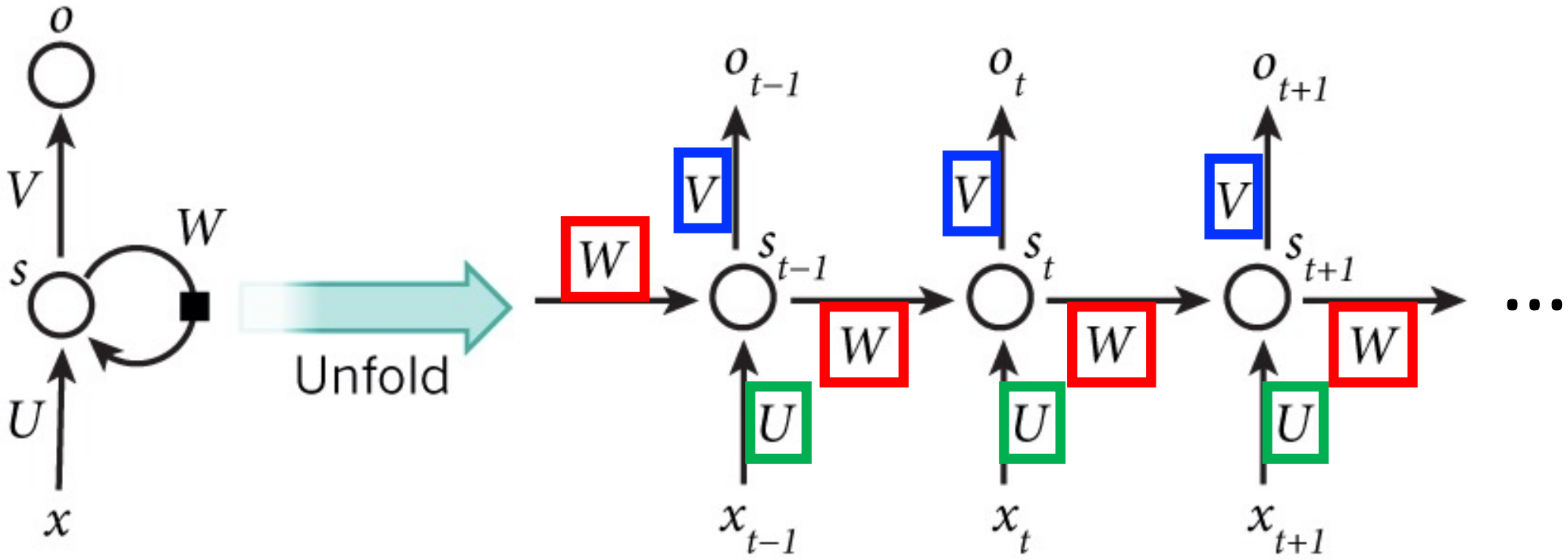
- When unfolded, a RNN is a deep feedforward network with shared weights!



http://www.wildml.com/2015/09/recurrent-neural-networks-tutorial-part-1-introduction-to-rnns/

RNN: Advantages

- Overcomes problem that weights of each layer are learned **independently** by using previous hidden state
- Overcomes problem that model has many parameters by sharing the same weights for all input sizes



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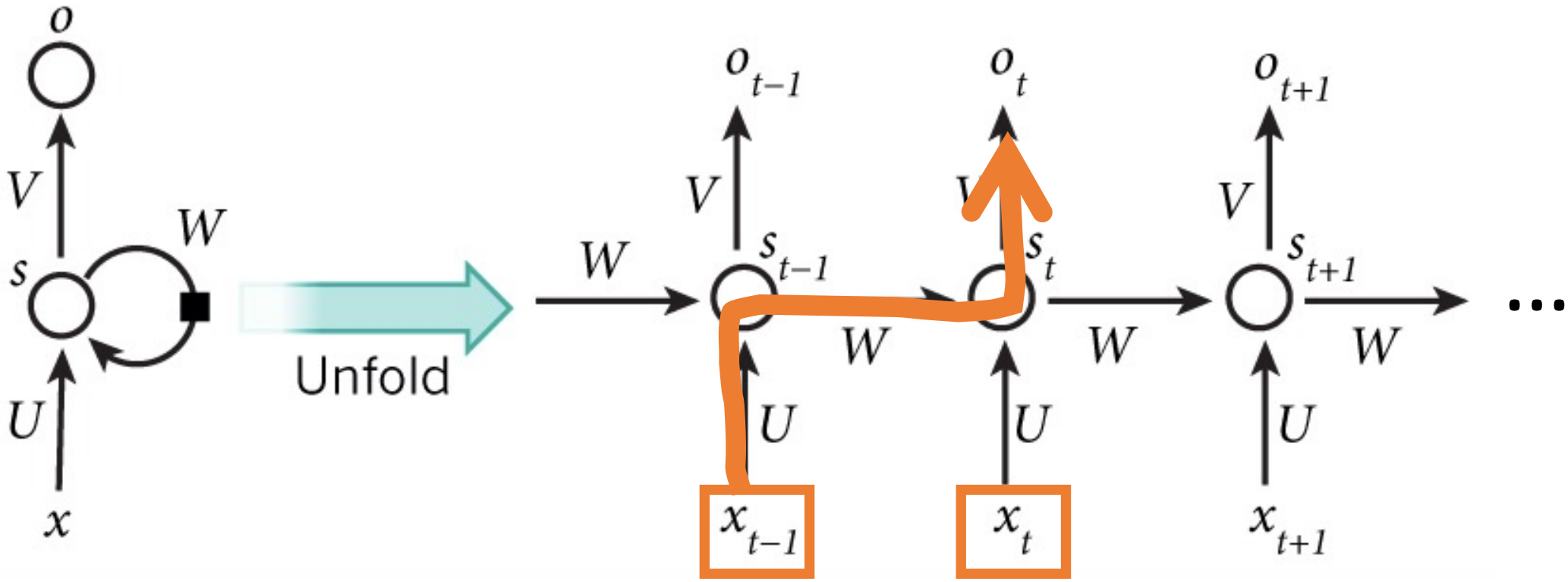
RNN: Advantages

- Retains information about past inputs for an amount of time that depends on the model's weights and input data rather than a fixed duration selected a priori



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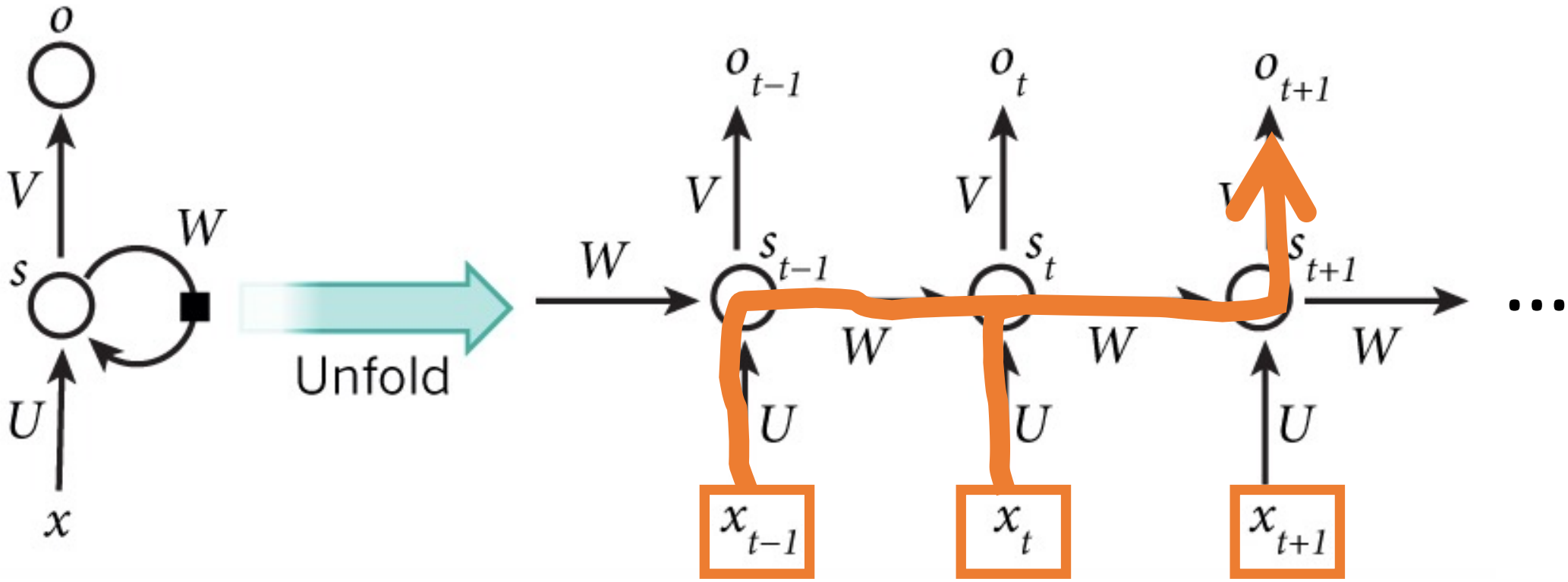
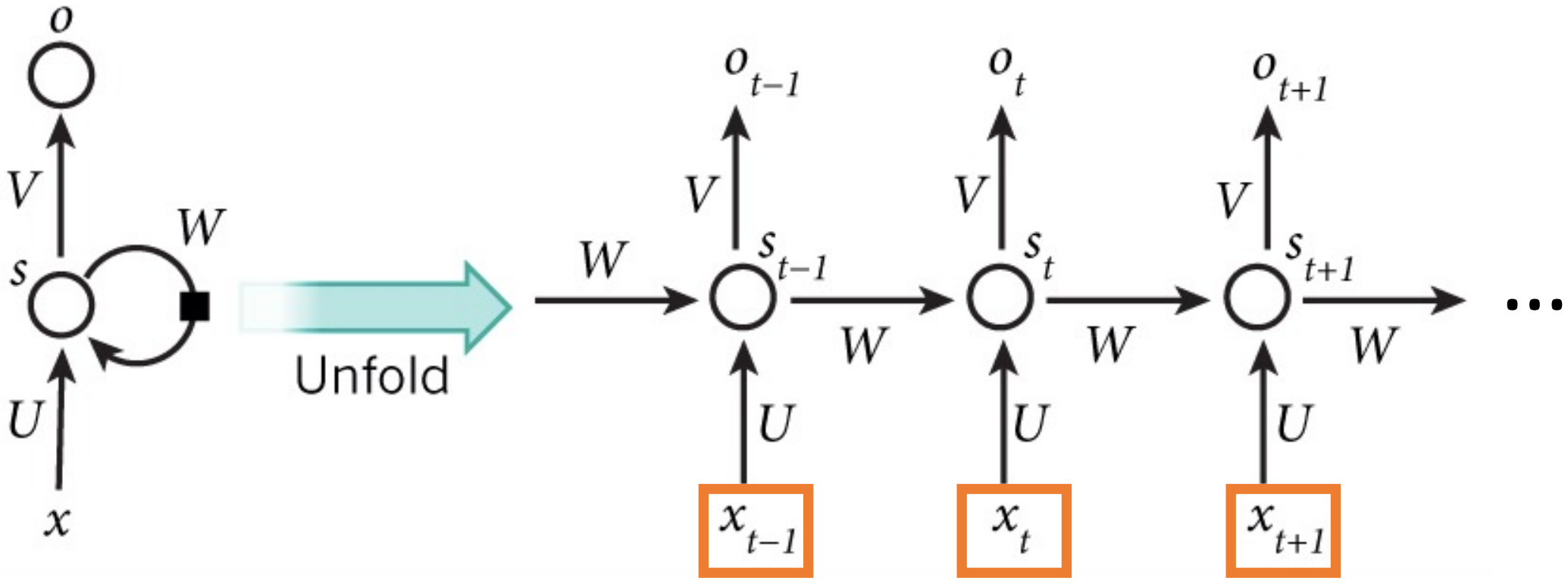


http://www.wildml.com/2015/09/recurrent-neural-networks-tutorial-part-1-introduction-to-rnns/

RNN: Advantages

- Can theoretically handle any input size by unfolding less/more time steps



http://www.wildml.com/2015/09/recurrent-neural-networks-tutorial-part-1-introduction-to-rnns/

RNN Example: Predict Sequence of Characters

- Goal: predict next character in text (i.e., automatic text completion)
- Training Data: sequence of characters represented as one-hot vectors

