Recurrent Neural Networks

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University of Texas at Austin
Spring 2020

https://www.ischool.utexas.edu/~dannag/Courses/IntroToMachineLearning/CourseContent.html

Review

- Last week:
  - History of Convolutional Neural Networks (CNNs)
  - CNNs – Convolutional Layers
  - CNNs – Pooling Layers

- Assignments (Canvas):
  - Project pre-proposal due yesterday
  - Project proposal next week

- Questions?

Today’s Topics

- Machine Learning for Sequential Data
- Recurrent Neural Networks (RNNs)
- Training Deep Neural Networks: Hardware & Software
- Lab

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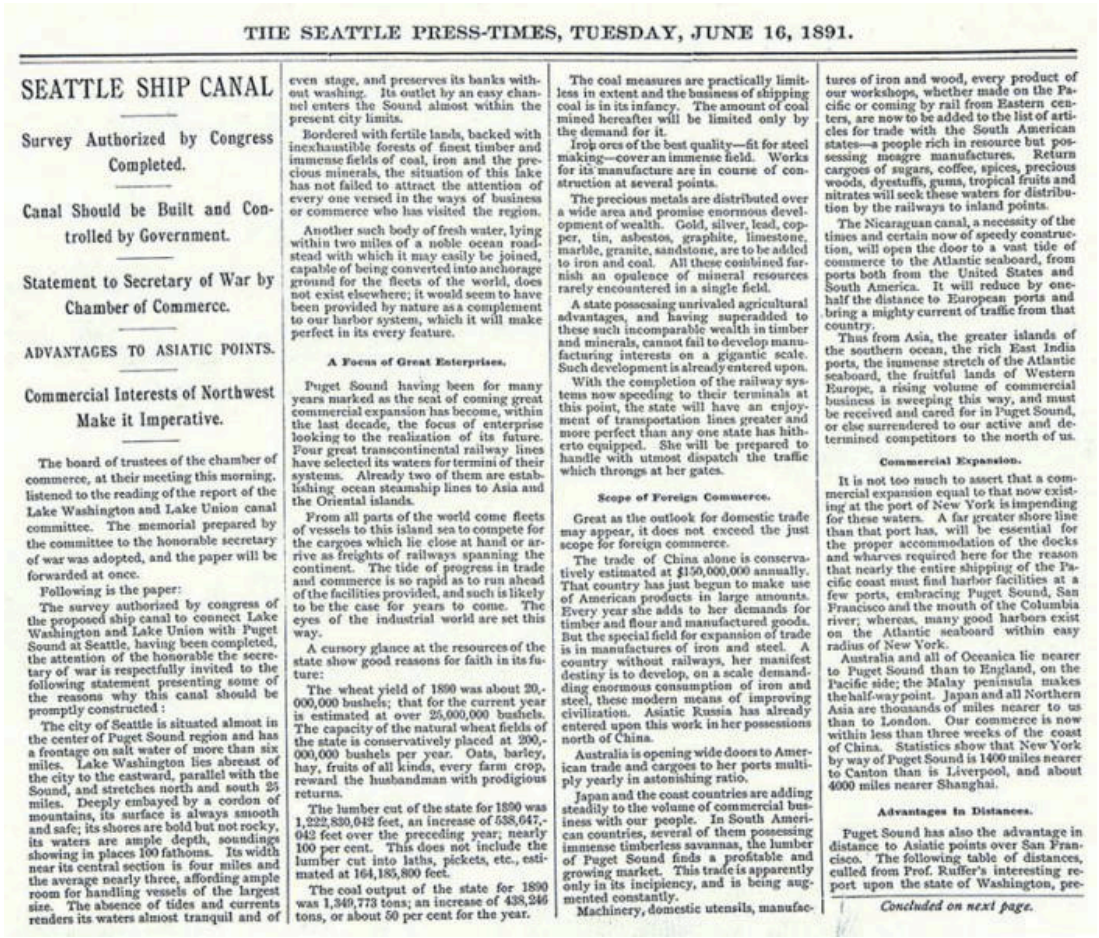
Sequence Definition: Data of Arbitrary Length

e.g., Document



THE SEATTLE PRESS-TIMES, TUESDAY, JUNE 16, 1891.

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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.

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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.

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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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Advantages in Distances.

Puget Sound has also the advantage in distance to Asiatic points over San Francisco. The following table of distances, culled from Prof. Ruffer's interesting report upon the state of Washington, pre-

Concluded on next page.

e.g., Images

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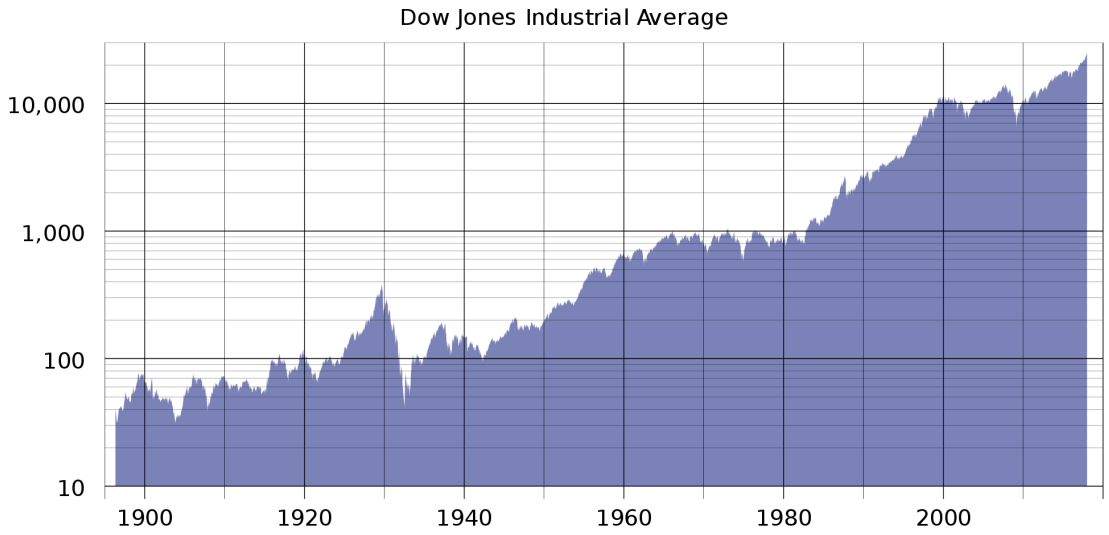

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Properties of Sequences?

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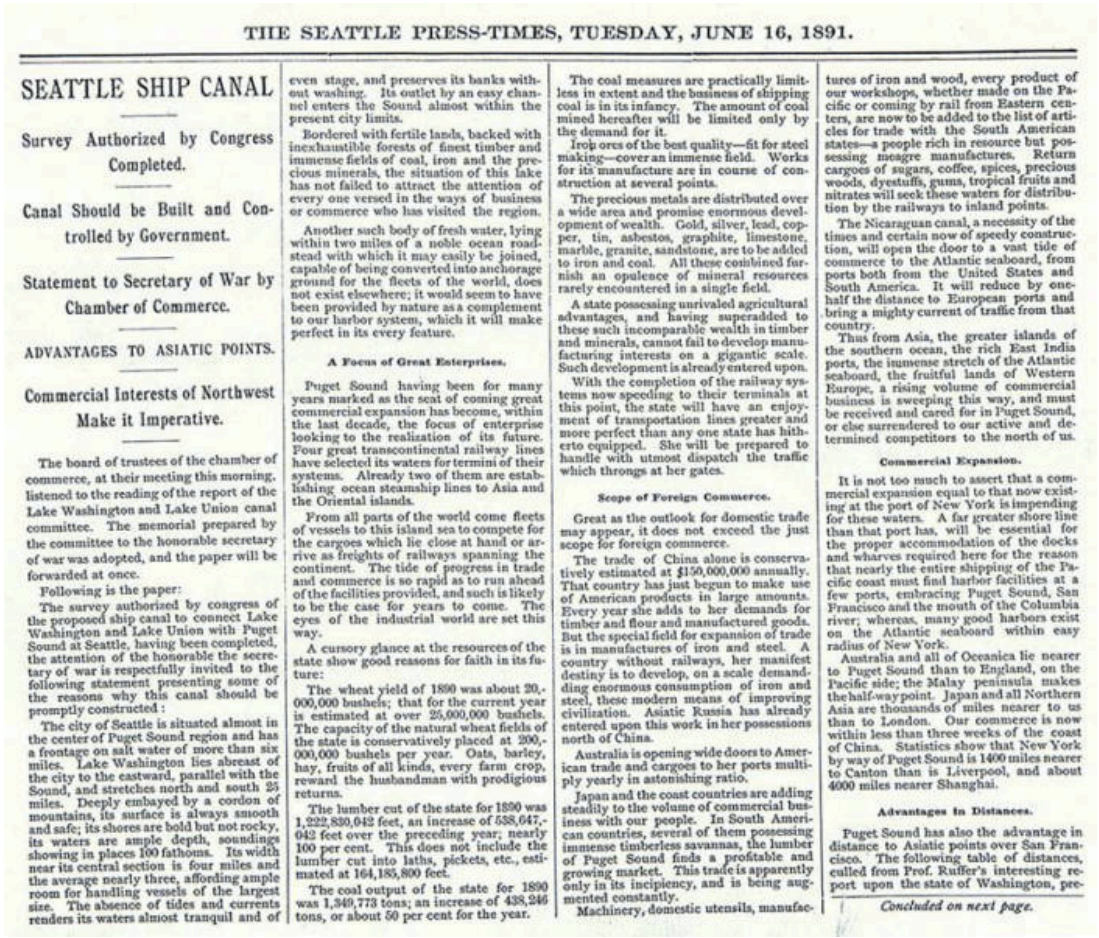

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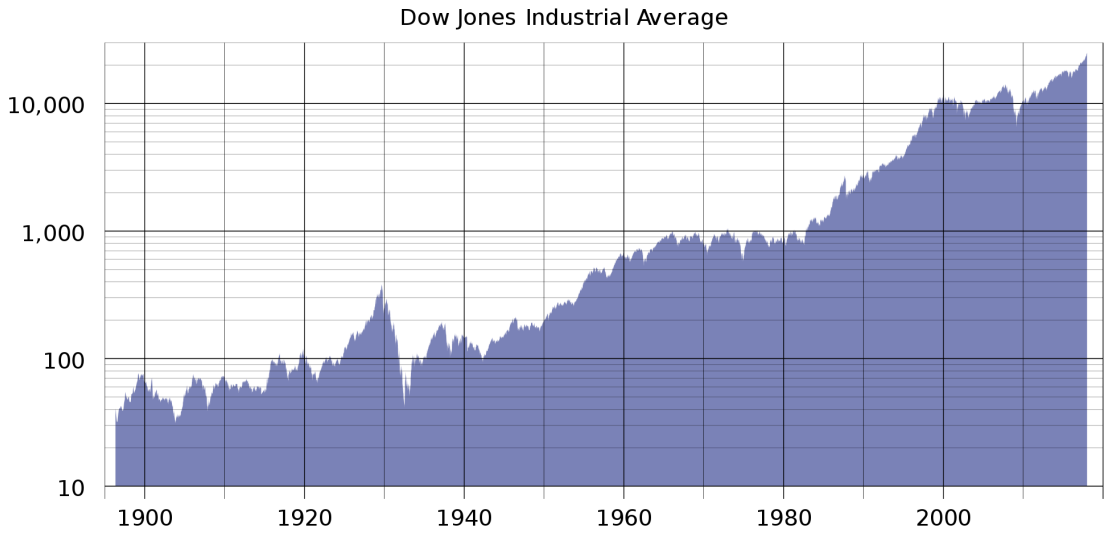
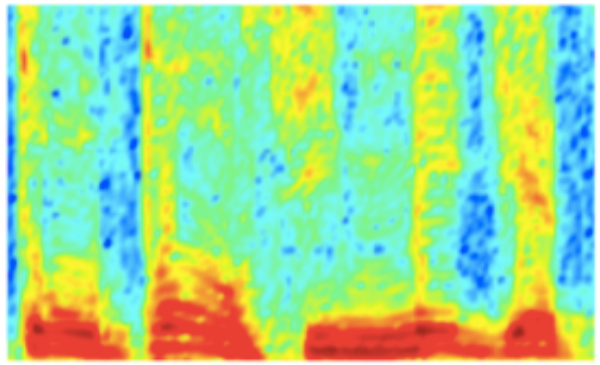


e.g., sentences, audio samples, brain waves, radio waves, air temperature

Sequence Sources

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

AUDIO



Audio Spectrogram

IMAGES

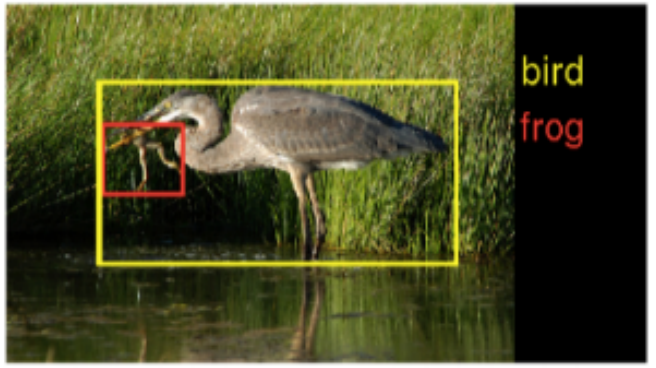


Image pixels

TEXT

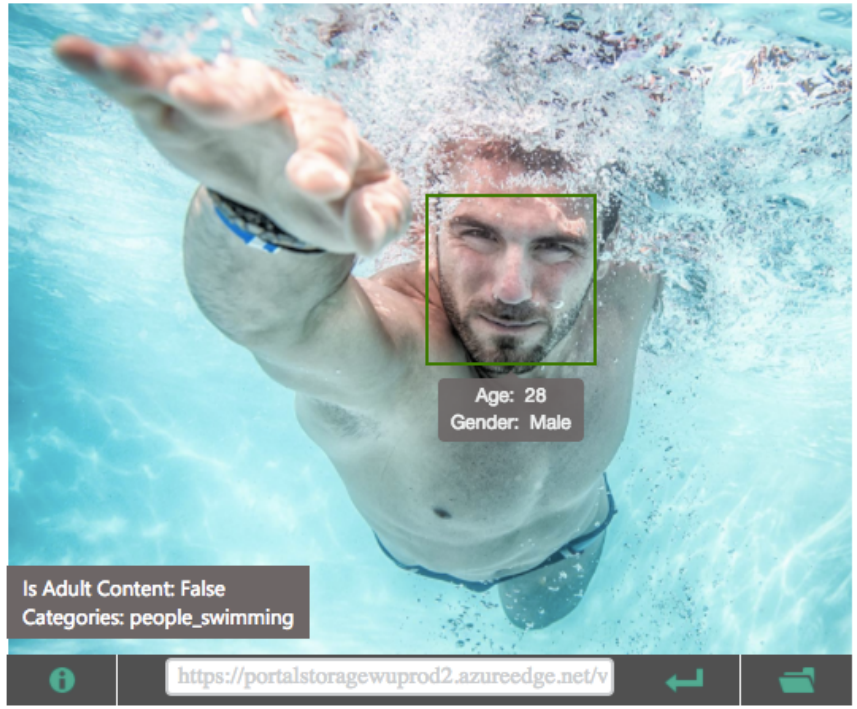
0	0	0	0.2	0	0.7	0	0	0	...	...

