

Seq2Seq ICML Tutorial

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Site: <https://sites.google.com/view/seq2seq-icml17>

Sydney, Australia, 2017

Outline

- An Overview of seq2seq (~25 minutes)
 - Applications
- Attention (~20 minutes)
 - Applications
- Break (15 mins)
- Loss functions (~15 minutes)
- Advanced Topics
 - Autoregressive Models (~5 mins)
 - Online Seq2Seq (~10 mins)
- New Architectures (~10 mins)
- Questions, discussion, etc. (15 minutes)

Seq2Seq Overview

What we WON'T cover

- Machine Learning Basics
- Deep Learning Basics
- (too many) Historical Remarks

Related Tutorials:

<https://sites.google.com/site/acl16nmt/>



Oriol Vinyals ✅
@OriolVinyalsML

Navdeep and I are giving a tutorial at #ICML (August) on seq2seq. What do you prefer to see (most) in a tutorial?

2017.icml.cc/Conferences/2017 ...

34% Code Examples & Apps

6% Historical Remarks

16% Basics & Intro to seq2seq

44% Advanced & Future Topics

402 votes • Final results

Sequences!

- Words, Letters

50 years ago, the fathers of artificial intelligence convinced everybody that logic was the key to intelligence. Somehow we had to get computers to do logical reasoning. The alternative approach, which they thought was crazy, was to forget logic and try and understand how networks of brain cells learn things. Curiously, two people who rejected the logic based approach to AI were Turing and Von Neumann. If either of them had lived I think things would have turned out differently... now neural networks are everywhere and the crazy approach is winning.

Geoff Hinton

- Speech



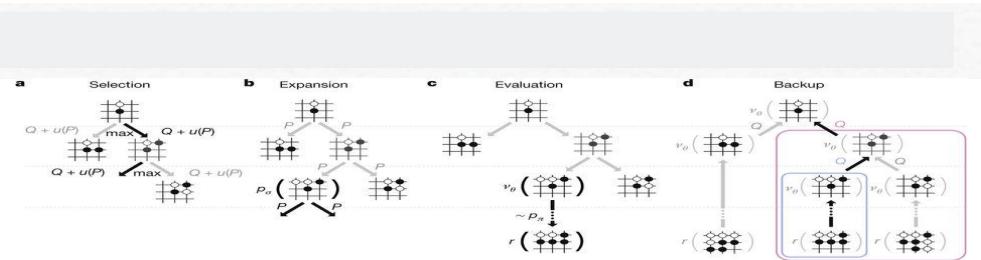
- Images, Videos



- Programs

```
while (*d++ = *s++);
```

- Sequential Decision Making (RL)



Classical Models for Sequence Prediction

- Sequence prediction was classically handled as a structured prediction tasks
 - Most were built on conditional independence assumptions
 - Other such as DAGGER were based on supervisory signals and auxiliary information

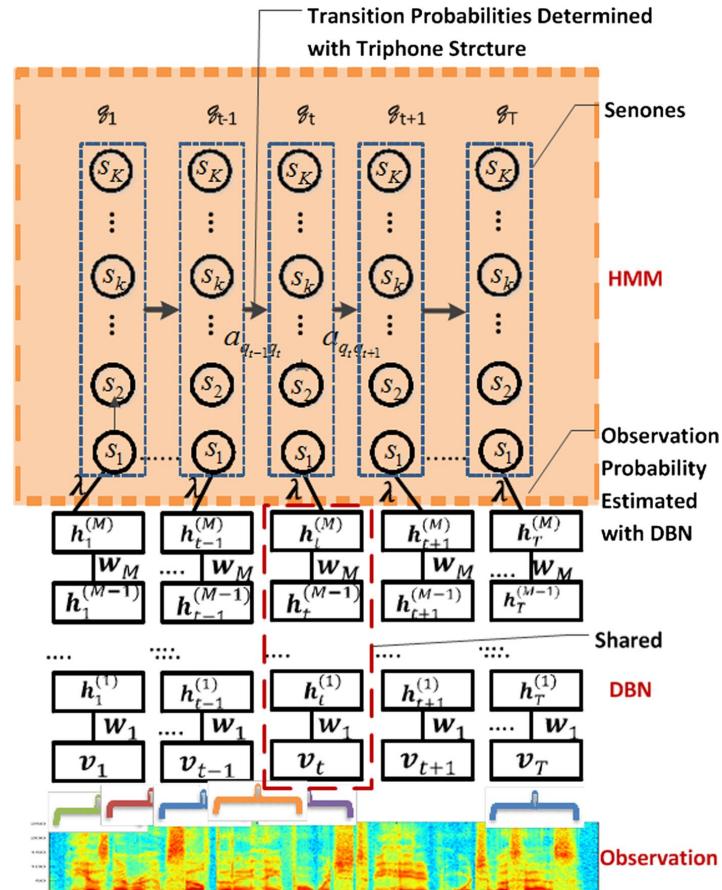


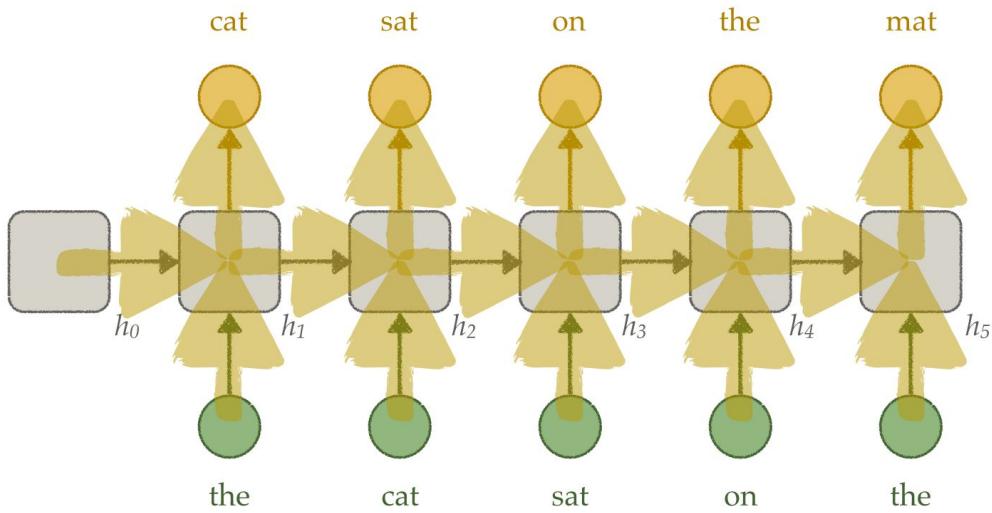
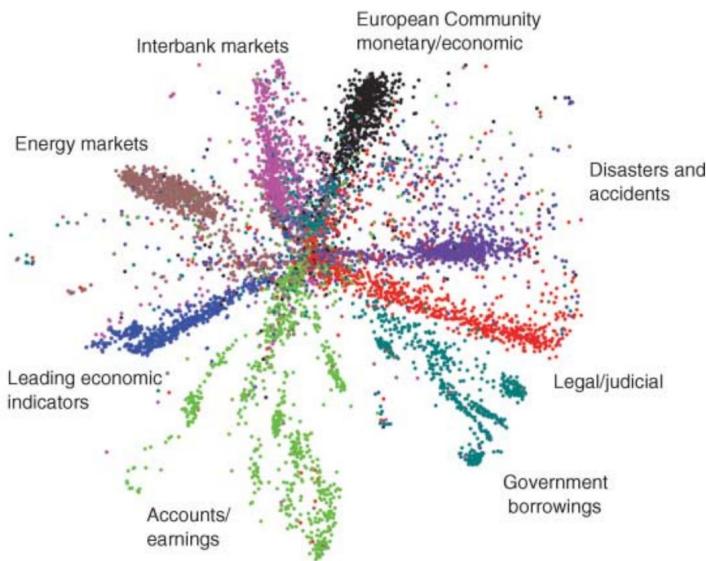
Figure credit: Li Deng

Two Key Ingredients

Neural Embeddings



Recurrent Language Models

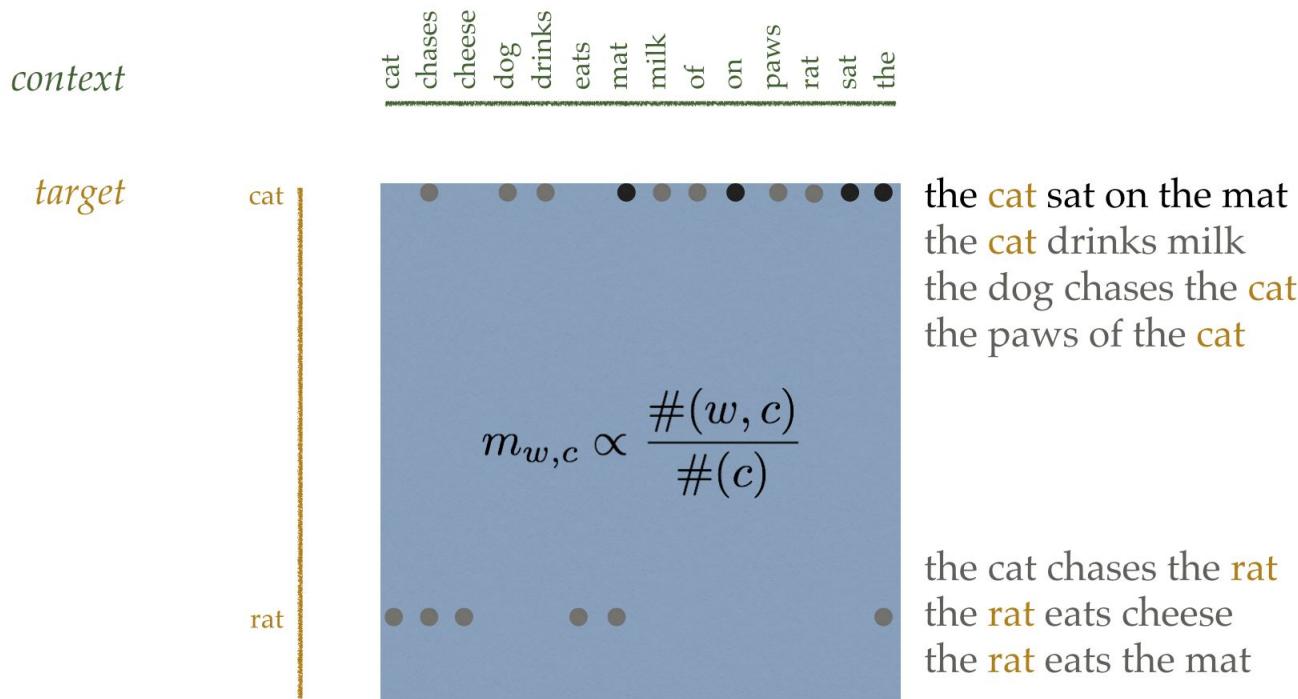


1. Hinton, G., Salakhutdinov, R. "Reducing the Dimensionality of Data with Neural Networks." *Science* (2006)
2. Mikolov, T., et al. "Recurrent neural network based language model." *Interspeech* (2010)

Language Models

<i>context</i>						<i>target</i>	$P(w_t w_{t-1}, w_{t-2}, \dots w_{t-5})$
the	cat	sat	on	the	mat		0.15
w_{t-5}	w_{t-4}	w_{t-3}	w_{t-2}	w_{t-1}	w_t		
the	cat	sat	on	the	rug		0.12
the	cat	sat	on	the	hat		0.09
the	cat	sat	on	the	dog		0.01
the	cat	sat	on	the	the		0
the	cat	sat	on	the	sat		0
the	cat	sat	on	the	robot		?
the	cat	sat	on	the	printer		?

n-grams



n-grams

$$P(w_1, w_2, \dots, w_{T-1}, w_T) \approx \prod_{t=1}^T P(w_t | w_{t-1}, \dots, w_{t-n+1})$$

the	cat	sat	on	the	mat	$P(w_1)$
the	cat	sat	on	the	mat	$P(w_2 w_1)$
the	cat	sat	on	the	mat	$P(w_3 w_2, w_1)$
the	cat	sat	on	the	mat	$P(w_4 w_3, w_2)$
the	cat	sat	on	the	mat	$P(w_5 w_4, w_3)$
the	cat	sat	on	the	mat	$P(w_6 w_5, w_4)$

The Chain Rule

$$P(w_1, w_2, \dots, w_{T-1}, w_T) = \prod_{t=1}^T P(w_t | w_{t-1}, w_{t-2}, \dots, w_1)$$

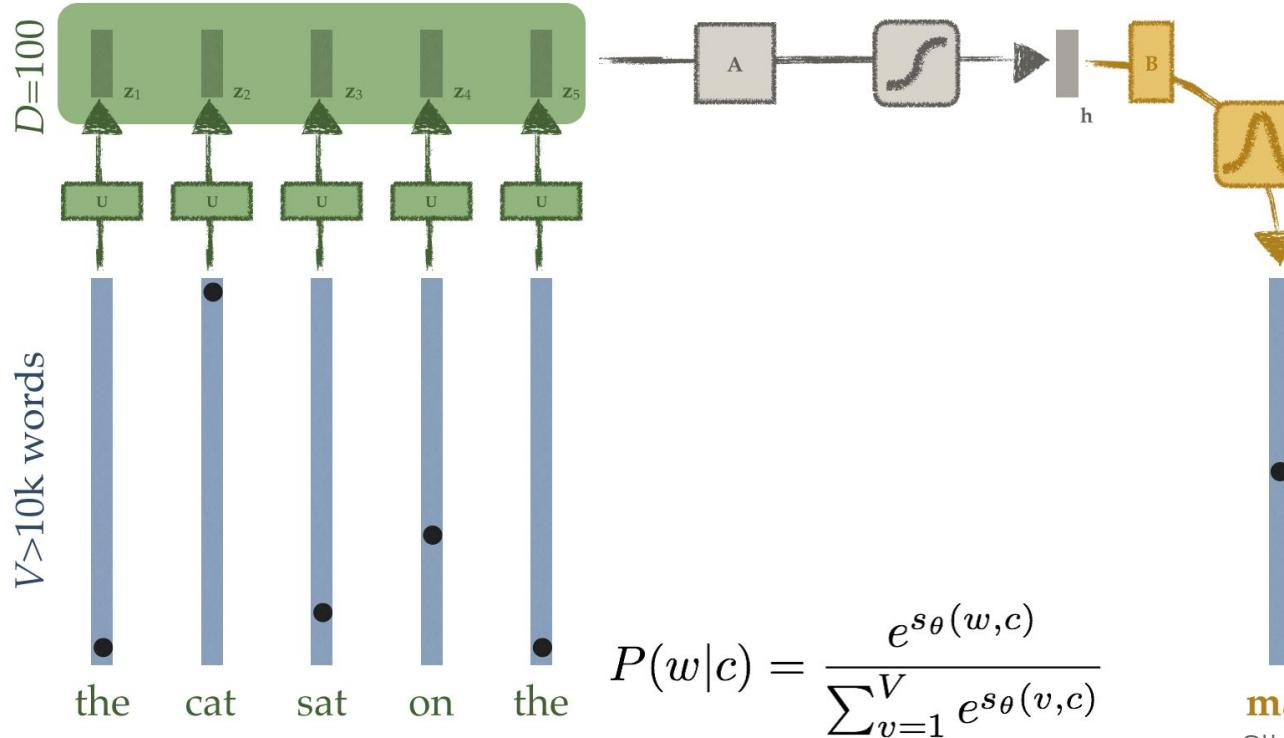
the	cat	sat	on	the	mat	$P(w_1)$
the	cat	sat	on	the	mat	$P(w_2 w_1)$
the	cat	sat	on	the	mat	$P(w_3 w_2, w_1)$
the	cat	sat	on	the	mat	$P(w_4 w_3, w_2, w_1)$
the	cat	sat	on	the	mat	$P(w_5 w_4, w_3, w_2, w_1)$
the	cat	sat	on	the	mat	$P(w_6 w_5, w_4, w_3, w_2, w_1)$

A Key Insight: vectorizing context

Bengio, Y. et al., "A Neural Probabilistic Language Model", *JMLR* (2001, 2003)

Mnih, A., Hinton, G., "Three new graphical models for statistical language modeling", *ICML 2007*

$$p(w_t | w_1, \dots, w_{t-1}) = p_\theta(w_t | f_\theta(w_1, \dots, w_{t-1}))$$

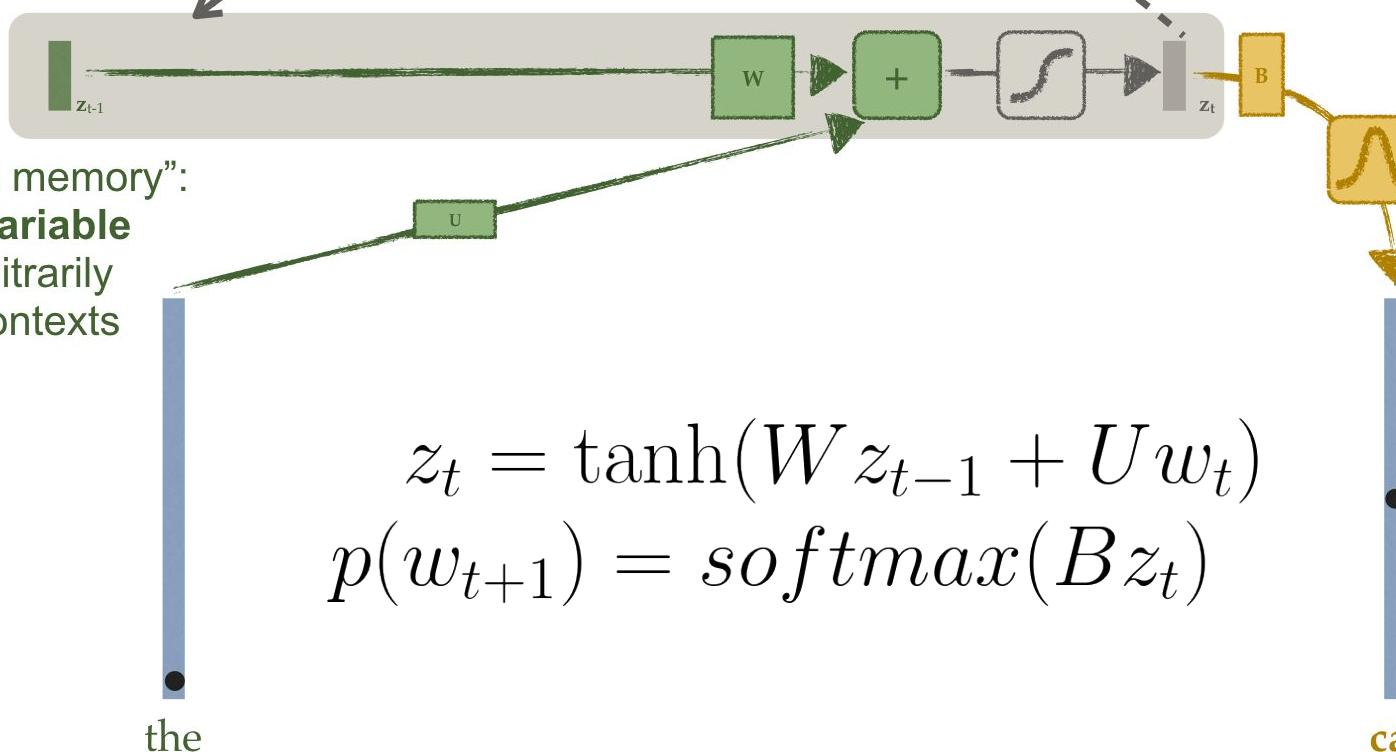


mat

Slide Credit: Piotr Mirowski

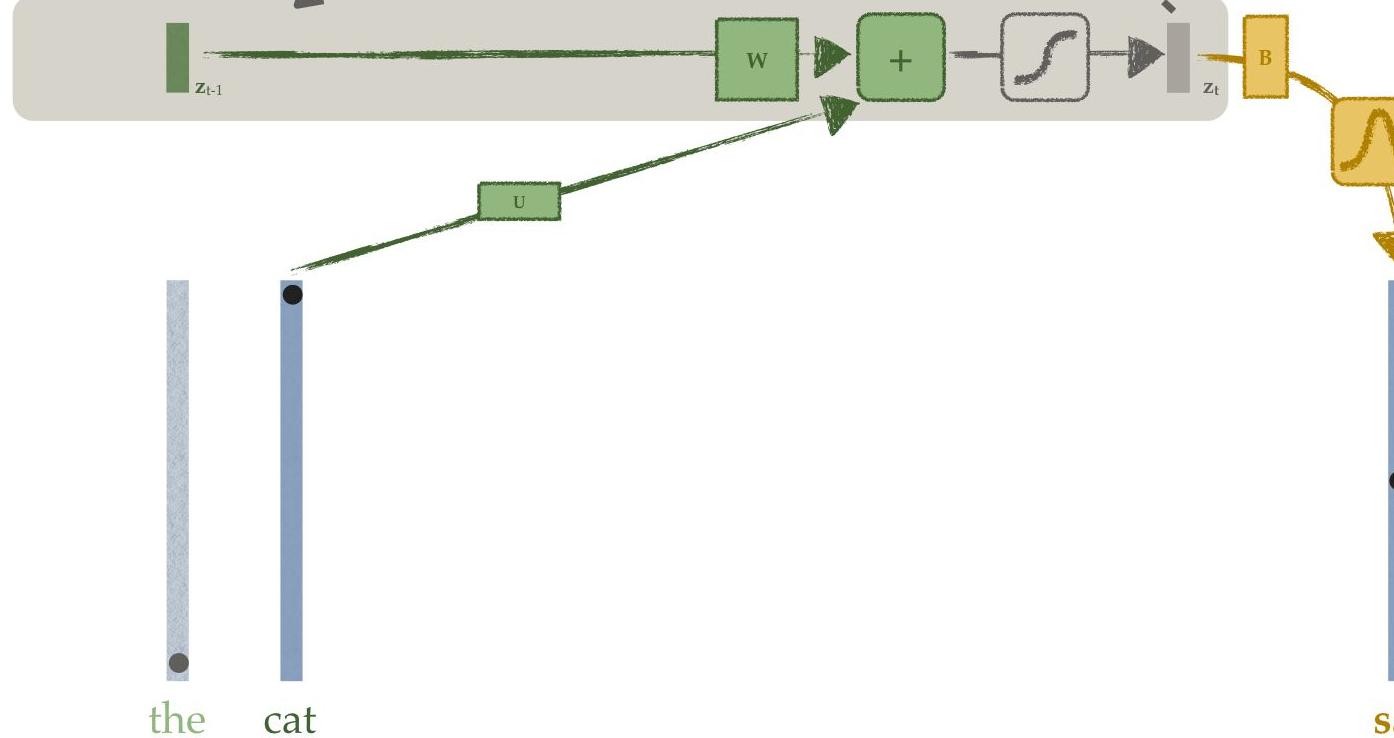
Recurrent Neural Network Language Models

[Jeffrey L Elman (1991) "Distributed representations, simple recurrent networks and grammatical structure", *Machine Learning*; Tomas Mikolov et al. (2010) "Recurrent neural network based language model", *INTERSPEECH*]

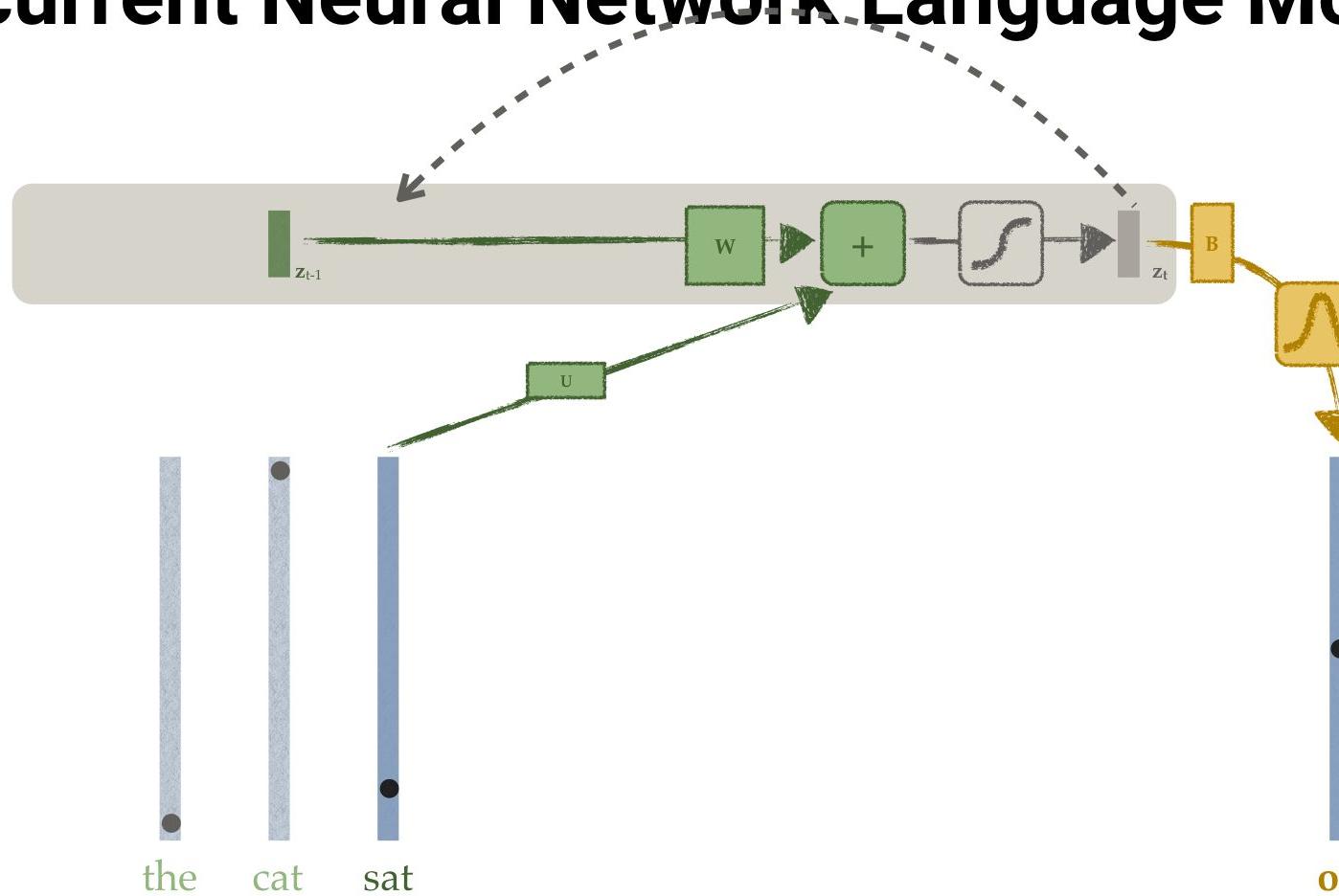


$$\begin{aligned} z_t &= \tanh(Wz_{t-1} + Uw_t) \\ p(w_{t+1}) &= softmax(Bz_t) \end{aligned}$$

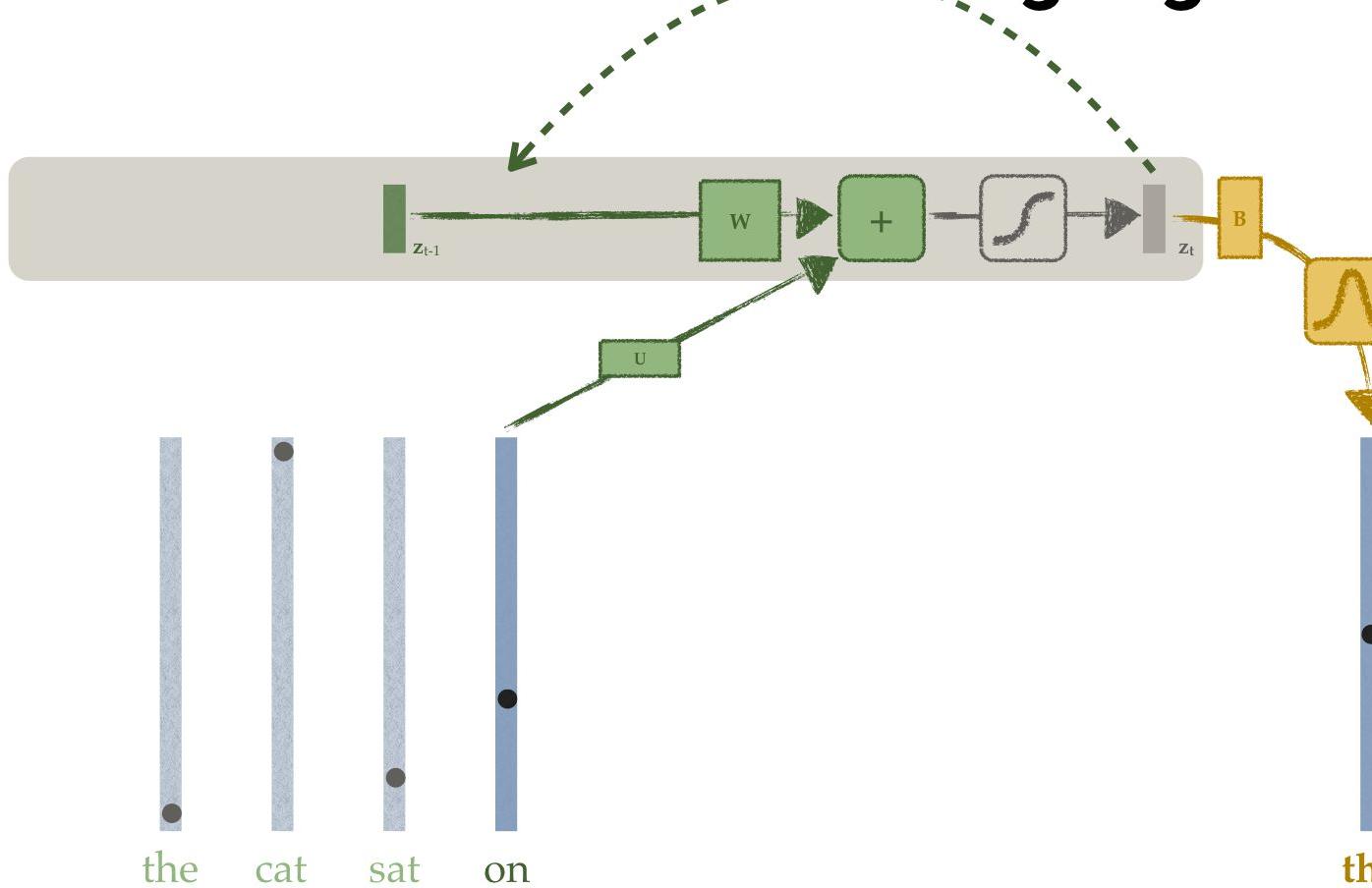
Recurrent Neural Network Language Models



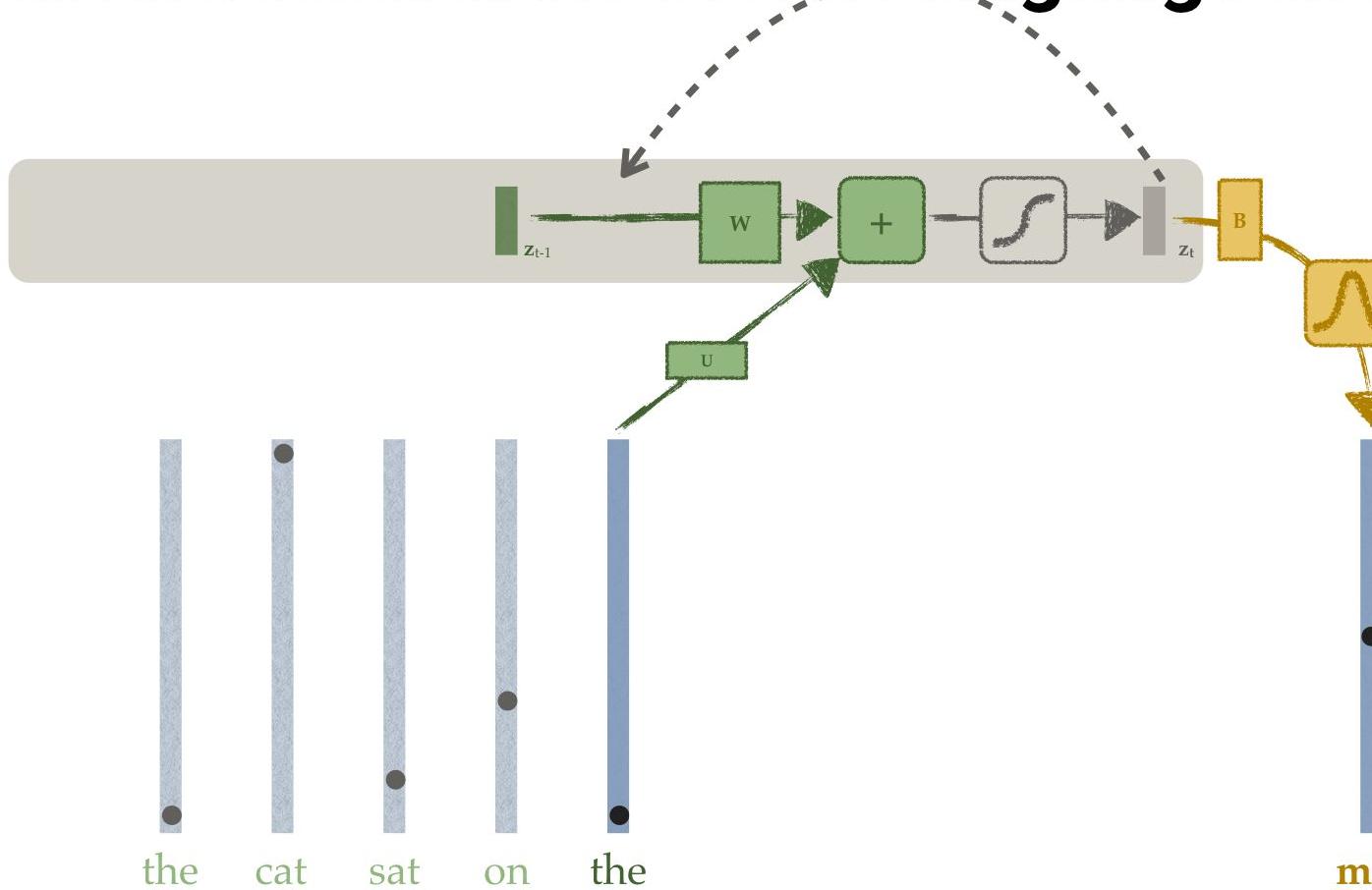
Recurrent Neural Network Language Models



Recurrent Neural Network Language Models



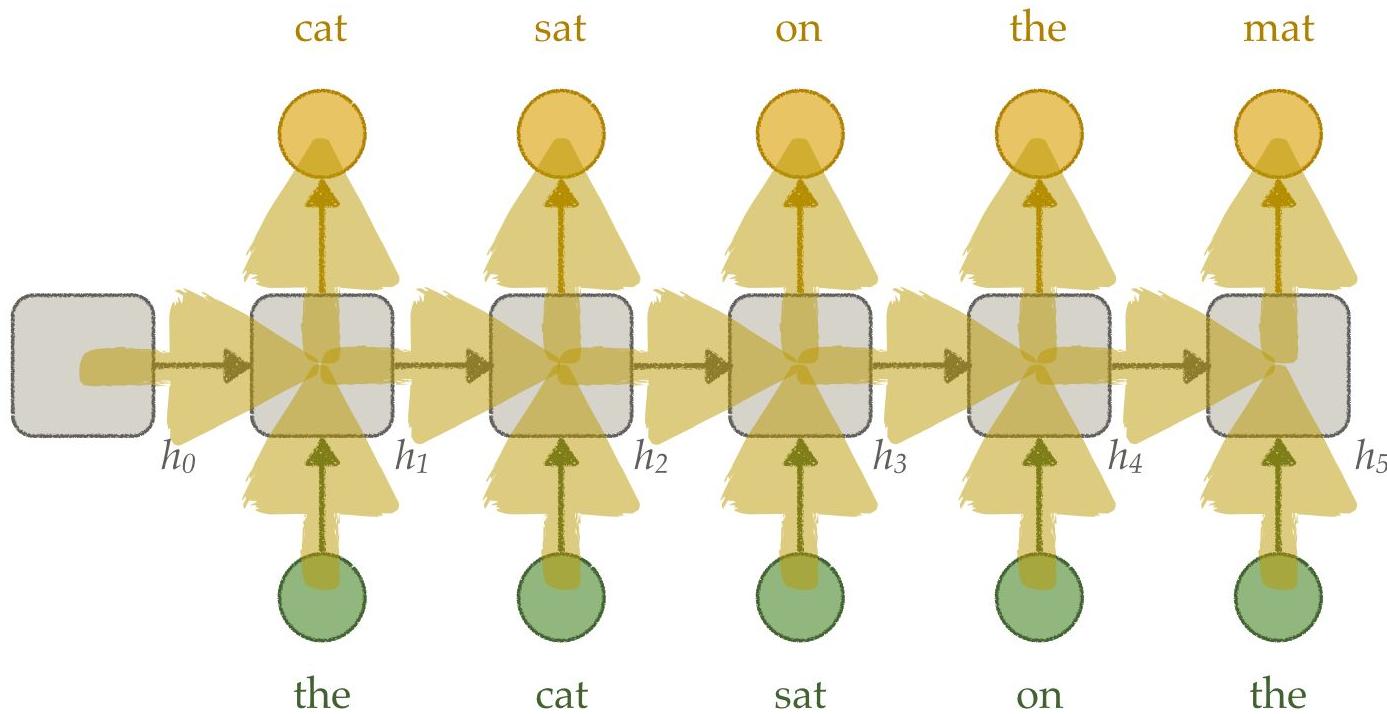
Recurrent Neural Network Language Models



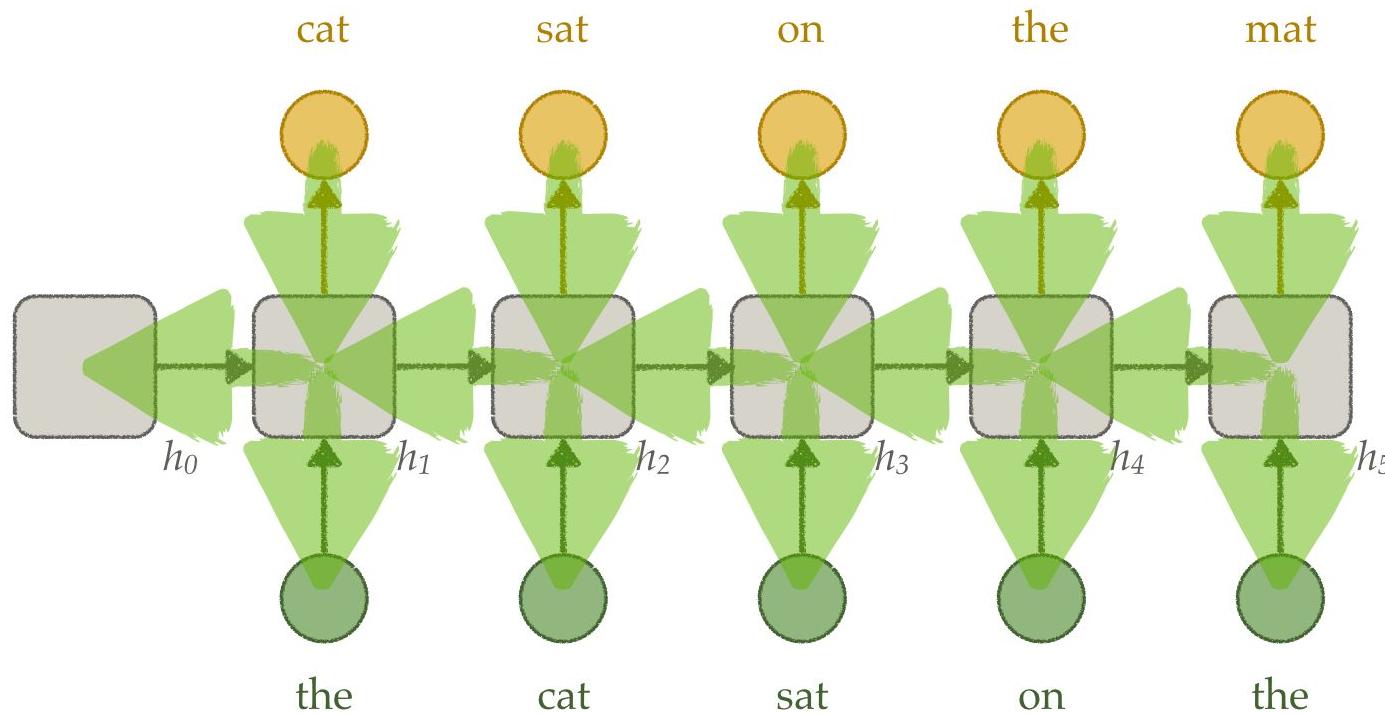
What do we Optimize?

$$\theta^* = \arg \max_{\theta} E_{w \sim data} \log P_{\theta}(w_1, \dots, w_T)$$

Recurrent Neural Network Language Models



Recurrent Neural Network Language Models



Mini-Turing Test

Some of the obese people lived five to eight years longer than others.

Abu Dhabi is going ahead to build solar city and no pollution city.

Or someone who exposes exactly the truth while lying.

VIERA , FLA . -- Sometimes, Rick Eckstein dreams about baseball swings.

For decades, the quintessentially New York city has elevated its streets to the status of an icon.

The lawsuit was captioned as United States ex rel.

Seq2Seq

Joint Language and Translation Modeling with Recurrent Neural Networks

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Abstract

We present a joint language and translation model based on a recurrent neural network which predicts target words based on an unbounded history of both source and target words. The weaker independence assumption of this model results in a more larger space of inputs compared to most feed-forward-based language or translation models. We tackle this issue with a new lattice-based training algorithm that estimate the dependencies between words. Our joint model builds on a well known recurrent neural language model (Mikolov, 2012) augmented by a layer of additional inputs for the source language. We show comparable accuracy compared to the traditional channeled model features. Our best result improve the output of a system trained on WMT 2012 French-English dataset by up to 1.5 BLEU, and by 1.1 BLEU on average across several test sets.

1 Introduction

Recently, several feed-forward neural network-based language and translation models have achieved impressive accuracy improvements on statistical machine translation tasks (Almeida et al., 2011; Le et al., 2012b; Schwenk et al., 2012). In this paper we focus on recurrent neural network architectures, which have recently advanced the state of the art in language modeling (Mikolov et al., 2010; Mikolov et al., 2012) and machine translation (MT) using multi-task feed-forward based networks in both perplexity and word error rate in speech recognition (Ariyoshi et al., 2012; Sundermeyer et al., 2012). The major attraction of recurrent architectures is their potential to capture long-span dependencies since

predictions are based on an *unbounded history* of previous words. This is in contrast to feed-forward networks as well as conventional n-gram models, both of which are limited to fixed-length contexts. Based on the success of this model architecture, we base our joint language and translation model on an extension of the recurrent neural network language model (Mikolov and Zweig, 2012) that introduces a layer of additional inputs (S2).

Most previous work on neural networks for speech recognition or machine translation used a re-scoring setup based on n-best lists (Ariyoshi et al., 2012; Molko et al., 2012) for evaluation, though some explore the algorithmic engineering challenges of direct decoder-degeneration.¹ Instead, we exploit *lattices*, which offer a much richer representation of the decoder output, since they compactly encode an exponential number of translation hypotheses in polynomial space. In contrast, n-best lists are typically very redundant, representing only a few combinations of words in the sequence. This is a major challenge in lattice rescoring with a recurrent neural network model is the effect of the unbounded history on search since the usual dynamic programming assumptions which are exploited for efficiency do not hold up anymore. We apply a novel algorithm to the task of rescoring with an unbounded language model as empirically demonstrated its effectiveness (S3).

The main contribution is learning to predict translation improvements with the recurrent neural network language model over a competitive n-gram baseline across several language pairs. We even observe consistent gains when pairing the model with a large n-gram model trained on up to 575 times more training data. The joint model is trained on a state-of-the-art system when rescoring a n-best lists of translations.

1 Introduction

In most statistical approaches to machine translation the basic units of translation are phrases that are composed of one or more words. A crucial component of translation systems are models that estimate translation probabilities for pairs of phrases, one phrase being from the source language and the other from the target language. Some models compare phrase pairs and others compare as distinct forms the surface forms of the phrases are distinct. Although distinct phrase pairs often share significant simili-

¹One notable exception is Li et al. (2012) who propose reading lattices with a feed-forward network-based model.

