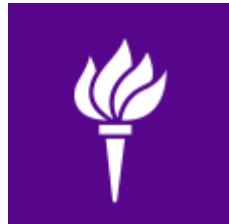


# Neural Machine Translation



NYU



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Kyunghyun Cho  
Christopher Manning

@lmthang · @kchonyc · @chrmanning

ACL 2016 tutorial · <https://sites.google.com/site/acl16nmt/>

# **1a. Intro to (Neural) Machine Translation**

## Ideas connecting Phrase-Based Statistical MT and NMT Neural Language Models

# Machine Translation

The classic test of language understanding!

Both language analysis & generation

Big MT needs ... for humanity ... and commerce

Translation is a US\$40 billion a year industry

Huge in Europe, growing in Asia

Large social/government/military  
as well as commercial needs



# The need for machine translation

Huge commercial use

**Google** translates over 100 billion words a day

**Facebook** has just rolled out new homegrown MT

“When we turned [MT] off for some people, they went nuts!”

**eBay** uses MT to enable cross-border trade

<http://www.commonsenseadvisory.com/AbstractView.aspx?ArticleID=36540>

<https://googleblog.blogspot.com/2016/04/ten-years-of-google-translate.html>

<https://techcrunch.com/2016/05/23/facebook-translation/>

# Scenarios for machine translation

1. The dream of fully automatic high-quality MT (FAHQMT)

This still seems a distant goal

2. User- or platform-initiated low quality translation

The current mainstay of MT

Google Translate

Bing Translator

# Scenarios for machine translation

## 3. Author-initiated high quality translation

MT with human post-editing or MT as a translation aid is clearly growing ... but remains painful

Great opportunities for a much brighter future where MT assists humans: e.g., MateCat or LiLT

<https://lilt.com/>

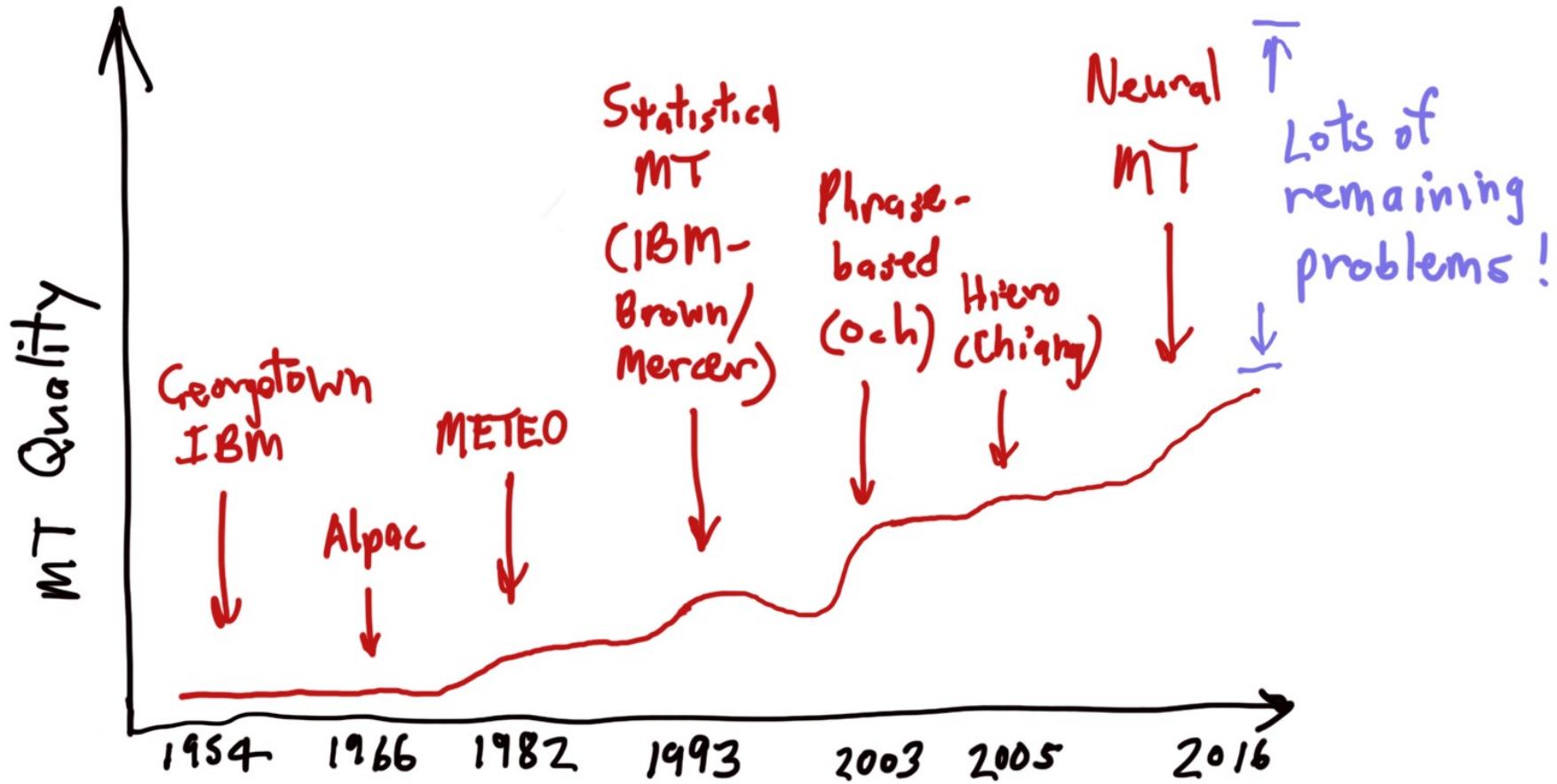
Talk in Sess 1C!

Durante nuestro período de pruebas, Lilt es completamente gratuito y no tiene límites de uso.

During our trial period, Lilt is completely free and has no

During our trial period, Lilt is completely free and has no limits.

# Progress in MT





Graham Neubig  
@gneubig



Wow, @stanfordnlp 's neural MT system for the IWSLT en-de task outperforms 2nd place by a massive 4.7 BLEU points: [workshop2015.iwslt.org/downloads/IWSLT2015.html](http://workshop2015.iwslt.org/downloads/IWSLT2015.html)

12/3/15, 7:18 PM

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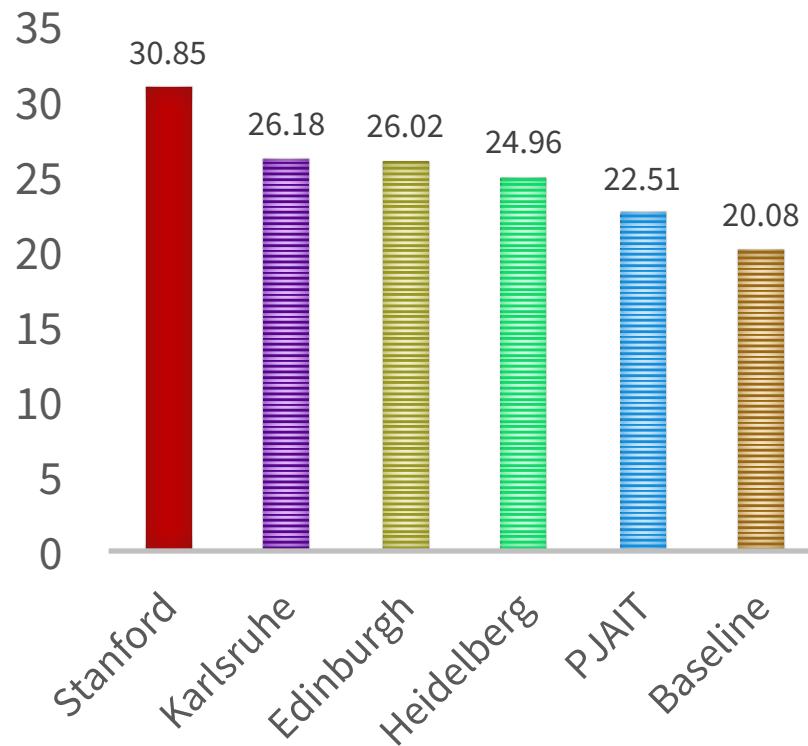
12 RETWEETS 21 LIKES

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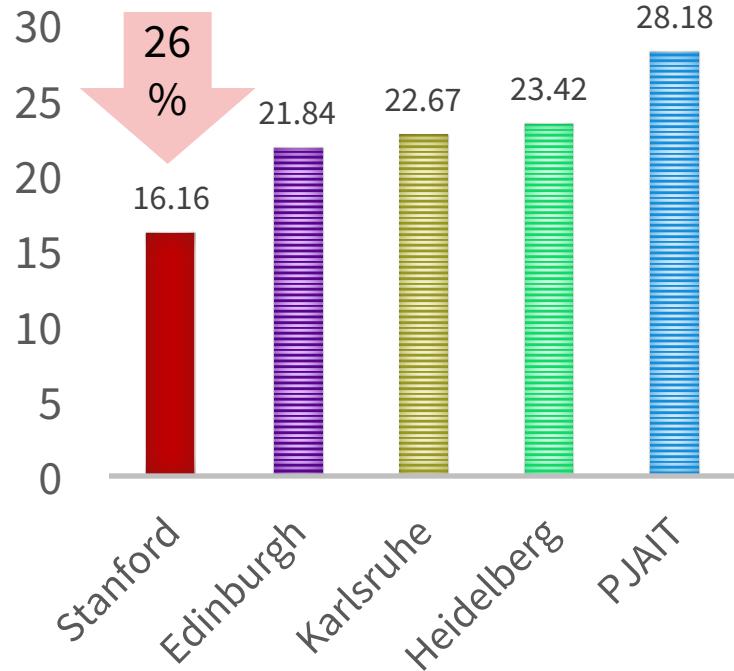


# IWSLT 2015, TED talk MT, English-German

## BLEU (CASED)

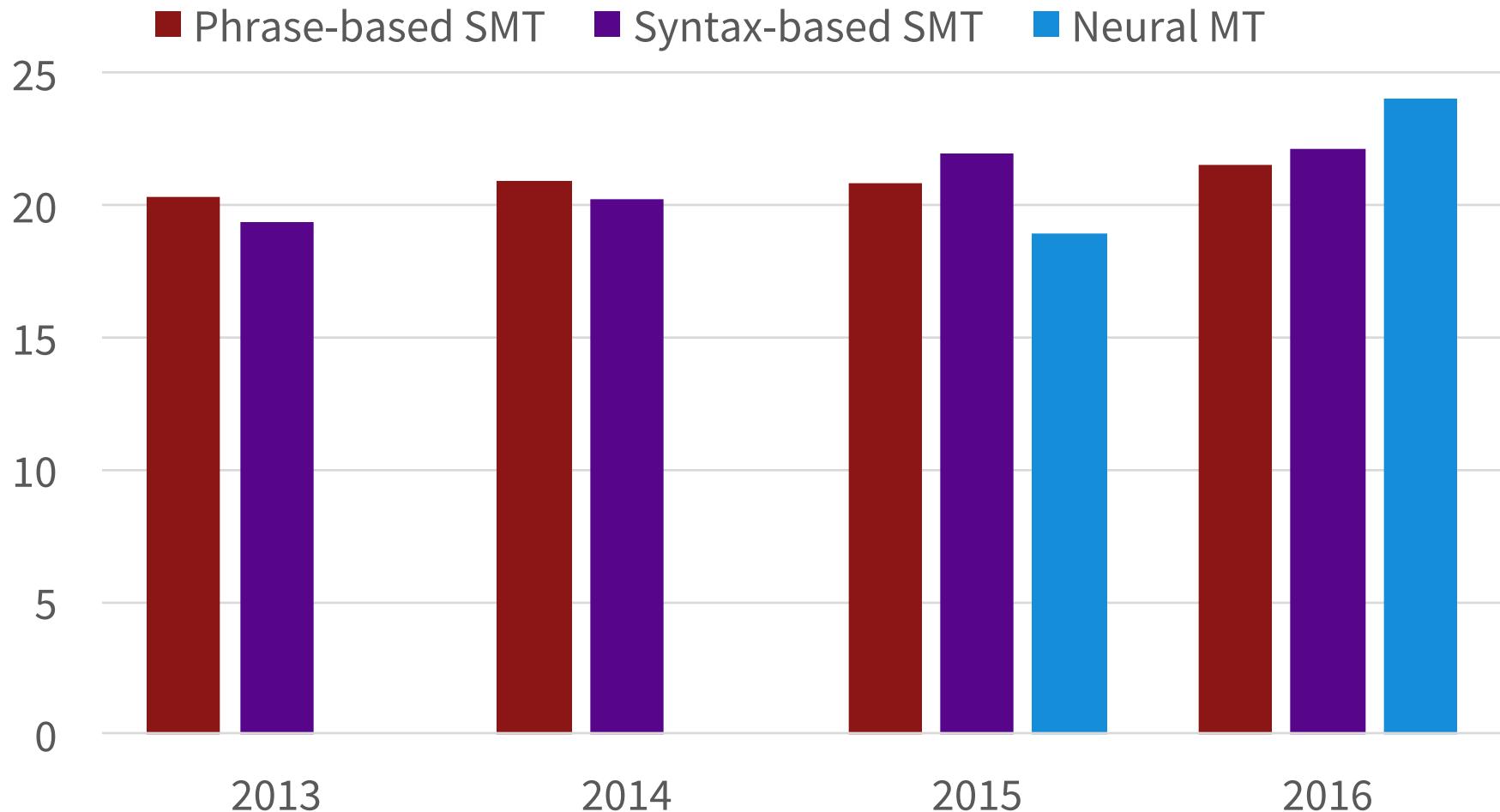


## HUMAN EVALUATION (HTER )



# Progress in Machine Translation

[Edinburgh En-De WMT newstest2013 Cased BLEU; NMT 2015 from U. Montréal]



From [Sennrich 2016, [http://www.meta-net.eu/events/meta-forum-2016/slides/09\\_sennrich.pdf](http://www.meta-net.eu/events/meta-forum-2016/slides/09_sennrich.pdf)]

# Phrase-based Statistical Machine Translation

A **marvelous** use of **big data** but ... it's mined out?!?

1519年600名西班牙人在墨西哥登陆，去征服几百万人口的阿兹特克帝国，初次交锋他们损兵三分之二。

In 1519, six hundred Spaniards landed in Mexico to conquer **the Aztec Empire** with a population of a few million. They lost two thirds of their soldiers in the first clash.

[translate.google.com \(2009\)](#): 1519 600 Spaniards landed in Mexico, **millions of people to conquer the Aztec empire**, the first two-thirds of soldiers against their loss.

[translate.google.com \(2013\)](#): 1519 600 Spaniards landed in Mexico **to conquer the Aztec empire**, **hundreds of millions of people**, the initial confrontation loss of soldiers two-thirds.

[translate.google.com \(2014\)](#): 1519 600 Spaniards landed in Mexico, **millions of people to conquer the Aztec empire**, the first two-thirds of the loss of soldiers they clash.

[translate.google.com \(2015\)](#): 1519 600 Spaniards landed in Mexico, **millions of people to conquer the Aztec empire**, the first two-thirds of the loss of soldiers they clash.

[translate.google.com \(2016\)](#): 1519 600 Spaniards landed in Mexico, **millions of people to conquer the Aztec empire**, the first two-thirds of the loss of soldiers they clash.



Neural MT is good!

Neural MT went from a fringe  
research activity in 2014 to the  
widely-adopted leading way to  
do MT in 2016.

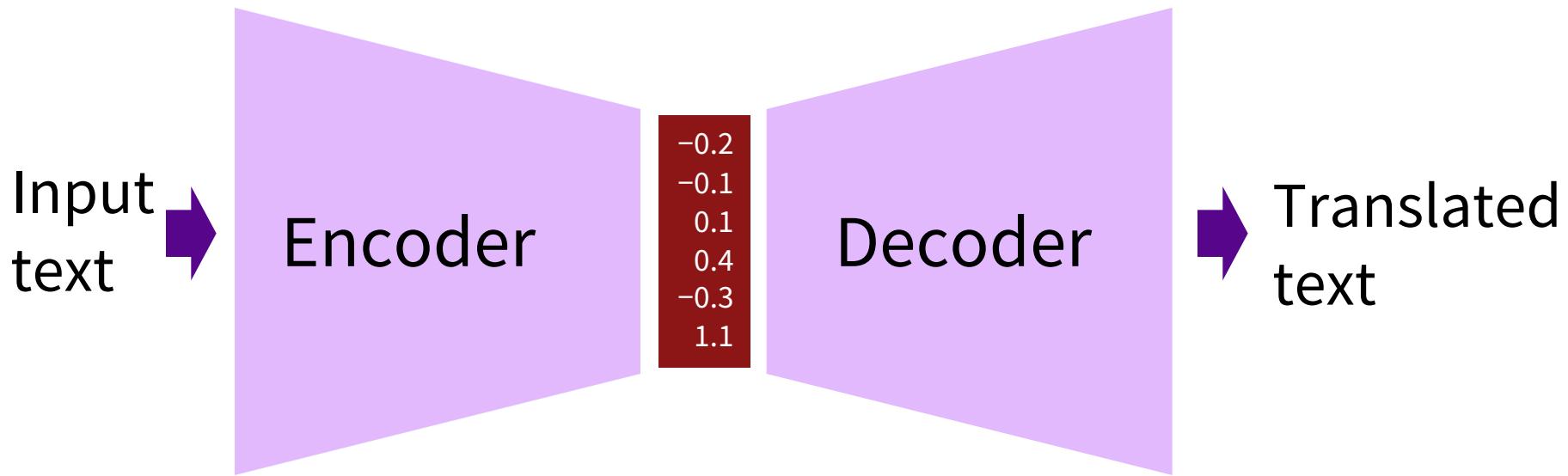
Amazing!