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



Features:

Feature Name	Value
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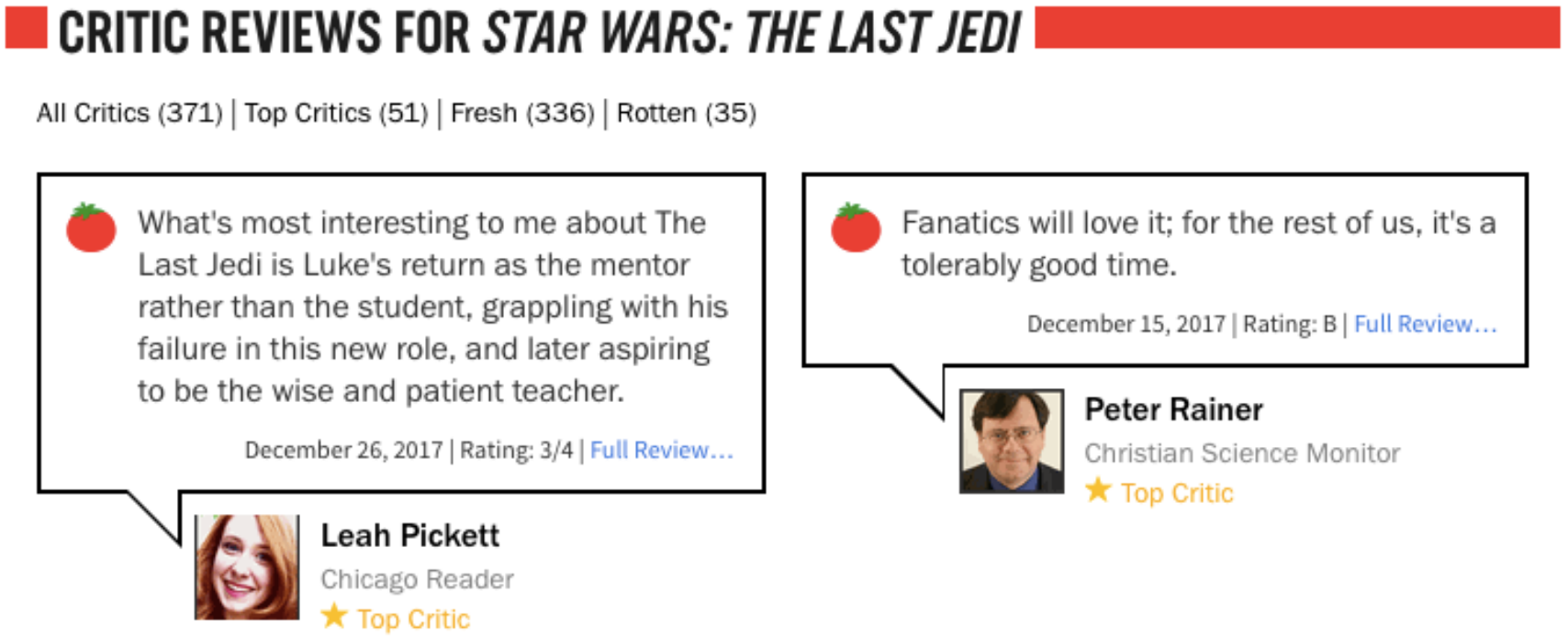
Tags	[{ "name": "water", "confidence": 0.9996442794799805 }, { "name": "sport", "confidence": 0.9504992365837097 }, { "name": "swimming", "confidence": 0.9062818288803101, "hint": "sport" }, { "name": "pool", "confidence": 0.8787588477134705 }, { "name": "water sport", "confidence": 0.631849467754364, "hint": "sport" }]
Image Format	jpeg
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

Breakout Discussion: Sequence Applications

1. What are other examples of “one-to-many” applications?
2. What are other examples of “many-to-one” applications?
3. What are other examples of “many-to-many” applications?

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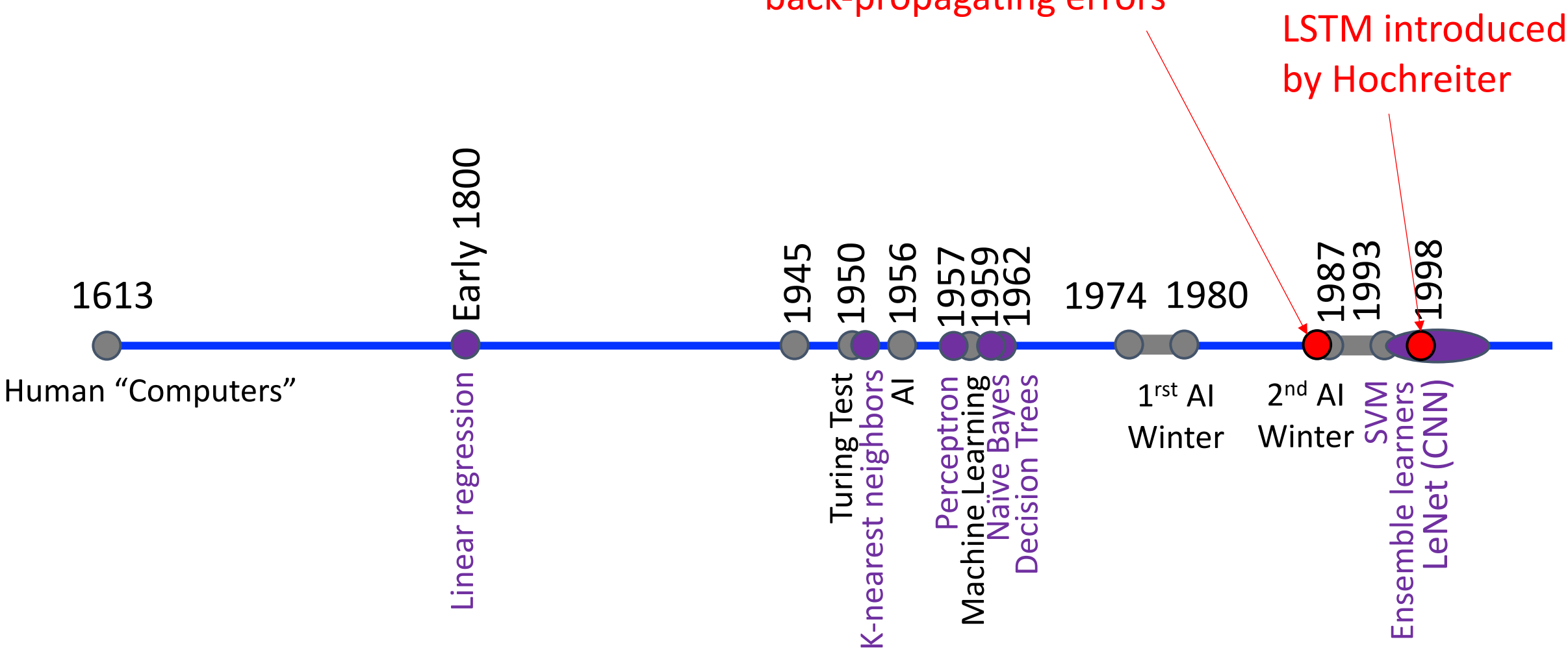
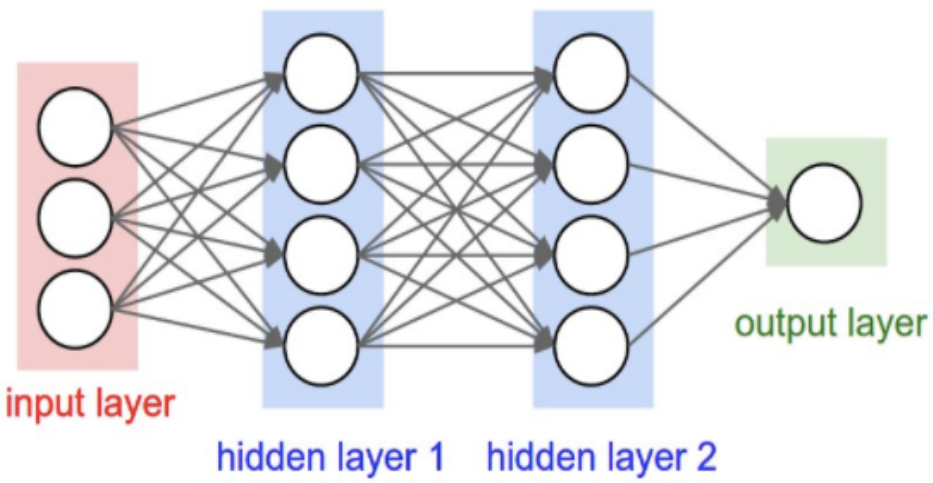
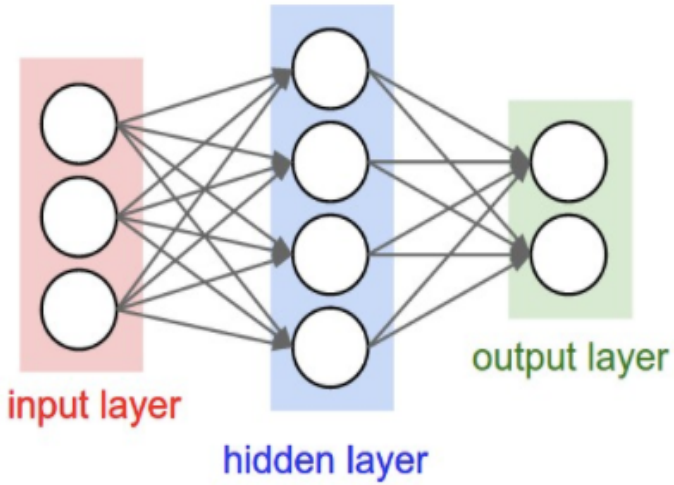
RNN History


Rumelhart, Hinton, & Williams.
"Learning Representations by
back-propagating errors"
LSTM introduced
by Hochreiter
1613
Early 1800
1945
1950
1956
1957
1959
1962
1974
1980
1987
1993
1998
Human "Computers"
Linear regression
Turing Test
K-nearest neighbors
AI
Perceptron
Machine Learning
Naïve Bayes
Decision Trees
1rst AI
Winter
2nd AI
Winter
SVM
Ensemble learners
LeNet (CNN)

Recall: Feedforward Neural Networks





Problem: many model parameters!!

Problem: no memory of past since weights learned independently

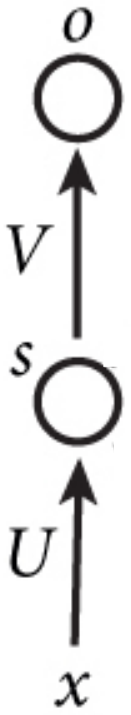
Each layer serves as input to the next layer with no loops

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

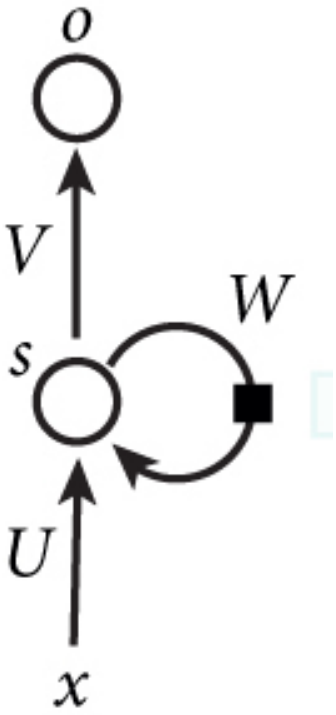
Recurrent Neural Networks (RNNs)

- 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



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

RNN

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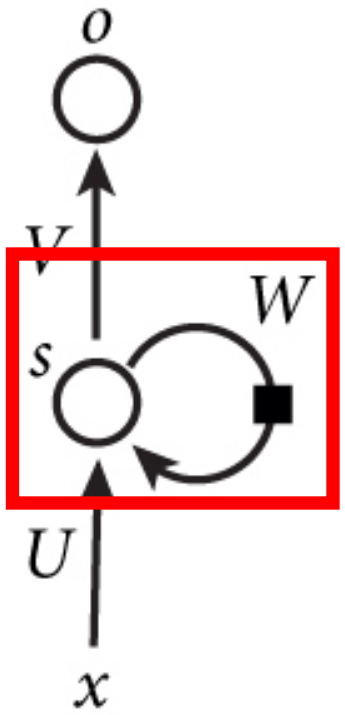

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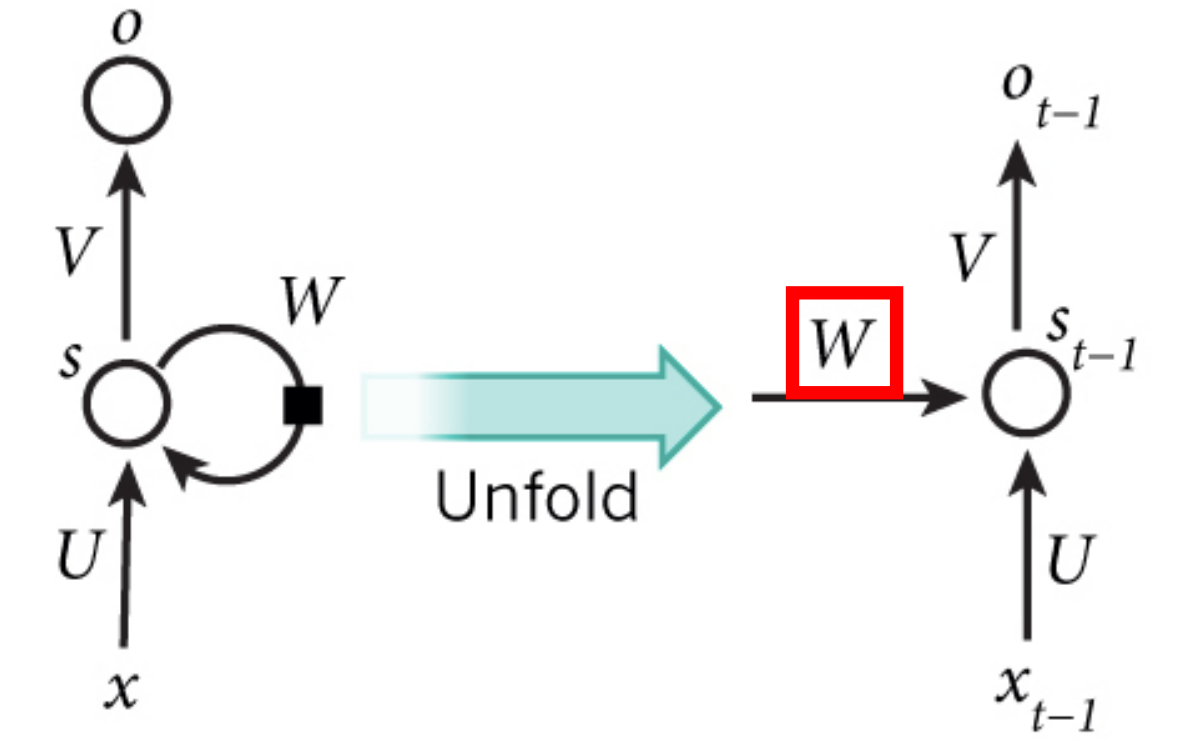
RNN: Time Step 1

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



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RNN: Time Step 2

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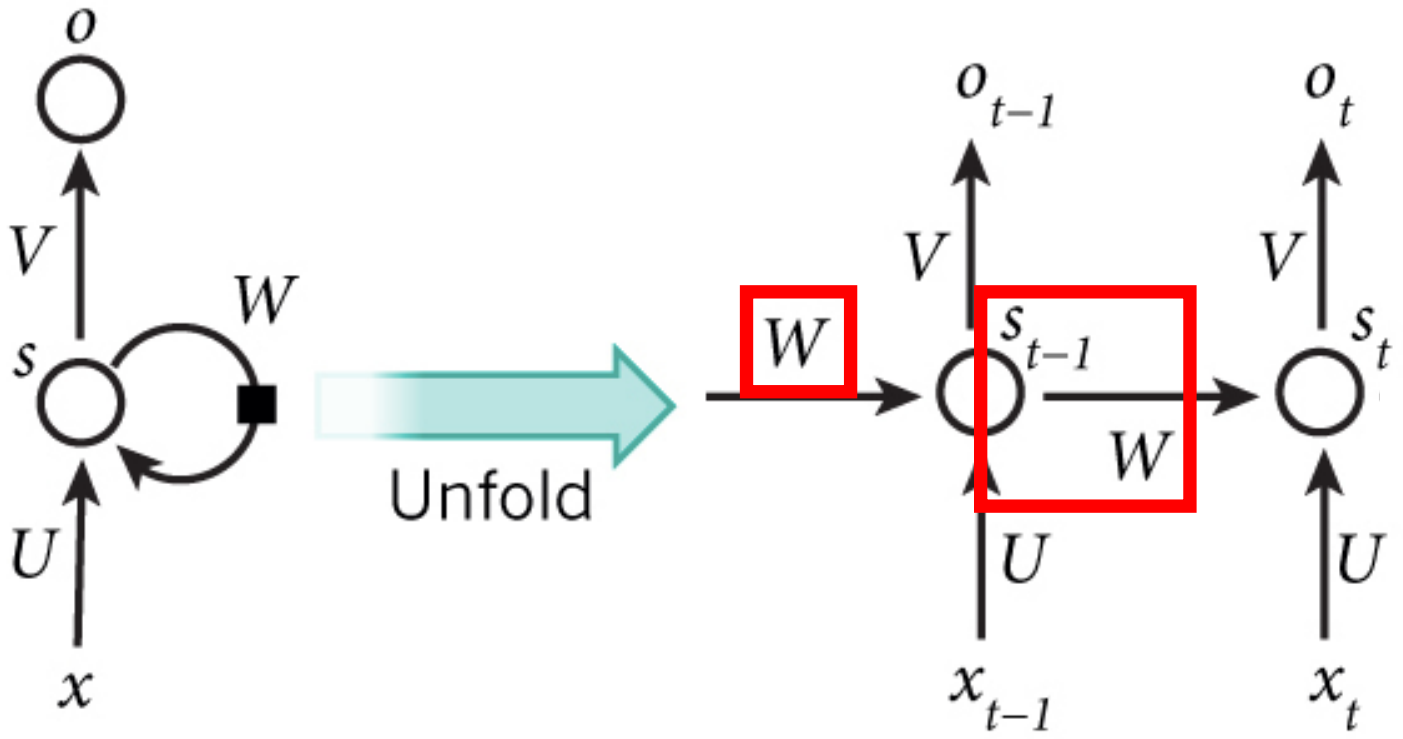