Recurrent Continuous Translation Models

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Abstract

We introduce a class of probabilistic translation models called Recurrent Continuous Translation Models that are purely based on continuous representations for words, phrases and sentences and do not rely on discrete units of phrases and sentences. The models have an induction and a decoding aspect. The generation of the translation is modelled with a target Recurrent Language Model, while the induction on the source side is modelled with a Continuous Sentence Model. Through various experiments, we show that if models obtain a perplexity with respect to gold translations that is comparable to state-of-the-art alignment-based translation models. Secondly, we show that they are remarkably sensitive to the word order, syntax, and meaning of the input sentence despite lacking a alignment. Finally we show that they match a state-of-the-art system when rescoring a n-best lists of translations.

1 Introduction

In most statistical approaches to machine translation the basic units of translation are phrases that are composed of one or more words. A crucial component of translation systems are models that estimate translation probabilities for pairs of phrases, one phrase being from the source language and the other from the target language. Some models compare phrase pairs and others compare as distinct forms the surface forms of the phrases are distinct. Although distinct phrase pairs often share significant simili-

ties, linguistic or otherwise, they do not share statistical weight in the models' estimation of their translation probabilities. Besides ignoring the similarity of phrase pairs, this leads to general sparsity issues. The estimation is sparse or skewed for the large majority of phrase pairs, and the weight which grows exponentially in the length of the phrases, and the generalization to other domains is often limited.

Continuous representations have shown promise at tackling these issues. Continuous representations for words are able to capture their semantic, syntactic and semantic similarity (Collerhoff and Weston, 2008). They have been applied in continuous language models demonstrating the ability to outperform state-of-the-art alignment-based translation models. Secondly, we show that they are remarkably sensitive to the word order, syntax, and meaning of the input sentence despite lacking a alignment. Finally we show that they match a state-of-the-art system when rescoring a n-best lists of translations.

The proposed continuous representations have also been constructed for phrases and sentences. The representations are able to carry similarity and task dependent information, e.g. sentiment, paraphrase or dialogue labels, significantly beyond the word level and to accurately predict labels for a highly diverse range of unaligned phrases and sentences (Grefenstette et al., 2011; Socher et al., 2011; Socher et al., 2012; Hermann and Blunsom, 2013; Kalchbrenner and Blunsom, 2013).

Phrase-based continuous translation models were first proposed in (Schwenk et al., 2006) and re-

proposed in (Cho et al., 2014) and (Kalchbrenner et al., 2014). The proposed continuous representations are able to capture the semantic and syntactic structure of the phrases, and the generalization to other domains is often limited.

¹One notable exception is Li et al. (2012) who propose reading lattices with a feed-forward network-based model.

Proceedings of the 2013 Conference on Empirical Methods in Natural Language Processing, pages 1044–1054, Seattle, Washington, USA, 18–21 October 2013. ©2013 Association for Computational Linguistics

Learning Phrase Representations using RNN Encoder-Decoder for Statistical Machine Translation

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Abstract

In this paper, we propose a novel neural network model based on an RNN Encoder-Decoder that consists of two recurrent neural networks (RNN). One RNN encodes a sequence of symbols into a fixed-length vector representation, and the other decodes the representation into another sequence of symbols. The encoder and the decoder act as an encoder and a decoder pair. The encoder maps a variable-length source sequence to a fixed-length vector, and the decoder maps the vector representation back to a variable-length target sequence. The two networks are trained jointly to maximize the conditional probability of the target sequence given the source sequence. Additionally, we propose to use a rather sophisticated hidden unit in order to improve both the memory capacity and the ease of training.

The proposed RNN Encoder-Decoder with a novel hidden unit is empirically evaluated on the task of translating from English to French. We train the model to learn the translation probability of an English phrase to a corresponding French phrase. The model is then used as part of a standard phrase-based SMT system by scoring each phrase pair in the phrase table. The empirical evaluation shows that this approach of scoring phrase pairs with an RNN Encoder-Decoder improves the translation performance.

We qualitatively analyze the trained RNN Encoder-Decoder by comparing its phrase scores with those given by the existing translation model. The qualitative analysis shows that the RNN Encoder-Decoder is better at capturing linguistic regularities in the phrase table, indirectly explaining the improved performance in the empirical translation performance. The further analysis of the model reveals that the RNN Encoder-Decoder learns a continuous space representation of a phrase that preserves both the semantic and syntactic structure of the phrase.

Sequence to Sequence Learning with Neural Networks

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Abstract

Deep Neural Networks (DNNs) are powerful models that have achieved excellent performance on difficult learning tasks. Although DNNs work well whenever large labeled training sets are available, they cannot be used to map sequences to sequences. In this paper, we present a general end-to-end approach to sequence learning that makes minimal assumptions on the sequence structure. Our method uses a deep layered neural network that takes a short-term memory (STM) of the input sequence to a vector of a fixed dimensionality and then a deep LSTM to decode the target sequence from the vector. Our main result is that an English to French translation task from the WMT'14 dataset, the translations produced by the LSTM achieve a BLEU score of 34.8 on the entire test set, where the LSTM's BLEU score was previously 31.5. Another interesting finding is that the LSTM's performance is not significantly different on long sentences. For comparing a phrase-based SMT system achieves a BLEU score of 33.3 on the same dataset. When we used the LSTM to rerank the 1000 hypotheses produced by the aforementioned SMT system, its BLEU score increased to 36.5, which is close to the previous best result on this task. The LSTM also handles semantic dependencies between words in the source sentence to word order and are relatively invariant to the active and the passive voice. Finally, we found that reversing the order of the words in all source sentences (but not target sentences) improved the LSTM's performance markedly, because doing so introduced many short term dependencies between the source and the target sentence which made the optimization problem easier.

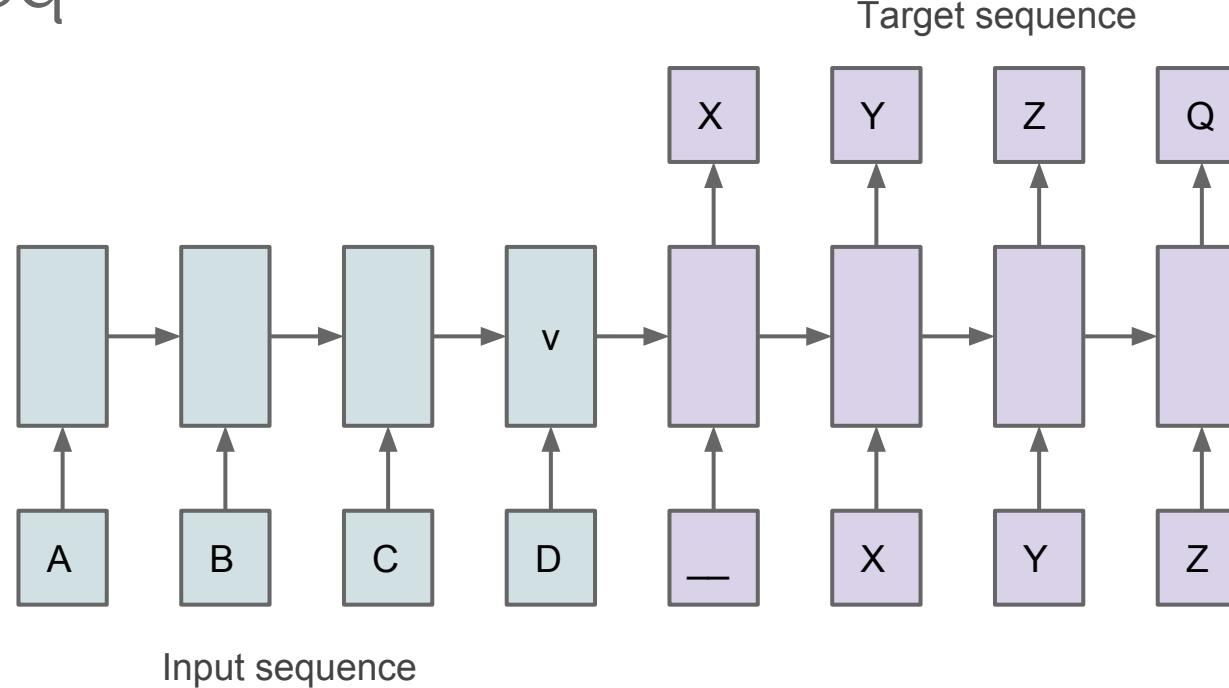
1 Introduction

Deep Neural Networks (DNNs) are extremely powerful machine learning models that achieve excellent performance on difficult problems such as speech recognition [13,7] and visual object recognition [19, 6, 21, 20]. DNNs are powerful because they can perform arbitrary parallel computation for a modest number of steps. A simple example of the power of the DNN is the ability to learn an N-gram language model using a 2-layered layer of neurons [27], while linear networks are related to conventional statistical models, they learn an intricate computation. Furthermore, large DNNs can be trained with supervised backpropagation whenever the labeled training set has enough information to specify the network's parameters. Thus, if there exists a parameter setting of a large DNN that achieves good results (for example, because humans can solve the task very rapidly), supervised backpropagation will find it and solve the task.

Despite their flexibility and power, DNNs can only be applied to problems whose inputs and targets can be sensibly encoded with vectors of fixed dimensionality. It is a significant limitation, since many important problems are best expressed with sequences whose lengths are not known *a-priori*. For example, speech recognition and machine translation are sequential problems. Likewise, question answering can also be seen as mapping a sequence of words representing the question to a

1. Auli, M., et al. "Joint Language and Translation Modeling with Recurrent Neural Networks." *EMNLP (2013)*
2. Kalchbrenner, N., et al. "Recurrent Continuous Translation Models." *EMNLP (2013)*
3. Cho, K., et al. "Learning Phrase Representations using RNN Encoder-Decoder for Statistical MT." *EMNLP (2014)*
4. Sutskever, I., et al. "Sequence to Sequence Learning with Neural Networks." *NIPS (2014)*

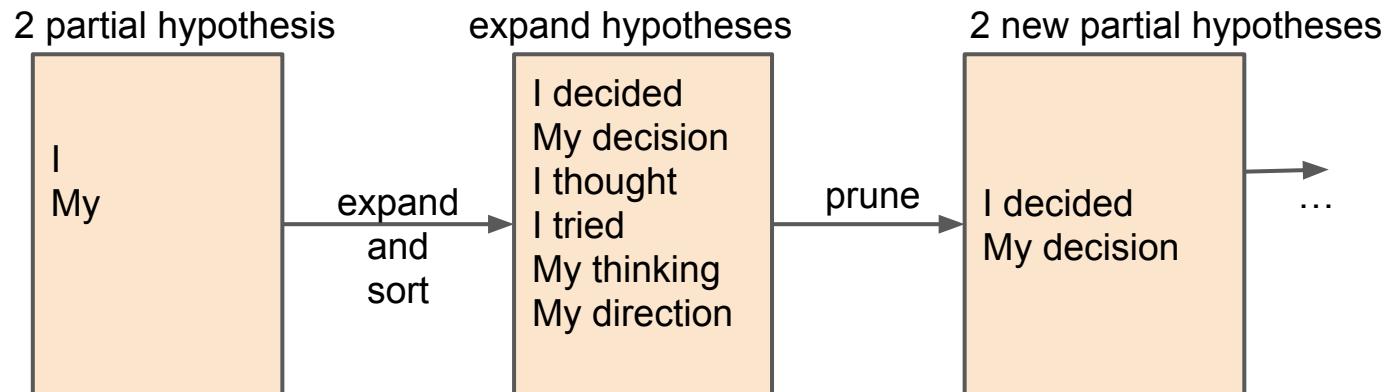
Seq2Seq



$$P(y_1, \dots, y_{T'} | x_1, \dots, x_T) = \prod_{t=1}^{T'} p(y_t | v, y_1, \dots, y_{t-1})$$

Decoding in a Nutshell (Beam Size 2)

$$y^* = \arg \max_{y_1, \dots, y_{T'}} P(y_1, \dots, y_{T'} | x_1, \dots, x_T)$$



Code

Source: <https://github.com/keveman/tensorflow-tutorial/blob/master/PTB%20Word%20Language%20Modeling.ipynb>

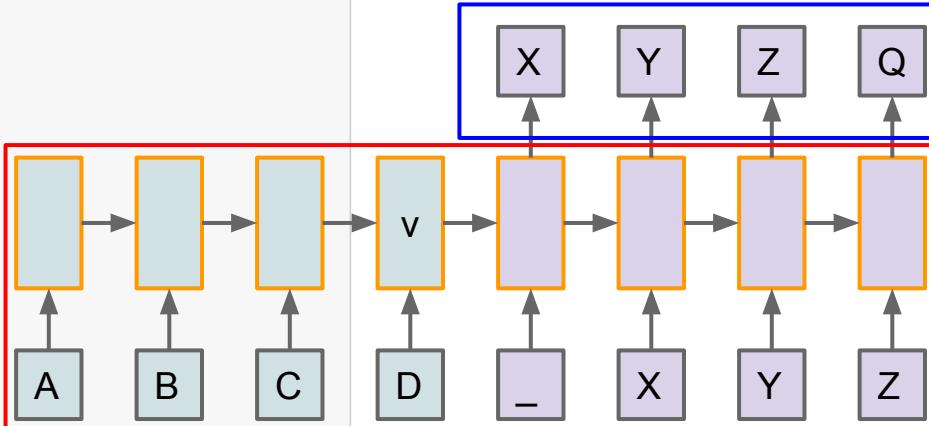
```
class LSTMCell(object):
    def __init__(self, state_size):
        self.state_size = state_size
        self.W_f = tf.Variable(self.initializer())
        self.W_i = tf.Variable(self.initializer())
        self.W_o = tf.Variable(self.initializer())
        self.W_C = tf.Variable(self.initializer())
        self.b_f = tf.Variable(tf.zeros([state_size]))
        self.b_i = tf.Variable(tf.zeros([state_size]))
        self.b_o = tf.Variable(tf.zeros([state_size]))
        self.b_C = tf.Variable(tf.zeros([state_size]))
    def __call__(self, x_t, h_t1, C_t1):
        X = tf.concat(1, [h_t1, x_t])
        f_t = tf.sigmoid(tf.matmul(X, self.W_f) + self.b_f)
        i_t = tf.sigmoid(tf.matmul(X, self.W_i) + self.b_i)
        o_t = tf.sigmoid(tf.matmul(X, self.W_o) + self.b_o)
        Ctilde_t = tf.tanh(tf.matmul(X, self.W_C) + self.b_C)
        C_t = f_t * C_t1 + i_t * Ctilde_t
        h_t = o_t * tf.tanh(C_t)
        return h_t, C_t
    def initializer(self):
        return tf.random_uniform([2*self.state_size, self.state_size],
                               -0.1, 0.1)
```

Code

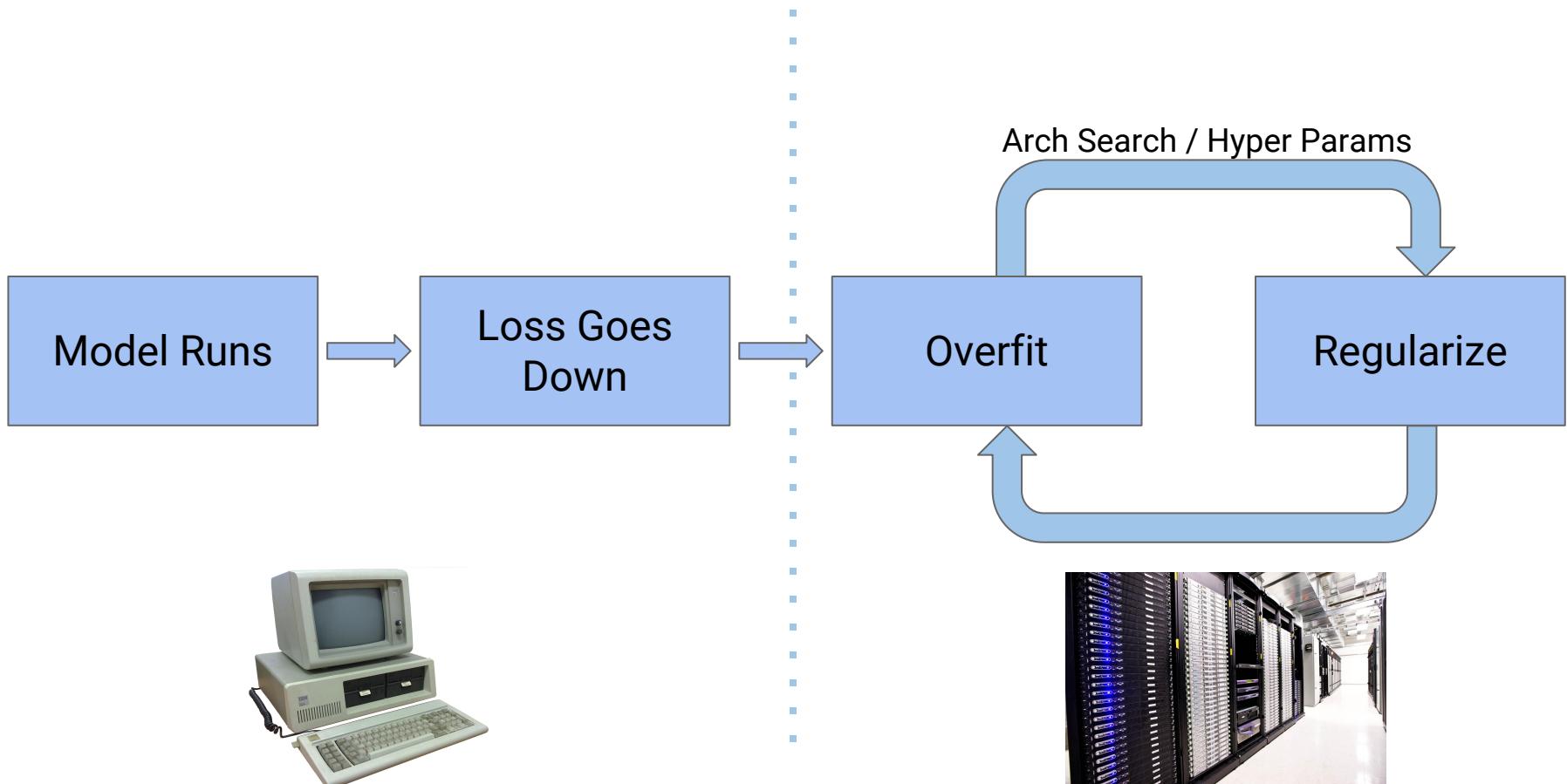
```
# words and targets are placeholders for [batch_size, num_steps]
# tensor of word and target ids
words = tf.placeholder(tf.int64, name='words')
targets = tf.placeholder(tf.int64, name='targets')

def model(batch_size, num_steps):
    output = [tf.zeros([batch_size, state_size])] * 4
    state = [tf.zeros([batch_size, state_size])] * 4
    preds = []
    cost = 0.0
    for i in range(num_steps):
        # Get the embedding for words
        embedding = tf.nn.embedding_lookup(embedding_params, words[:, i])
        # Run the LSTM cells
        output[0], state[0] = lstm[0](embedding, output[0], state[0])
        for d in range(1, 4):
            output[d], state[d] = lstm[d](output[d-1], output[d], state[d])
        # Get the logits
        logits = tf.matmul(output[-1], sm_w) + sm_b
        # Get the softmax predictions
        preds.append(tf.nn.softmax(logits))
        # Cost per step
        cost = cost + tf.reduce_mean(
            tf.nn.sparse_softmax_cross_entropy_with_logits(logits,
                                                          targets[:, i]))
    # Average cost across time steps
    cost = cost / np.float32(num_steps)
    return preds, cost
```

```
class LSTMCell(object):
    def __init__(self, state_size):
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        self.W_f = tf.Variable(self.initializer())
        self.W_i = tf.Variable(self.initializer())
        self.W_o = tf.Variable(self.initializer())
        self.W_C = tf.Variable(self.initializer())
        self.b_f = tf.Variable(tf.zeros((state_size)))
        self.b_i = tf.Variable(tf.zeros((state_size)))
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        self.b_C = tf.Variable(tf.zeros((state_size)))
    def __call__(self, x_t, h_t, C_t):
        X = tf.concat(1, (h_t, x_t))
        f_t = tf.sigmoid(tf.matmul(X, self.W_f) + self.b_f)
        i_t = tf.sigmoid(tf.matmul(X, self.W_i) + self.b_i)
        o_t = tf.sigmoid(tf.matmul(X, self.W_o) + self.b_o)
        C_tilde_t = tf.tanh(tf.matmul(X, self.W_C) + self.b_C)
        C_t = f_t * C_tilde_t + i_t * C_tilde_t
        h_t = o_t * tf.tanh(C_t)
        return h_t, C_t
    def initializer(self):
        return tf.random_uniform([2*state_size, state_size],
                               -0.1, 0.1)
```



Deep Learning Vicious Cycle



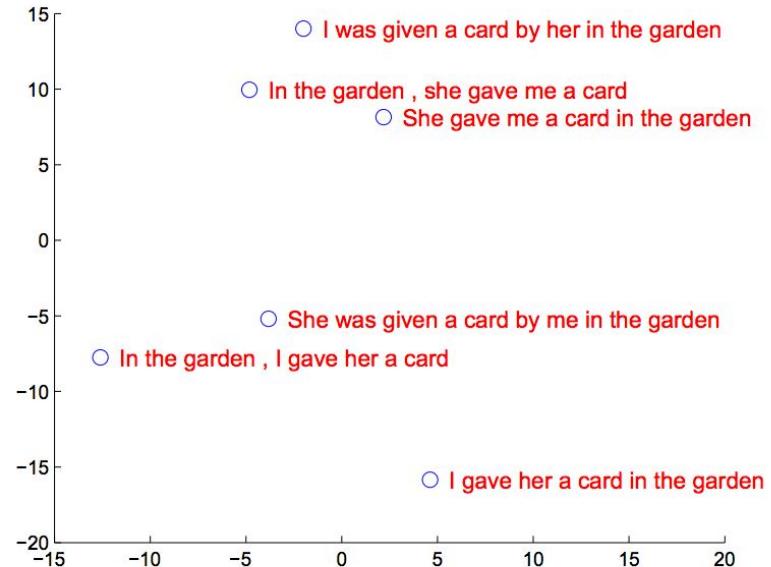
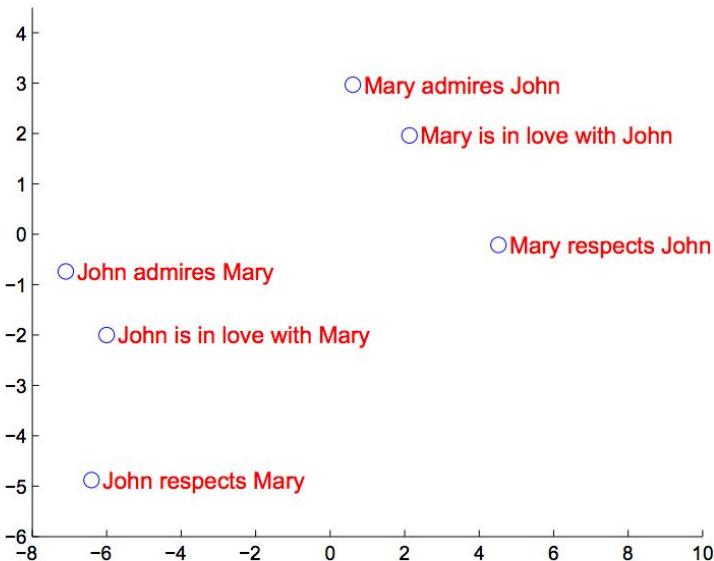
(Some) Tricks of the Trade

- Long sequences?
 - Attention
 - Bigger state
- Can't overfit?
 - Bigger hidden state
 - Deep LSTM + Skip Connections
- Overfit?
 - Dropout + Ensembles
- Tuning
 - Keep calm and decrease your learning rate
 - Initialization of parameters is critical (in seq2seq we used $U(-0.05, 0.05)$)
 - Clip the gradients!
 - E.g. if $\|grad\| > 5$: $grad = grad / \|grad\| * 5$

Applications

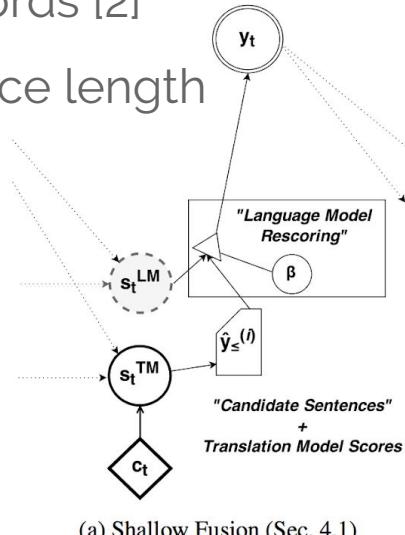
Machine Translation

Method	test BLEU score (ntst14)
Bahdanau et al. [2]	28.45
Baseline System [29]	33.30
Single forward LSTM, beam size 12	26.17
Single reversed LSTM, beam size 12	30.59
Ensemble of 5 reversed LSTMs, beam size 1	33.00
Ensemble of 2 reversed LSTMs, beam size 12	33.27
Ensemble of 5 reversed LSTMs, beam size 2	34.50
Ensemble of 5 reversed LSTMs, beam size 12	34.81

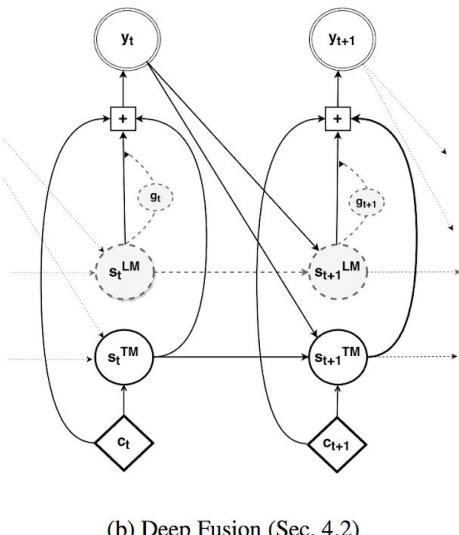


Machine Translation - other concerns

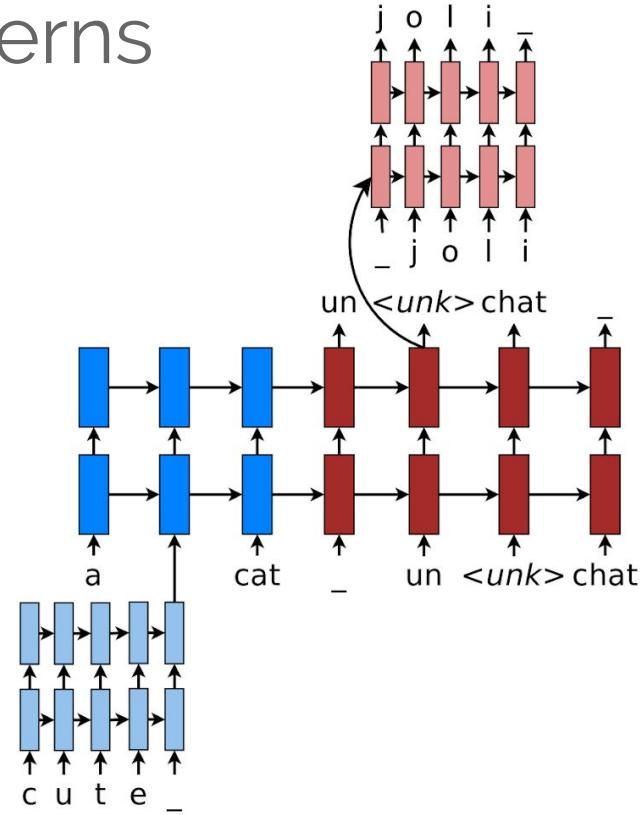
- Using Language Models [1]
- OOV words [2]
- Sequence length



(a) Shallow Fusion (Sec. 4.1)



(b) Deep Fusion (Sec. 4.2)



1. Gulcehre, C., et al. "On using monolingual corpora in neural machine translation." *arXiv* (2015).
2. Luong, T., and Manning, C. "Achieving open vocabulary neural MT with hybrid word-character models." *arXiv* (2016).

Image Captioning

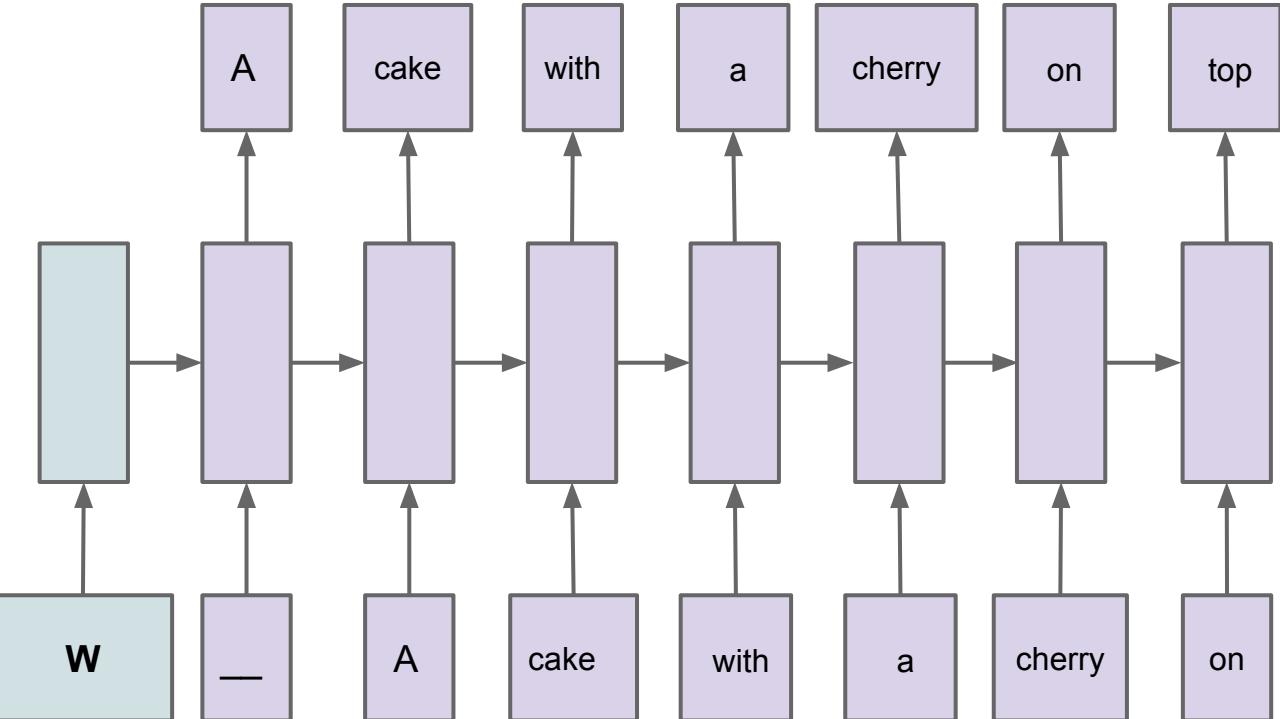
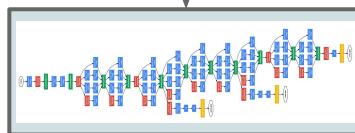
$p(\text{English} \mid \text{French})$



$p(\text{English} \mid \text{Image})$

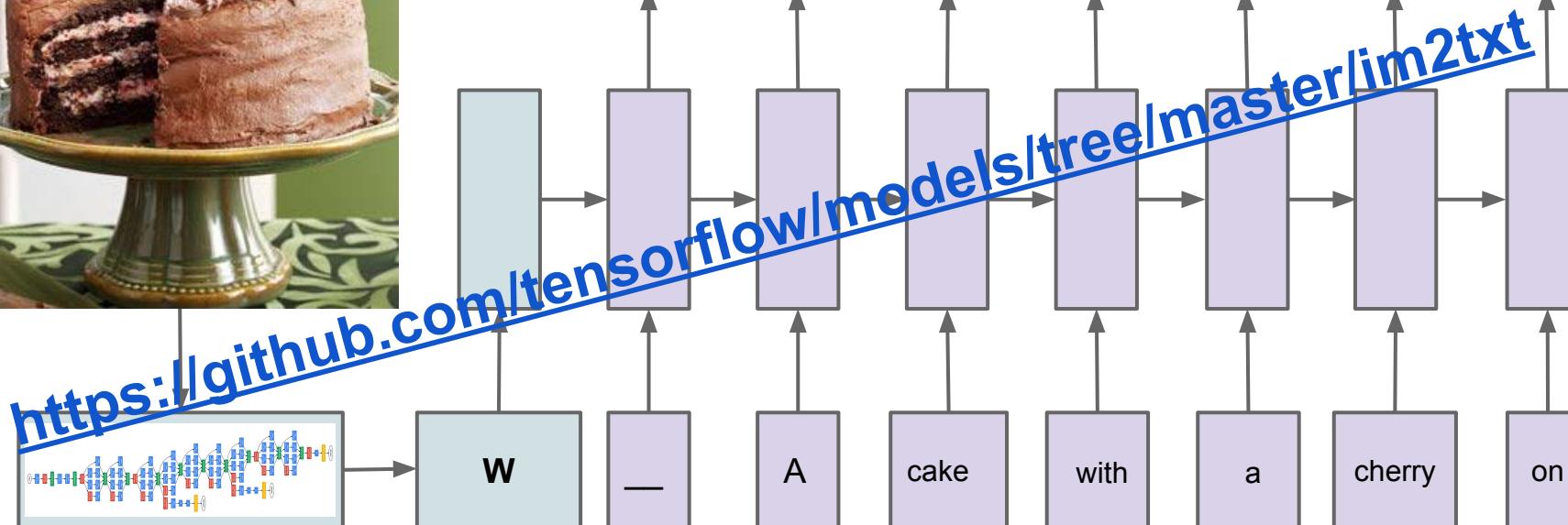
1. Vinyals, O., et al. "Show and Tell: A Neural Image Caption Generator." *CVPR* (2015).
2. Mao, J., et al. "Deep captioning with multimodal recurrent neural networks (m-rnn)." *ICLR* (2015).
3. Karpathy, A., Li, F., "Deep visual-semantic alignments for generating image descriptions." *CVPR* (2015).

Image Captioning



$$\theta^* = \arg \max_{\theta} p(S|I)$$

Image Captioning



$$\theta^* = \arg \max_{\theta} p(S|I)$$

Image Captioning



Human: A close up of two bananas with bottles in the background.

BestModel: A bunch of bananas and a bottle of wine.

InitialModel: A close up of a plate of food on a table.

Image Captioning



Human: A woman holding up a yellow banana to her face.

BestModel: A woman holding a banana up to her face.

InitialModel: A close up of a person eating a hot dog.

Image Captioning



Human: A man outside cooking with a sub in his hand.

BestModel: A man is holding a sandwich in his hand.

InitialModel: A man cutting a cake with a knife.

Image Captioning



Human: Someone is using a small grill to melt his sandwich.

BestModel: A person is cooking some food on a grill.

InitialModel: A pizza sitting on top of a white plate.

Image Captioning



Human: A blue , yellow and red train travels across the tracks near a depot.

BestModel: A blue and yellow train traveling down train tracks.

InitialModel: A train that is sitting on the tracks.

Learning To Execute [Zaremba & Sutskever, 2014]

- One of the first (modern) examples of learning algorithms
- 2014--??? “era of discovery” → Apply seq2seq to *everything*

Input:

```
j=8584  
for x in range(8):  
    j+=920  
    b=(1500+j)  
    print((b+7567))
```

Target: 25011.

Input:

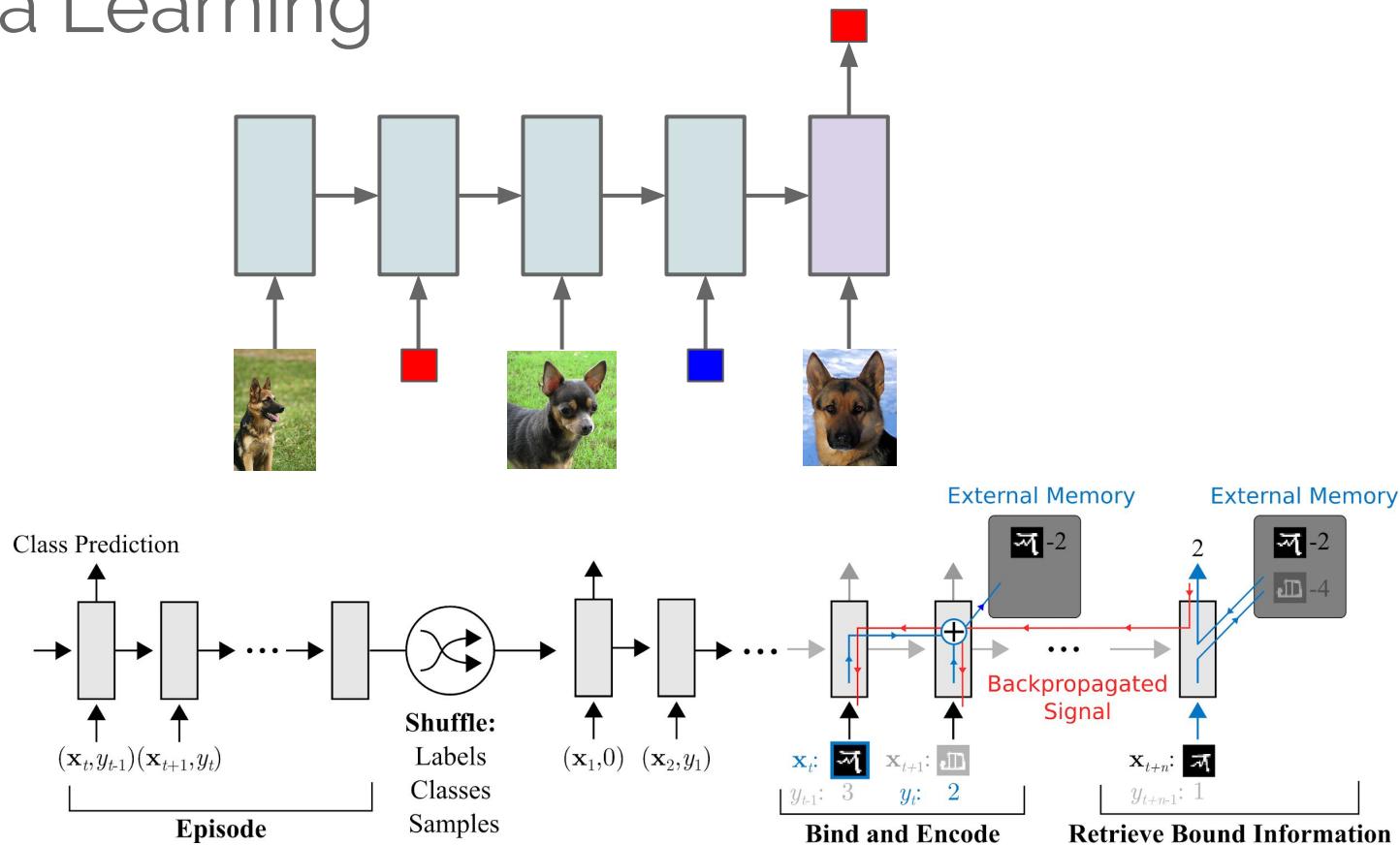
```
i=8827  
c=(i-5347)  
print((c+8704) if 2641<8500 else 5308)
```

Target: 12184.

Input:

```
vqppkn  
sqdvfljmnc  
y2vxdddsepnimcbvubkomhrpliibtwztbljipcc  
Target: hkhpg
```

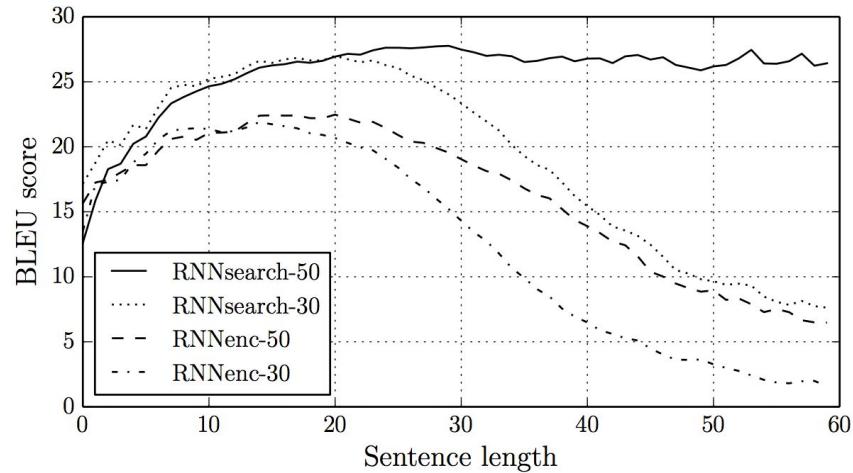
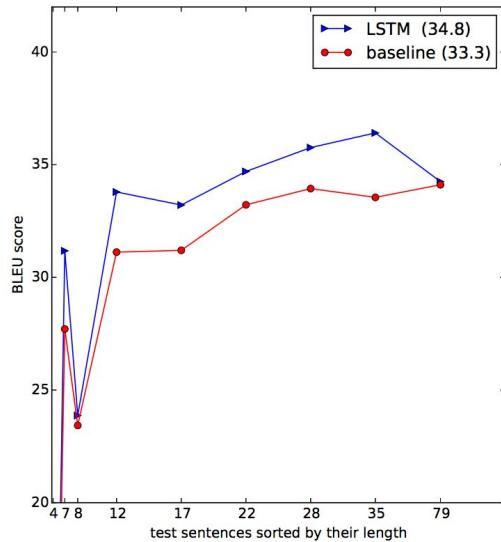
Meta Learning



1. Young, A., et al. "Meta-learning with backpropagation." *Neural Nets* (2001).
2. Santoro, A., et al. "Meta-Learning with Memory-Augmented Neural Networks." *ICML* (2016).
3. Vinyals, O., et al. "Matching Networks for One Shot Learning." *NIPS* (2016).