# What is Neural MT (NMT)?

Neural Machine Translation is the approach of modeling the entire MT process via one big artificial neural network\*

\*But sometimes we compromise this goal a little

# Neural encoder-decoder architectures



# NMT system for translating a single word

$V_s \times 1$      $d \times V_s$      $d \times 1$

$$w \quad L \quad x = Lw$$
$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} - & - & 0.2 & - & - \\ - & - & -1.4 & - & - \\ - & - & 0.3 & - & - \\ - & - & -0.1 & - & - \\ - & - & 0.1 & - & - \\ - & - & 0.5 & - & - \end{bmatrix} \begin{bmatrix} 0.2 \\ -1.4 \\ 0.3 \\ -0.1 \\ 0.1 \\ 0.5 \end{bmatrix}$$

↑  
one hot  
word  
symbol  
↑  
word

↑  
Looks up  
column of  
word embedding  
matrix

# NMT system for translating a single word

Nonlinearity  $f = \text{---}$

$$V_s \times 1 \quad d \times V_s \quad d \times 1 \quad d \times d \quad d \times 1 \quad a = f(z)$$

$$w \quad L \quad x = Lw \quad A \quad z = Ax + b \quad d \times 1$$

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} - & 0.2 & - & - \\ - & -1.4 & - & - \\ - & 0.3 & - & - \\ - & -0.1 & - & - \\ - & 0.1 & - & - \\ - & 0.5 & - & - \end{bmatrix} \begin{bmatrix} 0.2 \\ 1.4 \\ 0.3 \\ -0.1 \\ 0.1 \\ 0.5 \end{bmatrix} \begin{bmatrix} -0.2 & 0.1 & 0.1 & 0.3 & -0.1 & 0.2 \\ 1.2 & 0.3 & 1.1 & -0.5 & 0.7 & 0.1 \\ 0.1 & 0.1 & 0.7 & 1.0 & -0.3 & 0.1 \\ 0.5 & 0.3 & 0.3 & 0.7 & -0.2 & -0.2 \\ -0.2 & -0.2 & 0.1 & 0.2 & 0.3 & 0.2 \\ -0.1 & -0.1 & -0.1 & -0.1 & 0.5 & 0.4 \end{bmatrix} \begin{bmatrix} 1.1 \\ 0.3 \\ -0.1 \\ -0.3 \\ 0.5 \\ 0.7 \end{bmatrix} \begin{bmatrix} 1.1 \\ 0.3 \\ -0.01 \\ -0.07 \\ 0.5 \\ 0.07 \end{bmatrix}$$

↑  
one hot  
word  
symbol  
↑  
word

↑  
Looks up  
column of  
word embedding  
matrix

↑  
Transformation  
Matrix maps  
words in  
vector space

$$\begin{bmatrix} 0.4 \\ 0.1 \\ -0.3 \\ -0.2 \\ -0.1 \\ 0.2 \end{bmatrix}$$

Bias  $b$

# NMT system for translating a single word

Nonlinearity  $f = \text{ReLU}$

$$w \in V_s \times 1 \quad L \in d \times V_s \quad x = Lw \in d \times 1$$

$$\begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \\ 0 \\ 1 \\ 0 \\ 0 \\ 0 \end{bmatrix} \begin{bmatrix} - & 0.2 & - & - \\ - & - & 1.4 & - & - \\ - & - & 0.3 & - & - \\ - & - & -0.1 & - & - \\ - & - & 0.1 & - & - \\ - & - & 0.5 & - & - \end{bmatrix} \begin{bmatrix} 0.2 \\ 1.4 \\ 0.3 \\ -0.1 \\ 0.1 \\ 0.5 \end{bmatrix}$$

$$A \in d \times d \quad z = Ax + b \in d \times 1 \quad a = f(z) \in d \times 1$$

$$\begin{bmatrix} -0.2 & 0.1 & 0.1 & 0.3 & -0.1 & 0.2 \\ 1.2 & 0.3 & 1.1 & -0.5 & 0.7 & 0.1 \\ 0.1 & 0.1 & 0.7 & 1.0 & -0.3 & 0.1 \\ 0.5 & 0.3 & 0.3 & 0.7 & -0.2 & -0.2 \\ -0.2 & -0.2 & 0.1 & 0.2 & 0.3 & 0.2 \\ -0.1 & -0.1 & -0.1 & -0.1 & 0.5 & 0.4 \end{bmatrix} \begin{bmatrix} 1.1 \\ 0.3 \\ -0.1 \\ -0.3 \\ 0.5 \\ 0.7 \end{bmatrix} \begin{bmatrix} 0.1 \\ 0.3 \\ -0.2 \\ -0.4 \\ -0.1 \\ 0.2 \end{bmatrix}$$

$$V \in V_t \times d$$

$$\begin{bmatrix} 0.4 \\ 0.1 \\ -0.3 \\ -0.2 \\ -0.1 \\ 0.2 \end{bmatrix} \quad \text{Bias } b$$

↑  
one hot  
word  
symbol  
↑  
word

↑  
Looks up  
column of  
word embedding  
matrix

↑  
Transformation  
Matrix maps  
words in  
vector space

Softmax

$$p_i = \frac{e^{u_i}}{\sum_j e^{u_j}}$$

$$u = Vz \quad p$$

$$\begin{bmatrix} -0.1 \\ -0.3 \\ 0.9 \\ 0.7 \\ -0.1 \\ 6.1 \\ 0.9 \\ -0.2 \\ 0.1 \\ 0.2 \\ 0.1 \\ 1.0 \end{bmatrix} \quad \begin{bmatrix} 0.02 \\ 0.01 \\ 0.15 \\ 0.75 \\ 0.01 \\ 0.05 \\ 0.15 \\ 0.01 \\ 0.01 \\ 0.01 \\ 0.01 \\ 0.235 \end{bmatrix}$$

↑  
Word  
decoding  
matrix

↑  
Weight  
on each  
word

↑  
Word  
prob

$V_t \times 1 \quad V_t \times 1$

# Softmax function: Standard map from $\mathbb{R}^V$ to a probability distribution

*Exponentiate to make positive*

Softmax

$$e^{u_i}$$

$$p_i = \frac{e^{u_i}}{\sum_j e^{u_j}}$$

*Normalize to give probability*

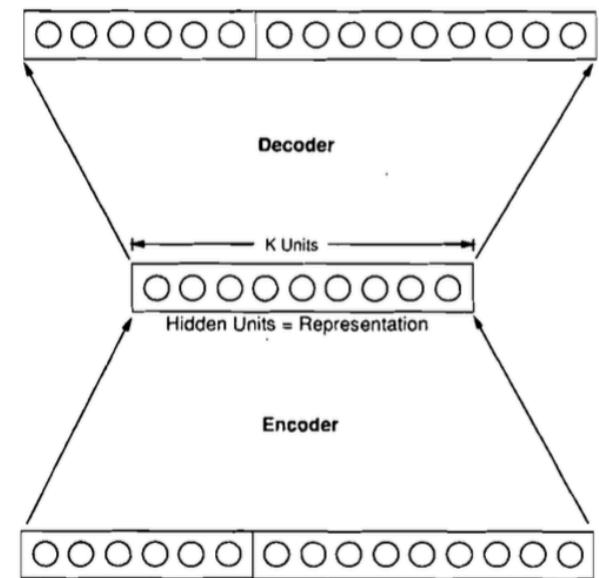
# Neural MT: The Bronze Age

[Allen 1987 IEEE 1<sup>st</sup> ICNN]

3310 En-Es pairs constructed on 31 En, 40 Es words, max 10/11 word sentence; 33 used as test set

The grandfather offered the little girl a book →  
El abuelo le ofrecio un libro a la nina pequena

Binary encoding of words – 50 inputs, 66 outputs; 1 or 3 hidden 150-unit layers. Ave WER: 1.3 words



# Neural MT: The Bronze Age

[Chrisman 1992 *Connection Science*]

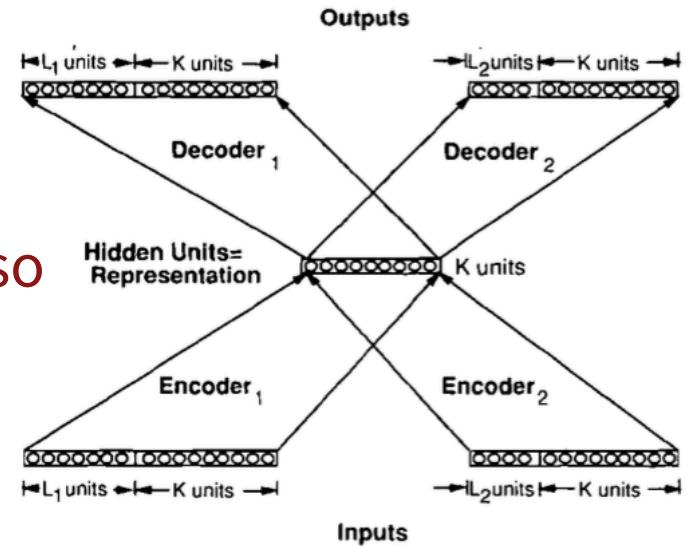
Dual-ported RAAM architecture

[Pollack 1990 *Artificial Intelligence*]

applied to corpus of 216 parallel pairs of simple En-Es sentences:

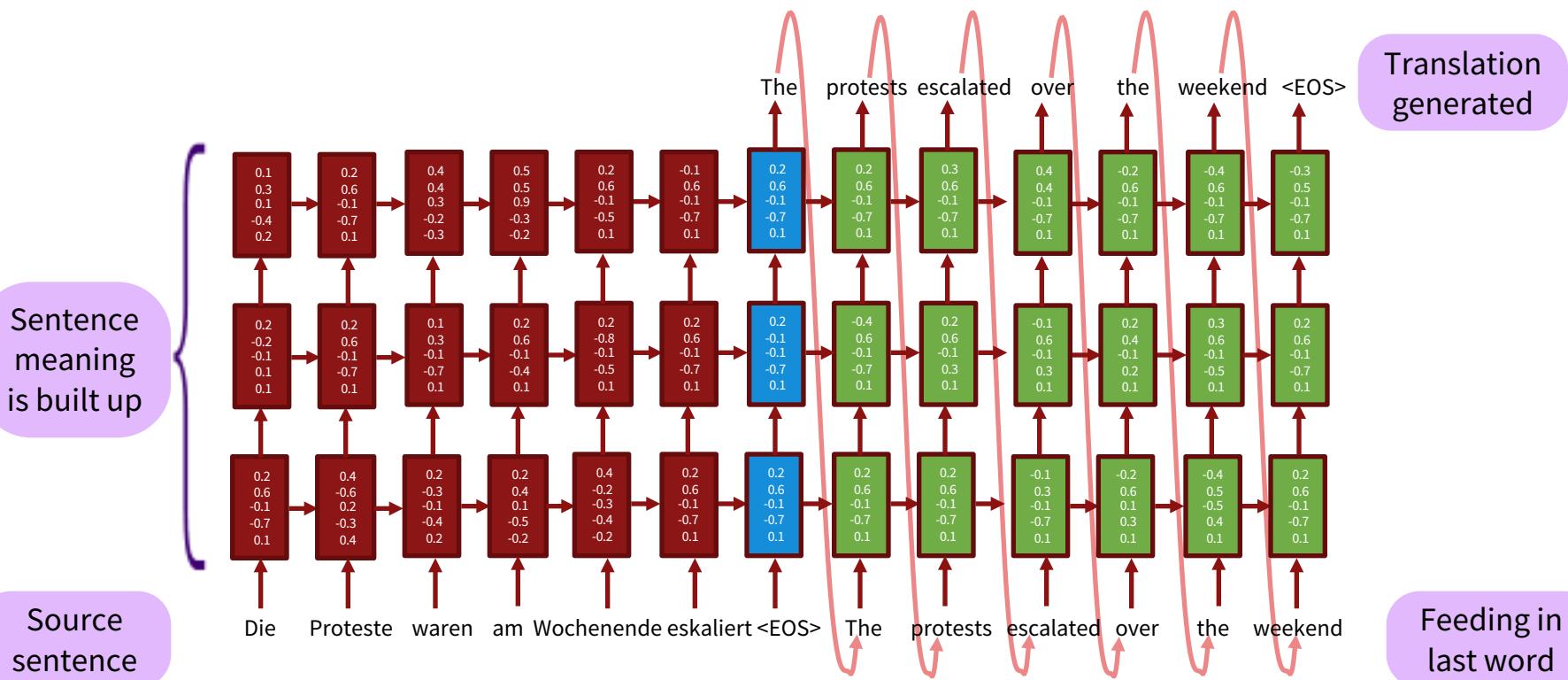
You are not angry  $\leftrightarrow$  Usted no esta furioso

Split 50/50 as train/test, 75% of sentences correctly translated!



# Modern Sequence Models for NMT

[Sutskever et al. 2014, Bahdanau et al. 2014, et seq.]  
following [Jordan 1986] and more closely [Elman 1990]



A deep recurrent neural network

# The three big wins of Neural MT

## 1. End-to-end training

All parameters are simultaneously optimized to minimize a loss function on the network's output

## 2. Distributed representations share strength

Better exploitation of word and phrase similarities

## 3. Better exploitation of context

NMT can use a much bigger context – both source and partial target text – to translate more accurately

# What wasn't on that list?

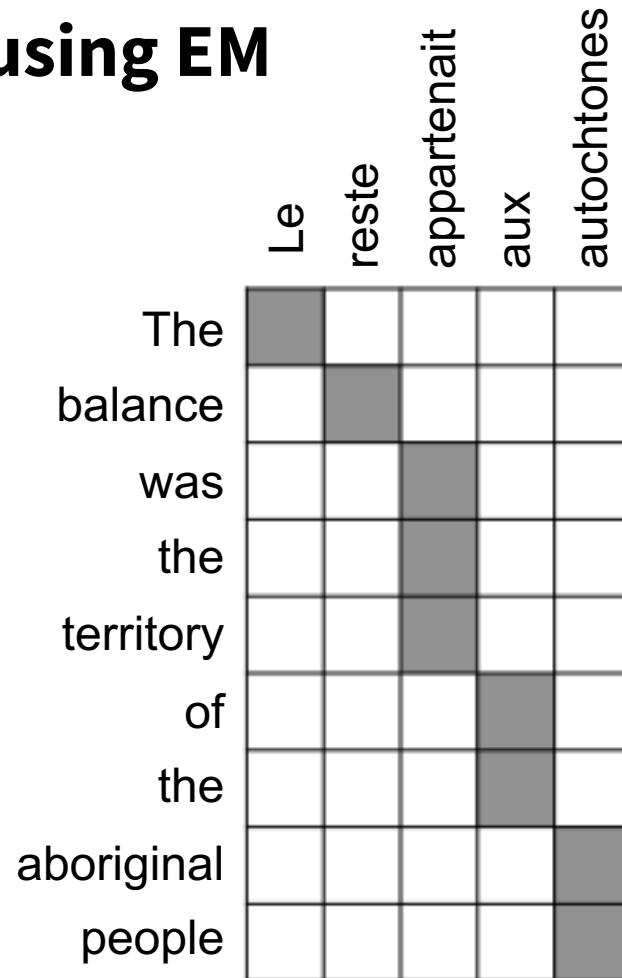
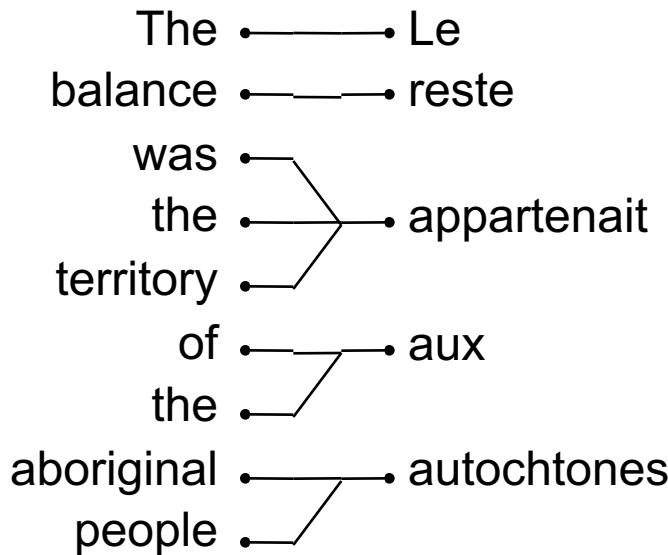
1. Explicit use of syntactic or semantic structures
2. Explicit use of discourse structure, anaphora, etc.
3. Black box component models for reordering, transliteration, etc.

The current baseline and its enduring ideas

## **1b. Ideas connecting Phrase-Based Statistical MT and NMT**

# Word alignments

Phrase-based SMT aligned words in a preprocessing-step, usually using EM

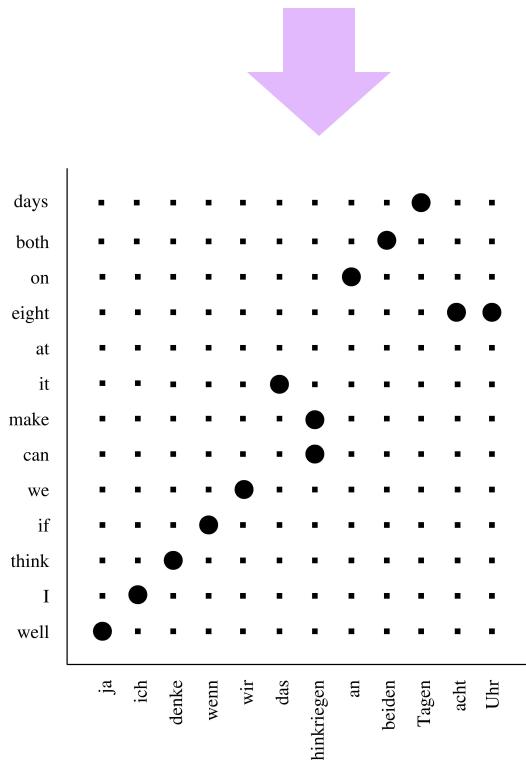


→ Models of attention  
[Bahdanau et al. 2014; ICLR 2015]

Part 3b later

# Constraints on “distortion” (displacement) and fertility

SMT: Alignment probability depends on positions of the words, and position relative to neighbors



The likelihood of an alignment depends on how many words align to a certain position



*farmers*

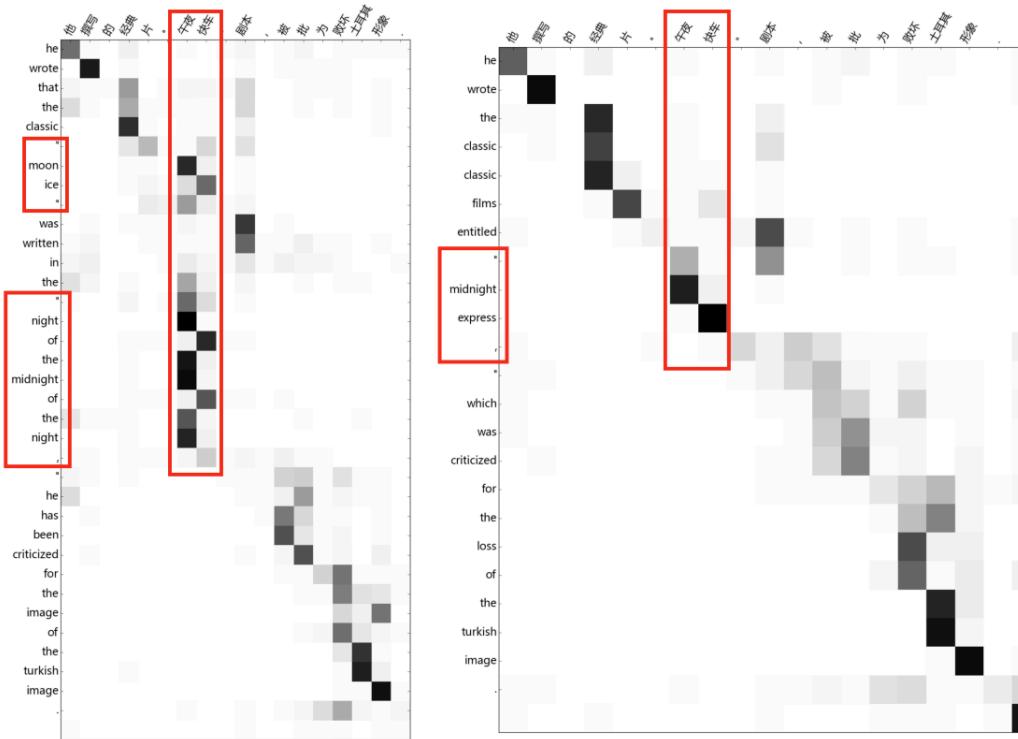
*the*

f	$t(f   e)$	$\phi$	$n(\phi   e)$
agriculteurs	0.442	2	0.731
les	0.418	1	0.228
cultivateurs	0.046	0	0.039
producteurs	0.021		

$\phi$	$n(\phi   e)$
1	0.746
0	0.254

# Constraints on “distortion” (displacement) and fertility

→ Constraints on attention [Cohn, Hoang, Vymolova, Yao, Dyer & Haffari NAACL 2016; Feng, Liu, Li, Zhou 2016 arXiv; Yang, Hu, Deng, Dyer, Smola 2016 arXiv].