RNN Example: Predict Sequence of Characters; e.g., To Write a Wikipedia Page

Training Input

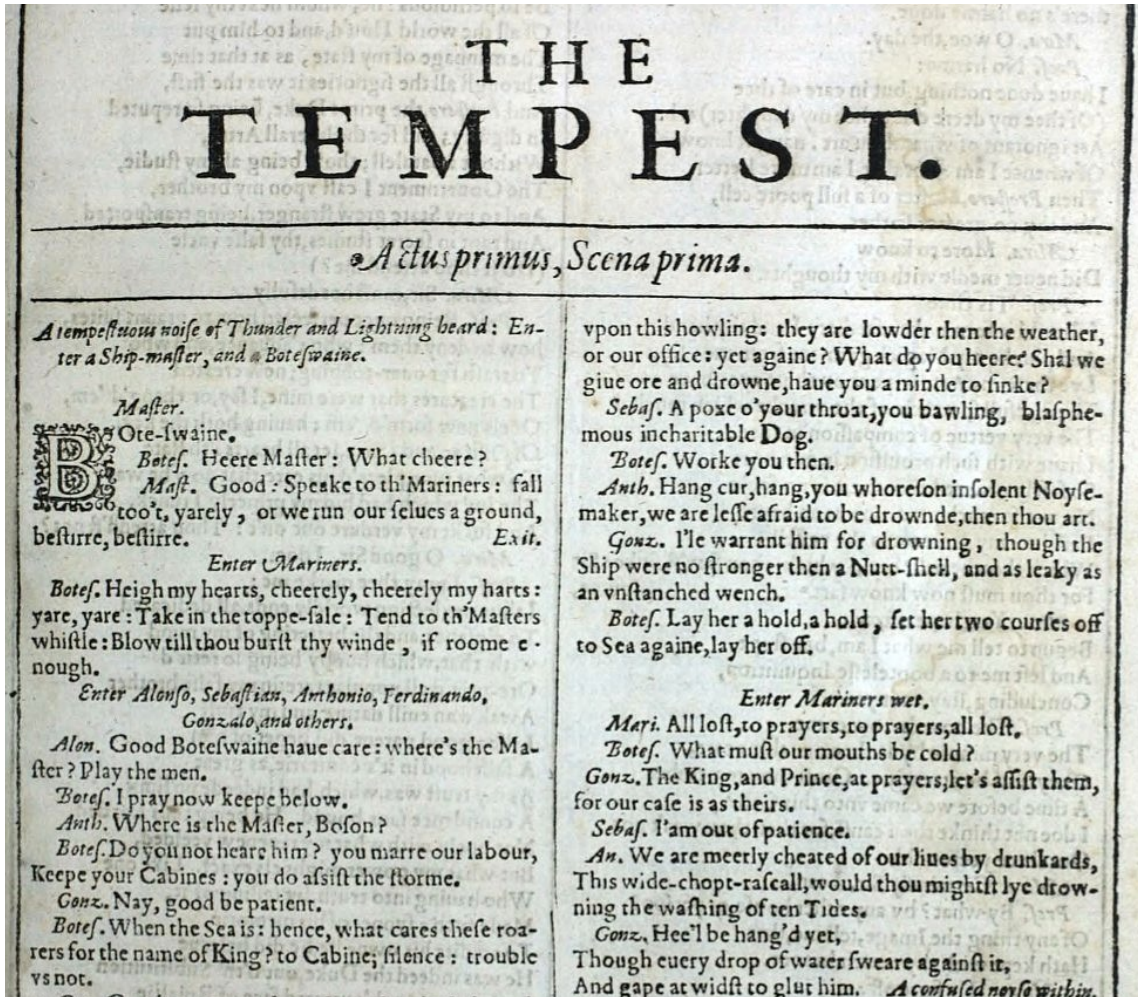
Predicted Output

```
Naturalism and decision for the majority of Arab countries' capitalide was grounded
by the Irish language by [[John Clair]], [[An Imperial Japanese Revolt]], associated
with Guangzham's sovereignty. His generals were the powerful ruler of the Portugal
in the [[Protestant Immineners]], which could be said to be directly in Cantonese
Communication, which followed a ceremony and set inspired prison, training. The
emperor travelled back to [[Antioch, Perth, October 25|21]] to note, the Kingdom
of Costa Rica, unsuccessful fashioned the [[Thrales]], [[Cynth's Dajoard]], known
in western [[Scotland]], near Italy to the conquest of India with the conflict.
Copyright was the succession of independence in the slop of Syrian influence that
was a famous German movement based on a more popular servicious, non-doctrinal
and sexual power post. Many governments recognize the military housing of the
[[Civil Liberalization and Infantry Resolution 265 National Party in Hungary]],
that is sympathetic to be to the [[Punjab Resolution]]
(PJS)[http://www.humah.yahoo.com/guardian.
cfm/7754800786d17551963s89.htm Official economics Adjoint for the Nazism, Montgomery
was swear to advance to the resources for those Socialism's rule,
was starting to signing a major tripad of aid exile.]]
```

http://karpathy.github.io/2015/05/21/rnn-effectiveness/

RNN Example: Predict Sequence of Characters; e.g., To Write Like Shakespeare

Training Input (All Works of Shakespeare)



THE
TEMPEST.

Actus primus, Scena prima.

A tempestuous noise of Thunder and Lightning heard: Enter a Ship-master, and a Boteswaine.

Master.

BOte-swaine.

Bote. Heere Master: What cheere?

Mast. Good: Speake to th'Mariners: fall too't, yarely, or we run our selues a ground, bestirre, bestirre. *Exit.*

Enter Mariners.

Bote. Heigh my hearts, cheerely, cheerely my harts: yare, yare: Take in the toppe-sale: Tend to th'Masters whistle: Blow till thou burst thy winde, if roome enough.

Enter Alonso, Sebastian, Anthonio, Ferdinando, Gonzalo, and others.

Alon. Good Boteswaine haue care: where's the Master? Play the men.

Bote. I pray now keepe below.

Anth. Where is the Master, Boson?

Bote. Do you not heare him? you marre our labour, Keepe your Cabines: you do assist the storme.

Gonz. Nay, good be patient.

Bote. When the Sea is: hence, what cares these roarers for the name of King? to Cabine; silence: trouble vs not.

Gonz. Good, yet remember whom thou hast aboord.

Bote. None that I more loue then my selfe. You are a Counsellor, if you can command these Elements to silence, and worke the peace of the present, we will not hand a rope more; vse your authority: if you cannot, giue thankes you haue liu'd so long, and make your selfe ready in your Cabine for the mischance of the houre, if it so hap. Cheerely good hearts: Out of our way I say.

Gonz. I haue great comfort from this fellow: Methinks he hath no drowning marke vpon him; his complexion is perfect Gallowes. Stand fast good Fate to his hanging: make the rope of his destiny our cable, for our owne doth little aduantage. If he be not borne to be hang'd, our case is miserable.

Exeunt.

Enter Boteswaine.

Bote. Downe with the Top-mast: yare, lower, lower, bring her to try with main-course. A plague vpon this howling: they are louder then the weather, or our office: yet againe? What do you heere? Shal we giue ore and drowne, haue you a minde to sinke?

Sebast. A poxe o'your throat, you bawling, blasphemous incharitable Dog.

Bote. Worke you then.

Anth. Hang cur, hang, you whoreson insolent Noyse-maker, we are leſſe afraid to be drownde, then thou art.

Gonz. I'le warrant him for drowning, though the Ship were no stronger then a Nutt-shell, and as leaky as an vnstanched wench.

Bote. Lay her a hold, a hold, set her two courses off to Sea againe, lay her off.

Enter Mariners wet.

Mari. All lost, to prayers, to prayers, all lost.

Bote. What must our mouths be cold?

Gonz. The King, and Prince, at prayers, let's assist them, for our case is as theirs.

Sebast. I'am out of patience.

An. We are merely cheated of our liues by drunkards, This wide-chopt-rascall, would thou mightst lye drowning the washing of ten Tides.

Gonz. Hee'l be hang'd yet, Though euery drop of water sweare against it, And gape at widst to glut him. *A confused noyse within.*

Predicted Output

```
PANDARUS:
Alas, I think he shall be come approached and the day
When little srain would be attain'd into being never fe
And who is but a chain and subjects of his death,
I should not sleep.

Second Senator:
They are away this miseries, produced upon my soul,
Breaking and strongly should be buried, when I perish
The earth and thoughts of many states.

DUKE VINCENTIO:
Well, your wit is in the care of side and that.

Second Lord:
They would be ruled after this chamber, and
my fair nues begun out of the fact, to be conveyed,
Whose noble souls I'll have the heart of the wars.

Clown:
Come, sir, I will make did behold your worship.

VIOLA:
I'll drink it.
```

http://karpathy.github.io/2015/05/21/rnn-effectiveness/ https://github.com/martin-gorner/tensorflow-rnn-shakespeare

RNN Example: Predict Sequence of Characters; e.g., To Write Code

Training Input (C code on GitHub)

```c
/*
 * Bad block management
 *
 * - Heavily based on MD badblocks code from Neil Brown
 *
 * Copyright (c) 2015, Intel Corporation.
 *
 * This program is free software; you can redistribute it and/or modify it
 * under the terms and conditions of the GNU General Public License,
 * version 2, as published by the Free Software Foundation.
 *
 * This program is distributed in the hope it will be useful, but WITHOUT
 * ANY WARRANTY; without even the implied warranty of MERCHANTABILITY or
 * FITNESS FOR A PARTICULAR PURPOSE.  See the GNU General Public License for
 * more details.
 */

#include <linux/badblocks.h>
#include <linux/seqlock.h>
#include <linux/device.h>
#include <linux/kernel.h>
#include <linux/module.h>
#include <linux/stddef.h>
#include <linux/types.h>
#include <linux/slab.h>
```

Predicted Output

```c
 * Increment the size file of the new incorrect UI_FILTER group information
 * of the size generatively.
 */
static int indicate_policy(void)
{
  int error;
  if (fd == MARN_EPT) {
    /*
     * The kernel blank will coeld it to userspace.
     */
    if (ss->segment < mem_total)
      unblock_graph_and_set_blocked();
    else
      ret = 1;
    goto bail;
  }
  segaddr = in_SB(in.addr);
  selector = seg / 16;
  setup_works = true;
  for (i = 0; i < blocks; i++) {
    seq = buf[i++];
    bpf = bd->bd.next + i * search;
    if (fd) {
      current = blocked;
    }
  }
  rw->name = "Getjbbregs";
  bprm_self_clearl(&iv->version);
  regs->new = blocks[(BPF_STATS << info->historidac)] | PFMR_CLOBATHINC_SECONDS << 12;
  return segtable;
}
```

http://karpathy.github.io/2015/05/21/rnn-effectiveness/ https://github.com/martin-gorner/tensorflow-rnn-shakespeare

RNN Example: Predict Sequence of Characters; e.g., To Write Facebook Messages

Training Input

Facebook messages from…

Hendrik J. Weideman

Ph.D. candidate at Rensselaer Polytechnic Institute

Predicted Output

1. *The meaning of life is to* find them? Oh, I don't know if I would be able to publish a paper on that be climbing today, but it will definitely know what that makes sense. I'm sure they wanted to socialis that I am bringing or

2. *What a cruel twist of fate, that we should* be persuate that 😂 And cook :D I will think that's mean I think I need to go to the phoebe? That's awesome though Haha, sorry, I don't know if it was more time to clas for it's badass though I jus

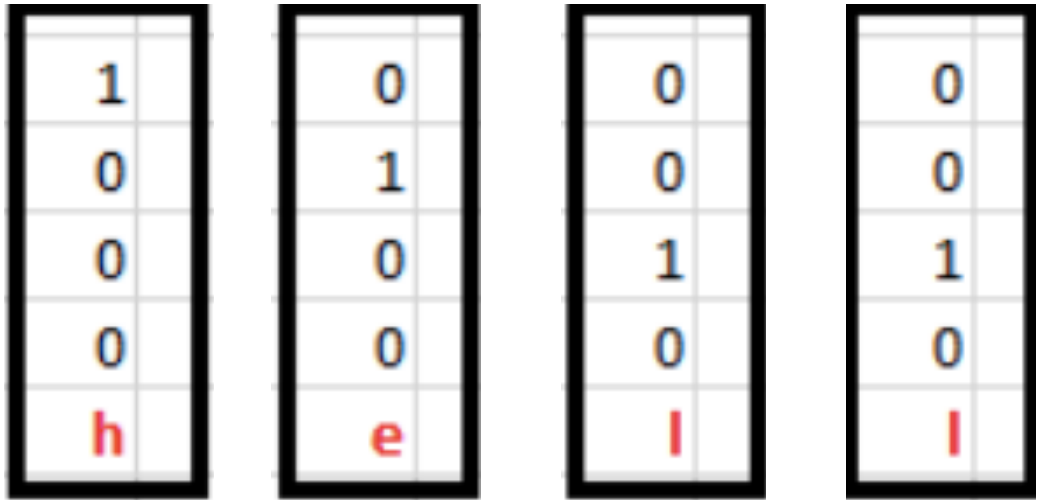
3. *The fact of the matter is* just the world to invite your stuff? I don't know how to right it wouldn't be as offriving for anything, so that would be awesome, thanks :) I have no idea... She would get to worry about it :P And I

4. *At the very least, you should remember that* as a house of a perfect problems 😂 Yeah :D I wonder how perfect for this trank though So it's probably foltower before the bathers will be fine and haven't want to make it worse Thanks for one of

https://hjweide.github.io/char-rnn

Example: Predict Sequence of Characters

- Goal: predict next character in text
- Prediction: feed training sequence of one-hot encoded characters; e.g., “hello”
  - For simplicity, assume the following vocabulary (i.e., character set): {h, e, l, o}
  - What is our input at time step 1?
  - What is our input at time step 2?
  - What is our input at time step 3?
  - What is our input at time step 4?
  - And so on…

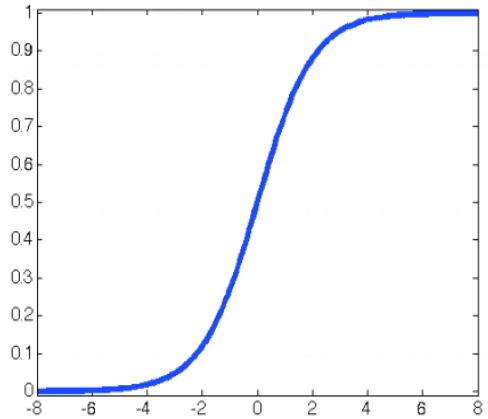


https://www.analyticsvidhya.com/blog/2017/12/introduction-to-recurrent-neural-networks/

Example: Predict Sequence of Characters

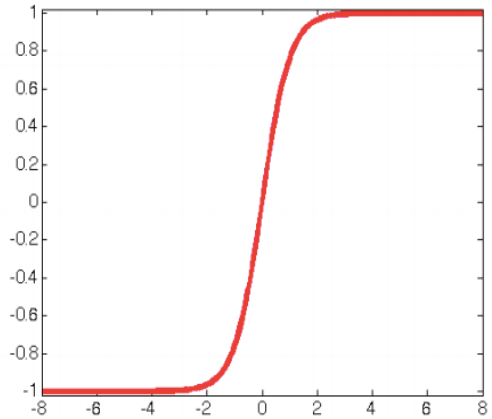
Recall activation functions: tanh is common choice for RNNs