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RNN: Time Step 3

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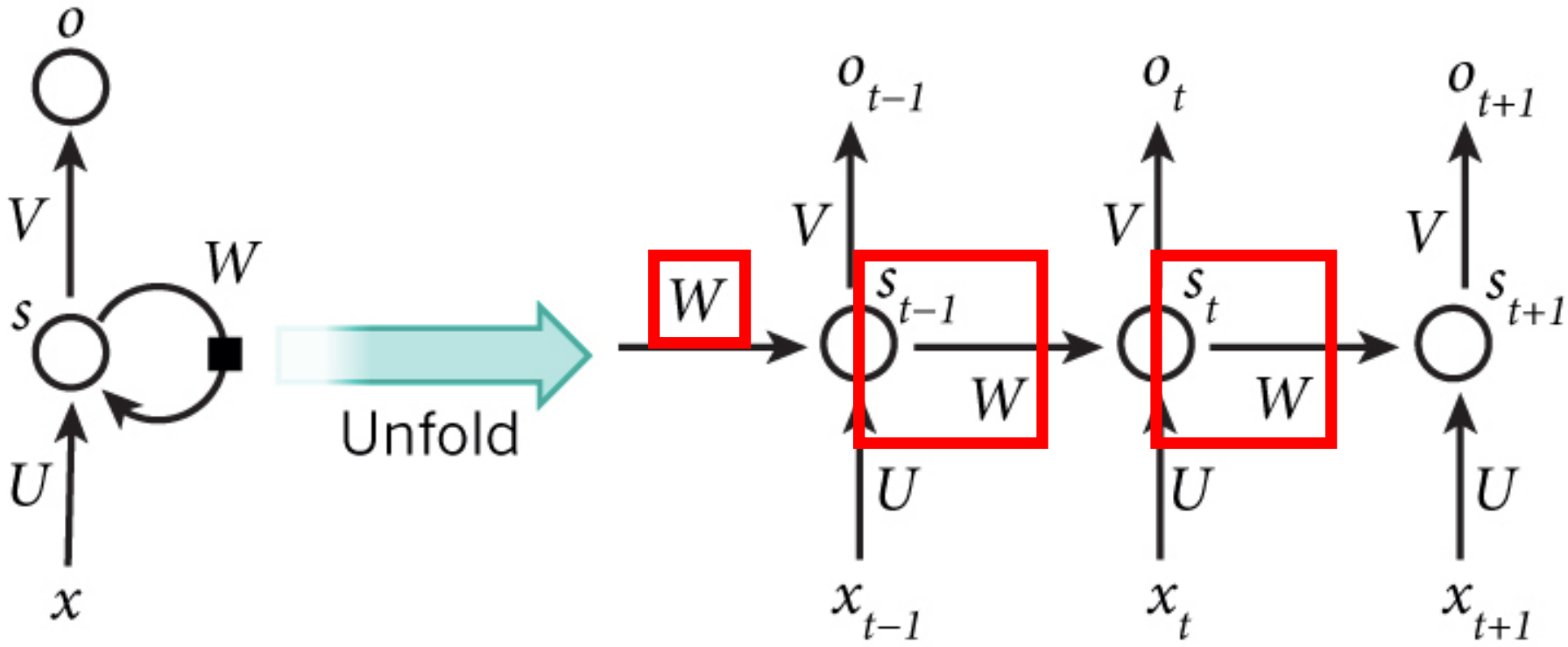

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RNN: And So On…

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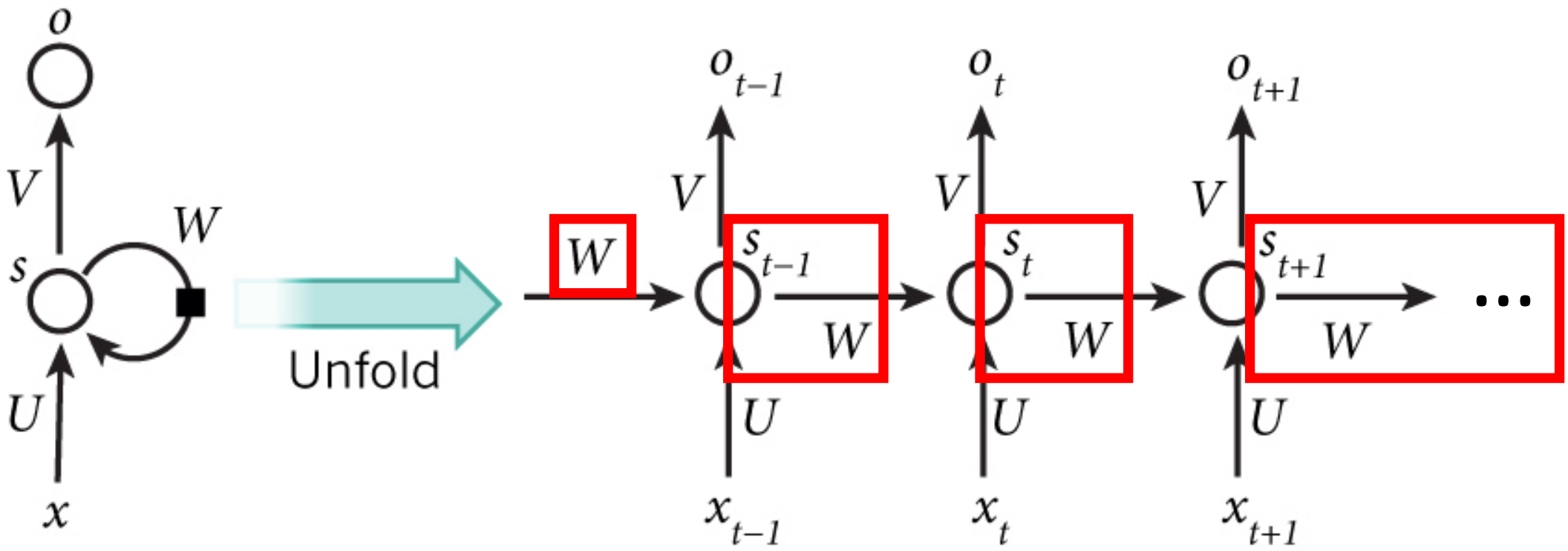

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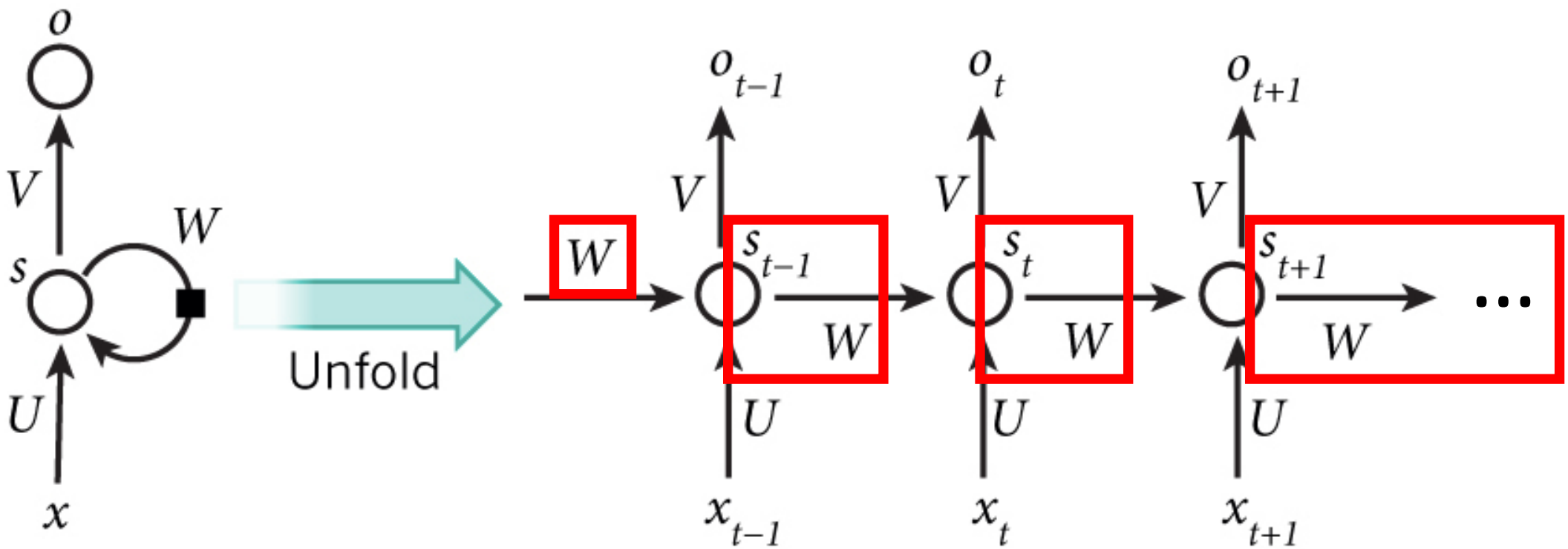

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Recurrence formula applied at every time step:

Model parameters

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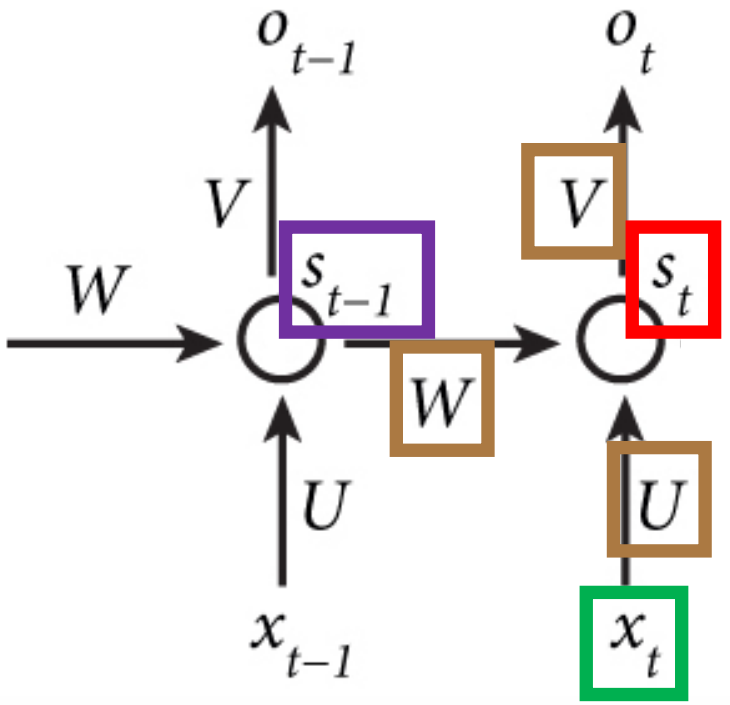
New state | Old state | Input at time step



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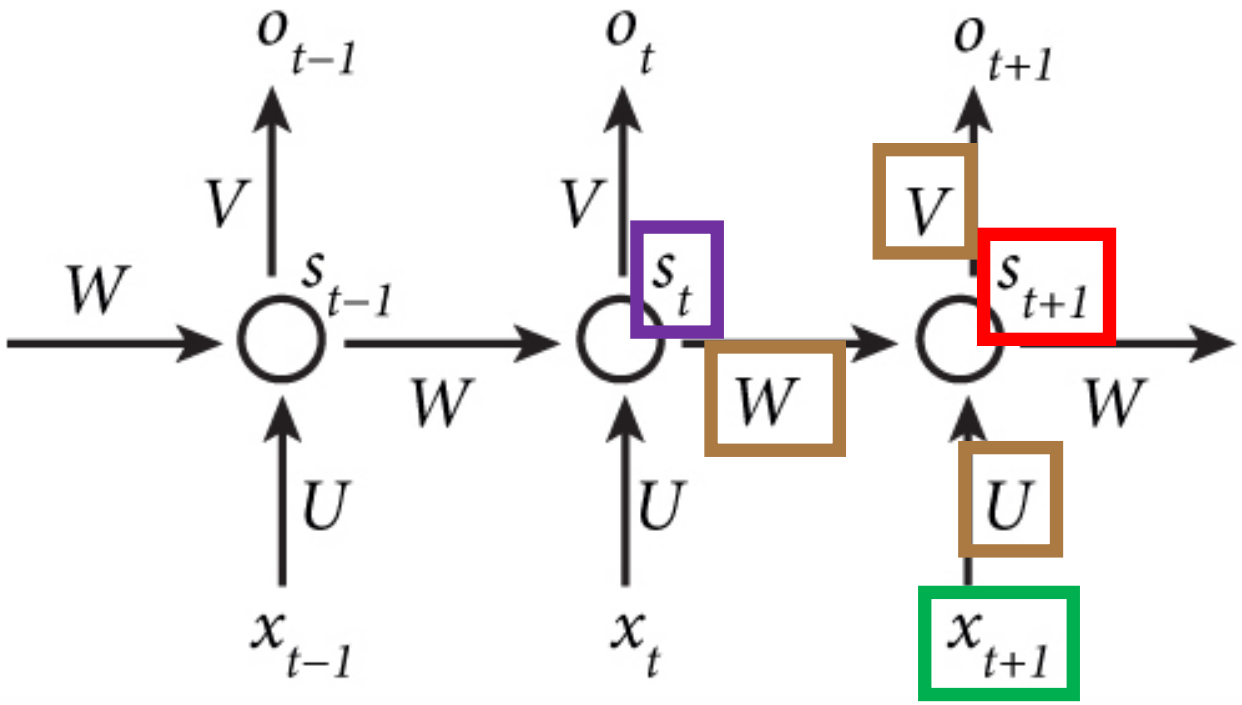
Model parameters

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

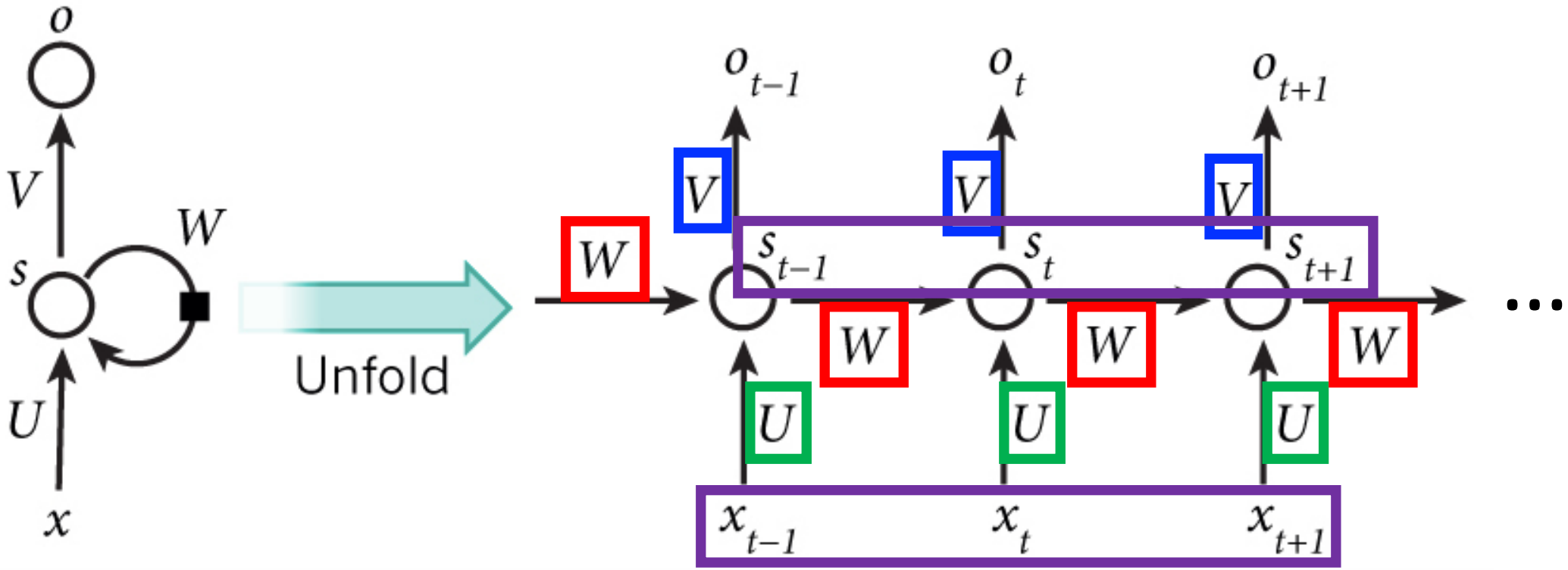
New state — Old state — Input at time step



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

RNN: Model Parameters and Inputs

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

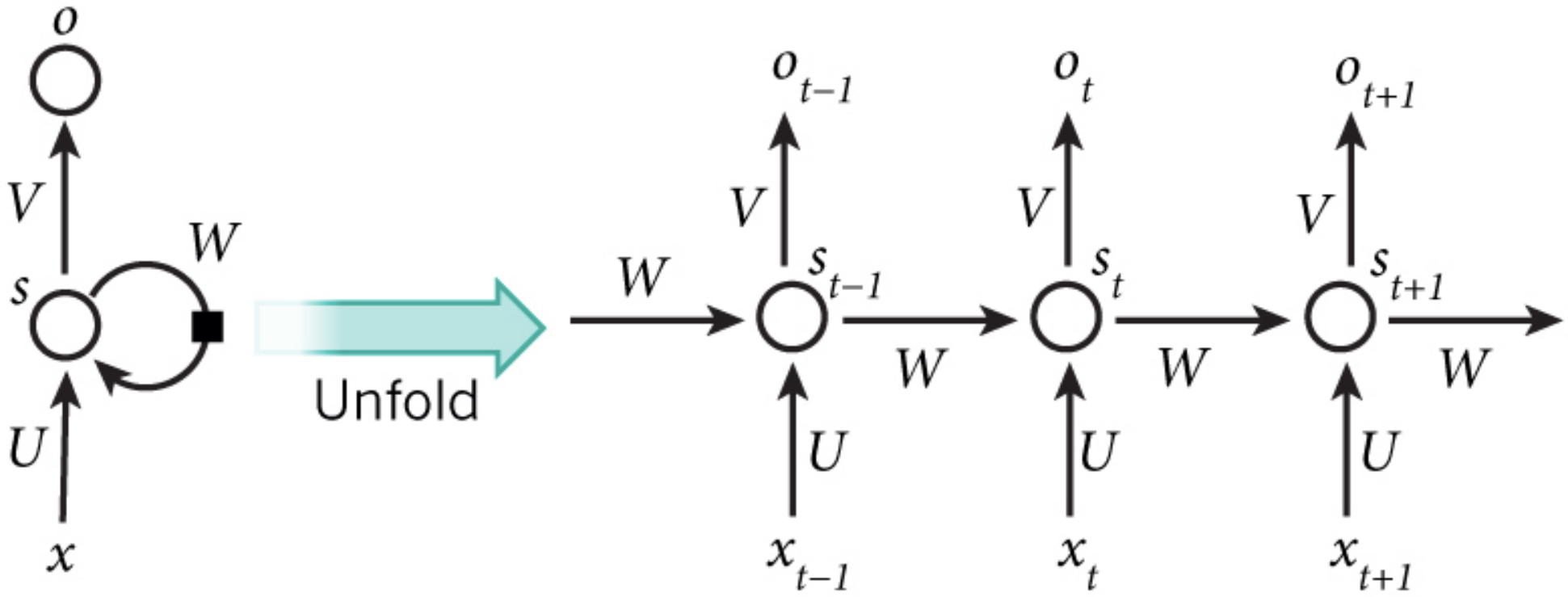


http://www.wildml.com/2015/09/recurrent-neural-networks-tutorial-part-1-introduction-to-rnns/

RNN: Model Parameters and Inputs

How many hidden layers are in this neural network example?