# Automatic evaluation method for learning

Before usually BLEU; NMT → usually differentiable LM score, i.e., predict each word

Reference translation 1:

The U.S. island of Guam is maintaining a high state of alert after the Guam airport and its offices both received an e-mail from someone calling himself the Saudi Arabian Osama bin Laden and threatening a biological/chemical attack against public places such as the airport.

BLEU score against  
4 reference  
translations

Reference translation 2:

Guam International Airport and its offices are maintaining a high state of alert after receiving an e-mail that was from a person claiming to be the wealthy Saudi Arabian businessman Bin Laden and that threatened to launch a biological and chemical attack on the airport and other public places .

Machine translation:

The American [?] International airport and its office all receives one calls self the sand Arab rich and so on electronic mail , which sends out ; The threat will be able after public place and so on the airport to start the biochemistry attack , [?] highly alerts after the maintenance.

Reference translation 3:

The US International Airport of Guam and its office has received an email from a self-claimed Arabian millionaire named Laden, which threatens to launch a biochemical attack on such public places as airport . Guam authority has been on alert .

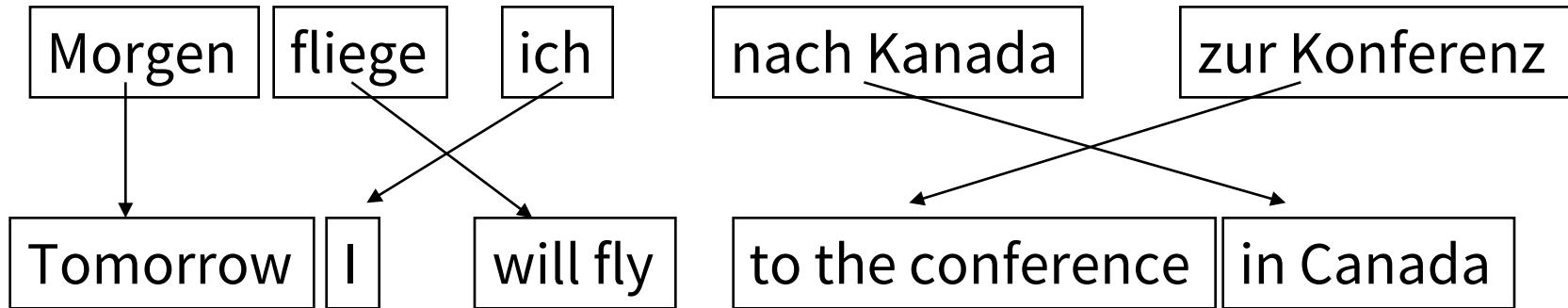
Reference translation 4:

US Guam International Airport and its office received an email from Mr. Bin Laden and other rich businessman from Saudi Arabia . They said there would be biochemistry air raid to Guam Airport and other public places . Guam needs to be in high precaution about this matter .

[Papineni et al. 2002]

# Phrase-Based Statistical MT: Pharaoh/Moses

[Koehn et al, 2003]



Source input segmented into phrases

- “phrase” is a subsequence of words – not linguistic phrase

→ Do we need phrases in NMT?

Or not, as have in-context word translation?

Cf. [Kalchbrenner & Blunsom 2013] source CNN and  
[Eriguchi, Hashimoto & Tsuruoka 2016] source tree

# SMT phrase table weights gave a context-independent translation score

Each phrase is probabilistically translated

- $P(\text{in spite} \mid \text{尽管})$
- $P(\text{in spite of the fact} \mid \text{尽管})$

开发 ||| development ||| (0) ||| (0) ||| -2.97 -2.72 -0.86 -0.95

开发 ||| development of ||| (0) ||| (0) () ||| -3.41 -2.72 -3.22 -3.50

进行 监督 ||| that carries out a supervisory ||| (1,2,3) (4) ||| () (0) (0) (0) (1) ||| 0.0 -3.68 -7.27 -21.24

进行 监督 ||| carries out a supervisory ||| (0,1,2) (3) ||| (0) (0) (0) (1) ||| 0.0 -3.68 -7.27 -17.17

监督 ||| supervisory ||| (0) ||| (0) ||| -1.03 -0.80 -3.68 -3.24

监督 检查 ||| supervisory inspection ||| (0) (1) ||| (0) (1) ||| 0.0 -2.33 -6.07 -4.

检查 ||| inspection ||| (0) ||| (0) ||| -1.54 -1.53 -2.05 -1.60

尽管 ||| in spite ||| (1) ||| () (0) ||| -0.90 -0.50 -3.56 -6.14

尽管 ||| in spite of ||| (1) ||| () (0) () ||| -1.11 -0.50 -3.93 -8.68

尽管 ||| in spite of the ||| (1) ||| () (0) () () ||| -1.06 -0.50 -4.77 -10.50

尽管 ||| in spite of the fact ||| (1) ||| () (0) () () () ||| -1.18 -0.50 -6.54 -18.19

# Phrase-based SMT: Log-linear feature-based MT models

$$\begin{aligned}\hat{e} &= \operatorname{argmax}_e 1.9 \times \log P(e) + 1.0 \times \log P(f | e) + 1.1 \times \\ &\quad \log \text{length}(e) + \dots \\ &= \operatorname{argmax}_e \sum_i w_i \phi_i\end{aligned}$$

We have two things:

- “Features”  $\phi$ , such as log translation model score
- Weights  $w$  for each feature for how good it is

The weights were learned

Feature scores from separately trained models

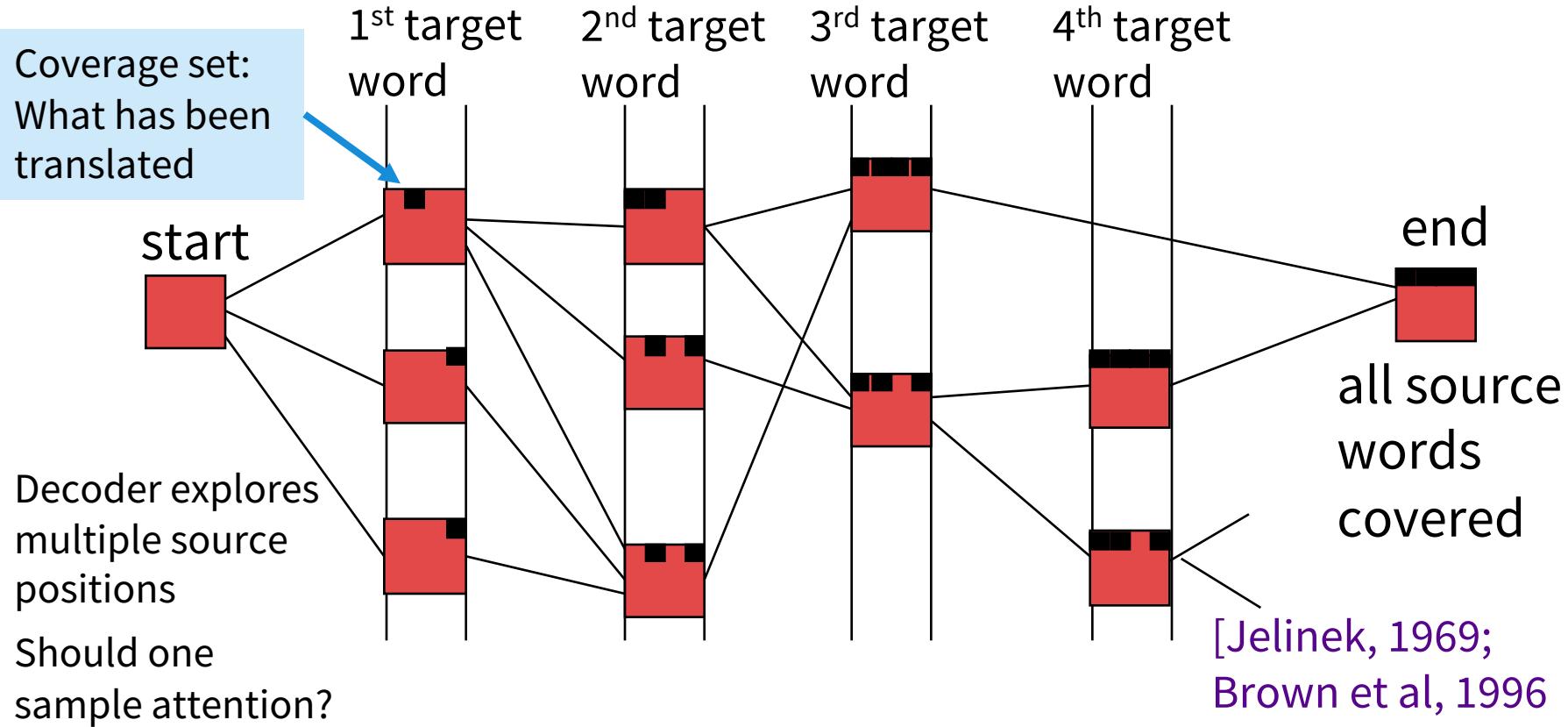
# Language Models (LM)

A language model -  $P(e)$  - gives the probability of a sequence of words

Most important feature! Why not just do more with language models?

E.g., generate a translation with LM also conditioned on source → Use NLM

# MT Decoder: Beam Search



→ NMT uses a similar beam decoder.  
It can be simpler, because contextual  
conditioning is much better: A beam of ~8 is sufficient.  
Work modeling coverage: [Tu, Lu, Liu, Liu, Li, ACL 2016]

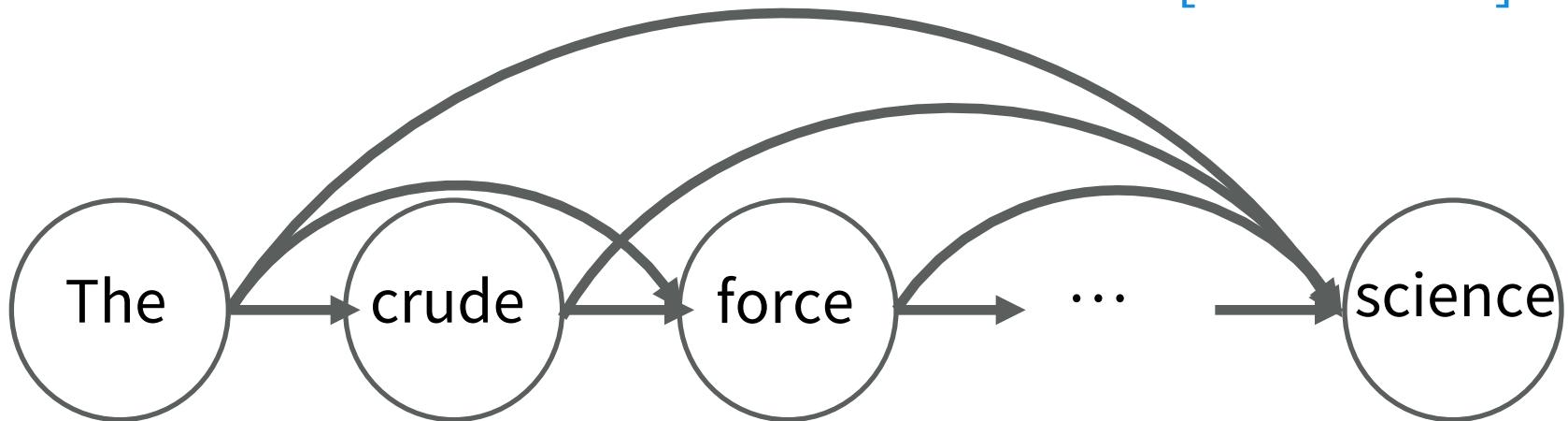
An NMT system is an NLM with extra conditioning!

## **1c. Neural Language Models**

# Language Models: Sentence probabilities

$$p(x_1, x_2, \dots, x_T) = \prod_{t=1}^T p(x_t | x_1, \dots, x_{t-1})$$

[Chain rule]



There are way too many histories once you're into a sentence a few words! Exponentially many.

# Traditional Fix: Markov Assumption

An  $n^{\text{th}}$  order Markov assumption assumes each word depends only on a short linear history

$$\begin{aligned} p(x_1, x_2, \dots, x_T) &= \prod_{t=1}^T p(x_t | x_1, \dots, x_{t-1}) \\ &\approx \prod_{t=1}^T p(x_t | x_{t-n}, \dots, x_{t-1}) \end{aligned}$$

# Problems of Traditional Markov Model Assumptions (1): Sparsity

**Issue:** *Very small window gives bad prediction; statistics for even a modest window are sparse*

**Example:**

$$P(w_0 | w_{-3}, w_{-2}, w_{-1}) \quad |V| = 100,000 \rightarrow 10^{15} \text{ contexts}$$

Most have not been seen

The traditional answer is to use various backoff and smoothing techniques, but no good solution

# Neural Language Models

The neural approach [Bengio, Ducharme, Vincent & Jauvin JMLR 2003] represents words as **dense** distributed vectors so there can be **sharing of statistical weight** between similar words

Doing just this solves the sparseness problem of conventional n-gram models

# Neural (Probabilistic) Language Model

## [Bengio, Ducharme, Vincent & Jauvin JMLR 2003]

$w_{-3}$   
registration

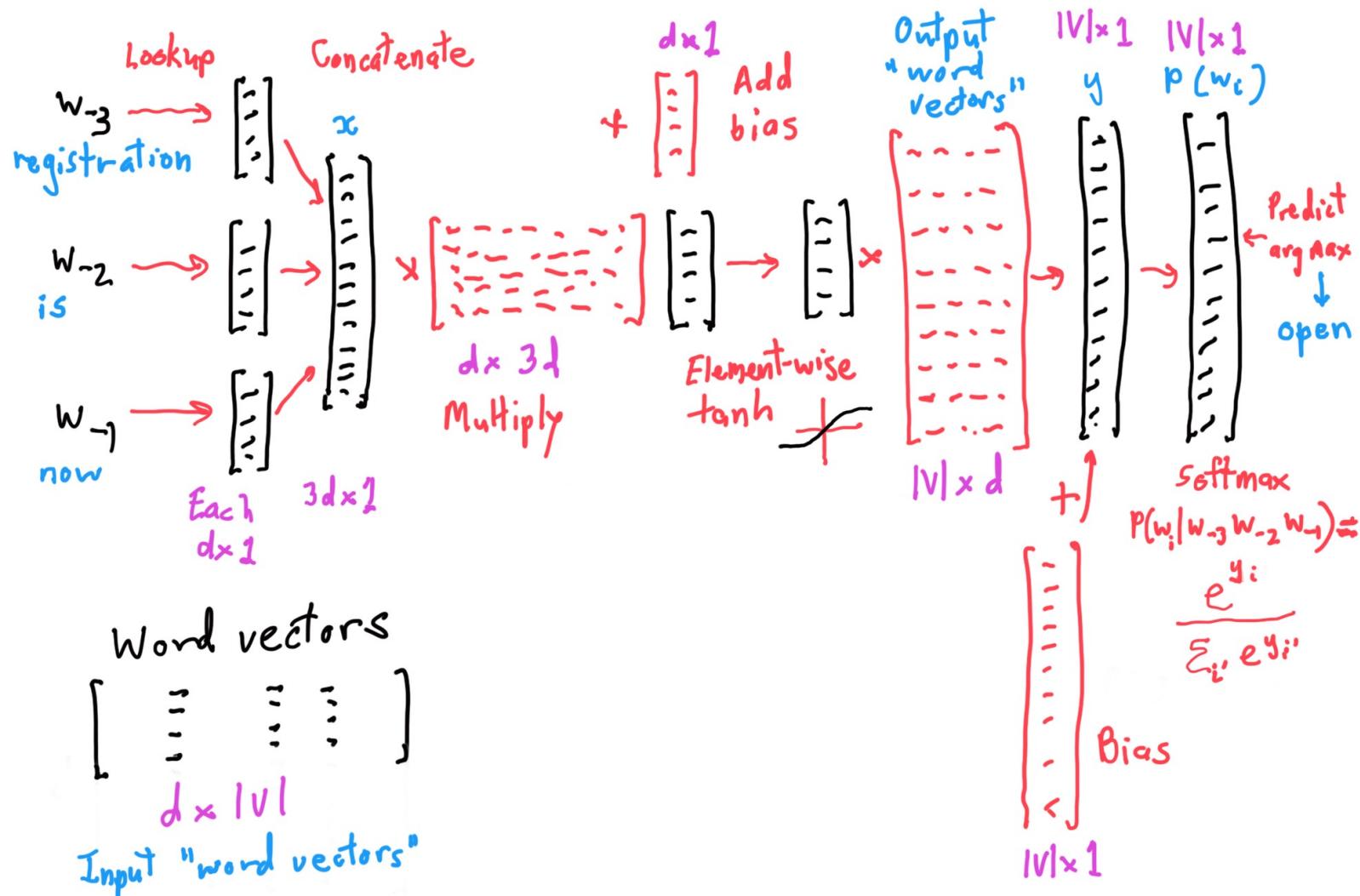
$w_{-2}$   
is

$w_{-1}$   
now

Predict  
 $\arg \max$   
↓  
open

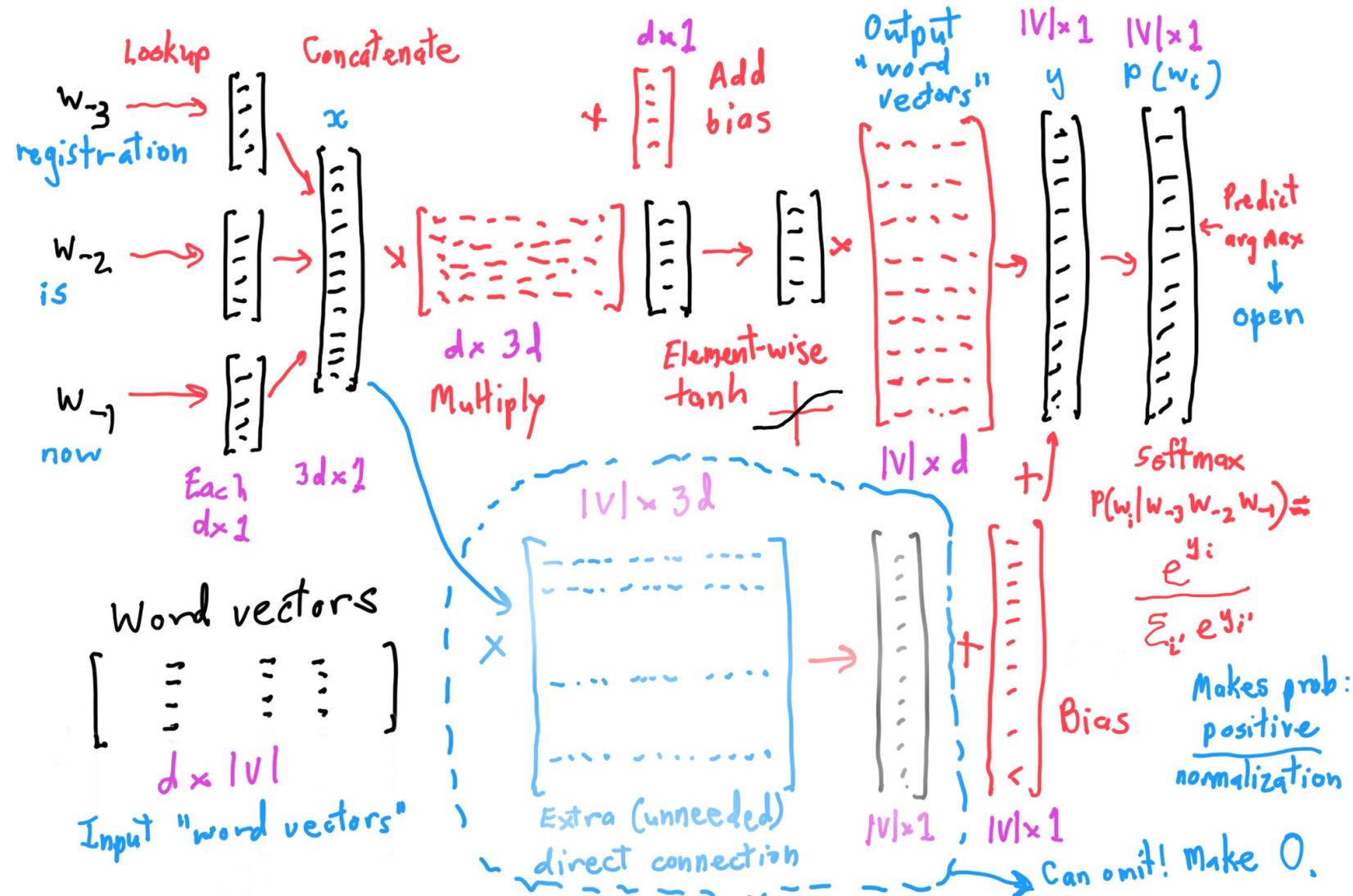
# Neural (Probabilistic) Language Model

# [Bengio, Ducharme, Vincent & Jauvin JMLR 2003]



# Neural (Probabilistic) Language Model

[Bengio, Ducharme, Vincent & Jauvin JMLR 2003]



# Problems of Traditional Markov Model Assumptions (2): Context

**Issue:** *Dependency beyond the window is ignored*

**Example:**

*the same **stump** which had impaled the car of many a guest in the past thirty years and which **he** refused to have **removed***

# A Non-Markovian Language Model

Can we directly model the true conditional probability?

$$p(x_1, x_2, \dots, x_T) = \prod_{t=1}^T p(x_t | x_1, \dots, x_{t-1})$$

Can we build a neural language model for this?