Sigmoid



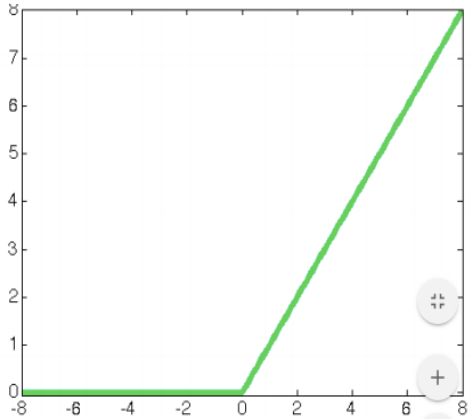
$$\sigma(z) = \frac{1}{1+\exp(-z)}$$

Tanh



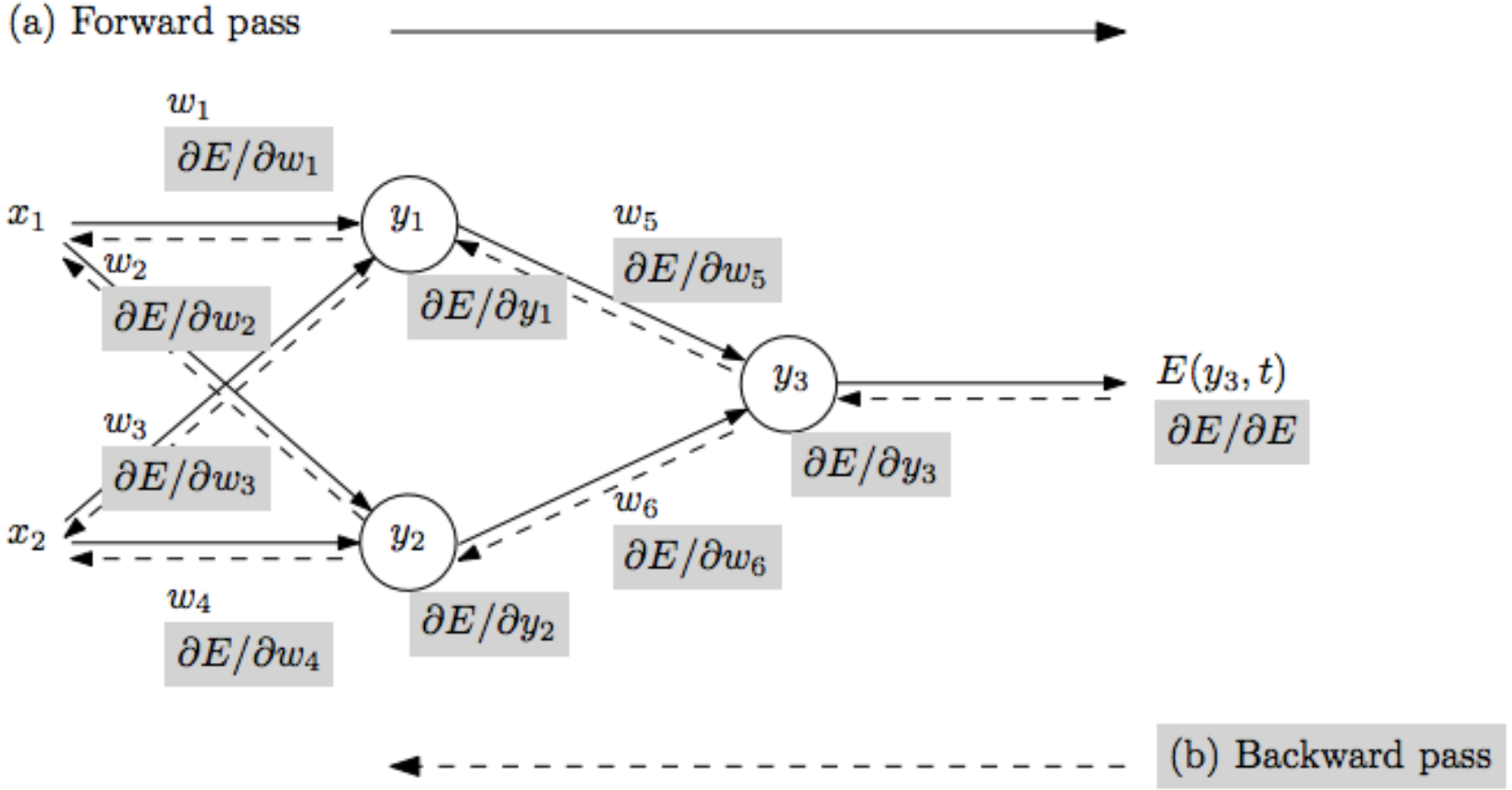
$$\tanh(z) = \frac{\exp(z)-\exp(-z)}{\exp(z)+\exp(-z)}$$

ReLU



$$\mathrm{ReLU}(z) = \max(0, z)$$

Training Approach



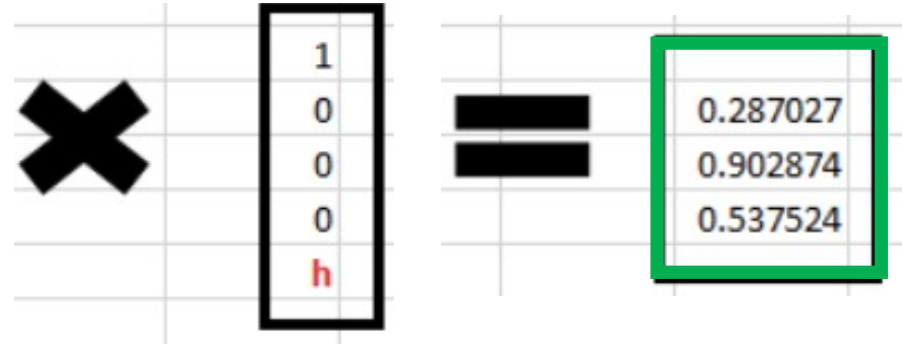
- Repeat until stopping criterion met:
  1. **Forward pass**: propagate training data through unfolded network to predict
  2. Quantify the dissatisfaction with a model's results on the training data
  3. **Backward pass**: using predicted output, calculate gradients backward to assign blame to each model parameter; weight sharing accounted for by summing gradients for all time steps
  4. Update each parameter using calculated gradients

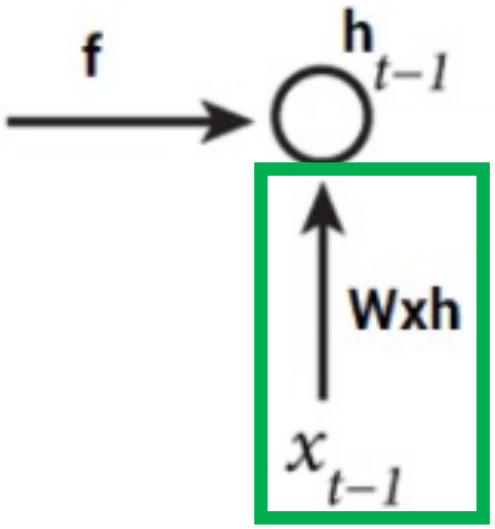
Figure from: Atilim Gunes Baydin, Barak A. Pearlmutter, Alexey Andreyevich Radul, Jeffrey Mark Siskind; Automatic Differentiation in Machine Learning: a Survey; 2018

Example: Forward Pass

$$h_t = \tanh(W_{hh}h_{t-1} + W_{xh}x_t + \text{bias})$$

wxh			
0.287027	0.84606	0.572392	0.486813
0.902874	0.871522	0.691079	0.18998
0.537524	0.09224	0.558159	0.491528





Why do we use three rows instead of 1 row for the weight matrix?

- provides more model parameters and so can generate a more complex function; the number of rows is a hyperparameter set by the developer

https://www.analyticsvidhya.com/blog/2017/12/introduction-to-recurrent-neural-networks/

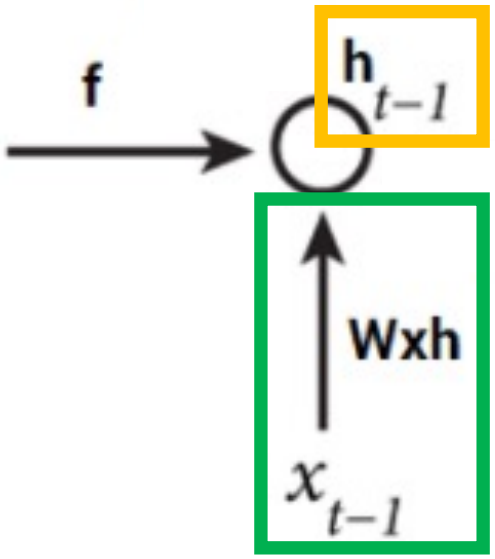
Example: Forward Pass

Initialize to random value: 0.567001

$h_t = \tanh(W_{hh} h_{t-1} + W_{xh} x_t + \text{bias})$

Initialize to 0

Input at next time step



wxh			
0.287027	0.84606	0.572392	0.486813
0.902874	0.871522	0.691079	0.18998
0.537524	0.09224	0.558159	0.491528

1			0.287027
0			0.902874
0			0.537524
0			
h			

Ht	=	TANH	0.287027359 0.902874425 0.537523791	+ 0.567001 0.567001 0.567001
	=		0.693168 0.899554 0.802118	

https://www.analyticsvidhya.com/blog/2017/12/introduction-to-recurrent-neural-networks/

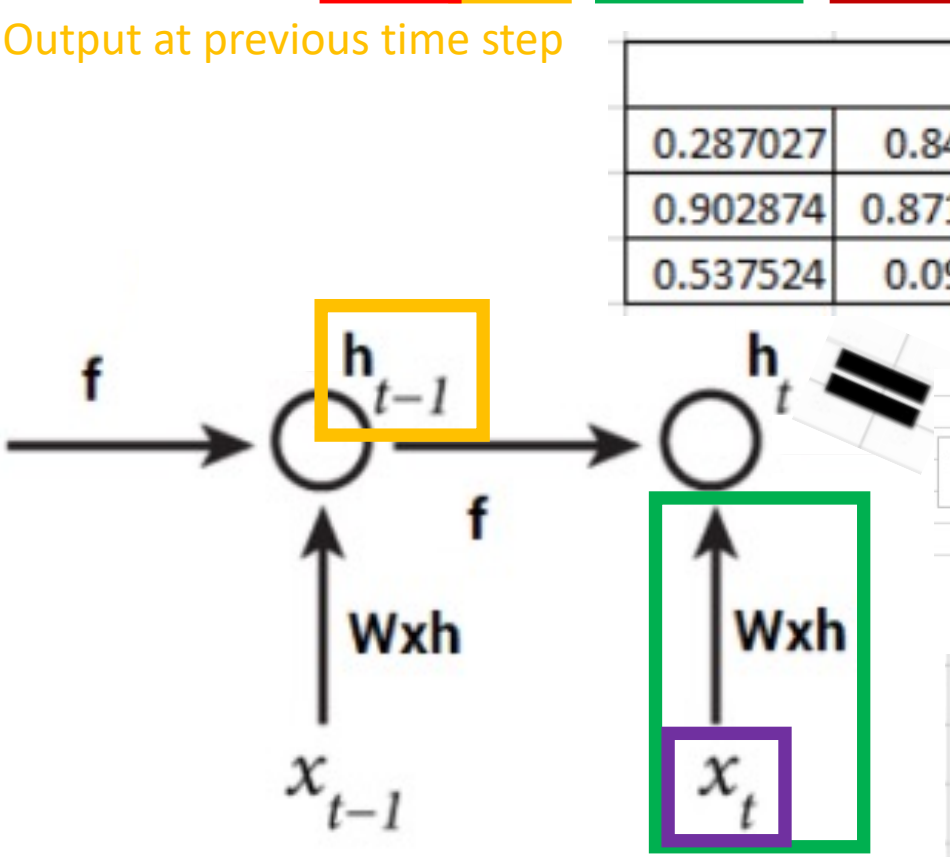
Example: Forward Pass

Initialize to random value: 0.427043

Recall: Initialized to random value: 0.567001

$$h_t = \tanh(W_{hh} h_{t-1} + W_{xh} x_t + \text{bias})$$

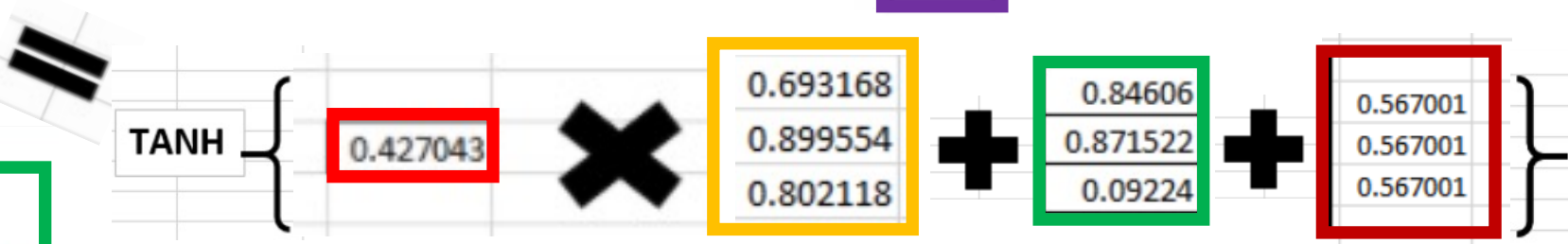
Output at previous time step

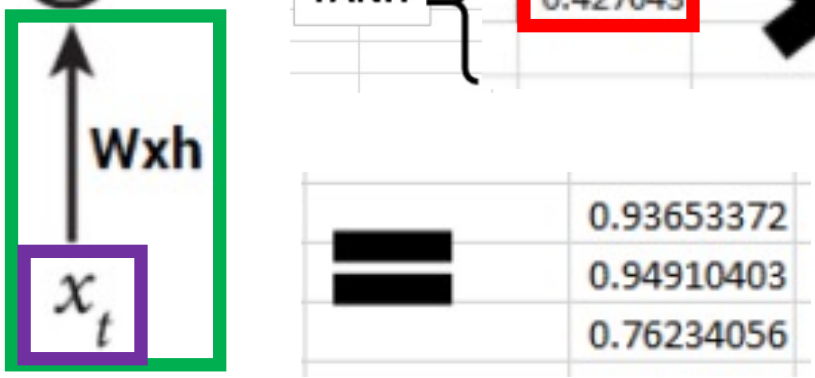


wxh			
0.287027	0.84606	0.572392	0.486813
0.902874	0.871522	0.691079	0.18998
0.537524	0.09224	0.558159	0.491528