Seq2Seq - Limitations

- Fixed Size Embeddings are easily overwhelmed by long inputs or long outputs



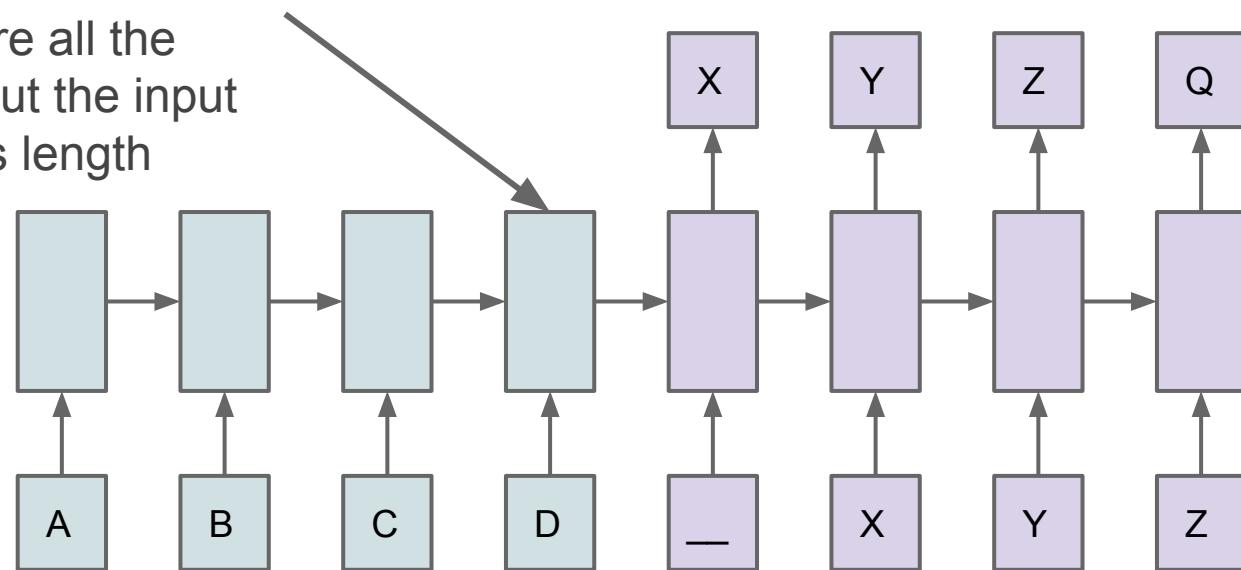
1. Sutskever, I., et al. "Sequence to Sequence Learning with Neural Networks." *NIPS* (2014)
2. Bahdanau, D., et al. "Neural Machine Translation by Jointly Learning to Align and Translate." *ICLR* (2015)

Attention

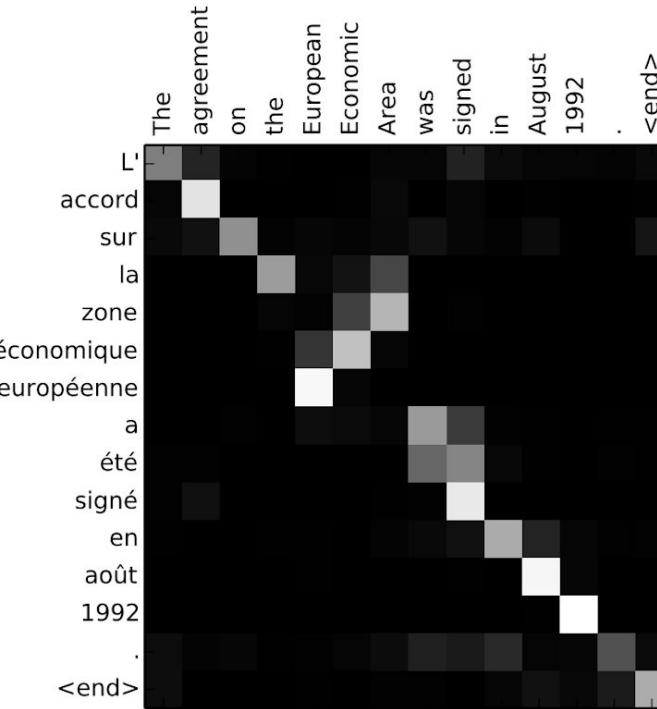
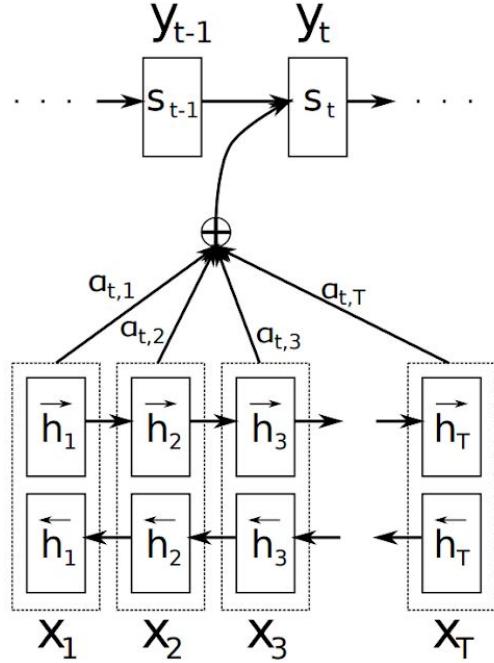
Seq2Seq -- The issue with long inputs

- Same embedding informs the entire output
- Needs to capture all the information about the input regardless of its length

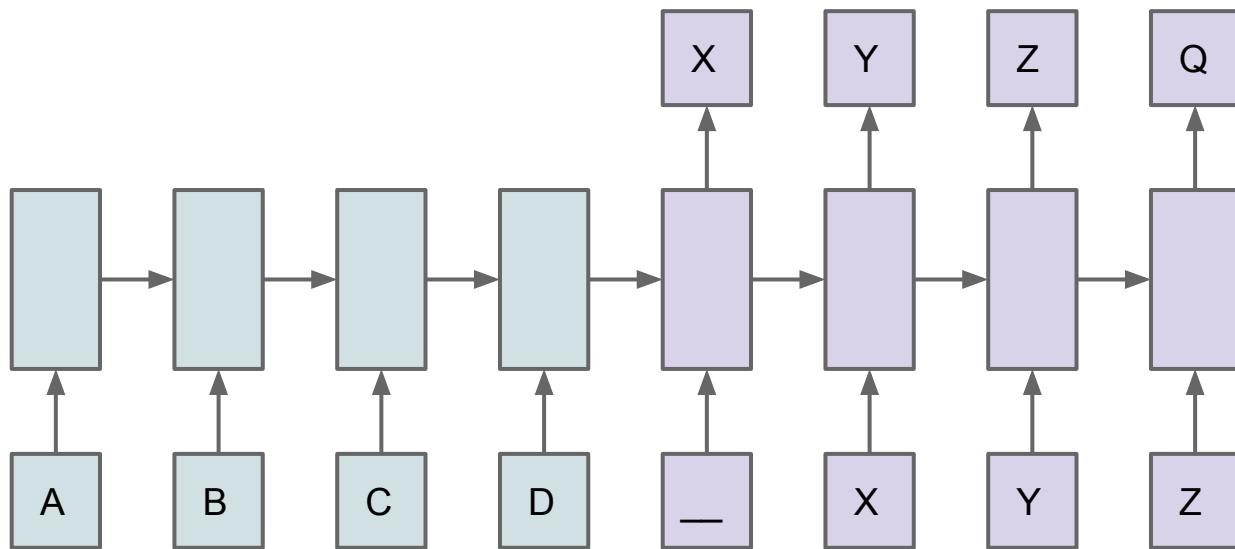
Is there a better way to pass the information from encoder to the decoder ?



Seq2Seq with Attention

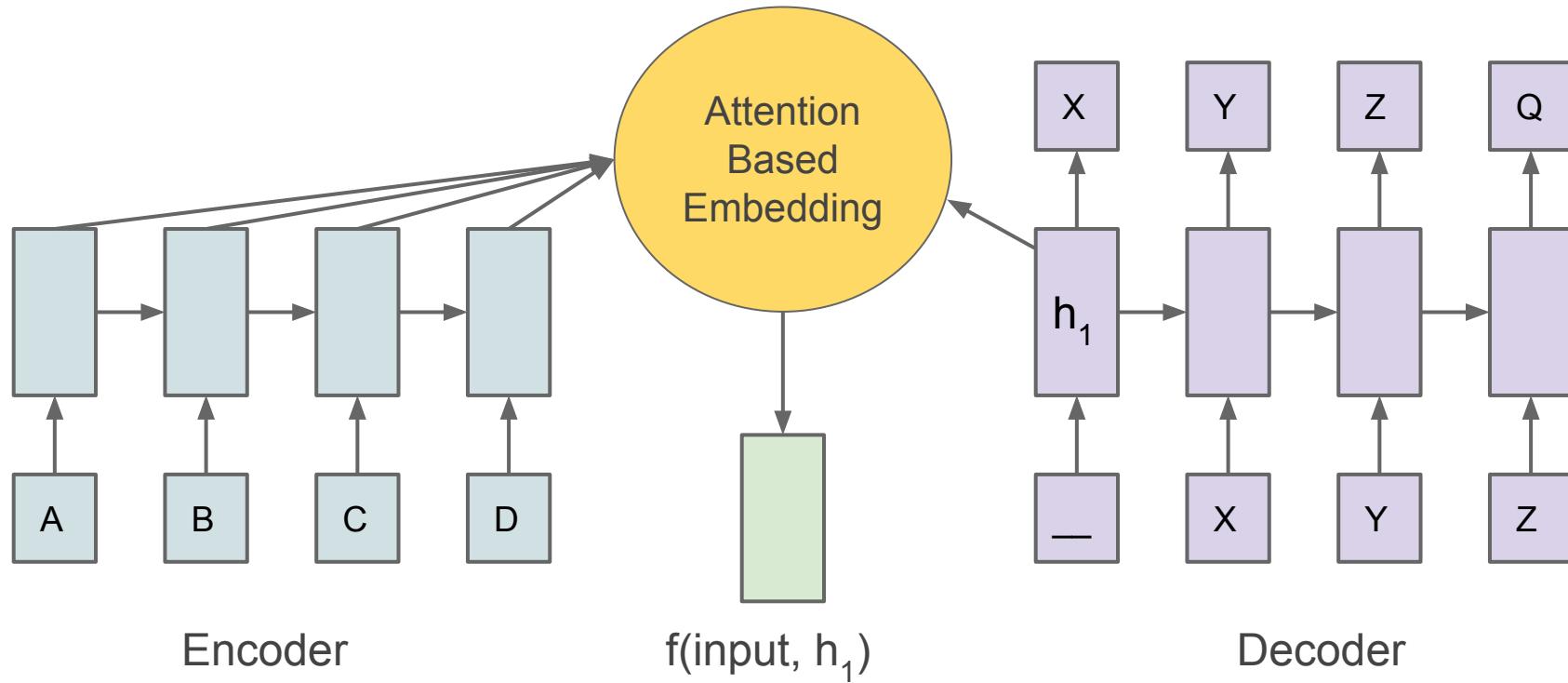


Seq2Seq



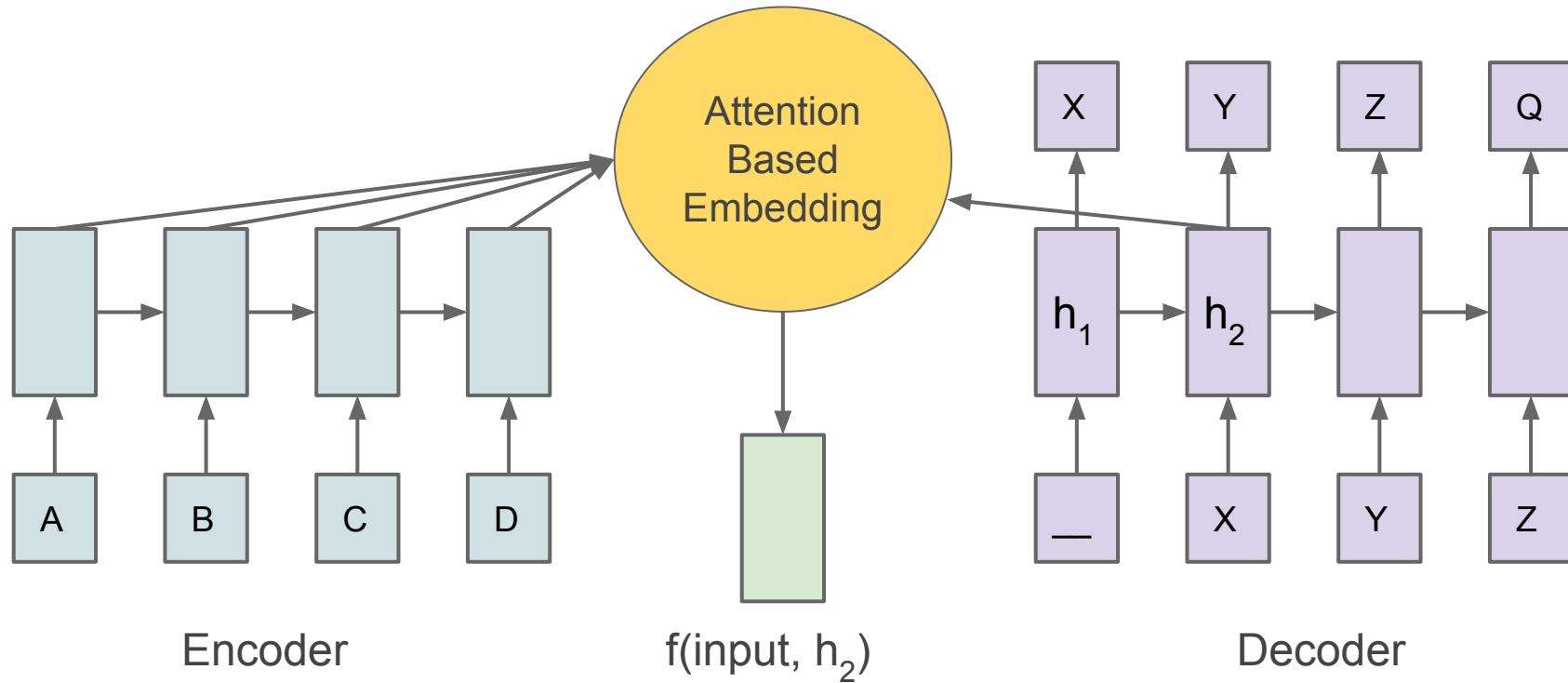
Seq2Seq with Attention

- A different embedding computed for every output step



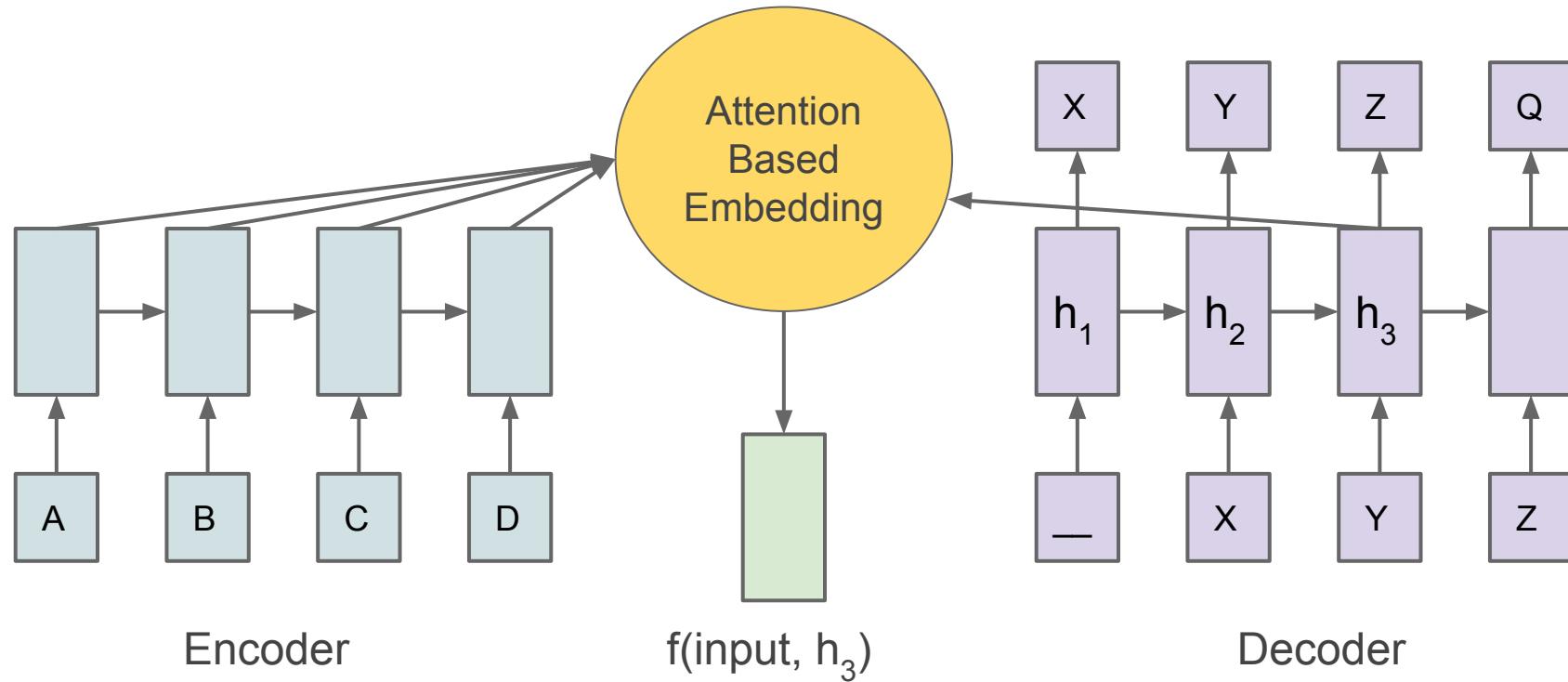
Seq2Seq with Attention

- A different embedding computed for every output step



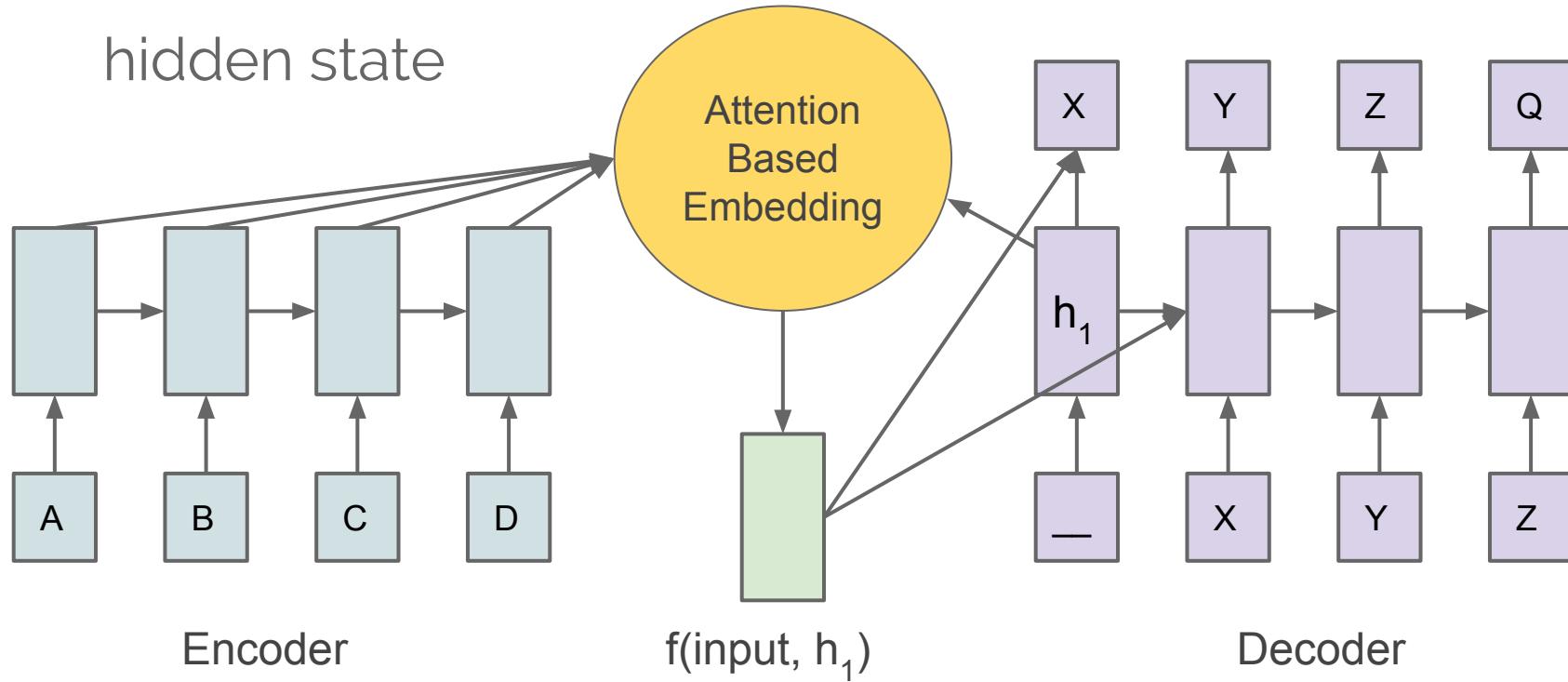
Seq2Seq with Attention

- A different embedding computed for every output step



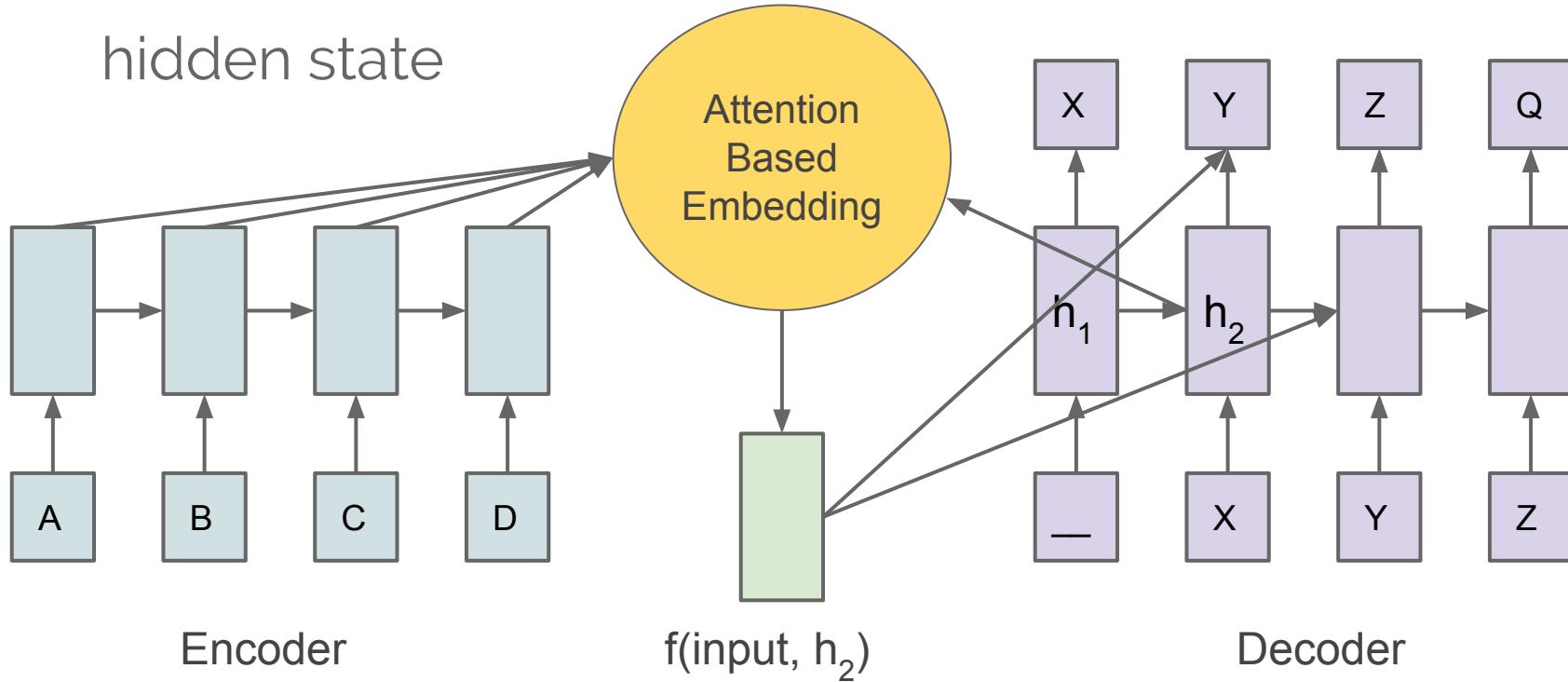
Seq2Seq with Attention

- Embedding used to predict output, and compute next hidden state



Seq2Seq with Attention

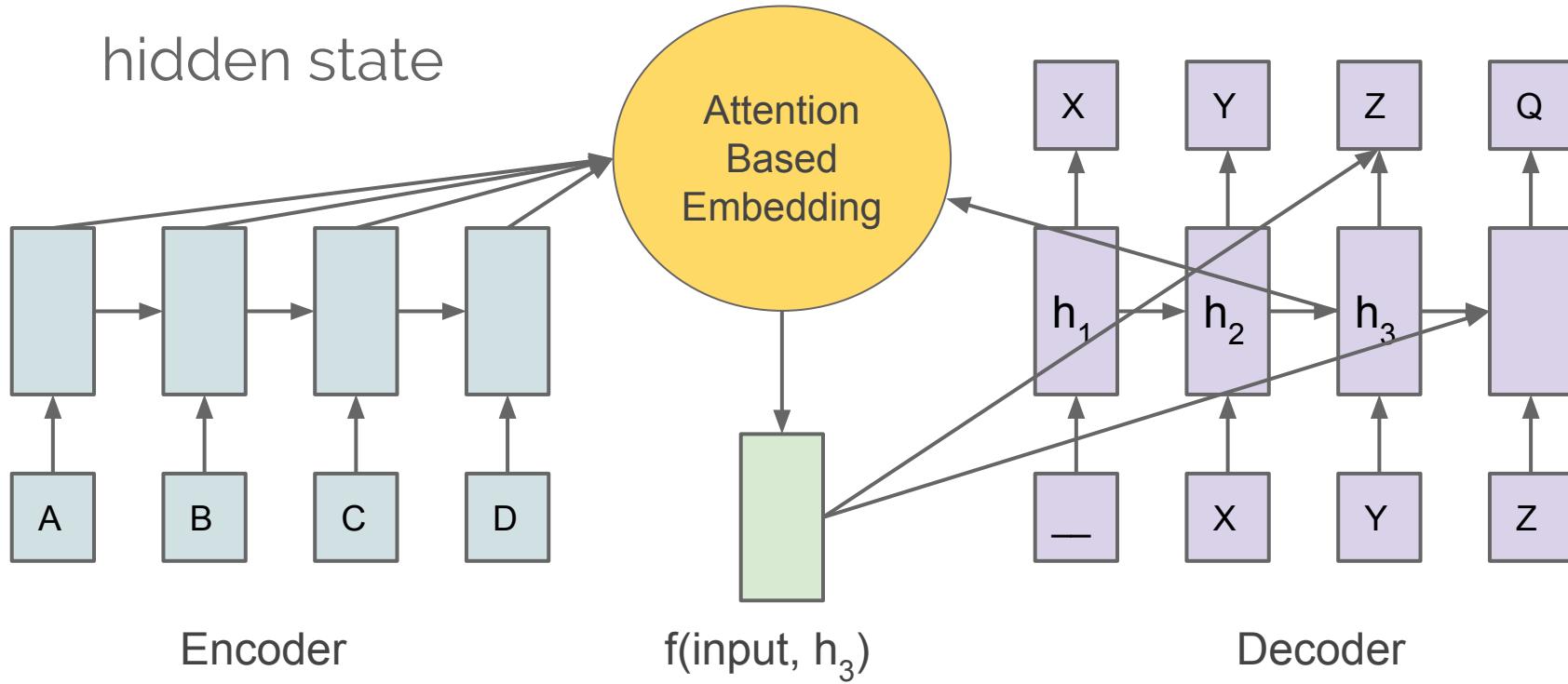
- Embedding used to predict output, and compute next hidden state



- Attention arrows for step 1 omitted

Seq2Seq with Attention

- Embedding used to predict output, and compute next hidden state

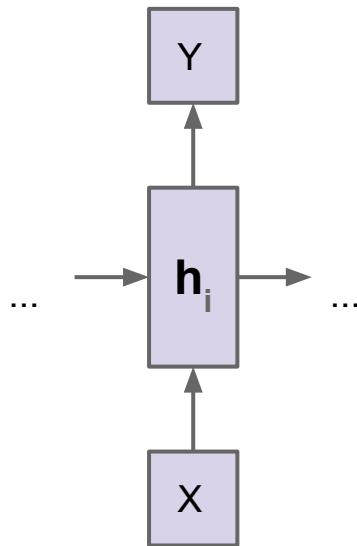


Attention Based Embedding

- Linear blending of embedding RNN states $e_1 e_2 e_3 e_4$ is a natural choice
- How to produce the coefficients (attention vector) for blending ?
 - Content based coefficients based on query state h_i and embedding RNN states $e_1 e_2 e_3 e_4$

Dot product Attention

- Inputs: “I am a cat.”
- Input RNN states: $e_1 e_2 e_3 e_4$
- Decoder RNN state at step i (query): h_i
- Compute scalars $h_i^T e_1, h_i^T e_2, h_i^T e_3, h_i^T e_4$ representing similarity / relevance between encoder steps and query.
- Normalize $[h_i^T e_1, h_i^T e_2, h_i^T e_3, h_i^T e_4]$ with softmax to produce attention weights, e.g. [0.0 0.05 0.9 0.05]



Content Based Attention

Attention [Bahdanau, Cho and Bengio, 2014]

$$u_j = v^T \tanh(W_1 e_j + W_2 d) \quad j \in (1, \dots, n)$$

$$a_j = \text{softmax}(u_j) \quad j \in (1, \dots, n)$$

$$d' = \sum_{j=1}^n a_j e_j$$

Neural Turing Machine [1] & Memory Networks [2]:

Given a key vector \mathbf{k} and a strength scalar s emitted by the controller, get a weighting (w_1, \dots, w_N) over memory locations where

$$w_i = \frac{e^{\hat{w}_i}}{\sum_j e^{\hat{w}_j}} \quad ; \quad \hat{w}_i = \log(1 + e^s) C(\mathbf{k}, \mathbf{m}_i) \quad ; \quad C(\mathbf{k}, \mathbf{m}_i) = \frac{\mathbf{k} \cdot \mathbf{m}_i}{\|\mathbf{k}\| \|\mathbf{m}_i\|}$$

and $C(\mathbf{k}, \mathbf{m}_i)$ is the cosine similarity between the key and the word \mathbf{m}_i at memory location i

1. Graves, A., et al. "Neural Turing Machines." *arxiv* (2014)
2. Weston, J., et al. "Memory Networks." *arxiv* (2014)

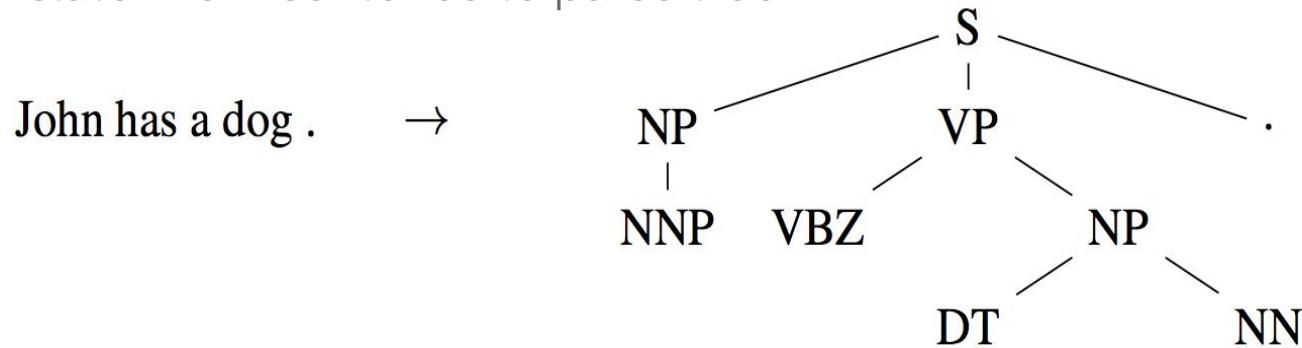
Other strategies for attention models

- Tensored attention
 - Minh-Thang Luong, Hieu Pham, and Christopher D. Manning. "Effective Approaches to Attention-based Neural Machine Translation." EMNLP'15.
- Multiple heads
- Pyramidal encoders
 - William Chan, Navdeep Jaitly, Quoc Le, Oriol Vinyals. "Listen Attend and Spell". ICASSP 2015.
- Hierarchical Attention
 - Andrychowicz, Marcin, and Karol Kurach. "Learning efficient algorithms with hierarchical attentive memory." *arXiv preprint arXiv:1602.03218* (2016).
- Hard Attention
 - Xu, Kelvin, et al. "Show, attend and tell: Neural image caption generation with visual attention." ICML 2015

Applications

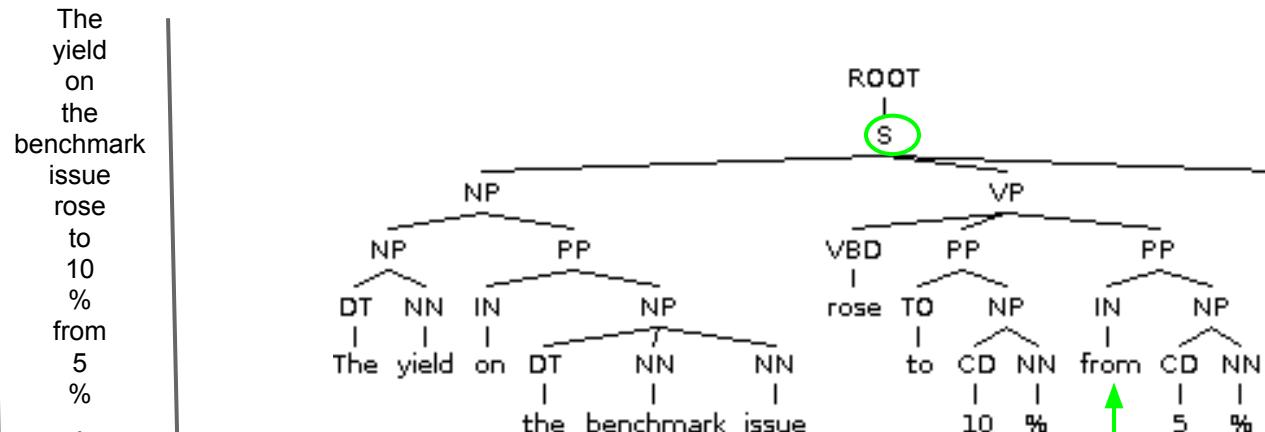
Sentence to Constituency Parse Tree

1. Read a sentence
2. Flatten the tree into a sequence (adding (,))
3. “Translate” from sentence to parse tree



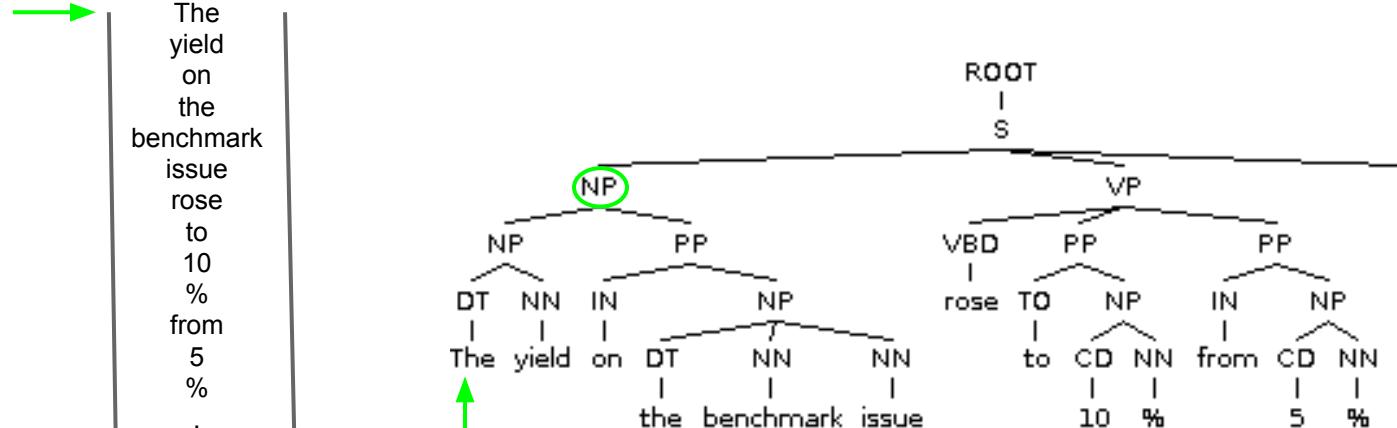
John has a dog . → (S (NP NNP)_{NP} (VP VBZ (NP DT NN)_{NP})_{VP} .)_S

Parsing Example



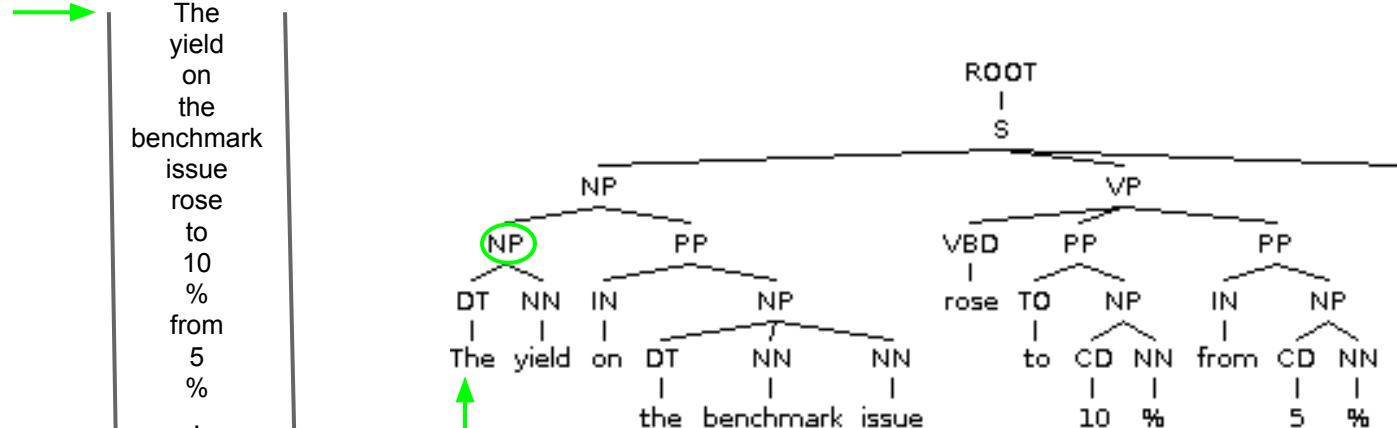
Encoder LSTM
(reverse input)

Parsing Example



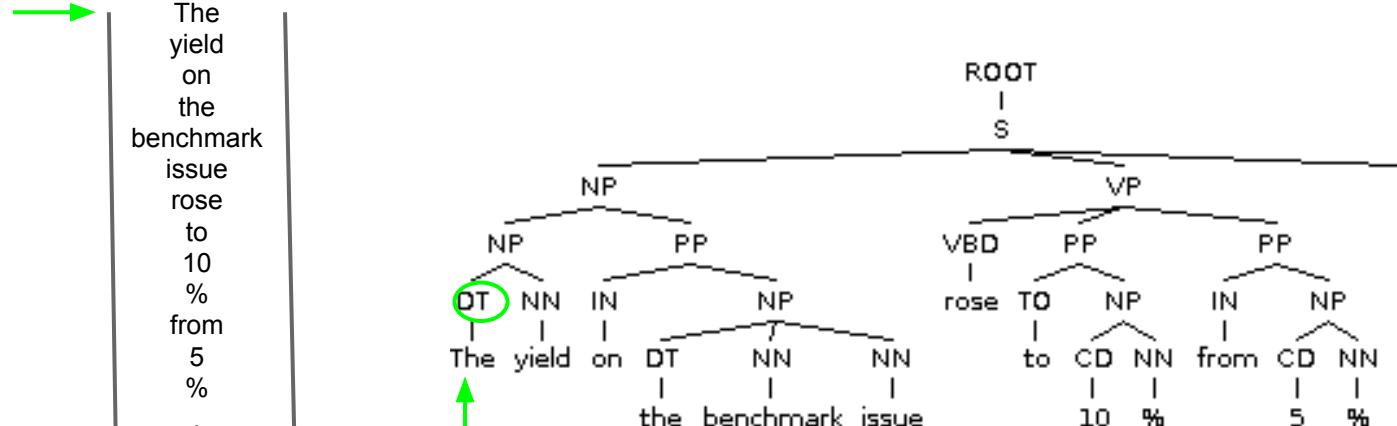
Encoder LSTM
(reverse input)

Parsing Example



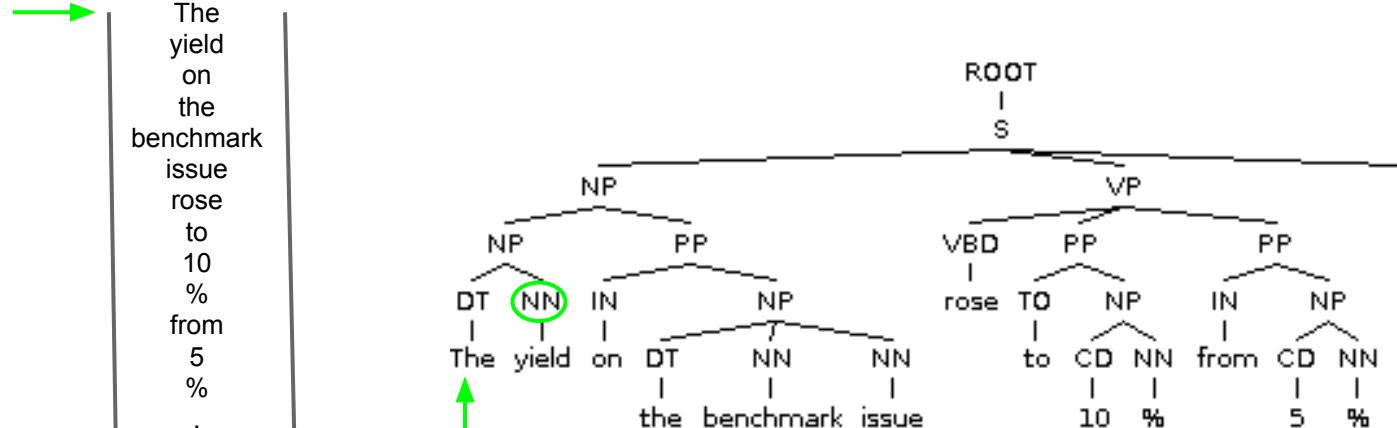
Encoder LSTM
(reverse input)

Parsing Example



Encoder LSTM
(reverse input)

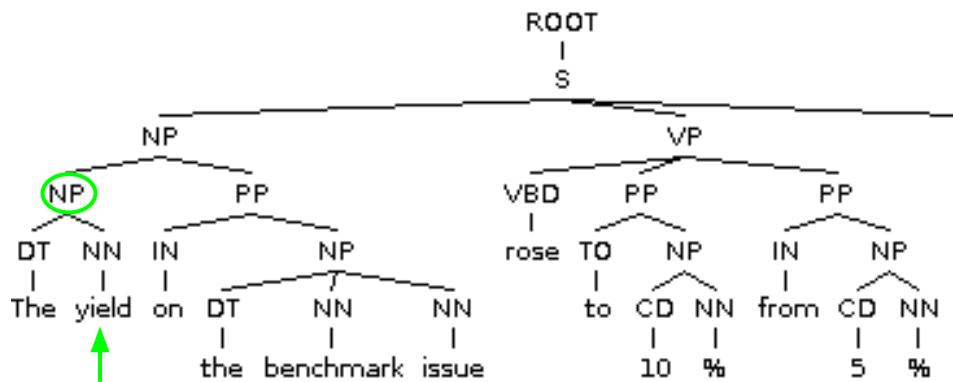
Parsing Example



Encoder LSTM
(reverse input)

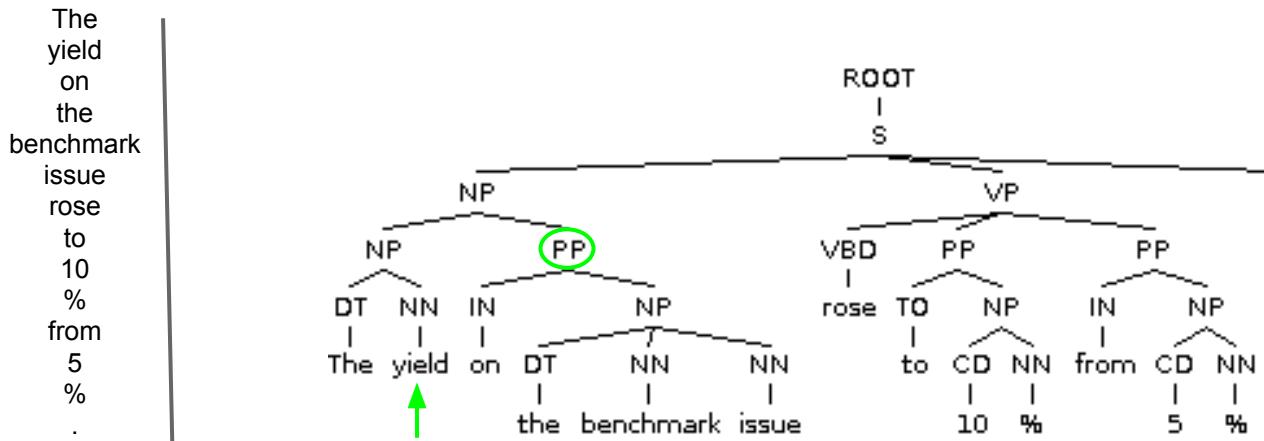
Parsing Example

The
yield
on
the
benchmark
issue
rose
to
10
%
from
5
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.