1. Feature extraction:  $h_t = f(x_1, x_2, \dots, x_t)$
2. Prediction:  $p(x_{t+1} | x_1, \dots, x_{t-1}) = g(h_t)$

How can  $f$  take a variable-length input?

# A Non-Markovian Language Model

Can we directly model the true conditional probability?

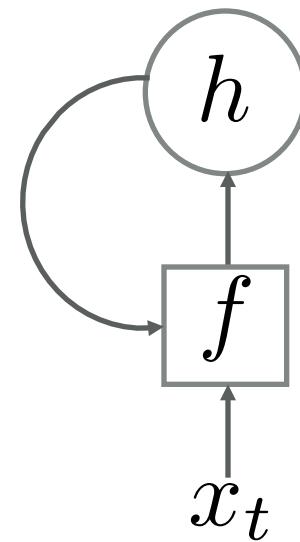
$$p(x_1, x_2, \dots, x_T) = \prod_{t=1}^T p(x_t | x_1, \dots, x_{t-1})$$

Recursive construction of  $f$

1. Initialization  $h_0 = 0$
2. Recursion  $h_t = f(x_t, h_{t-1})$

We call  $h_t$  a hidden state or memory

$h_t$  summarizes the history  $(x_1, \dots, x_t)$



# A Non-Markovian Language Model

*Example:*  $p(\text{the}, \text{cat}, \text{is}, \text{eating})$

(1) Initialization:  $h_0 = 0$

(2) Recursion with Prediction:

$$h_1 = f(h_0, \langle \text{bos} \rangle) \rightarrow p(\text{the}) = g(h_1)$$

$$h_2 = f(h_1, \text{cat}) \rightarrow p(\text{cat}|\text{the}) = g(h_2)$$

$$h_3 = f(h_2, \text{is}) \rightarrow p(\text{is}|\text{the}, \text{cat}) = g(h_3)$$

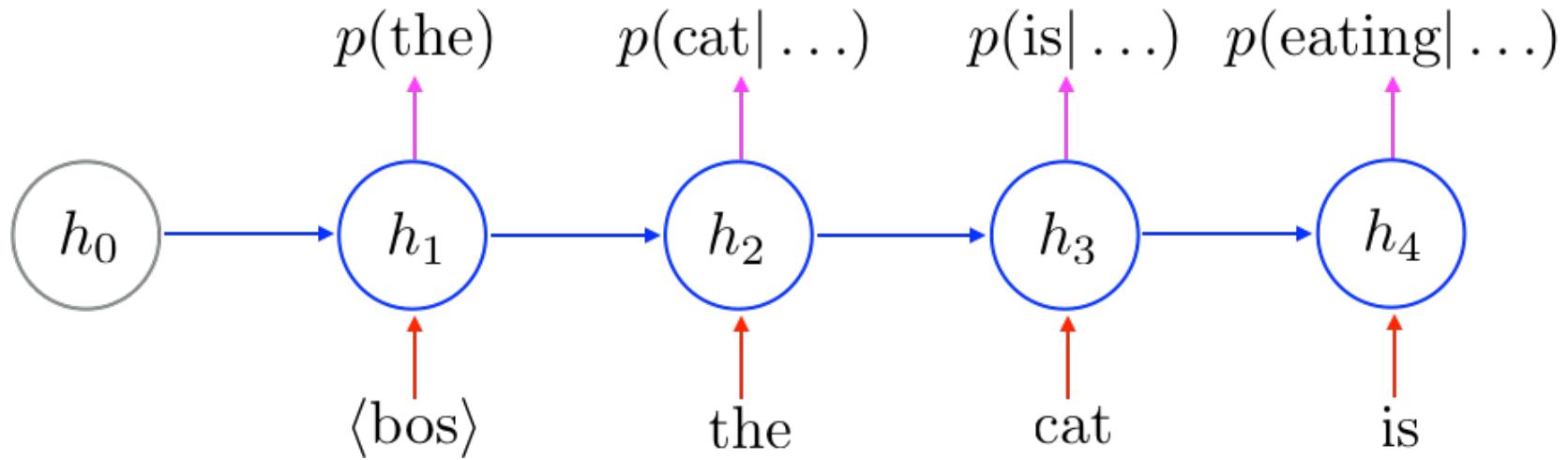
$$h_4 = f(h_3, \text{eating}) \rightarrow p(\text{eating}|\text{the}, \text{cat}, \text{is}) = g(h_4)$$

(3) Combination:

$$p(\text{the}, \text{cat}, \text{is}, \text{eating}) = g(h_1)g(h_2)g(h_3)g(h_4)$$

# A Recurrent Neural Network Language Model solves the second problem!

*Example:*  $p(\text{the}, \text{cat}, \text{is}, \text{eating})$



*Read, Update and Predict*

# Building a Recurrent Language Model

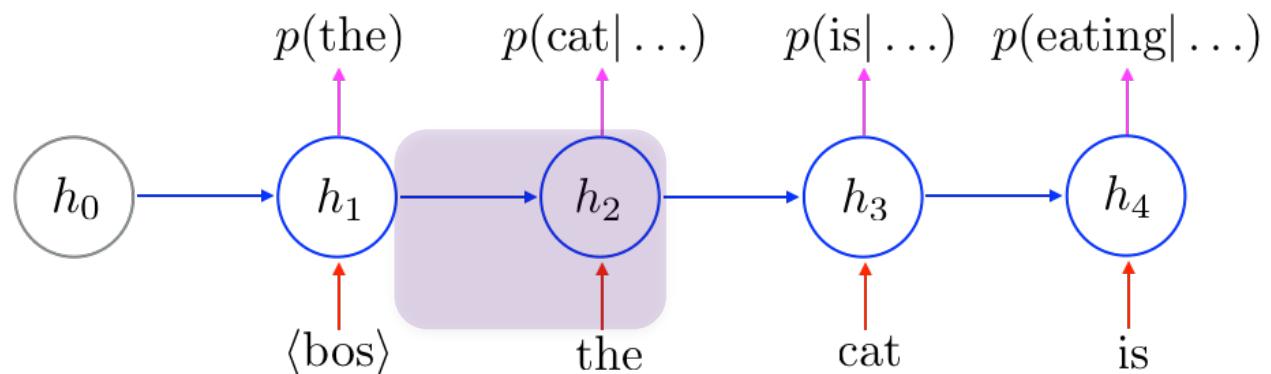
Transition Function  $h_t = f(h_{t-1}, x_t)$

Inputs

- i. Current word  $x_t \in \{1, 2, \dots, |V|\}$
- ii. Previous state  $h_{t-1} \in \mathbb{R}^d$

Parameters

- i. Input weight matrix  $W \in \mathbb{R}^{|V| \times d}$
- ii. Transition weight matrix  $U \in \mathbb{R}^{d \times d}$
- iii. Bias vector  $b \in \mathbb{R}^d$



# Building a Recurrent Language Model

Transition Function  $h_t = f(h_{t-1}, x_t)$

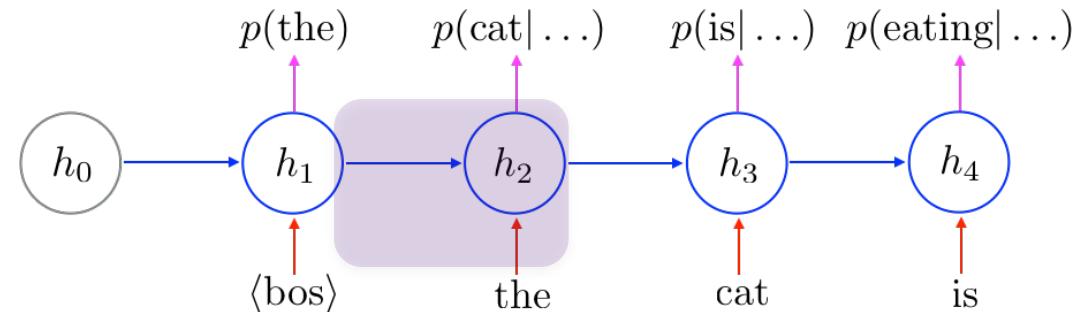
Naïve Transition Function

$$f(h_{t-1}, x_t) = \tanh(W [x_t] + Uh_{t-1} + b)$$

*Element-wise nonlinear transformation*

*Trainable word vector*

*Linear transformation of previous state*



# Building a Recurrent Language Model

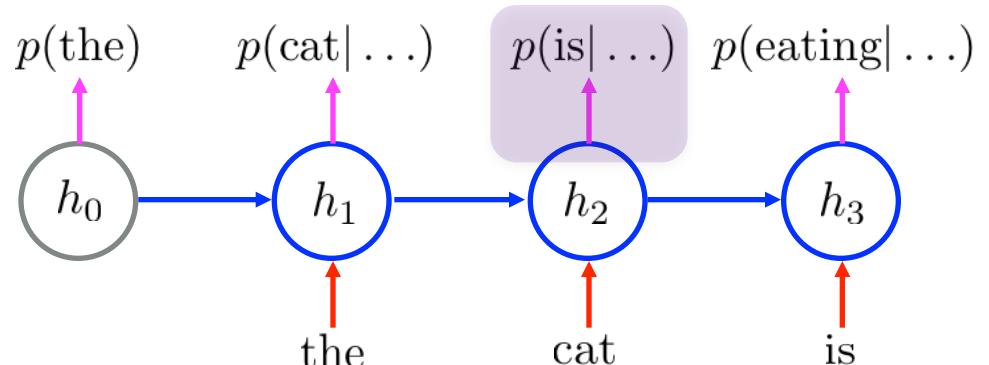
*Prediction Function*  $p(x_{t+1} = w | x_{\leq t}) = g_w(h_t)$

Inputs

- i. Current state  $h_t \in \mathbb{R}^d$

Parameters

- i. Softmax matrix  $R \in \mathbb{R}^{|V| \times d}$
- ii. Bias vector  $c \in \mathbb{R}^{|V|}$



# Building a Recurrent Language Model

*Prediction Function*  $p(x_{t+1} = w | x_{\leq t}) = g_w(h_t)$

$$p(x_{t+1} = w | x_{\leq t}) = g_w(h_t) = \frac{\exp(R[w]^\top h_t + c_w)}{\sum_{i=1}^{|V|} \exp(R[i]^\top h_t + c_i)}$$

**Compatibility between trainable word vector and hidden state**

**Exponentiate**

**Normalize**

```
graph LR; h0((h0)) --> h1((h1)); h1 --> h2((h2)); h2 --> h3((h3)); h0 -- "p(the)" --> p1["p(the)"]; h1 -- "p(cat|...)" --> p2["p(cat|...)"]; h2 -- "p(is|...)" --> p3["p(is|...)"]; h3 -- "p(eating|...)" --> p4["p(eating|...)"]; cat[cat] --> h2; is[is] --> h3;
```

# Training a recurrent language model

Having determined the model form, we:

1. Initialize all parameters of the models, including the word representations with small random numbers
2. Define a loss function: how badly we predict actual next words [log loss or cross-entropy loss]
3. Repeatedly attempt to predict each next word
4. Backpropagate our loss to update **all** parameters
5. Just doing this learns good word representations and good prediction functions – it's almost magic

# Neural Language Models as MT components

You can just replace the target-side language model of a conventional phrase-based SMT system with an NLM

NLM / Continuous space language models

[Schwenk, Costa-Jussà & Fonollosa 2006; Schwenk 2007; Auli & Gao 2013;  
Vaswani, Zhao, Fossum & Chiang 2013]

You can use **the source** as well as target words to predict next target word, usually using phrase alignment

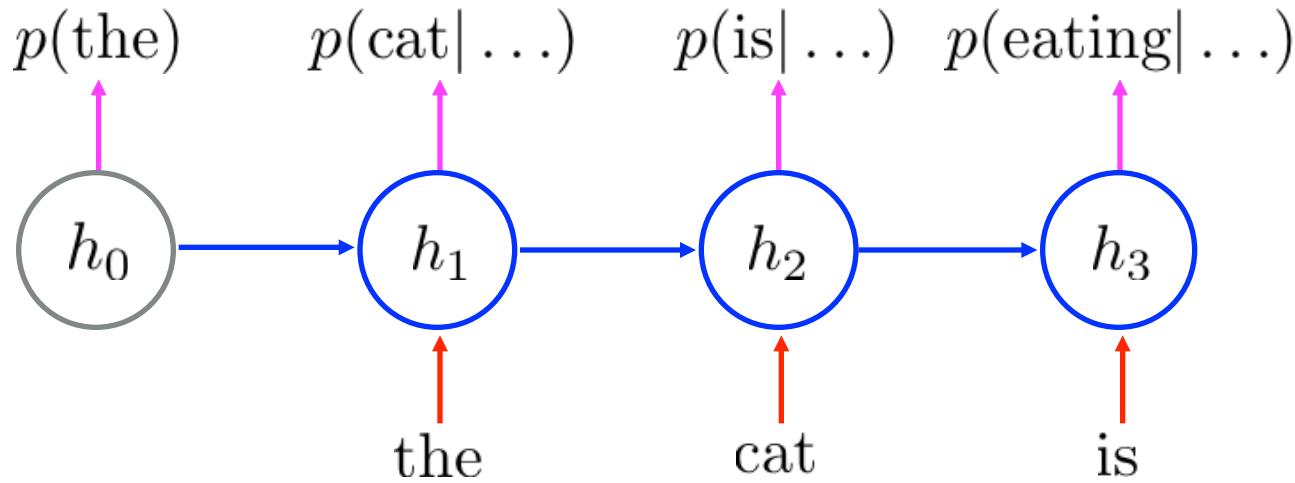
Neural Joint Language Models

[Auli, Galley, Quirk & Zweig 2013; Devlin, Zbib, Huang, Lamar, Schwartz & Makhool 2014]

However,  
we want to move on to the  
goal of an end-to-end trained  
neural translation model!

# Recurrent Language Model

*Example)  $p(\text{the}, \text{cat}, \text{is}, \text{eating})$*



*Read, Update and Predict*

## **2a. Training a Recurrent Language Model**

**Maximum likelihood estimation with stochastic gradient descent and backpropagation through time**

# Training a Recurrent Language Model

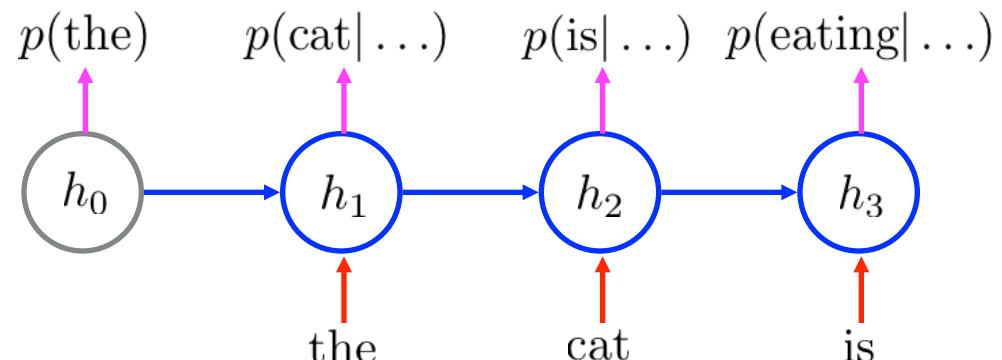
- Log-probability of one training sentence

$$\log p(x_1^n, x_2^n, \dots, x_{T^n}^n) = \sum_{t=1}^{T^n} \log p(x_t^n | x_1^n, \dots, x_{t-1}^n)$$

- Training set  $D = \{X^1, X^2, \dots, X^N\}$
- Log-likelihood Functional

$$\mathcal{L}(\theta, D) = \frac{1}{N} \sum_{n=1}^N \sum_{t=1}^{T^n} \log p(x_t^n | x_1^n, \dots, x_{t-1}^n)$$

**Minimize  $-\mathcal{L}(\theta, D)$  !!**

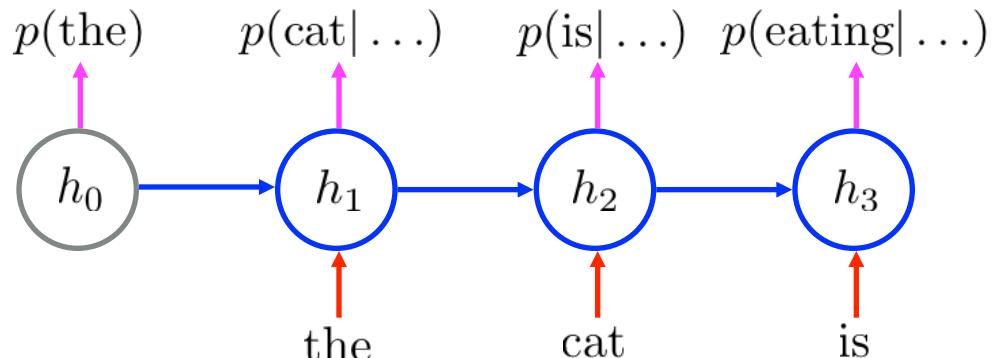
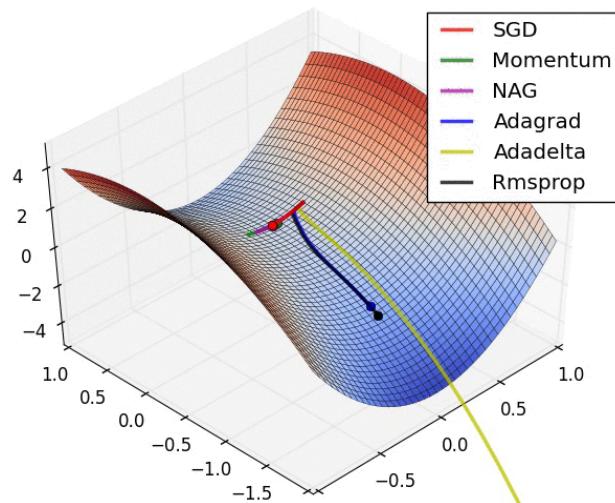


