

Recurrent Neural Networks (RNN) and Long-Short-Term-Memory (LSTM)

Yuan YAO

HKUST



Summary

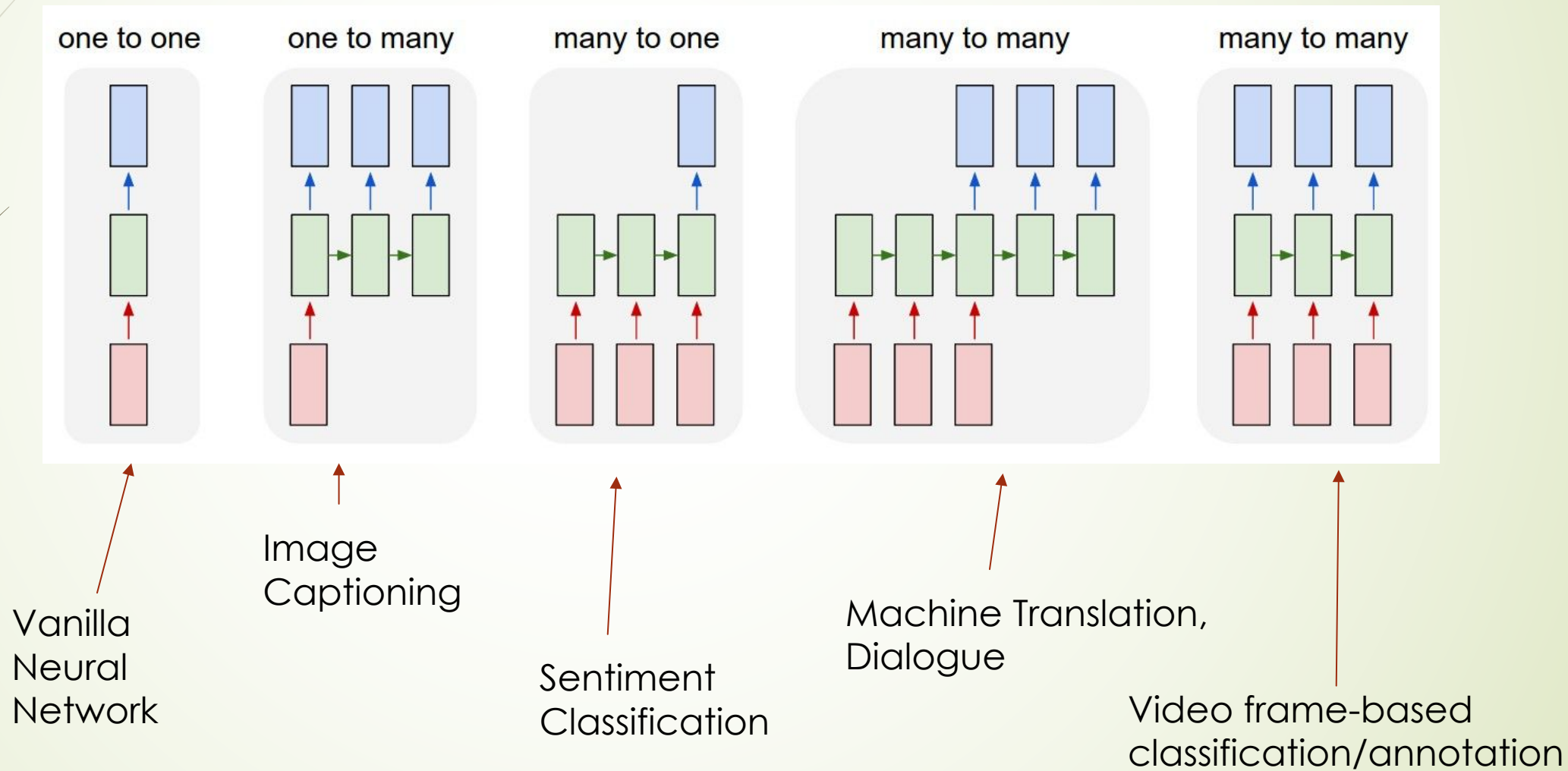


- ▶ We have shown:
 - ▶ CNN Architectures: LeNet5, Alexnet, VGG, GoogleNet, Resnet
- ▶ Today:
 - ▶ **Recurrent Neural Networks**
 - ▶ **LSTM/GRU**
- ▶ Reference:
 - ▶ Feifei Li, Stanford cs231n
 - ▶ Chris Manning, Stanford cs224n

A decorative graphic on the left side of the slide. It features a solid red arrow pointing to the right, positioned horizontally. Behind the arrow and extending upwards and to the right are several thin, dark grey, curved lines that resemble stylized grass or abstract brushstrokes.

Recurrent Neural Networks

Recurrent Neural Networks: Process Sequences



Sequential Processing of Non-Sequence Data

Classify images by taking a series of “glimpses”

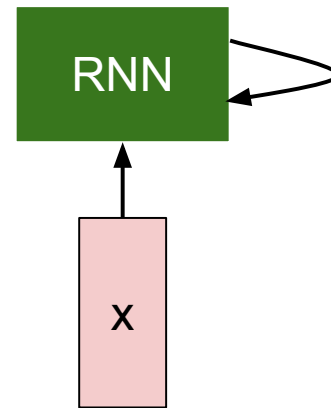


Ba, Mnih, and Kavukcuoglu, “Multiple Object Recognition with Visual Attention”, ICLR 2015.

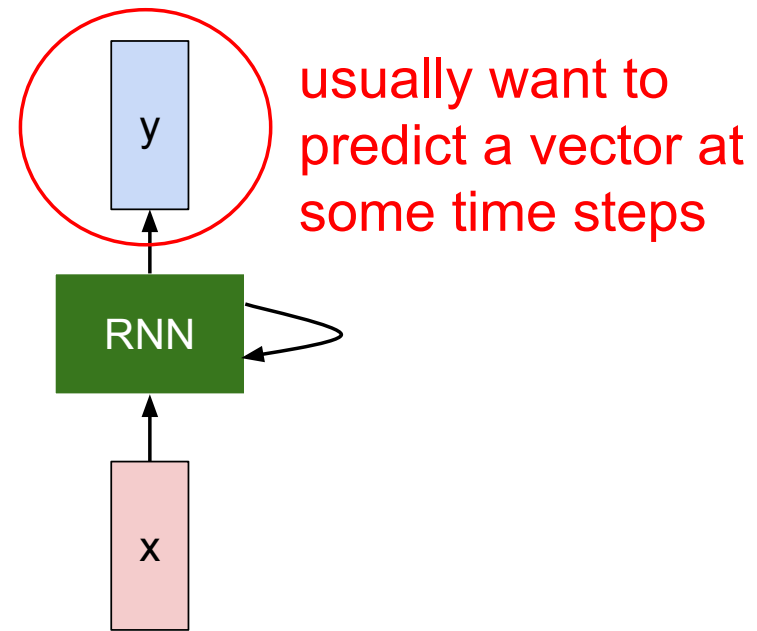
Gregor et al, “DRAW: A Recurrent Neural Network For Image Generation”, ICML 2015

Figure copyright Karol Gregor, Ivo Danihelka, Alex Graves, Danilo Jimenez Rezende, and Daan Wierstra, 2015. Reproduced with permission

Recurrent Neural Network



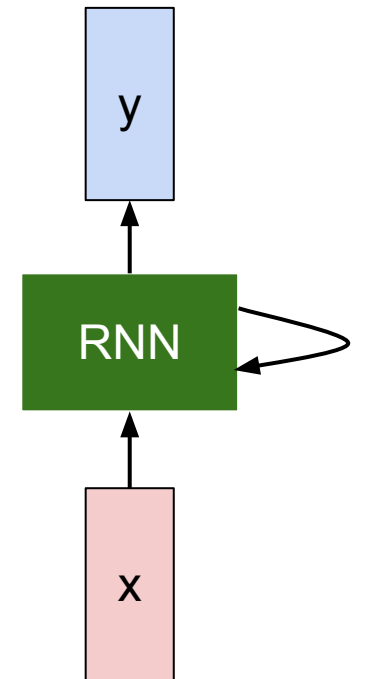
Recurrent Neural Network



We can process a sequence of vectors \mathbf{x} by applying a **recurrence formula** at every time step:

$$\boxed{h_t} = \boxed{f_W}(\boxed{h_{t-1}}, \boxed{x_t})$$

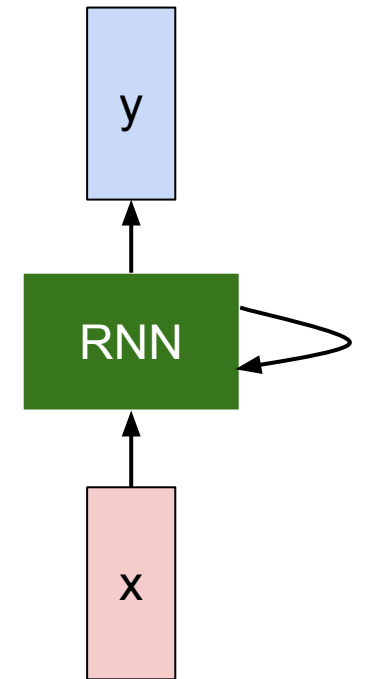
new state some function with parameters W old state input vector at some time step



We can process a sequence of vectors \mathbf{x} by applying a **recurrence formula** at every time step:

$$h_t = f_W(h_{t-1}, x_t)$$

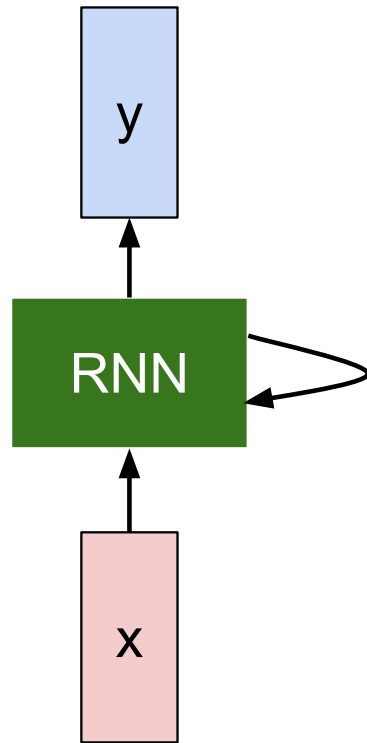
Notice: the same function and the same set of parameters are used at every time step.



Vanilla Recurrent Neural Networks

State Space equations in feedback dynamical systems

The state consists of a single “*hidden*” vector \mathbf{h} :



$$h_t = f_W(h_{t-1}, x_t)$$

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

$$y_t = W_{hy}h_t$$

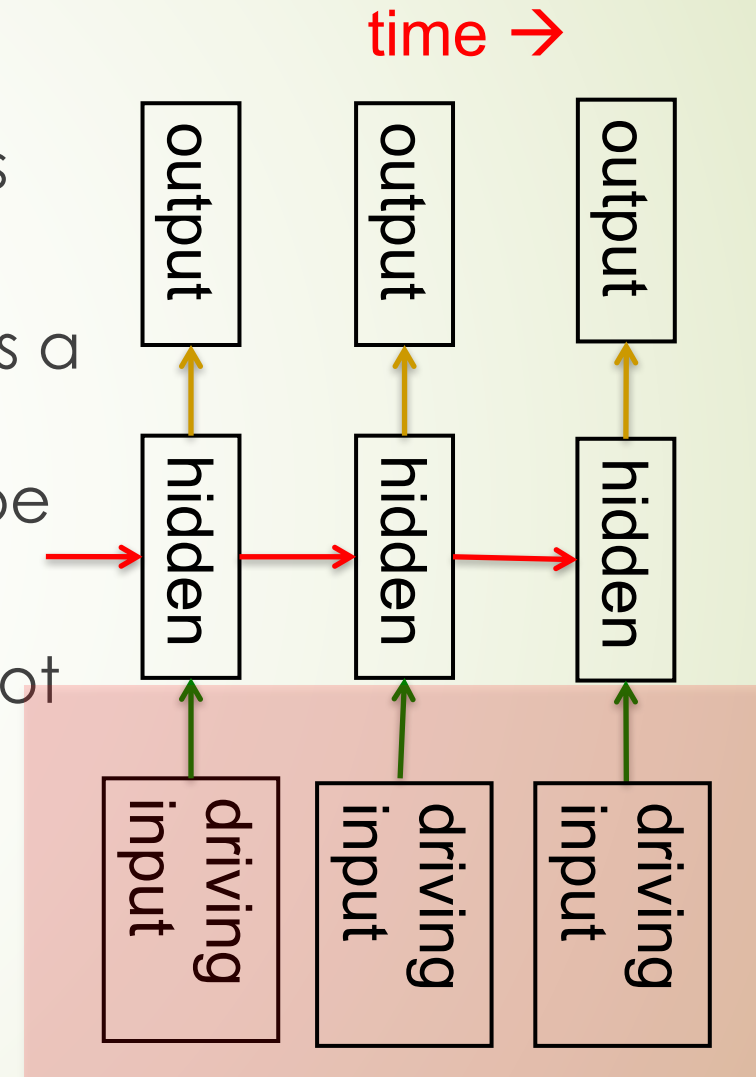
Or,
$$y_t = \text{softmax}(W_{hy}h_t)$$

Linear Dynamical Systems (1940s-)

- ▶ The hidden state has linear dynamics with Gaussian noise and produces the observations using a linear model with Gaussian noise.
- ▶ Kalman Filter: A linearly transformed Gaussian is a Gaussian. So the distribution over the hidden state given the data so far is Gaussian. It can be computed using “Kalman filtering”.
- ▶ To predict the next output (so that we can shoot down the missile) we need to infer the hidden state.

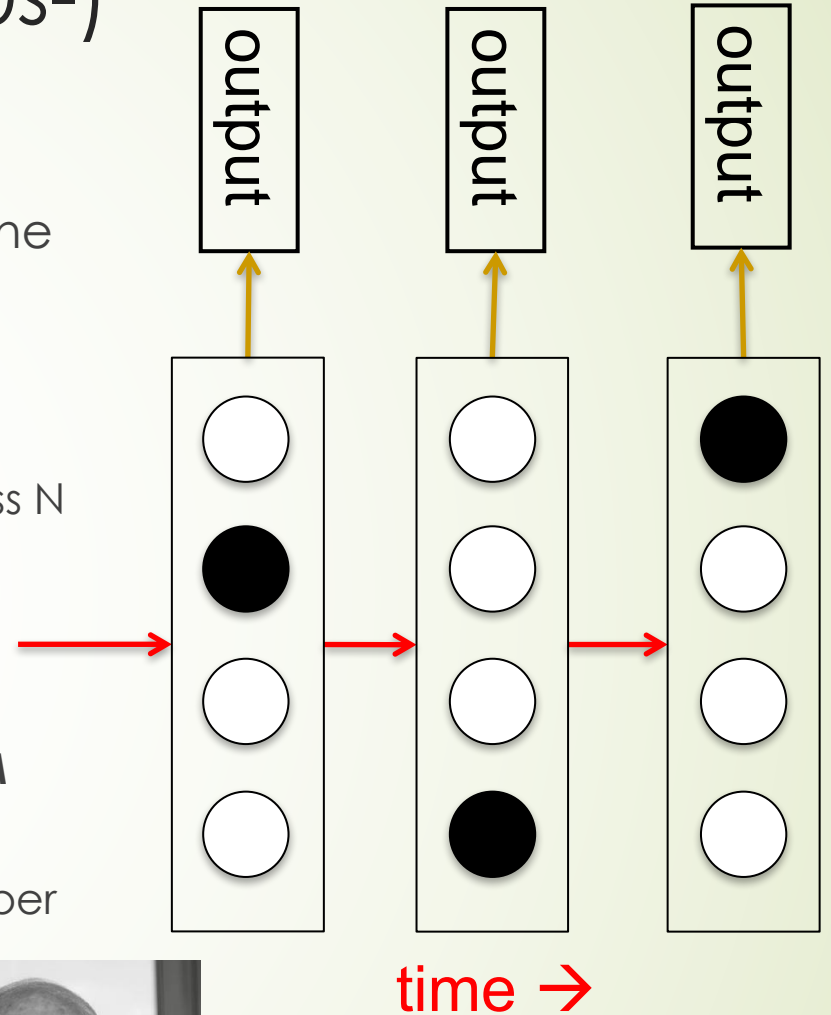
$$h_t = W_{hh}h_{t-1} + W_{hx}x_t + \epsilon_t^h$$

$$y_t = W_{yh}h_t + W_{yx}x_t + \epsilon_t^y$$

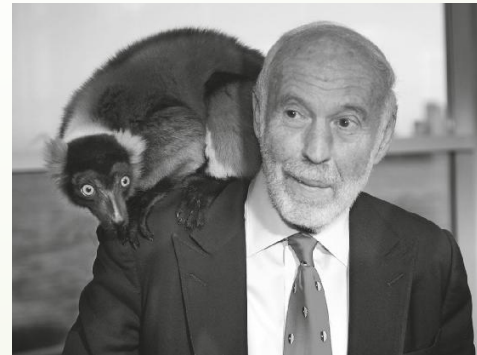


Hidden Markov Models (1970s-)

- ▶ Hidden Markov Models have a discrete one-of-N hidden state. Transitions between states are stochastic and controlled by a transition matrix. The outputs produced by a state are stochastic.
 - ▶ We cannot be sure which state produced a given output. So the state is “hidden”.
 - ▶ It is easy to represent a probability distribution across N states with N numbers.
- ▶ To predict the next output we need to infer the probability distribution over hidden states.
 - ▶ HMMs have efficient algorithms (**Baum-Welch or EM Algorithm**) for inference and learning.
 - ▶ Jim Simons hires Lenny Baum as the founding member of Renaissance Technologies in 1979



Lenny Baum became a devoted Go player despite his deteriorating eyesight.

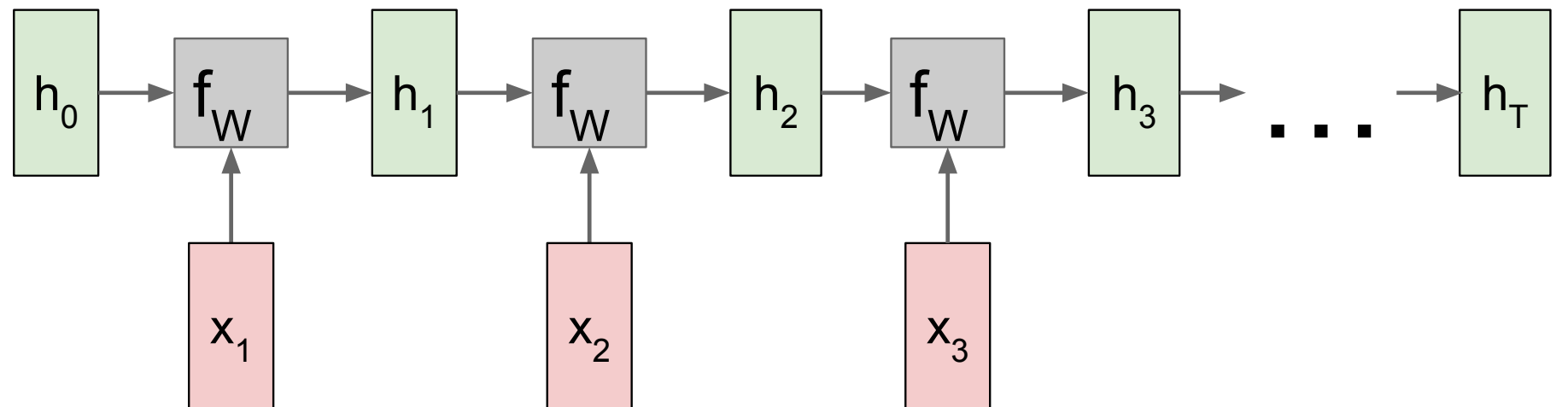




Recurrent Neural Networks

- ▶ **The issue of a hidden Markov model (HMM):**
 - ▶ At each time step it must select one of its hidden states. So with N hidden states it can only remember $\log(N)$ bits about what it generated so far.
- ▶ RNNs are very powerful, because they combine two properties:
 - ▶ Distributed hidden state that allows them to store a lot of information about the past efficiently.
 - ▶ Non-linear dynamics that allows them to update their hidden state in complicated ways.
- ▶ With enough neurons and time, RNNs can compute anything that can be computed by your computer.