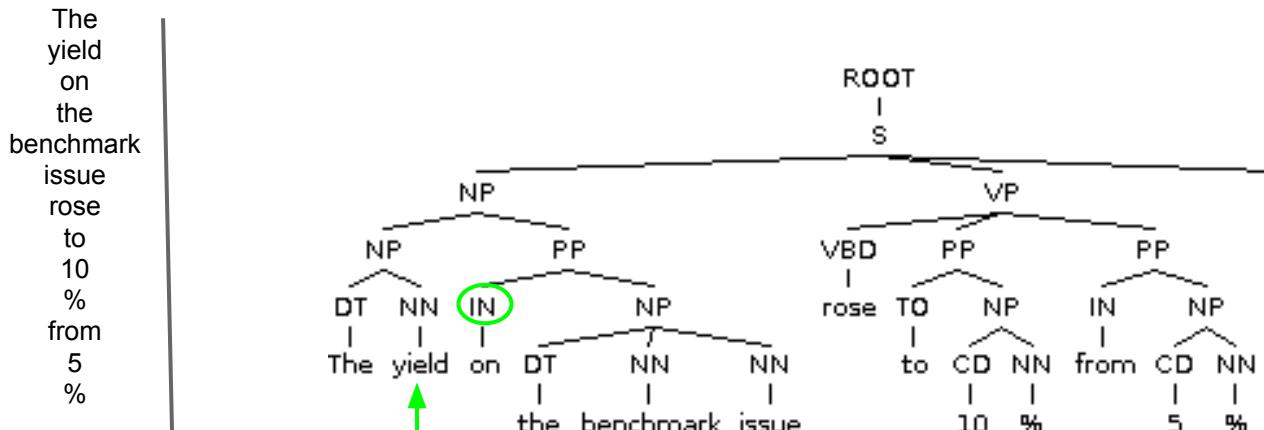
Encoder LSTM
(reverse input)

Parsing Example



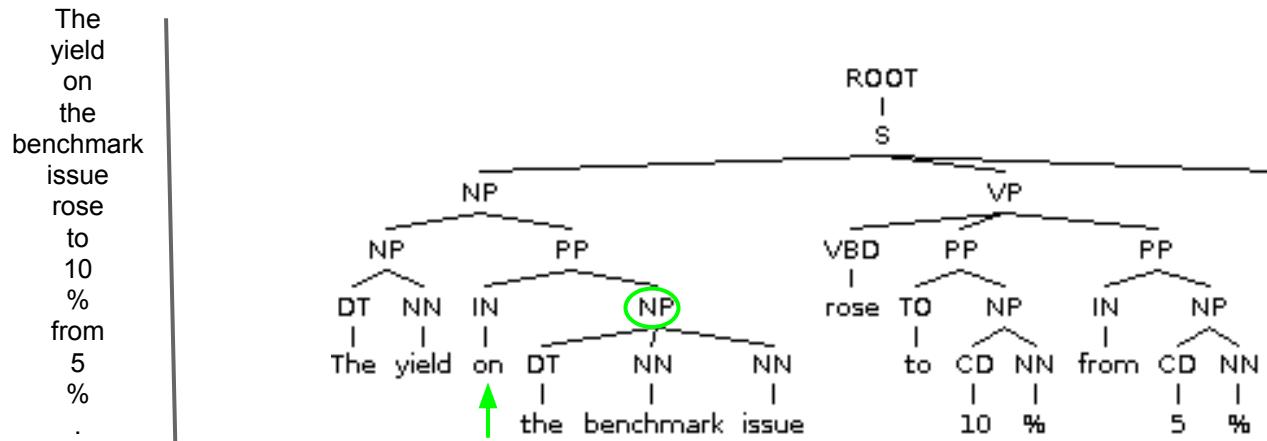
Encoder LSTM
(reverse input)

Parsing Example



Encoder LSTM
(reverse input)

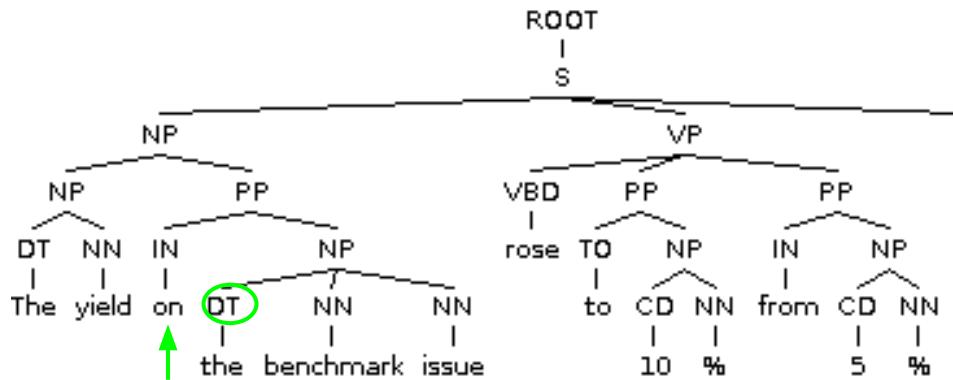
Parsing Example



Encoder LSTM
(reverse input)

Parsing Example

The
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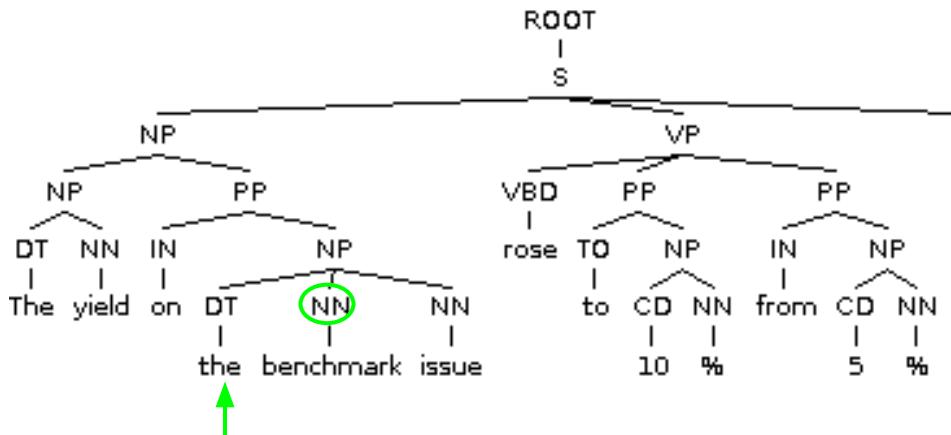


Encoder LSTM
(reverse input)

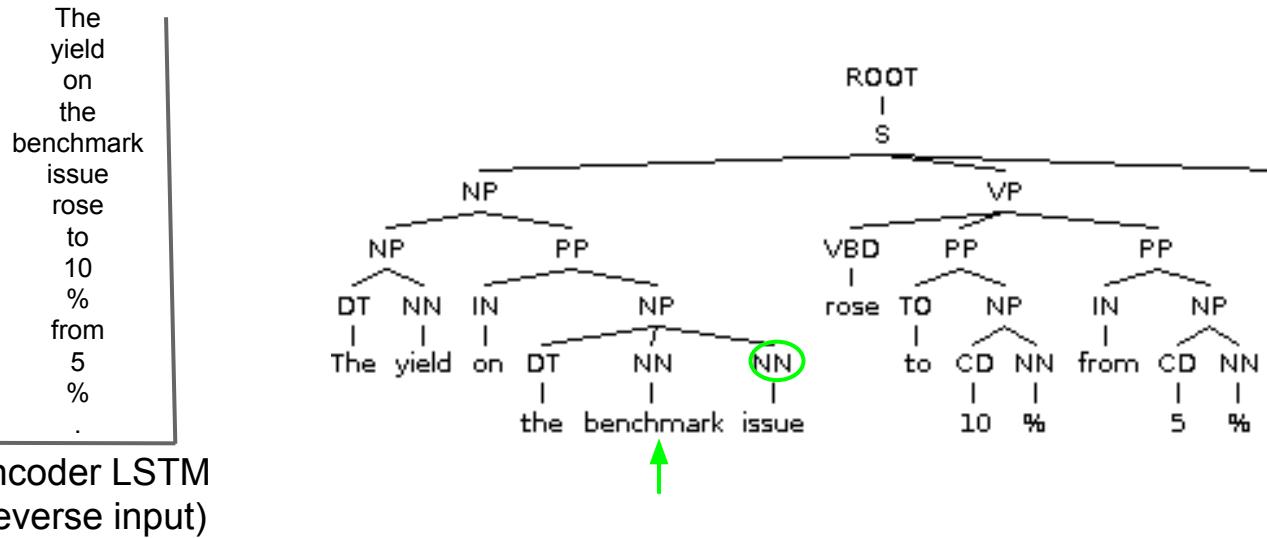
Parsing Example

The
yield
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to
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%
from
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.

Encoder LSTM
(reverse input)

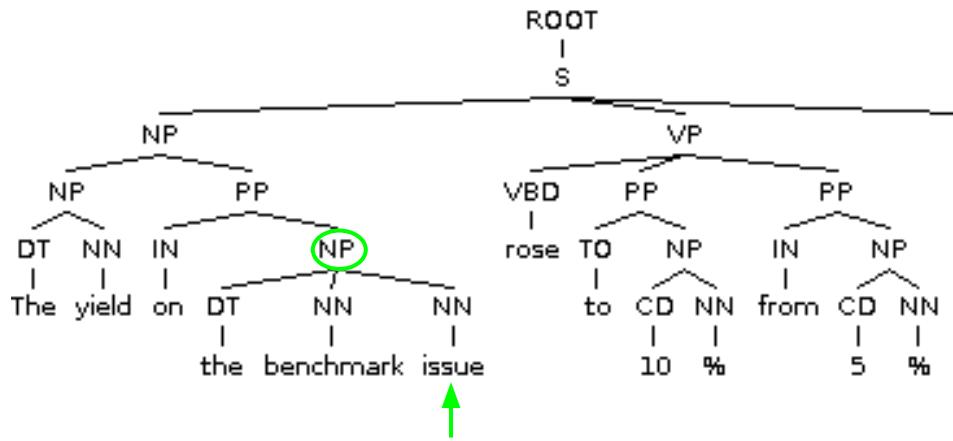


Parsing Example



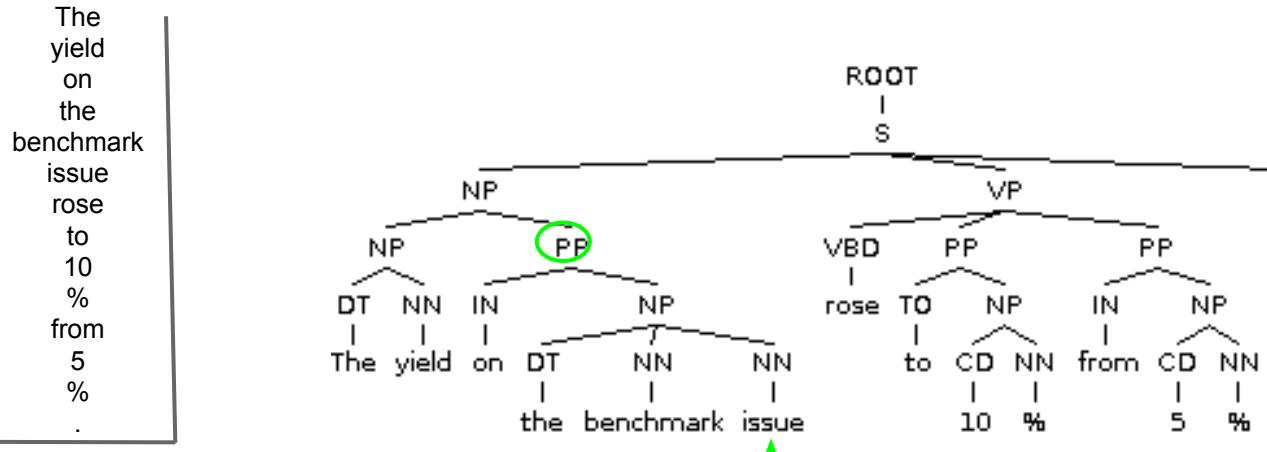
Parsing Example

The
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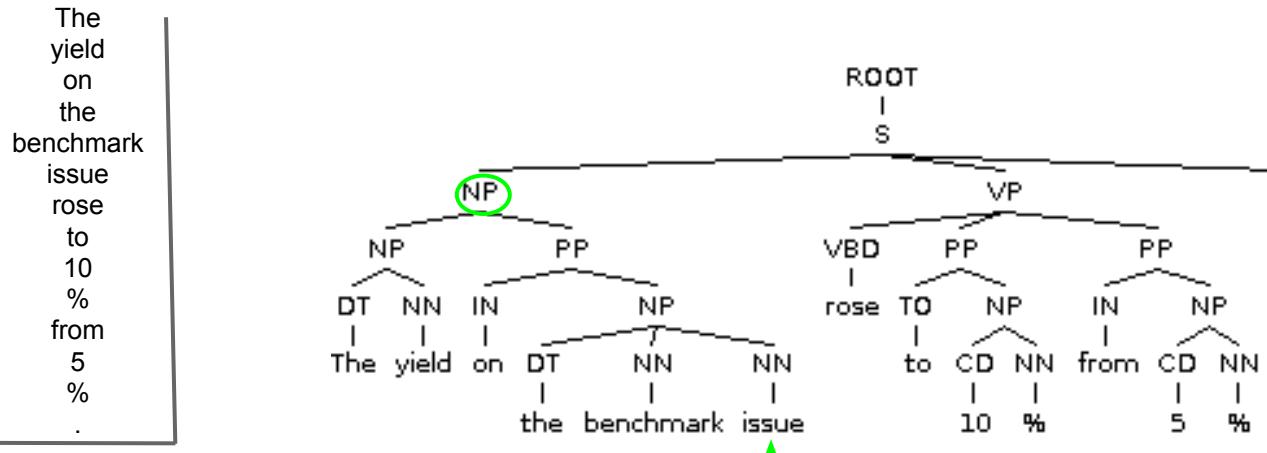
Encoder LSTM
(reverse input)

Parsing Example



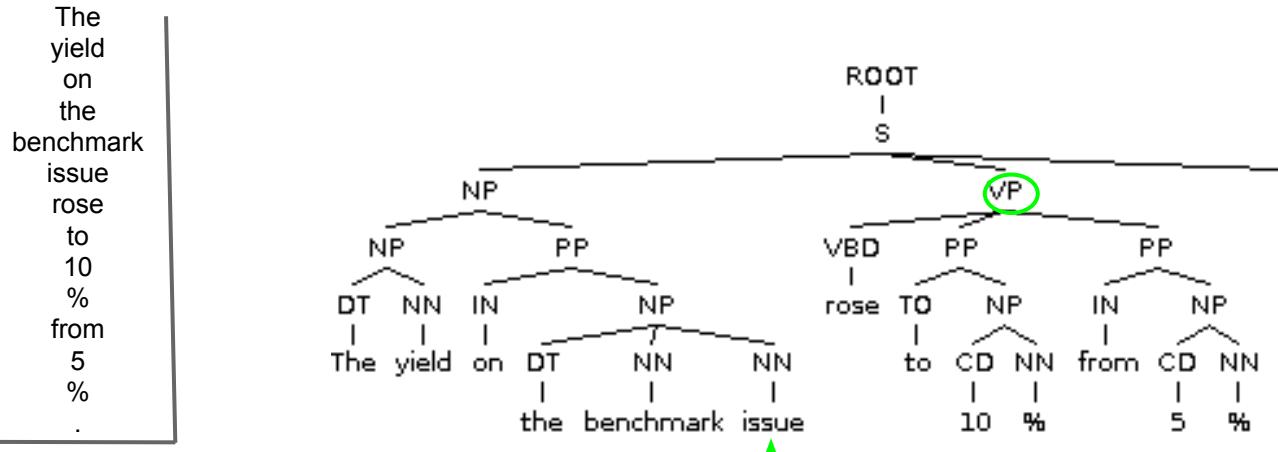
Encoder LSTM
(reverse input)

Parsing Example

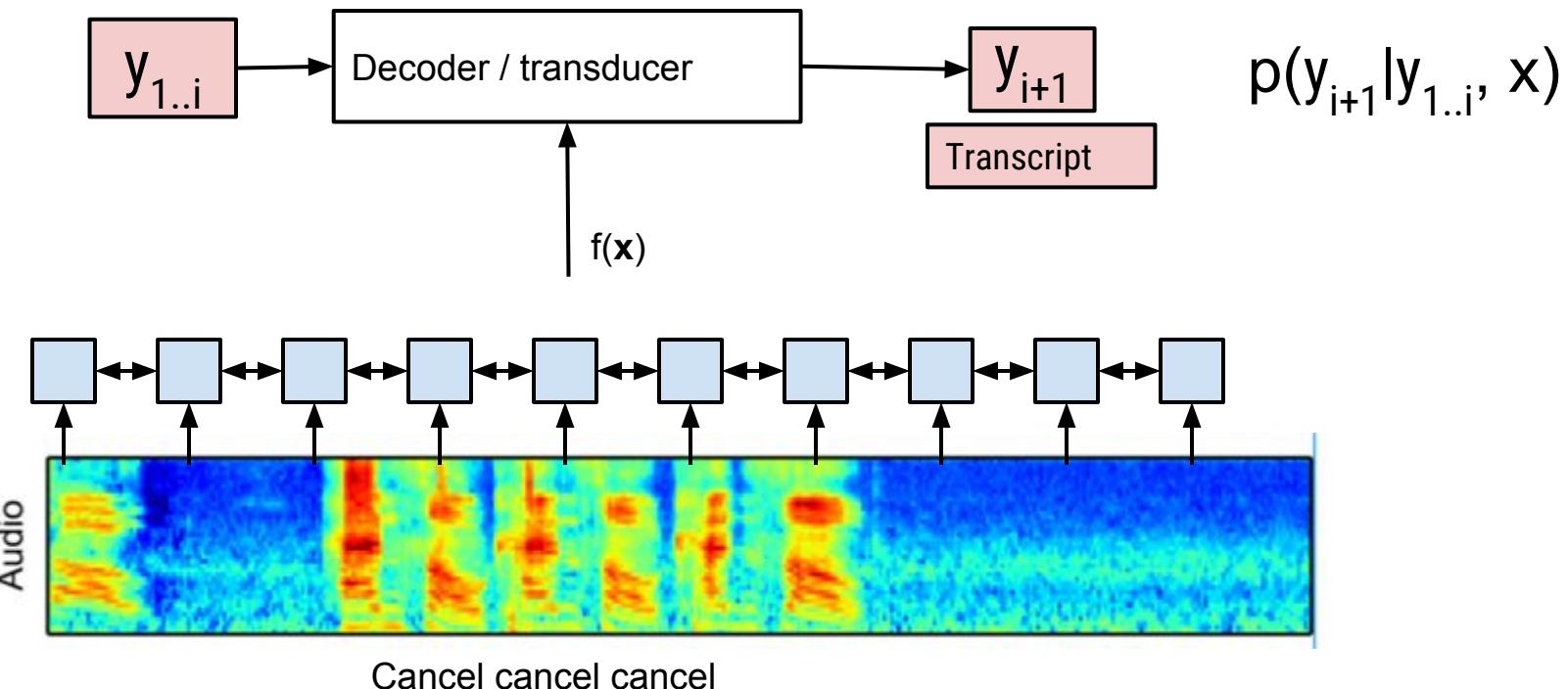


Encoder LSTM
(reverse input)

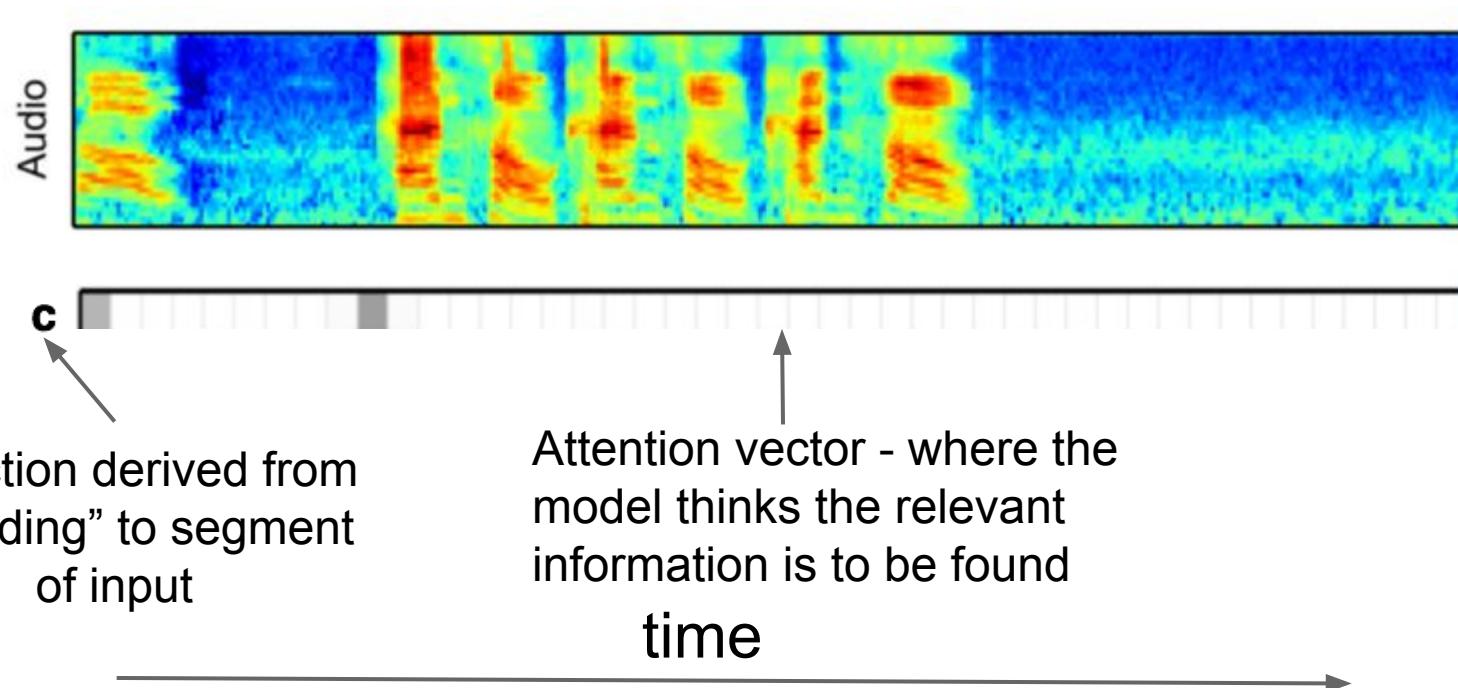
Parsing Example



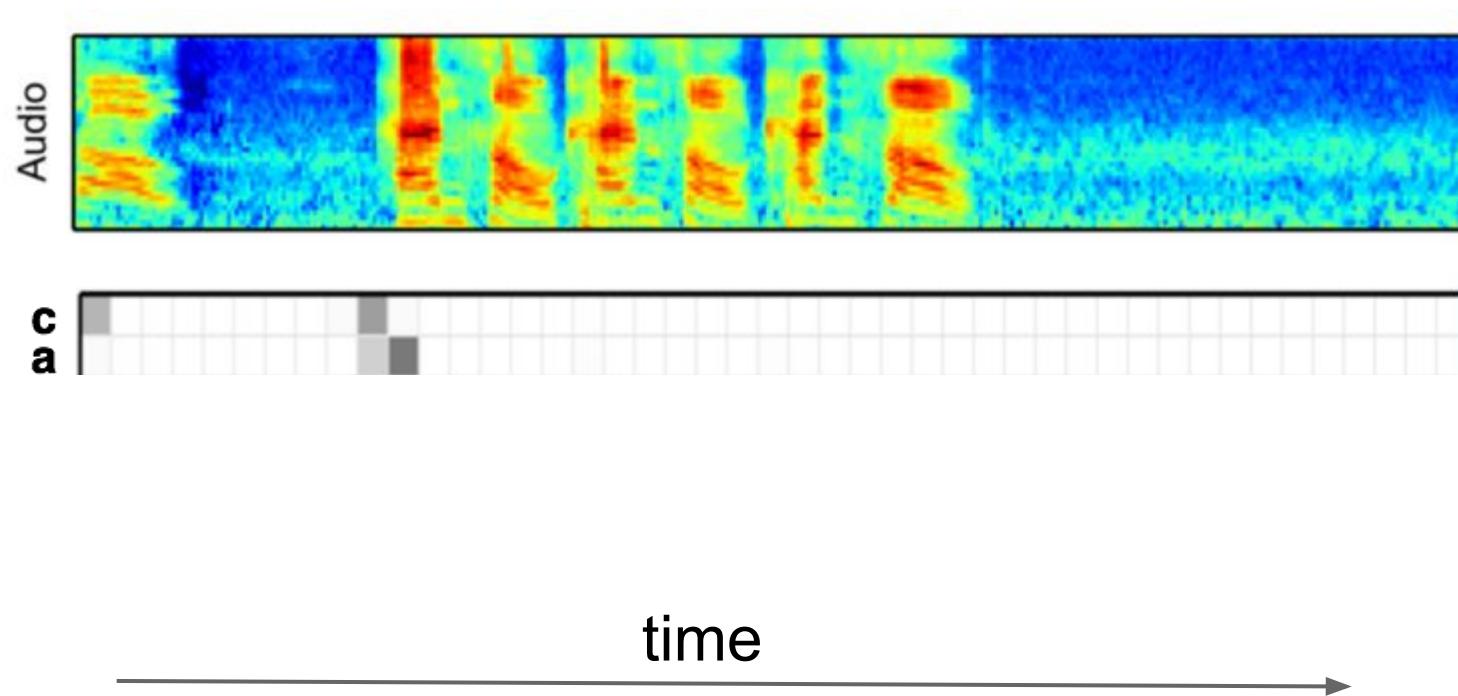
Speech Recognition



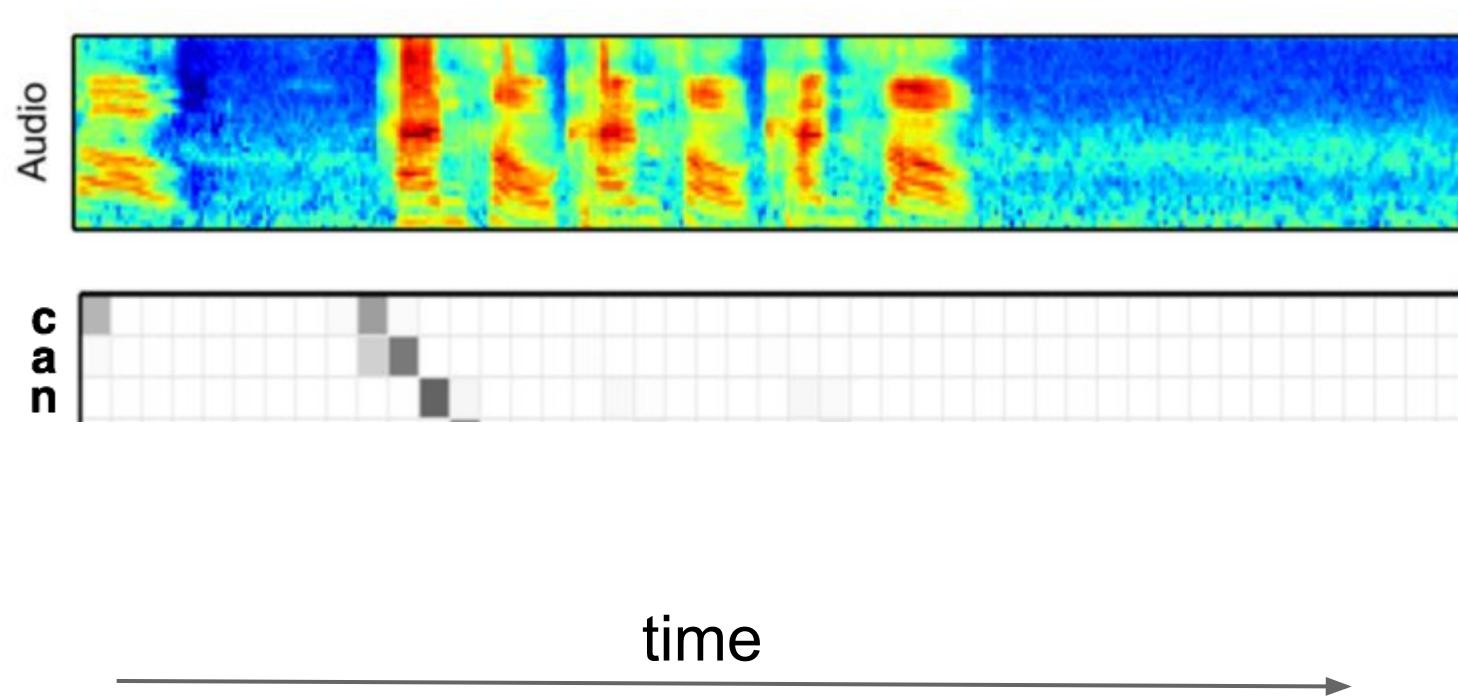
Attention Example



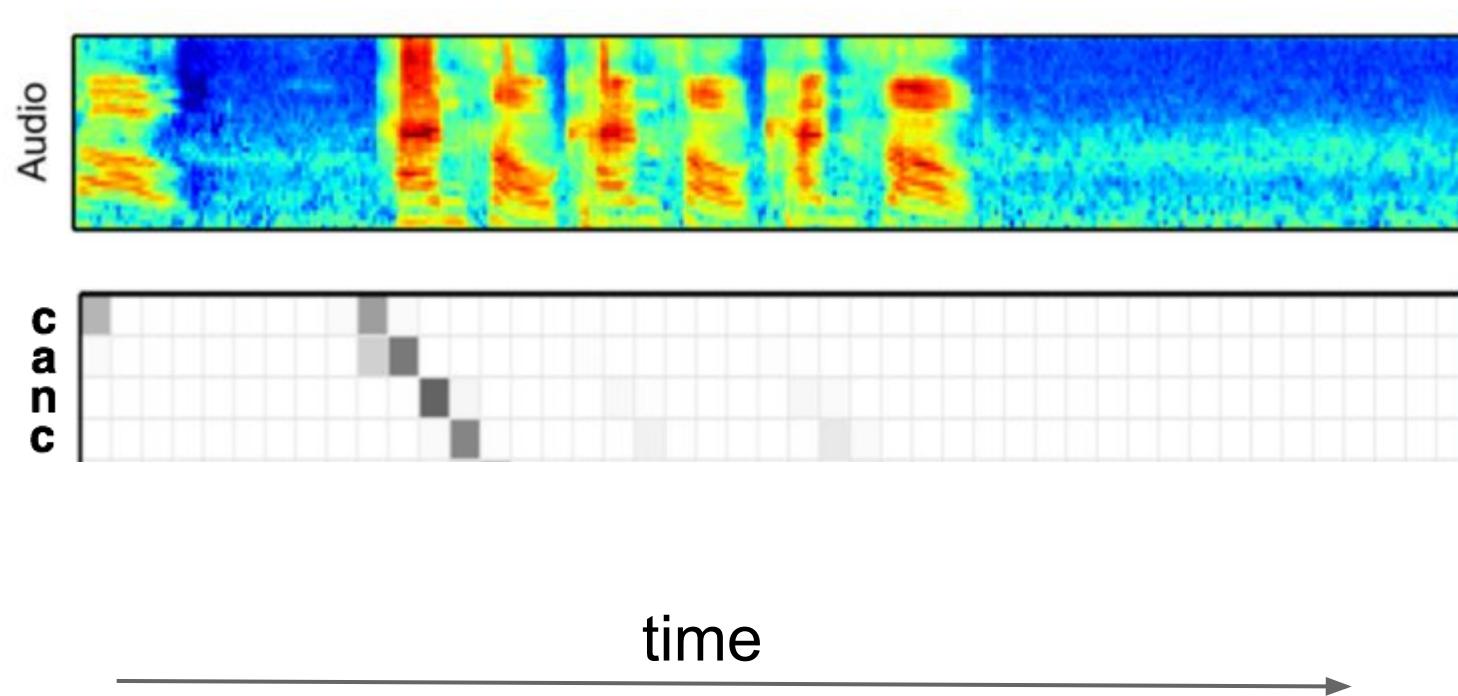
Attention Example



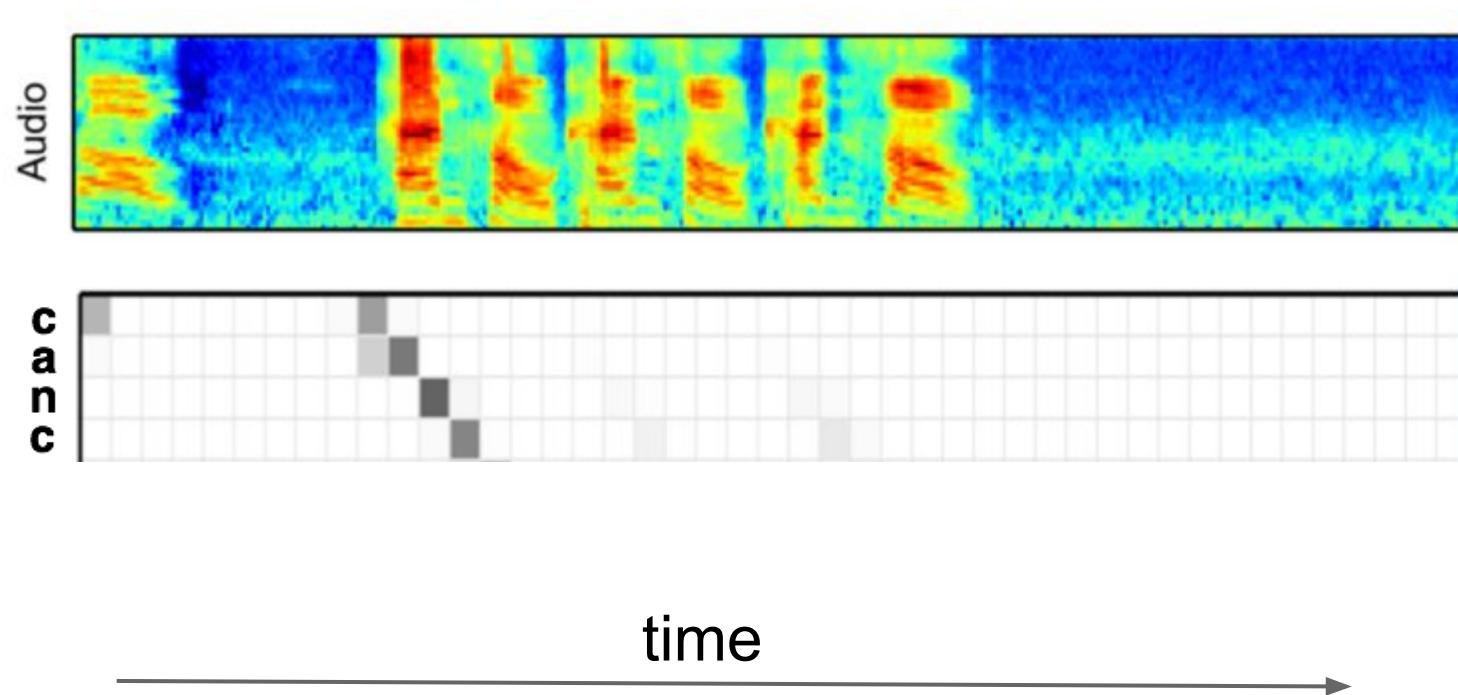
Attention Example



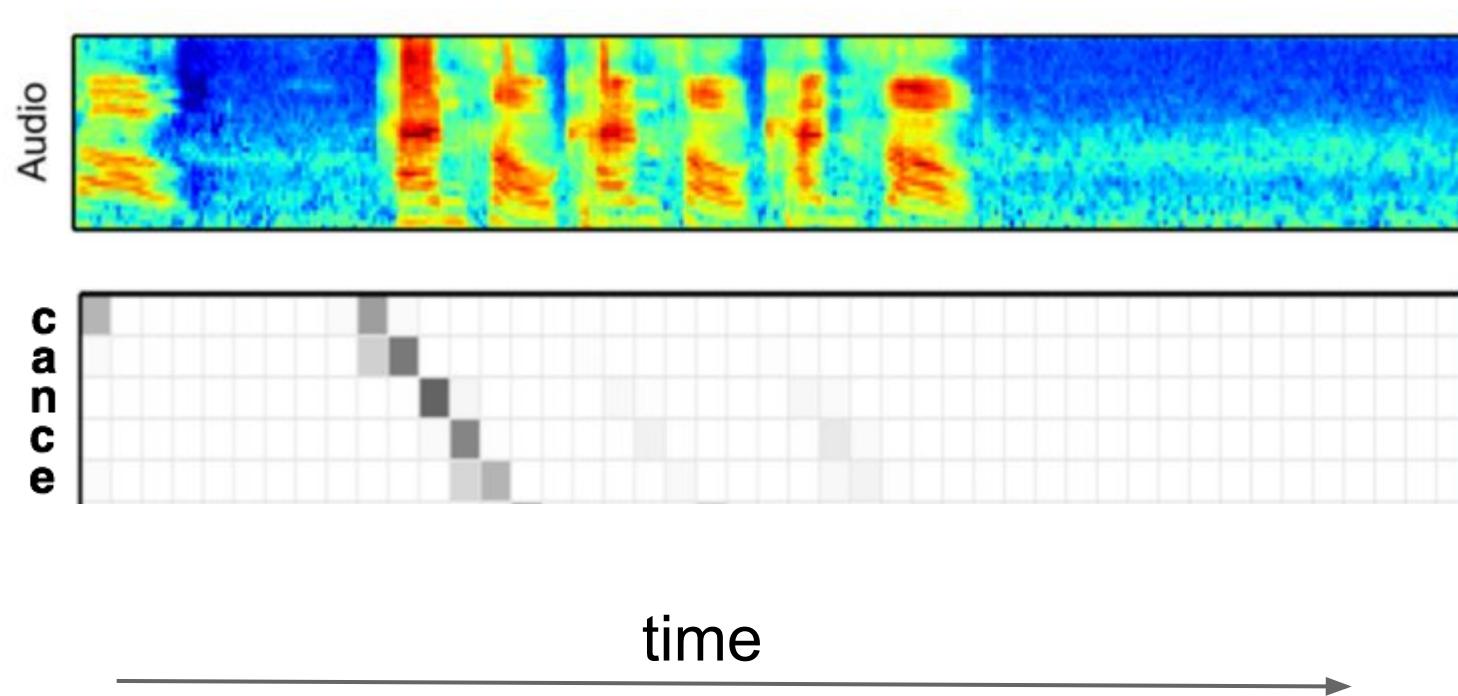
Attention Example



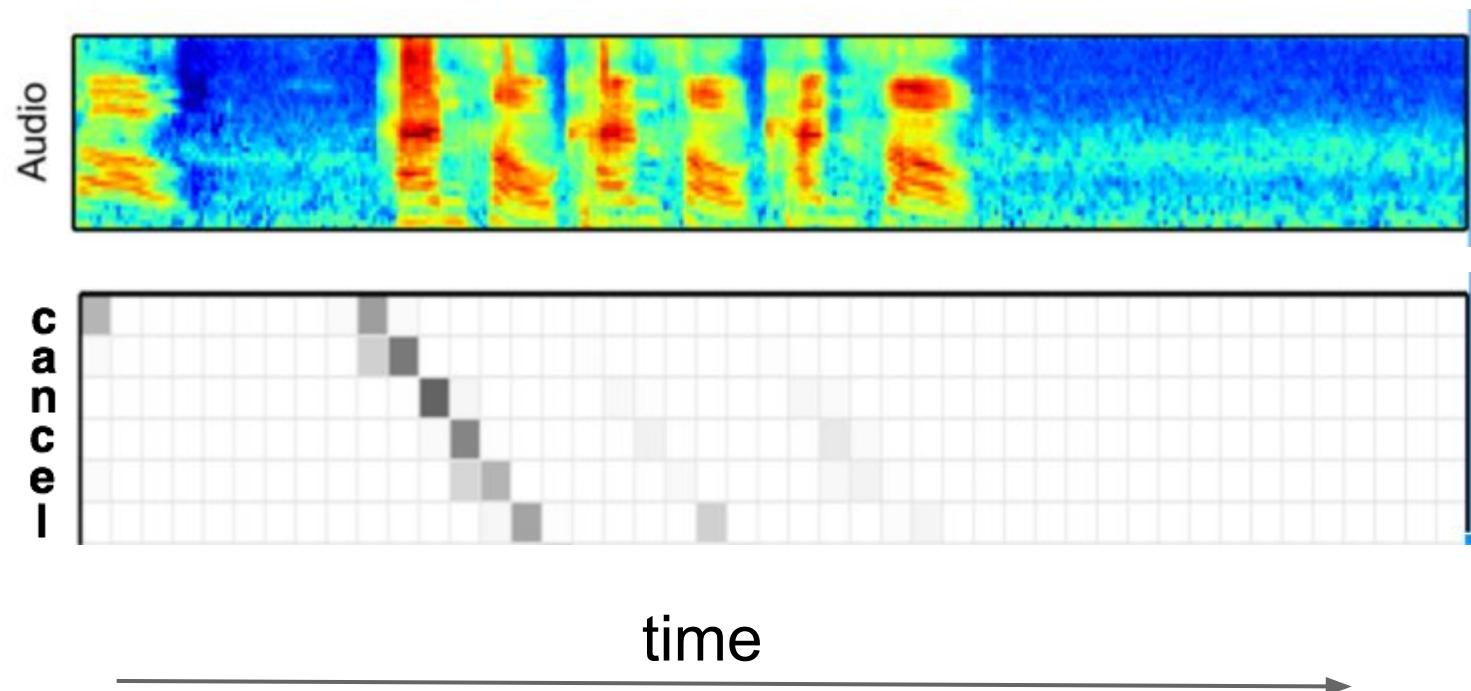
Attention Example



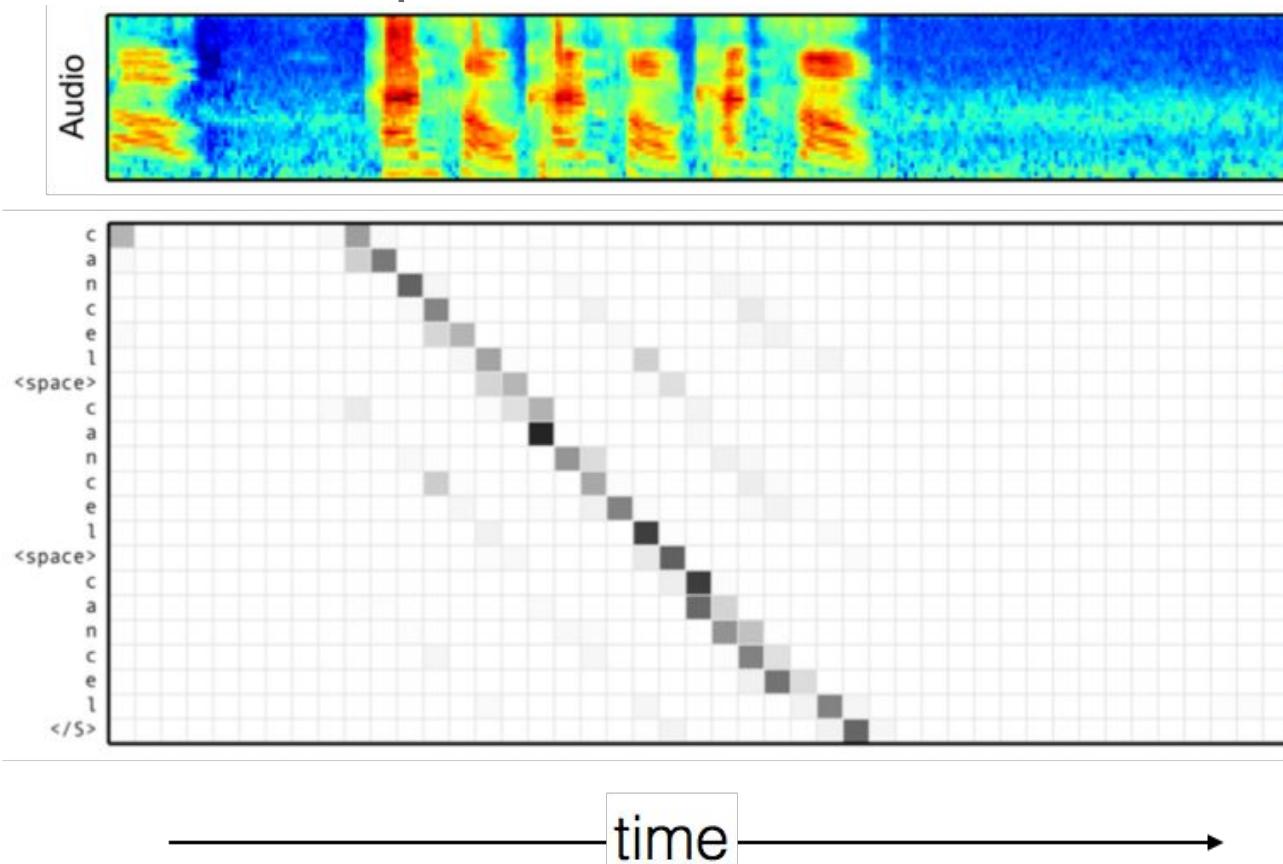
Attention Example



Attention Example

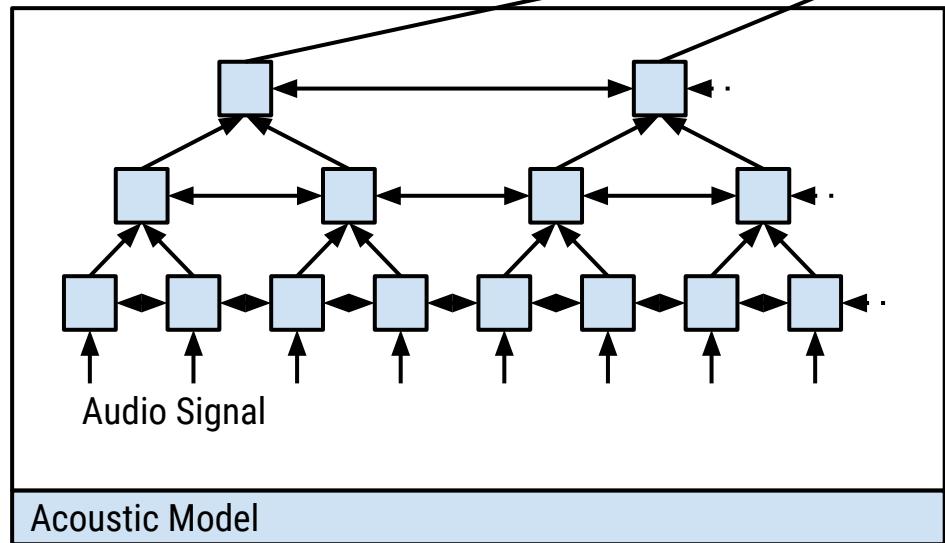


Attention Example



Listen Attend and Spell (LAS)