# Gradient Descent

- Move slowly in the steepest descent direction

$$\theta \leftarrow \theta - \eta \nabla \mathcal{L}(\theta, D)$$

- Computational cost of a single update:  $O(N)$
- Not suitable for a large corpus



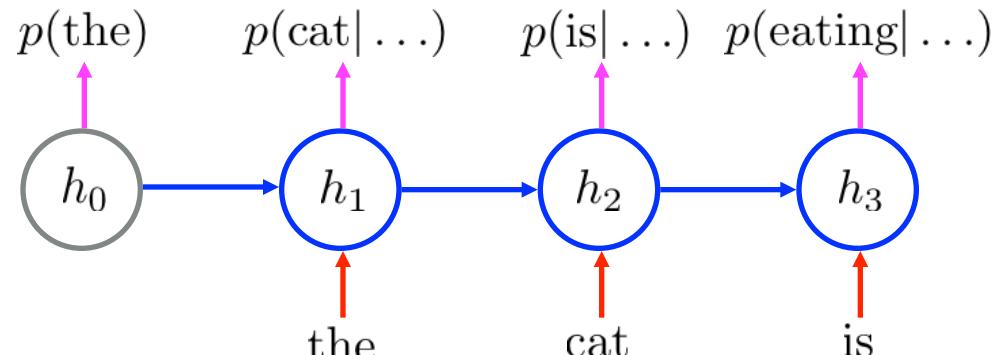
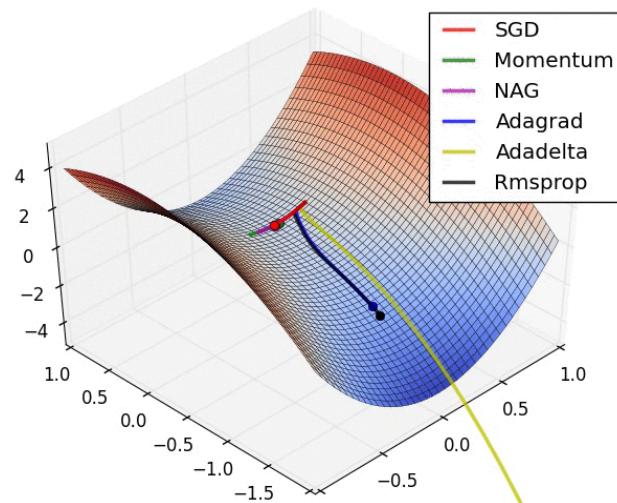
# Stochastic Gradient Descent

- Estimate the steepest direction with a minibatch

$$\nabla \mathcal{L}(\theta, D) \approx \nabla \mathcal{L}(\theta, \{X^1, \dots, X^n\})$$

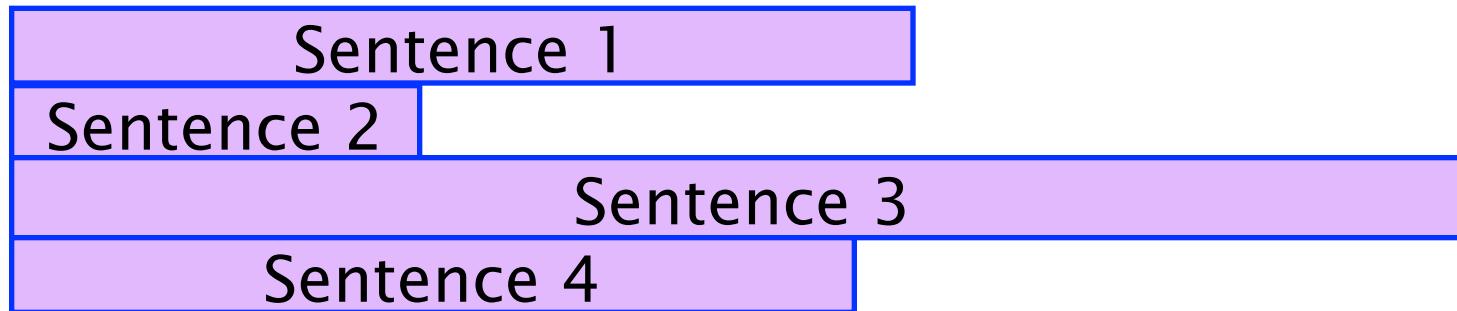
- Until the convergence (w.r.t. a validation set)

$$|\mathcal{L}(\theta, D_{\text{val}}) - \mathcal{L}(\theta - \eta \nabla \mathcal{L}(\theta, D), D_{\text{val}})| \leq \epsilon$$

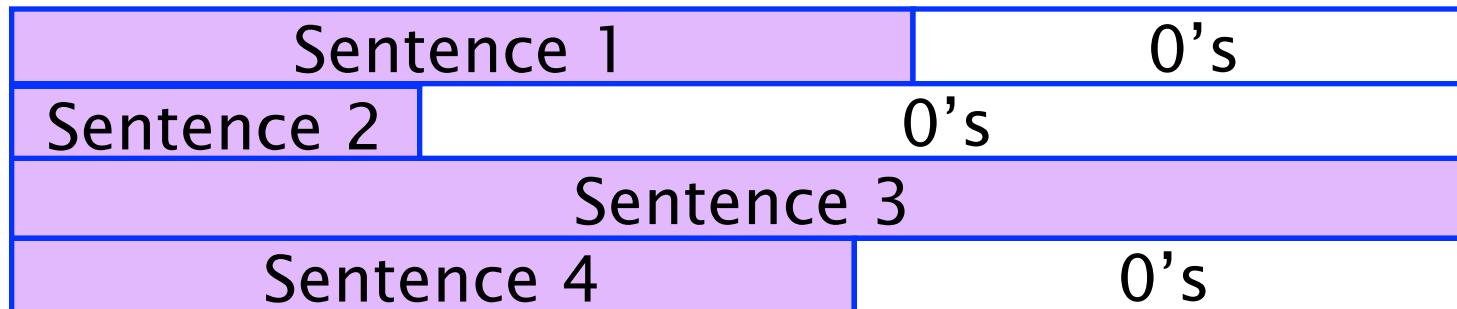


# Stochastic Gradient Descent

- Not trivial to build a minibatch



1. Padding and Masking: *suitable for GPU's, but wasteful*
  - *Wasted computation*



# Stochastic Gradient Descent

1. Padding and Masking: *suitable for GPU's, but wasteful*
  - *Wasted computation*

Sentence 1	0's
Sentence 2	0's
Sentence 3	
Sentence 4	0's

2. Smarter Padding and Masking: *minimize the waste*
  - *Ensure that the length differences are minimal.*
  - *Sort the sentences and sequentially build a minibatch*

Sentence 1	0's
Sentence 2	0's
Sentence 3	0's
Sentence 4	

# Backpropagation through Time

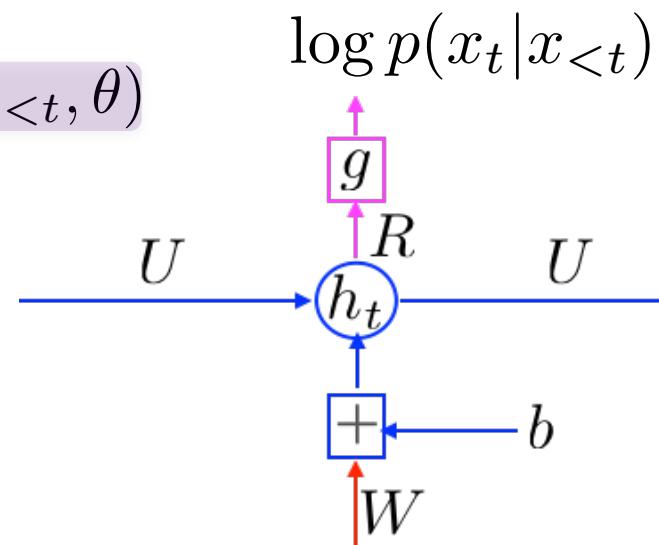
How do we compute  $\nabla \mathcal{L}(\theta, D)$ ?

- Cost as a sum of per-sample cost function

$$\nabla \mathcal{L}(\theta, D) = \sum_{X \in D} \nabla \mathcal{L}(\theta, X)$$

- Per-sample cost as a sum of per-step cost functions

$$\nabla \mathcal{L}(\theta, X) = \sum_{t=1}^T \nabla \log p(x_t | x_{<t}, \theta)$$



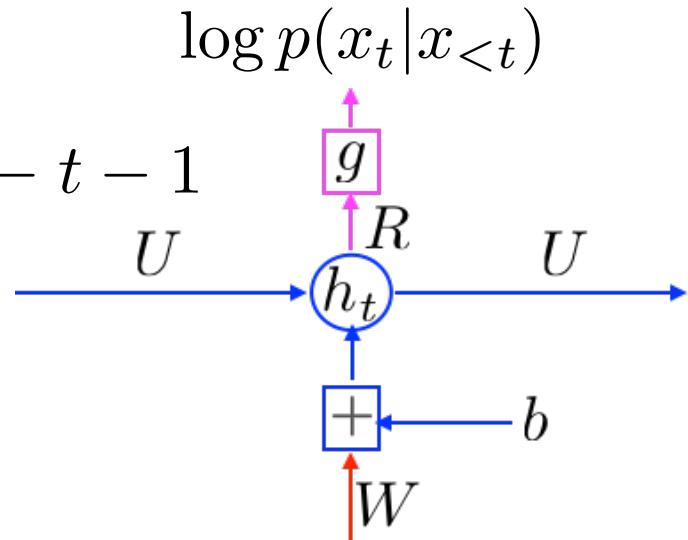
# Backpropagation through Time

How do we compute  $\nabla \log p(x_t | x_{<t}, \theta)$ ?

- Compute per-step cost function from time  $t = T$

1. Cost derivative  $\partial \log p(x_t | x_{<t}) / \partial g$
2. Gradient w.r.t.  $R$  :  $\times \partial g / \partial R$
3. Gradient w.r.t.  $h_t$  :  $\times \partial g / \partial h_t + \partial h_{t+1} / \partial h_t$
4. Gradient w.r.t.  $U$  :  $\times \partial h_t / \partial U$
5. Gradient w.r.t.  $b$  and  $W$  :  
 $\times \partial h_t / \partial b$  and  $\times \partial h_t / \partial W$
6. Accumulate the gradient and  $t \leftarrow t - 1$

Note: I'm abusing math a lot here!!



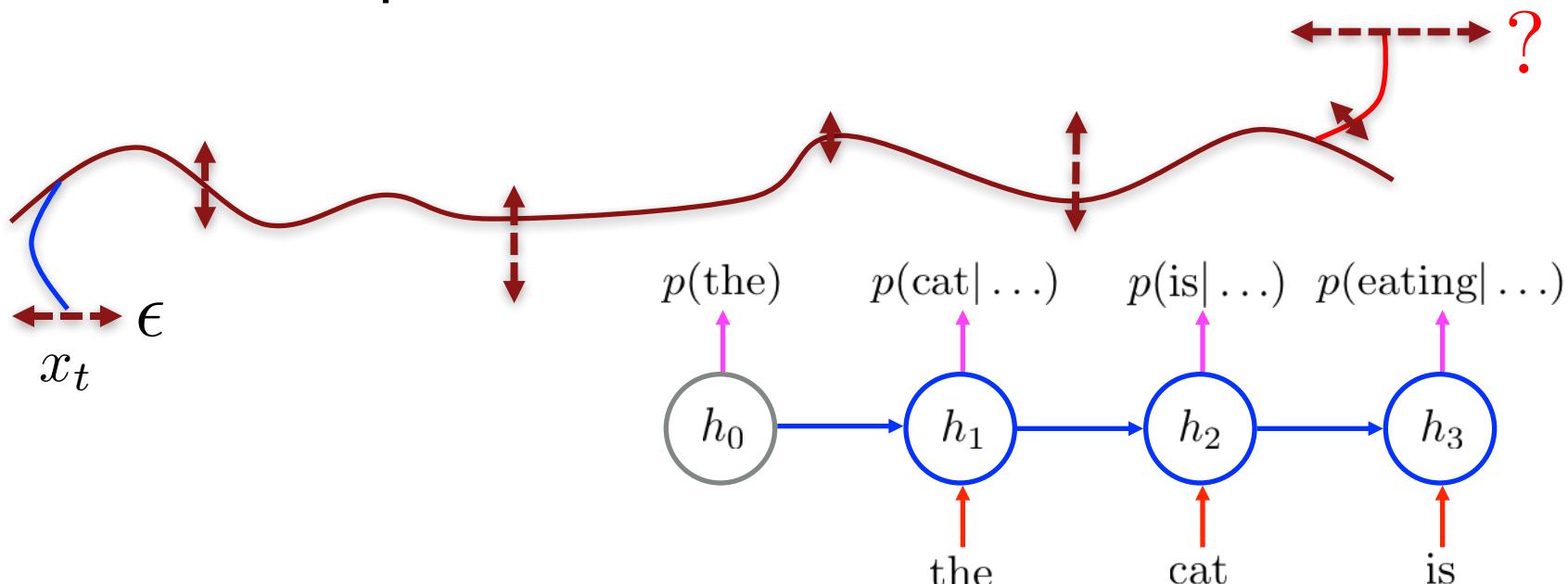
# Backpropagation through Time

*Intuitively, what's happening here?*

1. Measure the influence of the past on the future

$$\frac{\partial \log p(x_{t+n} | x_{$$

2. How does the perturbation at  $t$  affect  $p(x_{t+n} | x_{?$



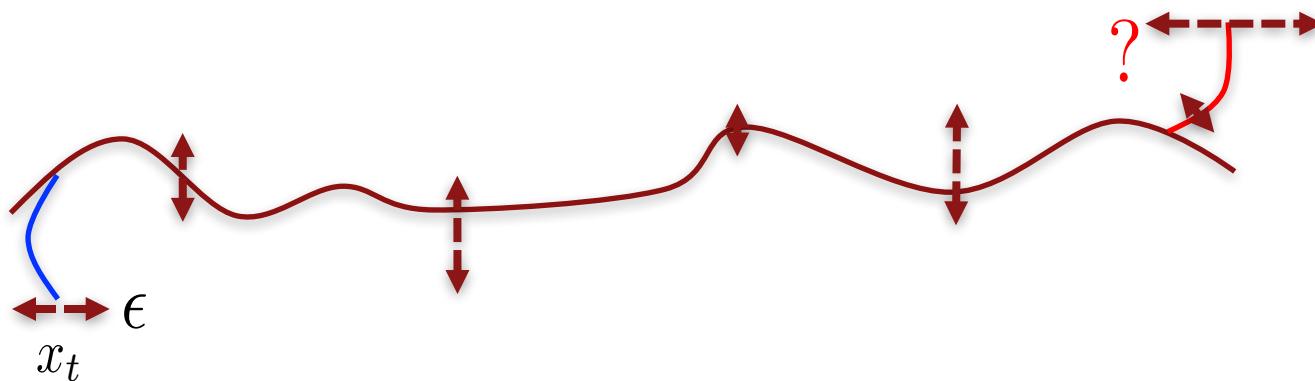
# Backpropagation through Time

*Intuitively, what's happening here?*

1. Measure the influence of the past on the future

$$\frac{\partial \log p(x_{t+n} | x_{$$

2. How does the perturbation at  $t$  affect  $p(x_{t+n} | x_{?$



3. Change the parameters to maximize  $p(x_{t+n} | x_{$

# Backpropagation through Time

*Intuitively, what's happening here?*

1. Measure the influence of the past on the future

$$\frac{\partial \log p(x_{t+n} | x_{<t+n})}{\partial h_t} = \frac{\partial \log p(x_{t+n} | x_{<t+n})}{\partial g} \frac{\partial g}{\partial h_{t+n}} \frac{\partial h_{t+n}}{\partial h_{t+n-1}} \dots \frac{\partial h_{t+1}}{\partial h_t}$$

2. With a naïve transition function

$$f(h_{t-1}, x_{t-1}) = \tanh(W [x_{t-1}] + U h_{t-1} + b)$$

We get  $\frac{\partial J_{t+n}}{\partial h_t} = \frac{\partial J_{t+n}}{\partial g} \frac{\partial g}{\partial h_{t+N}} \underbrace{\prod_{n=1}^N U^\top \text{diag} \left( \frac{\partial \tanh(a_{t+n})}{\partial a_{t+n}} \right)}_{\text{Problematic!}}$

**Problematic!**

# Backpropagation through Time

*Gradient either vanishes or explodes*

- What happens?

$$\frac{\partial J_{t+n}}{\partial h_t} = \frac{\partial J_{t+n}}{\partial g} \frac{\partial g}{\partial h_{t+N}} \underbrace{\prod_{n=1}^N U^\top \text{diag} \left( \frac{\partial \tanh(a_{t+n})}{\partial a_{t+n}} \right)}$$

1. The gradient *likely* explodes if

$$e_{\max} \geq \frac{1}{\max \tanh'(x)} = 1$$

2. The gradient *likely* vanishes if

$$e_{\max} < \frac{1}{\max \tanh'(x)} = 1, \text{ where } e_{\max} : \text{largest eigenvalue of } U$$

[Bengio, Simard, Frasconi, TNN1994;  
Hochreiter, Bengio, Frasconi, Schmidhuber, 2001]

# Backpropagation through Time

## Addressing Exploding Gradient

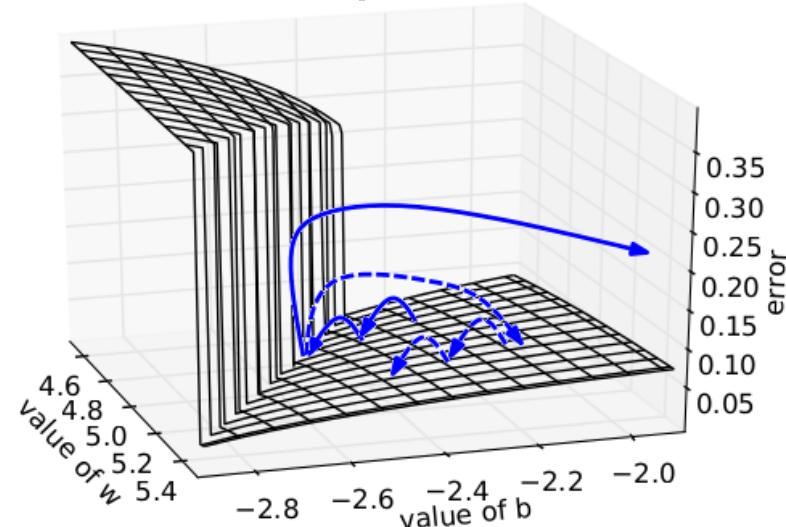
- “when gradients explode so does the curvature along  $v$ , leading to a wall in the error surface”

- Gradient Clipping
  - Norm clipping

$$\tilde{\nabla} \leftarrow \begin{cases} \frac{c}{\|\nabla\|} \nabla & \text{,if } \|\nabla\| \geq c \\ \nabla & \text{,otherwise} \end{cases}$$