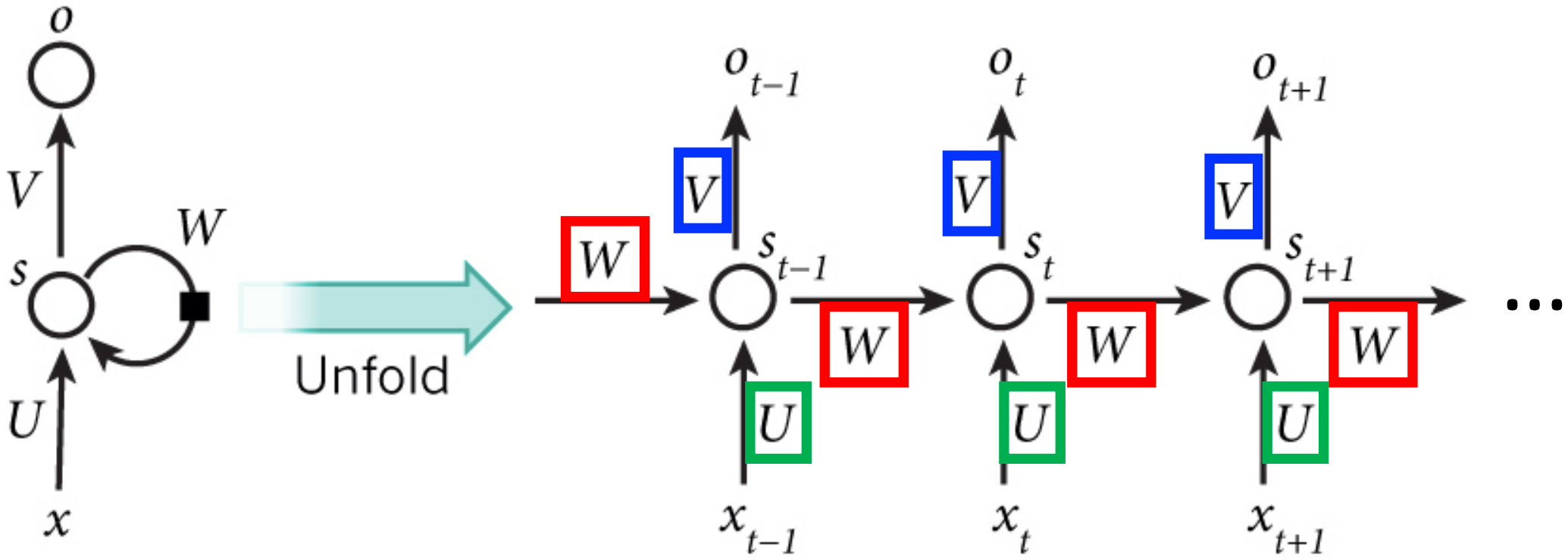
How many sets of input does each neuron in a RNN receive?



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

RNN: Advantages

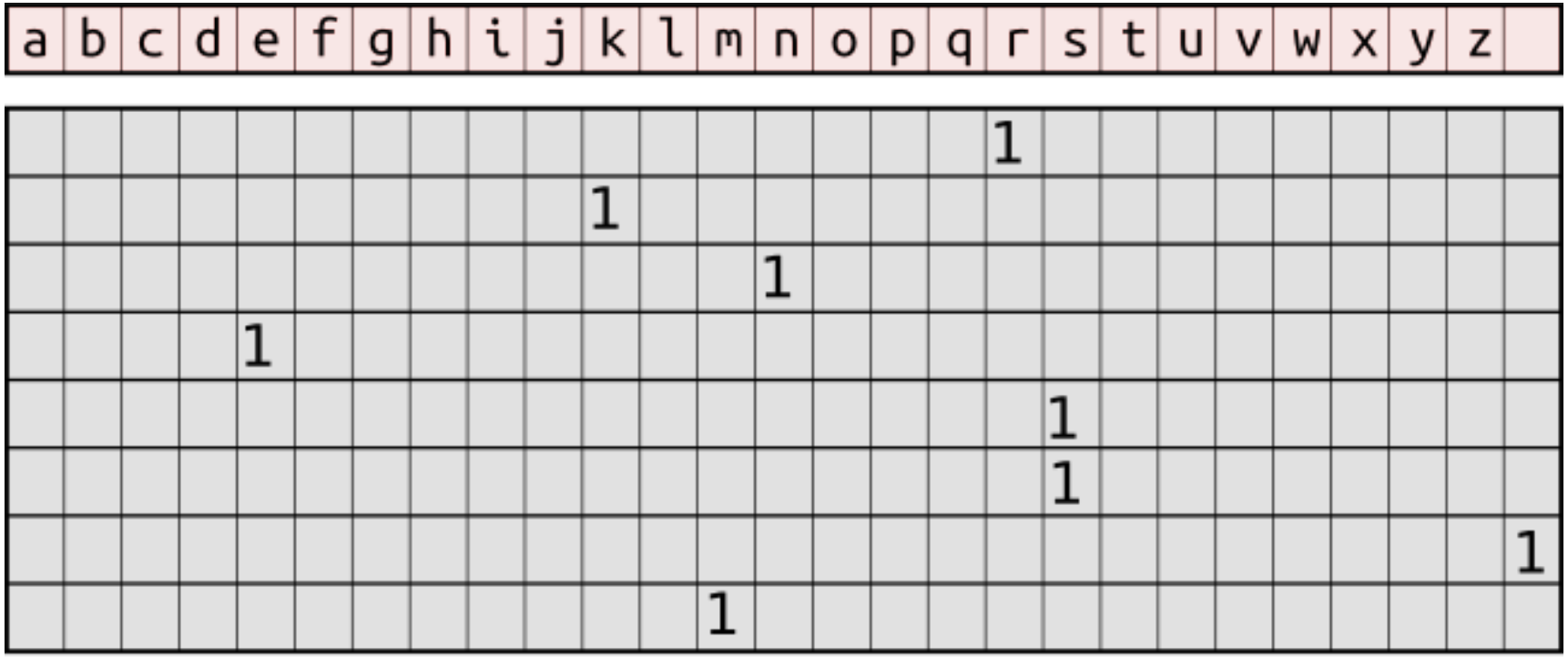
- Overcomes problem that weights of each layer are learned **independently** by using previous hidden state
- Overcomes problem that model has many parameters since weights are shared across layers



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
- Training Data: sequence of characters represented as one-hot vectors