- Reducing time resolution with a pyramidal encoder

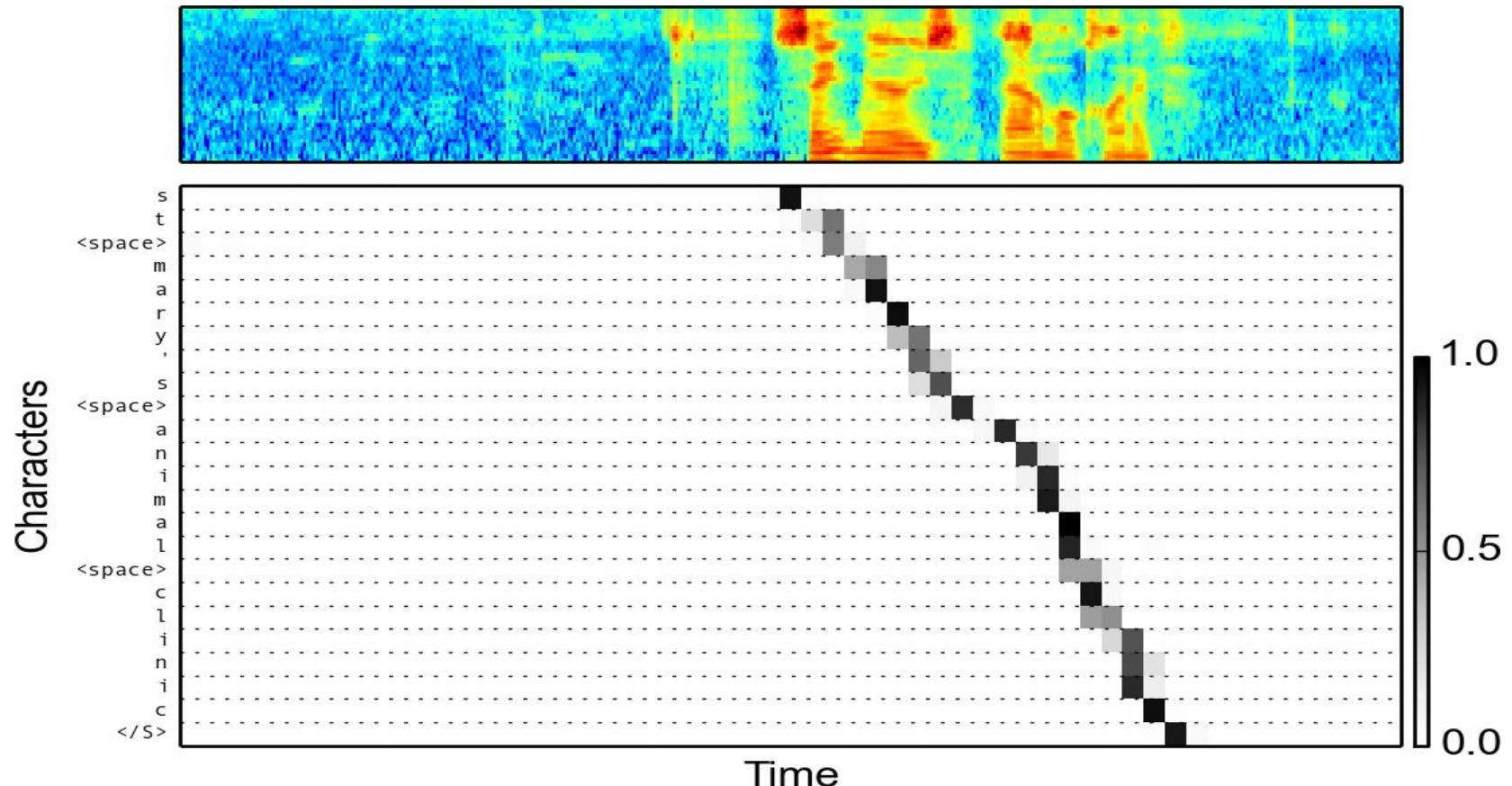


LAS - Multimodal outputs

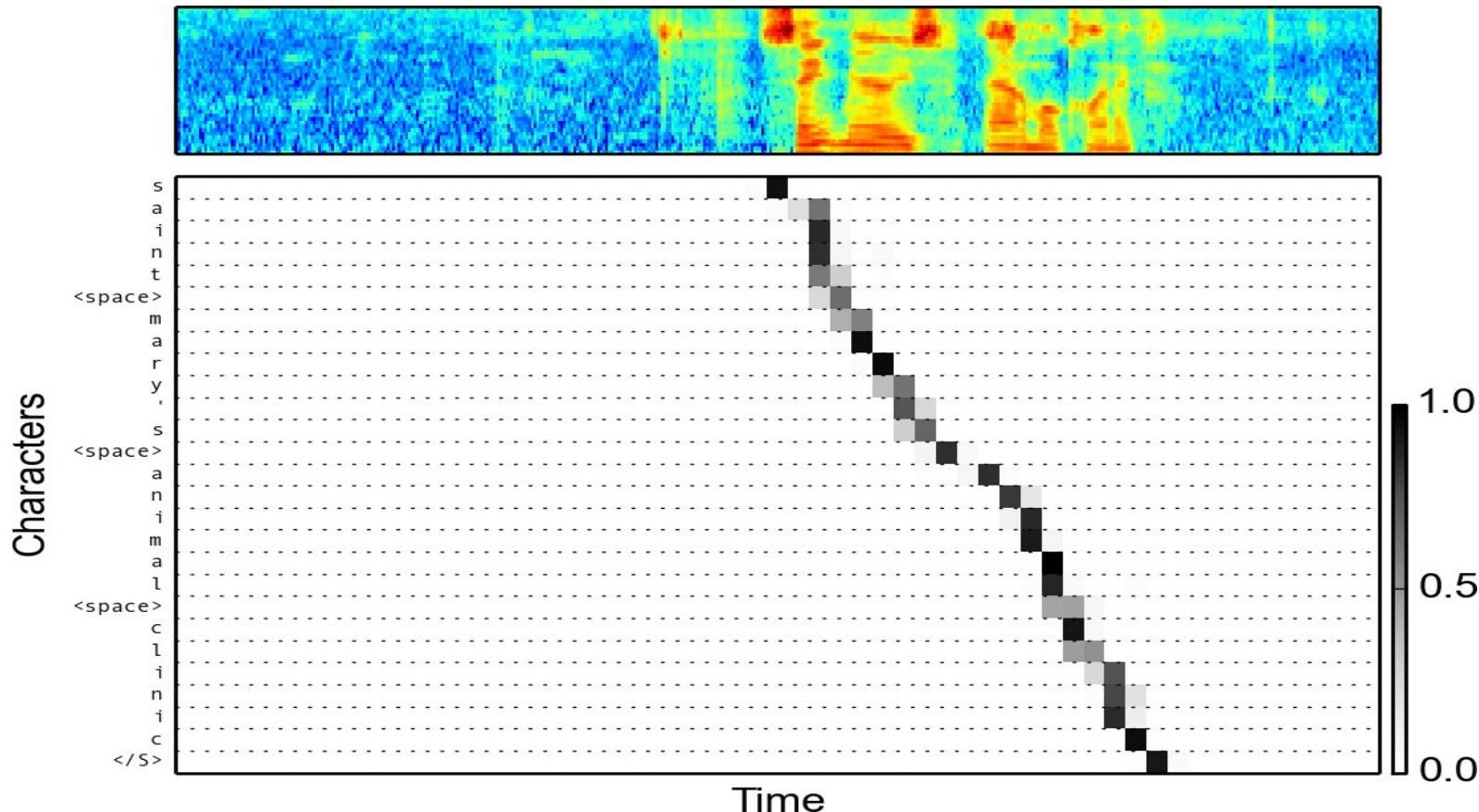
Beam	Text	LogProb	WER
Truth	call aaa roadside assistance	-	-
1	call aaa roadside assistance	-0.5740	0.00
2	call triple a roadside assistance	-1.5399	50.0
3	call trip way roadside assistance	-3.5012	50.0
4	call xxx roadside assistance	-4.4375	25.0

Very different outputs for same input!

LAS - Impact of Autoregressive Inputs on Attention



LAS - Impact of Autoregressive Inputs on Attention



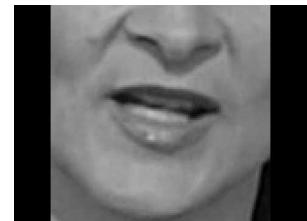
LAS - Results

Model	Clean WER	Noisy WER
CLDNN-HMM (baseline)	8	8.9
Listen Attend and Spell (LAS)	14	16.5
LAS + external language model	10.3	12.0

Comparable to some of our best models without extensive engineering !

Lip Reading

Channel	Series name	# hours	# sent.
BBC 1 HD	News [†]	1,584	50,493
BBC 1 HD	Breakfast	1,997	29,862
BBC 1 HD	Newsnight	590	17,004
BBC 2 HD	World News	194	3,504
BBC 2 HD	Question Time	323	11,695
BBC 4 HD	World Today	272	5,558
All		4,960	118,116

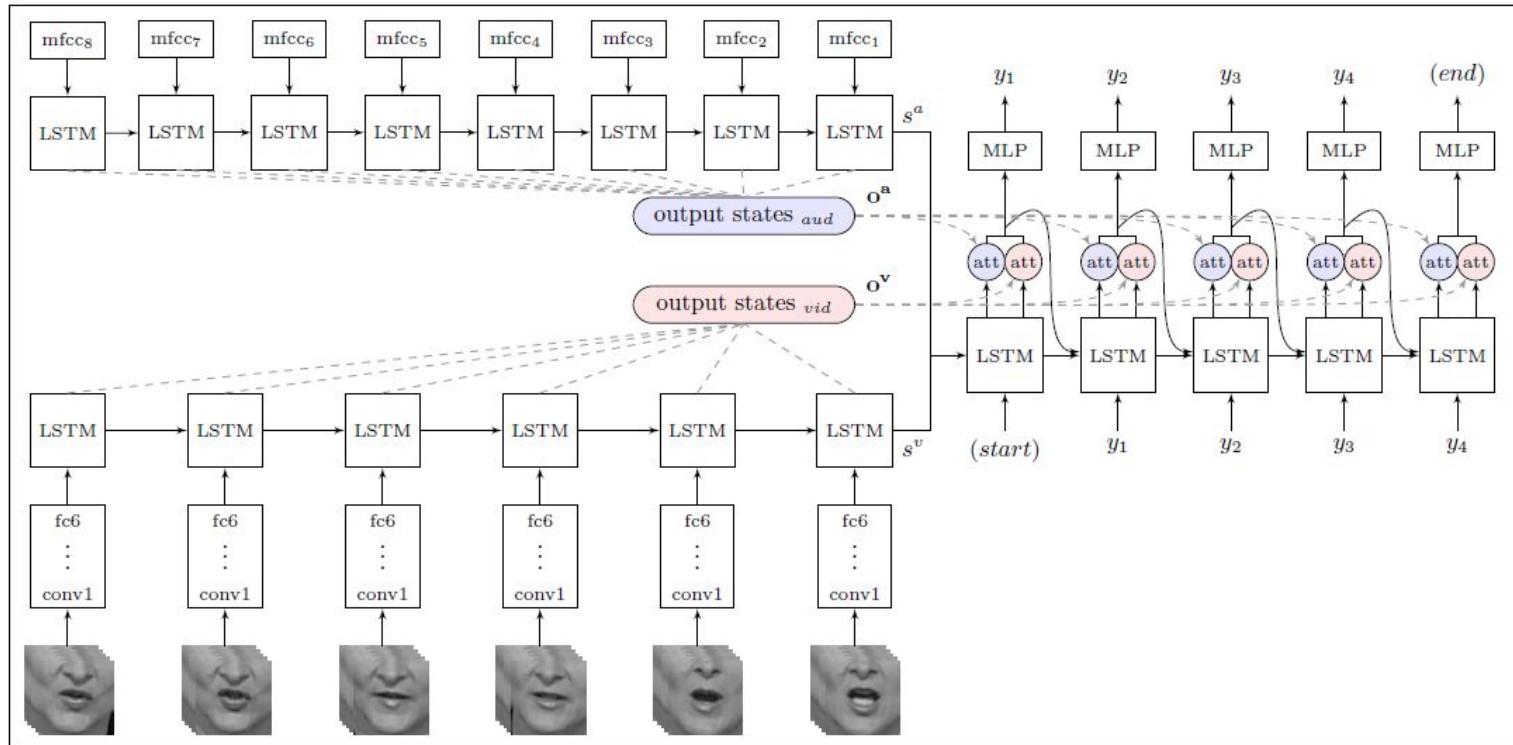


http://www.robots.ox.ac.uk/~vgg/data/lip_reading/

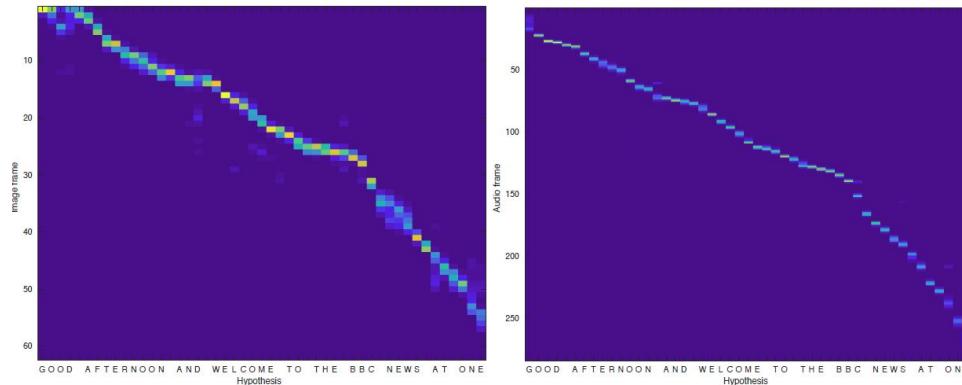
1. Chung, J., et al. "Lip reading sentences in the wild." *CVPR* (2017).
2. Assael, Y., et al. "Lipnet: Sentence-level lipreading." *arxiv* (2016).

Lip Reading

Separate
embedding
and attention
for audio and
visual
streams

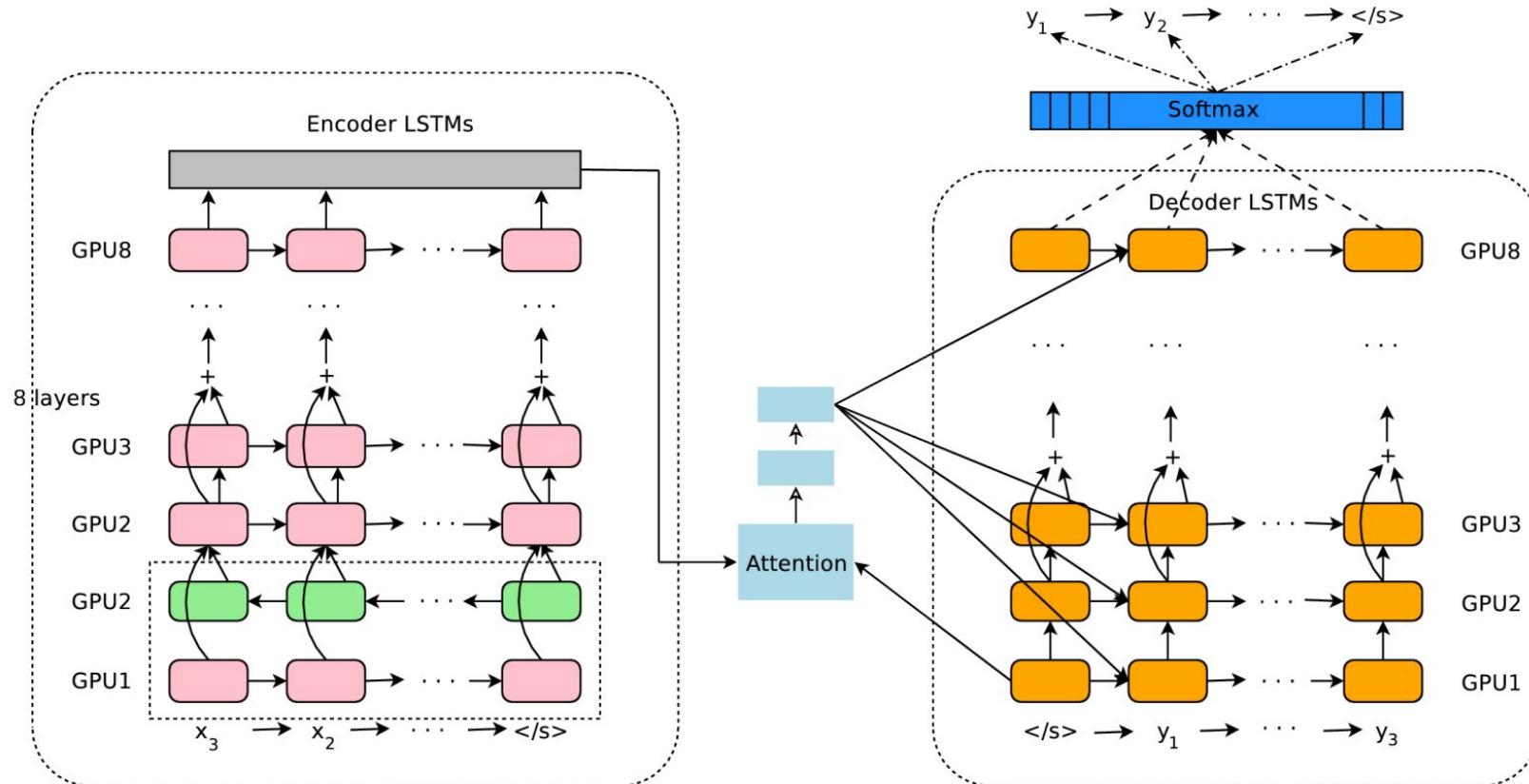


Lip Reading



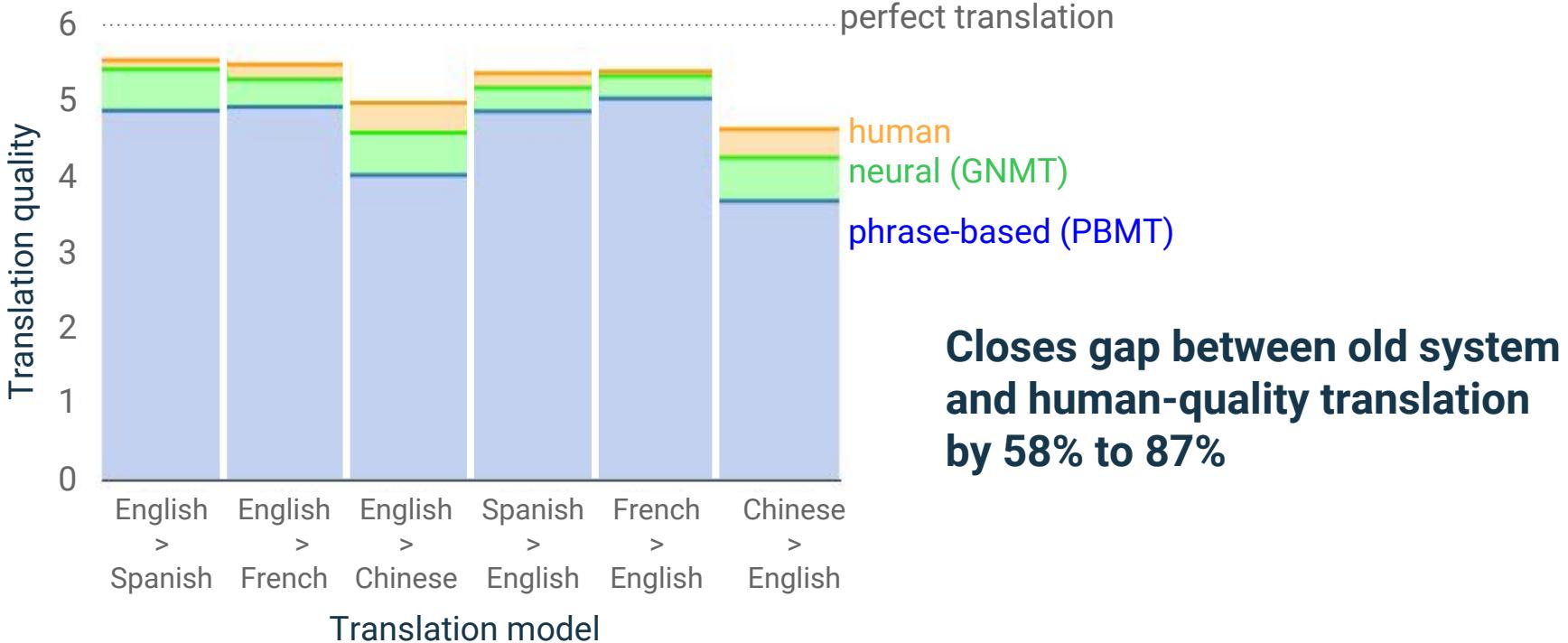
Method	SNR	CER	WER	BLEU [†]
Lips only				
Professional [‡]	-	58.7%	73.8%	23.8
WAS	-	59.9%	76.5%	35.6
WAS+CL	-	47.1%	61.1%	46.9
WAS+CL+SS	-	42.4%	58.1%	50.0
WAS+CL+SS+BS	-	39.5%	50.2%	54.9

Google Neural Machine Translation System



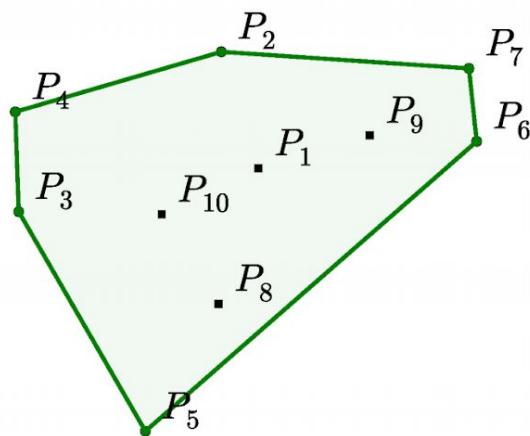
Wu, Y., et al. "Google's Neural Machine Translation System: Bridging the Gap between Human and Machine Translation." arxiv (2016).

Google Neural Machine Translation

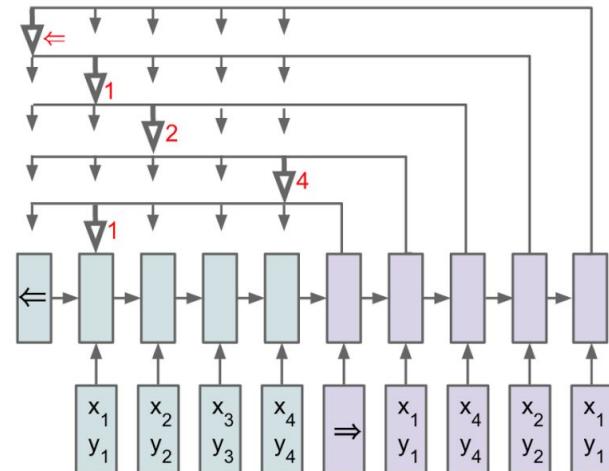
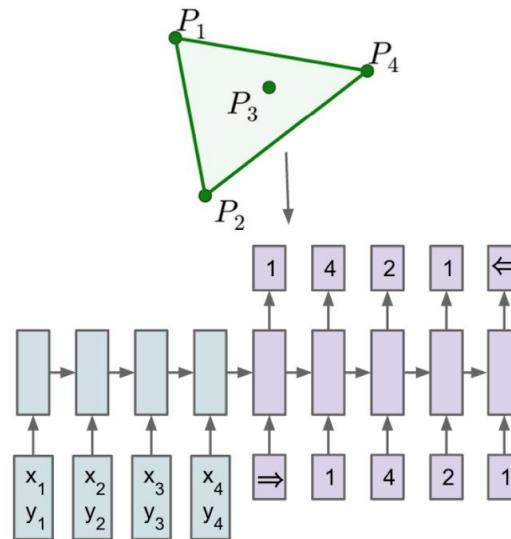


Pointer Networks

- Adaptation of sequence to sequence with attention for self referential outputs

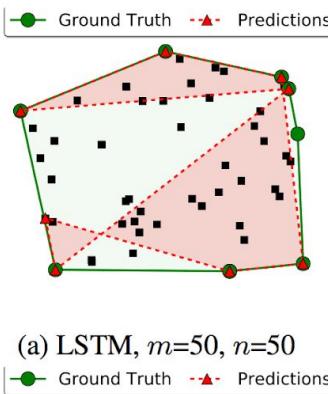


Convex Hull

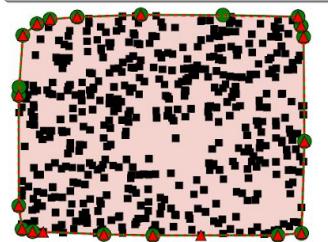


Pointer Networks

Convex hull

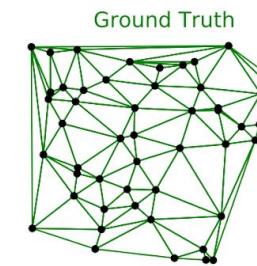


(a) LSTM, $m=50, n=50$

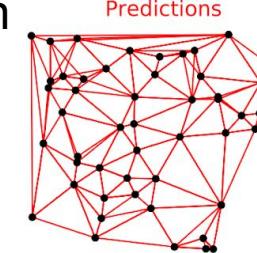


(d) Ptr-Net, $m=5-50, n=500$

Delauney Triangulation

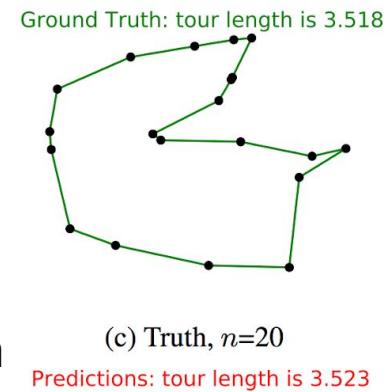


(b) Truth, $n=50$



(e) Ptr-Net , $m=50, n=50$

Travelling Salesman Problem



(c) Truth, $n=20$

Predictions: tour length is 3.523

(f) Ptr-Net , $m=5-20, n=20$

- Merity, Stephen, et al. "Pointer sentinel mixture models." *arXiv preprint arXiv:1609.07843* (2016).
- Kadlec, Rudolf, et al. "Text understanding with the attention sum reader network." *arXiv preprint arXiv:1603.01547* (2016).
- Gulchere, C., et. al. "Pointing the unknown words" *ACL* (2016)

Break

Loss Function

Loss Functions

- Cross Entropy
- Scheduled Sampling [1]
- Expected Loss [2]
- Augmented Loss [3]
- Sequence to Sequence as a beam search optimization [4]
- Learning decoders with different loss function [5]

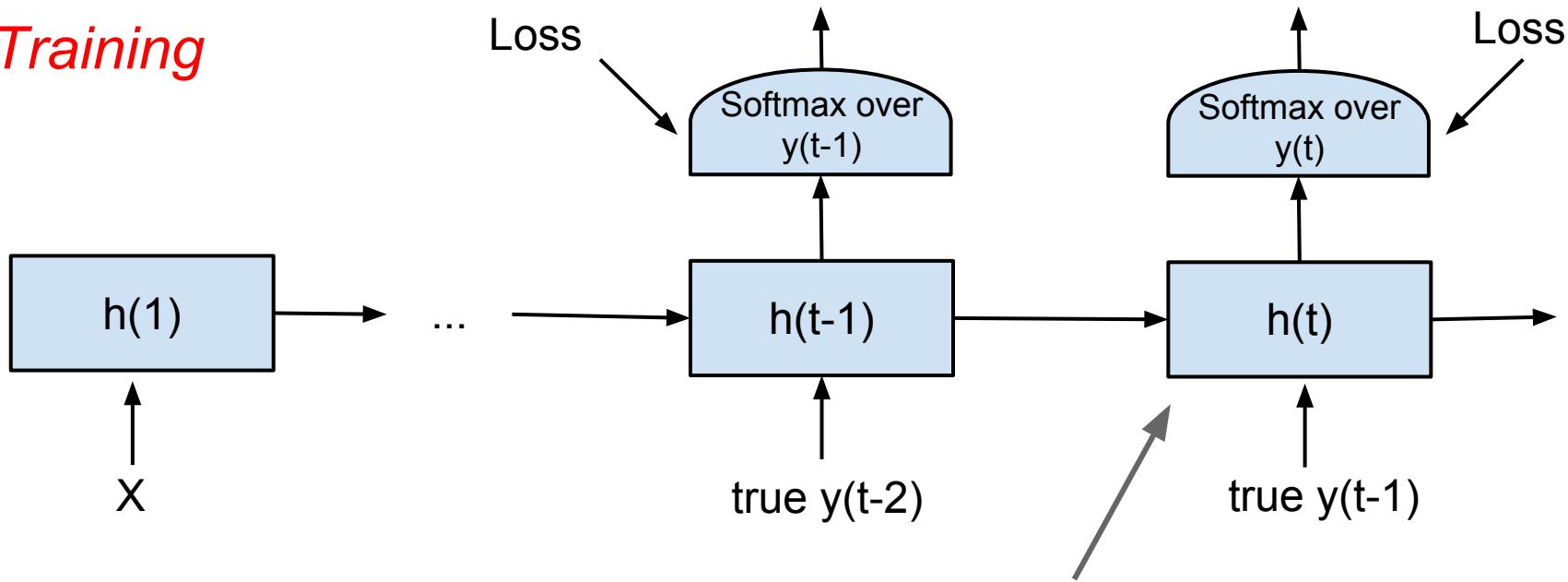
1. Bengio, S., et al. "Scheduled sampling for sequence prediction with recurrent neural networks." *NIPS* (2015).
2. Ranzato, M., et al. "Sequence level training with recurrent neural networks." *ICLR* (2016).
3. Norouzi, M., et al. "Reward augmented maximum likelihood for neural structured prediction." *NIPS* (2016).
4. Wiseman, S., Rush, A. "Sequence-to-sequence learning as beam-search optimization." *EMLP* (2016).
5. Gu, J, Cho, K and Li, V.O.K. "Trainable greedy decoding for neural machine translation." *arXiv preprint arXiv:1702.02429* (2017).

Cross Entropy (Negative Log Likelihood) Loss

- Log Likelihood, by chain rule is sum of next step log likelihoods $\log p(\mathbf{y}|\mathbf{x}) = \sum_{i=1}^N \log p(y_i|y_{<i}, \mathbf{x})$
- Supervised classification for each time step
 - depends on input, past outputs, which are known during training

Training and Inference Mismatch

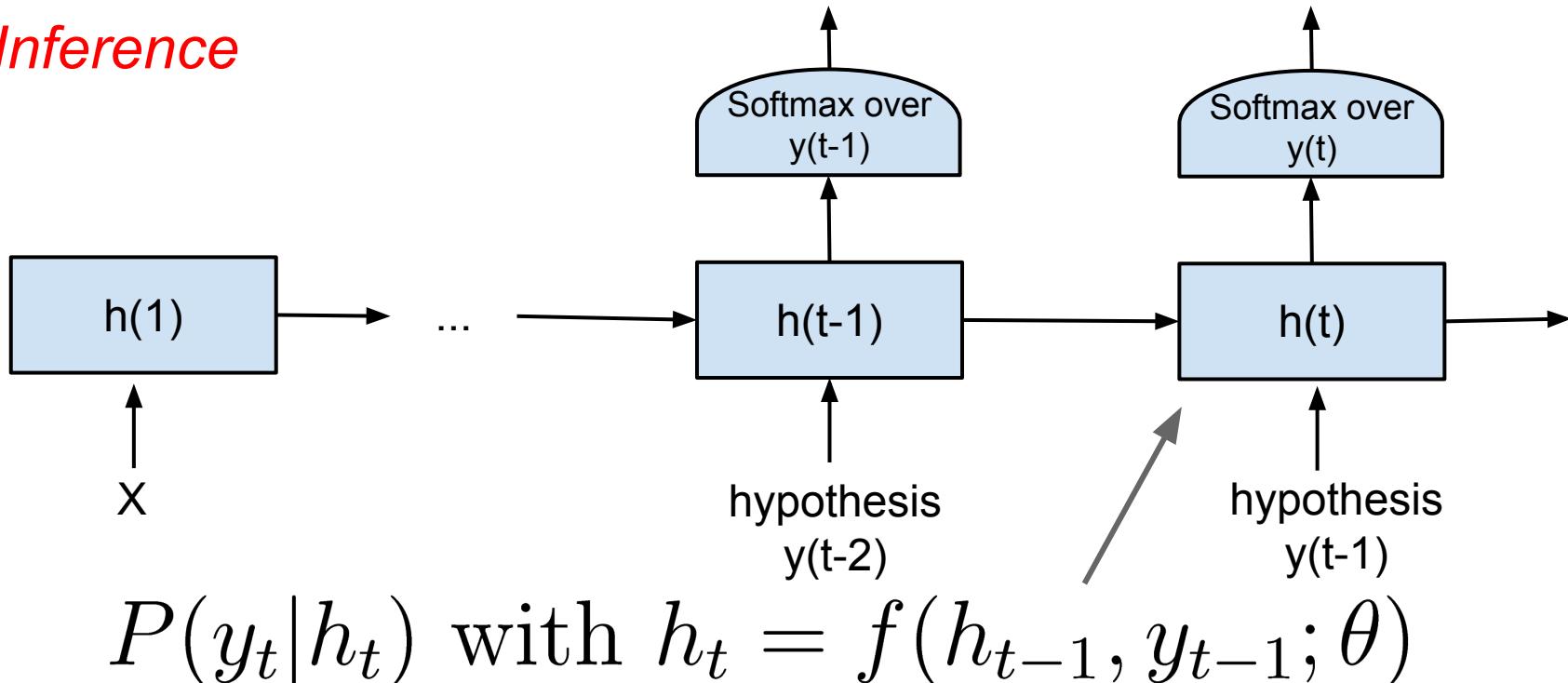
Training



$$P(y_t|h_t) \text{ with } h_t = f(h_{t-1}, y_{t-1}; \theta)$$

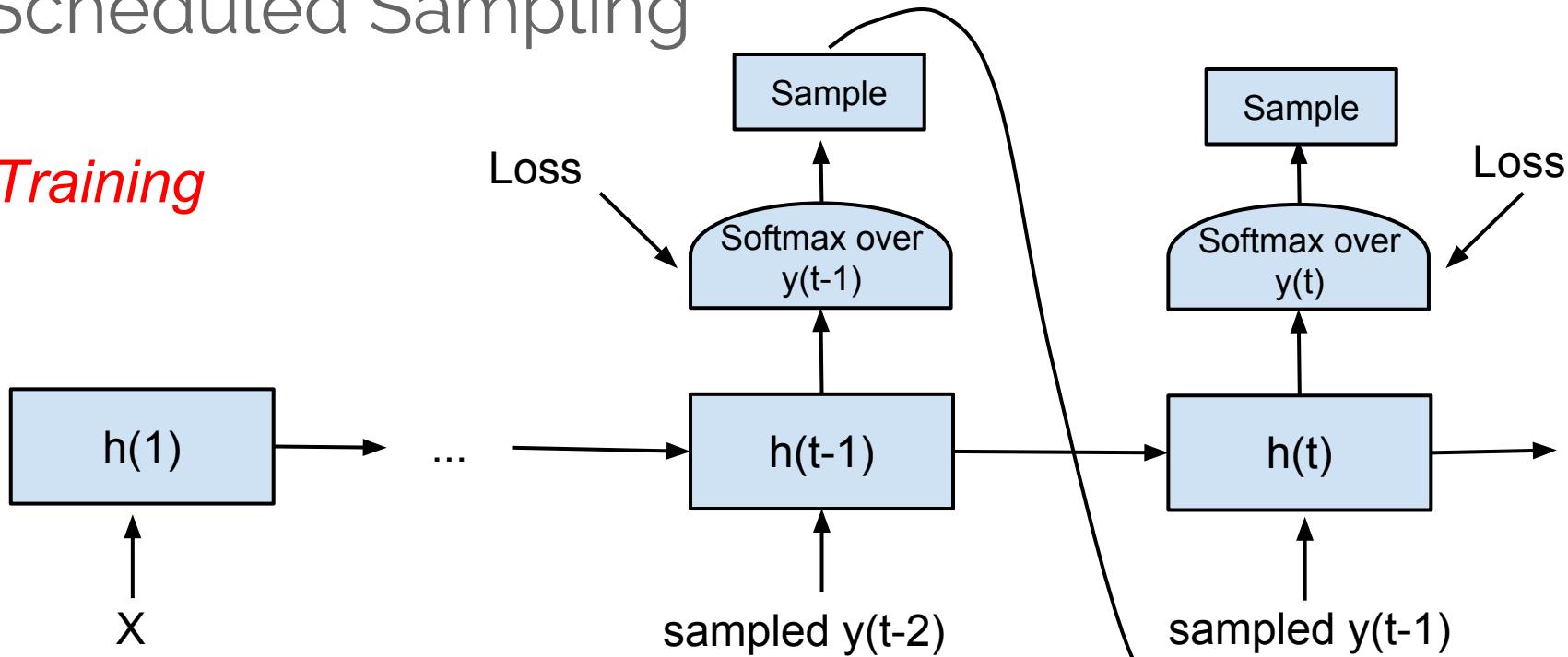
Training and Inference Mismatch

Inference



Scheduled Sampling

Training



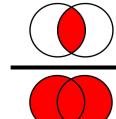
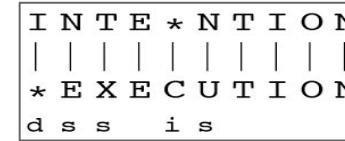
$$P(y_t|h_t) \text{ with } h_t = f(h_{t-1}, \hat{y}_{t-1}; \theta)$$

Scheduled Sampling

Machine Translation Model	Bleu-4	Meteor	Cider
Baseline	28.8	24.2	89.5
Baseline with dropout	28.1	23.9	87.0
Scheduled sampling	30.6	24.3	92.1

Parsing Model	F1	Speech Recognition Model	WER
Baseline LSTM with dropout	87.00	LAS + LM Rescoring	12.6
Scheduled sampling with dropout	88.68	LAS + Sampling + LM Rescoring	10.3

Rewards (-loss) used in Structured Prediction

TASK	REWARD	
Classification	0/1 rewards	$r(\mathbf{y}, \mathbf{y}^*) = \mathbb{1}[\mathbf{y} = \mathbf{y}^*]$
Segmentation	Intersection over Union	$r(\mathbf{y}, \mathbf{y}^*) = \cap(\mathbf{y}, \mathbf{y}^*) / \cup(\mathbf{y}, \mathbf{y}^*)$ 
Speech Recognition	Edit Distance	$r(\mathbf{y}, \mathbf{y}^*) = (\#d + \#i + \#s)$ 
Machine Translation	BLEU	

Expected reward (-loss)

Given a dataset of input output pairs, $\mathcal{D} \equiv \{(\mathbf{x}^{(i)}, \mathbf{y}^{(i)*})\}_{i=1}^N$

learn a conditional distribution $p_\theta(\mathbf{y} \mid \mathbf{x})$ that minimizes

expected loss:
$$\mathcal{L}_{\text{RL}}(\boldsymbol{\theta}) = \sum_{(\mathbf{x}, \mathbf{y}^*) \in \mathcal{D}} - \sum_{\mathbf{y} \in \mathcal{Y}} p_\theta(\mathbf{y} \mid x) r(\mathbf{y}, \mathbf{y}^*)$$



*Sample from the
model distribution*

Difficult / Impossible to train from scratch!!

Mixed Incremental Cross-Entropy Reinforce (MIXER)

- Gradually interpolate from Cross-Entropy to Expected Loss

Data: a set of sequences with their corresponding context.

Result: RNN optimized for generation.

Initialize RNN at random and set N^{XENT} , $N^{\text{XE+R}}$ and Δ ;

for $s = T, 1, -\Delta$ **do**

if $s == T$ **then**

 train RNN for N^{XENT} epochs using XENT only;

else

 train RNN for $N^{\text{XE+R}}$ epochs. Use XENT loss in the first s steps, and REINFORCE (sampling from the model) in the remaining $T - s$ steps;

end

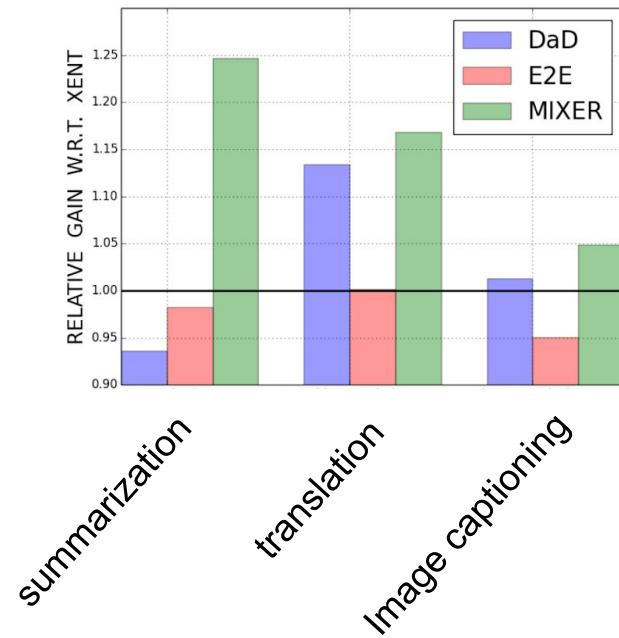
end

*More expected loss
optimization as training
proceeds*



Mixed Incremental Cross-Entropy Reinforce (MIXER)

TASK	XENT	DAD	E2E	MIXER
<i>summarization</i>	13.01	12.18	12.78	16.22
<i>translation</i>	17.74	20.12	17.77	20.73
<i>image captioning</i>	27.8	28.16	26.42	29.16



Ranzato, M., et al. "Sequence level training with recurrent neural networks." *ICLR* (2016).

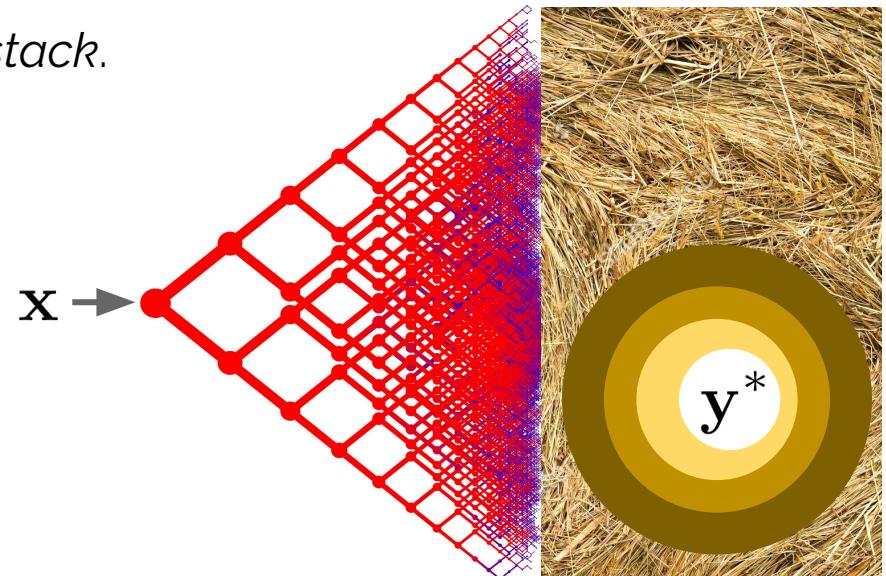
Reward Augmented Maximum Likelihood (RML)

Finding the *right output sequence*, for tasks like speech recognition or machine translation is like finding *a needle in a haystack*.

It is very risky to shoot
only for the *true target*.

What if we expand the targets
to make learning easier?

E.g. by inserting, deleting random words...