- Element-wise clipping

$$\nabla_i \leftarrow \min(c, |\nabla_i|) \text{sgn}(\nabla_i), \text{ for all } i \in \{1, \dots, \dim \nabla\}$$



# Backpropagation through Time

*Vanishing gradient is super-problematic*

- When we only observe

$$\left\| \frac{\partial h_{t+N}}{\partial h_t} \right\| = \left\| \prod_{n=1}^N U^\top \text{diag} \left( \frac{\partial \tanh(a_{t+n})}{\partial a_{t+n}} \right) \right\| \rightarrow 0 ,$$

- We cannot tell whether
  1. No dependency between  $t$  and  $t+n$  in data, or
  2. Wrong configuration of parameters:

$$e_{\max}(U) < \frac{1}{\max \tanh'(x)}$$

## **2b. Gated Recurrent Units**

**Vanishing gradient, gated recurrent units and long short-term memory units**

# Gated Recurrent Unit

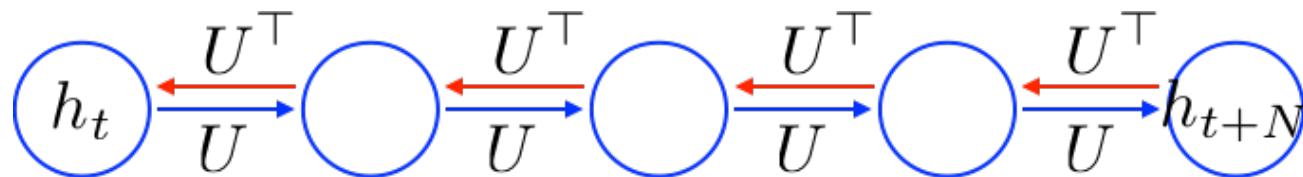
- Is the problem with the naïve transition function?

$$f(h_{t-1}, x_t) = \tanh(W [x_t] + U h_{t-1} + b)$$

- With it, the temporal derivative is

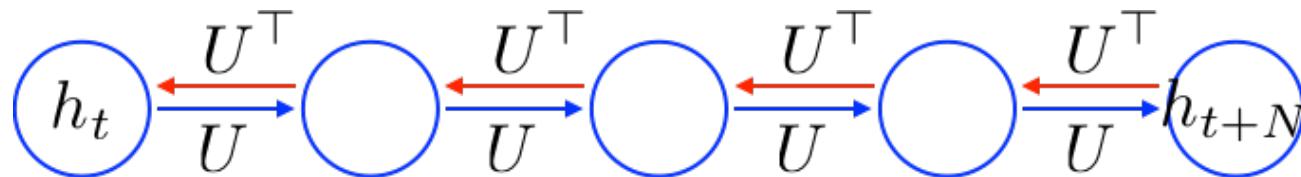
$$\frac{\partial h_{t+1}}{\partial h_t} = U^\top \frac{\partial \tanh(a)}{\partial a}$$

- It implies that the error must be backpropagated through all the intermediate nodes:

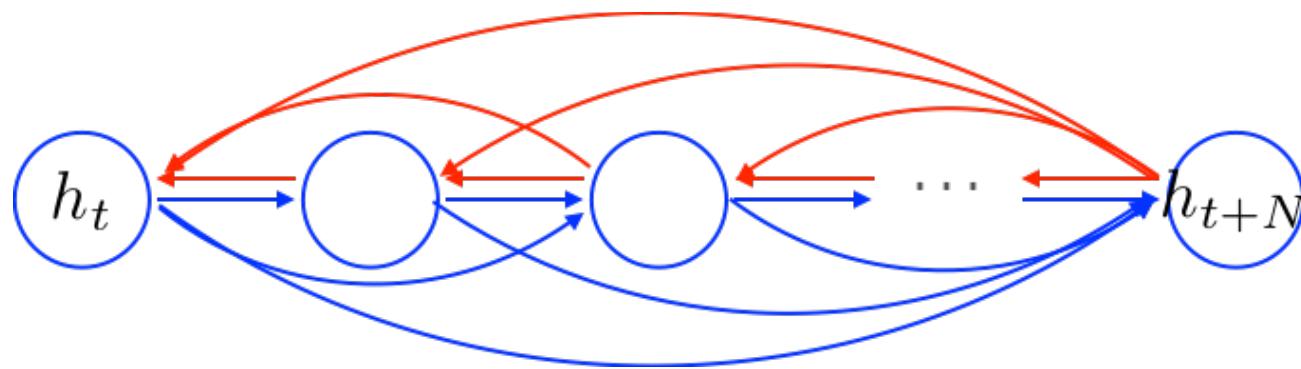


# Gated Recurrent Unit

- It implies that the error must backpropagate through all the intermediate nodes:

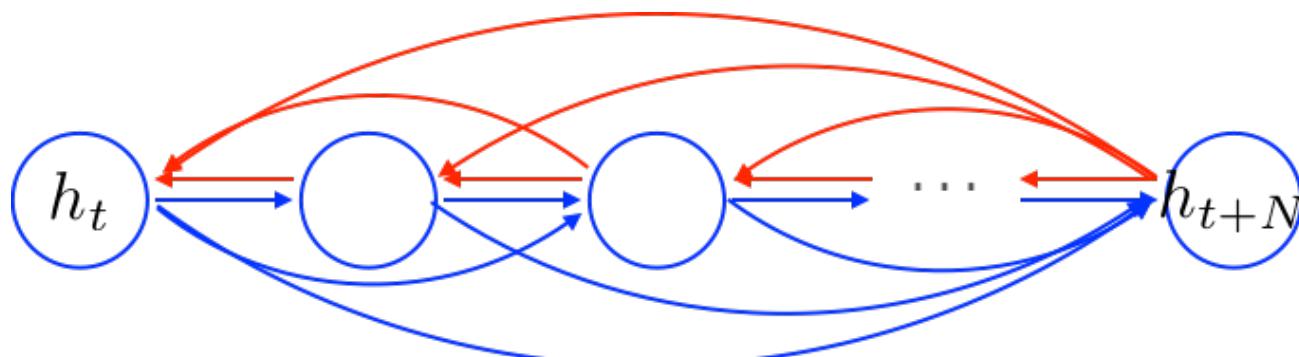


- Perhaps we can create shortcut connections.



# Gated Recurrent Unit

- Perhaps we can create *adaptive* shortcut connections.

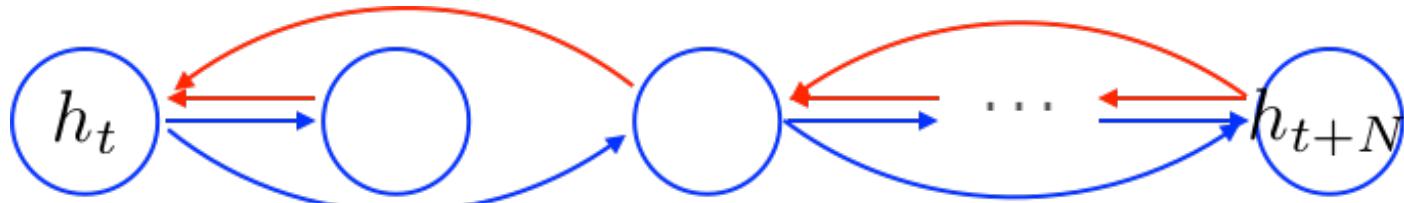


$$f(h_{t-1}, x_t) = u_t \odot \tilde{h}_t + (1 + u_t) \odot h_{t-1}$$

- Candidate Update  $\tilde{h}_t = \tanh(W [x_t] + U h_{t-1} + b)$
- Update gate  $u_t = \sigma(W_u [x_t] + U_u h_{t-1} + b_u)$

# Gated Recurrent Unit

- Let the net prune unnecessary connections *adaptively*.

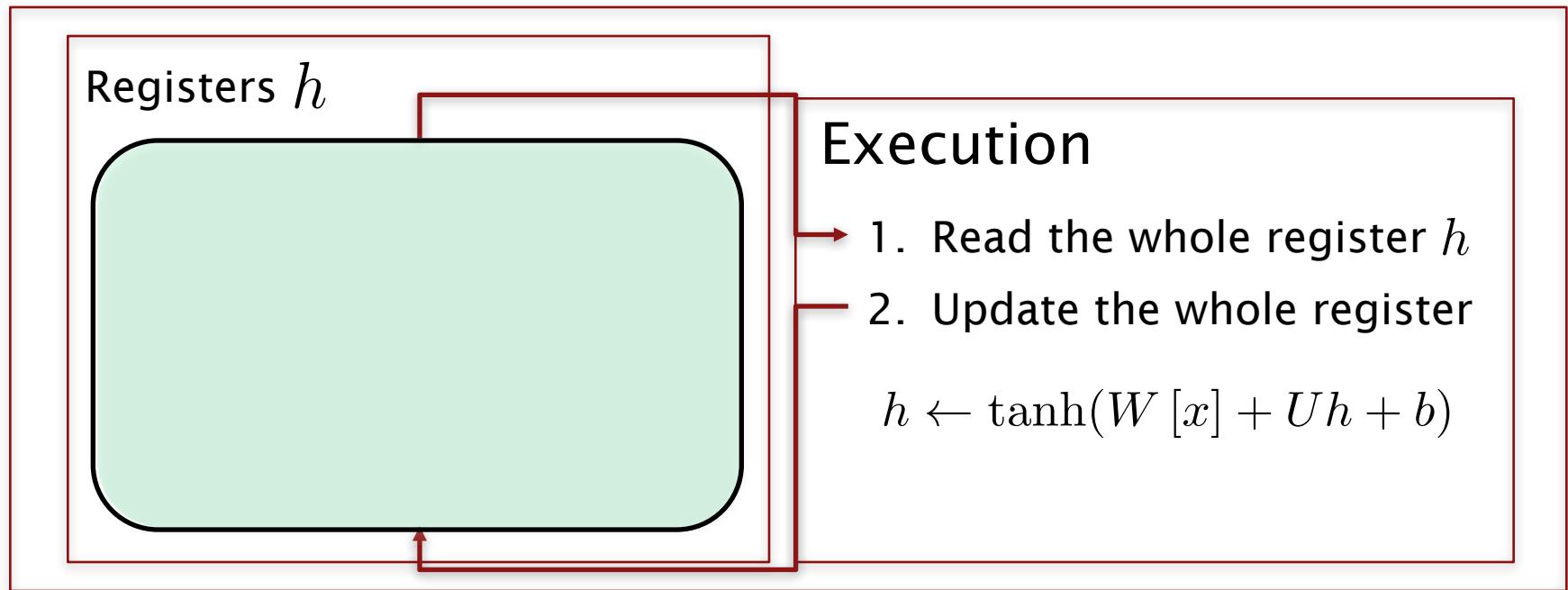


$$f(h_{t-1}, x_t) = u_t \odot \tilde{h}_t + (1 + u_t) \odot h_{t-1}$$

- Candidate Update  $\tilde{h}_t = \tanh(W [x_t] + U(r_t \odot h_{t-1}) + b)$
- Reset gate  $r_t = \sigma(W_r [x_t] + U_r h_{t-1} + b_r)$
- Update gate  $u_t = \sigma(W_u [x_t] + U_u h_{t-1} + b_u)$

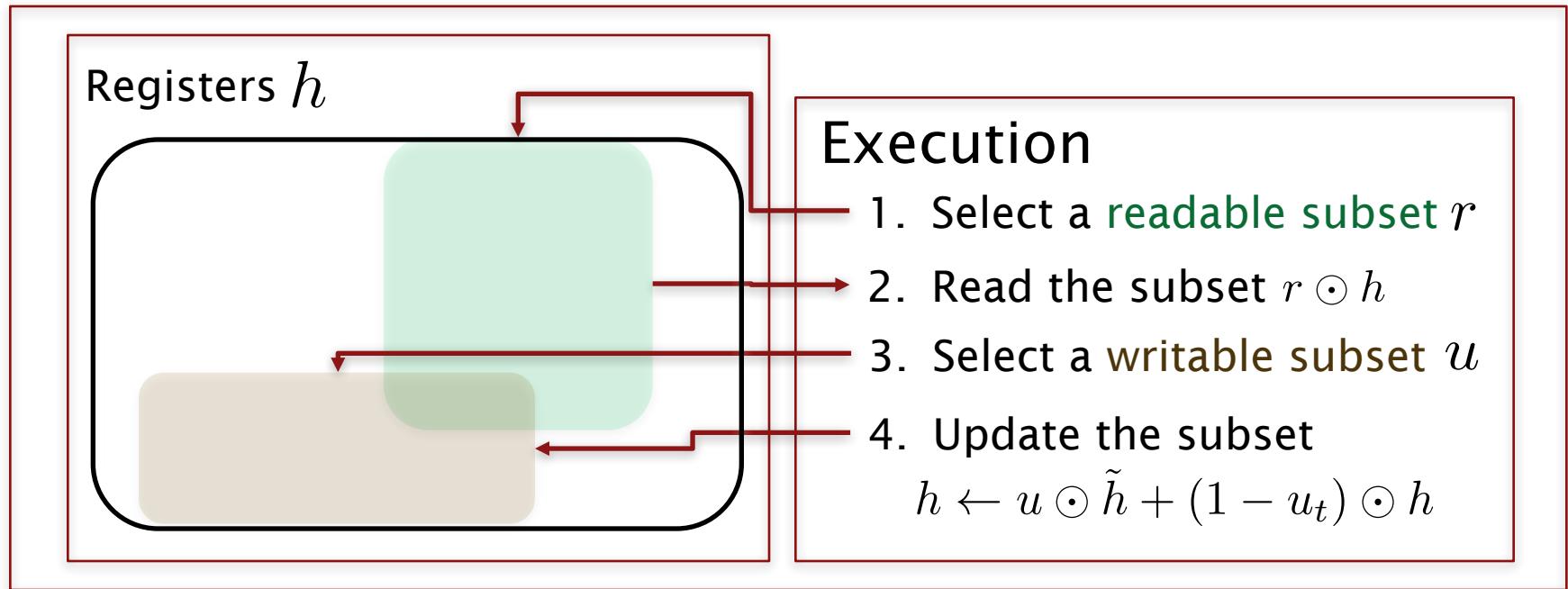
# Gated Recurrent Unit

*tanh-RNN ....*



# Gated Recurrent Unit

GRU ...



Clearly gated recurrent units are much more realistic.

# Gated Recurrent Unit

*Two most widely used gated recurrent units*

## Gated Recurrent Unit

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

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

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

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

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

## Long Short-Term Memory

[Hochreiter&Schmidhuber, NC1999;  
Gers, Thesis2001]

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

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

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

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

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

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

# Training an RNN

A few well-established + my personal wisdoms

1. Use LSTM or GRU: *makes your life so much simpler*
2. Initialize recurrent matrices to be orthogonal
3. Initialize other matrices with a sensible scale
4. Use adaptive learning rate algorithms: *Adam, Adadelta, ...*
5. Clip the norm of the gradient: “1” *seems to be a reasonable threshold when used together with adam or adadelta.*
6. *Be patient!*

[Saxe et al., ICLR2014;  
Ba, Kingma, ICLR2015;  
Zeiler, arXiv2012;  
Pascanu et al., ICML2013]

**Now, go build and train a  
recurrent language model!**

*Any questions?*

## **2c. Conditional Recurrent Language Model**

### **Encoder-Decoder Network for Machine Translation**

# Recurrent Language Model can

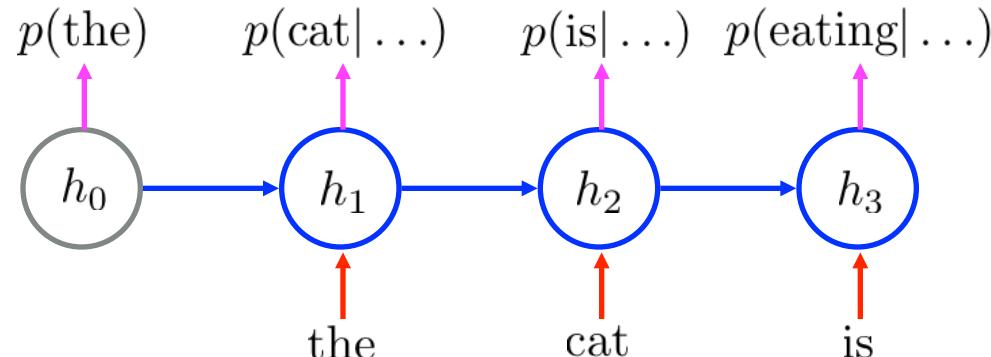
## 1. Score a given sentence very well

$$\log p(\text{the}, \text{cat}, \text{is}, \text{sitting}, \text{on}, \text{a}, \text{couch}, \cdot)$$

- Mere reranking significantly improves machine translation and speech recognition quality [Schwenk, 2007; Schwenk, 2012]
- Very good at sentence completion without much task-specific engineering [Tran, ..., Monz, NAACL 2016]

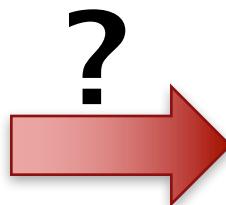
## 2. Generate a long, coherent text

- Observed earlier by Mikolov [2010, in his thesis] and Sutskever et al. [2011]

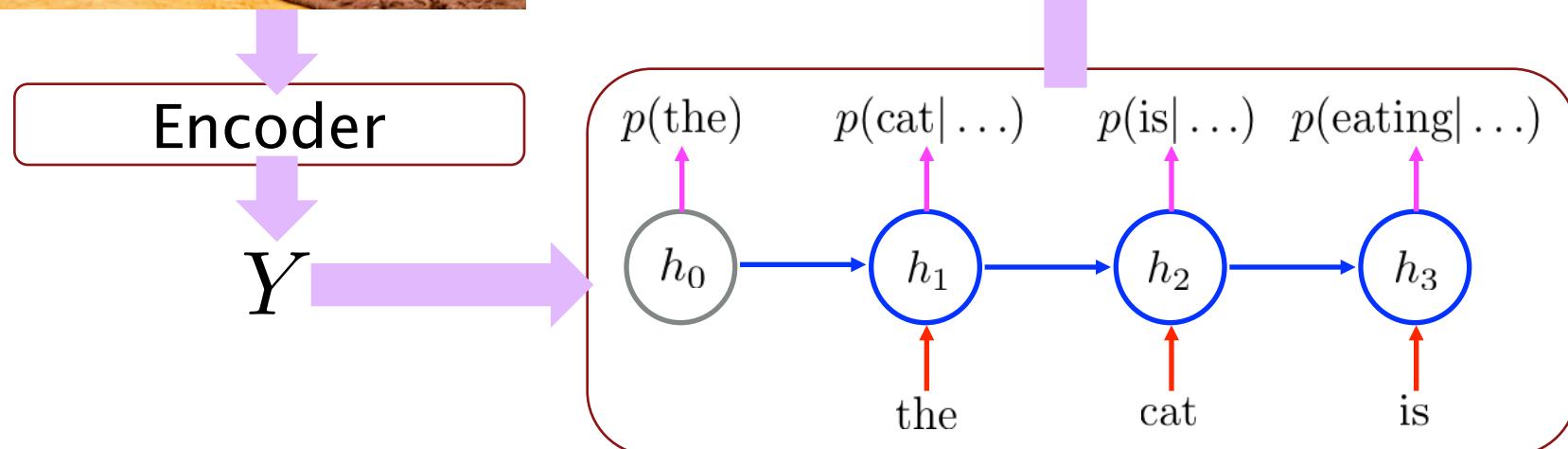


# Conditional Recurrent Language Model

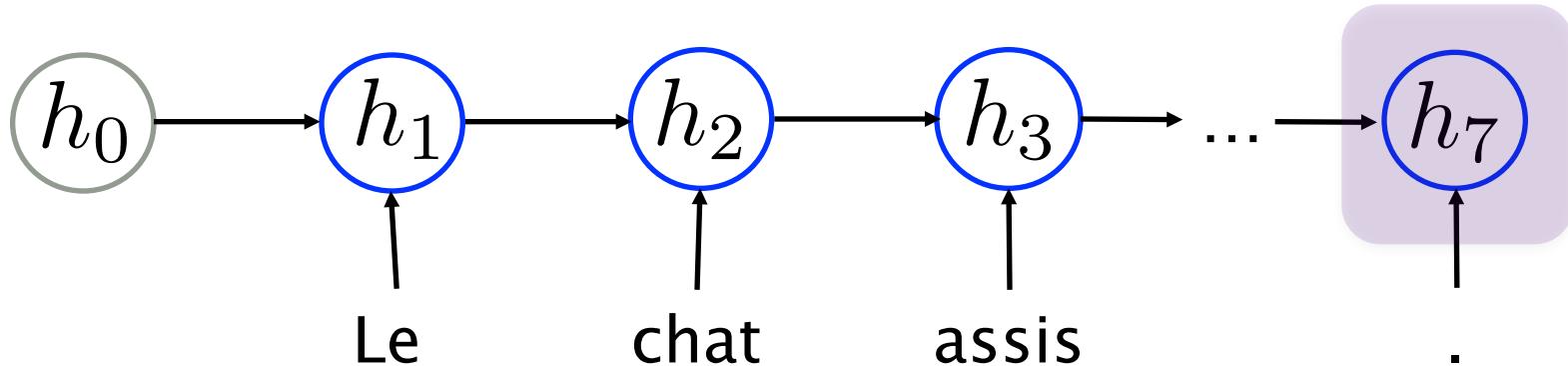
Le chat assis sur le tapis.