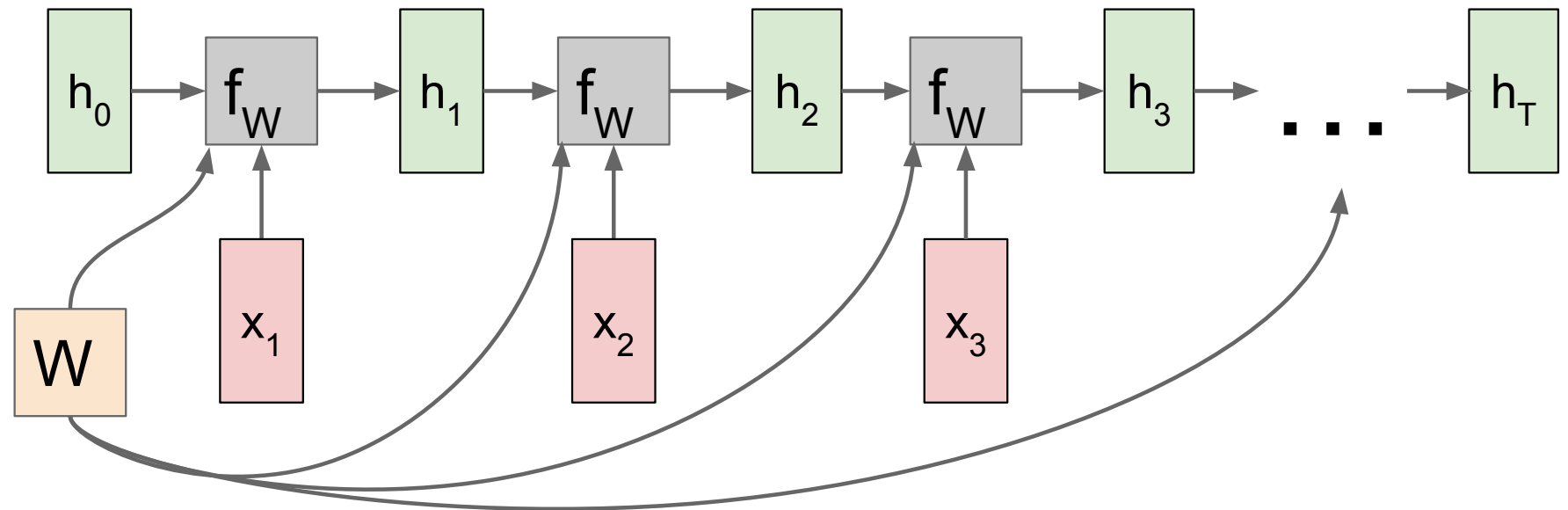
RNN: Computational Graph



Time invariant systems

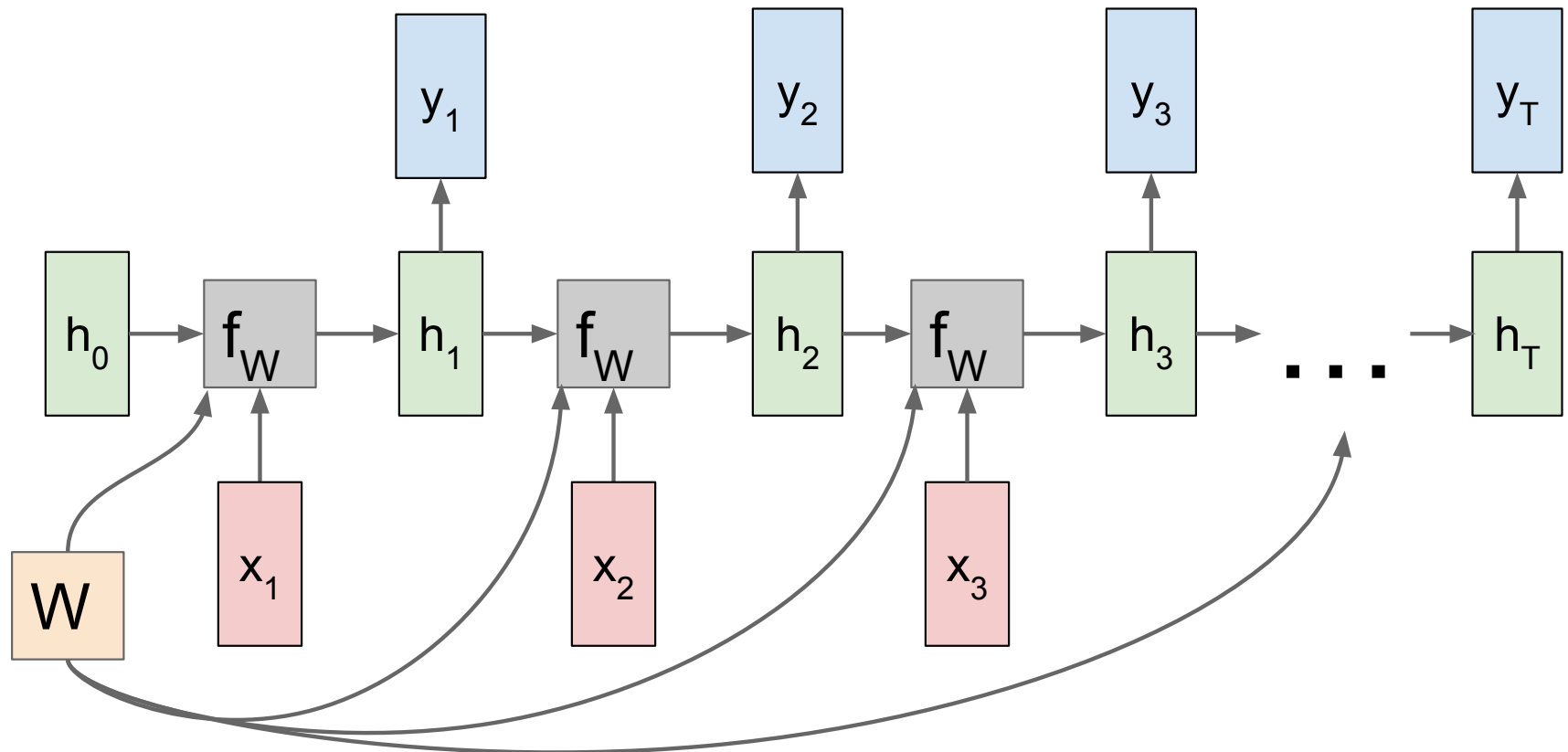
RNN: Computational Graph

Re-use the same weight matrix at every time-step



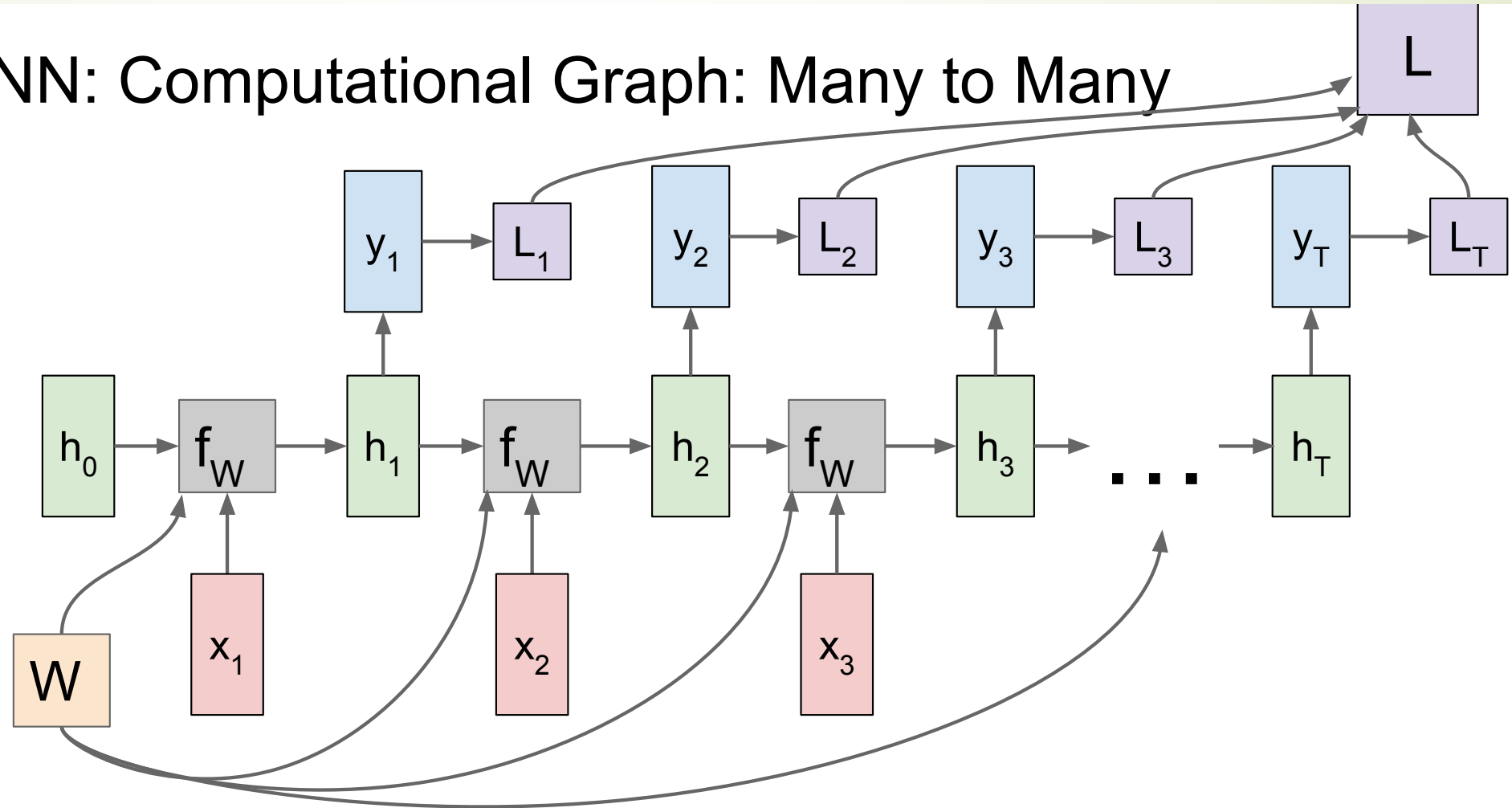
Outputs added

RNN: Computational Graph: Many to Many

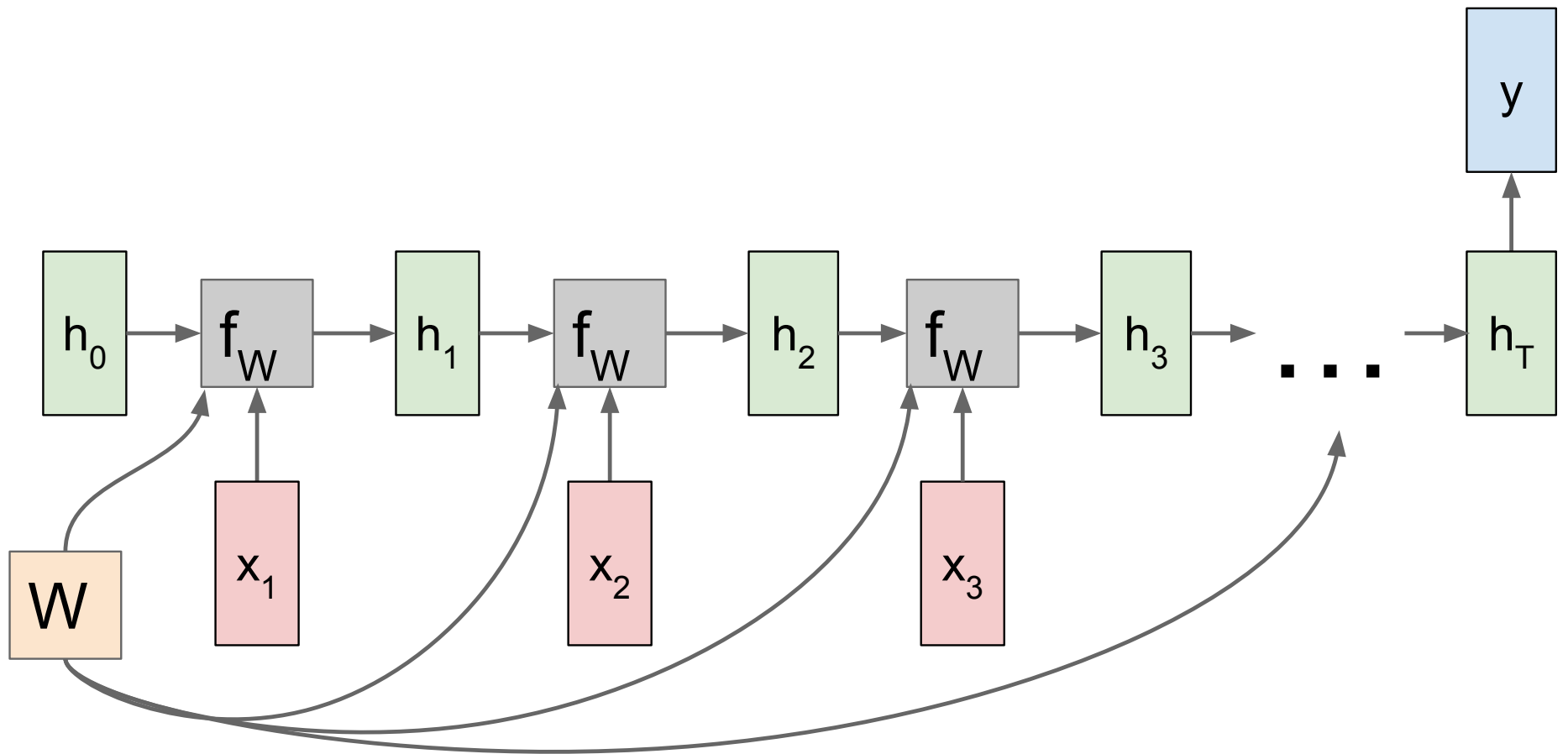


Loss modules

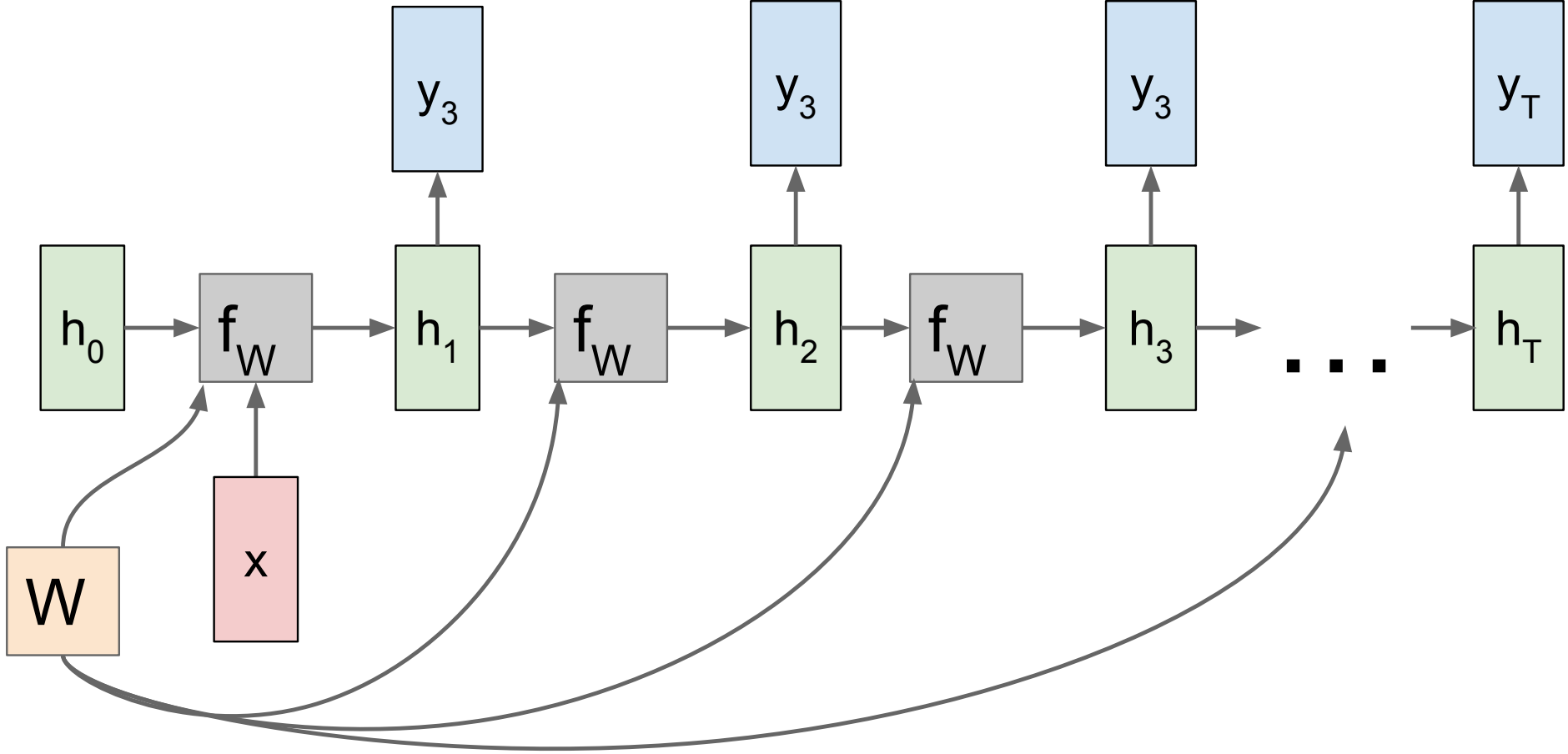
RNN: Computational Graph: Many to Many



RNN: Computational Graph: Many to One



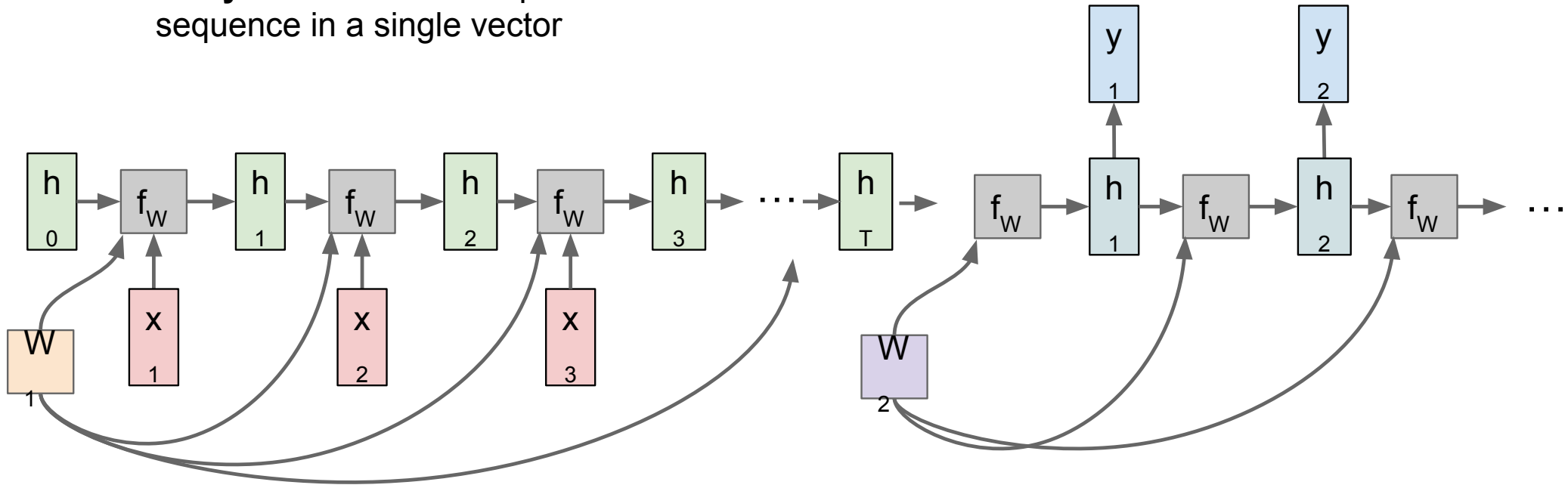
RNN: Computational Graph: One to Many



Sequence to Sequence: Many-to-one + one-to-many

Many to one: Encode input sequence in a single vector

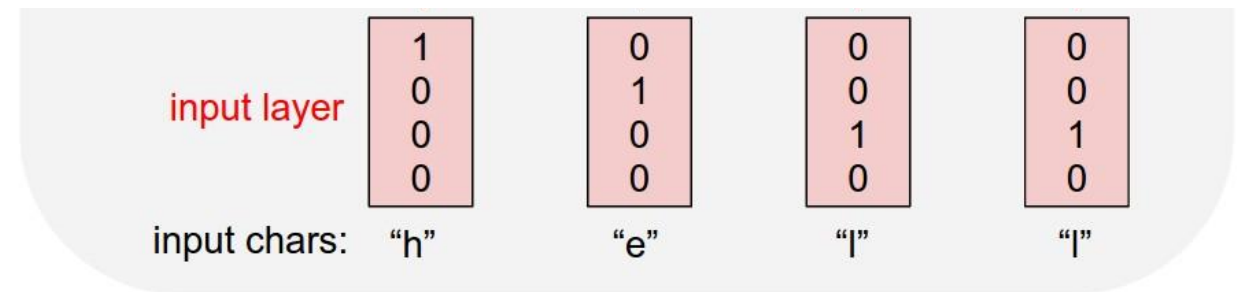
One to many: Produce output sequence from single input vector



Example: Character-level Language Model

Vocabulary:
[h,e,l,o]

Example training
sequence:
“hello”