0
1
0
0
e

0.84606
0.871522
0.09224

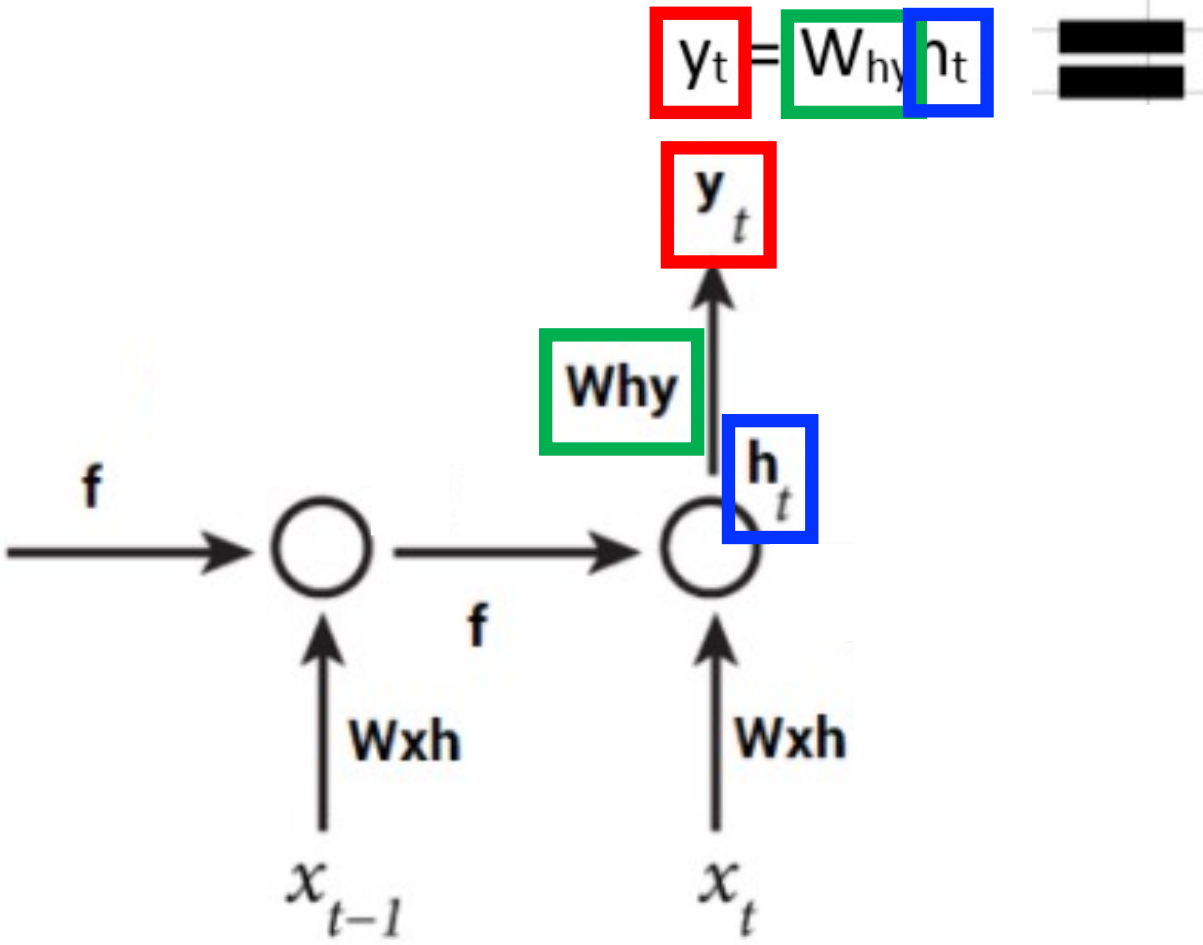




https://www.analyticsvidhya.com/blog/2017/12/introduction-to-recurrent-neural-networks/

Example: Forward Pass

(What Character Follows “he”?)



(assume bias term is 0 for this example)

why		
0.37168	0.974829459	0.830034886
0.39141	0.282585823	0.659835709
0.64985	0.09821557	0.334287084
0.91266	0.32581642	0.144630018

×

Ht
0.936534
0.949104
0.762341

=

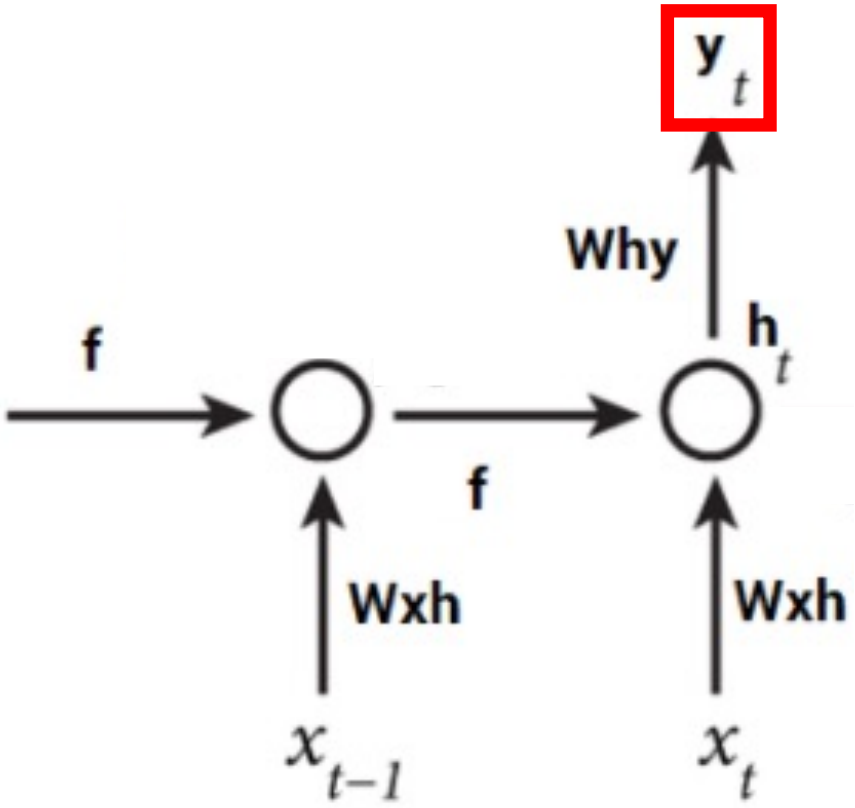
yt
1.90607732
1.13779113
0.95666016
1.27422602

Applying softmax, to compute letter probabilities:

0.419748
0.194682
0.162429
0.223141

https://www.analyticsvidhya.com/blog/2017/12/introduction-to-recurrent-neural-networks/

Example: Forward Pass



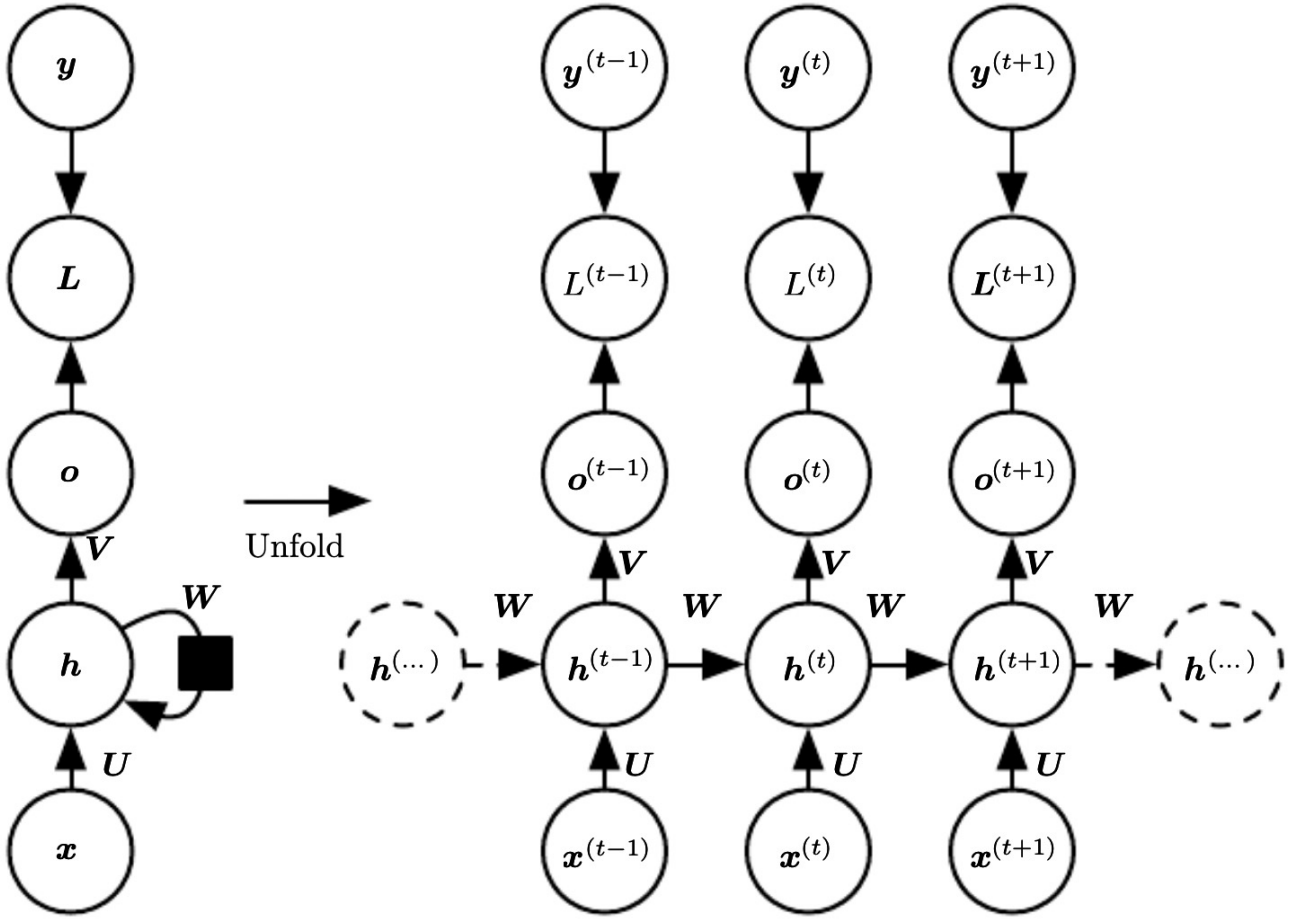
Given our vocabulary is {h, e, l, o}, what letter is predicted?

Applying softmax, to compute letter probabilities:

0.419748
0.194682
0.162429
0.223141

https://www.analyticsvidhya.com/blog/2017/12/introduction-to-recurrent-neural-networks/

Training Approach; e.g., Many-to-Many Loss Using Cross Entropy Loss



- Repeat until stopping criterion met:
  1. **Forward pass**: propagate training data through unfolded network to predict
  2. Quantify the dissatisfaction with a model's results on the training data
  3. **Backward pass**: using predicted output, calculate gradients backward to assign blame to each model parameter; weight sharing accounted for by summing gradients for all time steps
  4. Update each parameter using calculated gradients

Goodfellow, Bengio, and Courville, Deep Learning.

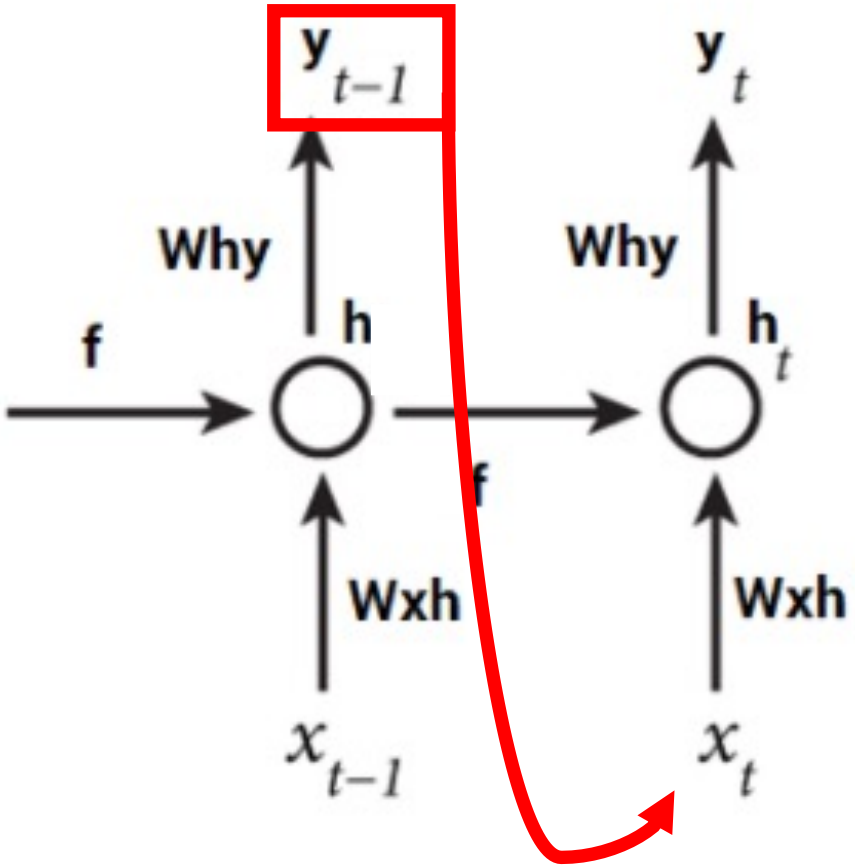
Training Approach

Called back-propagation through time (BPTT), it is the same generalized gradient derivation process we already have covered

- Repeat until stopping criterion met:
  1. **Forward pass**: propagate training data through unfolded network to predict
  2. Quantify the dissatisfaction with a model's results on the training data
  3. **Backward pass**: using predicted output, calculate gradients backward to assign blame to each model parameter; weight sharing accounted for by summing gradients for all time steps
  4. Update each parameter using calculated gradients

Figure from: Atilim Gunes Baydin, Barak A. Pearlmutter, Alexey Andreyevich Radul, Jeffrey Mark Siskind; Automatic Differentiation in Machine Learning: a Survey; 2018