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

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

Training Input

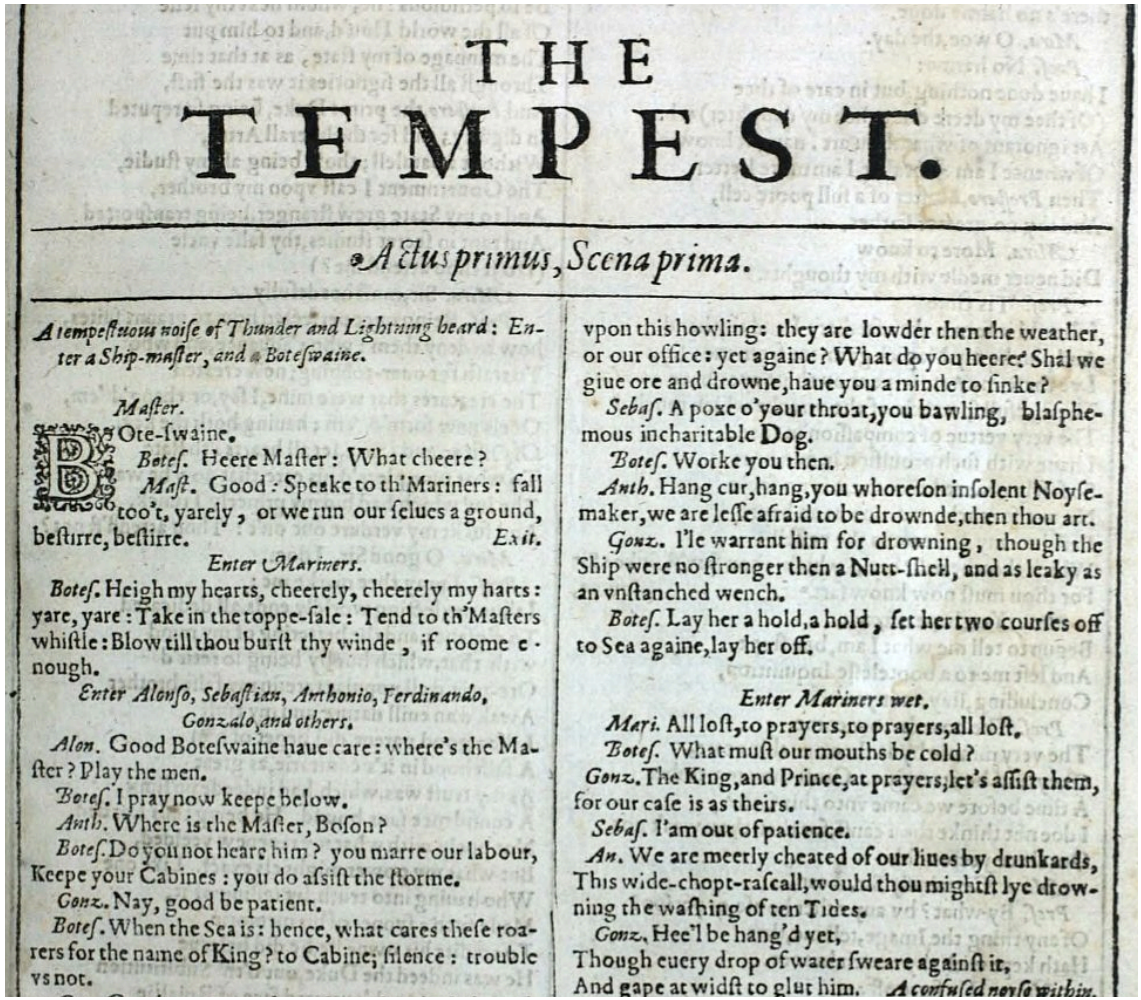
Predicted Output

```
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…

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

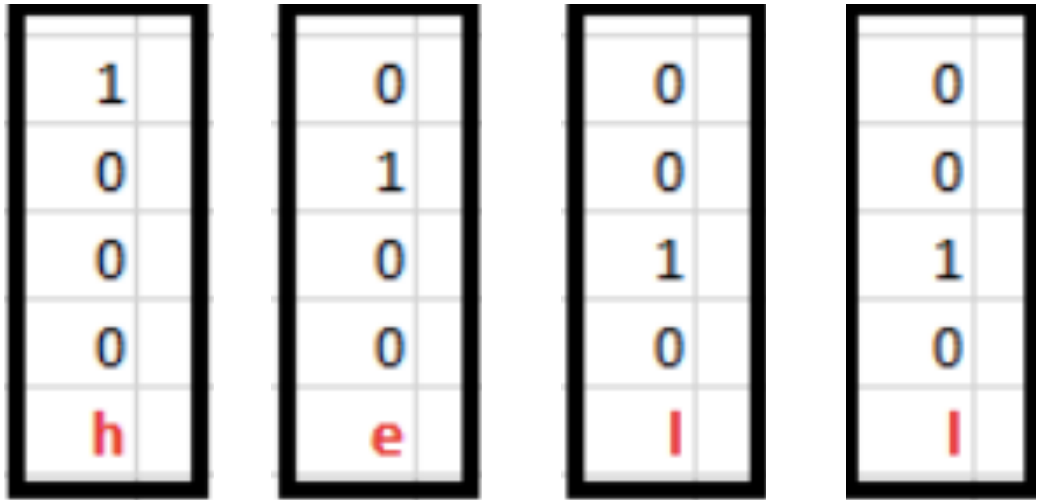
3. *The fact of the matter is* just the world to invite your stuff? I don't know how to right it wouldn't be as offriving for anything, so that would be awesome, thanks :) I have no idea... She would get to worry about it :P And I

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

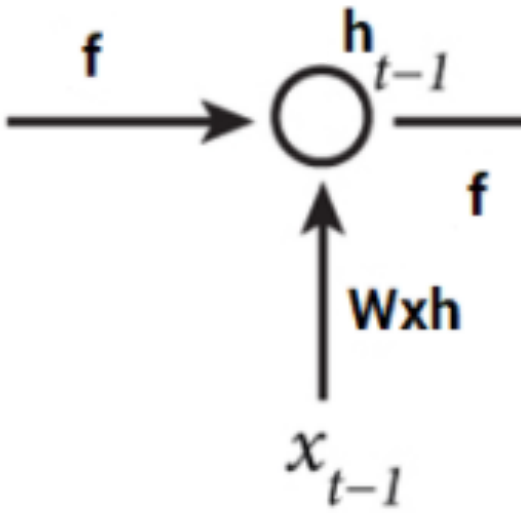
- Goal: predict next character in text
- Training: feed a training sequence of characters; e.g., “hello”
  - For simplicity, assume the following vocabulary (i.e., character set): {h, e, l, o}
  - What is our input at time step 1?
  - What is our input at time step 2?
  - What is our input at time step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



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

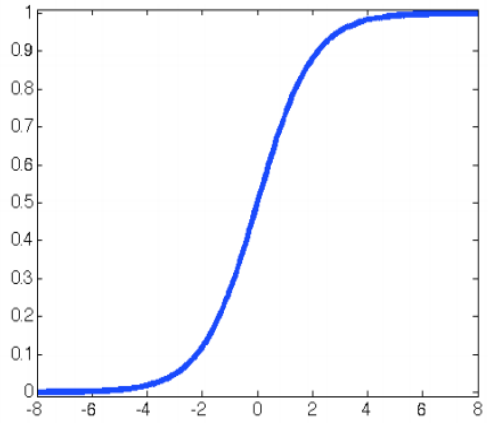
Example: Predict Sequence of Characters; Using tanh as Activation Function

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



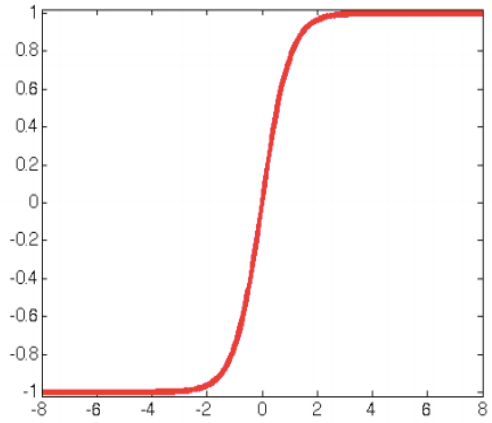
(recall activation functions)

Sigmoid



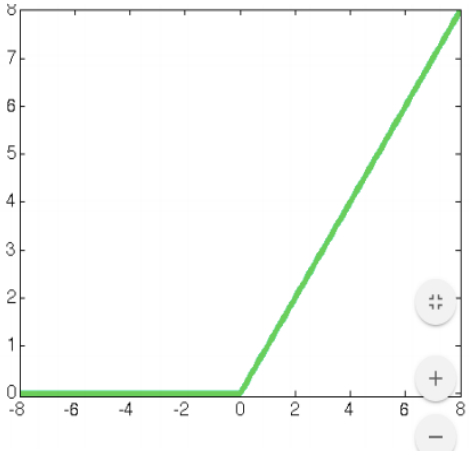
$$\sigma(z) = \frac{1}{1+\exp(-z)}$$

Tanh



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

ReLU



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

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Example: Predict Sequence of Characters; Forward Pass (time step 1)

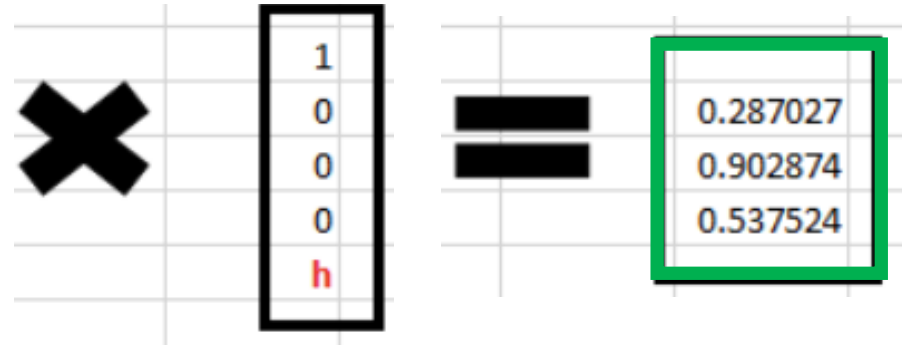
Initialize to random value: 0.427043

Initialize to random value: 0.567001

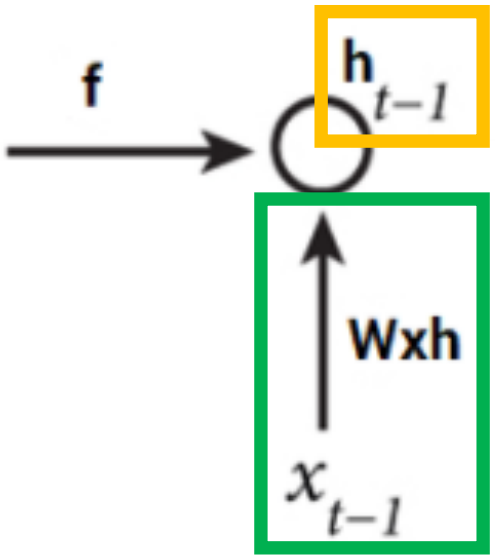
$$h_t = \tanh(W_{hh} h_{t-1} + W_{xh} x_t + \text{bias})$$

Initialize to 0

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



Input at next time step



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

Example: Predict Sequence of Characters; Forward Pass (time step 1)

Initialize to random value: 0.427043

Initialize to random value: 0.567001

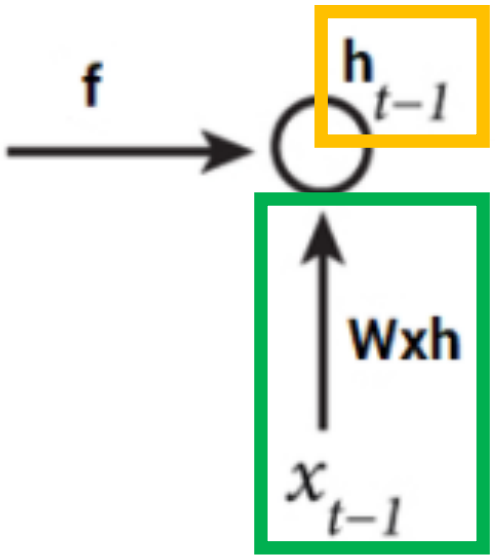
$$h_t = \tanh\left(W_{hh} h_{t-1} + W_{xh} x_t + \text{bias}\right)$$

Initialize to 0

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, 0, 0, h] = [0.287027, 0.902874, 0.537524]

Input at next time step



H_t = 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: Predict Sequence of Characters; Forward Pass (time step 2)

Initialize to random value: 0.427043

Initialize to random value: 0.567001

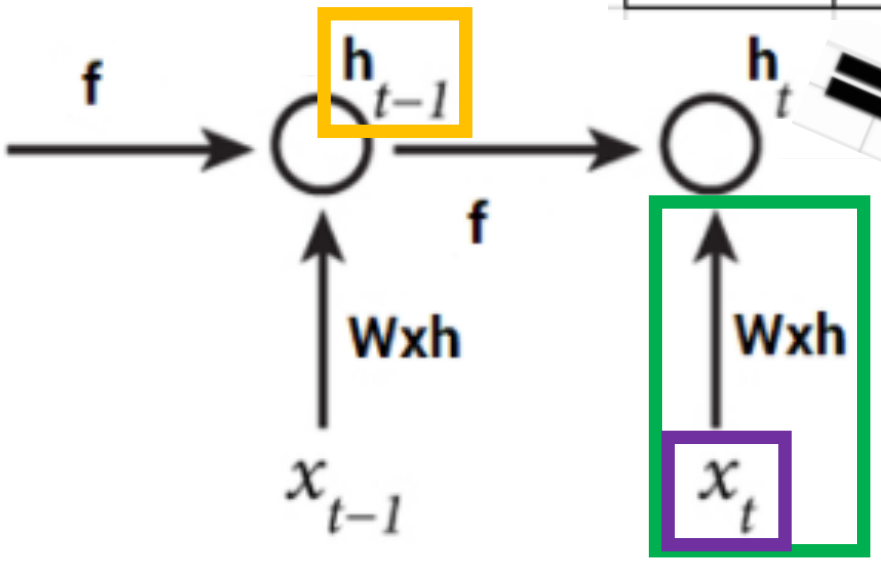
$$h_t = \tanh(W_{hh} h_{t-1} + W_{xh} x_t + \text{bias})$$

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

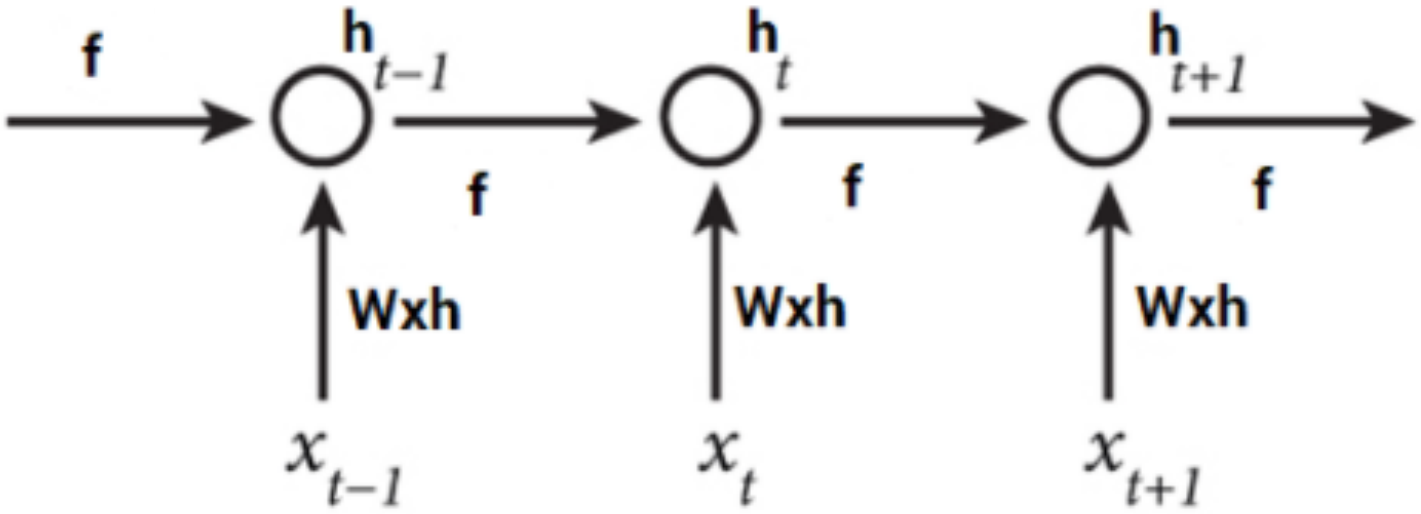


TANH { 0.427043 × | 0.693168 / 0.899554 / 0.802118 | + | 0.84606 / 0.871522 / 0.09224 | + | 0.567001 / 0.567001 / 0.567001 | }

0.93653372
0.94910403
0.76234056

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

Example: Predict Sequence of Characters; Forward Pass (and so on for remaining time steps…)



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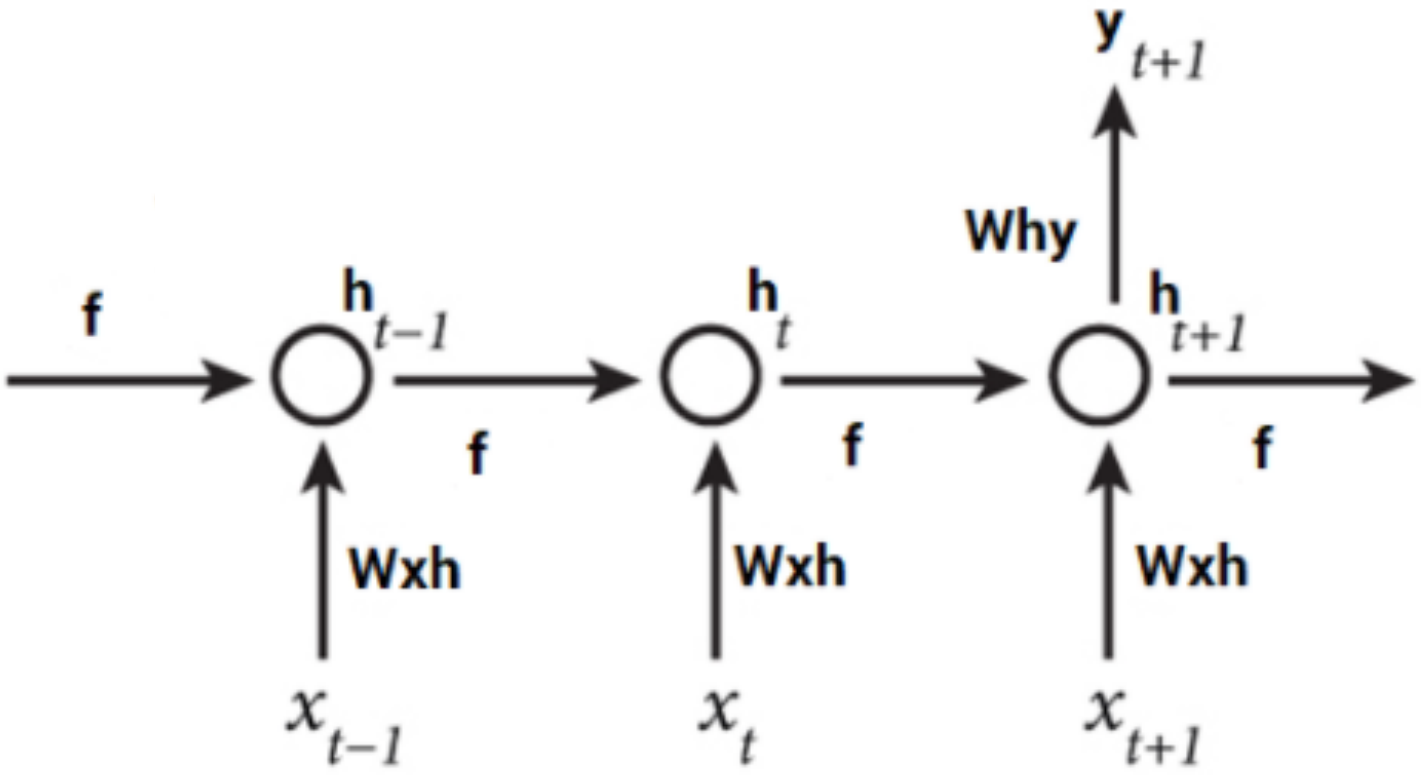
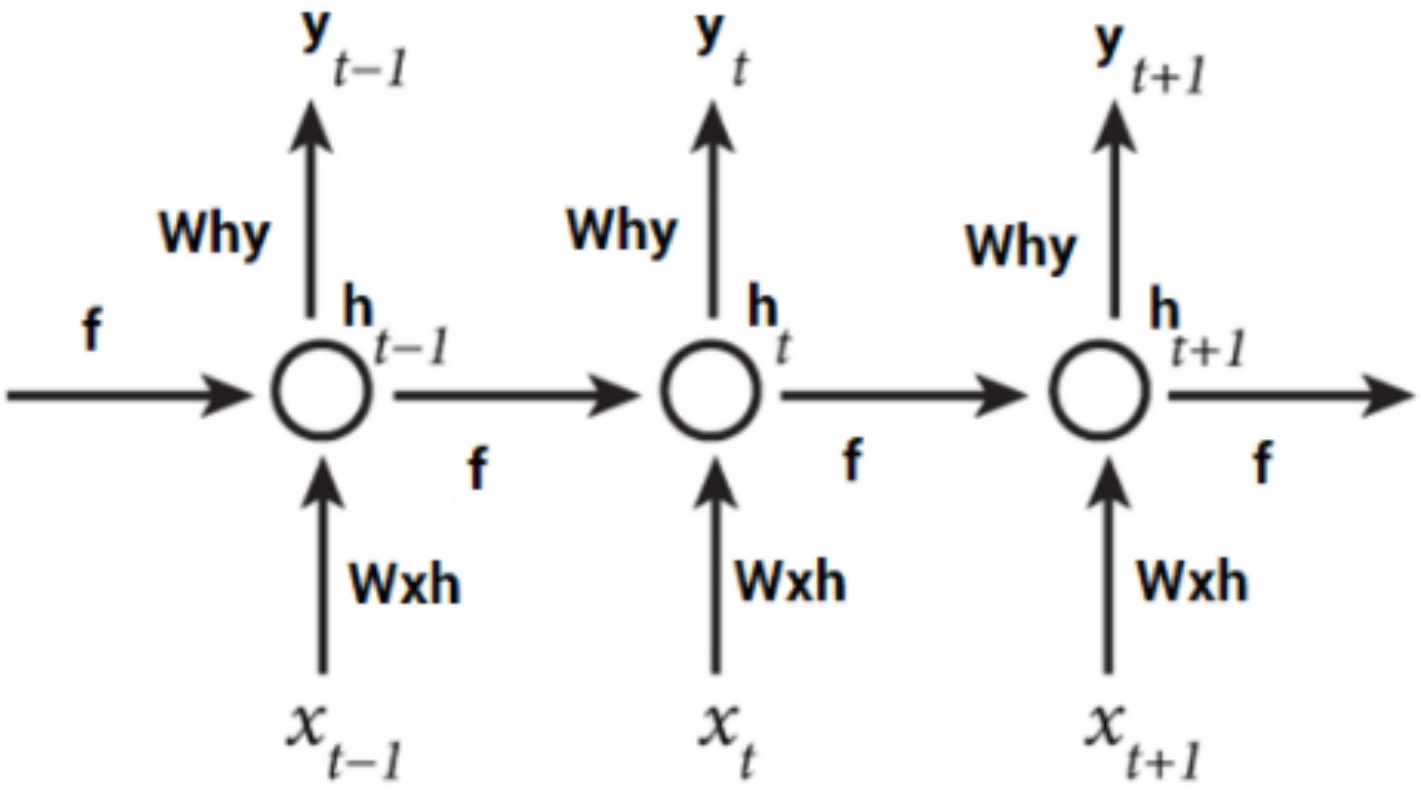
Example: Prediction (Many-To-One)



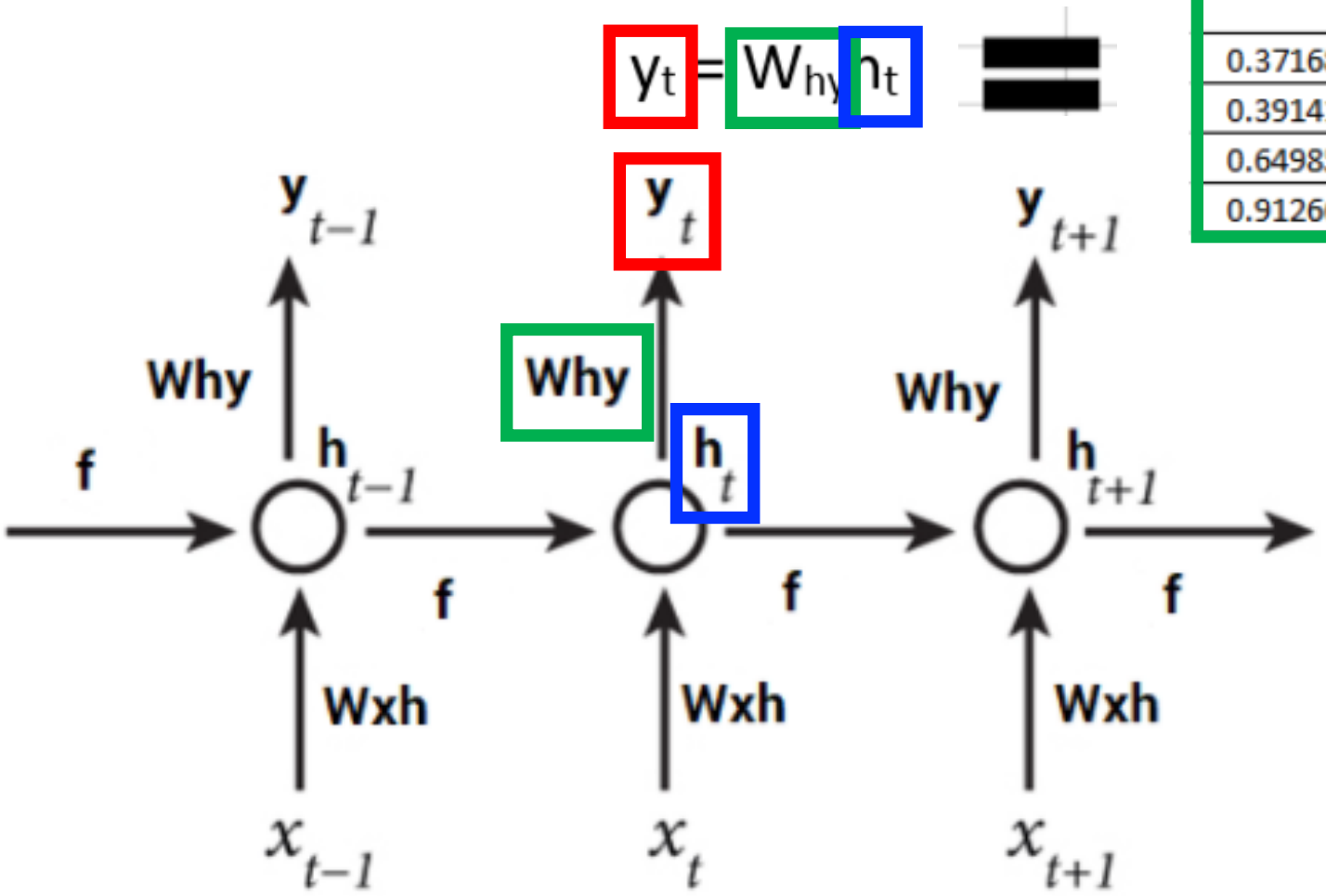
https://www.analyticsvidhya.com/blog/2017/12/introduction-to-recurrent-neural-networks/

Example: Prediction (Many-To-Many)



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

Example: Prediction for Time Step 2



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

=

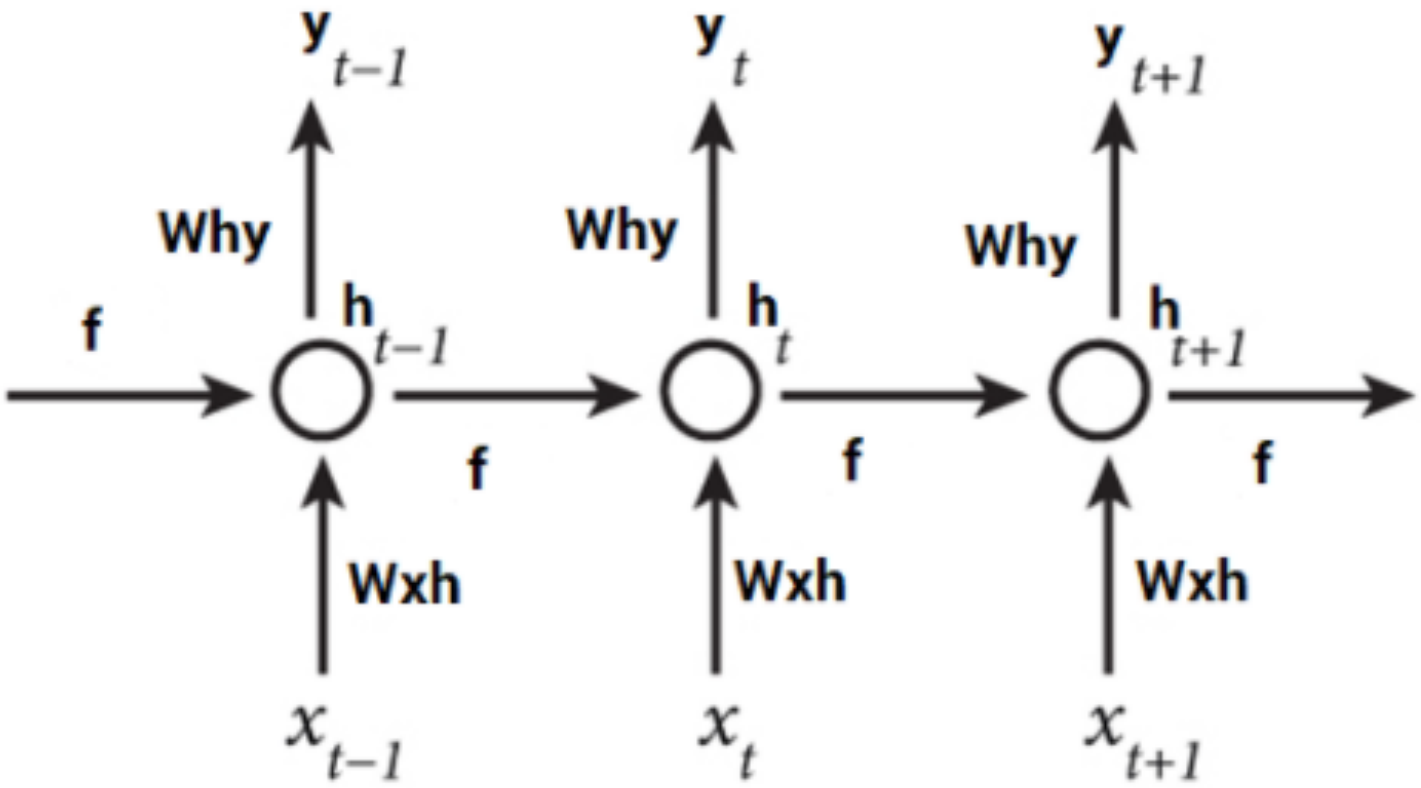
yt
1.90607732
1.13779113
0.95666016
1.27422602

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: Prediction for Time Step 2



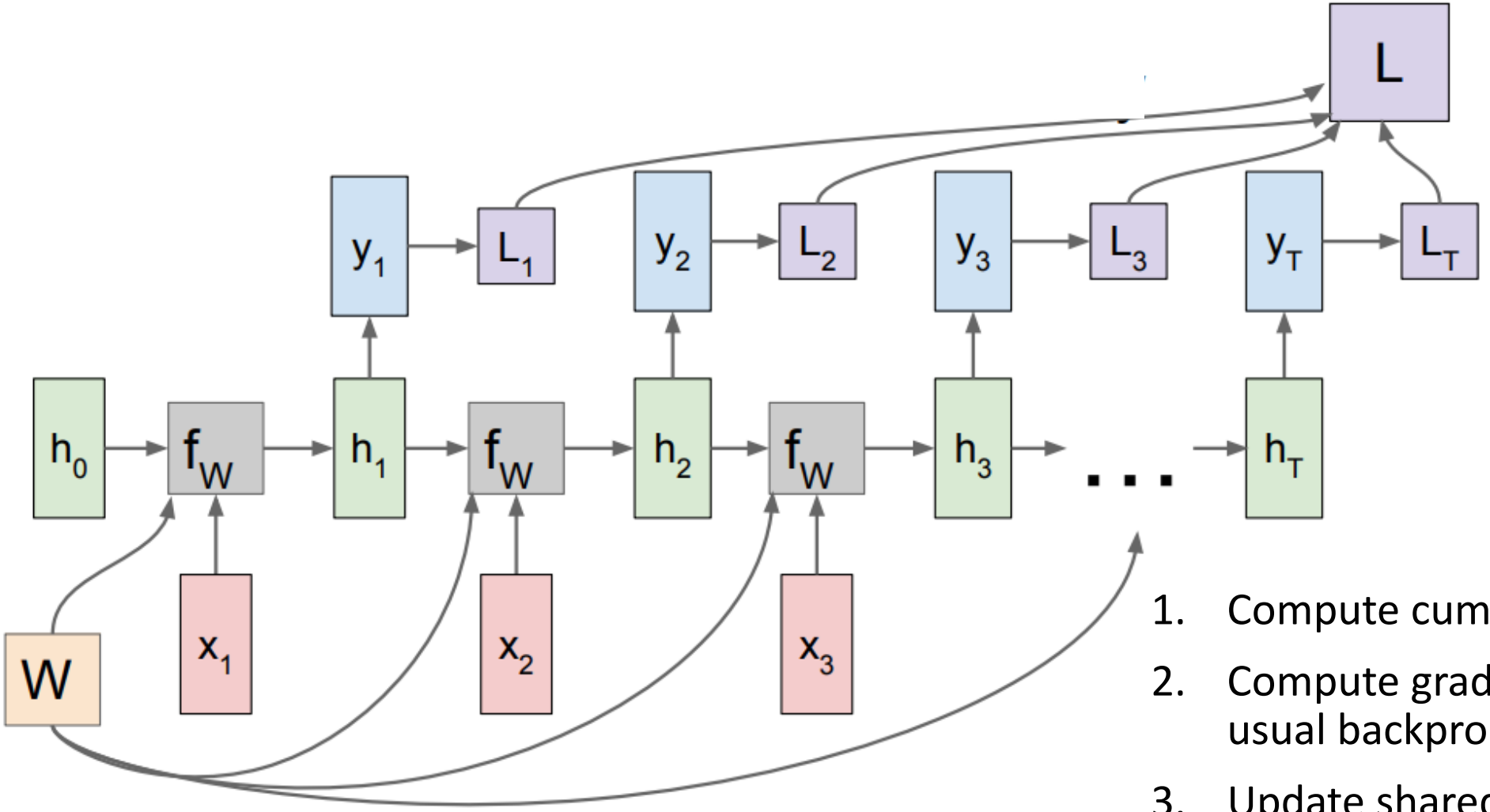
Given our vocabulary is {h, e, l, o}, what letter is predicted?

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/

Example: Update Weights During Training



1. Compute cumulative loss