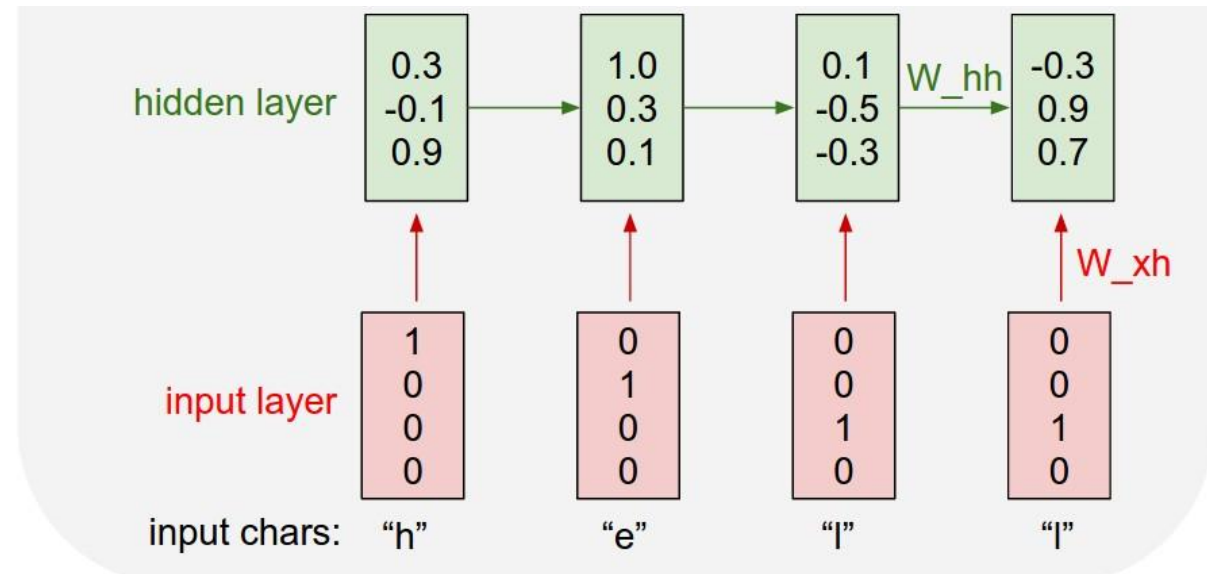


Example: Character-level Language Model

Vocabulary:
[h,e,l,o]

Example training
sequence:
“hello”

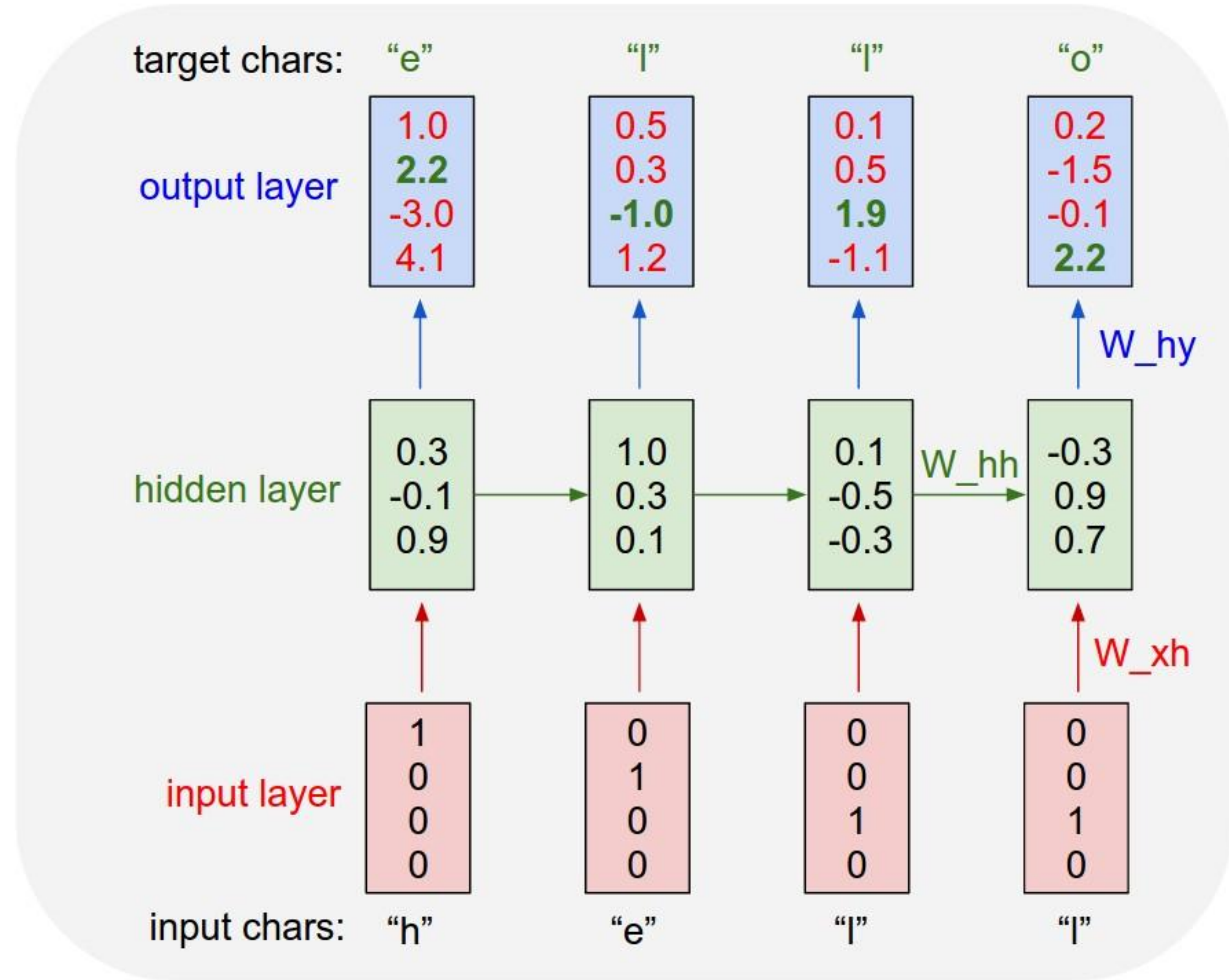
$$h_t = \tanh(W_{hh}h_{t-1} + W_{xh}x_t)$$



Example: Character-level Language Model

Vocabulary:
[h,e,l,o]

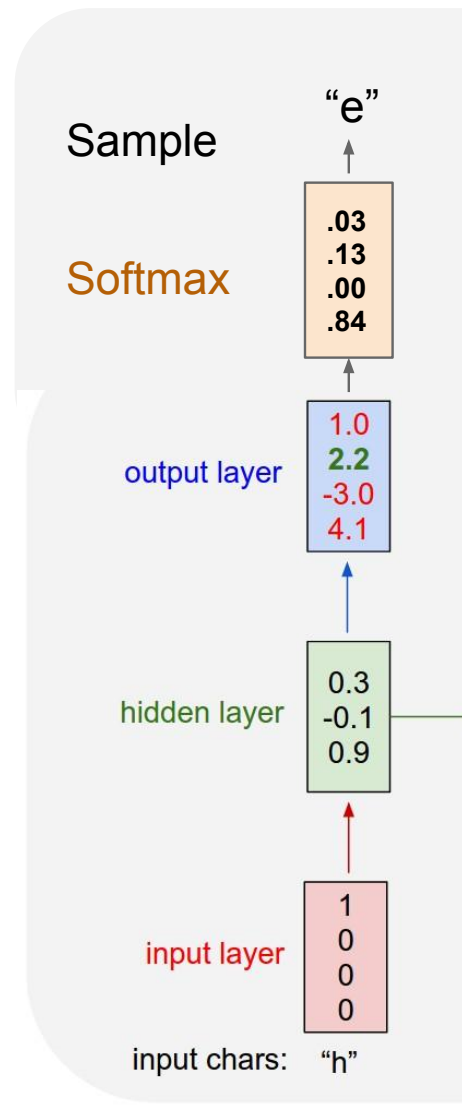
Example training
sequence:
“hello”



Example: Character-level Language Model Sampling

Vocabulary:
[h,e,l,o]

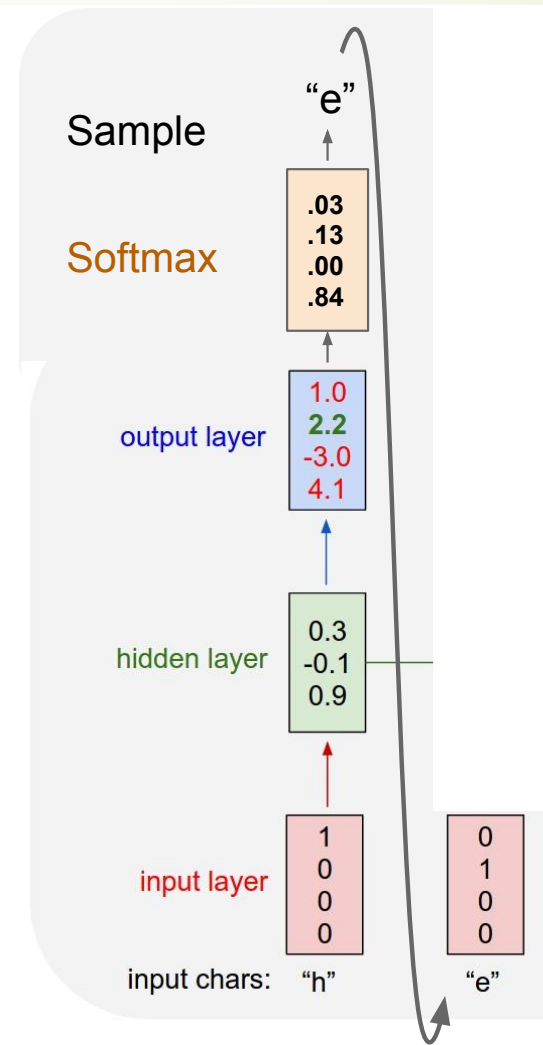
At test-time sample
characters one at a time,
feed back to model



Example: Character-level Language Model Sampling

Vocabulary:
[h,e,l,o]

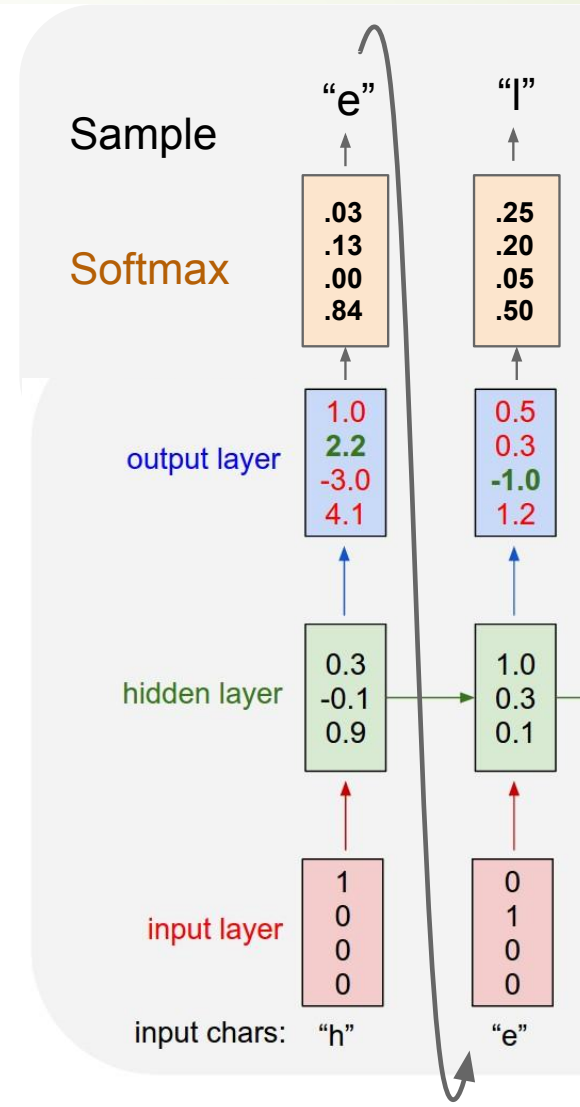
At test-time sample
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Example: Character-level Language Model Sampling

Vocabulary:
[h,e,l,o]

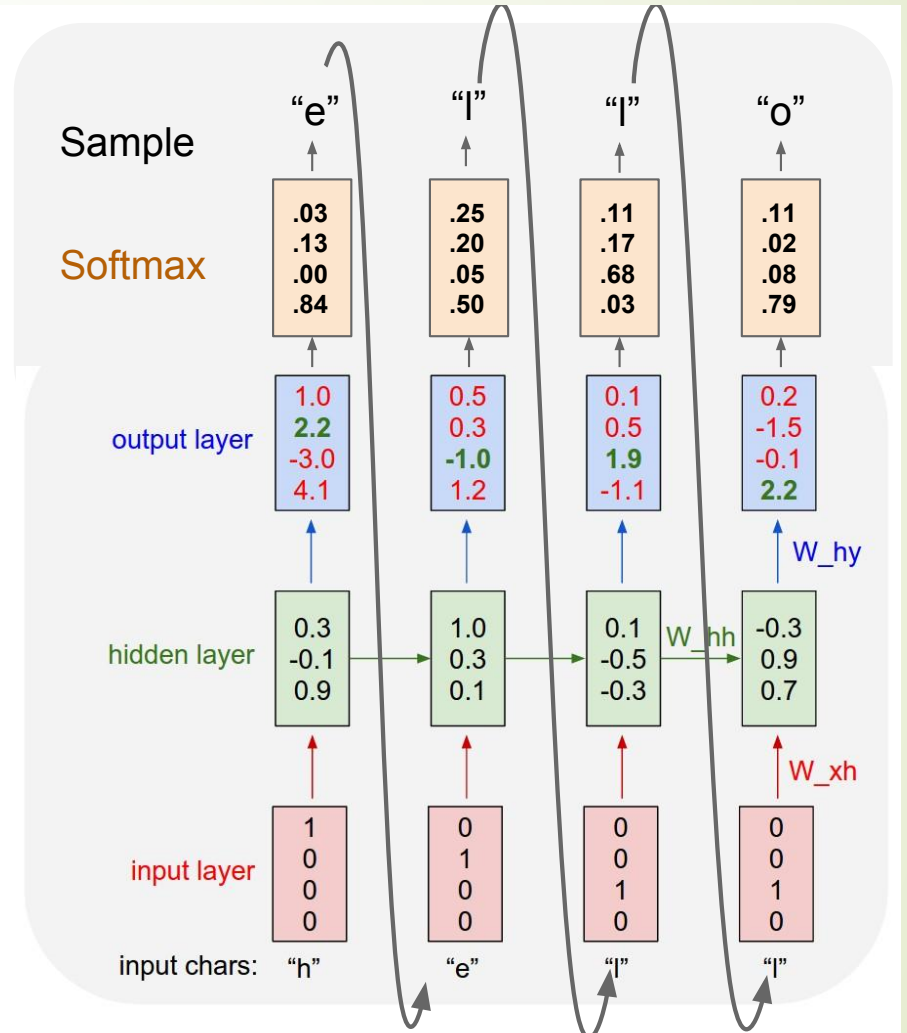
At test-time sample
characters one at a time,
feed back to model



Example: Character-level Language Model Sampling

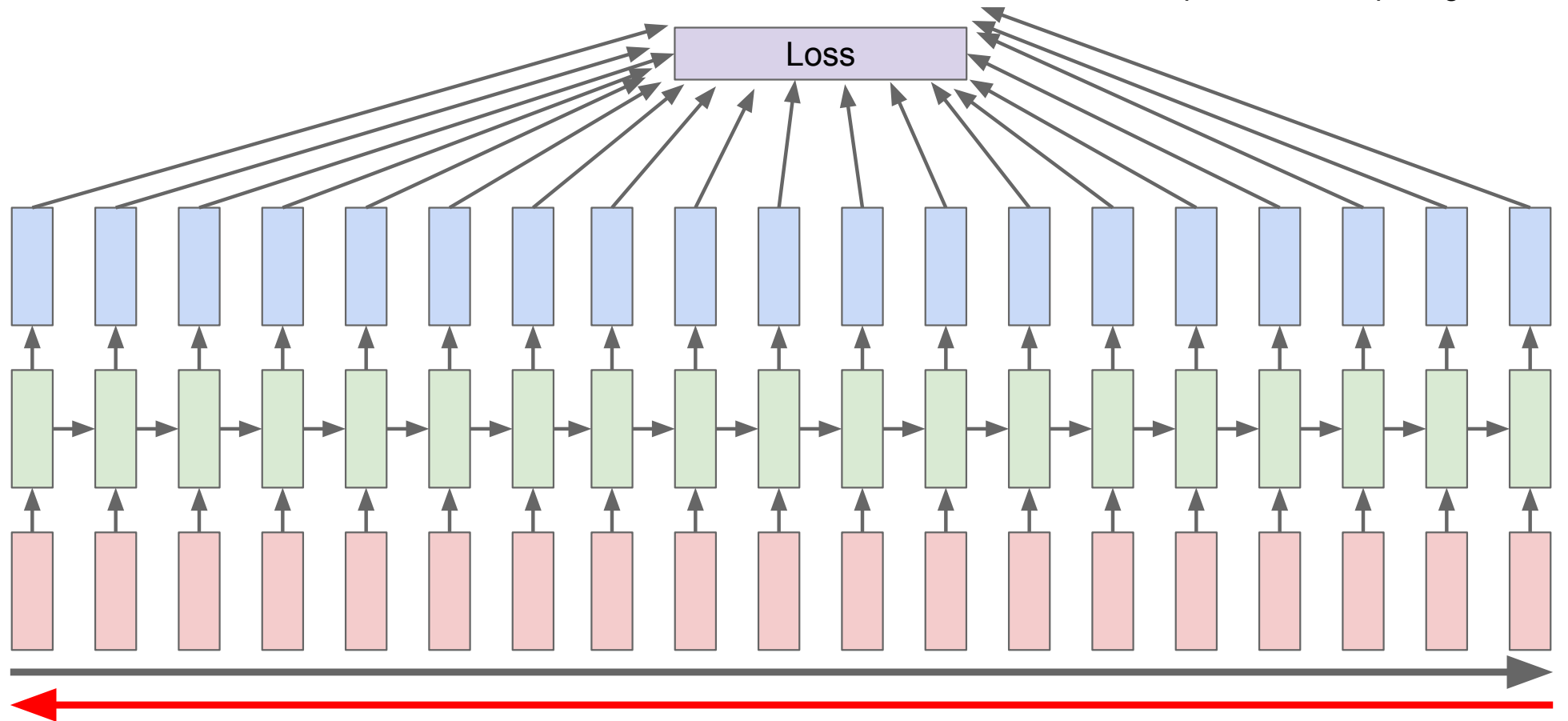
Vocabulary:
[h,e,l,o]

At test-time sample
characters one at a time,
feed back to model

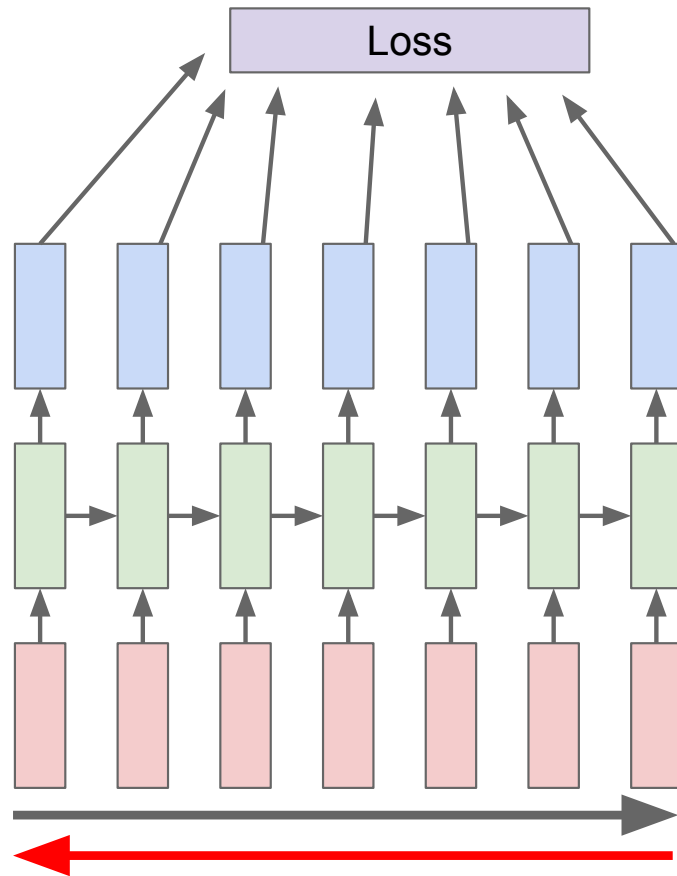


Backpropagation through time

Forward through entire sequence to compute loss, then backward through entire sequence to compute gradient