The cat sat on the mat.

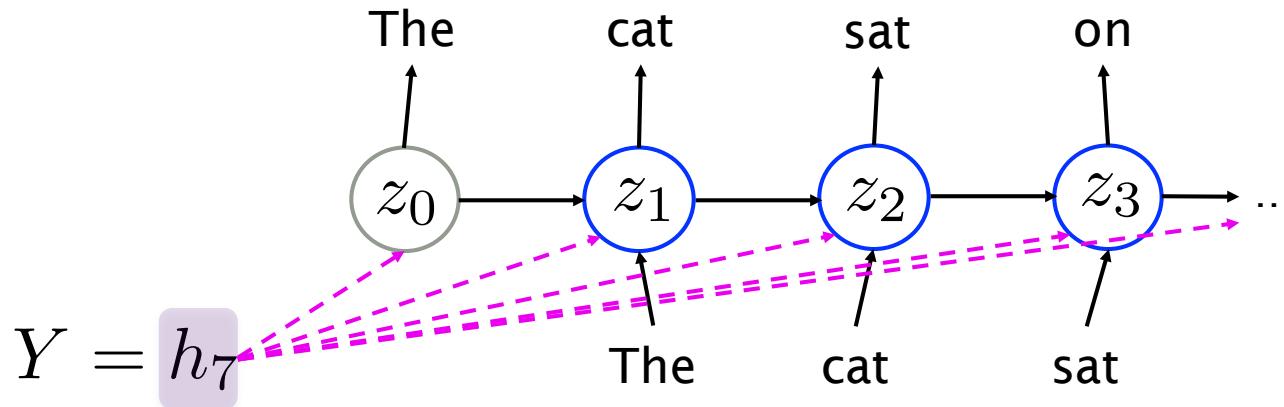


# Recurrent Neural Network Encoder



- Read a source sentence one symbol at a time.
- The last hidden state  $Y$  summarizes the entire source sentence.
- Any recurrent activation function can be used:
  - Hyperbolic tangent  $\tanh$
  - Gated recurrent unit [Cho et al., 2014]
  - Long short-term memory [Sutskever et al., 2014]
  - Convolutional network [Kalchbrenner&Blunsom, 2013]

# Decoder: Recurrent Language Model



- Usual recurrent language model, except
  1. Transition  $z_t = f(z_{t-1}, x_t, Y)$
  2. Backpropagation  $\sum_t \partial z_t / \partial Y$
- Same learning strategy as usual: MLE with SGD

$$\mathcal{L}(\theta, D) = \frac{1}{N} \sum_{n=1}^N \sum_{t=1}^{T^n} \log p(x_t^n | x_1^n, \dots, x_{t-1}^n, Y)$$

# With conditional recurrent language model,

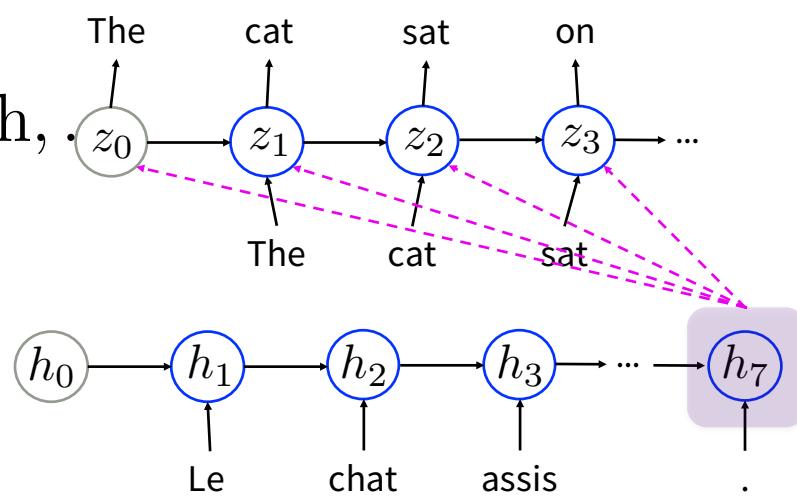
## 1. Score a translation

$$\log p(\text{the, cat, is, sitting, on, a, couch, .} | \text{le, chat, est, assis, sur, un, canap\'e, .}) = ?$$

## 2. Directly generate a translation

le,chat, est, assis, sur, un, canap\'e, .

↪ the, cat, is, sitting, on, a, couch, .



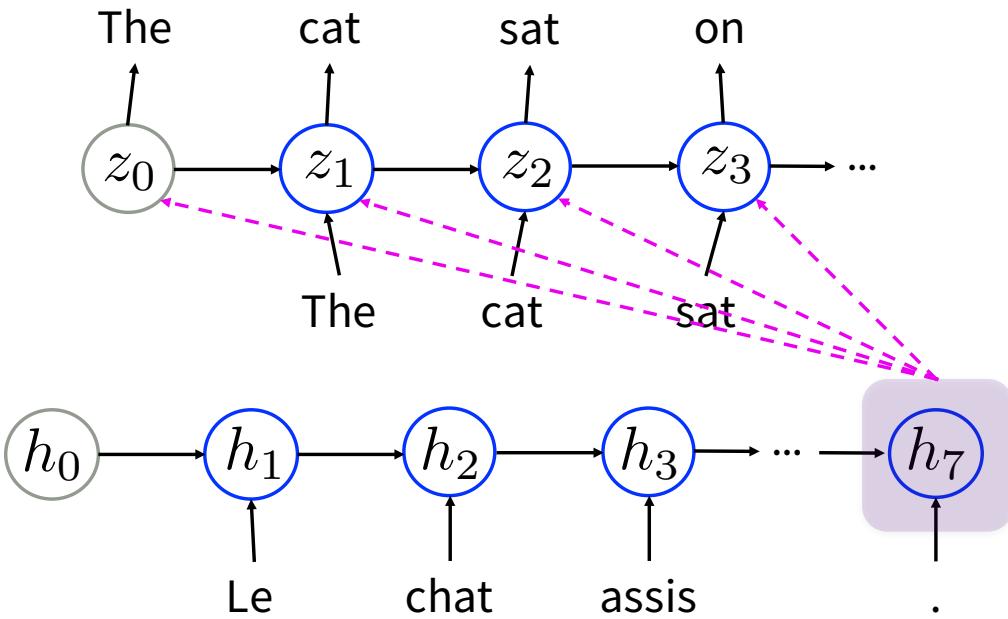
## **2d. Decoding Strategies**

Ancestral sampling, greedy decoding and beam search

# Decoding (0) – Exhaustive Search

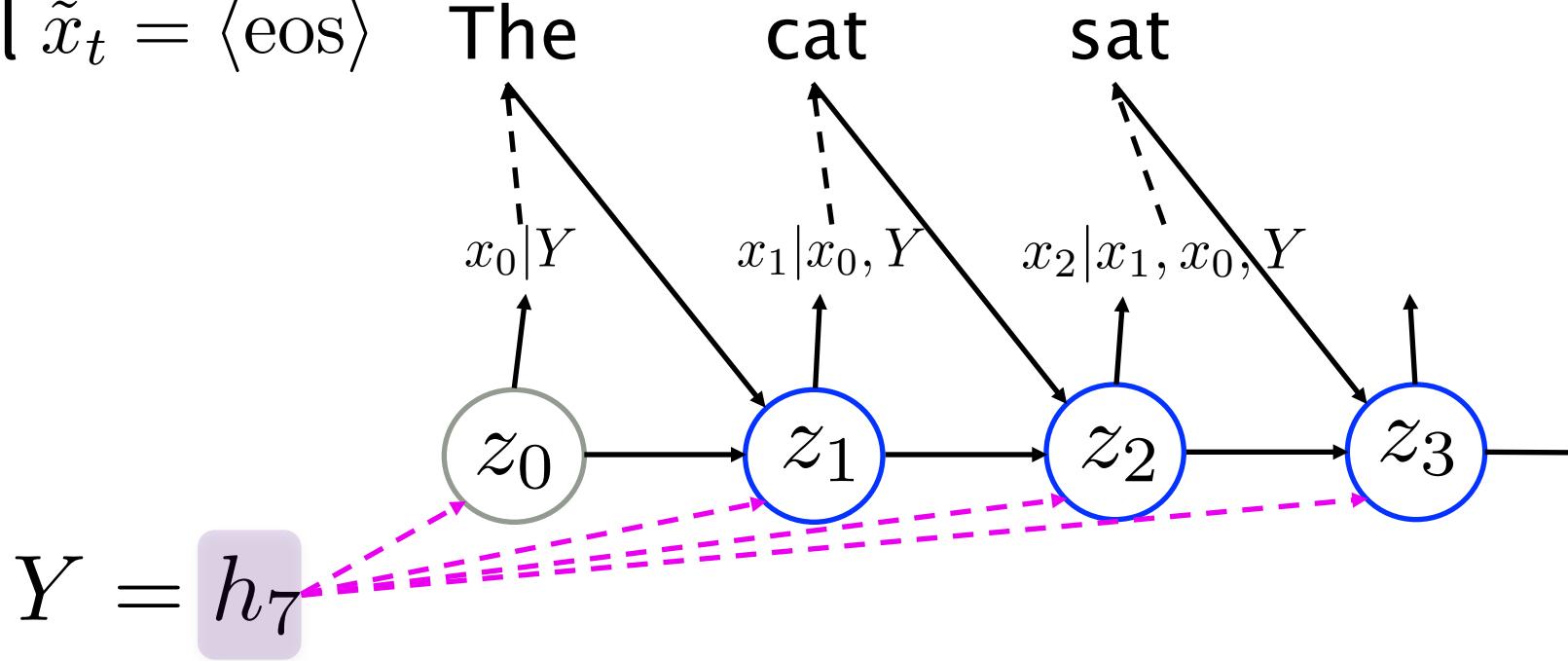
- Simple and exact decoding algorithm
- Score each and every possible translation
- Pick the best one

***DO NOT EVEN THINK  
of TRYING IT OUT!\****



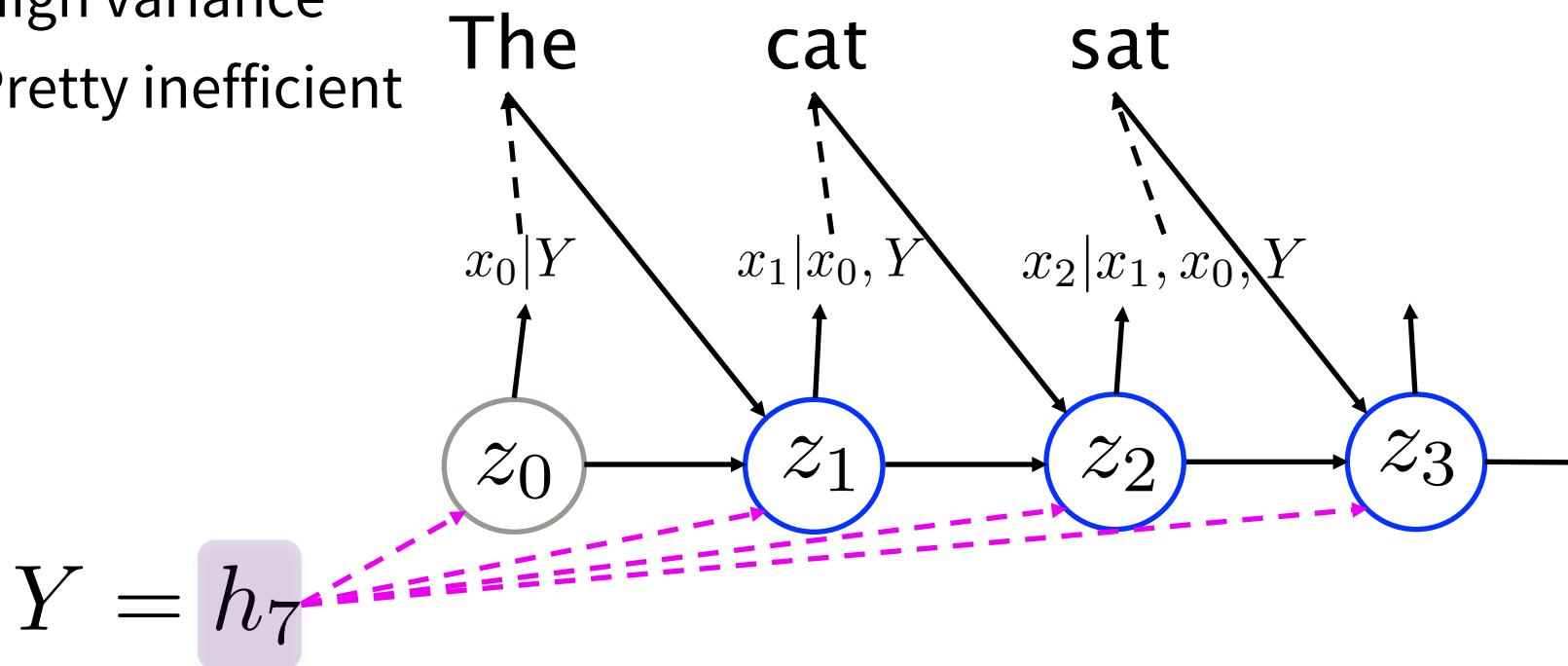
# Decoding (1) – Ancestral Sampling

- Efficient, unbiased sampling
- One symbol at a time from  $\tilde{x}_t \sim x_t | x_{t-1}, \dots, x_1, Y$
- Until  $\tilde{x}_t = \langle \text{eos} \rangle$



# Decoding (1) – Ancestral Sampling

- Pros:
  1. Unbiased (asymptotically exact)
- Cons:
  1. High variance
  2. Pretty inefficient

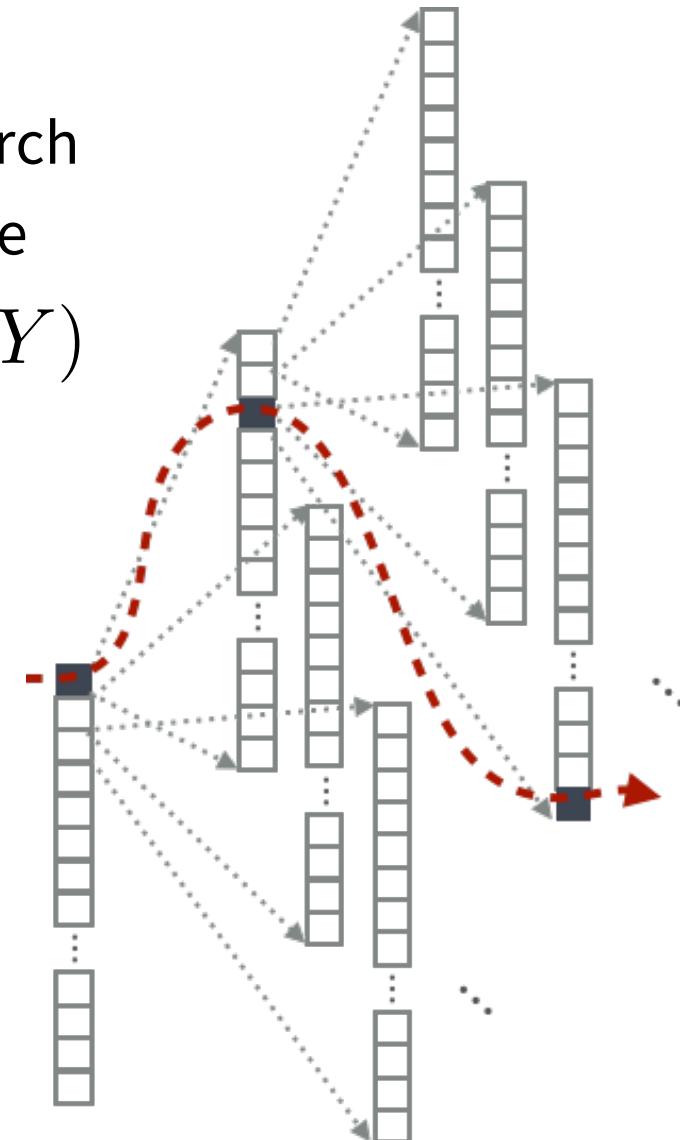


# Decoding (2) – Greedy Search

- Efficient, but heavily suboptimal search
- Pick the most likely symbol each time

$$\tilde{x}_t = \arg \max_x \log p(x|x_{<t}, Y)$$

- Until  $\tilde{x}_t = \langle \text{eos} \rangle$
- Pros:
  1. Super-efficient
    - Both computation and memory
- Cons:
  1. Heavily suboptimal