Reward augmented maximum likelihood (RML)

$$\mathcal{L}_{\text{RML}}(\boldsymbol{\theta}; \tau) = \sum_{(\mathbf{x}, \mathbf{y}^*) \in \mathcal{D}} \left\{ - \sum_{\mathbf{y} \in \mathcal{Y}} q(\mathbf{y} \mid \mathbf{y}^*; \tau) \log p_{\boldsymbol{\theta}}(\mathbf{y} \mid \mathbf{x}) \right\}$$

Optimal $p_{\boldsymbol{\theta}}(\mathbf{y} \mid \mathbf{x})$:

$$q(\mathbf{y} \mid \mathbf{y}^*; \tau) = \frac{1}{Z(\mathbf{y}^*, \tau)} \exp \{r(\mathbf{y}, \mathbf{y}^*)/\tau\}$$

*Sample from the
reward distribution,
irrespective of the
model*

$$\mathcal{L}_{\text{RML}}(\boldsymbol{\theta}; \tau) = \sum_{(\mathbf{x}, \mathbf{y}^*) \in \mathcal{D}} D_{\text{KL}}(q(\mathbf{y} \mid \mathbf{y}^*; \tau) \parallel p_{\boldsymbol{\theta}}(\mathbf{y} \mid \mathbf{x})) + \text{constant}$$

RML - Impact of temperature τ

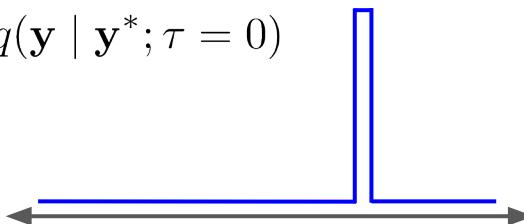
Temperature impacts spread of distribution we sample from

Cross Entropy Targets

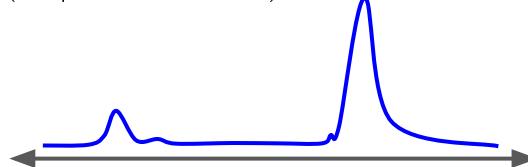


More spread

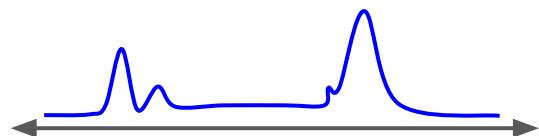
$$q(\mathbf{y} \mid \mathbf{y}^*; \tau = 0)$$



$$q(\mathbf{y} \mid \mathbf{y}^*; \tau = .1)$$



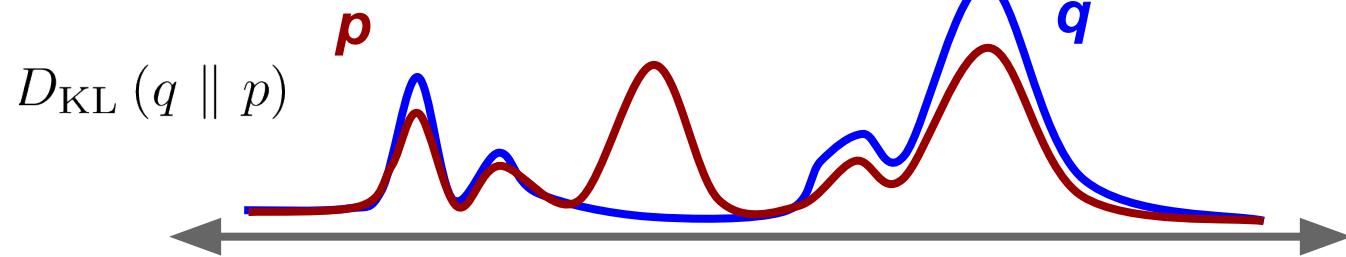
$$q(\mathbf{y} \mid \mathbf{y}^*; \tau = .2)$$



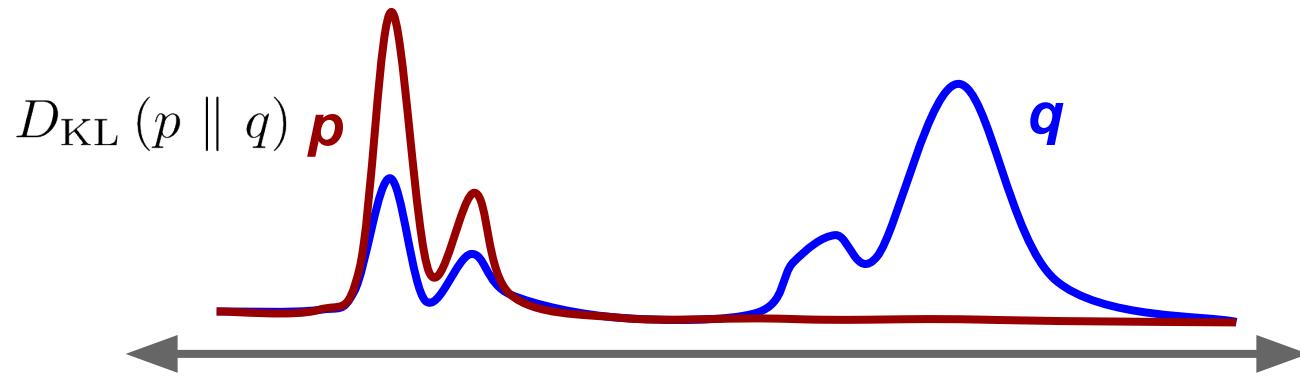
$$\mathcal{L}_{\text{RML}}(\boldsymbol{\theta}; \tau) = \sum_{(\mathbf{x}, \mathbf{y}^*) \in \mathcal{D}} D_{\text{KL}}(q(\mathbf{y} \mid \mathbf{y}^*; \tau) \parallel p_{\boldsymbol{\theta}}(\mathbf{y} \mid \mathbf{x})) + \text{constant}$$

Contrasting RML with RL

RML

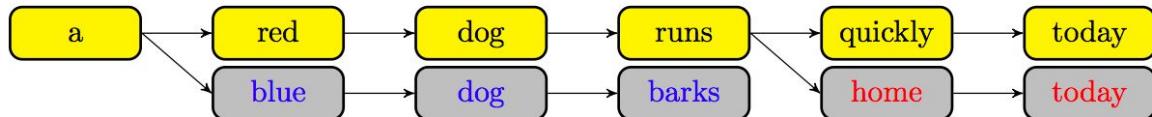
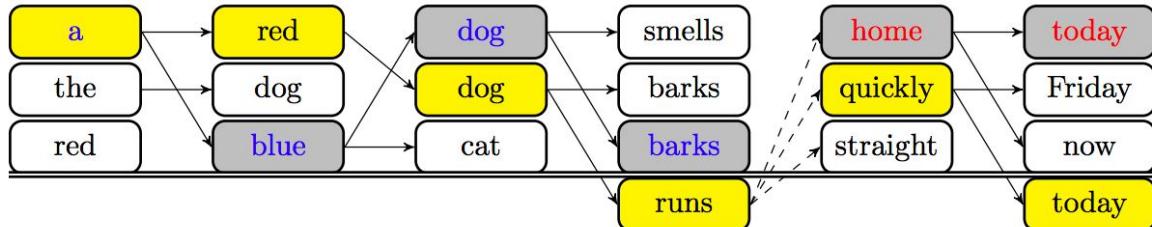


RL



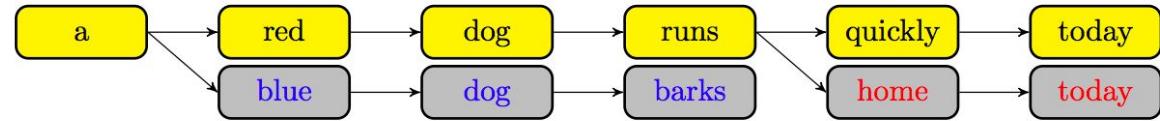
Margin Loss

- Perform beam search until correct hypothesis falls out of the beam
- Restart beam whenever there is a violation
- Extract correct hypothesis and competing hypotheses



Margin Loss

- Add a margin score for all time steps where the correct hypothesis is not better than the Kth best hypothesis by a certain margin



$$\mathcal{L}(f) = \sum_{t=1}^T \Delta(\hat{y}_{1:t}^{(K)}) \left[1 - f(y_t, \mathbf{h}_{t-1}) + f(\hat{y}_t^{(K)}, \hat{\mathbf{h}}_{t-1}^{(K)}) \right]$$

Loss for error; 0 when margin constraint is satisfied

Score function for prediction of K^{th} best output

Score function for prediction of current output

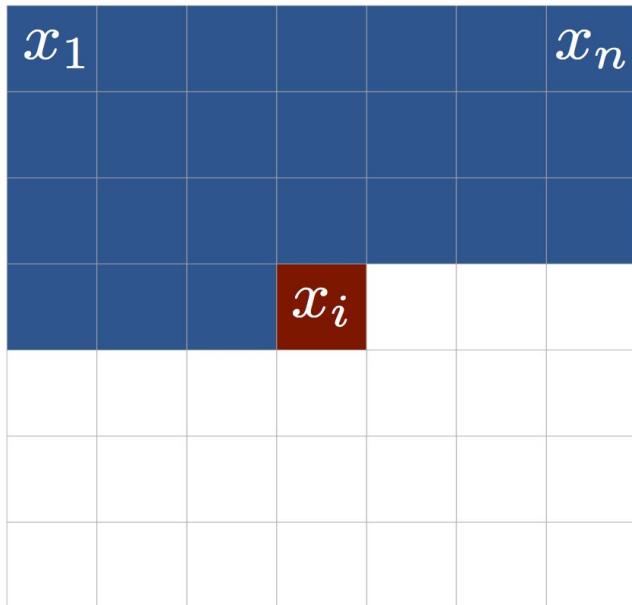
Margin Loss

Machine Translation (BLEU)			
	$K_{te} = 1$	$K_{te} = 5$	$K_{te} = 10$
seq2seq	22.53	24.03	23.87
BSO, SB- Δ	23.83	26.36	25.48
XENT	17.74	20.10	20.28
DAD	20.12	22.25	22.40
MIXER	20.73	21.81	21.83

Advanced Topics

Autoregressive Generative Models

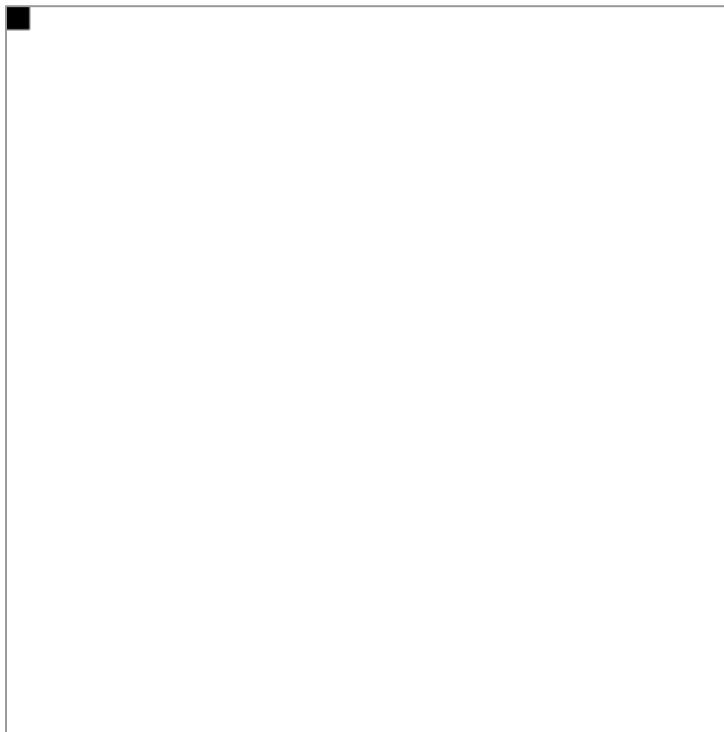
PixelRNN - Model



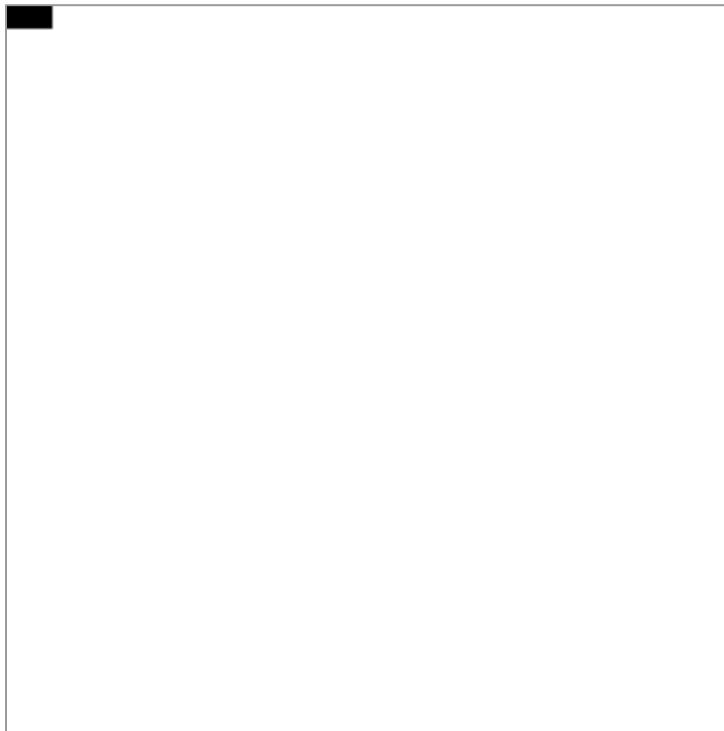
$$p(\mathbf{x}) = \prod_{i=1}^{n^2} p(x_i | x_1, \dots, x_{i-1})$$

- Fully visible
- Similar to language models with RNNs
- Model pixels with Softmax

Softmax Sampling



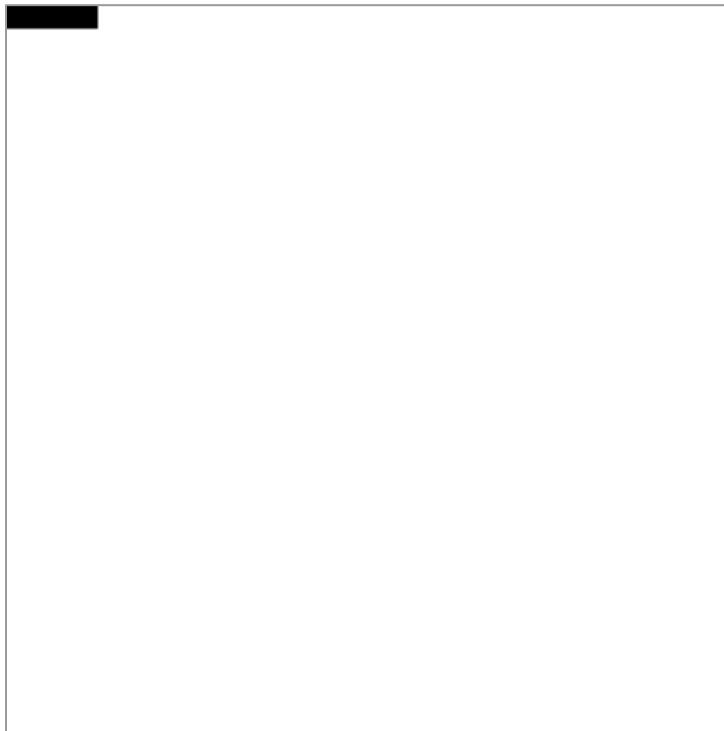
Softmax Sampling



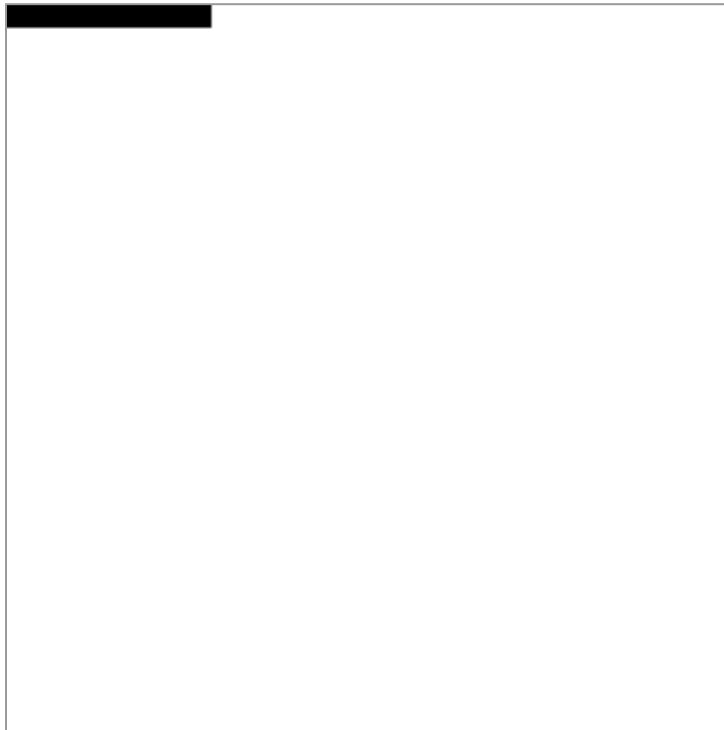
Softmax Sampling



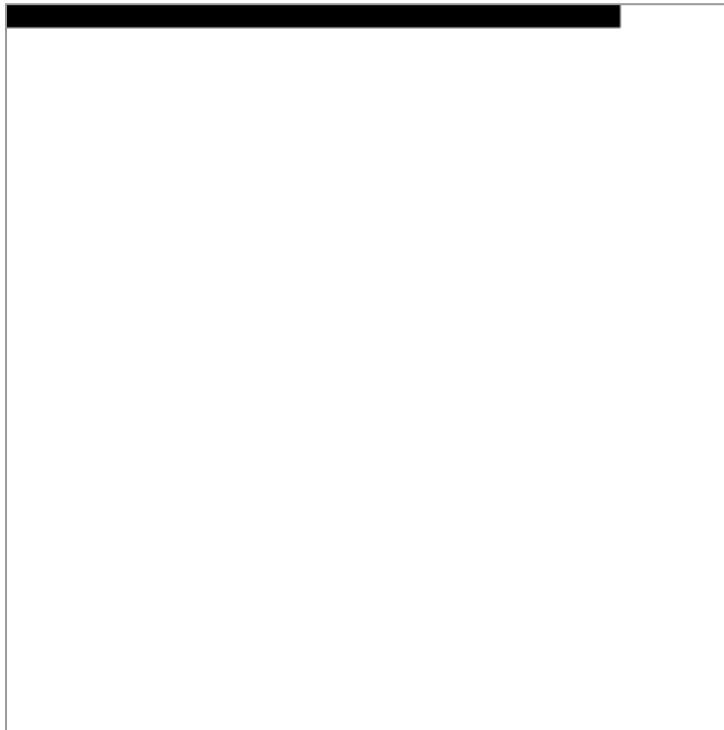
Softmax Sampling



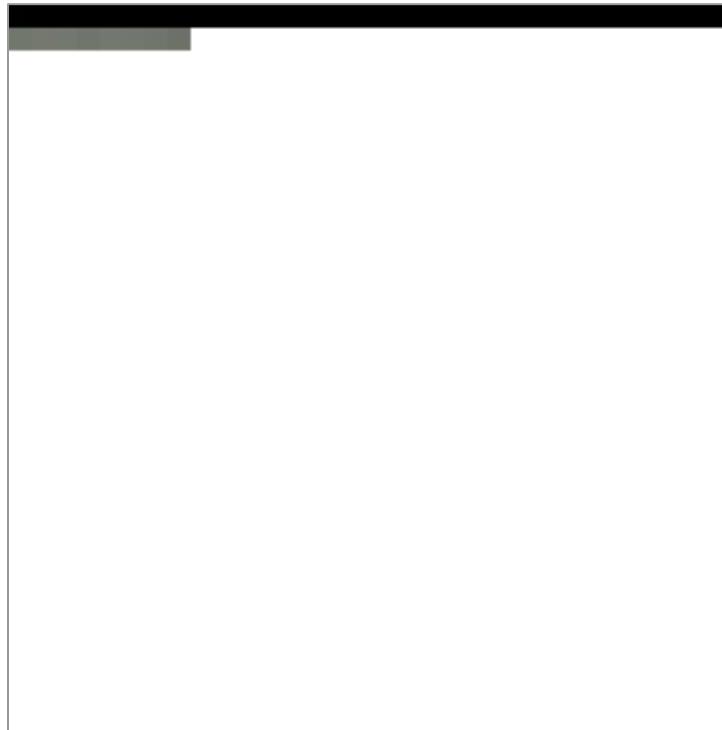
Softmax Sampling



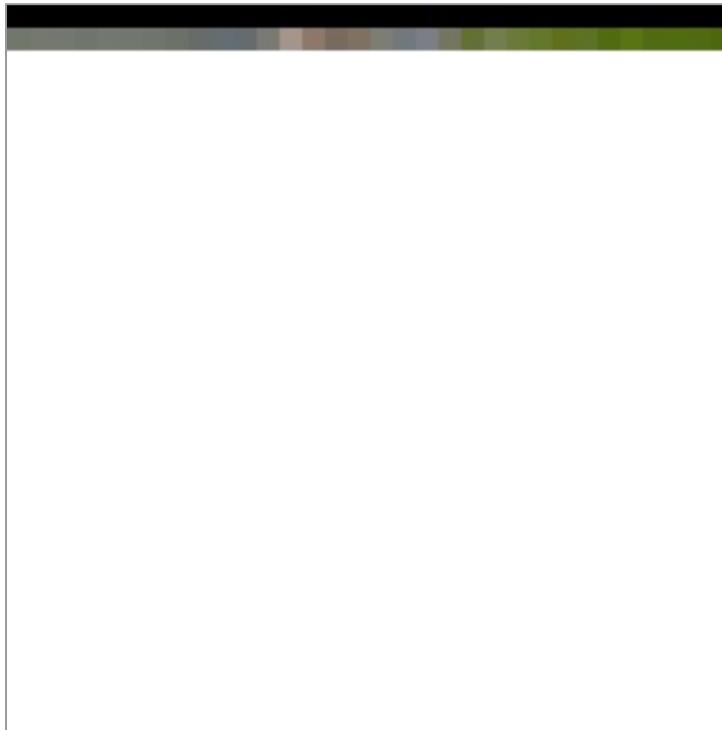
Softmax Sampling



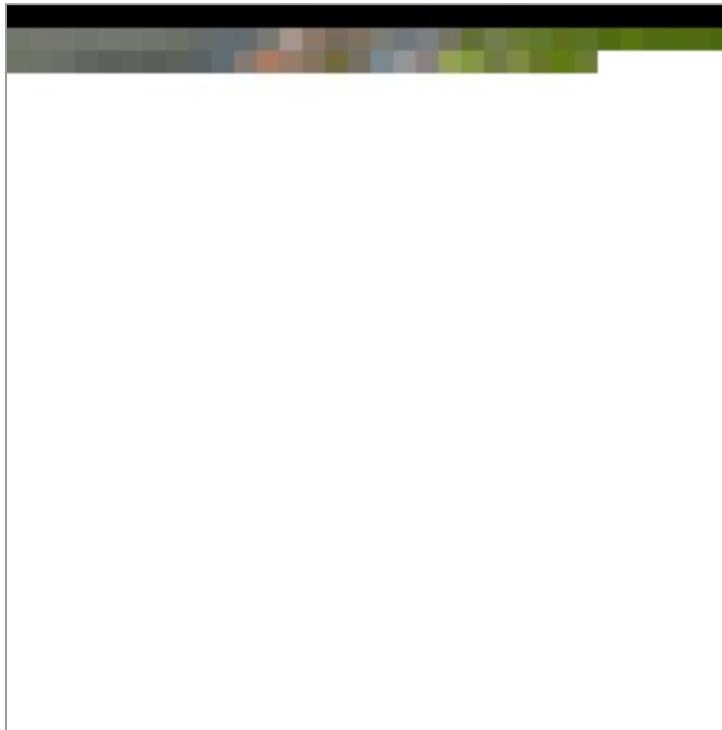
Softmax Sampling



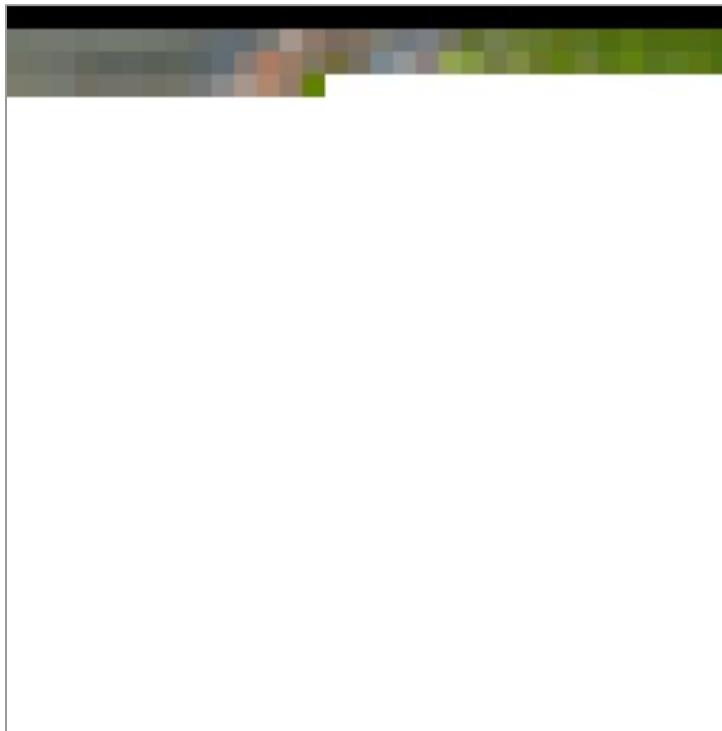
Softmax Sampling



Softmax Sampling



Softmax Sampling



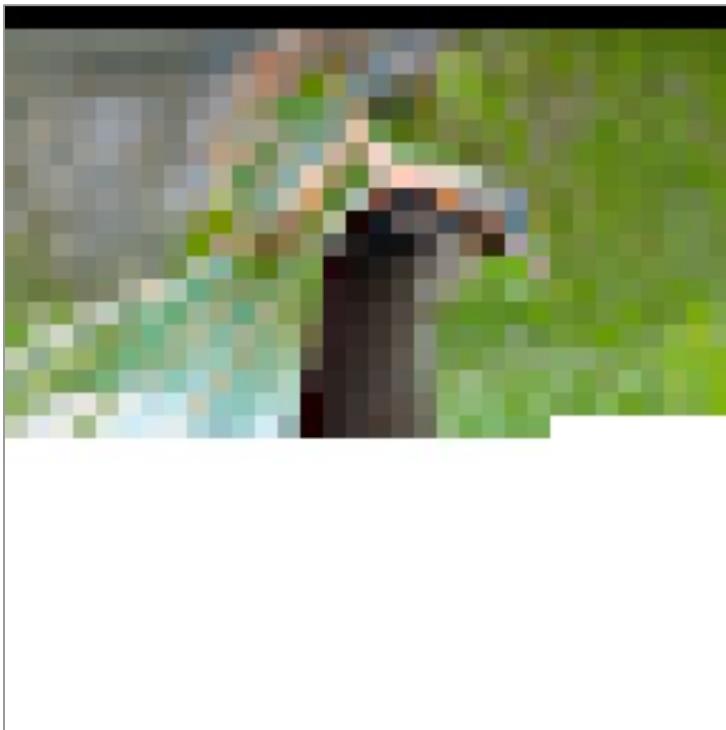
van den Oord, A., et al. "Pixel Recurrent Neural Networks." *ICML* (2016).

Softmax Sampling

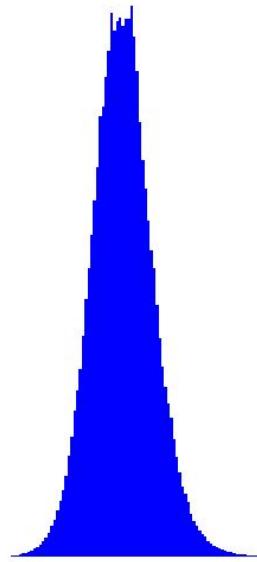


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Softmax Sampling

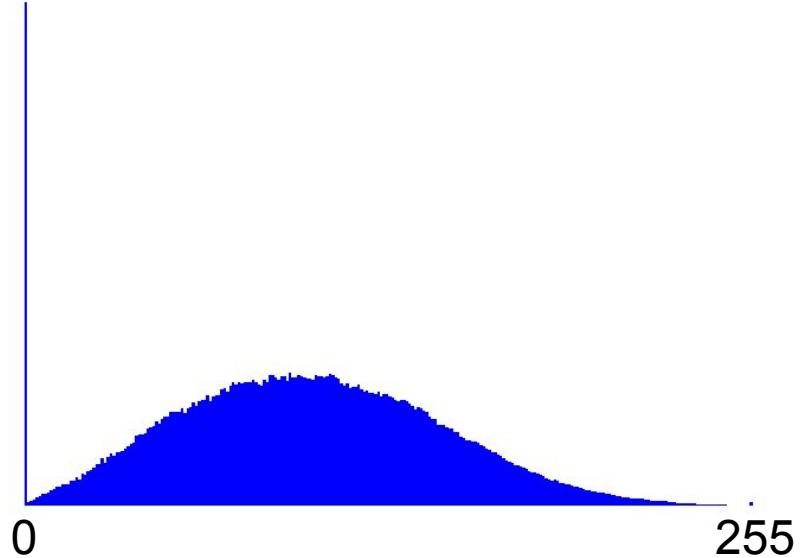
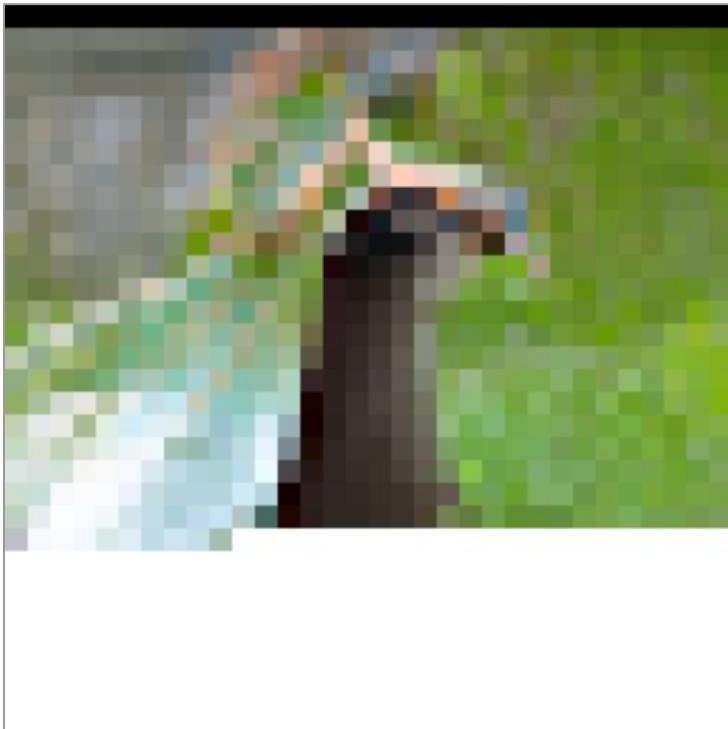


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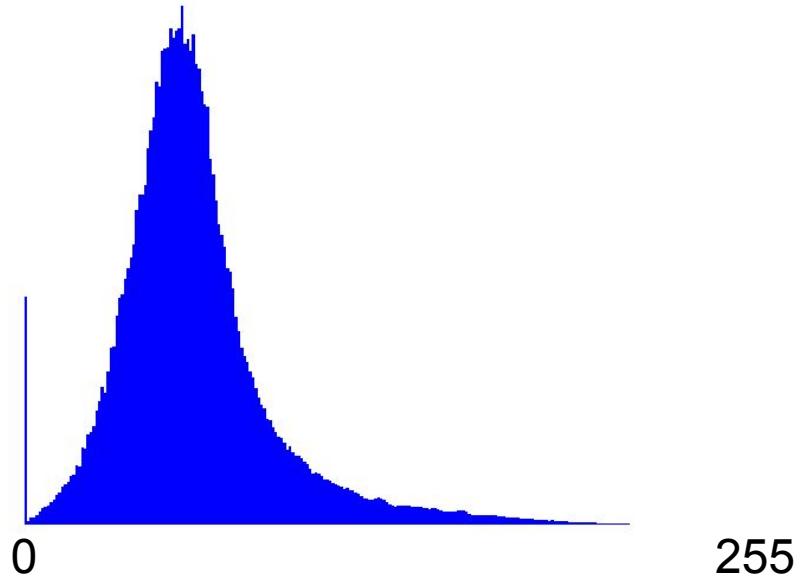
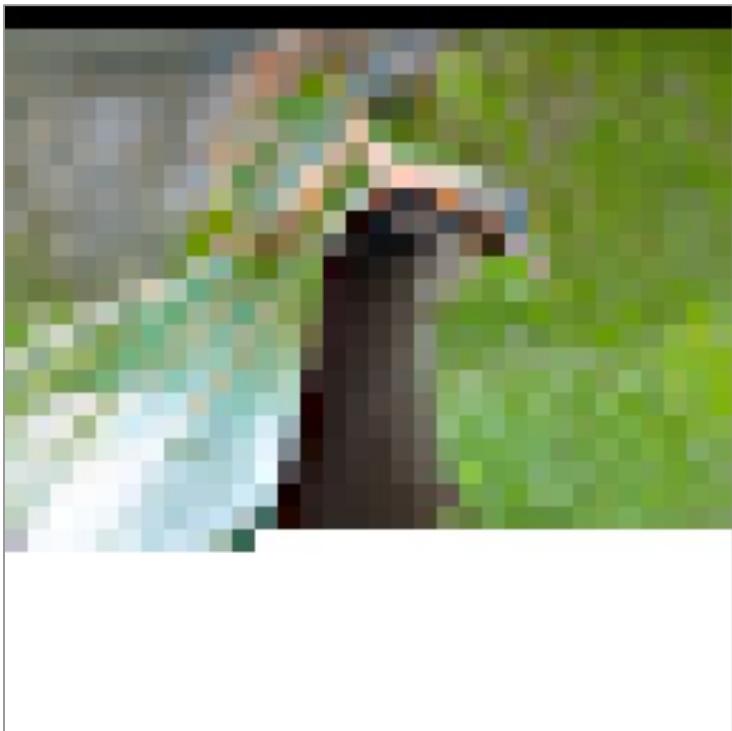


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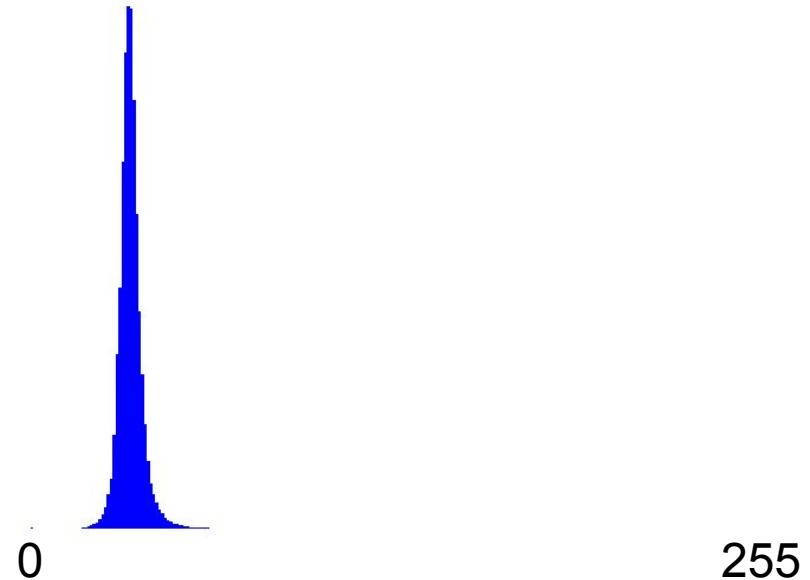
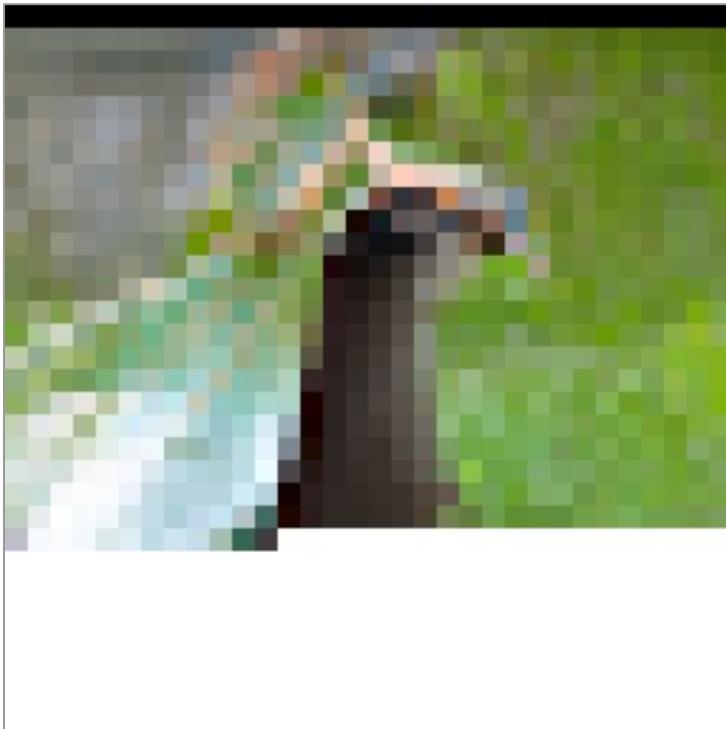
Softmax Sampling



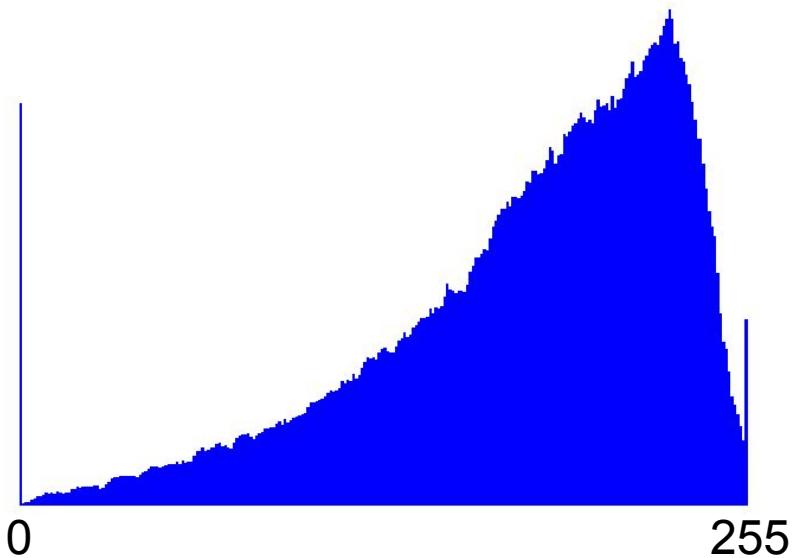
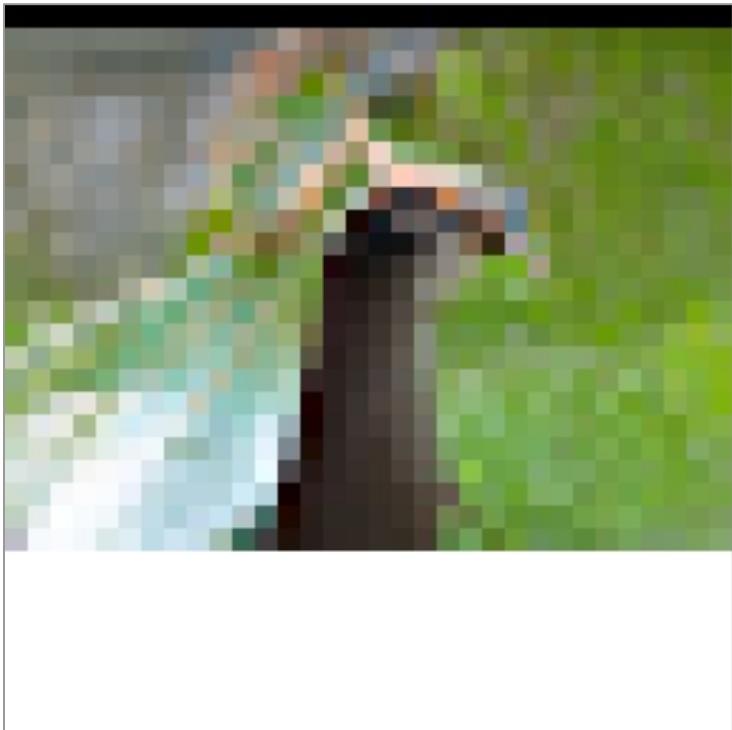
Softmax Sampling



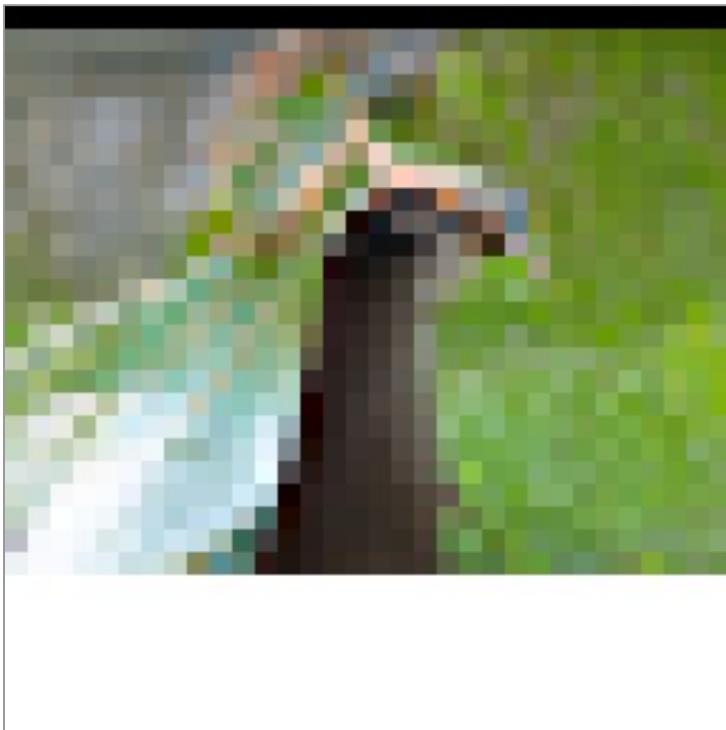
Softmax Sampling



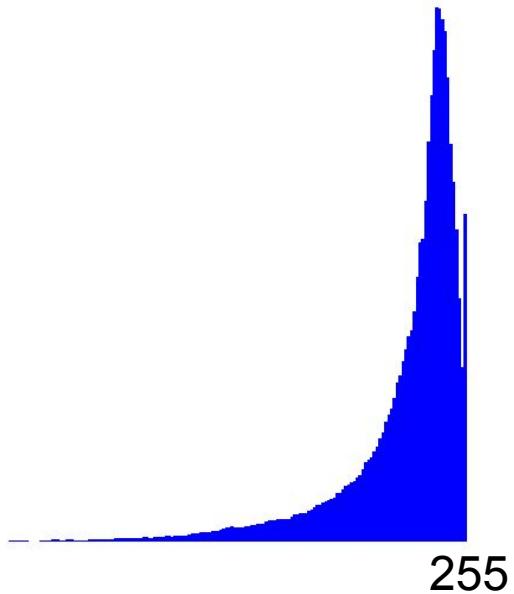
Softmax Sampling



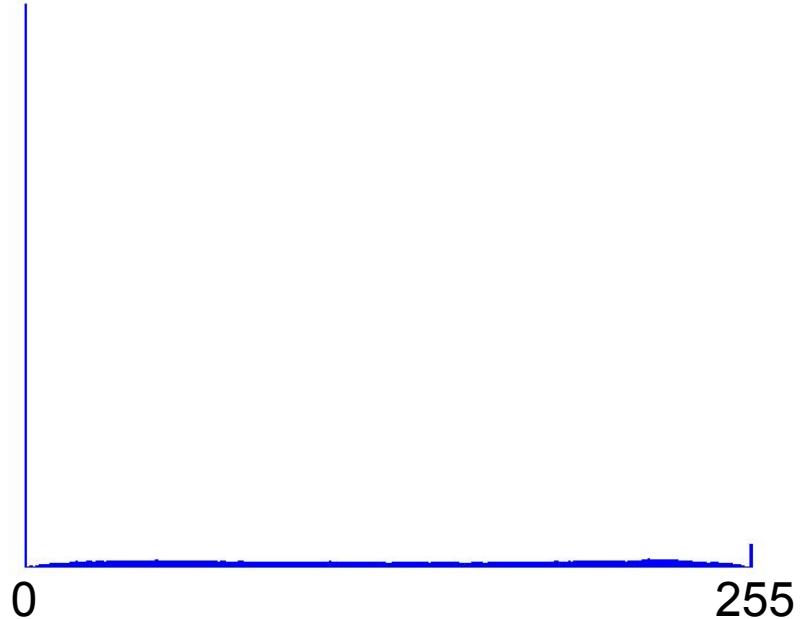
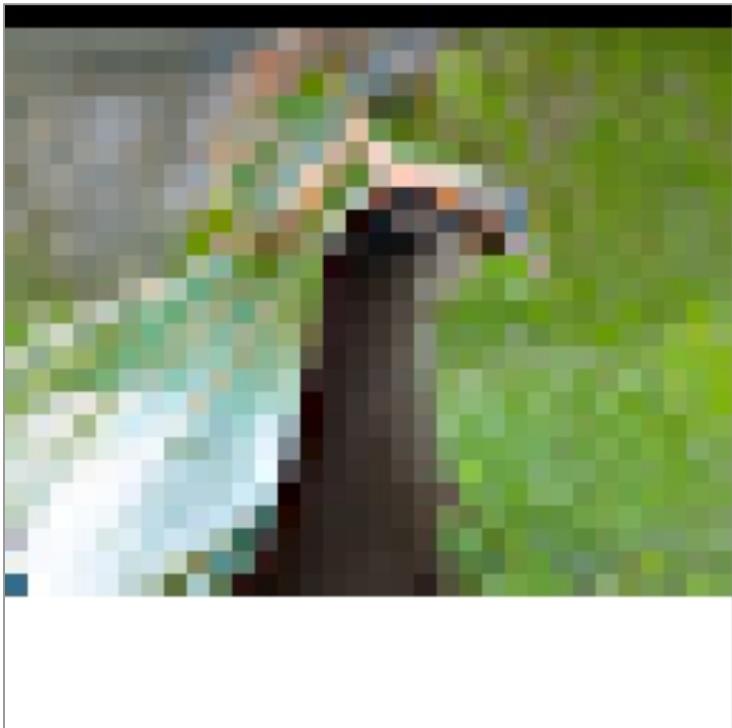
Softmax Sampling