2. Compute gradients through usual backpropagation
3. Update shared weights

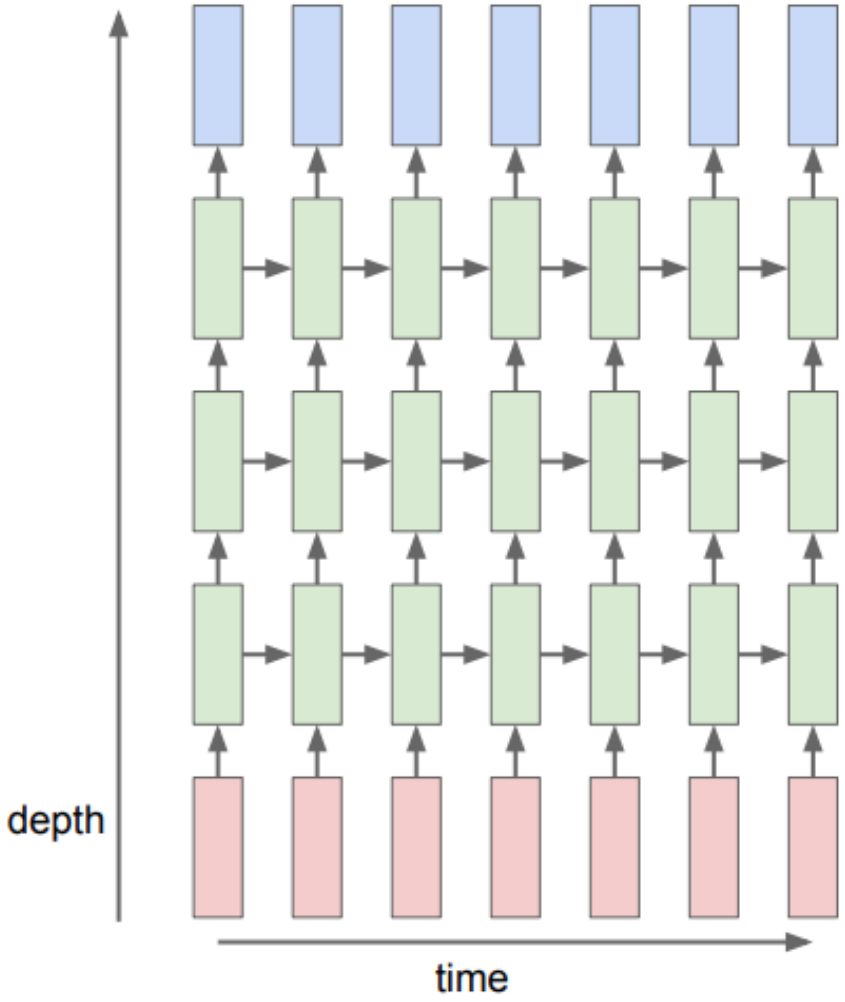
http://cs231n.stanford.edu/slides/2017/cs231n_2017_lecture10.pdf

RNNs - Summary

- Parameter sharing across previous outputs reduces number of model parameters and supports remembering the past

- Assumptions:
  - The same parameters can be used for different time steps
  - The relationship between the previous time step and the next time step does not depend on time

RNN Variants: Different Number of Hidden Layers



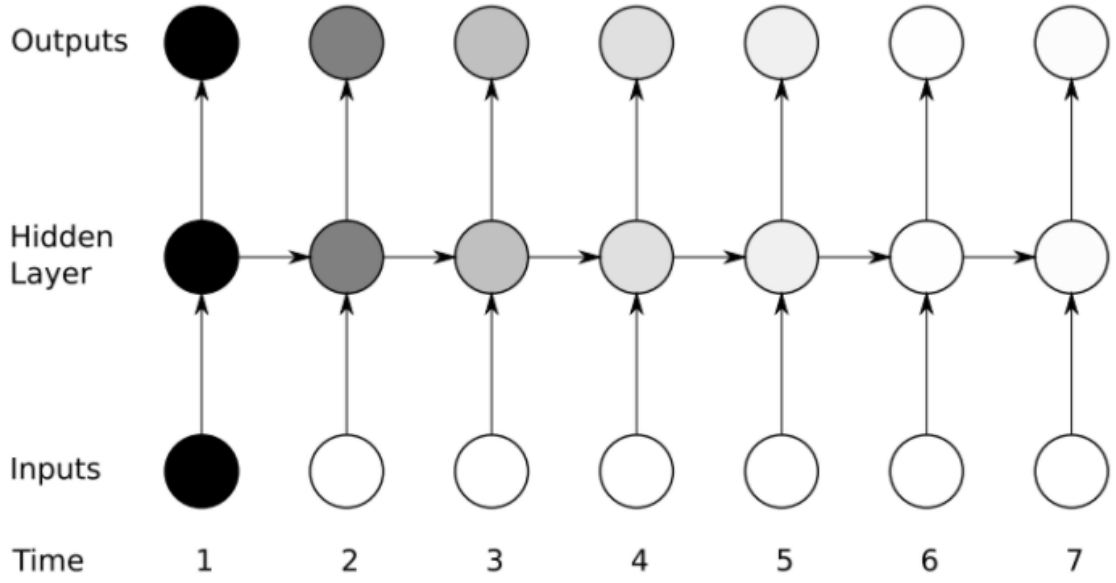
Experimental evidence suggests deeper models are better:

- 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

RNN Variants: Mitigate Vanishing Gradients

- Problem: training with long-term dependencies



  - 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
- Exploding gradient: a product of numbers greater than 1 explodes to infinity

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

RNN Variants: Mitigate Vanishing Gradients

- Long Short Term Memory (LSTM): modification of basic RNN architecture
- Introduces preservation of memory over time

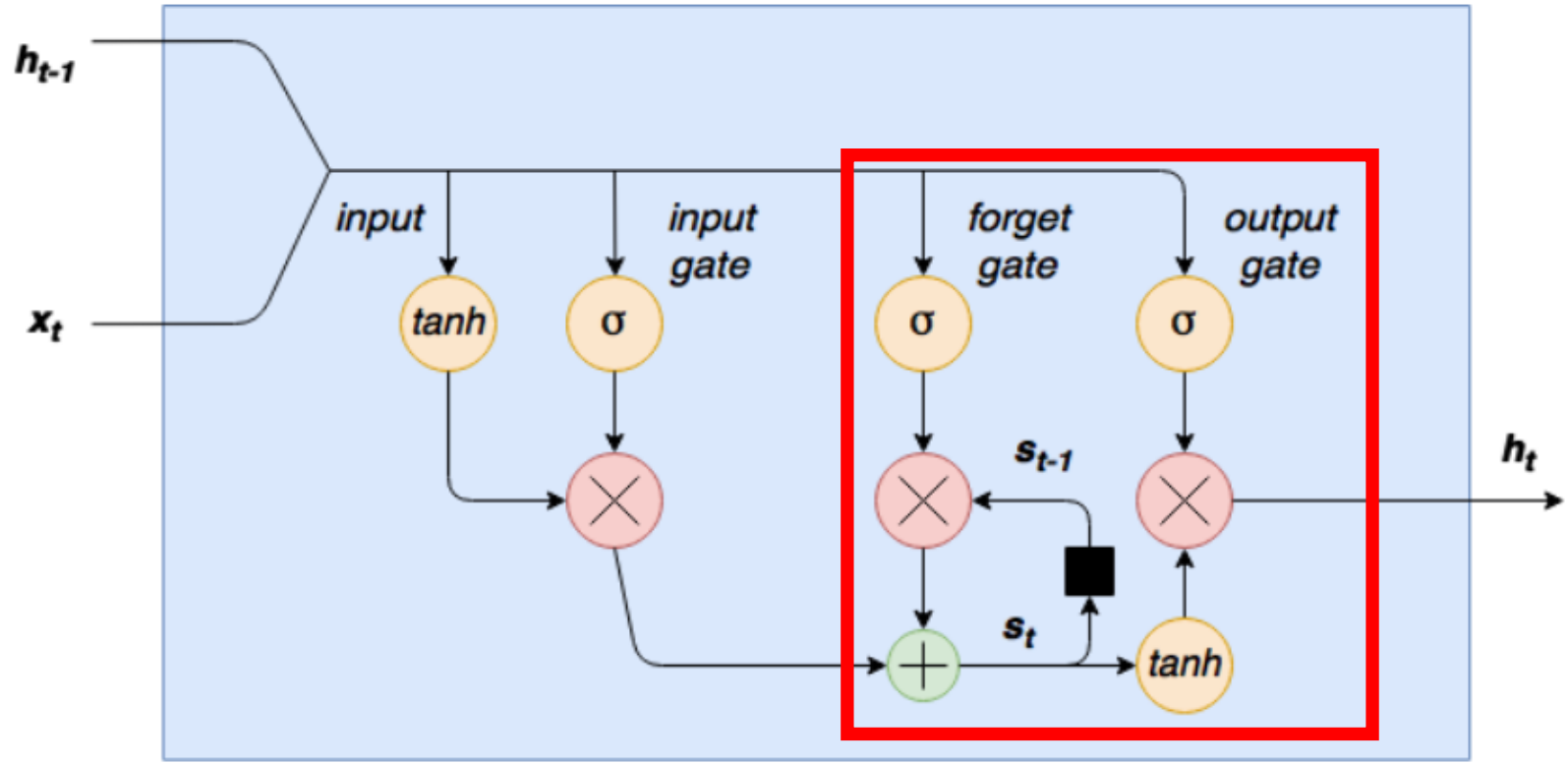
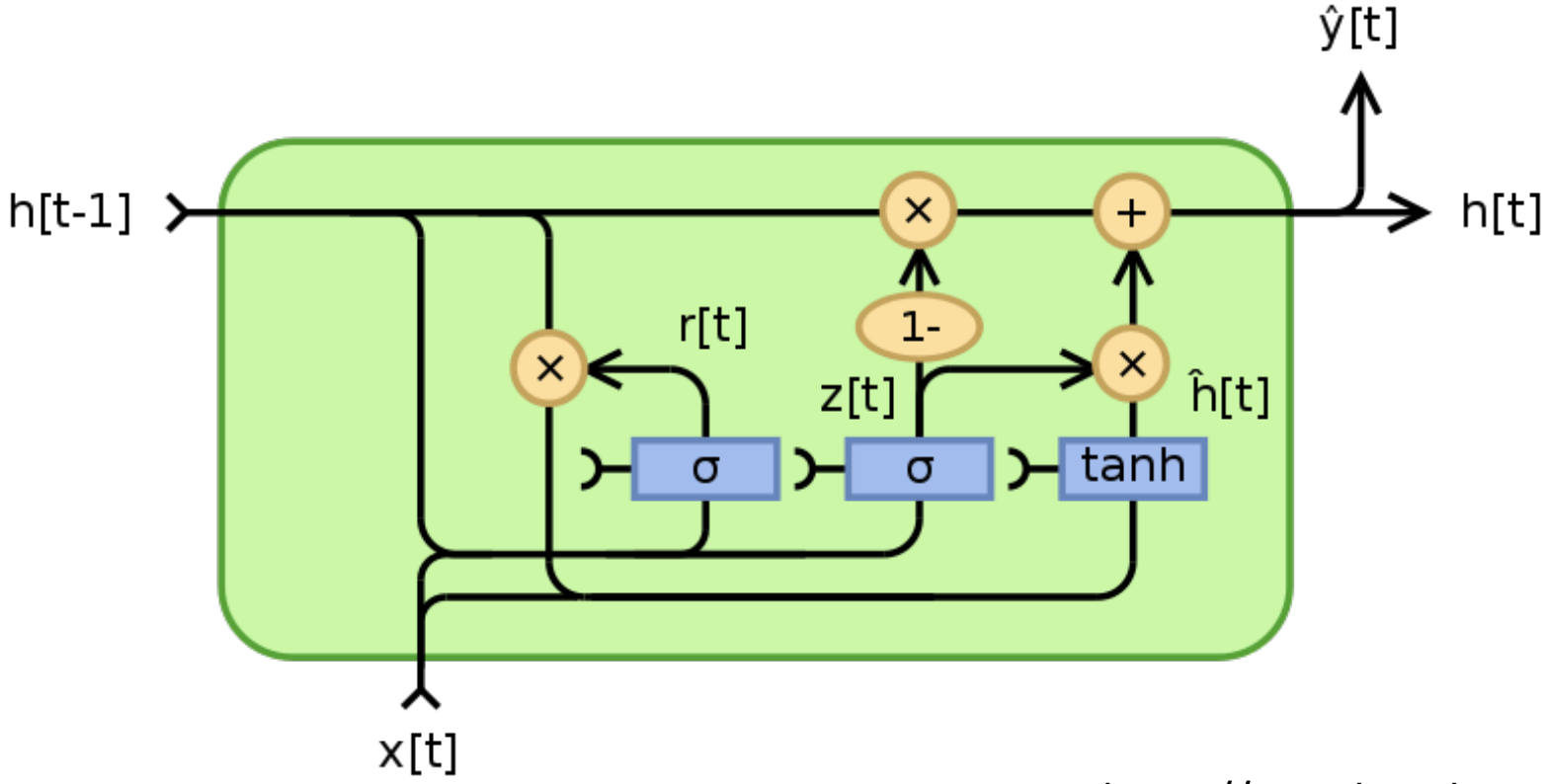


Figure Credit: http://adventuresinmachinelearning.com/recurrent-neural-networks-lstm-tutorial-tensorflow/

RNN Variants: Mitigate Vanishing Gradients

- Gated Recurrent Unit (GRU): modification of basic RNN unit



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

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

Group Discussion: Empirical Model Comparison

1. **What is the best model to use and why?**
2. **What is a good number of layers and why?**
3. **What is a good number of neurons and why?**

	LSTM			RNN			GRU		
Layers	1	2	3	1	2	3	1	2	3
Size	War and Peace Dataset								
64	1.449	1.442	1.540	1.446	1.401	1.396	1.398	**1.373**	1.472
128	1.277	1.227	1.279	1.417	1.286	1.277	1.230	**1.226**	1.253
256	1.189	**1.137**	1.141	1.342	1.256	1.239	1.198	1.164	1.138
512	1.161	1.092	1.082	-	-	-	1.170	1.201	**1.077**
Linux Kernel Dataset									
64	1.355	**1.331**	1.366	1.407	1.371	1.383	1.335	1.298	1.357
128	1.149	1.128	1.177	1.241	**1.120**	1.220	1.154	1.125	1.150
256	1.026	**0.972**	0.998	1.171	1.116	1.116	1.039	0.991	1.026
512	0.952	0.840	0.846	-	-	-	0.943	0.861	**0.829**

A. Karpathy, J. Johnson, and L. Fei-Fei; Visualizing and Understanding Recurrent Networks; 2016

Today's Topics

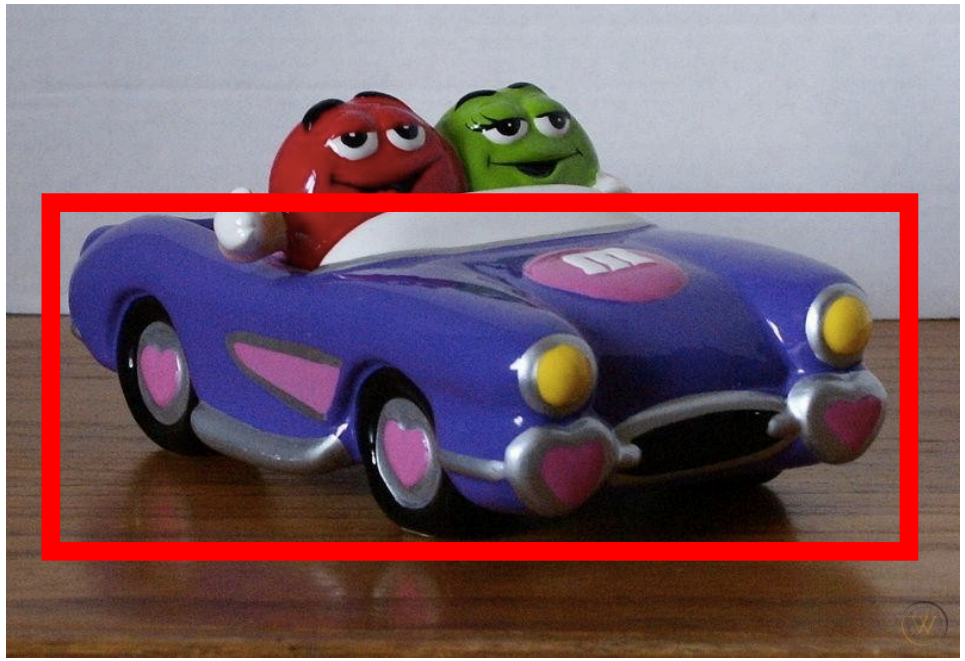
- Machine Learning for Sequential Data
- Recurrent Neural Networks (RNNs)
- Training Deep Neural Networks: Hardware & Software
- Lab

Recall: Machine Learning Analogous to a Love Story of Partnering Up and Road Tripping Somewhere

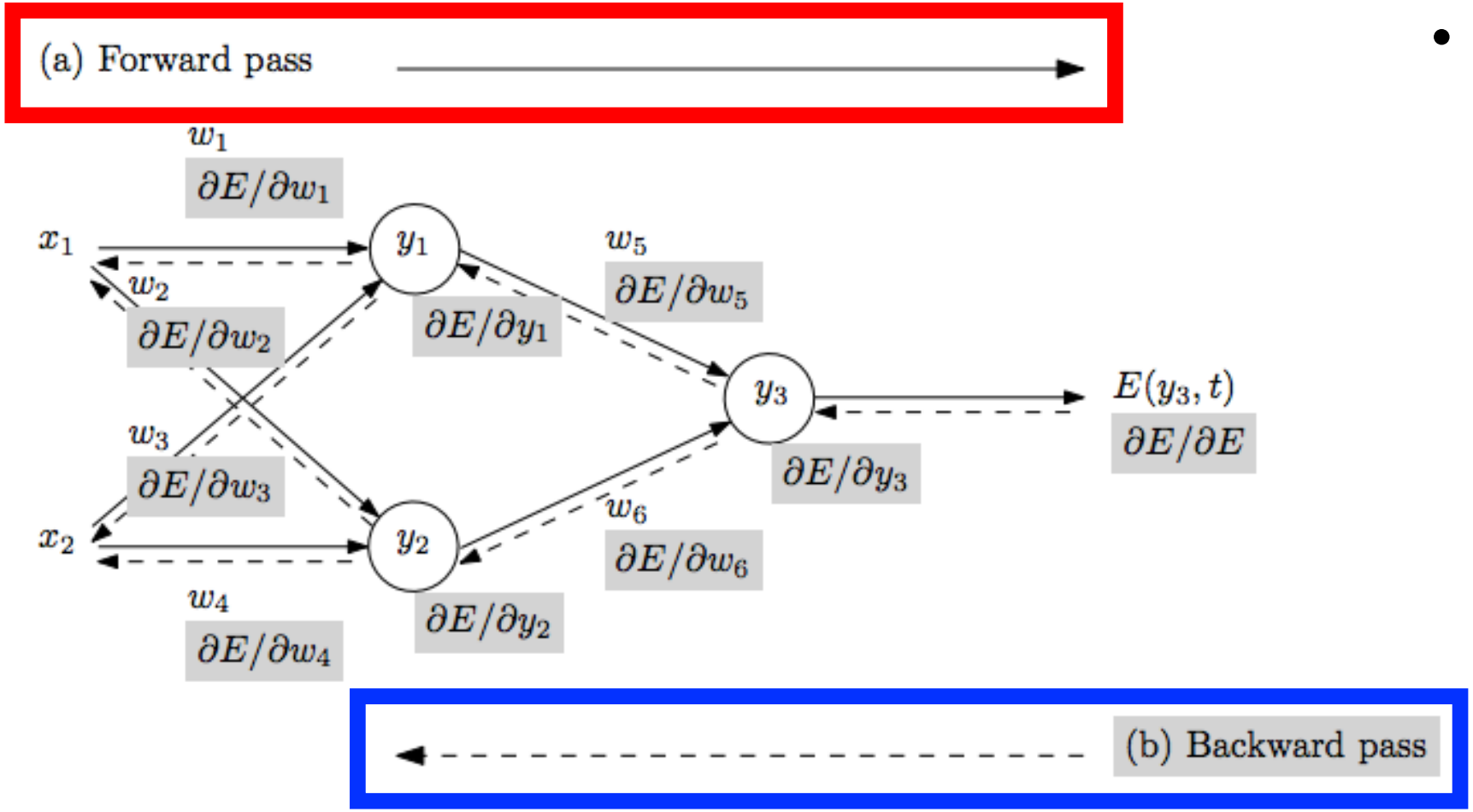
Algorithms learn to exploit patterns it finds in data

Recall: Machine Learning Analogous to a Love Story of Partnering Up and Road Tripping Somewhere

Key Issue: How Fast Will It Take to Get There?



Challenge: Training Neural Network **Requires Many Computations** (e.g., millions of model parameters)

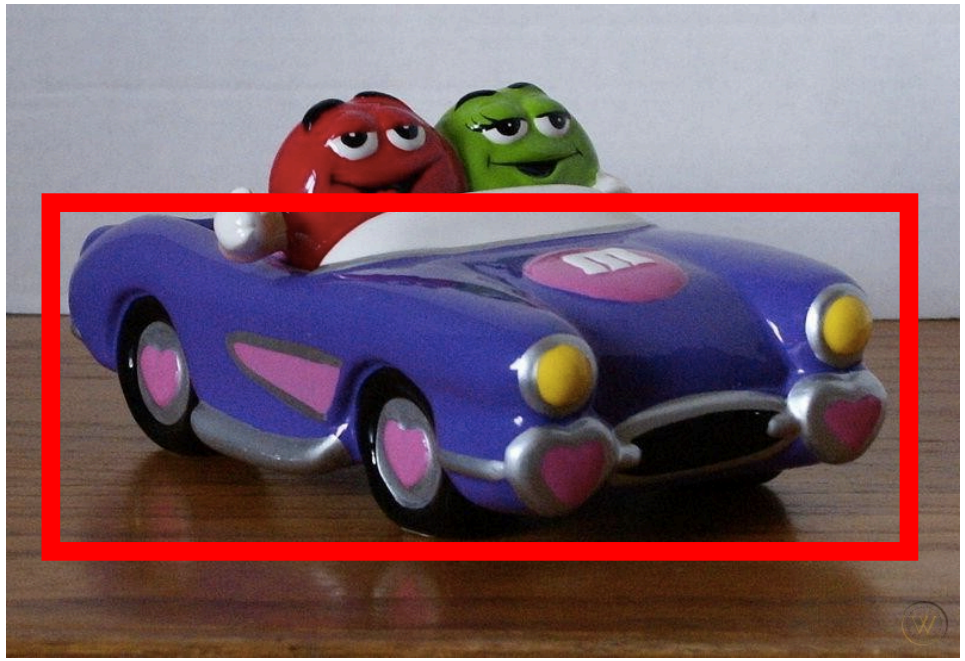


- **Repeat until stopping criterion met:**
  1. **Forward pass**: propagate training data through network to make prediction
  2. **Backward pass**: using predicted output, calculate gradients backward
  3. Update each weight using calculated gradients

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

Recall: Machine Learning Analogous to a Love Story of Partnering Up and Road Tripping Somewhere

Idea: Train Algorithms Using GPUs (think Porsche) Instead of CPUs (think Golf Cart)



Hardware: CPU versus GPU

Spot the CPU!

(central processing unit)

http://cs231n.stanford.edu/slides/2018/cs231n_2018_lecture08.pdf

Hardware: CPU versus GPU

Spot the GPUs!

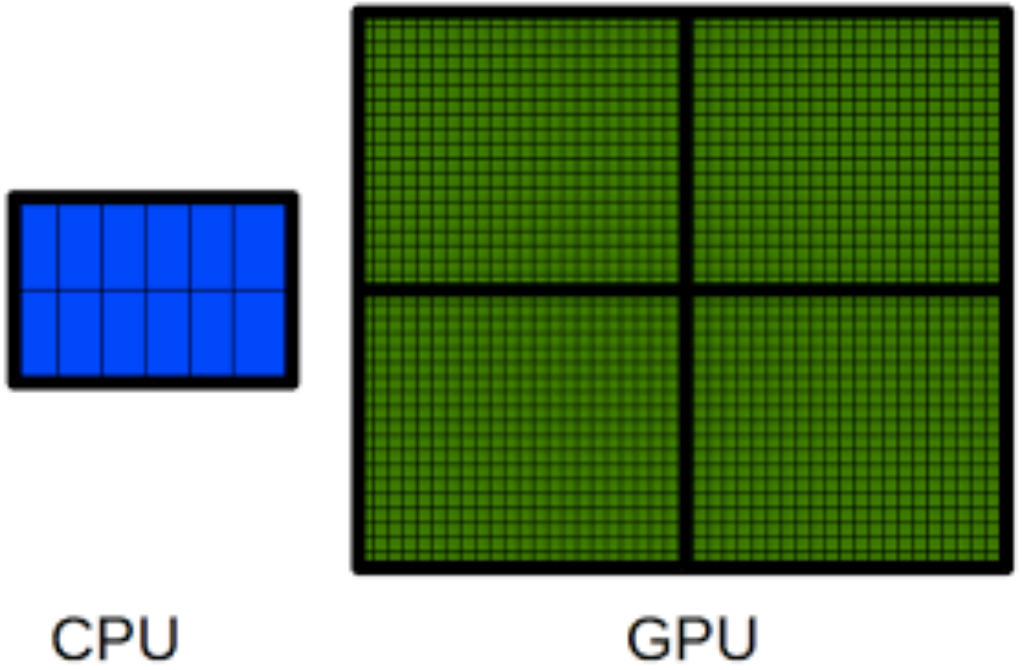
(graphics processing unit)

This image is in the public domain

http://cs231n.stanford.edu/slides/2018/cs231n_2018_lecture08.pdf

Hardware: CPU versus GPU

- Graphical Processing Units: accelerates computational workloads due to MANY more processing cores