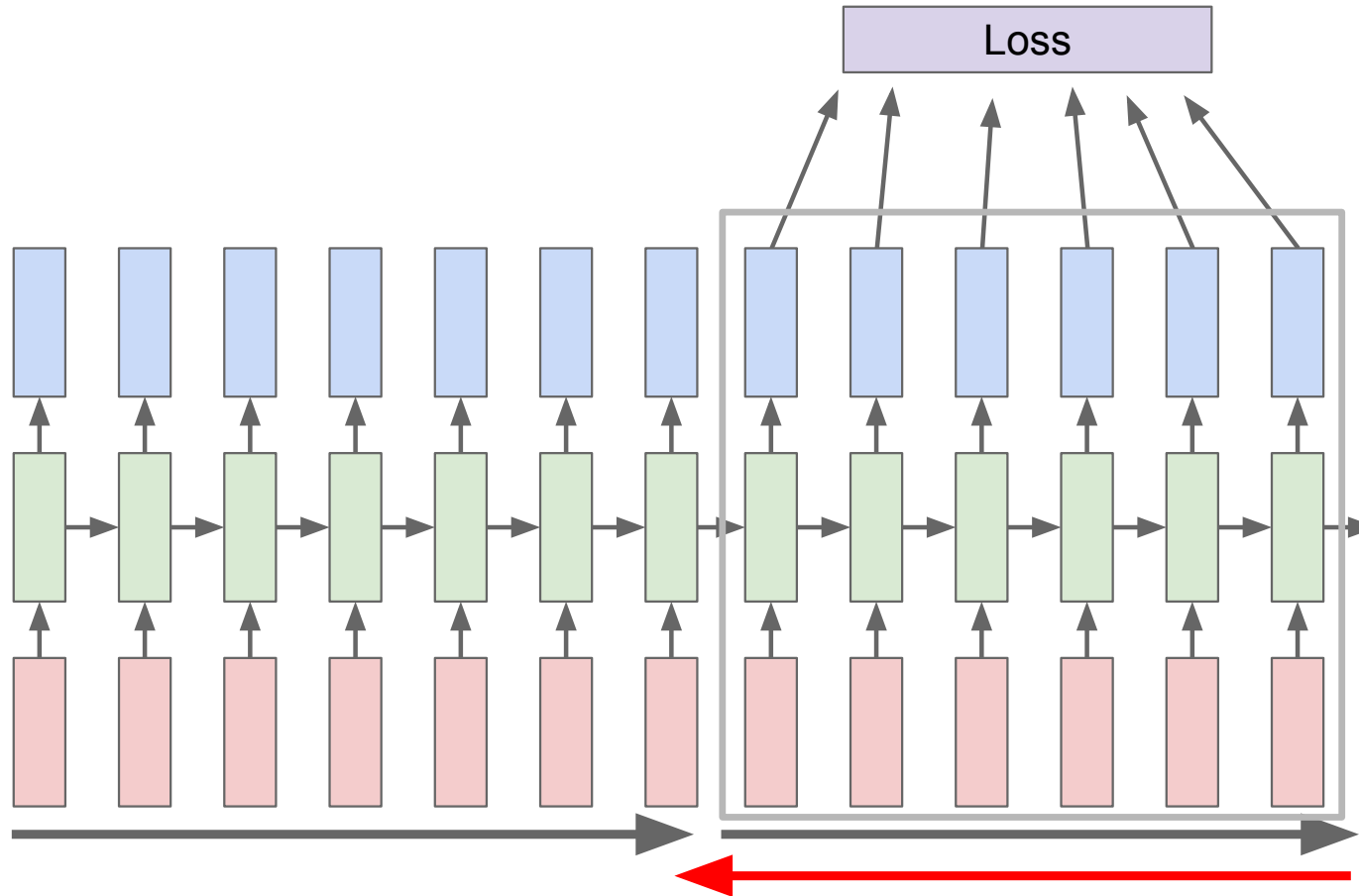


Truncated Backpropagation through time



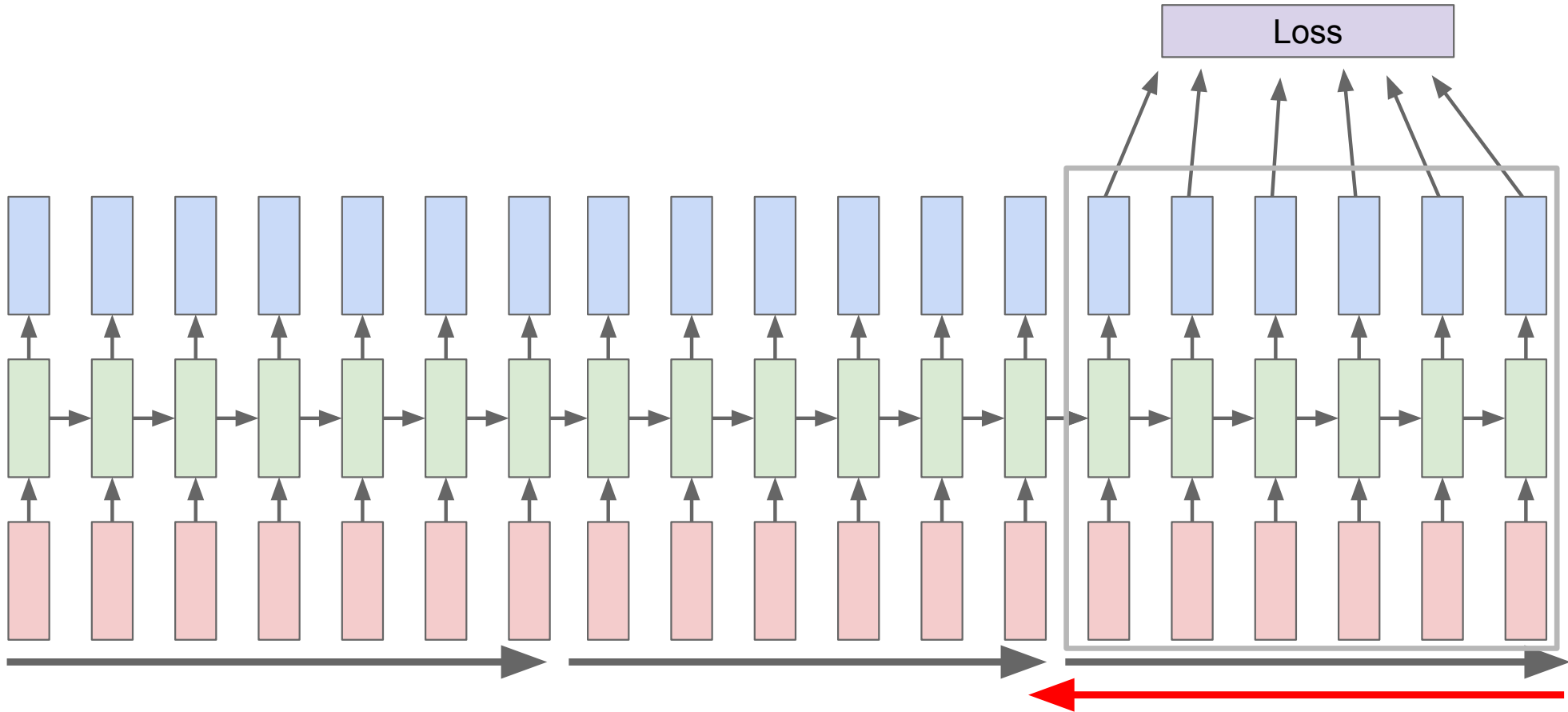
Run forward and backward through chunks of the sequence instead of whole sequence

Truncated Backpropagation through time



Carry hidden states forward in time forever, but only backpropagate for some smaller number of steps

Truncated Backpropagation through time



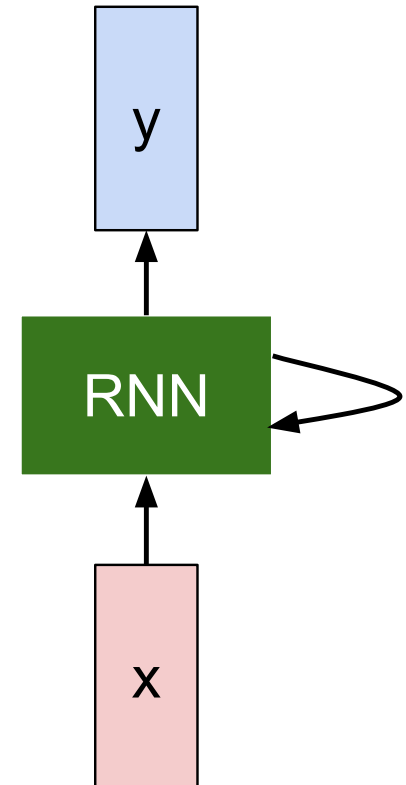
Example: Text->RNN

THE SONNETS

by William Shakespeare

From fairest creatures we desire increase,
That thereby beauty's rose might never die,
But as the ripper should by time decease,
His tender heir might bear his memory:
But thou, contracted to thine own bright eyes,
Feed'st thy light's flame with self-substantial fuel,
Making a famine where abundance lies,
Thyself thy foe, to thy sweet self too cruel:
Thou that art now the world's fresh ornament,
And only herald to the gaudy spring,
Within thine own bud buriest thy content,
And tender churl mak'st waste in niggarding:
 Pity the world, or else this glutton be,
 To eat the world's due, by the grave and thee.

When forty winters shall besiege thy brow,
And dig deep trenches in thy beauty's field,
Thy youth's proud livery so gazed on now,
Will be a tatter'd weed of small worth held:
Then being asked, where all thy beauty lies,
Where all the treasure of thy lusty days;
To say, within thine own deep sunken eyes,
Were an all-eating shame, and thriftless praise.
How much more praise deserv'd thy beauty's use,
If thou couldst answer 'This fair child of mine
Shall sum my count, and make my old excuse,'
Proving his beauty by succession thine!
 This were to be new made when thou art old,
 And see thy blood warm when thou feel'st it cold.





at first:

tyntd-iafhatawiaoahrdemot lytdws e ,tfti, astai f ogoh eoase rrranbyne 'nhtnee e
plia tkllrgd t o idoe ns,smtt h ne etie h,hregtrs nigtike,aoaenns lng

↓
train more

"Tmont thithey" fomesscerliund
Keushey. Thom here
sheulke, anmerenith ol sivh I lalterthend Bleipile shuw y fil on aseterlome
coaniogennc Phe lism thond hon at. MeiDimorotion in ther thize."

↓
train more

Aftair fall unsuch that the hall for Prince Velzonski's that me of
her hearly, and behs to so arwage fiving were to it beloge, pavu say falling misfort
how, and Gogition is so overelical and offer.

↓
train more

"Why do what that day," replied Natasha, and wishing to himself the fact the
princess, Princess Mary was easier, fed in had oftended him.
Pierre aking his soul came to the packs and drove up his father-in-law women.

Image Captioning

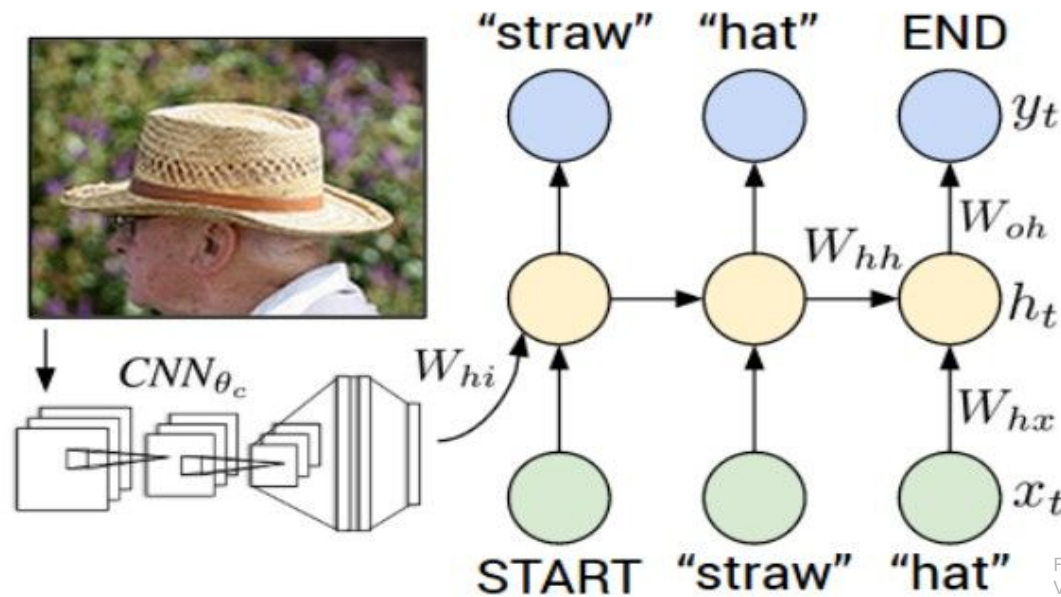


Figure from Karpathy et al, "Deep Visual-Semantic Alignments for Generating Image Descriptions", CVPR 2015; figure copyright IEEE, 2015. Reproduced for educational purposes.

Explain Images with Multimodal Recurrent Neural Networks, Mao et al.

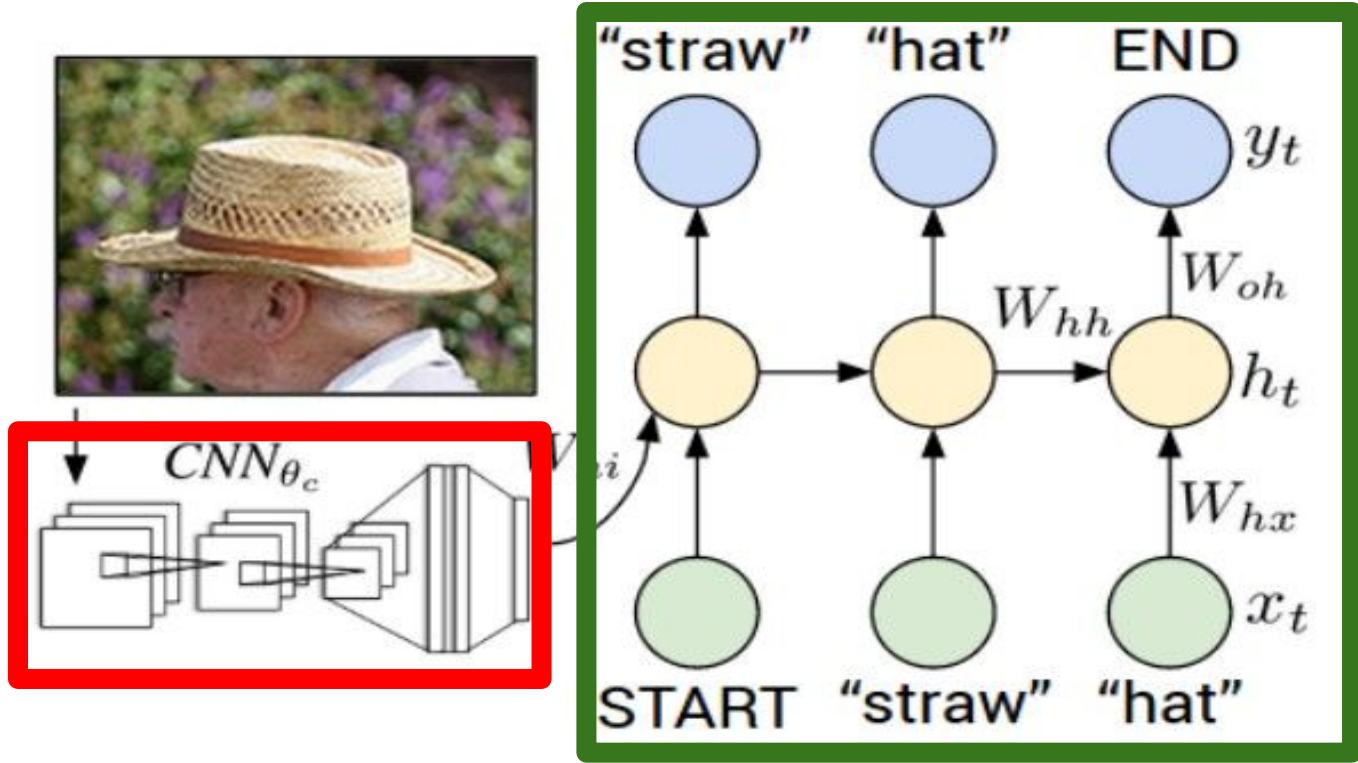
Deep Visual-Semantic Alignments for Generating Image Descriptions, Karpathy and Fei-Fei

Show and Tell: A Neural Image Caption Generator, Vinyals et al.

Long-term Recurrent Convolutional Networks for Visual Recognition and Description, Donahue et al.

Learning a Recurrent Visual Representation for Image Caption Generation, Chen and Zitnick

Recurrent Neural Network



Convolutional Neural Network



image

conv-64

conv-64

maxpool

conv-128

conv-128

maxpool

conv-256

conv-256

maxpool

conv-512

conv-512

maxpool

conv-512

conv-512

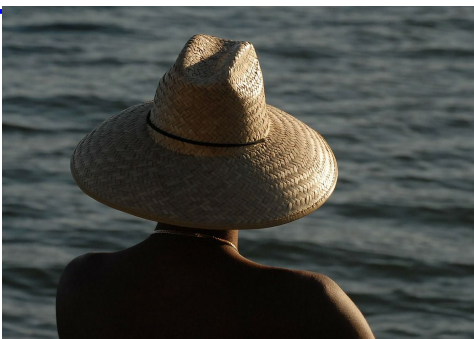
maxpool

FC-4096

FC-4096

FC-1000

softmax



test image



image



conv-64

conv-64

maxpool

conv-128

conv-128

maxpool

conv-256

conv-256

maxpool

conv-512

conv-512

maxpool

conv-512

conv-512

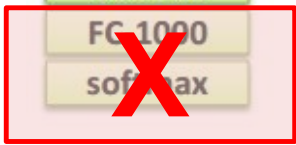
maxpool

FC-4096

FC-4096

FC-1000

softmax



test image



image

conv-64

conv-64

maxpool

conv-128

conv-128

maxpool

conv-256

conv-256

maxpool

conv-512

conv-512

maxpool

conv-512

conv-512

maxpool

FC-4096

FC-4096

V



test image

y0

h0

x0
<START>

Wih

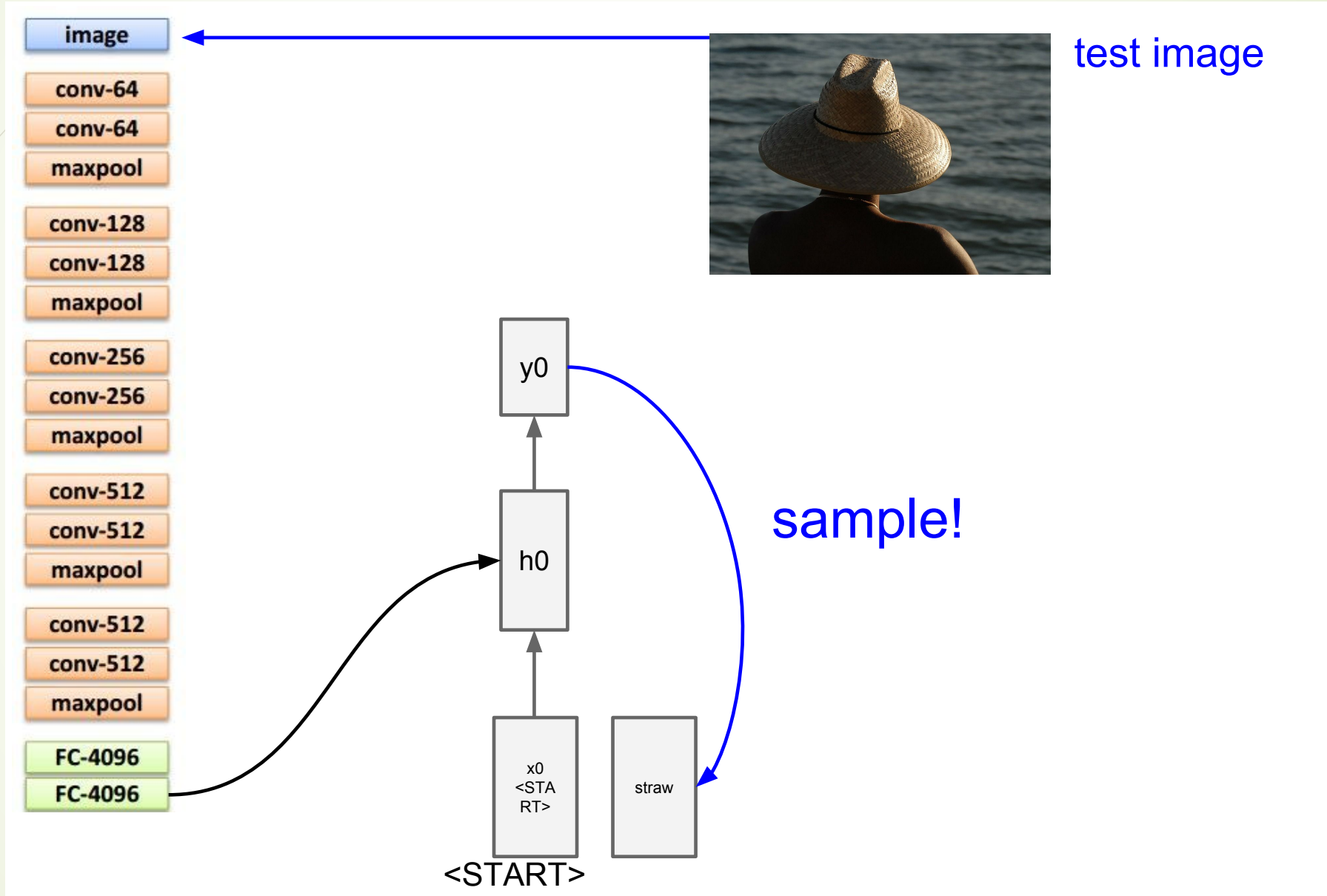
before:

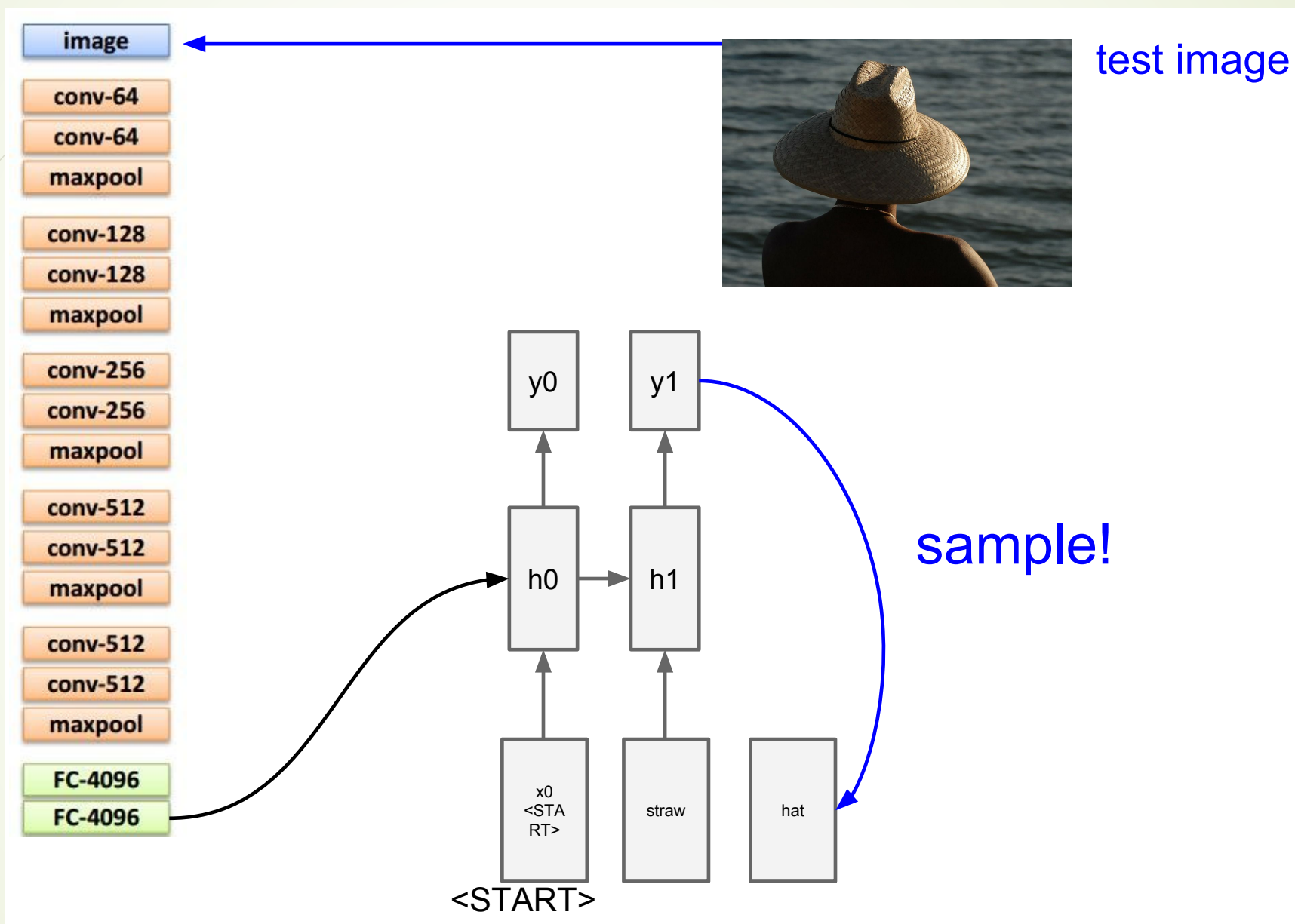
$$h = \tanh(W_{xh} * x + W_{hh} * h)$$

now:

$$h = \tanh(W_{xh} * x + W_{hh} * h + W_{ih} * v)$$

<START>





test image



sample!

<START>

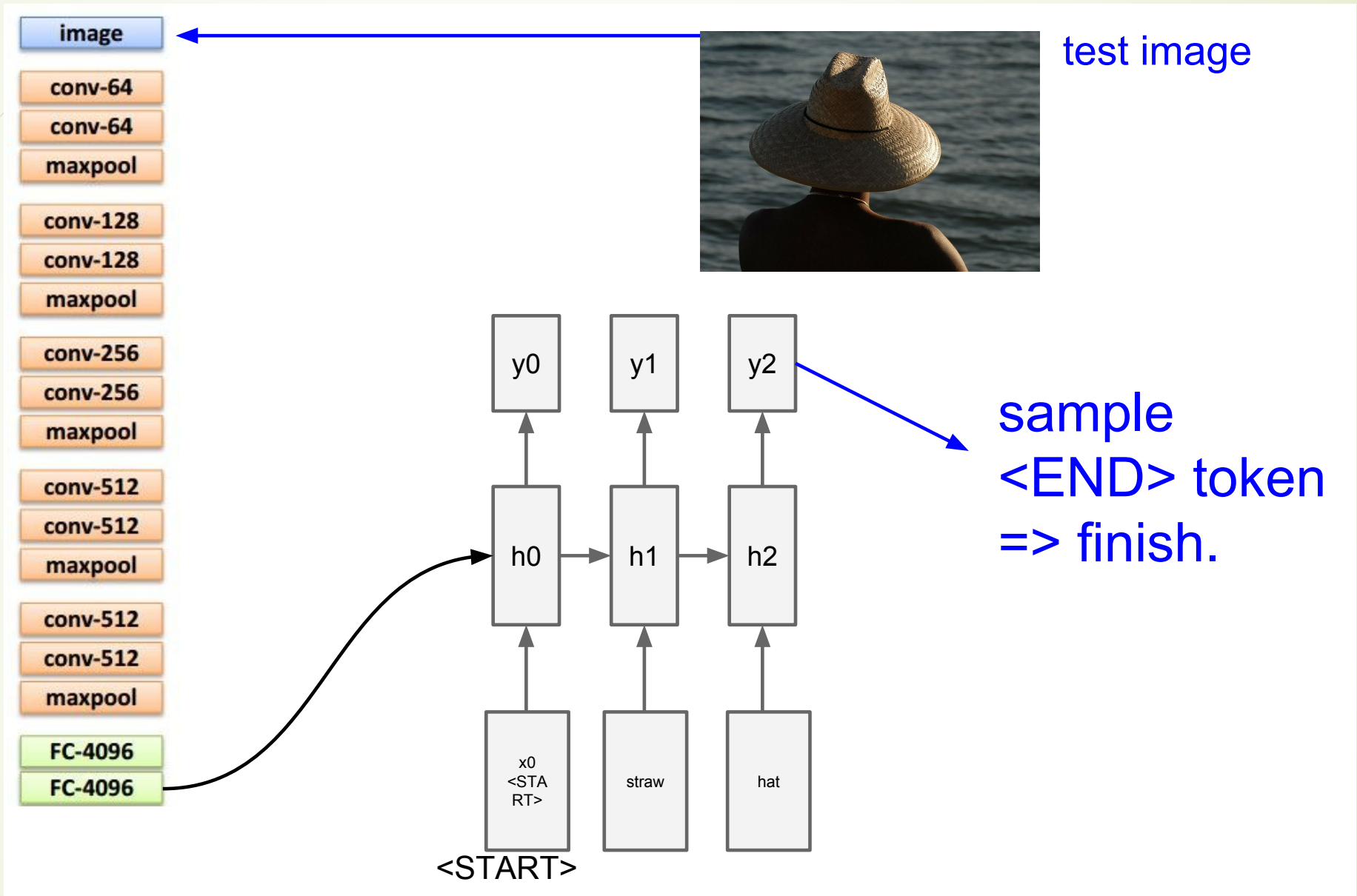


Image Captioning: Example Results

Captions generated using [neuraltalk2](#)
All images are [CC0 Public domain](#):
[cat](#), [suitcase](#), [cat tree](#), [dog](#), [bear](#),
[surfers](#), [tennis](#), [giraffe](#), [motorcycle](#)



A cat sitting on a suitcase on the floor



A cat is sitting on a tree branch



A dog is running in the grass with a frisbee



A white teddy bear sitting in the grass



Two people walking on the beach with surfboards



A tennis player in action on the court



Two giraffes standing in a grassy field



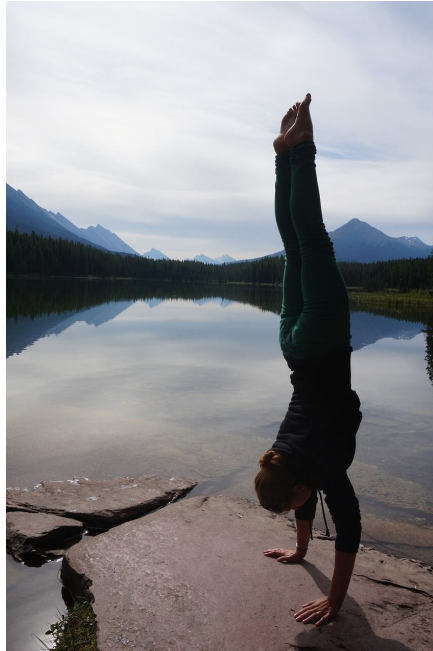
A man riding a dirt bike on a dirt track

Image Captioning: Failure Cases

Captions generated using [neuraltalk2](#)
All images are [CC0 Public domain](#): [fur coat](#), [handstand](#), [spider web](#), [baseball](#)



A woman is holding a cat in her hand



A woman standing on a beach holding a surfboard



A bird is perched on a tree branch



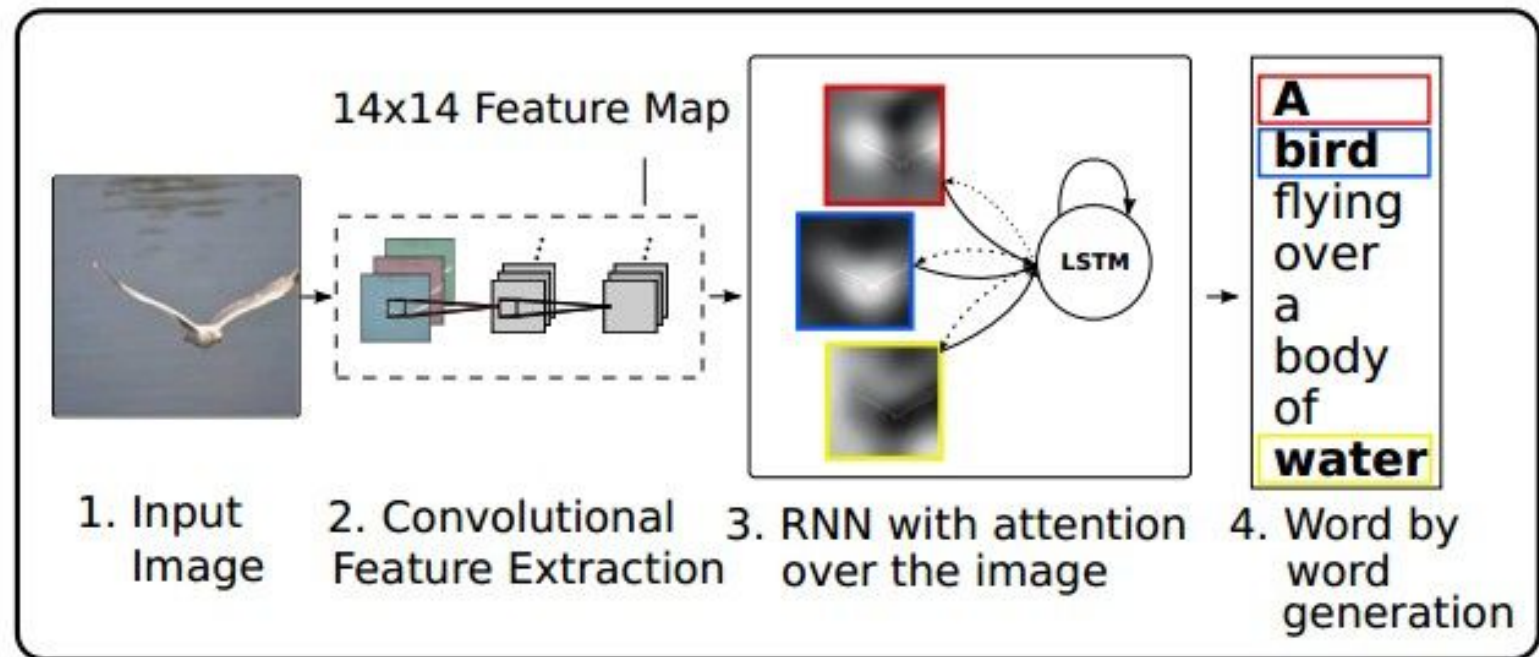
A person holding a computer mouse on a desk



A man in a baseball uniform throwing a ball

Image Captioning with Attention

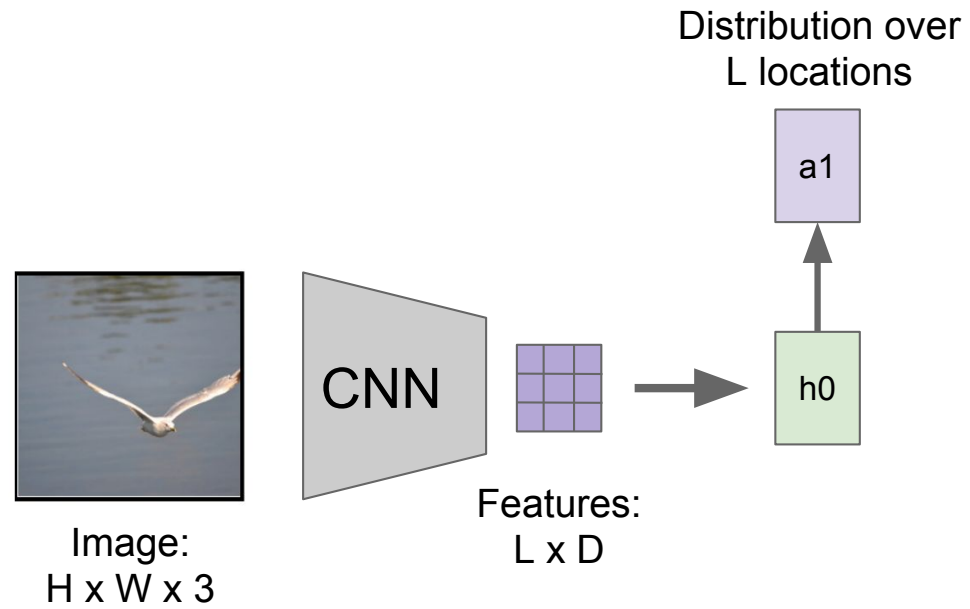
RNN focuses its attention at a different spatial location when generating each word



Xu et al, "Show, Attend, and Tell: Neural Image Caption Generation with Visual Attention", ICML 2015

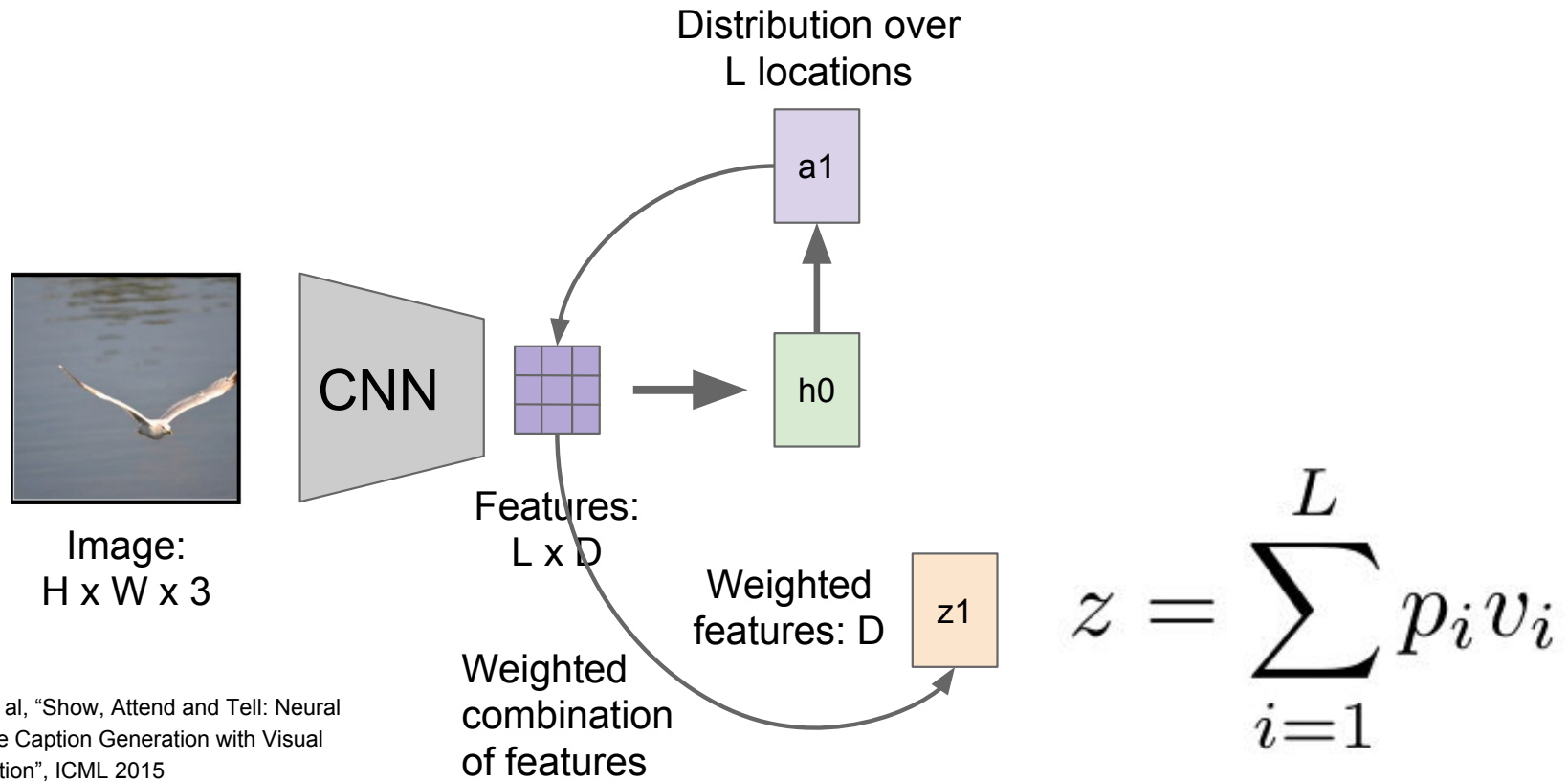
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Image Captioning with Attention



Xu et al, "Show, Attend and Tell: Neural Image Caption Generation with Visual Attention", ICML 2015

Image Captioning with Attention



Xu et al, "Show, Attend and Tell: Neural Image Caption Generation with Visual Attention", ICML 2015