Test Time: Predict Sequence of Characters

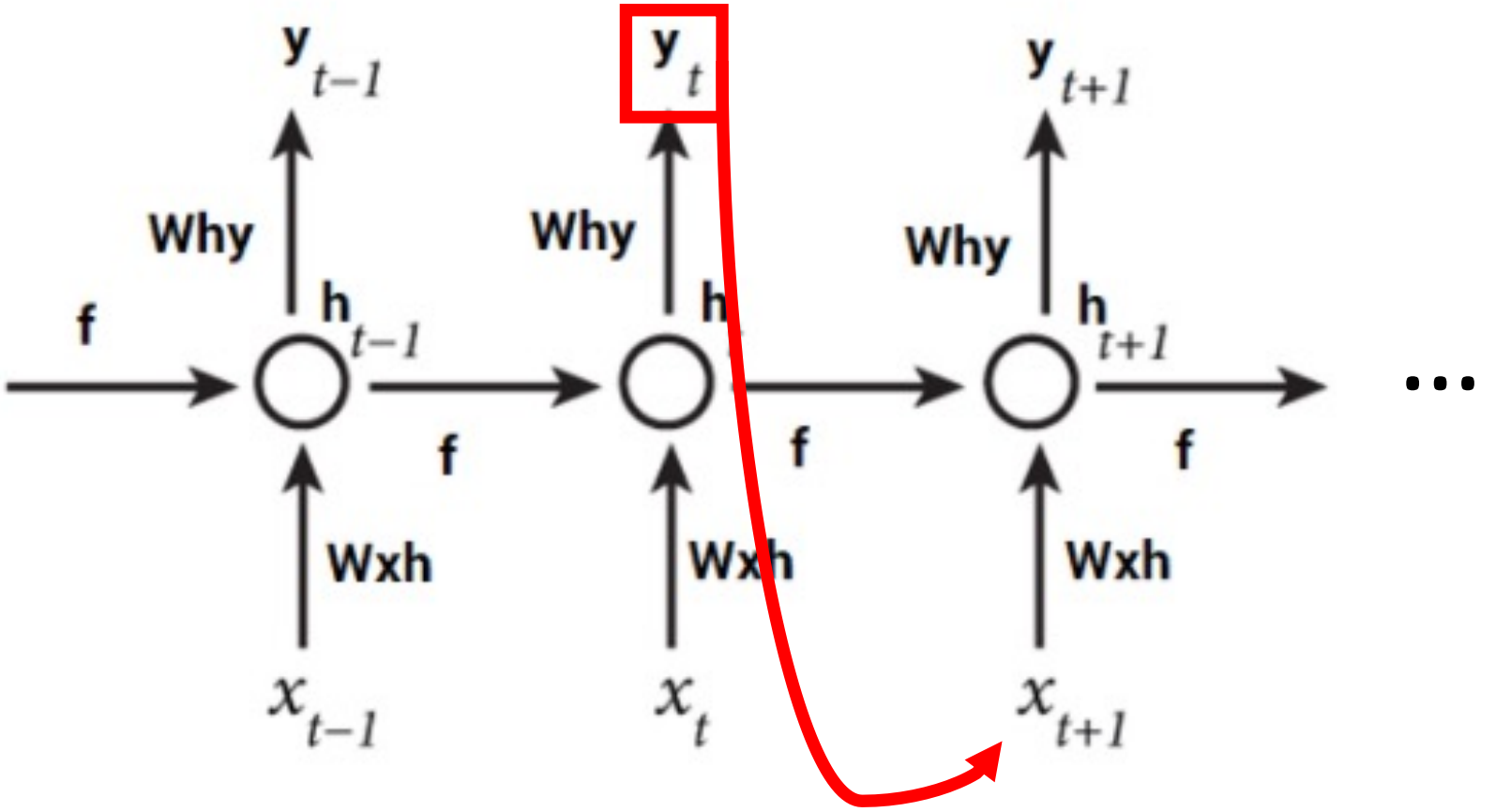


…

Feed previous prediction as input for next time step

https://www.analyticsvidhya.com/blog/2017/12/introduction-to-recurrent-neural-networks/

Test Time: Predict Sequence of Characters

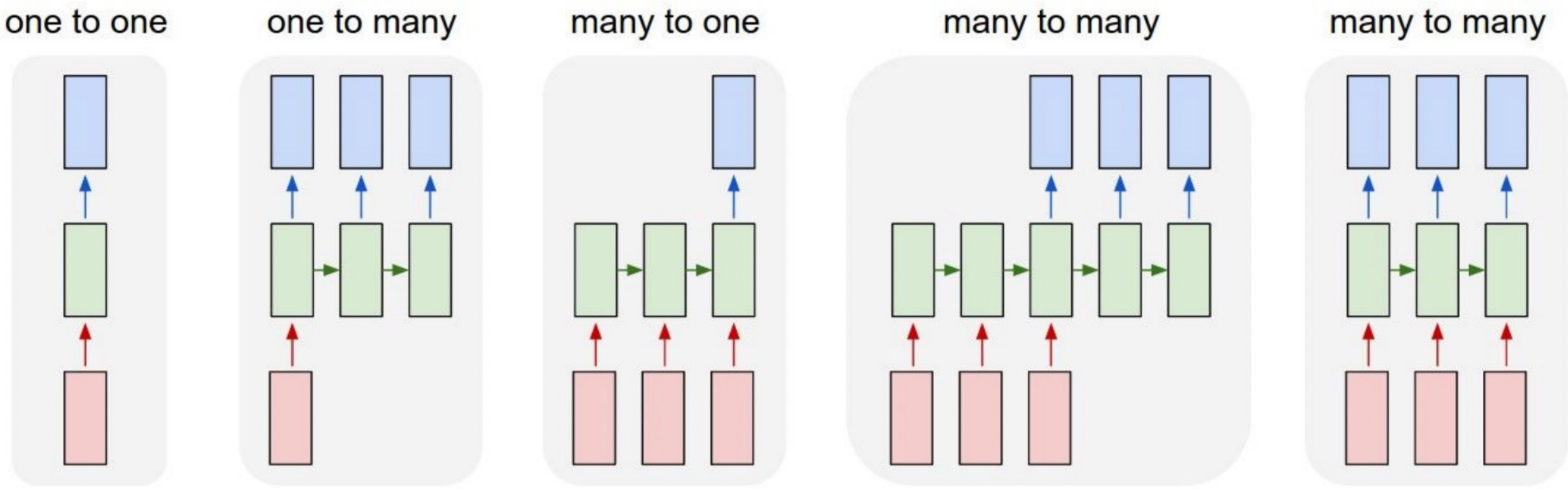


...

Feed previous prediction as input for next time step

https://www.analyticsvidhya.com/blog/2017/12/introduction-to-recurrent-neural-networks/

RNN Variants: Variable Input/Output Lengths



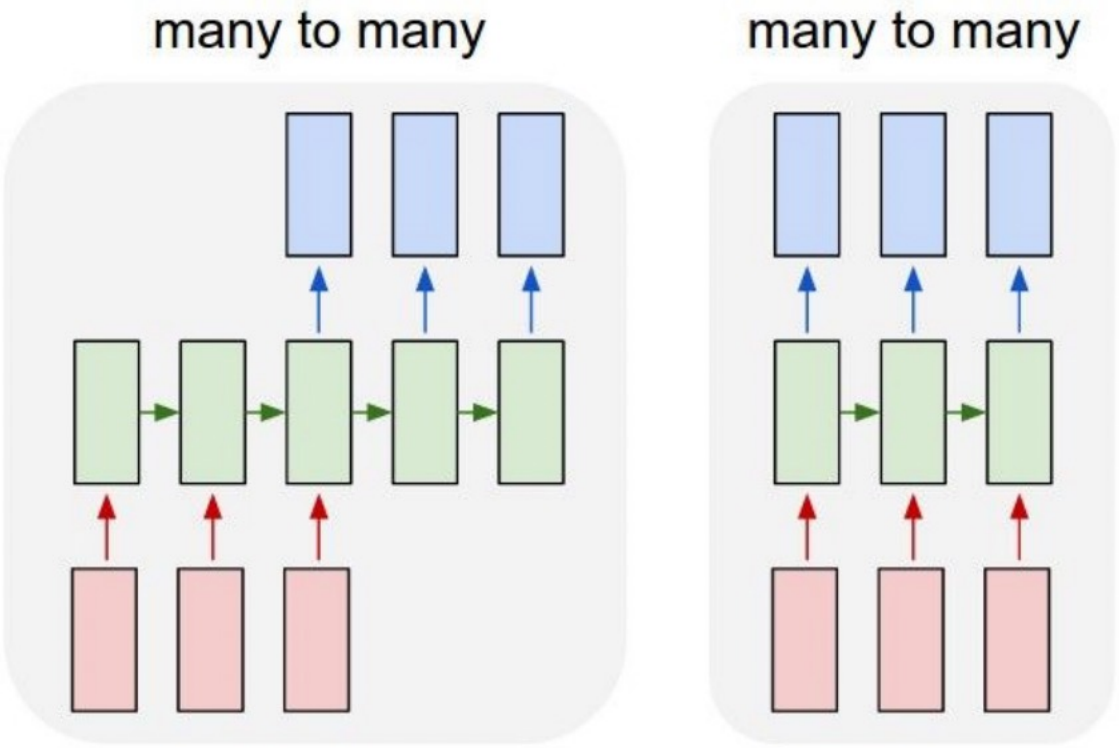
Which variant would you use for text classification?

http://cs231n.stanford.edu/slides/2016/winter1516_lecture10.pdf

RNN Variants: Variable Input/Output Lengths

Why would you choose the first variant of “many to many” over the second?

- Need full context before predicting; e.g., dialogue or Q&A

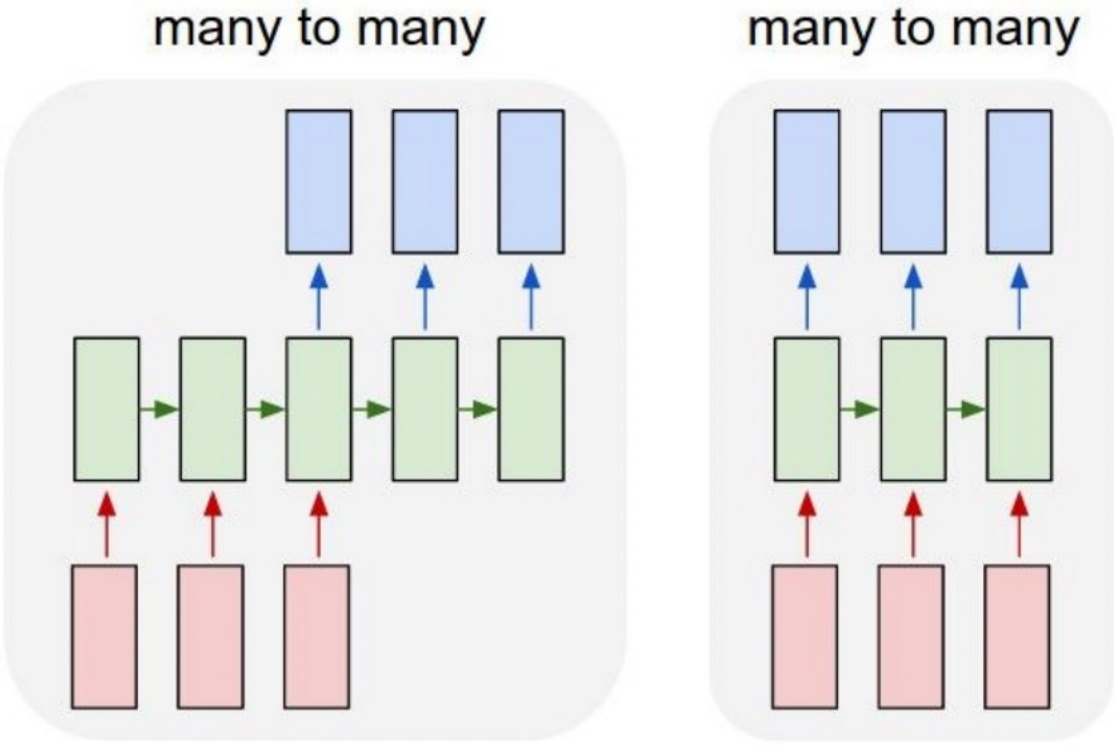


http://cs231n.stanford.edu/slides/2016/winter1516_lecture10.pdf

RNN Variants: Variable Input/Output Lengths

Why would you choose the latter variant of “many to many” over the former?

- Full context not needed to predict; e.g., named entity recognition

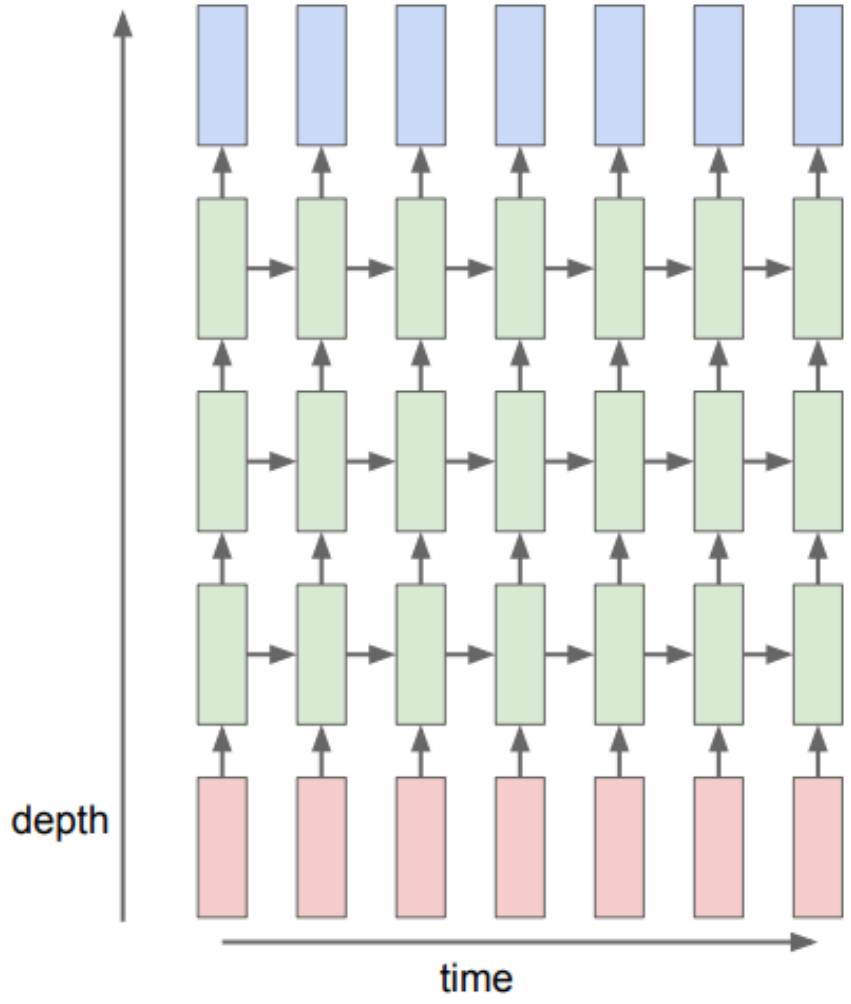


$[\text{Jim}]_{\text{Person}}$ bought 300 shares of $[\text{Acme Corp.}]_{\text{Organization}}$ in $[\text{2006}]_{\text{Time}}$

https://en.wikipedia.org/wiki/Named-entity_recognition

http://cs231n.stanford.edu/slides/2016/winter1516_lecture10.pdf

RNN Variants: Different Number of Hidden Layers and Number of Nodes Per Layer



Captures information about past, via hidden states, with more complex representations

Experimental evidence suggests deeper models can perform better:

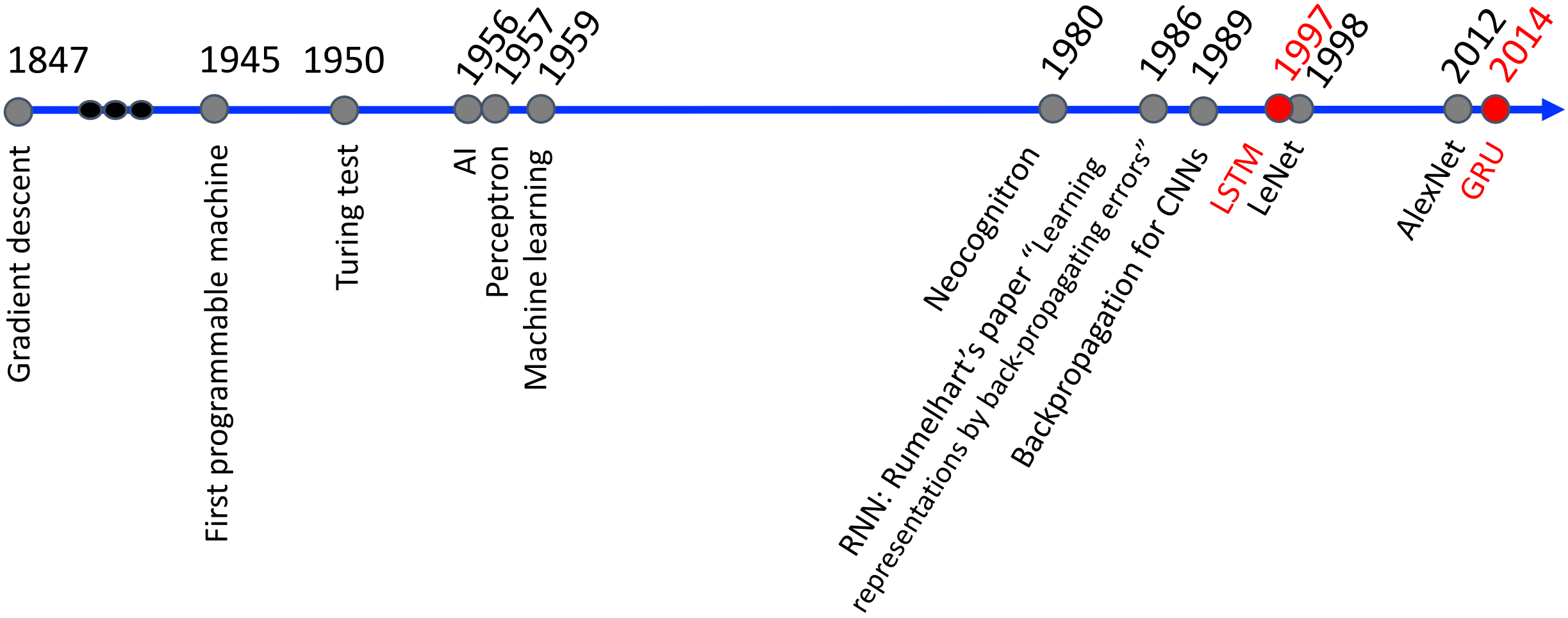
- Graves et al.; Speech Recognition with Deep Recurrent Neural Networks; 2013.
- Pascanu et al.; How to Construct Deep Recurrent Neural Networks; 2014.

http://cs231n.stanford.edu/slides/2016/winter1516_lecture10.pdf

Today's Topics

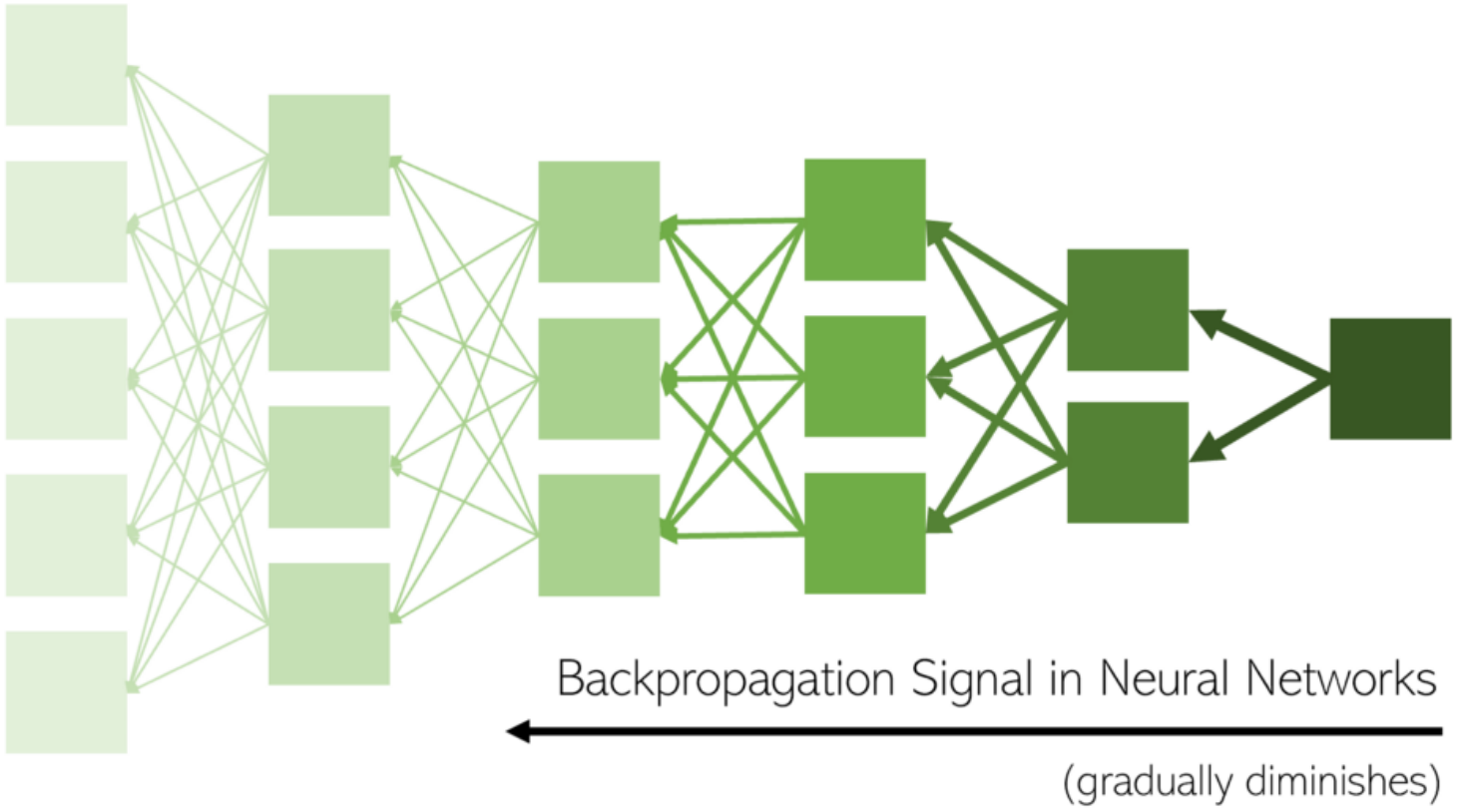
- Deep learning for sequential data
- Recurrent neural networks (RNNs)
- Gated RNNs
- Programming tutorial

Historical Context



Motivation: Recall Vanishing Gradients Problem

Smallest gradients at **earliest layers make them slowest to train**, yet later layers depend on those earlier layers to do something useful; consequently, NNs struggle with garbage in means garbage out



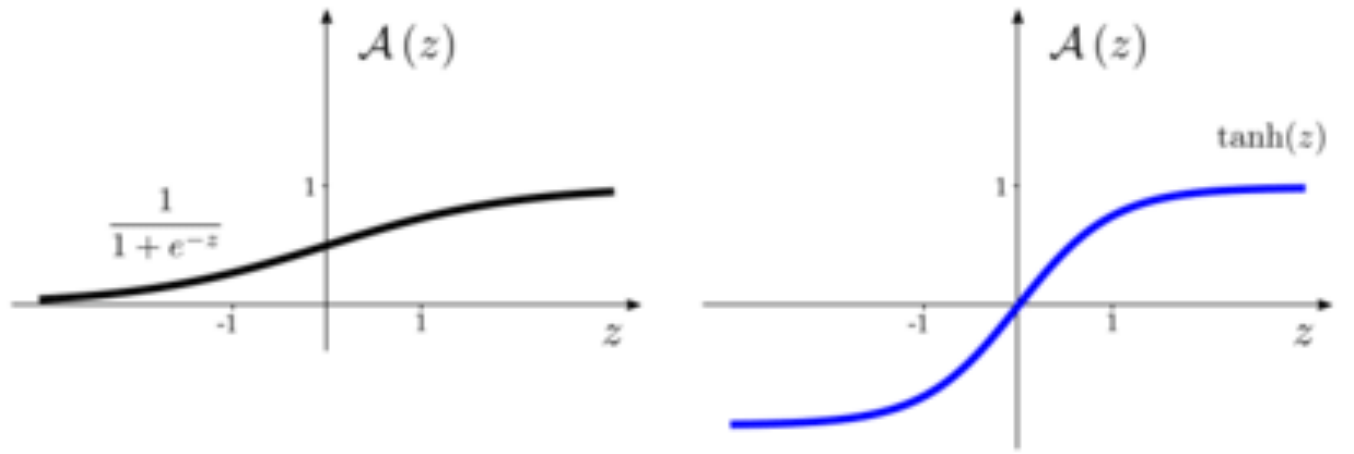
https://towardsdatascience.com/batch-normalization-the-greatest-breakthrough-in-deep-learning-77e64909d81d

Motivation: Recall Vanishing Gradients Problem

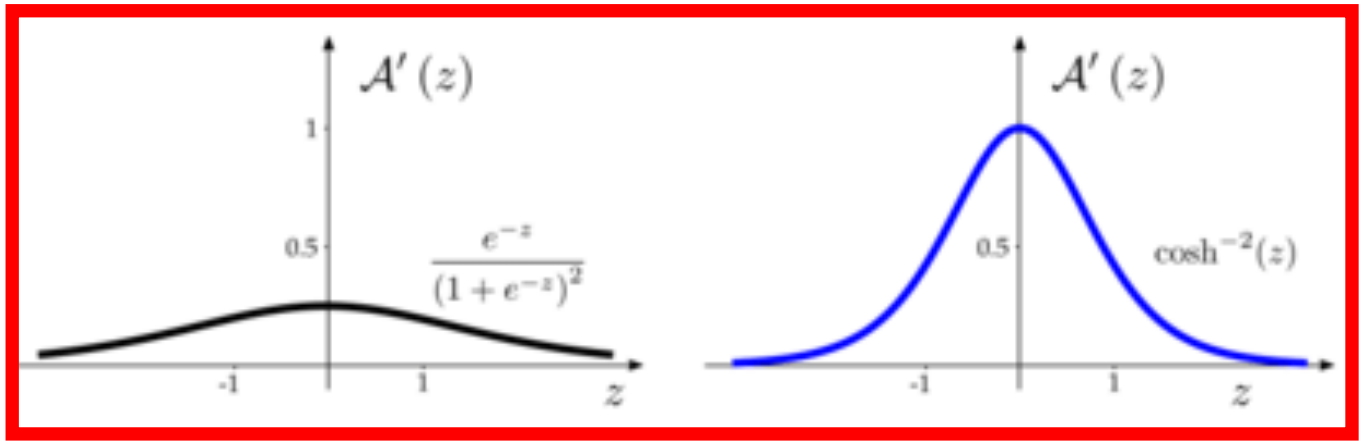
Sigmoid

Tanh

Main reason is activation functions and their derivatives:



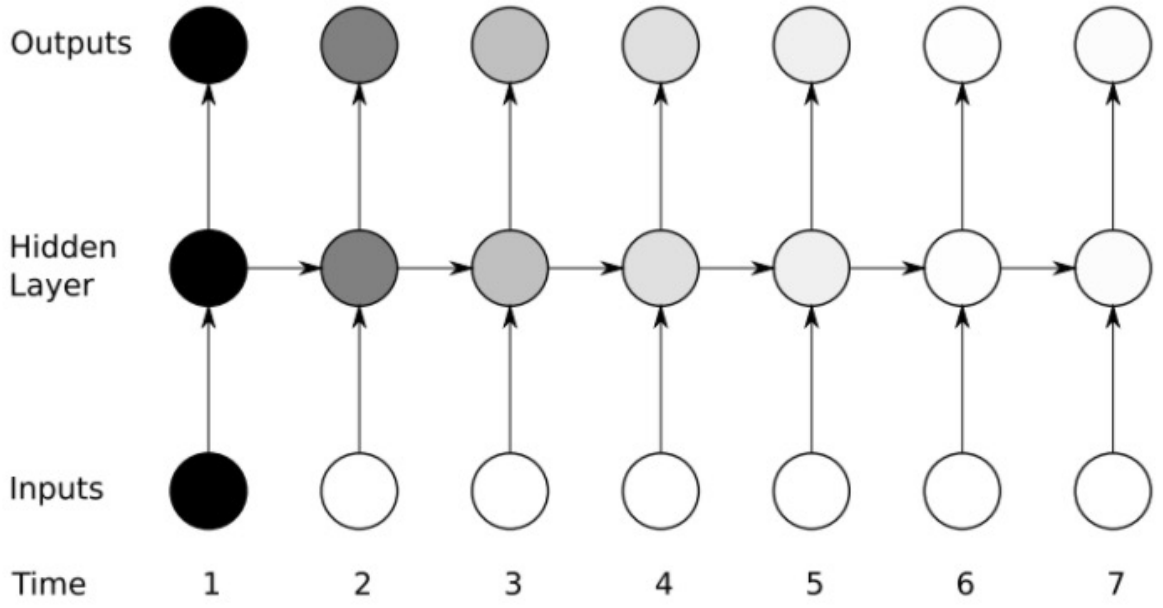
Ranges from 0 to 1, and typically less than 1:



Masi et al. Journal of the Mechanics and Physics of Solids. 2021

RNN Challenge: Learn Long-Term Dependencies

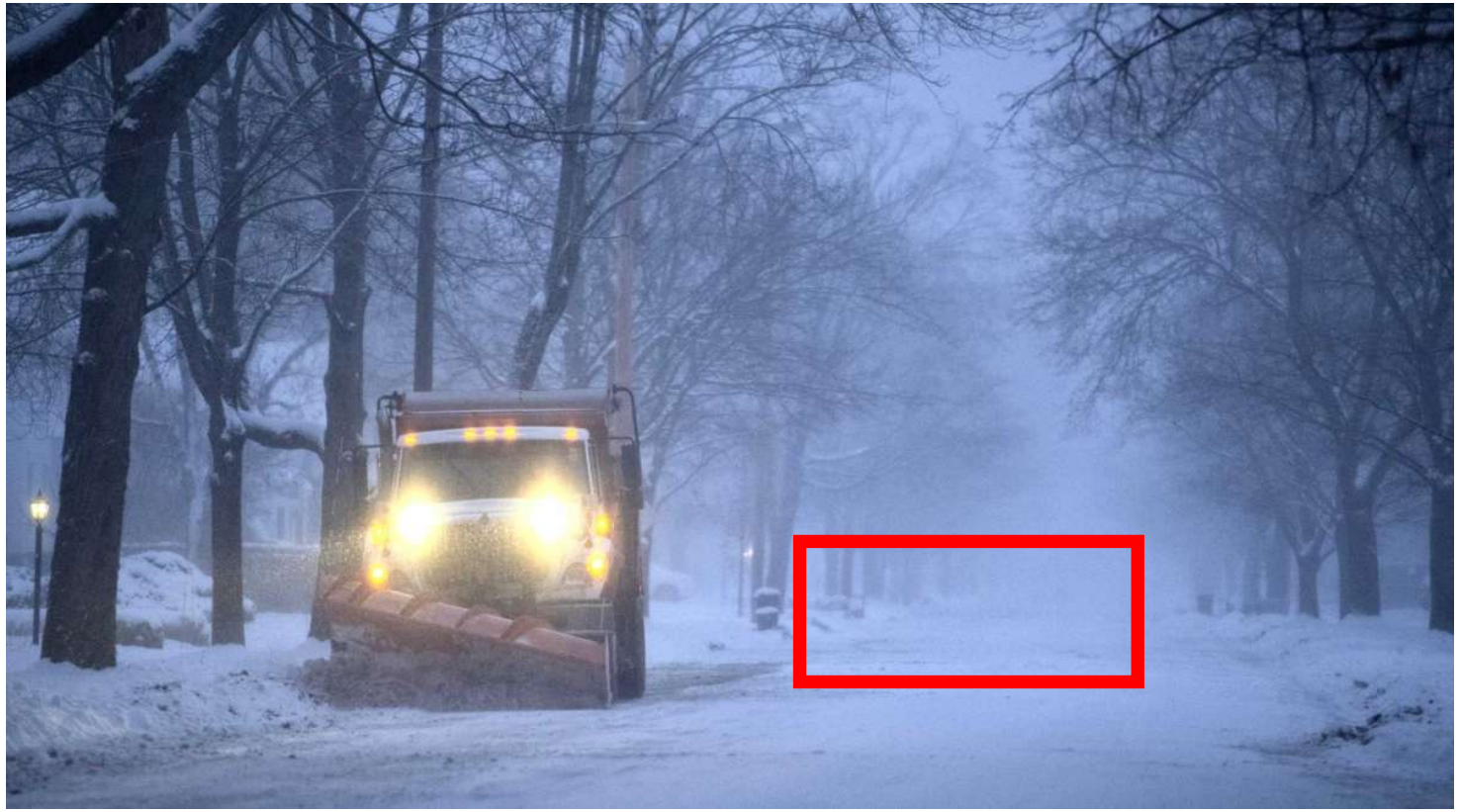
- e.g., language: “In 2004, I started college” vs “I started college in 2004”



- e.g., $\partial E/\partial W = \partial E/\partial y_3 * \partial y_3/\partial h_3 * \partial h_3/\partial y_2 * \partial y_2/\partial h_1$
  - Vanishing gradient: a product of numbers less than 1 shrinks to zero

https://www.analyticsvidhya.com/blog/2017/12/introduction-to-recurrent-neural-networks/

RNN Challenge: Learn Long-Term Dependencies



Analogy: memory of past in RNN diminishes similar to how the road starts to disappear as the vehicle that plowed the snow moves farther down the road

Image: https://www.timesunion.com/news/article/albany-saratoga-snow-totals-16826908.php

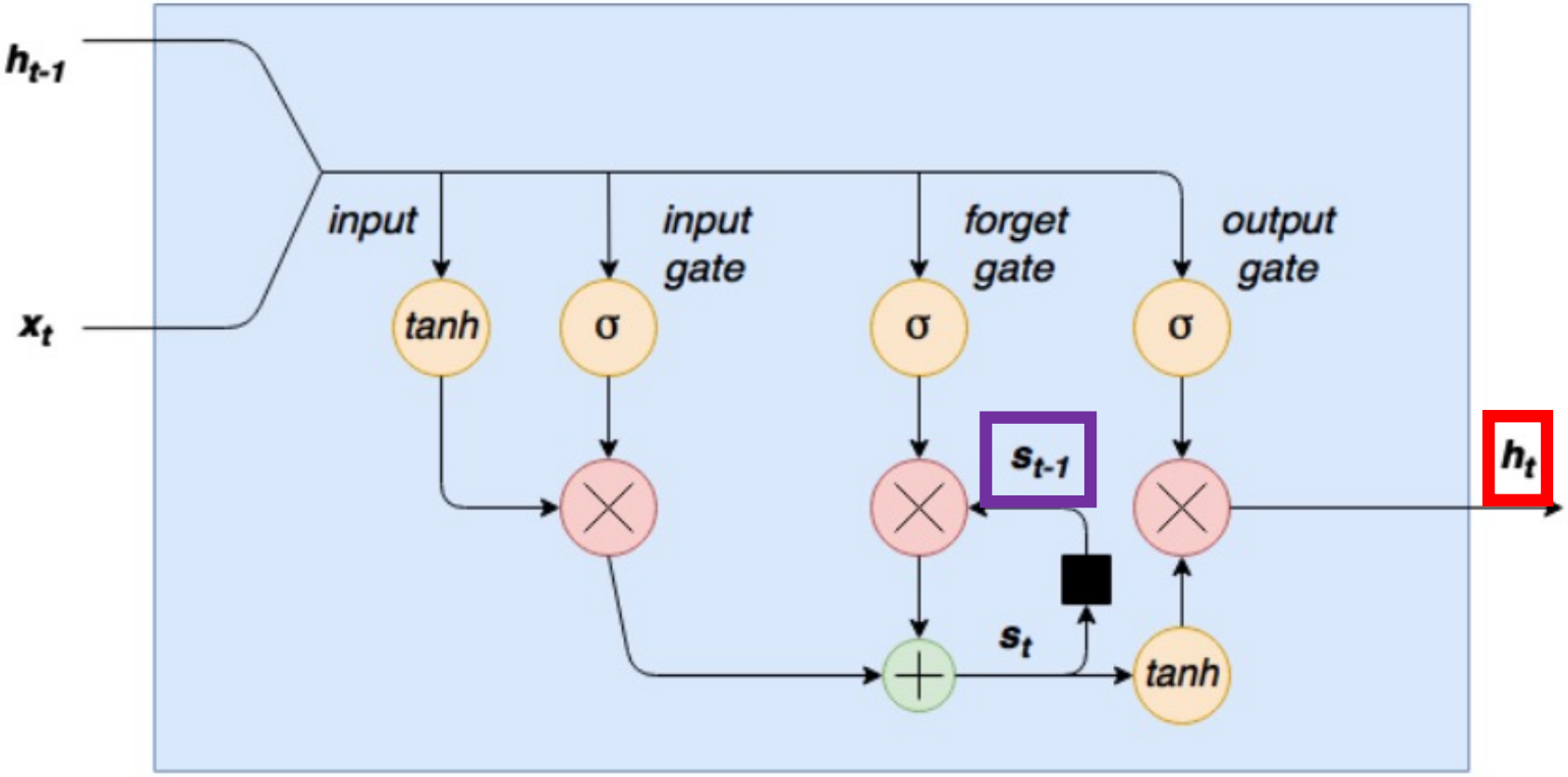
What Are Vanishing Gradient Remedies?

- Many remedies we have discussed can be used with RNNs; e.g.,
  - ReLU activation functions
  - Intelligent weight initialization
  - Skip connections

- Popular RNN Solution: gates

Popular RNN Variant #1: LSTM

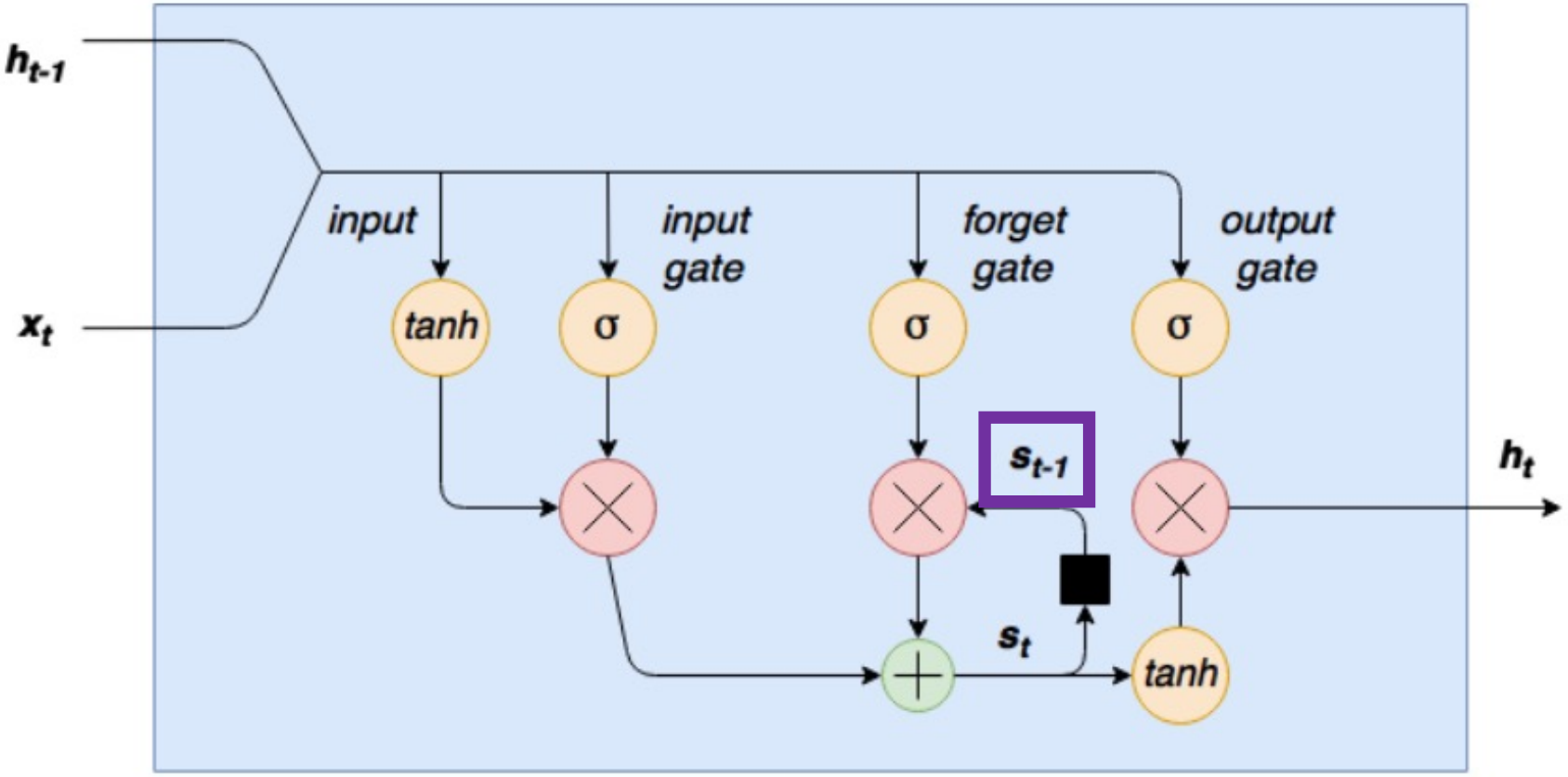
Both the previous hidden state and cell state are passed to next time steps



http://adventuresinmachinelearning.com/recurrent-neural-networks-lstm-tutorial-tensorflow/

Popular RNN Variant #1: LSTM

Cell state: can retain memory of the past for a long duration



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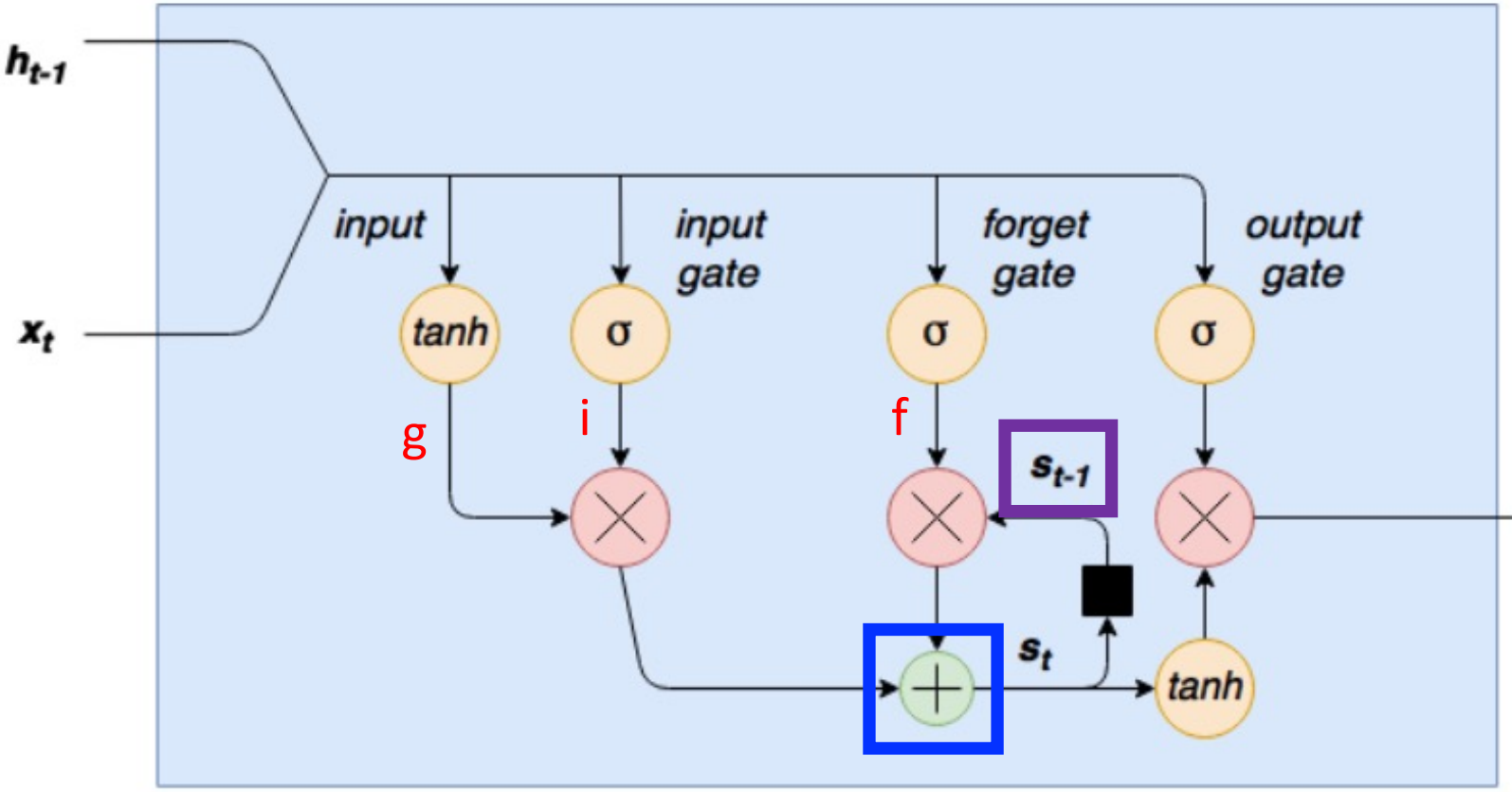
Popular RNN Variant #1: LSTM