https://www.researchgate.net/figure/The-main-difference-between-CPUs-and-GPUs-is-related-to-the-number-of-available-cores-A_fig7_273383346

Hardware: Training Models with GPUs

Model is here

Data is here

If you aren't careful, training can bottleneck on reading data and transferring to GPU!

Solutions:

- Read all data into RAM
- Use SSD instead of HDD
- Use multiple CPU threads to prefetch data

(TPU = Tensor Processing Unit)

Hardware: CPU versus GPU

	Cores	Clock Speed	Memory	Price	Speed
CPU (Intel Core i7-7700k)	4 (8 threads with hyperthreading)	4.2 GHz	System RAM	$339	~540 GFLOPs FP32
GPU (NVIDIA GTX 1080 Ti)	3584	1.6 GHz	11 GB GDDR5 X	$699	~11.4 TFLOPs FP32
TPU NVIDIA TITAN V	5120 CUDA, 640 Tensor	1.5 GHz	12GB HBM2	$2999	~14 TFLOPs FP32 ~112 TFLOP FP16
TPU Google Cloud TPU	?	?	64 GB HBM	$6.50 per hour	~180 TFLOP

CPU: Fewer cores, but each core is much faster and much more capable; great at sequential tasks

GPU: More cores, but each core is much slower and "dumber"; great for parallel tasks

TPU: Specialized hardware for deep learning

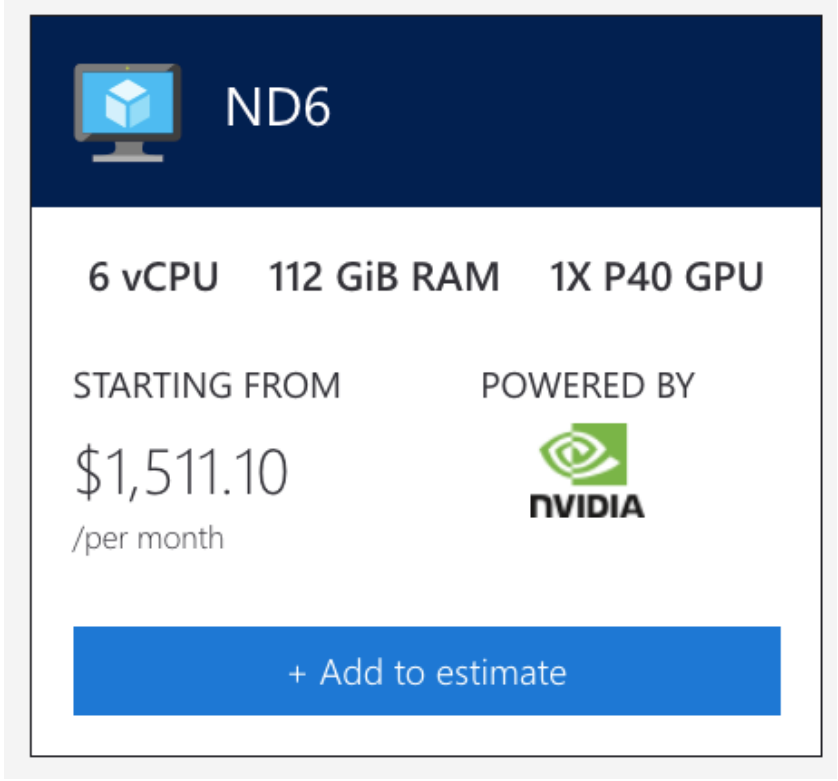
http://cs231n.stanford.edu/slides/2018/cs231n_2018_lecture08.pdf

GPU Clusters (Google Cloud's TPU Servers)

https://www.extremetech.com/extreme/249499-google-takes-swipe-nvidia-powerful-new-learning-capable-cloud-tpu

GPU Machines: Rent Versus Buy?

Rent from Cloud (Microsoft Azure):



Buy:

Basic

2x RTX 2080 Ti

2-Way NVLink

Intel i9-9820X (10 cores, 3.30 GHz)

2x RTX 2080 Ti (11 GB VRAM)

64 GB RAM

2 TB SSD

4 TB HDD

Starting at

$7,059

Customize

Rise of “Deep Learning” Open Source Platforms

Motivation:

Can run on GPUs:

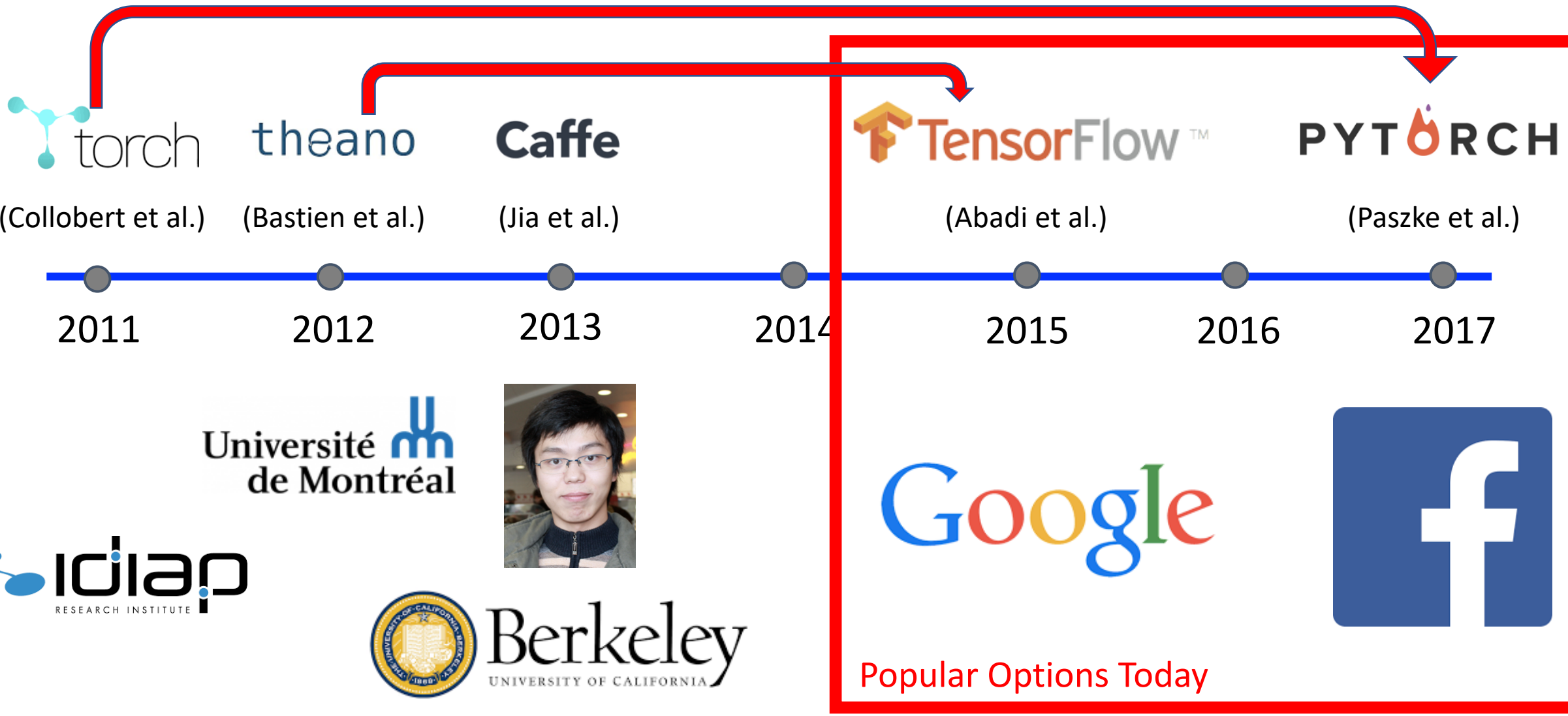
OpenMP support	OpenCL support	CUDA support	Automatic differentiation[1]

Simplifies using popular neural network architectures:

Has pretrained models	Recurrent nets	Convolutional nets	RBM/DBNs	Parallel execution (multi node)

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

Rise of “Deep Learning” Open Source Platforms



Rise of “Deep Learning” Open Source Platforms

Software	Creator	Software license[a]	Open source	Platform	Written in	Interface	OpenMP support	OpenCL support	CUDA support	Automatic differentiation[1]	Has pretrained models	Recurrent nets	Convolutional nets	RBM/DBNs	Parallel execution (multi node)	Actively Developed
roNNie.ai	Kevin Lok	MIT license	Yes	Linux, macOS, Windows	Python	Python			Yes		Yes	Yes	Yes			
BigDL	Jason Dai	Apache 2.0	Yes	Apache Spark	Scala	Scala, Python			No		Yes	Yes	Yes			
Caffe	Berkeley Vision and Learning Center	BSD	Yes	Linux, macOS, Windows[2]	C++	Python, MATLAB, C++	Yes	Under development[3]	Yes	Yes	Yes[4]	Yes	Yes	No	?	
Deeplearning4j	Skymind engineering team; Deeplearning4j community; originally Adam Gibson	Apache 2.0	Yes	Linux, macOS, Windows, Android (Cross-platform)	C++, Java	Java, Scala, Clojure, Python (Keras), Kotlin	Yes	On roadmap[5]	Yes[6][7]	Computational Graph	Yes[8]	Yes	Yes	Yes	Yes[9]	
Chainer	Preferred Networks	MIT license	Yes	Linux, macOS, Windows		Python	No	No[10][11]	Yes	Yes	Yes	Yes	Yes			
Darknet	Joseph Redmon	Public Domain	Yes	Cross-Platform	C	C, Python	Yes	No[12]	Yes	Yes						
Dlib	Davis King	Boost Software License	Yes	Cross-Platform	C++	C++	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes	
DataMelt (DMelt)	S.Chekanov	Freemium	Yes	Cross-Platform	Java	Java	No	No	No	No	No	No	No	No	No	
DyNet	Carnegie Mellon University	Apache 2.0	Yes	Linux, macOS, Windows		C++, Python		No[13]	Yes	Yes	Yes					
Intel Data Analytics Acceleration Library	Intel	Apache License 2.0	Yes	Linux, macOS, Windows on Intel CPU[14]	C++, Python, Java	C++, Python, Java[14]	Yes	No	No	Yes	No		Yes		Yes	
Intel Math Kernel Library	Intel	Proprietary	No	Linux, macOS, Windows on Intel CPU[15]		C[16]	Yes[17]	No	No	Yes	No	Yes[18]	Yes[18]		No	
Keras	François Chollet	MIT license	Yes	Linux, macOS, Windows	Python	Python, R	Only if using Theano as backend	Can use Theano or Tensorflow as backends	Yes	Yes	Yes[19]	Yes	Yes	Yes	Yes[20]	