Image Captioning with Attention

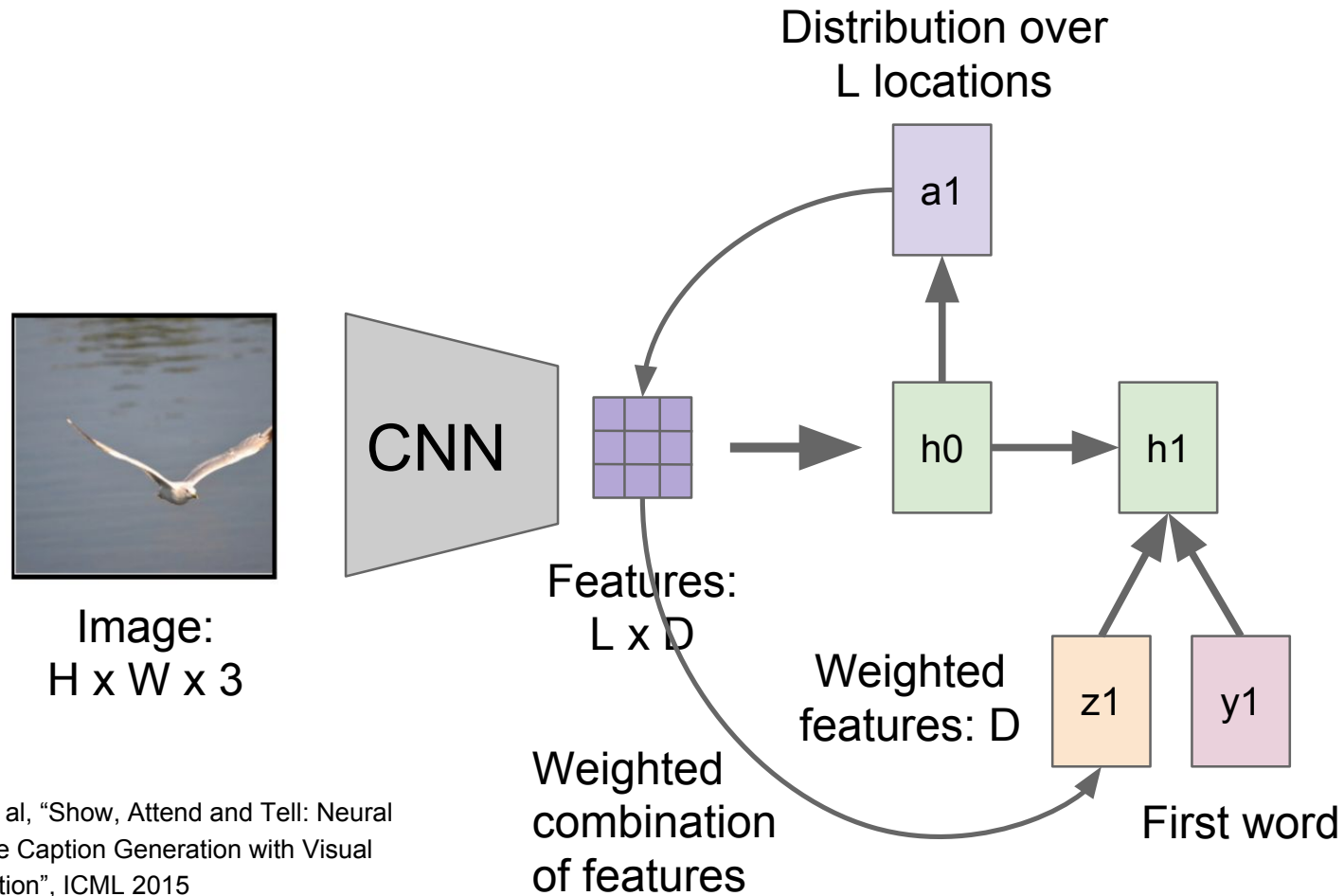
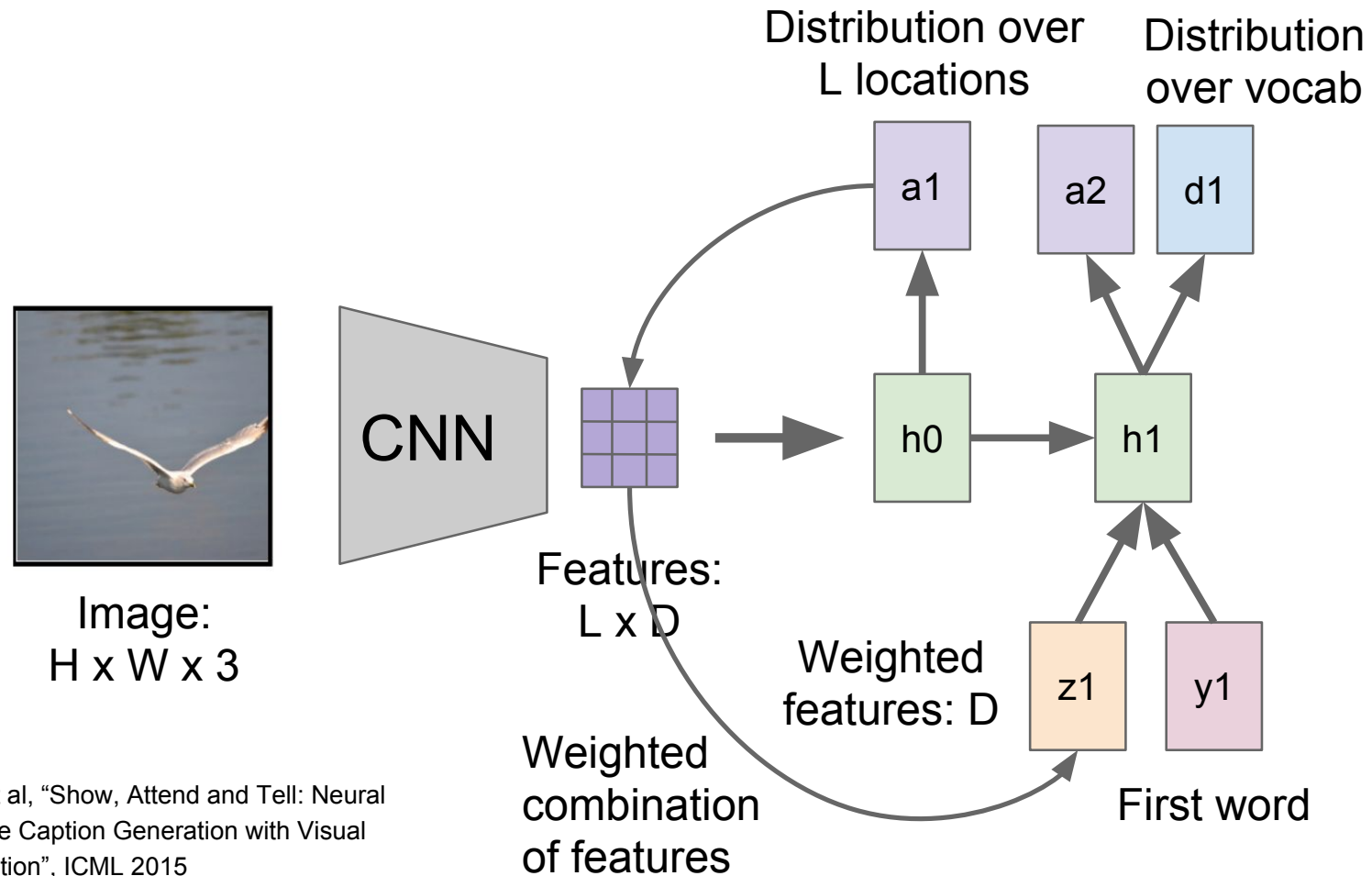
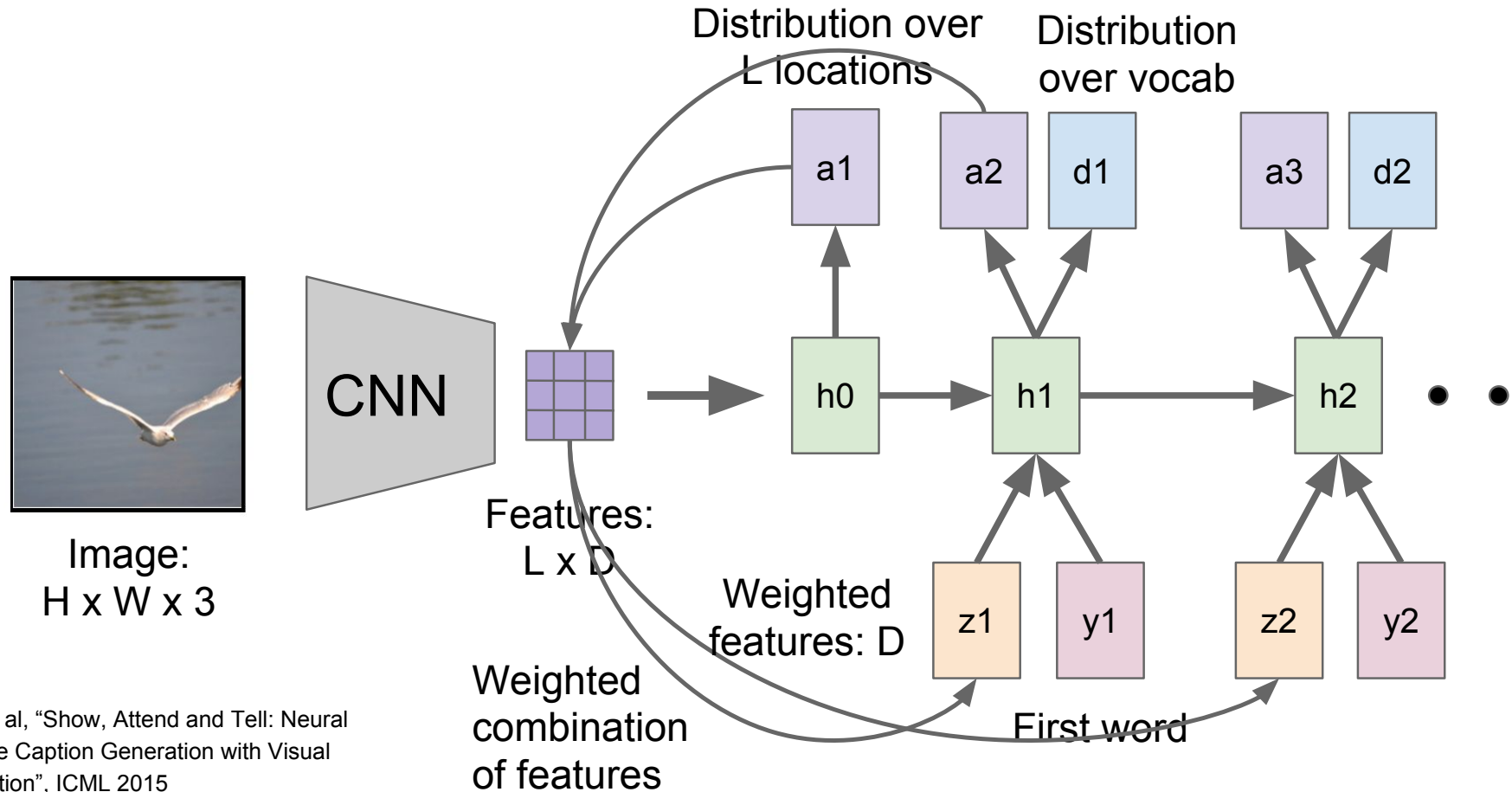


Image Captioning with Attention



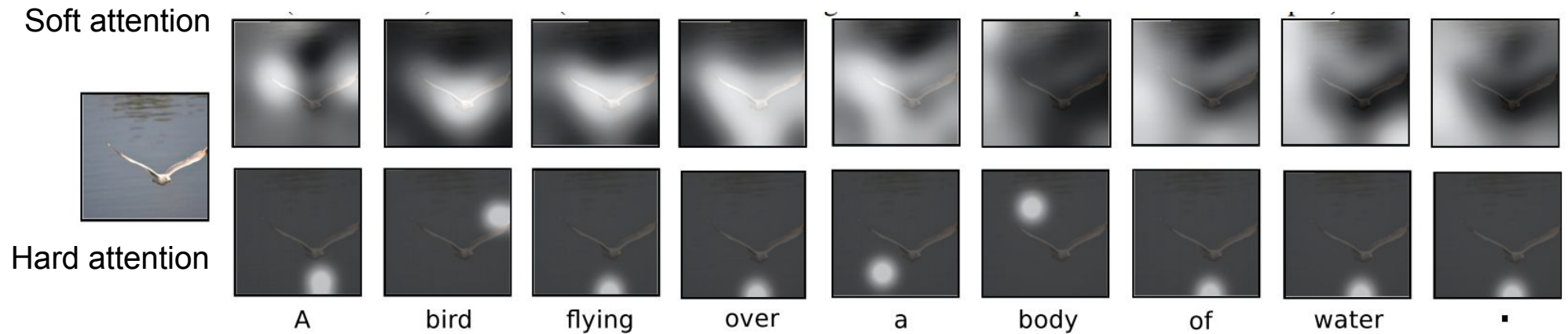
Xu et al, "Show, Attend and Tell: Neural Image Caption Generation with Visual Attention", ICML 2015

Image Captioning with Attention



Xu et al, "Show, Attend and Tell: Neural Image Caption Generation with Visual Attention", ICML 2015

Image Captioning with Attention



Xu et al, "Show, Attend, and Tell: Neural Image Caption Generation with Visual Attention", ICML 2015

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Image Captioning with Attention



A woman is throwing a frisbee in a park.



A dog is standing on a hardwood floor.



A stop sign is on a road with a mountain in the background.



A little girl sitting on a bed with a teddy bear.



A group of people sitting on a boat in the water.



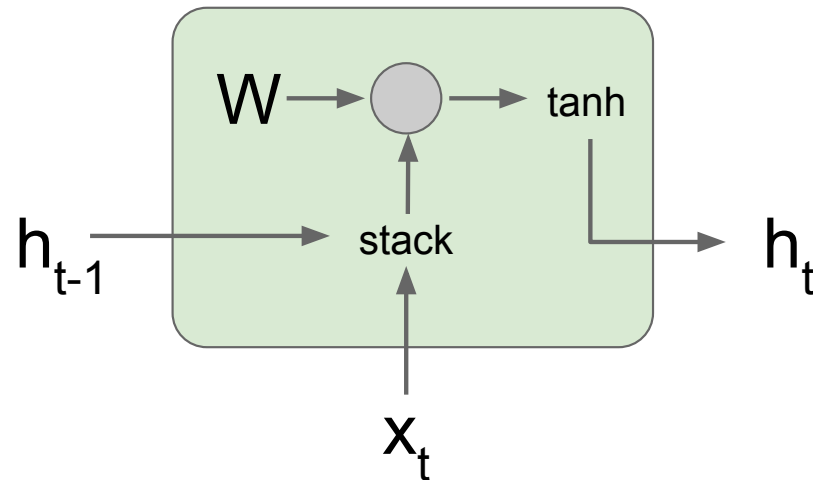
A giraffe standing in a forest with trees in the background.

Xu et al, "Show, Attend, and Tell: Neural Image Caption Generation with Visual Attention", ICML 2015

Figure copyright Kelvin Xu, Jimmy Lei Ba, Jamie Kiros, Kyunghyun Cho, Aaron Courville, Ruslan Salakhutdinov, Richard S. Zemel, and Yoshua Benchio, 2015. Reproduced with permission.

Vanilla RNN Gradient Flow

Bengio et al, "Learning long-term dependencies with gradient descent is difficult", IEEE Transactions on Neural Networks, 1994
Pascanu et al, "On the difficulty of training recurrent neural networks", ICML 2013

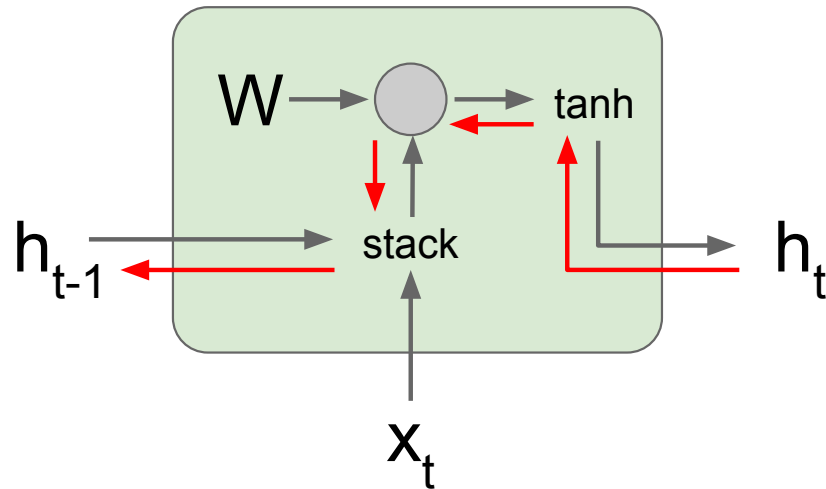


$$\begin{aligned} h_t &= \tanh(W_{hh}h_{t-1} + W_{hx}x_t) \\ &= \tanh\left(\begin{pmatrix} W_{hh} & W_{hx} \end{pmatrix} \begin{pmatrix} h_{t-1} \\ x_t \end{pmatrix}\right) \\ &= \tanh\left(W \begin{pmatrix} h_{t-1} \\ x_t \end{pmatrix}\right) \end{aligned}$$

Vanilla RNN Gradient Flow

Bengio et al, "Learning long-term dependencies with gradient descent is difficult", IEEE Transactions on Neural Networks, 1994
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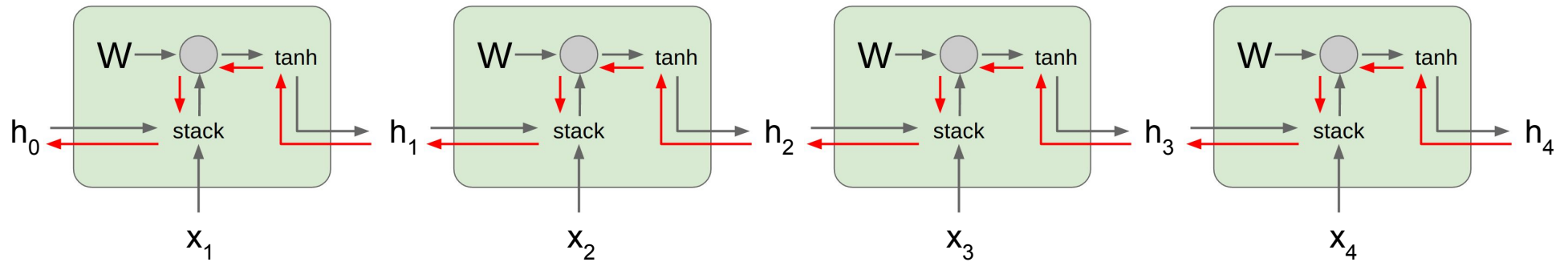
Backpropagation from h_t
to h_{t-1} multiplies by W
(actually W_{hh}^T)



$$\begin{aligned} h_t &= \tanh(W_{hh}h_{t-1} + W_{hx}x_t) \\ &= \tanh\left(\begin{pmatrix} W_{hh} & W_{hx} \end{pmatrix} \begin{pmatrix} h_{t-1} \\ x_t \end{pmatrix}\right) \\ &= \tanh\left(W \begin{pmatrix} h_{t-1} \\ x_t \end{pmatrix}\right) \end{aligned}$$

Vanilla RNN Gradient Flow

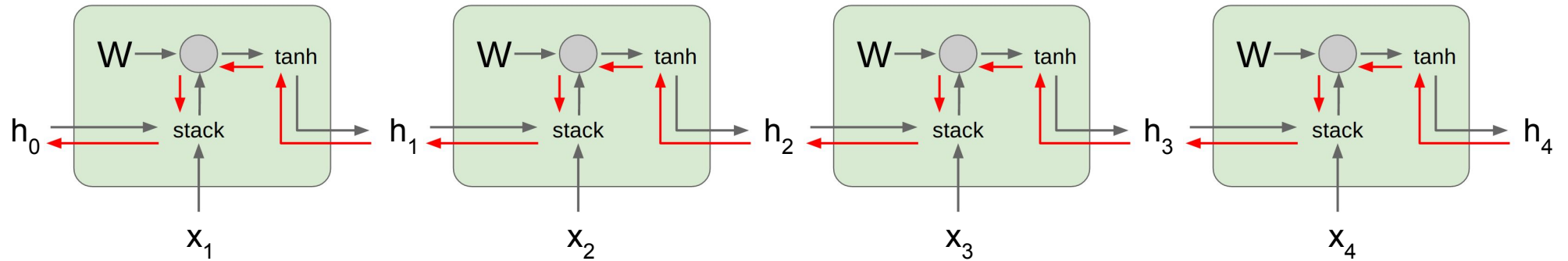
Bengio et al, "Learning long-term dependencies with gradient descent is difficult", IEEE Transactions on Neural Networks, 1994
Pascanu et al, "On the difficulty of training recurrent neural networks", ICML 2013



Computing gradient of h_0 involves many factors of W (and repeated \tanh)

Vanilla RNN Gradient Flow

Bengio et al, "Learning long-term dependencies with gradient descent is difficult", IEEE Transactions on Neural Networks, 1994
Pascanu et al, "On the difficulty of training recurrent neural networks", ICML 2013



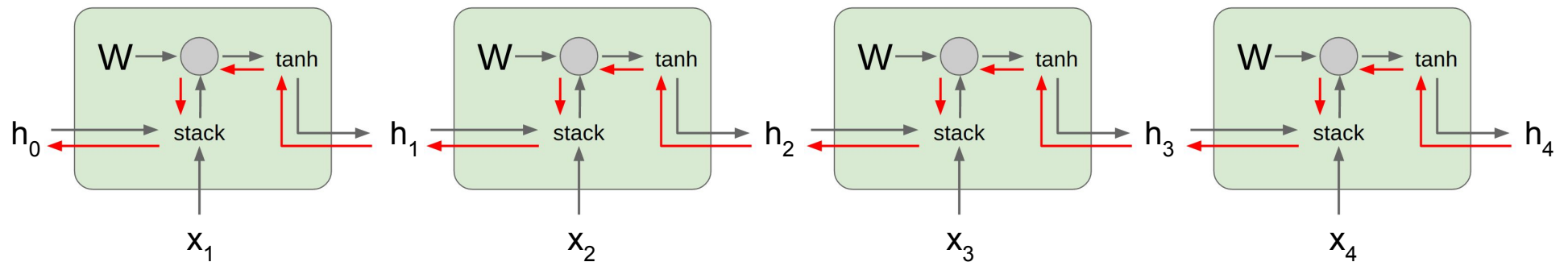
Computing gradient of h_0 involves many factors of W (and repeated tanh)