Cell state: can retain memory of the past for a long duration, based on the forget gate



$$s_t = s_{t-1} \circ f + g \circ i$$

$$\frac{\partial s_t}{\partial s_{t-1}} = f$$

The addition enables the cell state to flow back through time for long durations

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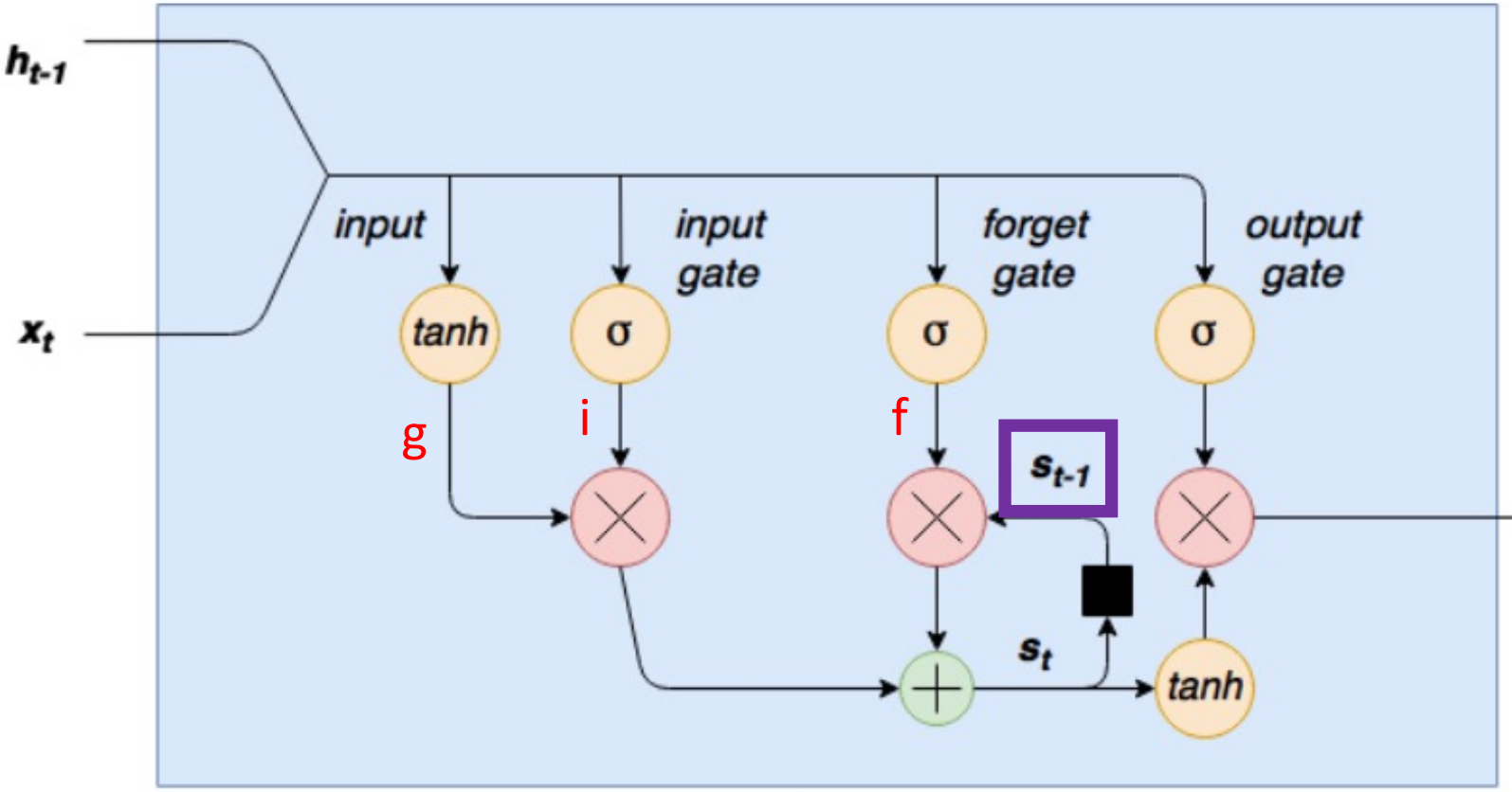

$$s_t = s_{t-1} \circ f + g \circ i$$

$$\frac{\partial s_t}{\partial s_{t-1}} = f$$

Forget gate range: 0 to 1

- What happens if 0?
  - Past discarded
- What happens if 1?
  - Past retained

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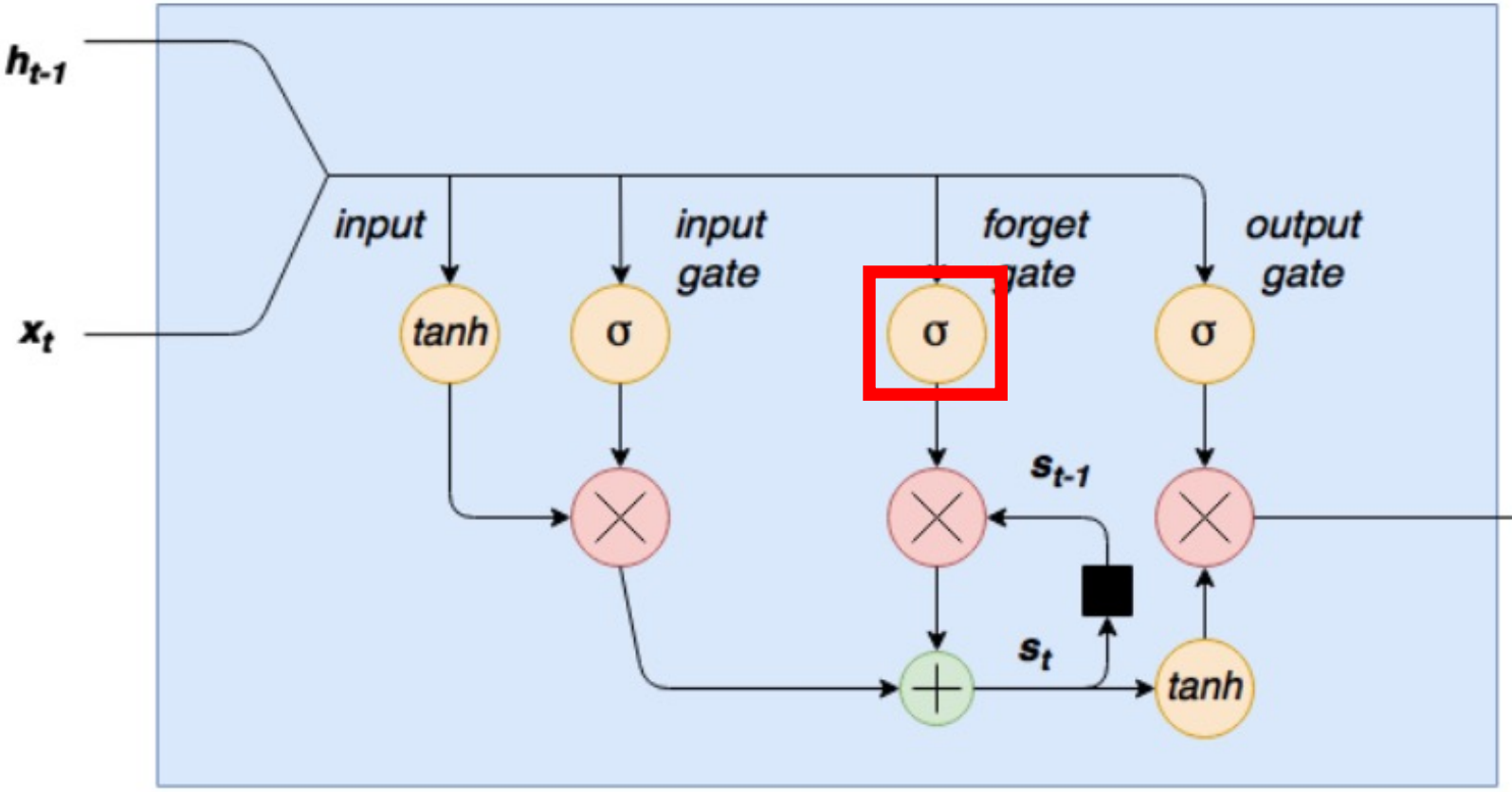
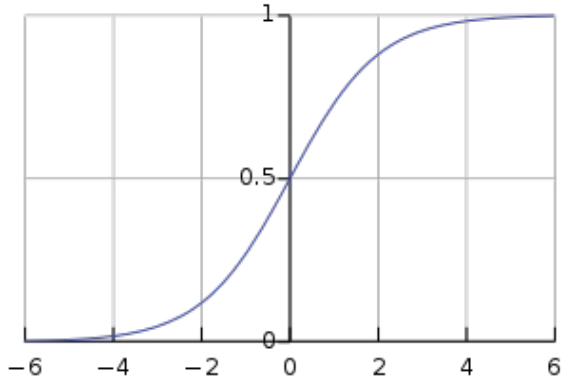


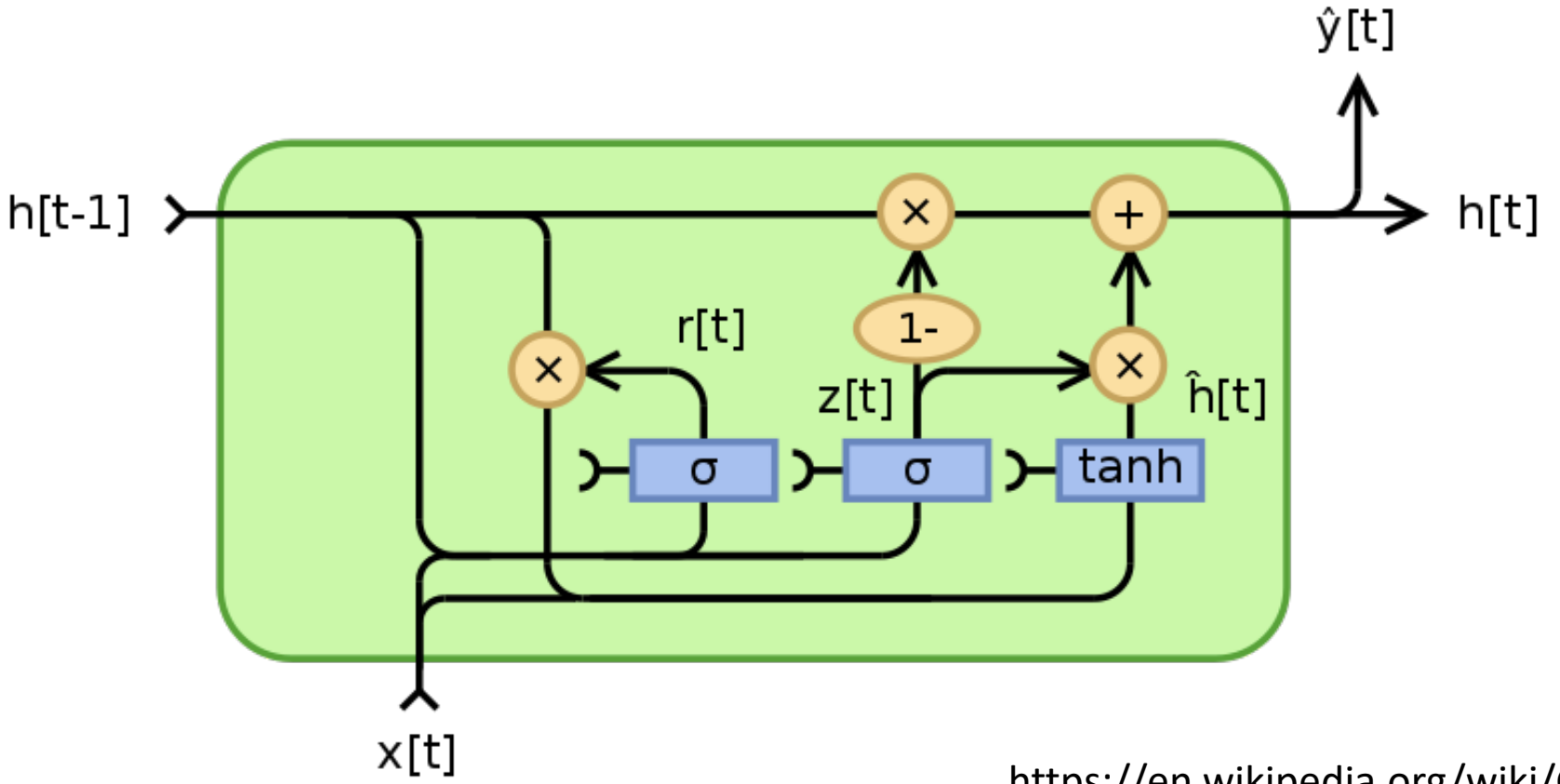


Called gate because sigmoid function mimics open (1) and closed (0)

http://adventuresinmachinelearning.com/recurrent-neural-networks-lstm-tutorial-tensorflow/

Popular RNN Variant #1: Gated Recurrent Unit

- Simplifies LSTM by merging: (1) cell and hidden states and (2) forget and input gates



https://en.wikipedia.org/wiki/Gated_recurrent_unit

K. Chou et al; Learning Phrase Representations using RNN Encoder-Decoder for Statistical Machine Translation; 2014

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The End