MATLAB + Neural Network Toolbox	MathWorks	Proprietary	No	Linux, macOS, Windows	C, C++, Java, MATLAB	MATLAB	No	No	Train with Parallel Computing Toolbox and generate CUDA code with GPU Coder[21]	No	Yes[22][23]	Yes[22]	Yes[22]	No	With Parallel Computing Toolbox[24]	
Microsoft Cognitive Toolkit	Microsoft Research	MIT license[25]	Yes	Windows, Linux[26] (macOS via Docker on roadmap)	C++	Python (Keras), C++, Command line,[27] BrainScript[28] (.NET on roadmap[29])	Yes[30]	No	Yes	Yes	Yes[31]	Yes[32]	Yes[32]	No[33]	Yes[34]	
Apache MXNet	Apache Software Foundation	Apache 2.0	Yes	Linux, macOS, Windows,[35][36] AWS, Android,[37] iOS, JavaScript[38]	Small C++ core library	C++, Python, Julia, Matlab, JavaScript, Go, R, Scala, Perl	Yes	On roadmap[39]	Yes	Yes[40]	Yes[41]	Yes	Yes	Yes	Yes[42]	
Neural Designer	Artelnics	Proprietary	No	Linux, macOS, Windows	C++	Graphical user interface	Yes	No	No	?	?	No	No	No	?	
OpenNN	Artelnics	GNU LGPL	Yes	Cross-platform	C++	C++	Yes	No	Yes	?	?	No	No	No	?	
PaddlePaddle	Baidu	Apache License	Yes	Linux, macOS, Windows	C++, Python	Python	No	Yes	Yes	Yes	Yes	Yes	Yes	?	Yes	
PlaidML	Vertex.AI	AGPL3	Yes	Linux, macOS, Windows	C++, Python	Keras, Python, C++, C	No	Yes	Yes	Yes		Yes	Yes	?	Yes	
PyTorch	Adam Paszke, Sam Gross, Soumith Chintala, Gregory Chanan	BSD	Yes	Linux, macOS, Windows	Python, C, CUDA	Python	Yes	Via separately maintained package[43][44][45]	Yes	Yes	Yes	Yes	Yes		Yes	
Apache SINGA	Apache Incubator	Apache 2.0	Yes	Linux, macOS, Windows	C++	Python, C++, Java	No	No	Yes	?	Yes	Yes	Yes	Yes	Yes	
TensorFlow	Google Brain team	Apache 2.0	Yes	Linux, macOS, Windows,[46] Android	C++, Python, CUDA	Python (Keras), C/C++, Java, Go, R[47], Julia, Swift	No	On roadmap[48] but already with SYCL[49] support	Yes	Yes[50]	Yes[51]	Yes	Yes	Yes	Yes	
TensorLayer	Hao Dong	Apache 2.0	Yes	Linux, macOS, Windows,[52] Android	C++, Python,	Python	No	On roadmap[48] but already with SYCL[49] support	Yes	Yes[53]	Yes[54]	Yes	Yes	Yes	Yes	
Theano	Université de Montréal	BSD	Yes	Cross-platform	Python	Python (Keras)	Yes	Under development[55]	Yes	Yes[56][57]	Through Lasagne's model zoo[58]	Yes	Yes	Yes	Yes[59]	No
Torch	Ronan Collobert, Koray Kavukcuoglu, Clement Farabet	BSD	Yes	Linux, macOS, Windows,[60] Android,[61] iOS	C, Lua	Lua, LuaJIT,[62] C, utility library for C++/OpenCL[63]	Yes	Third party implementations[64][65]	Yes[66][67]	Through Twitter's Autograd[68]	Yes[69]	Yes	Yes	Yes	Yes[70]	
Wolfram Mathematica	Wolfram Research	Proprietary	No	Windows, macOS, Linux, Cloud computing	C++, Wolfram Language, CUDA	Wolfram Language	Yes	No	Yes	Yes	Yes[71]	Yes	Yes	Yes	Under Development	
VerAI	VerAI	Proprietary	No	Linux, Web-based	C++,Python, Go, Angular	Graphical user interface, cli	No	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	

Excellent comparison: https://skymind.ai/wiki/comparison-frameworks-dl4j-tensorflow-pytorch

Excellent comparison: https://arxiv.org/pdf/1511.06435.pdf

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

Microsoft Azure: Supported Platforms

- Caffe: A deep learning framework built for speed, expressivity, and modularity
- Caffe2: A cross-platform version of Caffe
- Microsoft Cognitive Toolkit: A deep learning software toolkit from Microsoft Research
- H2O: An open-source big data platform and graphical user interface
- Keras: A high-level neural network API in Python for Theano and TensorFlow
- MXNet: A flexible, efficient deep learning library with many language bindings
- NVIDIA DIGITS: A graphical system that simplifies common deep learning tasks
- PyTorch: A high-level Python library with support for dynamic networks
- TensorFlow: An open-source library for machine intelligence from Google
- Theano: A Python library for defining, optimizing, and efficiently evaluating mathematical expressions involving multi-dimensional arrays
- Torch: A scientific computing framework with wide support for machine learning algorithms
- CUDA, cuDNN, and the NVIDIA driver
- Many sample Jupyter notebooks

https://docs.microsoft.com/en-us/azure/machine-learning/data-science-virtual-machine/dsvm-ubuntu-intro

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