Largest singular value > 1 :
Exploding gradients

Largest singular value < 1 :
Vanishing gradients

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Computing gradient of h_0 involves many factors of W (and repeated tanh)

Largest singular value > 1 :
Exploding gradients

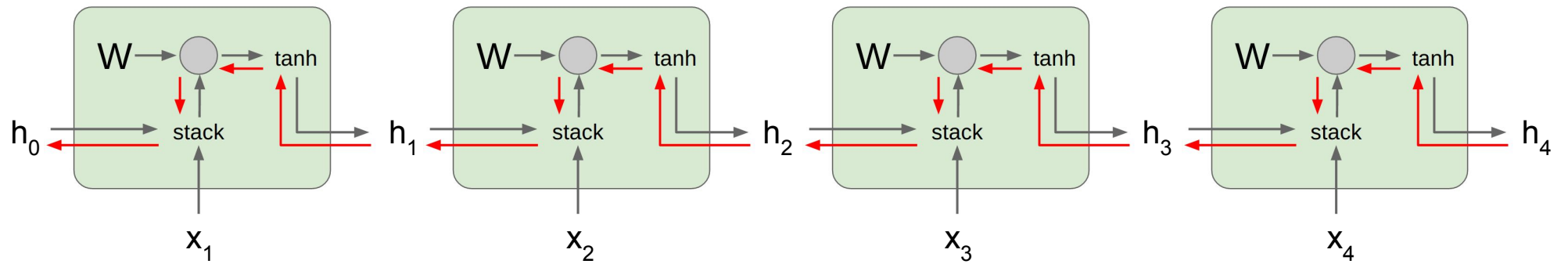
Largest singular value < 1 :
Vanishing gradients

Gradient clipping: Scale gradient if its norm is too big

```
grad_norm = np.sum(grad * grad)
if grad_norm > threshold:
    grad *= (threshold / grad_norm)
```


Vanilla RNN Gradient Flow

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Computing gradient of h_0 involves many factors of W (and repeated tanh)

Largest singular value > 1 :
Exploding gradients

Largest singular value < 1 :
Vanishing gradients

→ Change RNN architecture



Long Short Term Memory (LSTM)

Long-Short-Term-Memory (LSTM)

- ▶ A type of RNN proposed by Hochreiter and Schmidhuber in 1997 as a solution to the vanishing gradients problem.
 - ▶ “Long short-term memory”, Hochreiter and Schmidhuber, 1997. <https://www.bioinf.jku.at/publications/older/2604.pdf>
- ▶ On time step t , there is a hidden state h and a cell state c
 - ▶ Both are vectors length n
 - ▶ The **cell stores long-term information**
 - ▶ The LSTM can erase, write and read information from the cell
- ▶ The selection of which information is erased/written/read is controlled by three corresponding **gates**
 - ▶ The gates are also vectors length n
 - ▶ On each time step, each element of the gates can be open (1), closed (0),
 - ▶ or somewhere in-between.
 - ▶ The gates are **dynamic**: their value is computed based on the current context

Long-Short-Term-Memory (LSTM)

We have a sequence of inputs $\mathbf{x}^{(t)}$, and we will compute a sequence of hidden states $\mathbf{h}^{(t)}$ and cell states $\mathbf{c}^{(t)}$. On timestep t :

Forget gate: controls what is kept vs forgotten, from previous cell state

Input gate: controls what parts of the new cell content are written to cell

Output gate: controls what parts of cell are output to hidden state

New cell content: this is the new content to be written to the cell

Cell state: erase (“forget”) some content from last cell state, and write (“input”) some new cell content

Hidden state: read (“output”) some content from the cell

Sigmoid function: all gate values are between 0 and 1

$$\mathbf{f}^{(t)} = \sigma \left(\mathbf{W}_f \mathbf{h}^{(t-1)} + \mathbf{U}_f \mathbf{x}^{(t)} + \mathbf{b}_f \right)$$

$$\mathbf{i}^{(t)} = \sigma \left(\mathbf{W}_i \mathbf{h}^{(t-1)} + \mathbf{U}_i \mathbf{x}^{(t)} + \mathbf{b}_i \right)$$

$$\mathbf{o}^{(t)} = \sigma \left(\mathbf{W}_o \mathbf{h}^{(t-1)} + \mathbf{U}_o \mathbf{x}^{(t)} + \mathbf{b}_o \right)$$

$$\tilde{\mathbf{c}}^{(t)} = \tanh \left(\mathbf{W}_c \mathbf{h}^{(t-1)} + \mathbf{U}_c \mathbf{x}^{(t)} + \mathbf{b}_c \right)$$

$$\mathbf{c}^{(t)} = \mathbf{f}^{(t)} \circ \mathbf{c}^{(t-1)} + \mathbf{i}^{(t)} \circ \tilde{\mathbf{c}}^{(t)}$$

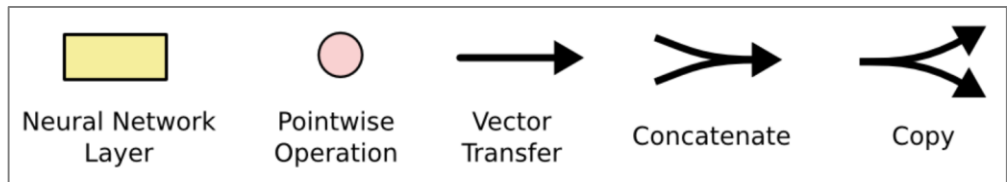
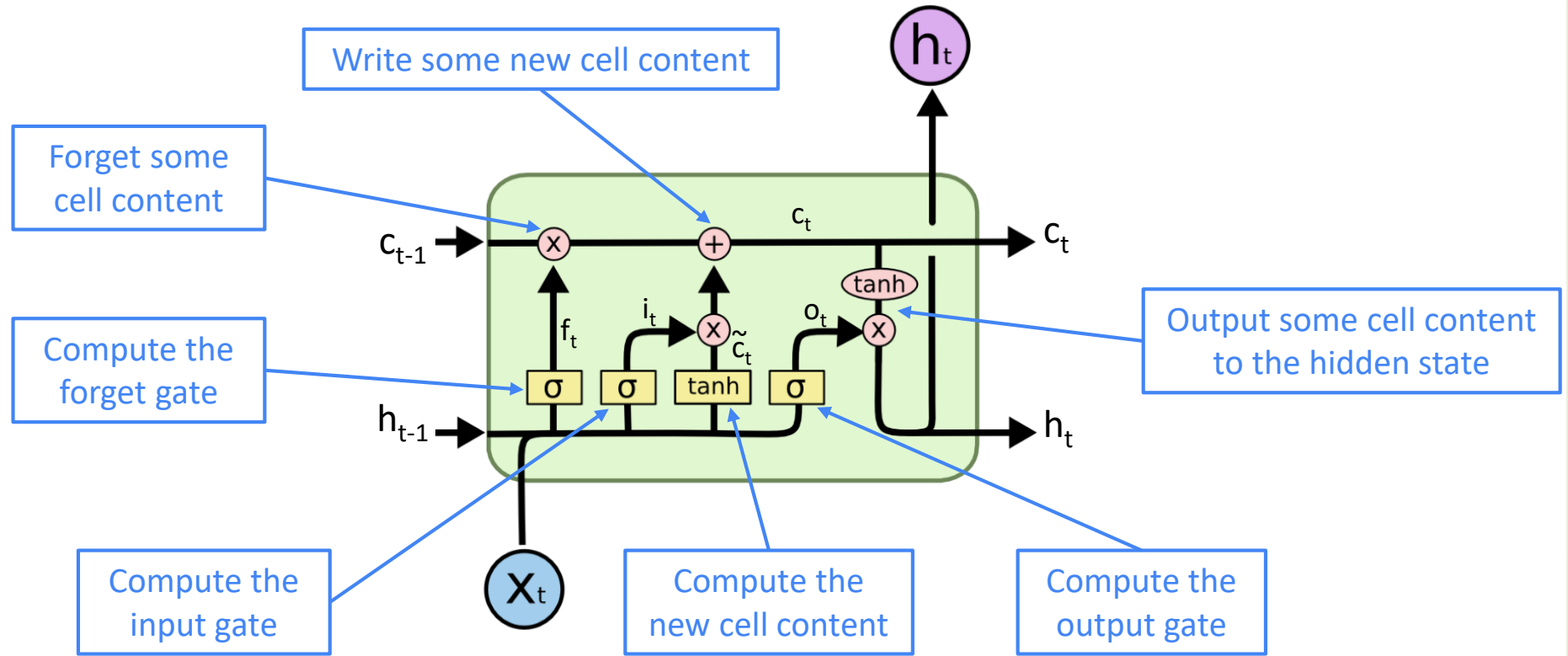
$$\mathbf{h}^{(t)} = \mathbf{o}^{(t)} \circ \tanh \mathbf{c}^{(t)}$$

All these are vectors of same length n

Gates are applied using element-wise product

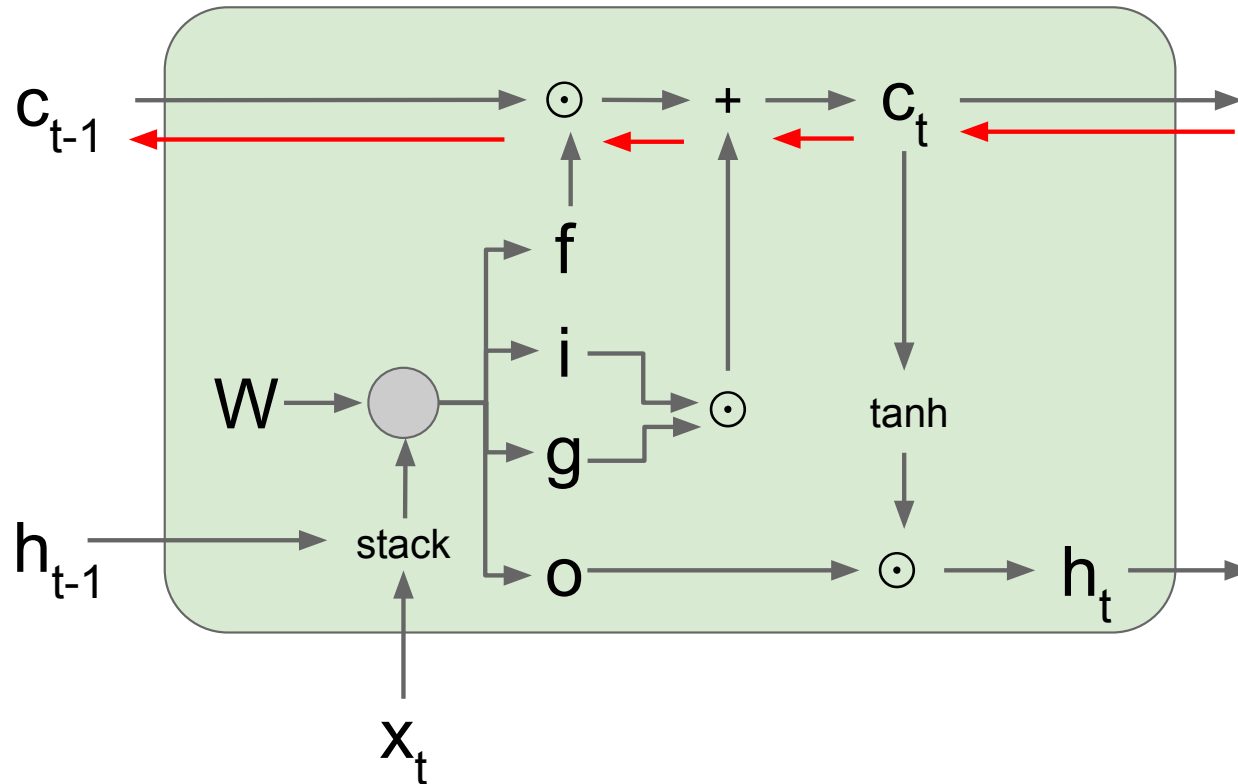
LSTM Flowchart

► **Source:** <http://colah.github.io/posts/2015-08-Understanding-LSTMs/>



Long Short Term Memory (LSTM): Gradient Flow

[Hochreiter et al., 1997]



Backpropagation from c_t to c_{t-1} only elementwise multiplication by f , no matrix multiply by W

$$\begin{pmatrix} i \\ f \\ o \\ g \end{pmatrix} = \begin{pmatrix} \sigma \\ \sigma \\ \sigma \\ \tanh \end{pmatrix} W \begin{pmatrix} h_{t-1} \\ x_t \end{pmatrix}$$

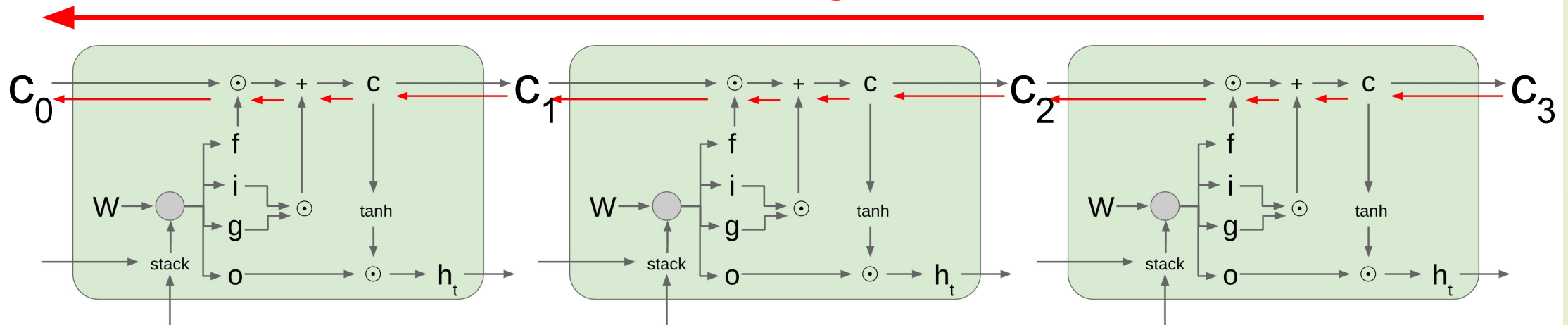
$$c_t = f \odot c_{t-1} + i \odot g$$

$$h_t = o \odot \tanh(c_t)$$

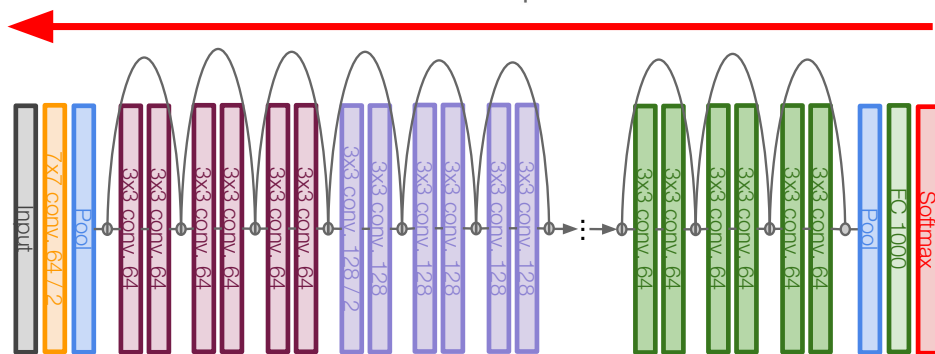
Long Short Term Memory (LSTM): Gradient Flow

[Hochreiter et al., 1997]

Uninterrupted gradient flow!



Similar to ResNet!



In between:
Highway Networks

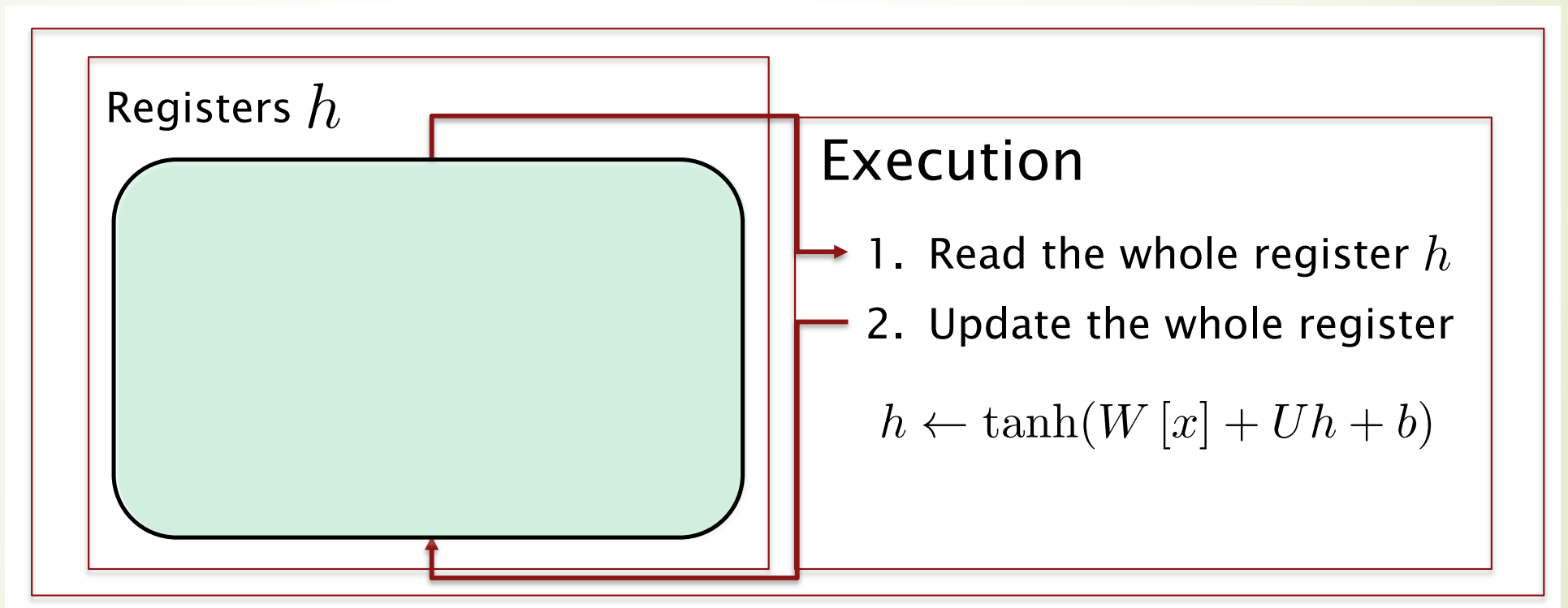
$$g = T(x, W_T)$$

$$y = g \odot H(x, W_H) + (1 - g) \odot x$$

Srivastava et al, "Highway Networks",
ICML DL Workshop 2015

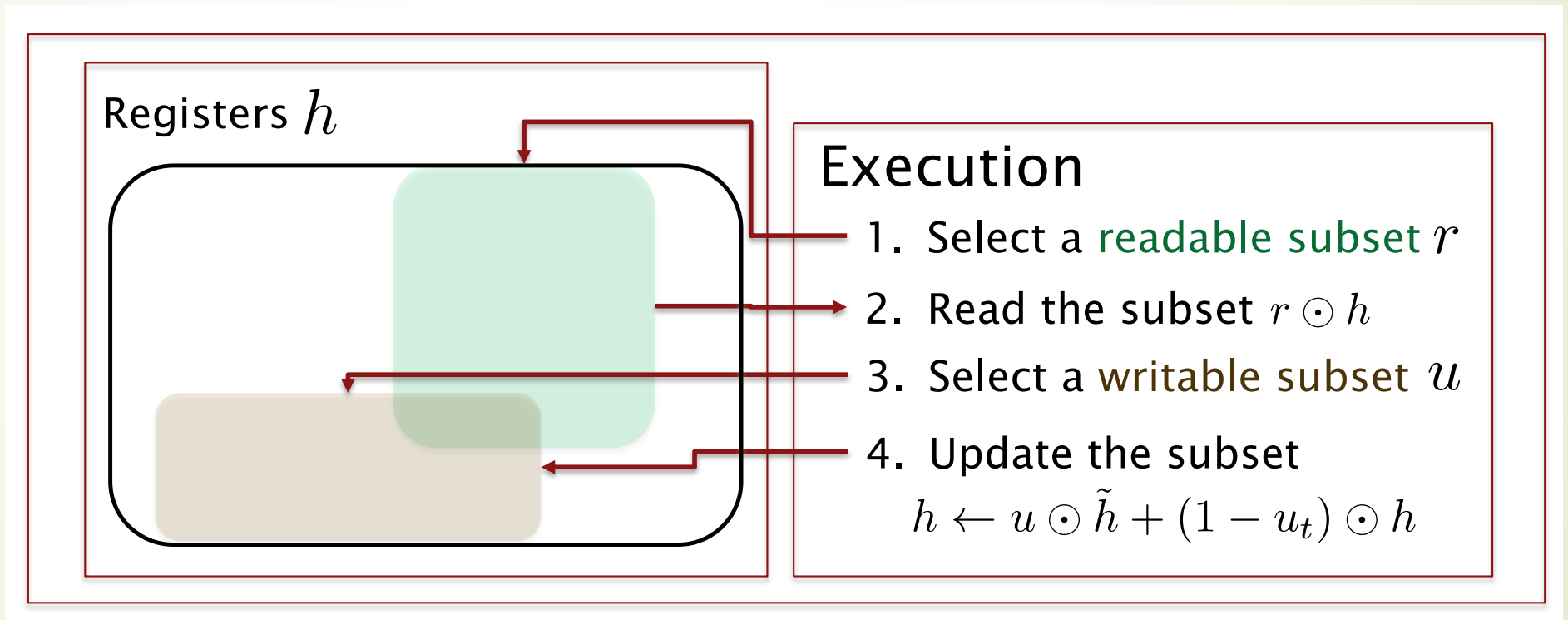
Gated Recurrent Unit: tanh RNN

- ▶ (tanh) RNN is expensive in exploiting the whole register



Gated Recurrent Unit (GRU)

- GRU is much more economic for computation!