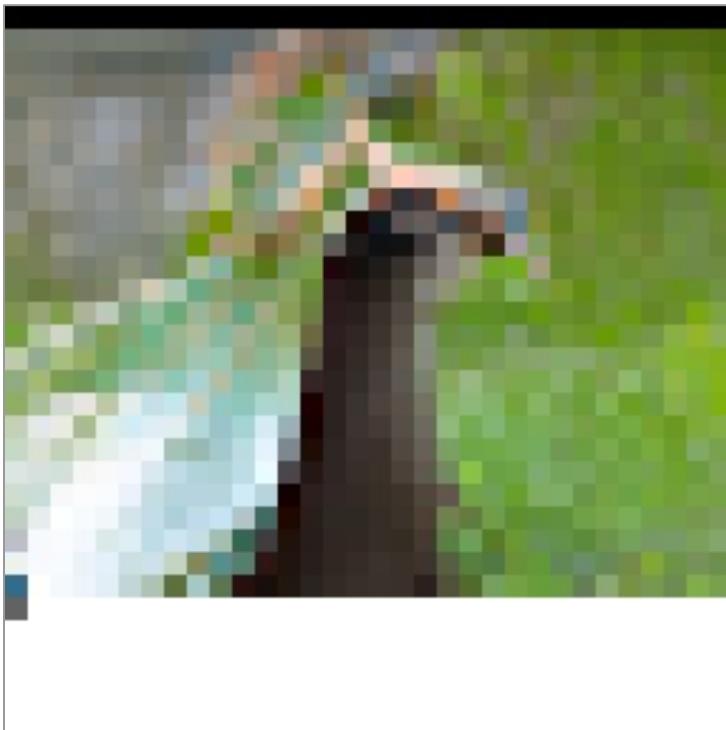
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Softmax Sampling

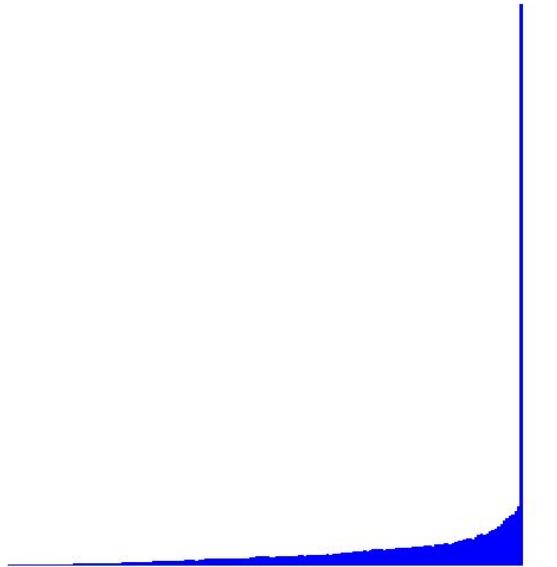


Softmax Sampling

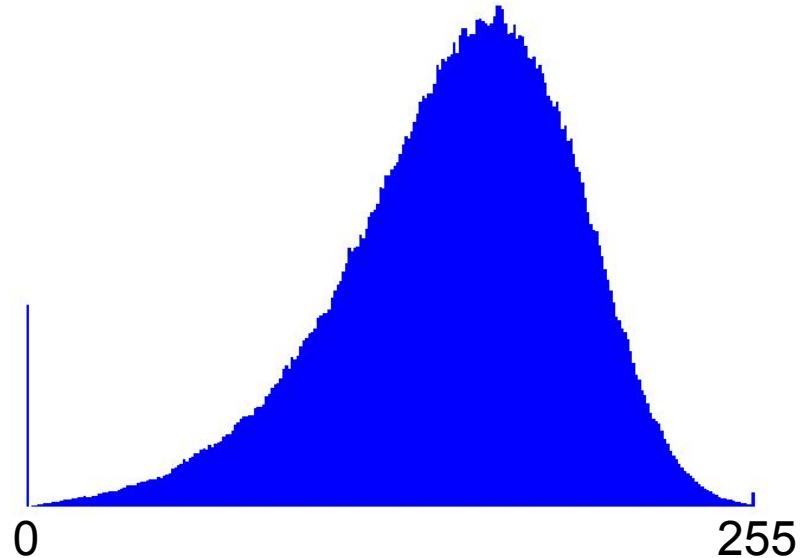
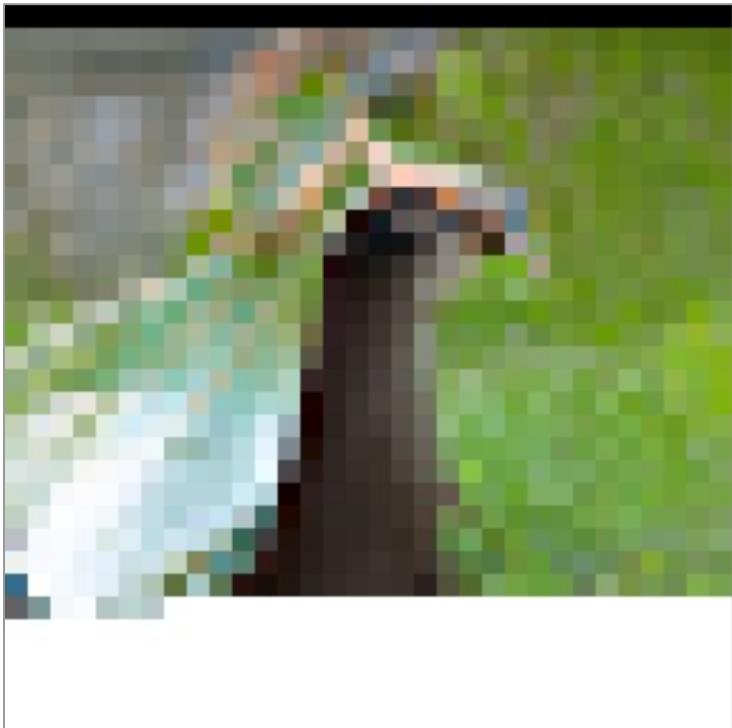


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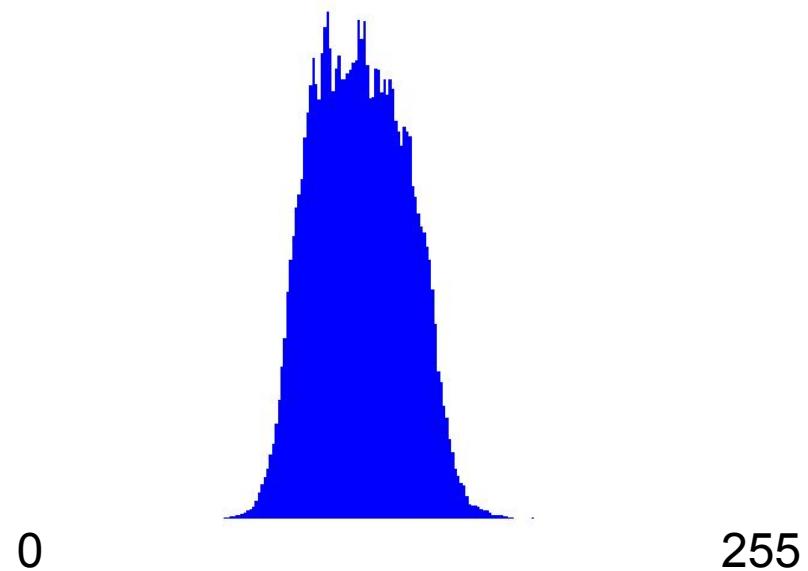
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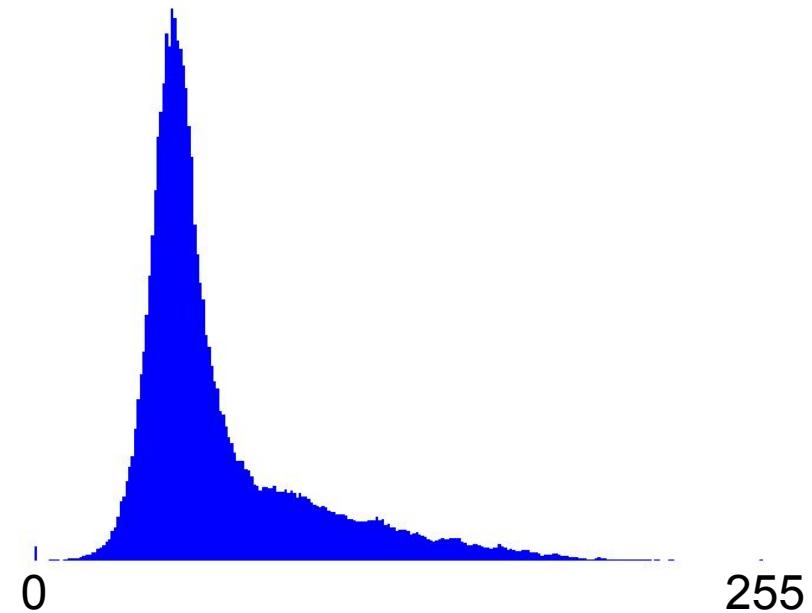
Softmax Sampling



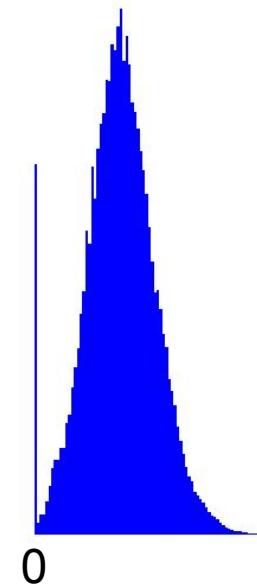
Softmax Sampling



Softmax Sampling



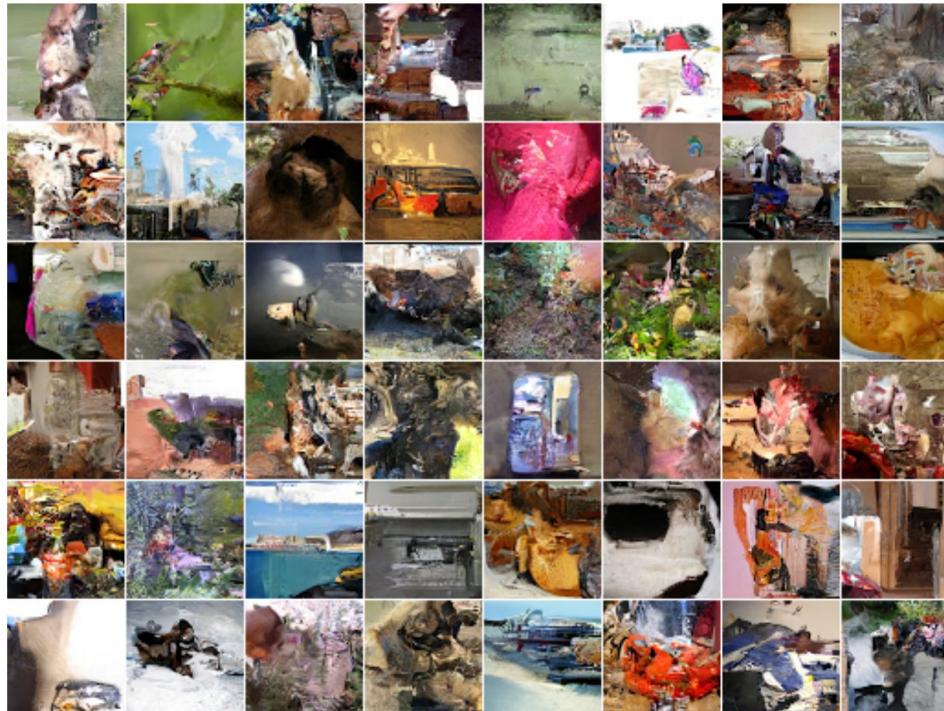
Softmax Sampling



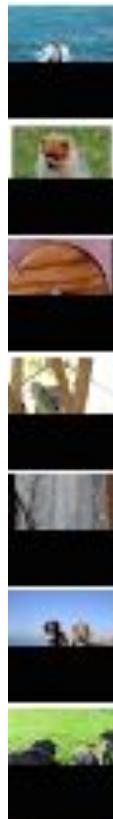
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Pixel RNN

Sequence of Words == Sequence of Pixels

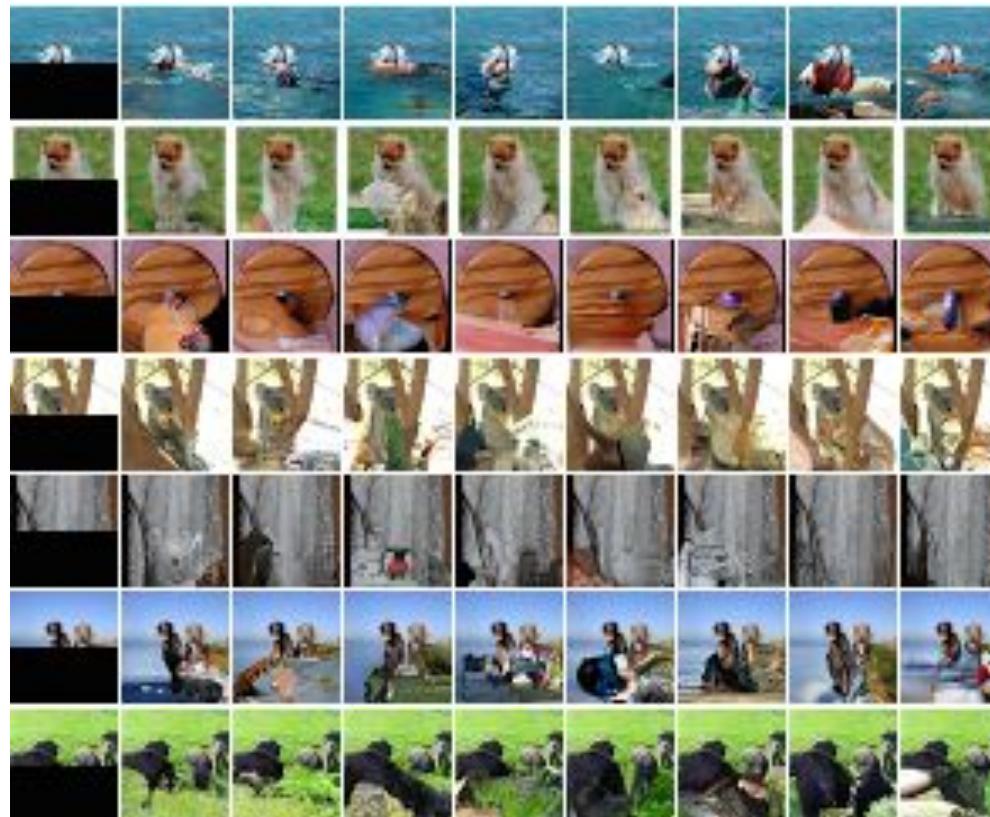


occluded



occluded

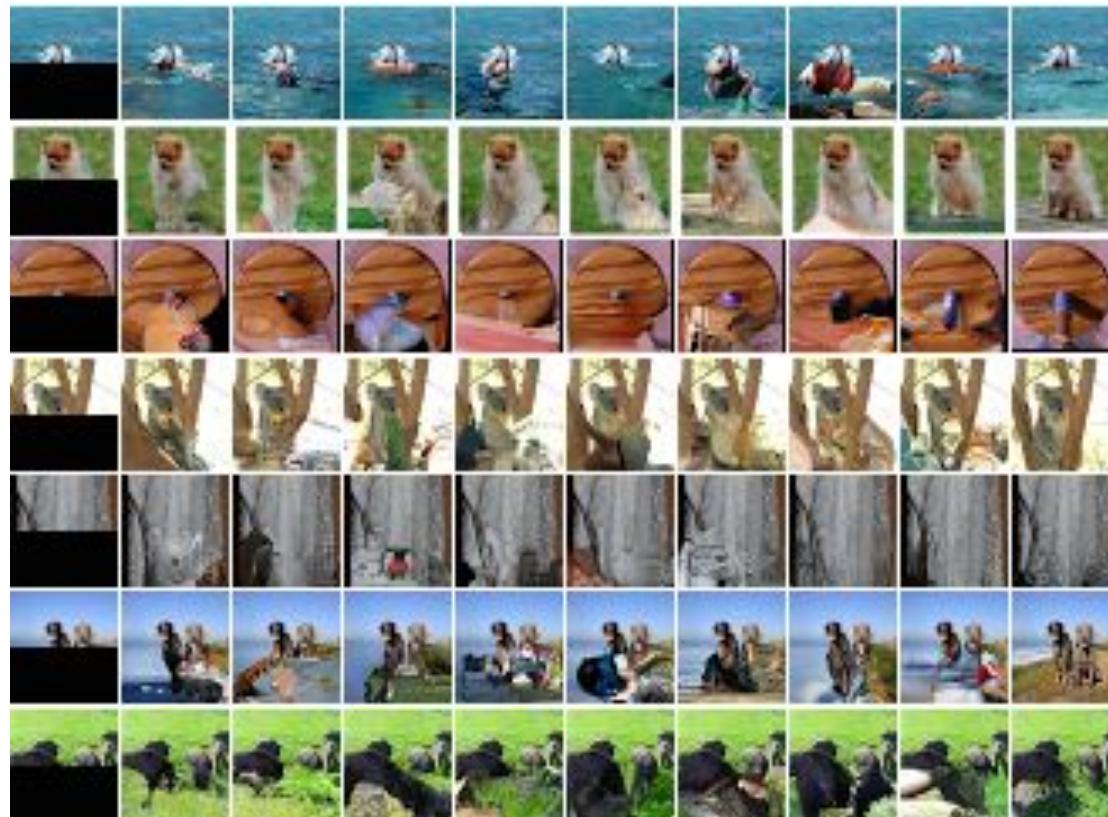
completions



occluded

completions

original



Conditional Pixel CNN



Geyser



Hartebeest



Grey whale



Tiger

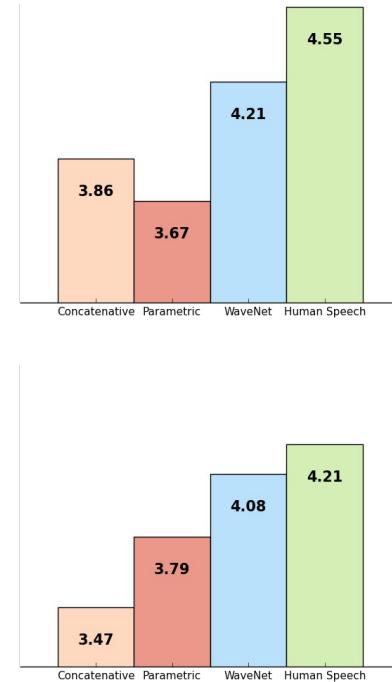
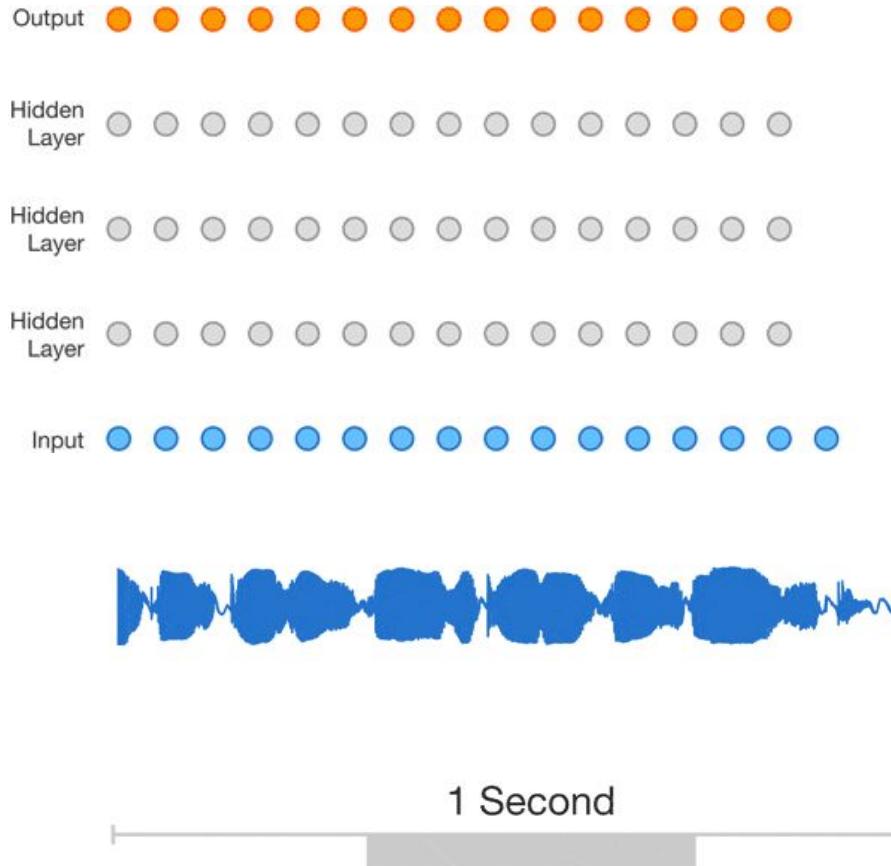


EntleBucher (dog)



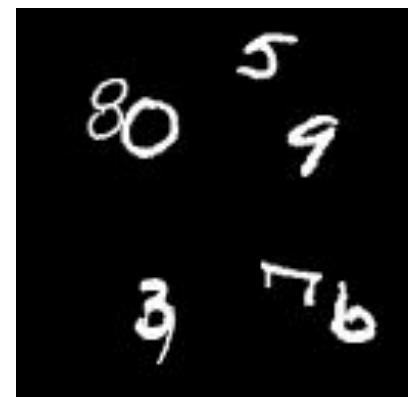
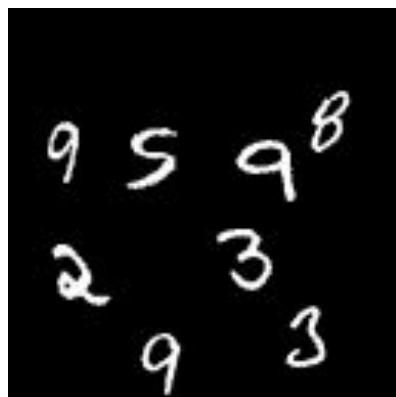
Yellow lady's slipper (flower)

WaveNets



Video Pixel Network (VPN)

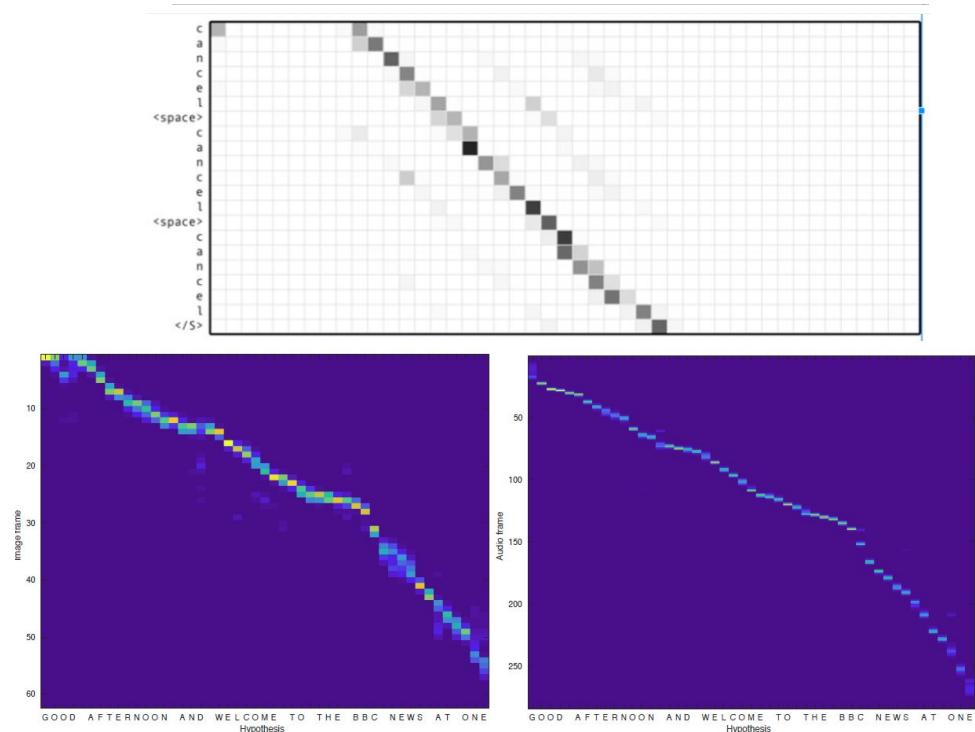
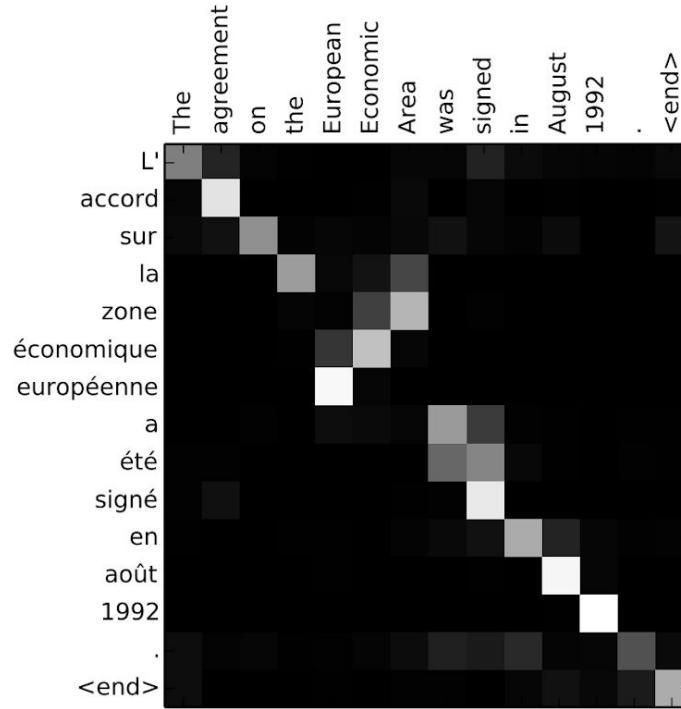
Model	Test
(Shi et al., 2015)	367.2
(Srivastava et al., 2015a)	341.2
(Brabandere et al., 2016)	285.2
(Patraucean et al., 2015)	179.8
Baseline model	110.1
VPN	87.6
Lower Bound	86.3



Online Seq2Seq

Practical limitations of Online Seq2Seq

- Have to wait for all of the input to arrive
- Yet, attention vector reveals a lot of globally monotonic structure

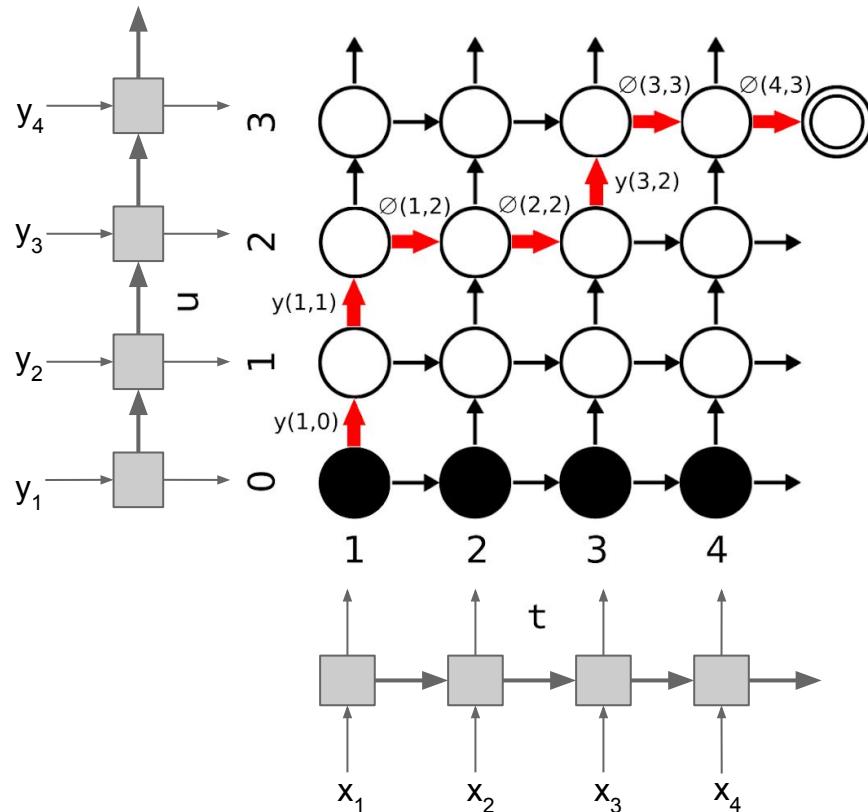


Online Sequence to Sequence Models

- Overcome limitations of sequence to sequence models
 - No need to wait for the entire input sequence to arrive
- Has to solve the following problem:
 - Has enough information arrived for the model to make its next prediction ?

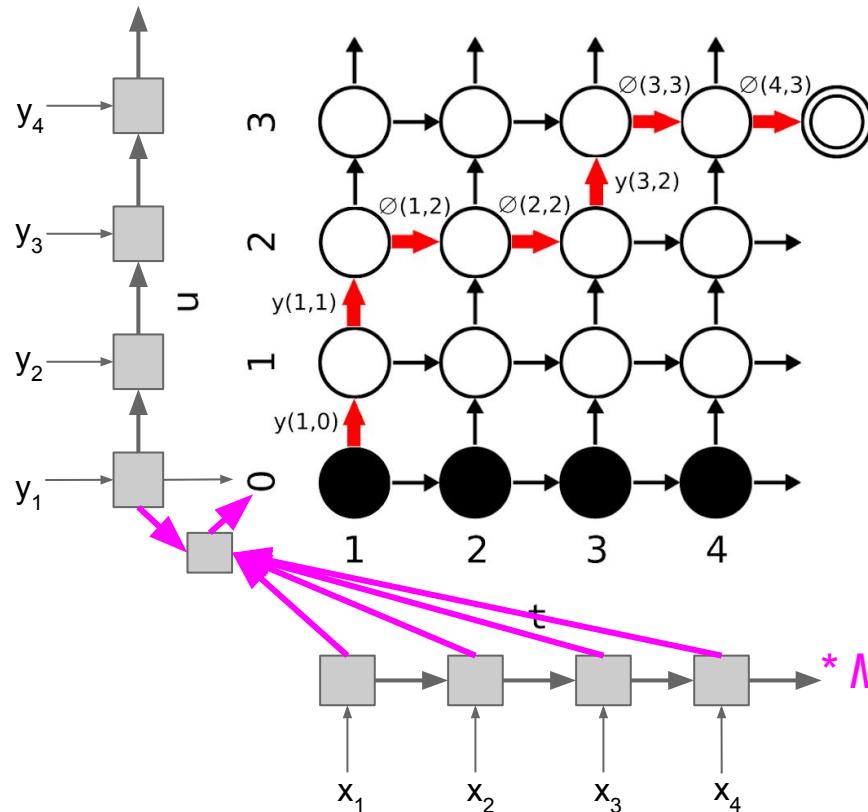
- Yu, L., Buys, J., Blunsom, P. "Online Segment to Segment Neural Transduction." *EMLP* (2016).
- Jaitly, N., et al. "An Online Sequence-to-Sequence Model Using Partial Conditioning." *NIPS* (2016).
- Luo, Y., et al. "Learning online alignments with continuous rewards policy gradient." *ICASSP* (2017).
- Gu, J, Neubig, G, Cho, K, Li, V.O.K.. "Learning to translate in real-time with neural machine translation". *EACL* (2017)
- Raffel, Colin, et al. "Online and Linear-Time Attention by Enforcing Monotonic Alignments." *ICML* 2017 (Tue Aug 8th 01:30)

Sequence Transducer



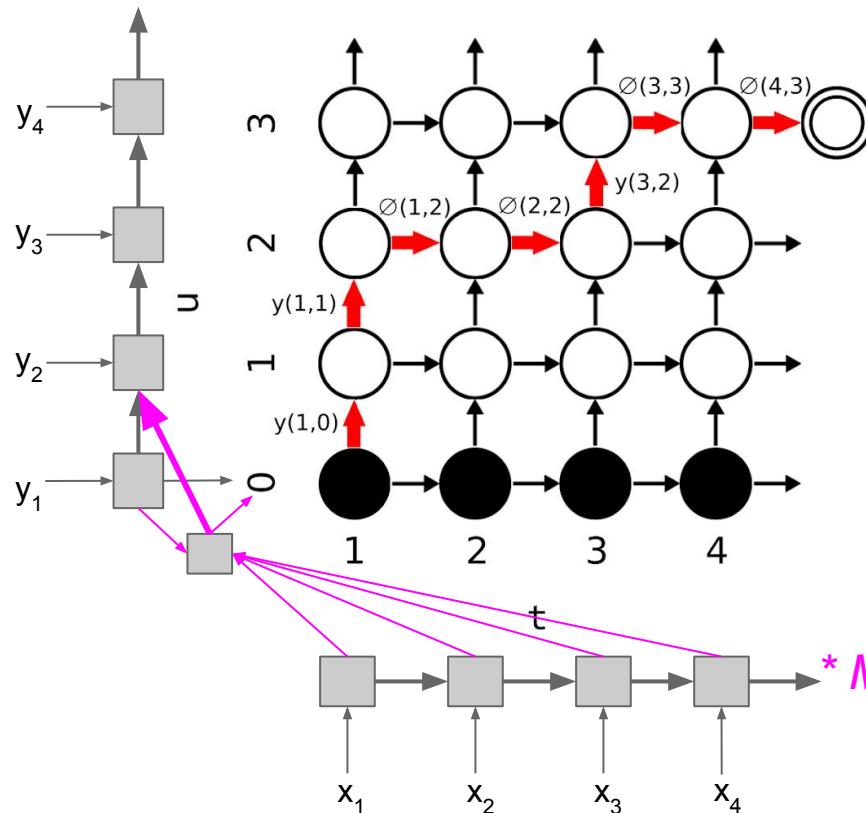
- RNN over input (encoder)
- RNN over output (transducer)
- Right arrow consumes input without producing output
- Up arrow produces output without consuming input
- Edge probabilities computed from softmax that is a sum of logits from the encoder and the decoder

Sequence Transducer vs Sequence-to-Sequence



- Transducer step interacts with only one input step

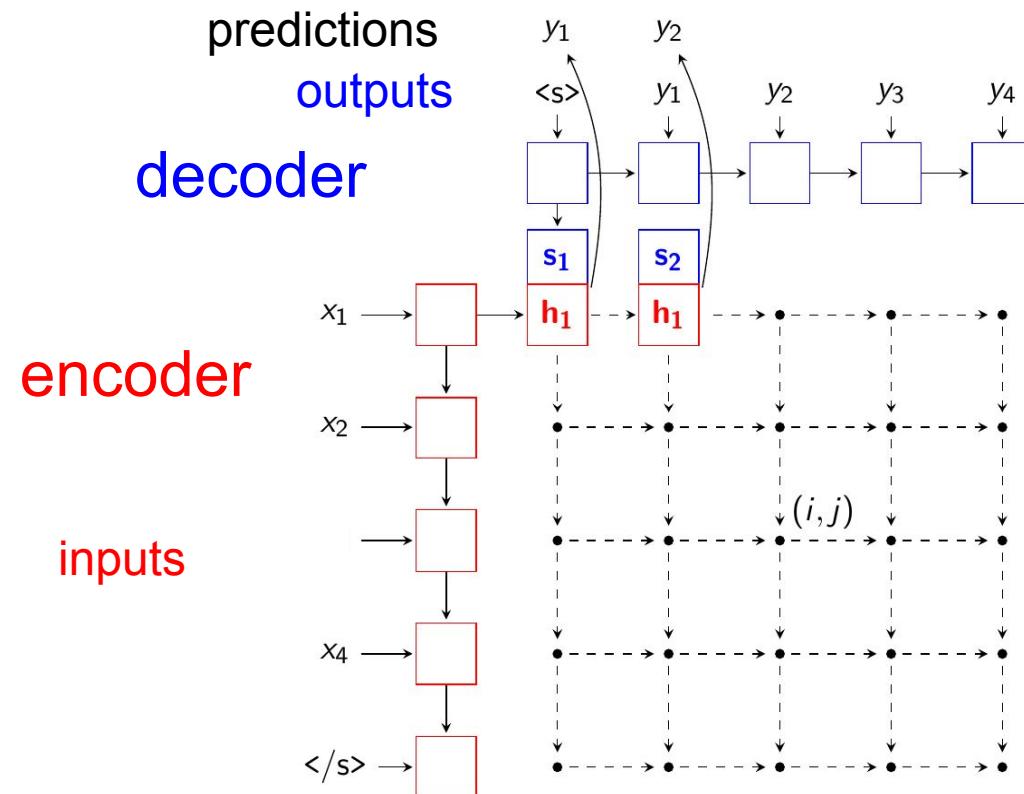
Sequence Transducer vs Sequence-to-Sequence



- Transducer output interacts with only one input step
- Transducer states do not depend on path history because context vector connection is missing

* Missing connections in sequence transducer

Online Segment to Segment Neural Transduction



Online Segment to Segment Neural Transduction

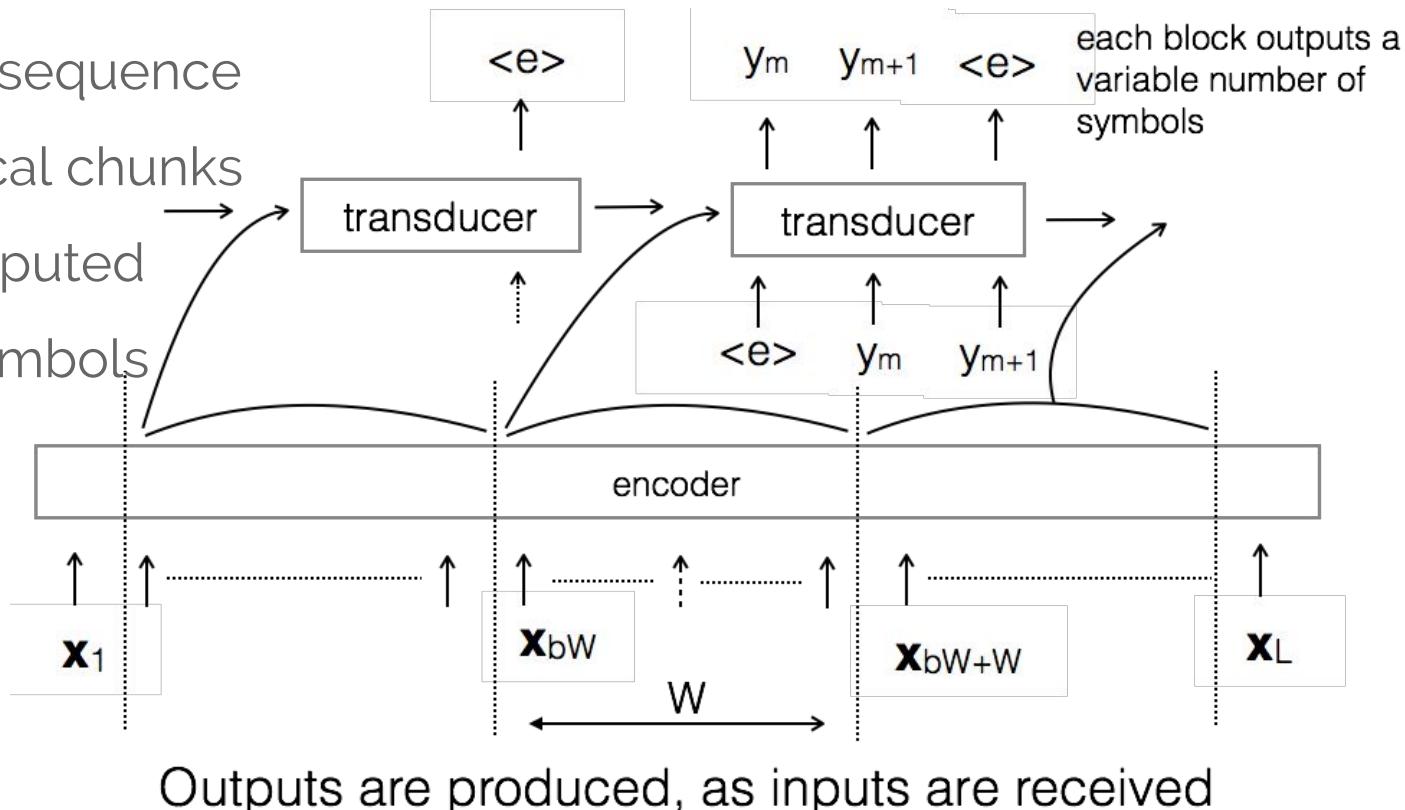
Model	ROUGE-1	ROUGE-2	ROUGE-L
Seq2Seq	25.2	9.1	23.1
Seq2Seq + attention	30.3	14.2	28.5
Neural Transduction	31.2	14.3	28.9
Neural Transduction + bidirectional encoder	31.7	14.7	29.3

F1 values on Abstractive sentence summarisation task

1. Yu, L., Buys, J., Blunsom, P. “Online Segment to Segment Neural Transduction.” *EMLP* (2016).
2. Yu, L., et al. “The Neural Noisy Channel.” *ICLR* (2017).