GRU

- ▶ "Learning Phrase Representations using RNN Encoder–Decoder for Statistical Machine Translation", Cho et al. 2014, <https://arxiv.org/pdf/1406.1078v3.pdf>

Update gate: controls what parts of hidden state are updated vs preserved

$$\mathbf{u}^{(t)} = \sigma \left(\mathbf{W}_u \mathbf{h}^{(t-1)} + \mathbf{U}_u \mathbf{x}^{(t)} + \mathbf{b}_u \right)$$

Reset gate: controls what parts of previous hidden state are used to compute new content

$$\mathbf{r}^{(t)} = \sigma \left(\mathbf{W}_r \mathbf{h}^{(t-1)} + \mathbf{U}_r \mathbf{x}^{(t)} + \mathbf{b}_r \right)$$

New hidden state content: reset gate selects useful parts of prev hidden state. Use this and current input to compute new hidden content.

$$\tilde{\mathbf{h}}^{(t)} = \tanh \left(\mathbf{W}_h (\mathbf{r}^{(t)} \circ \mathbf{h}^{(t-1)}) + \mathbf{U}_h \mathbf{x}^{(t)} + \mathbf{b}_h \right)$$

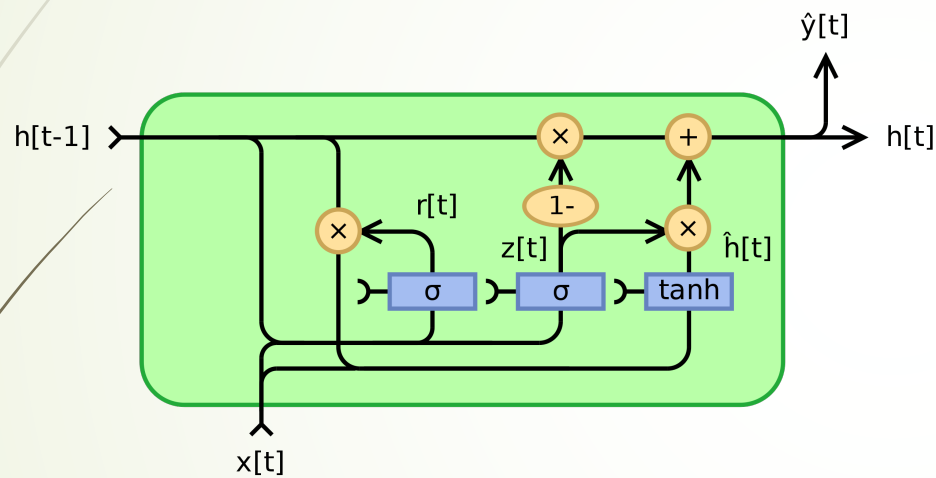
$$\mathbf{h}^{(t)} = (1 - \mathbf{u}^{(t)}) \circ \mathbf{h}^{(t-1)} + \mathbf{u}^{(t)} \circ \tilde{\mathbf{h}}^{(t)}$$

Hidden state: update gate simultaneously controls what is kept from previous hidden state, and what is updated to new hidden state content

How does this solve vanishing gradient?

Like LSTM, GRU makes it easier to retain info long-term (e.g. by setting update gate to 0)

Gated Recurrent Unit (GRU)



GRU [*Learning phrase representations using rnn encoder-decoder for statistical machine translation*, Cho et al. 2014]

$$r_t = \sigma(W_{xr}x_t + W_{hr}h_{t-1} + b_r)$$

$$z_t = \sigma(W_{xz}x_t + W_{hz}h_{t-1} + b_z)$$

$$\tilde{h}_t = \tanh(W_{xh}x_t + W_{hh}(r_t \odot h_{t-1}) + b_h)$$

$$h_t = z_t \odot h_{t-1} + (1 - z_t) \odot \tilde{h}_t$$

GRU and LSTM

Gated Recurrent Unit

[Cho et al., EMNLP2014;
Chung, Gulcehre, Cho, Bengio,
DLUFL2014]

$$h_t = u_t \odot \tilde{h}_t + (1 - u_t) \odot h_{t-1}$$

$$\tilde{h}_t = \tanh(W [x_t] + U(r_t \odot h_{t-1}) + b)$$

$$u_t = \sigma(W_u [x_t] + U_u h_{t-1} + b_u)$$

$$r_t = \sigma(W_r [x_t] + U_r h_{t-1} + b_r)$$

Long Short-Term Memory

[Hochreiter & Schmidhuber, NC1999;
Gers, Thesis2001]

$$h_t = o_t \odot \tanh(c_t)$$

$$c_t = f_t \odot c_{t-1} + i_t \odot \tilde{c}_t$$

$$\tilde{c}_t = \tanh(W_c [x_t] + U_c h_{t-1} + b_c)$$

$$o_t = \sigma(W_o [x_t] + U_o h_{t-1} + b_o)$$

$$i_t = \sigma(W_i [x_t] + U_i h_{t-1} + b_i)$$

$$f_t = \sigma(W_f [x_t] + U_f h_{t-1} + b_f)$$



LSTM vs. GRU

- ▶ Researchers have proposed many gated RNN variants, but LSTM and GRU are the most widely-used
- ▶ The biggest difference is that GRU is quicker to **compute** and has fewer parameters
- ▶ There is no conclusive evidence that one consistently performs better than the other
- ▶ LSTM is a good default choice (especially if your data has particularly long dependencies, or you have lots of training data)
- ▶ **Rule of thumb:** start with LSTM, but switch to GRU if you want something more efficient



Is vanishing/exploding gradient just a RNN problem?

- ▶ No! It can be a problem for all neural architectures (including **feed-forward** and **convolutional**), especially **deep** ones.
 - ▶ Due to chain rule / choice of nonlinearity function, gradient can become vanishingly small as it backpropagates
 - ▶ Thus lower layers are learnt very slowly (hard to train)
 - ▶ Solution: lots of new deep feedforward/convolutional architectures that add more **direct connections** (thus allowing the gradient to flow)
- ▶ For example:
 - ▶ “**HighwayNet**” with highway connections:
 - ▶ Similar to residual connections, but the identity connection vs the transformation layer is controlled by a dynamic gate
 - ▶ Inspired by LSTMs, but applied to deep feedforward/convolutional networks
 - ▶ **ResNet** with residual connections, inspired by **HighwayNet**
 - ▶ **DenseNet** directly connect everything to everything!



Summary

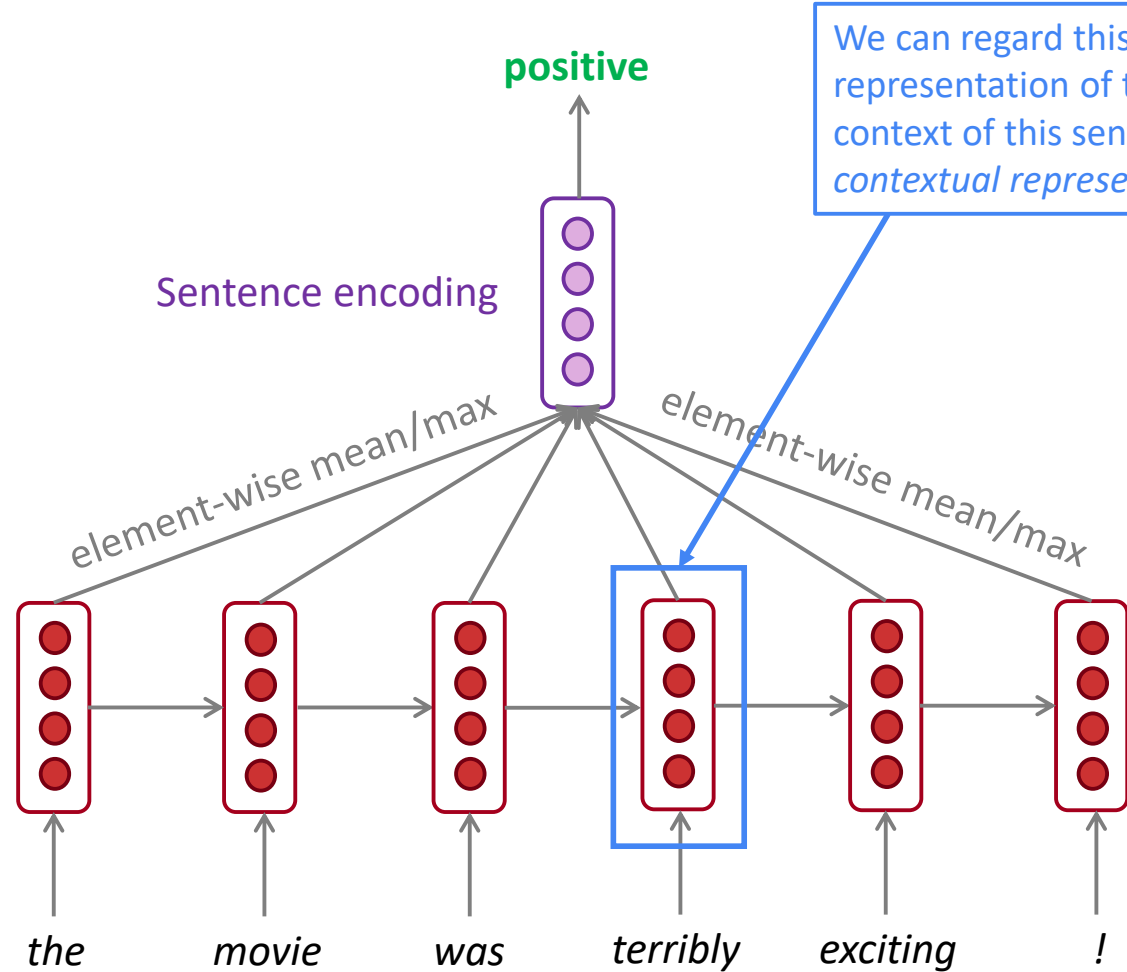
- RNN is flexible in architectures
- Vanilla RNNs are simple but don't work very well
- Common to use LSTM or GRU: their additive interactions improve gradient flow
 - Backward flow of gradients in RNN can explode or vanish.
 - Exploding is controlled with gradient clipping.
 - Vanishing is controlled with additive interactions

A decorative graphic on the left side of the slide. It features a solid red arrow pointing to the right, positioned horizontally. Behind the arrow and extending upwards and to the right are several thin, dark grey, curved lines that resemble stylized grass or reeds. The background is a light, pale green color.

Bi-Direction

Motivation of Bidirection

Task: Sentiment Classification



We can regard this hidden state as a representation of the word "terribly" in the context of this sentence. We call this a *contextual representation*.

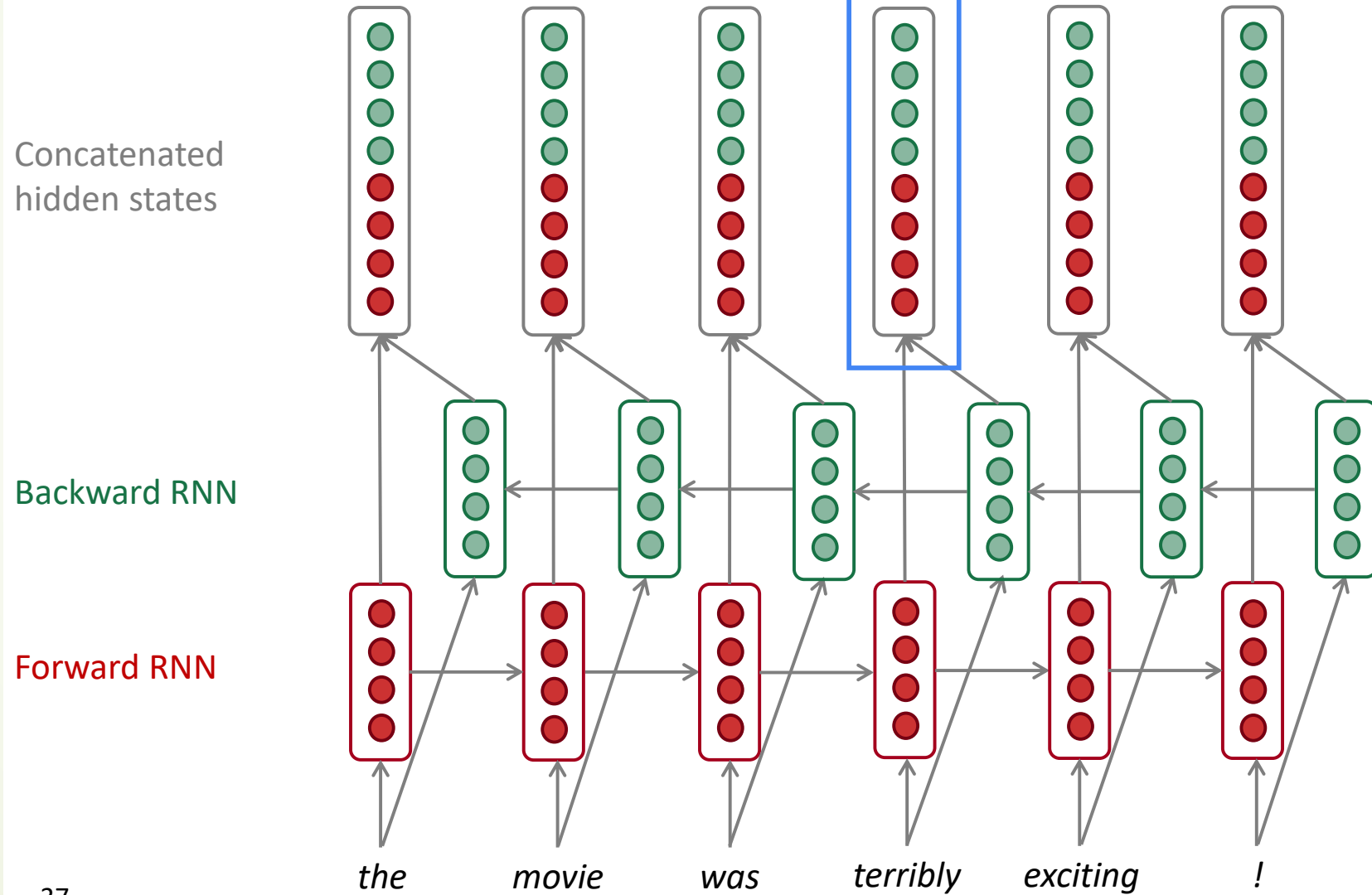
These contextual representations only contain information about the *left* context (e.g. "the movie was").

What about *right* context?

In this example, "exciting" is in the right context and this modifies the meaning of "terribly" (from negative to positive)

Bidirectional RNNs

This contextual representation of "terribly" has both left and right context!



Bidirectional RNN: simplified diagram

On timestep t :

This is a general notation to mean “compute one forward step of the RNN” – it could be a vanilla, LSTM or GRU computation.

Forward RNN $\vec{h}^{(t)} = \text{RNN}_{\text{FW}}(\vec{h}^{(t-1)}, \mathbf{x}^{(t)})$

Backward RNN $\overleftarrow{h}^{(t)} = \text{RNN}_{\text{BW}}(\overleftarrow{h}^{(t+1)}, \mathbf{x}^{(t)})$

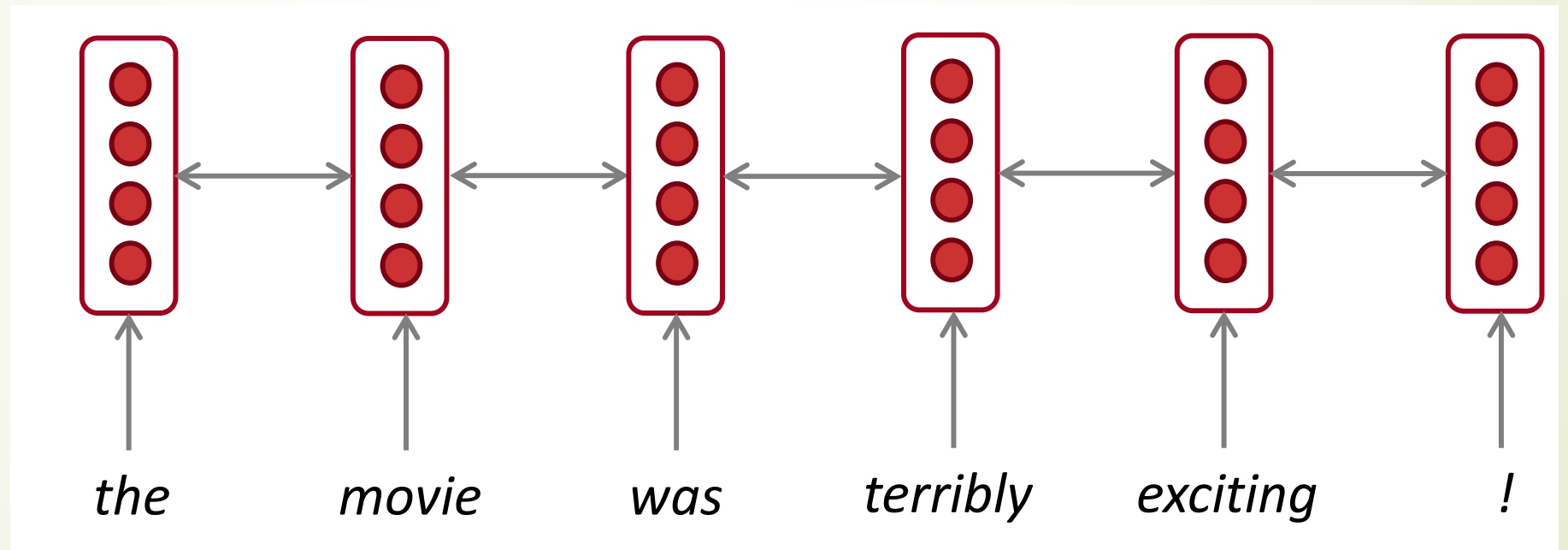
Generally, these two RNNs have separate weights

Concatenated hidden states $\mathbf{h}^{(t)} = [\vec{h}^{(t)}; \overleftarrow{h}^{(t)}]$

We regard this as “the hidden state” of a bidirectional RNN. This is what we pass on to the next parts of the network.

Bidirectional RNN: simplified diagram

- ▶ The two-way arrows indicate bidirectionality and the depicted hidden states are assumed to be the concatenated forwards+backwards states.





Bidirectional RNNs

- ▶ Note: bidirectional RNNs are only applicable if you have access to the **entire input sequence**.
 - ▶ They are **not** applicable to Language Modeling, because in LM you *only* have left context available.
- ▶ If you do have entire input sequence (e.g. any kind of encoding), bidirectionality is powerful (you should use it by default).
- ▶ For example, **BERT** (**Bidirectional** Encoder Representations from Transformers) is a powerful pretrained contextual representation system built on bidirectionality.

History note

- ▶ In 2013-2015, LSTMs started achieving state-of-the-art results
 - ▶ Successful tasks include: handwriting recognition, speech recognition, machine translation, parsing, image captioning
 - ▶ LSTM became the dominant approach
- ▶ Now (2019), other approaches (e.g. Transformers) have become more dominant for certain tasks.
 - ▶ For example in **WMT** (a MT conference + competition):
 - ▶ In WMT 2016, the summary report contains "RNN" 44 times
 - ▶ In WMT 2018, the report contains "RNN" 9 times and "Transformer" 63 times
 - ▶ **Source:** "Findings of the 2016 Conference on Machine Translation (WMT16)", Bojar et al. 2016, <http://www.statmt.org/wmt16/pdf/W16-2301.pdf>
 - ▶ **Source:** "Findings of the 2018 Conference on Machine Translation (WMT18)", Bojar et al. 2018, <http://www.statmt.org/wmt18/pdf/WMT028.pdf>

Thank you!