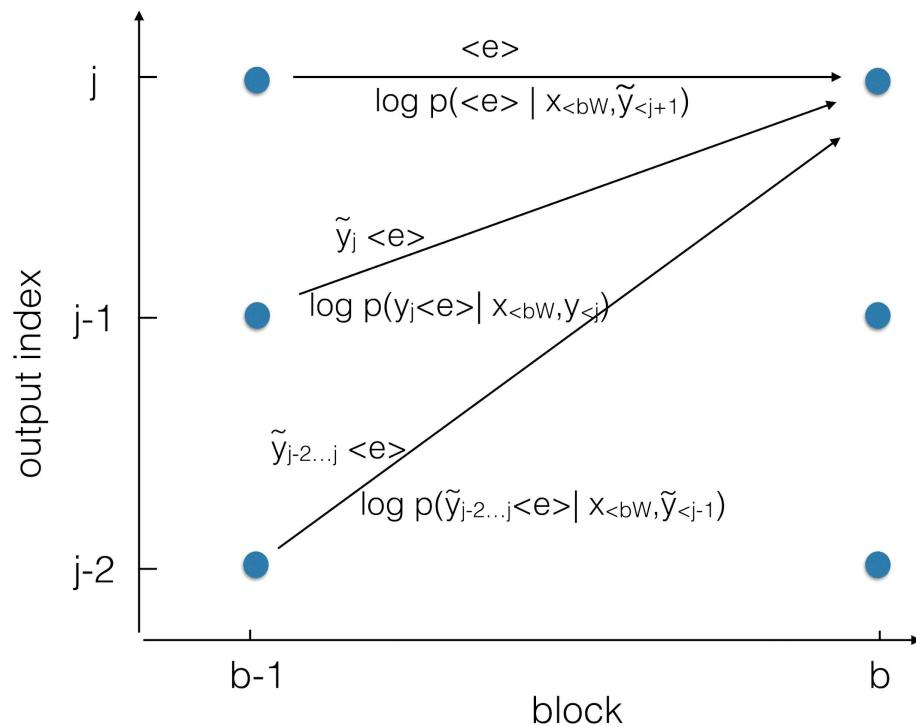
A Neural Transducer

- sequence-to-sequence models on local chunks
- Features computed depend on symbols output so far
- Introduces an alignment problem



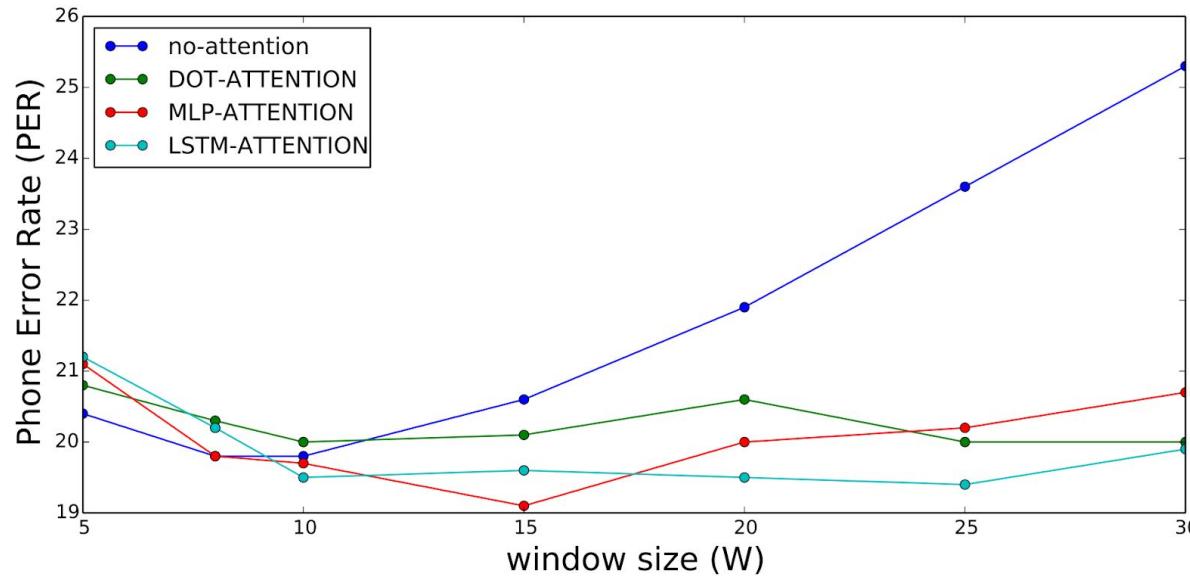
A Neural Transducer - Viterbi-like training

- Naive beam search for Viterbi training fails easily because of corner cases
- Approximate Dynamic programming for finding best alignment works quite well



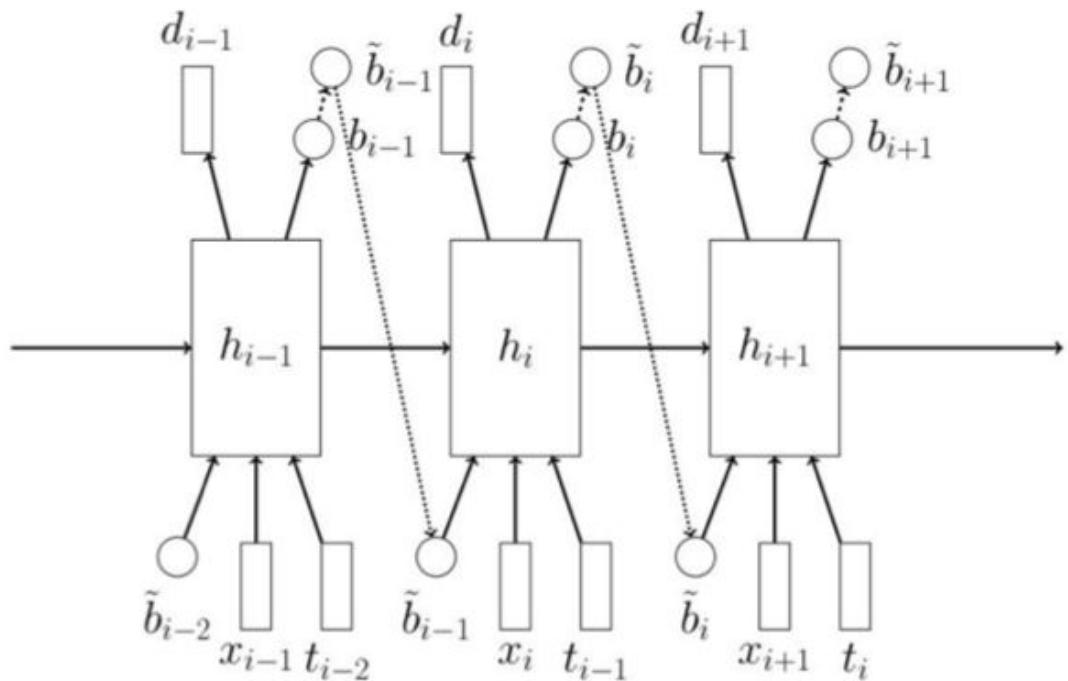
A Neural Transducer - Results

# of layers in encoder / transducer	1	2	3	4
2		19.2	18.9	18.8
3		18.5	18.2	19.4



A Stochastic Emissions Model

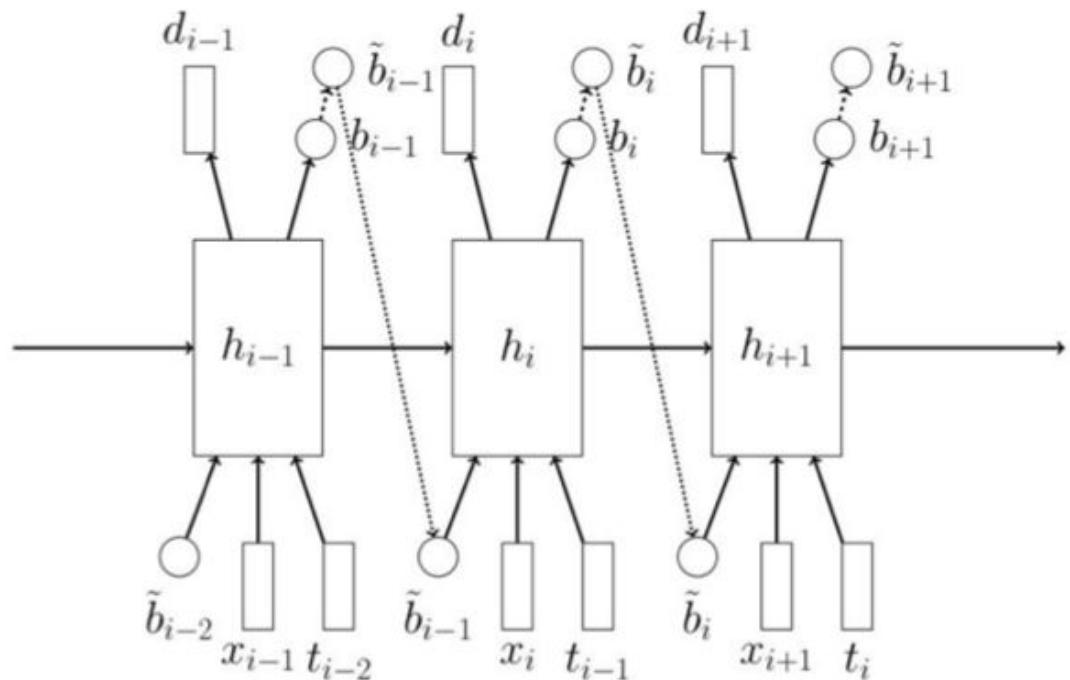
- Autoregressive at every step



d	distributions over phoneme
b	probabilities to emit
\tilde{b}	samplings of $Bernoulli(b)$
h	states of RN
x	input
t	last true label

A Stochastic Emissions Model

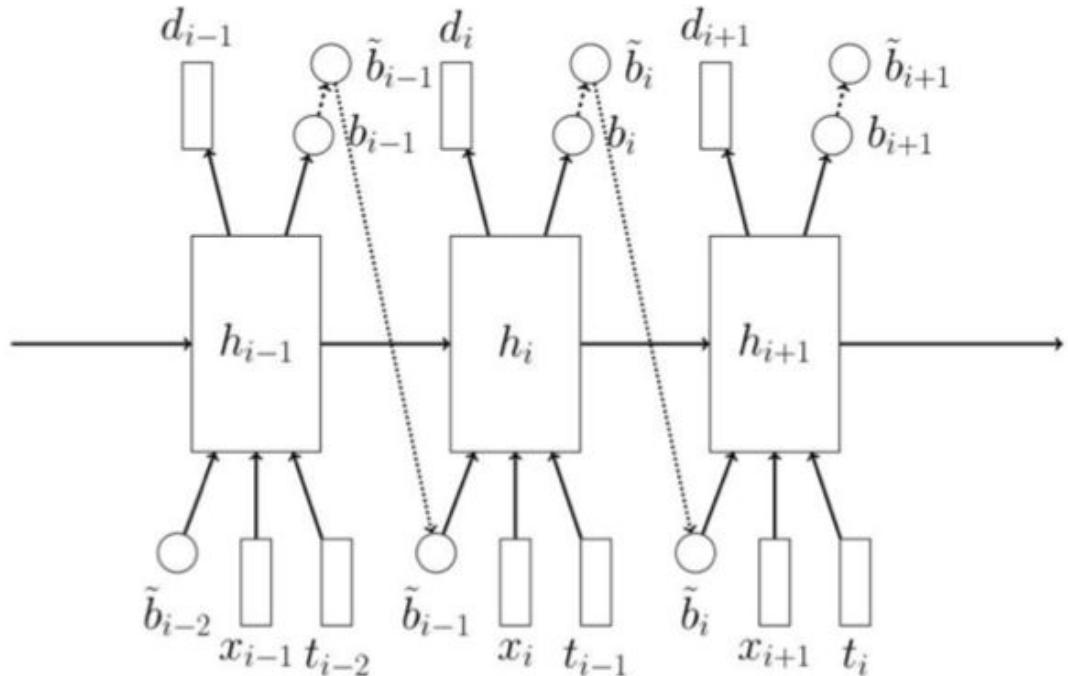
- Continuous Reward $R_i = \tilde{b}_i \log p(d_i = t_i | \mathbf{x}_{\leq i}, \tilde{\mathbf{b}}_{<i}, \mathbf{t}_{<i})$



\mathbf{d}	distributions over phoneme
\mathbf{b}	probabilities to emit
$\tilde{\mathbf{b}}$	samplings of $Bernoulli(b)$
\mathbf{h}	states of RN
\mathbf{x}	input
\mathbf{t}	last true label

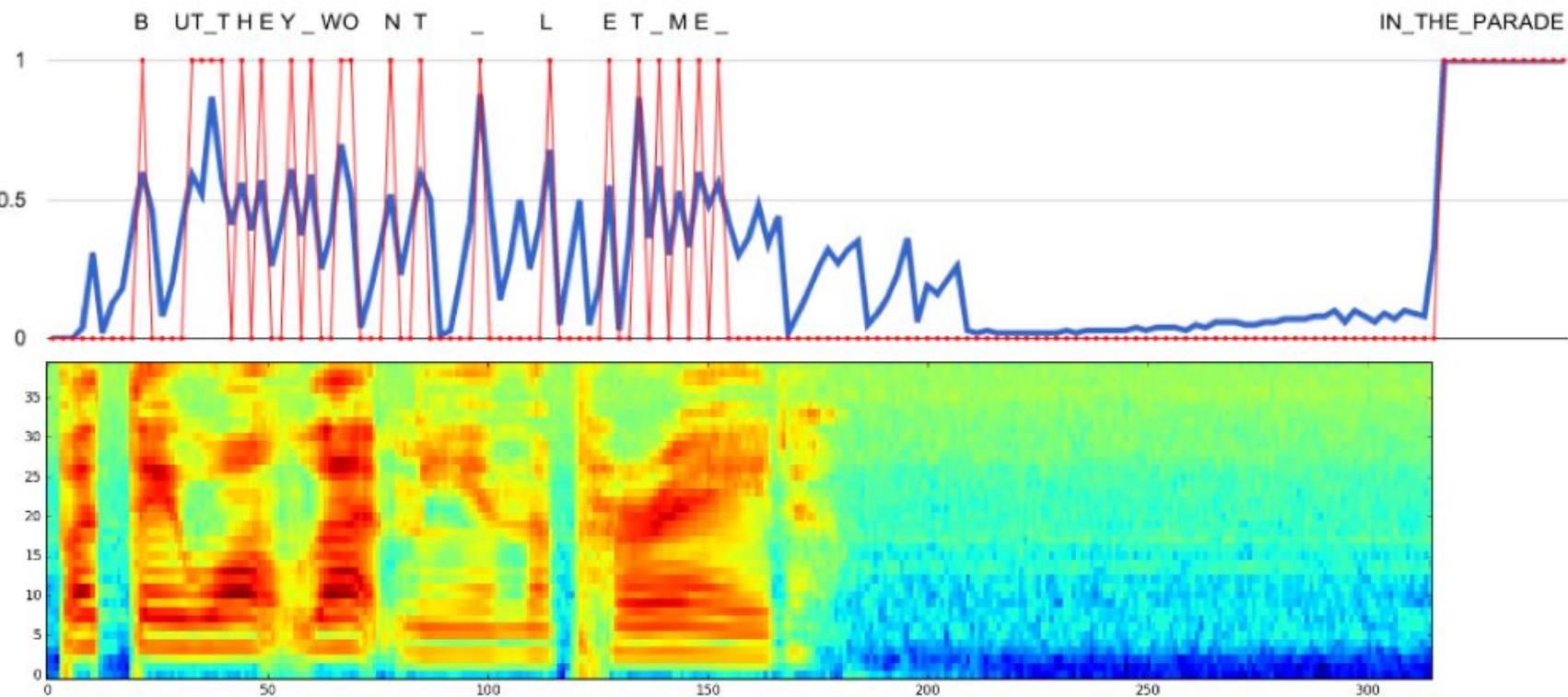
A Stochastic Emissions Model

- Optimize for expected reward: $\mathcal{R} = \mathbb{E}_{\tilde{\mathbf{b}}} [R(\tilde{\mathbf{b}})]$

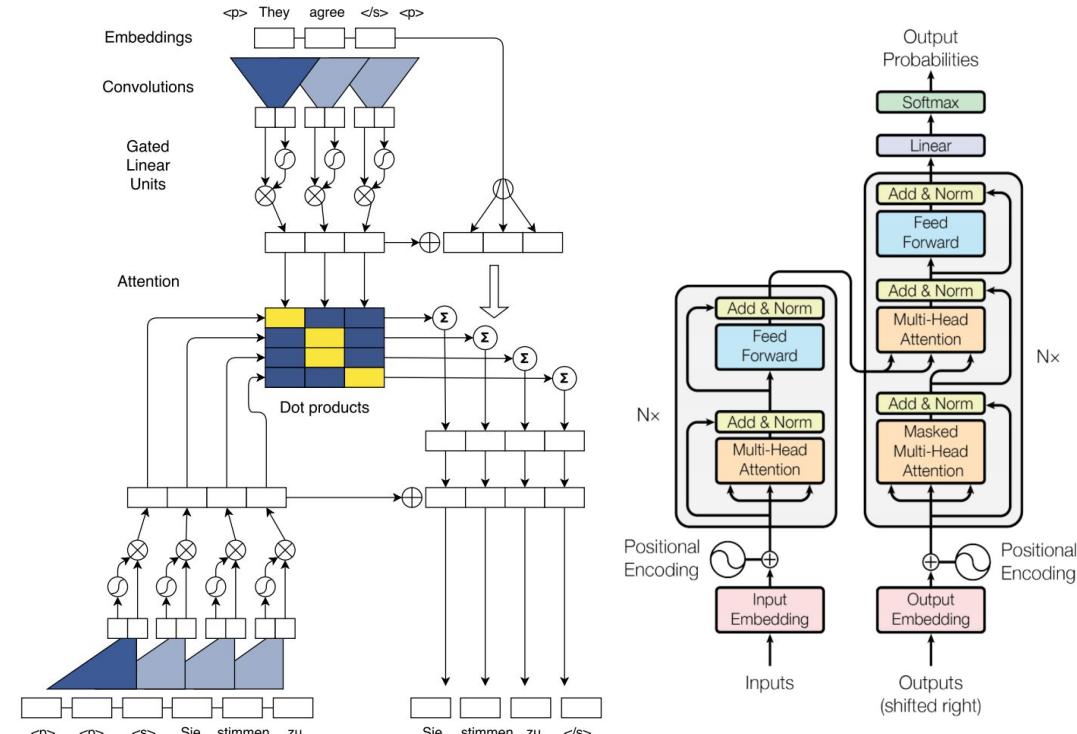
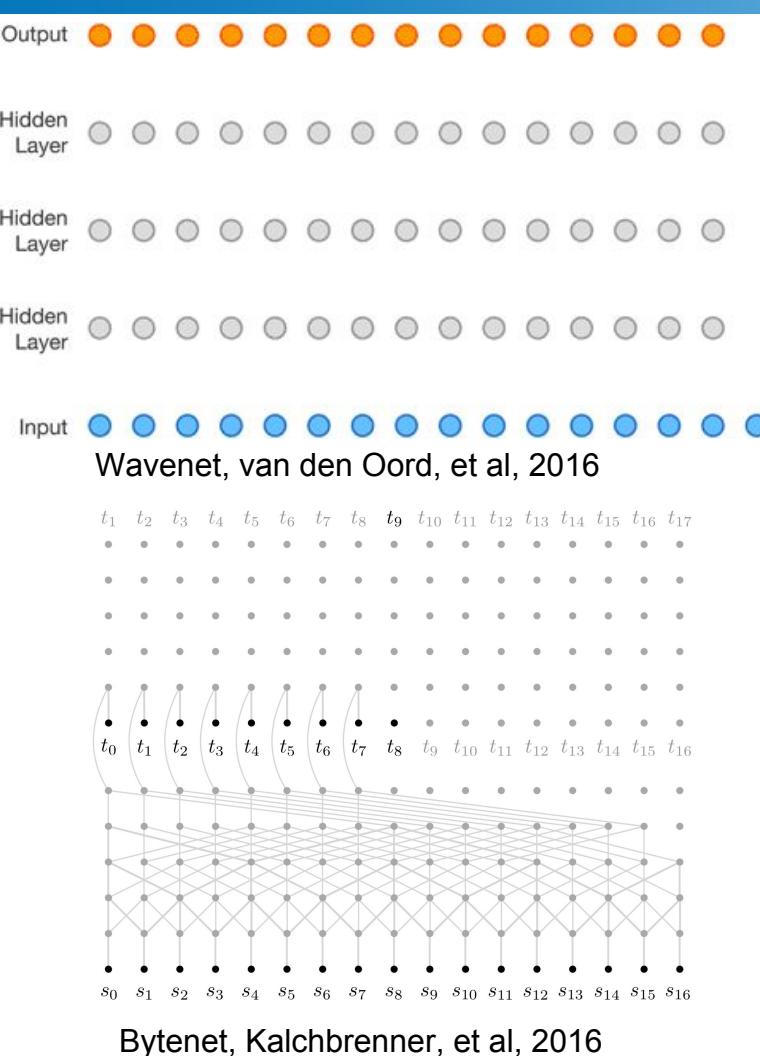


\mathbf{d}	distributions over phoneme
\mathbf{b}	probabilities to emit
$\tilde{\mathbf{b}}$	samplings of $Bernoulli(b)$
\mathbf{h}	states of RN
\mathbf{x}	input
\mathbf{t}	last true label

A Stochastic Emissions Model

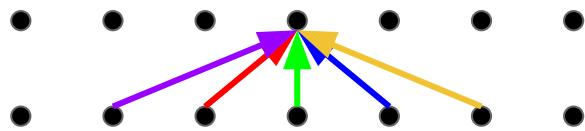


New Architectures

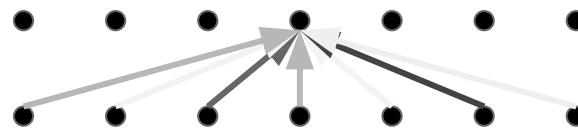


Self-Attention

Convolution

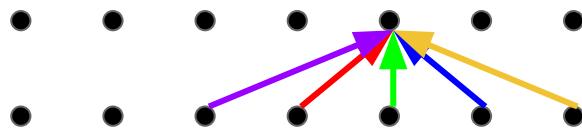


Self-Attention

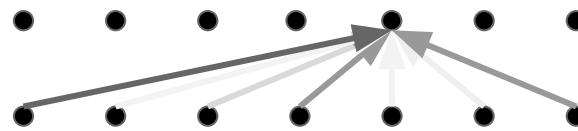


Self-Attention

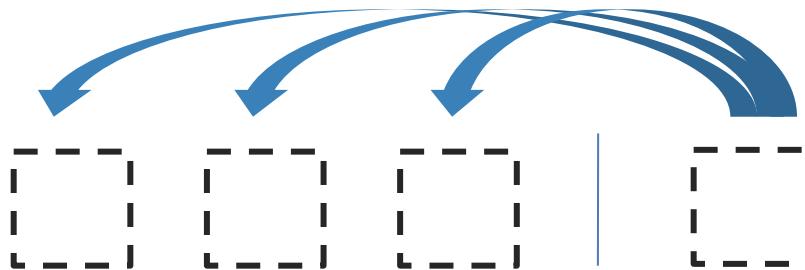
Convolution



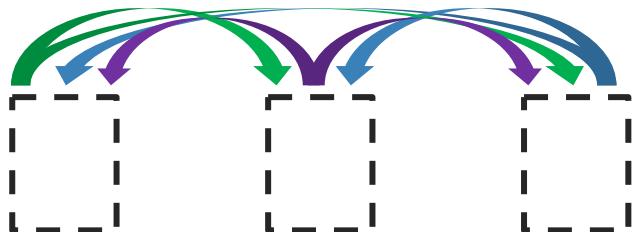
Self-Attention



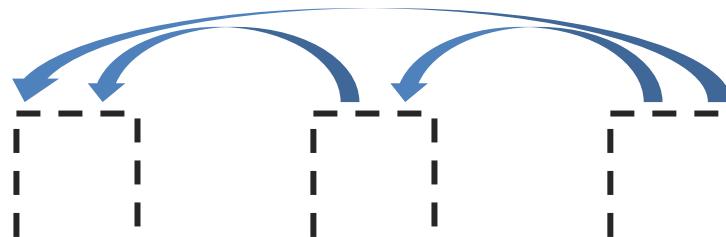
Three ways of attention



Encoder-Decoder Attention



Encoder Self-Attention

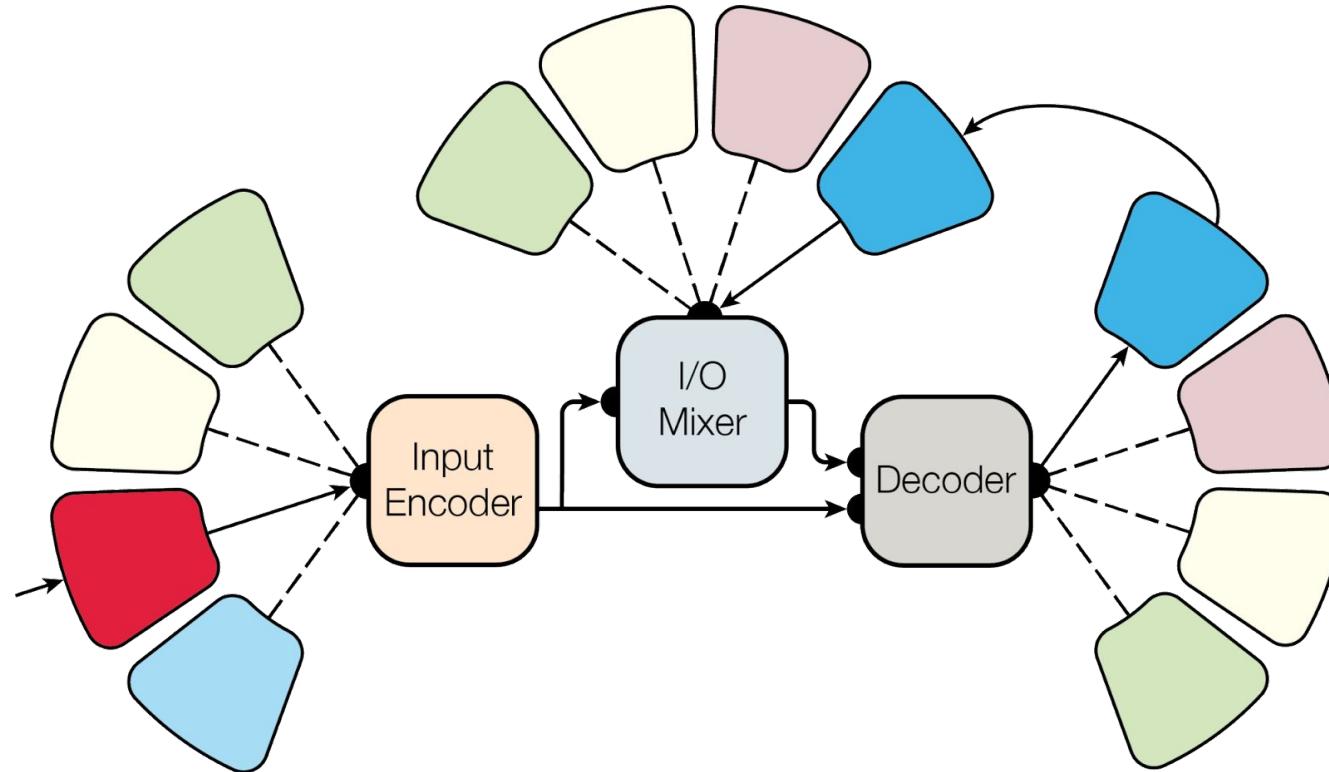


Masked Decoder Self-Attention

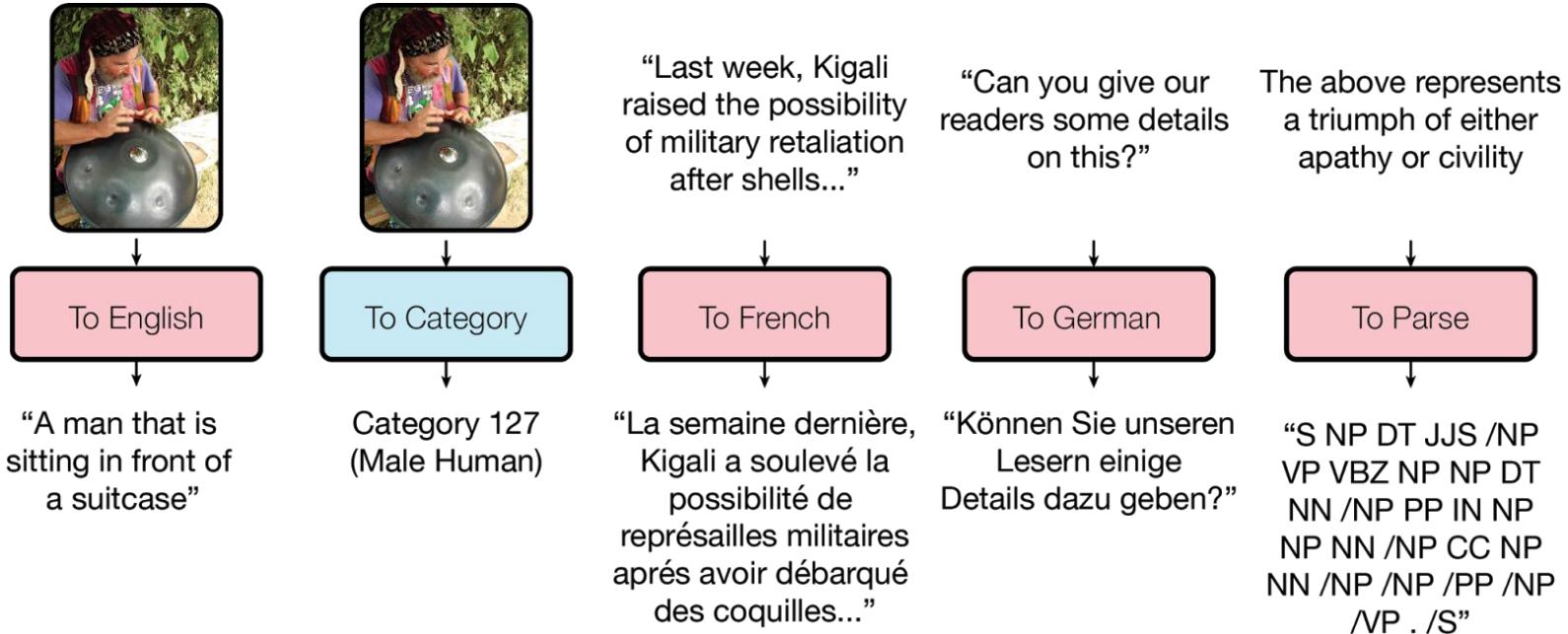
Machine Translation Results: WMT-14

Model	BLEU		Training Cost (FLOPs)	
	EN-DE	EN-FR	EN-DE	EN-FR
ByteNet [17]	23.75			
Deep-Att + PosUnk [37]		39.2		$1.0 \cdot 10^{20}$
GNMT + RL [36]	24.6	39.92	$2.3 \cdot 10^{19}$	$1.4 \cdot 10^{20}$
ConvS2S [9]	25.16	40.46	$9.6 \cdot 10^{18}$	$1.5 \cdot 10^{20}$
MoE [31]	26.03	40.56	$2.0 \cdot 10^{19}$	$1.2 \cdot 10^{20}$
Deep-Att + PosUnk Ensemble [37]		40.4		$8.0 \cdot 10^{20}$
GNMT + RL Ensemble [36]	26.30	41.16	$1.8 \cdot 10^{20}$	$1.1 \cdot 10^{21}$
ConvS2S Ensemble [9]	26.36	41.29	$7.7 \cdot 10^{19}$	$1.2 \cdot 10^{21}$
Transformer (base model)	27.3	38.1	$3.3 \cdot 10^{18}$	
Transformer (big)	28.4	41.0	$2.3 \cdot 10^{19}$	

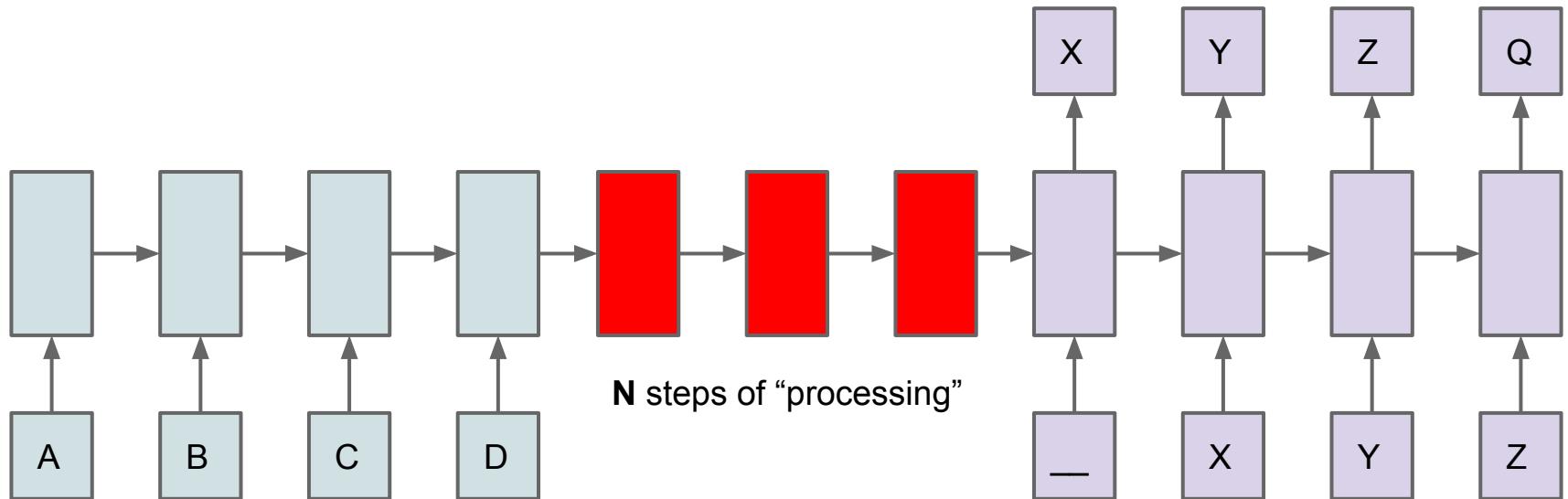
MultiModel



MultiModel



Processing Depth



1. Vinyals, O., et al. “Order Matters: Sequence to Sequence for sets.” *ICLR* (2015).
2. Sukhbaatar, S., et al. “End-to-End Memory Networks.” *NIPS* (2015).

How to pick N? Learn it of course!

Add a *halting unit* h to the output

$$h_t^n = \sigma(W_h s_t^n + b_h)$$

Use this to define the *halt probability* p_t^n at ponder step n

$$p_t^n = \begin{cases} R(t) & \text{if } n = N(t) \\ h_t^n & \text{otherwise} \end{cases}$$

Where $N(t)$ is # updates at t

$$N(t) = \min\{n' : \sum_{n=1}^{n'} h_t^n \geq 1 - \epsilon\}$$

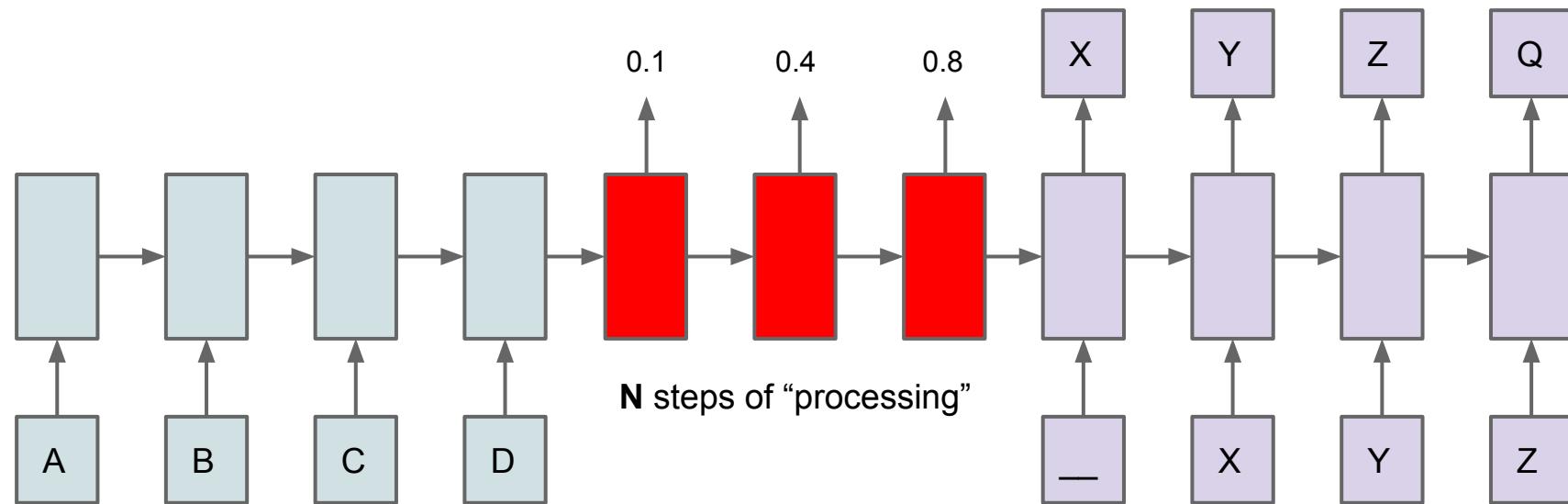
And $R(t)$ is the *remainder* at t

$$R(t) = 1 - \sum_{n=1}^{N(t)-1} h_t^n$$

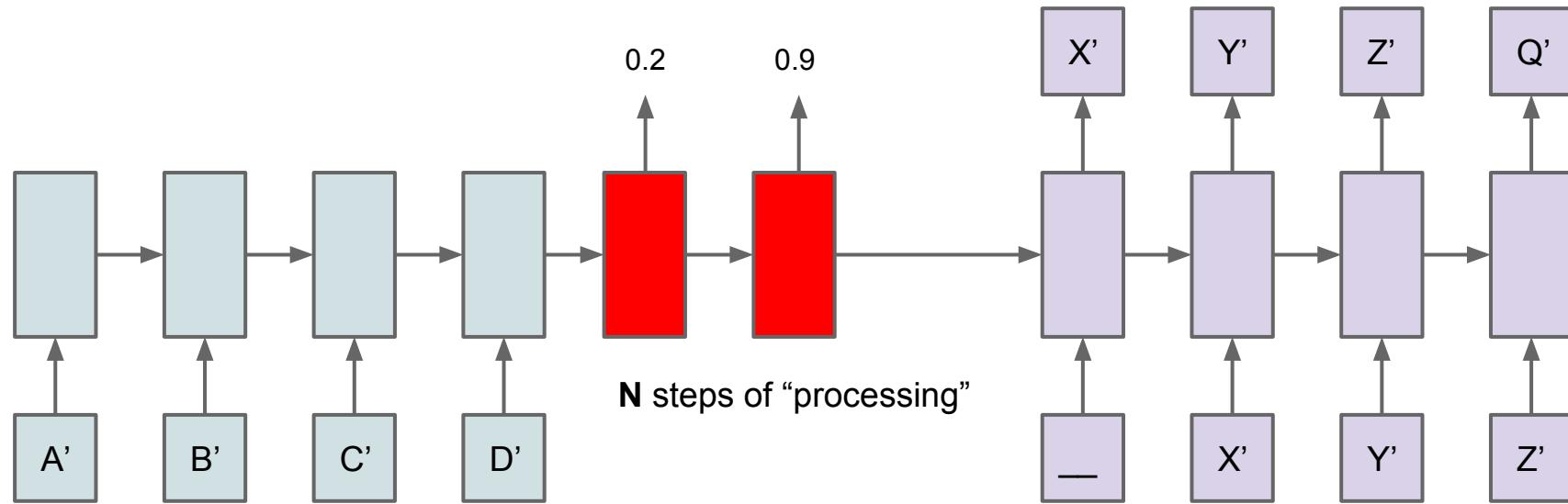
The final states and outputs at t are *weighted sums* (!)

$$s_t = \sum_{n=1}^{N(t)} p_t^n s_t^n \quad y_t = \sum_{n=1}^{N(t)} p_t^n y_t^n$$

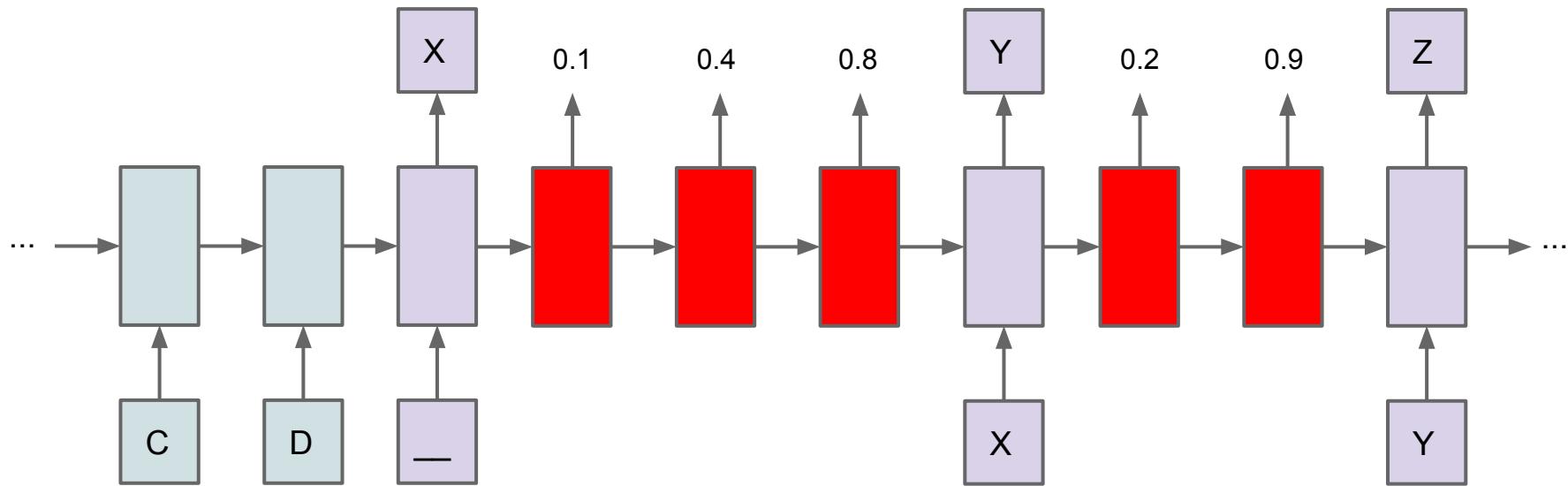
Adaptive Computation Time (ACT)



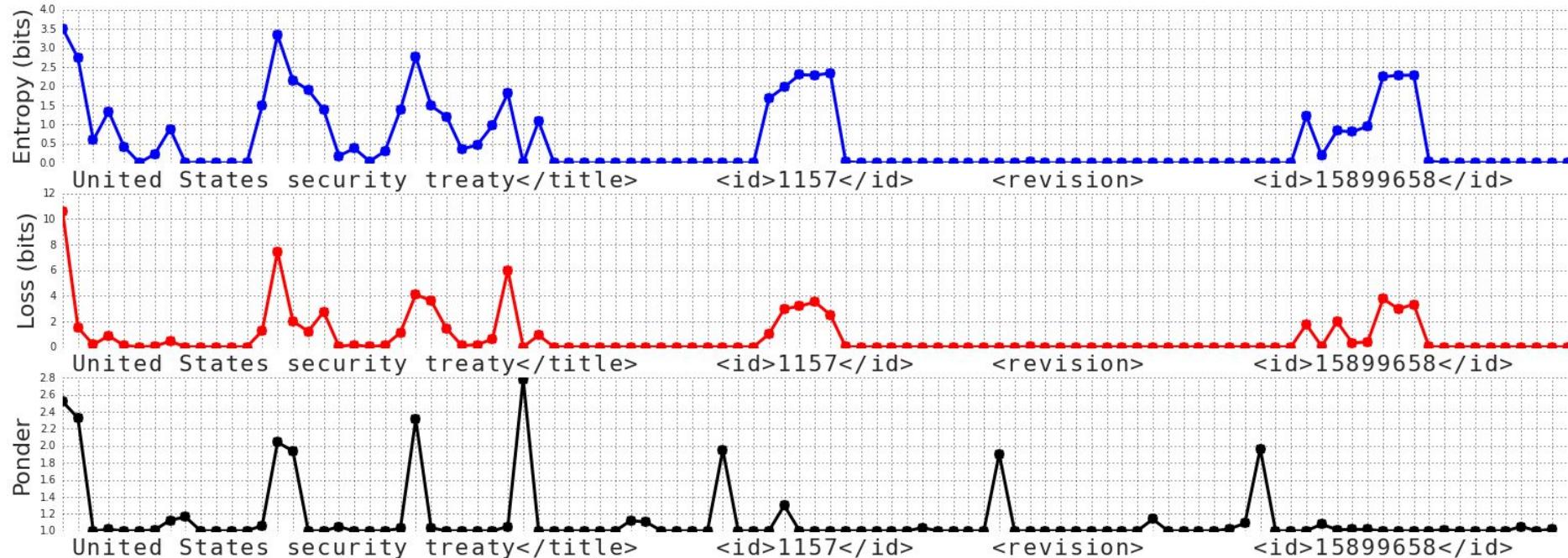
Adaptive Computation Time (ACT) [Graves, 2016]



(in)ACT [Graves, 2016]



Character level LM



A black and white photograph of the Sydney Opera House and the surrounding city skyline across the water. The iconic white shells of the opera house are prominent in the center, with the city buildings visible in the background under a cloudy sky.

The End / Questions

Oriol Vinyals and Navdeep Jaitly

@OriolVinyalsML | @NavdeepLearning

Site: <https://sites.google.com/view/seq2seq-icml17>