# Decoding (3)

## - Beam Search

- Pretty, but *not quite* efficient

- Maintain  $K$  hypotheses at a time

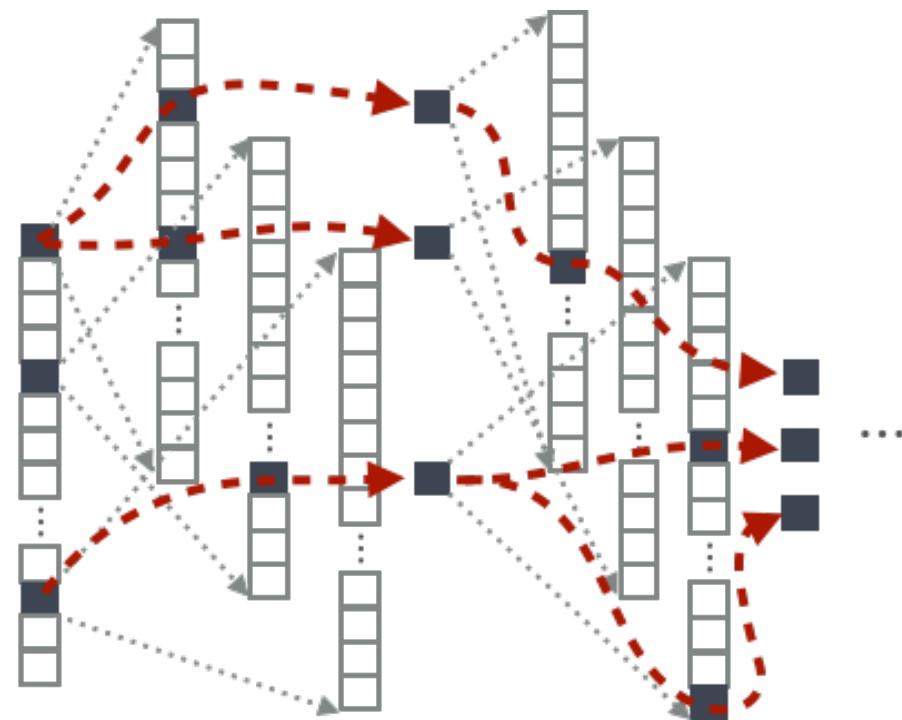
$$\mathcal{H}_{t-1} = \{(\tilde{x}_1^1, \tilde{x}_2^1, \dots, \tilde{x}_{t-1}^1), (\tilde{x}_1^2, \tilde{x}_2^2, \dots, \tilde{x}_{t-1}^2), \dots, (\tilde{x}_1^K, \tilde{x}_2^K, \dots, \tilde{x}_{t-1}^K)\}$$

- Expand each hypothesis

$$\mathcal{H}_t^k = \{(\tilde{x}_1^k, \tilde{x}_2^k, \dots, \tilde{x}_{t-1}^k, v_1), (\tilde{x}_1^k, \tilde{x}_2^k, \dots, \tilde{x}_{t-1}^k, v_2), \dots, (\tilde{x}_1^k, \tilde{x}_2^k, \dots, \tilde{x}_{t-1}^k, v_{|V|})\}$$

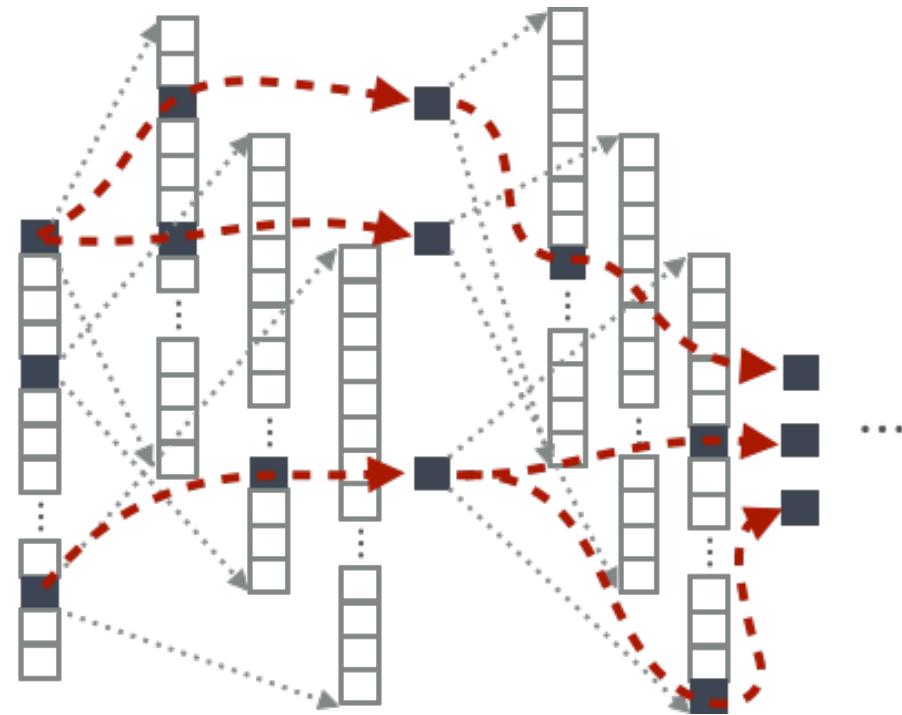
- Pick top- $K$  hypotheses from the union  $\mathcal{H}_t = \cup_{k=1}^K \mathcal{B}_k$ , where

$$\mathcal{B}_k = \arg \max_{\tilde{X} \in \mathcal{A}_k} \log p(\tilde{X} | Y), \quad \mathcal{A}_k = \mathcal{A}_{k-1} - \mathcal{B}_{k-1}, \text{ and } \mathcal{A}_1 = \cup_{k'=1}^K \mathcal{H}_t^{k'}.$$



# Decoding (3)

## - Beam Search



- Asymptotically exact, as  $K \rightarrow \infty$
- But, not necessarily monotonic improvement w.r.t.  $K$
- $K$  should be selected to maximize the translation quality on a validation set.

# Decoding

- En-Cz: 12m training sentence pairs

Strategy	# Chains	Valid Set		Test Set	
		NLL	BLEU	NLL	BLEU
Ancestral Sampling	50	22.98	15.64	26.25	16.76
Greedy Decoding	-	27.88	15.50	26.49	16.66
Beamsearch	5	20.18	17.03	22.81	18.56
Beamsearch	10	19.92	17.13	22.44	18.59

# Decoding

- Greedy Search
  - Computationally efficient
  - Not great quality
- Beam Search
  - Computationally expensive
  - Not easy to parallelize
  - Much better quality

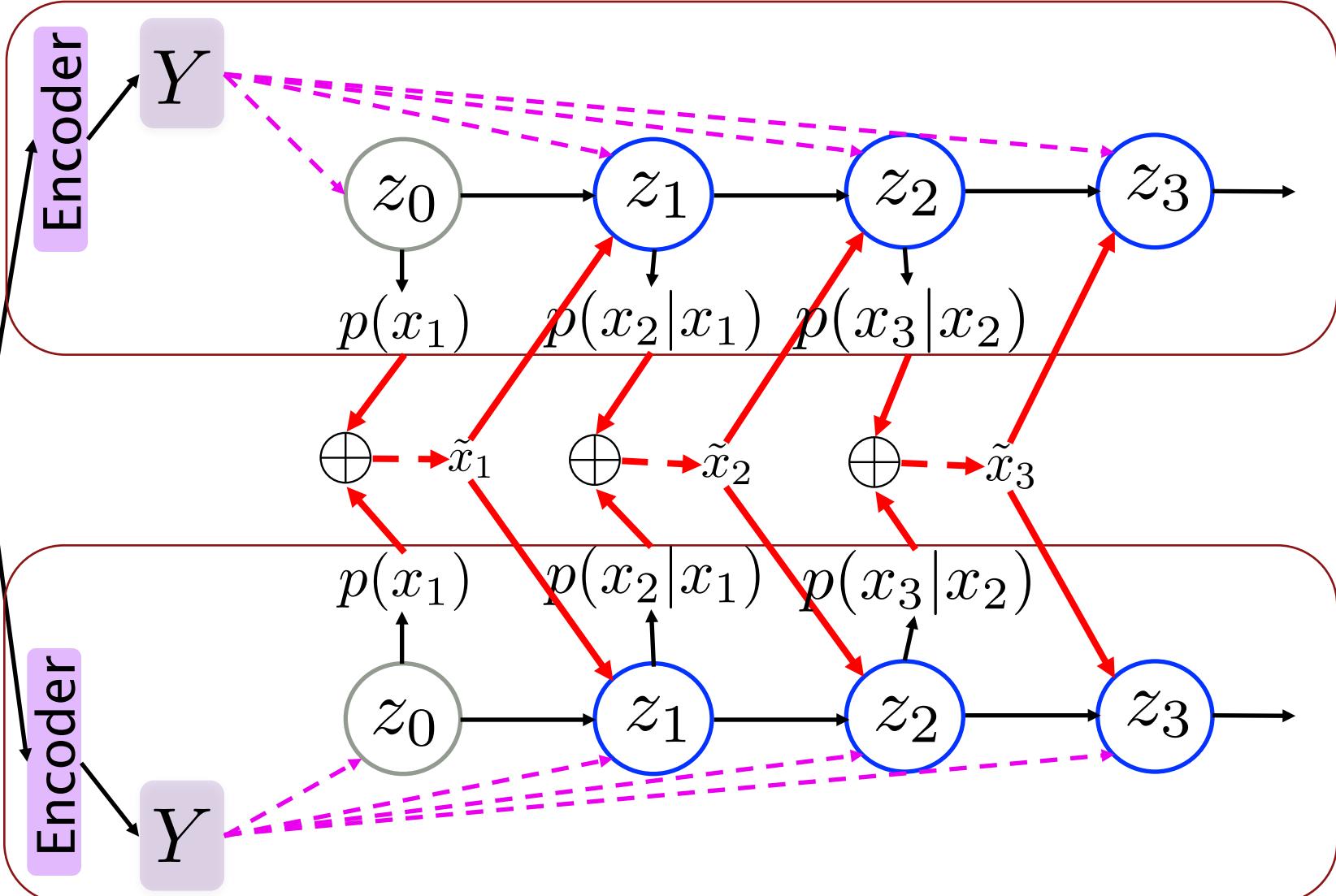
*Is there anything in-between?*

## **2d. Ensemble of Neural MT**

**Decoding from an ensemble of encoder-decoder's.**

# Ensemble of Conditional Recurrent LM

Le chat assis sur le tapis.



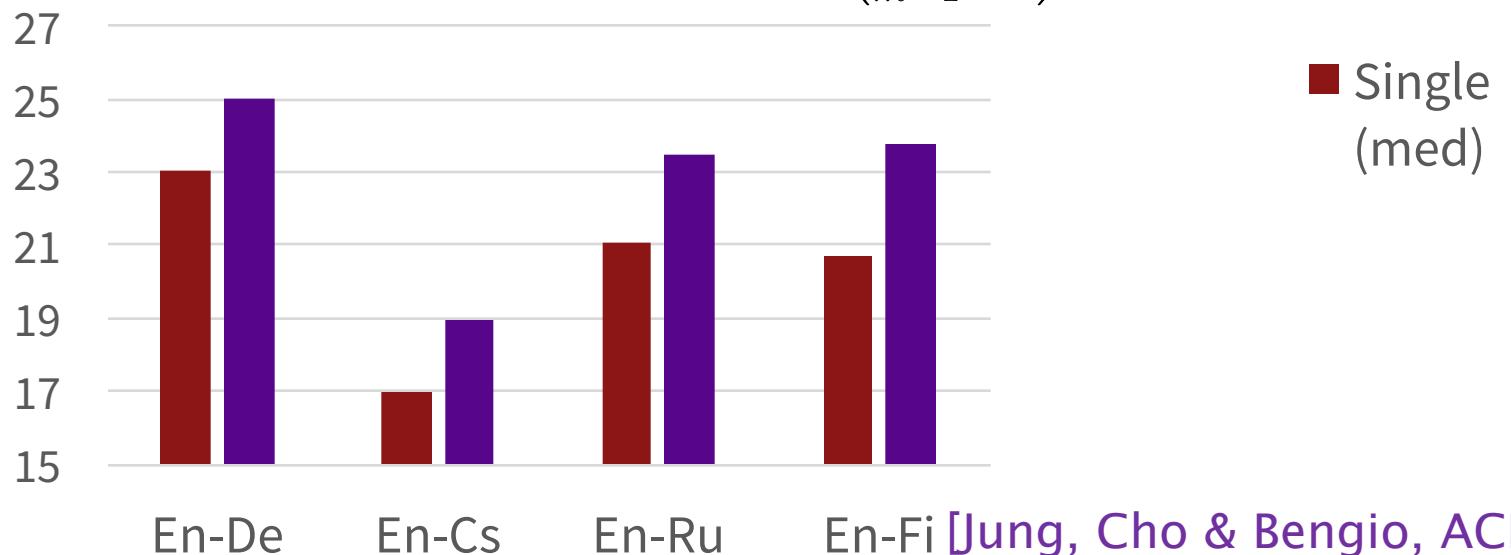
# Ensemble of Conditional Recurrent LM

- Step-wise Ensemble:  $p(x_t^{\text{ens}} | x_{<t}^{\text{ens}}, Y) = \bigoplus_{m=1}^M p(x_t^m | x_{<t}^m, Y)$
- Ensemble operator  $\bigoplus$  implementations
  1. Majority voting scheme (OR):

$$\bigoplus_{m=1}^M p^{\text{ens}} = \frac{1}{M} \sum_{m=1}^M p^m$$

2. Consensus building scheme (AND):

$$\bigoplus_{m=1}^M p^{\text{ens}} = \left( \prod_{m=1}^M p^m \right)^{1/M}$$



Jung, Cho & Bengio, ACL2016]

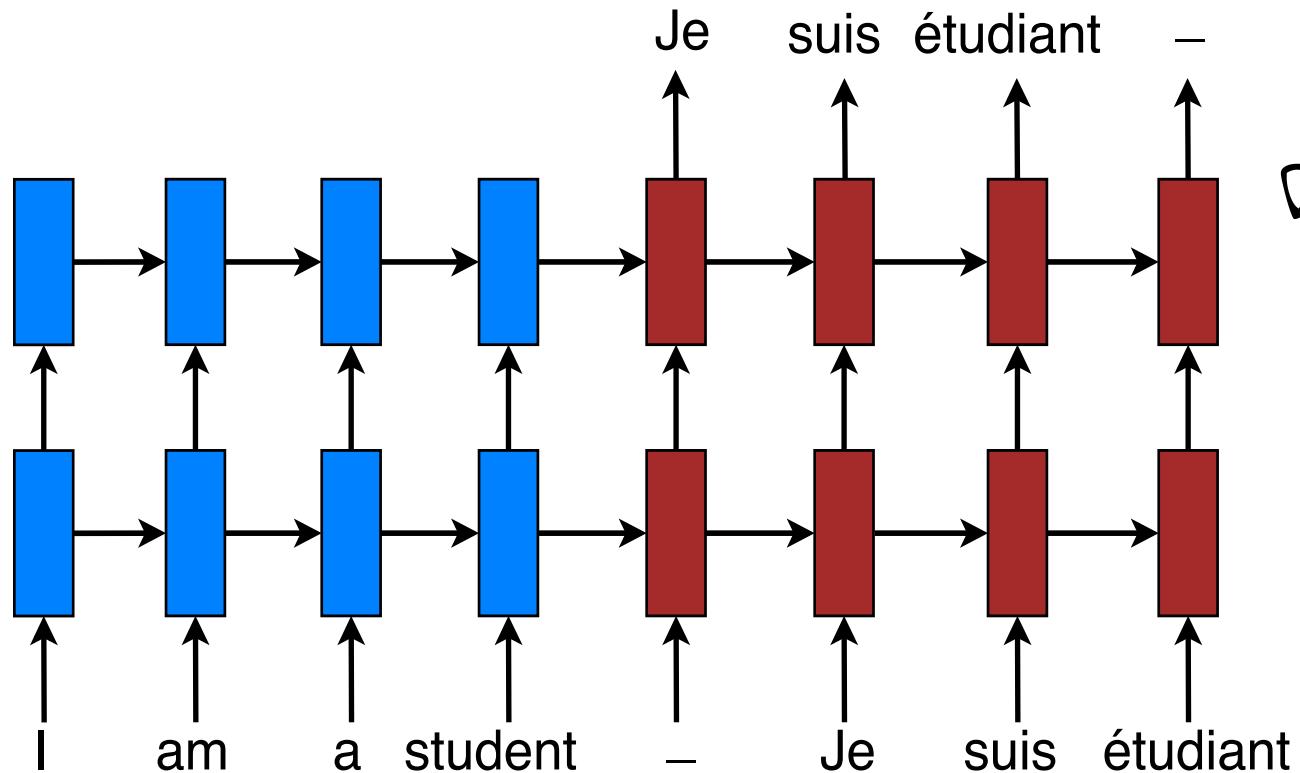
# Wrap up

1. Training a recurrent language model efficiently
2. Building a better model with gated recurrent units
3. Building a conditional recurrent language model
4. Generating a translation from a trained conditional recurrent language model

# **Do I smell coffee...?**

# Have we convinced you about NMT?

Encoder



Decoder

### 3. Advancing NMT

#### a. The **vocabulary** aspect

- *Goal:* extend the vocabulary coverage.

#### b. The **memory** aspect

- *Goal:* translate long sentences better.

#### c. The **language complexity** aspect

- *Goal:* handle more language variations.

#### d. The **data** aspect

- *Goal:* utilize more data sources.

### 3. Advancing NMT

#### a. The **vocabulary** aspect

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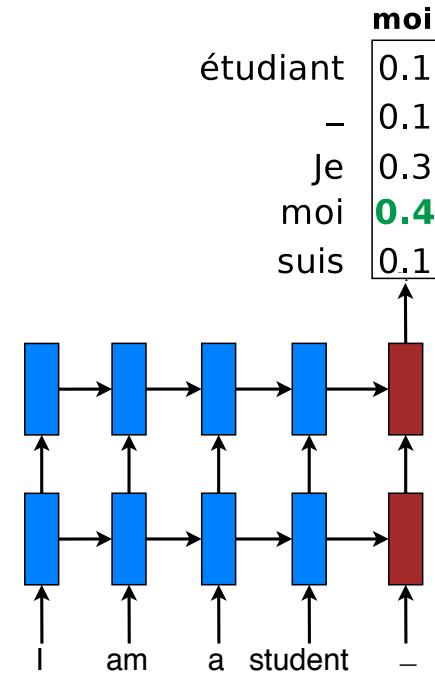
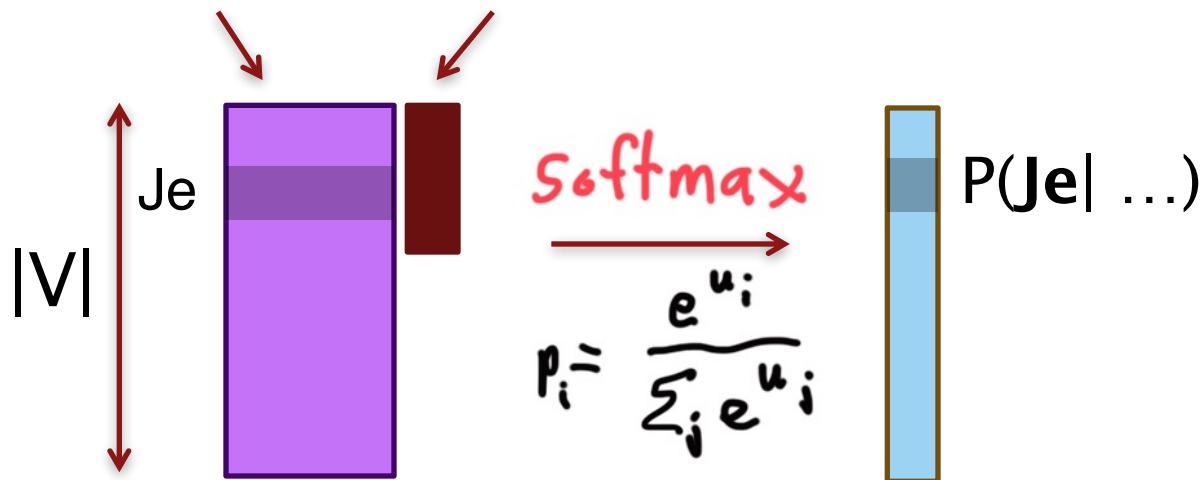
- *Goal:* handle more language variations.

#### d. The **data** aspect

- *Goal:* utilize more data sources.

# The word generation problem

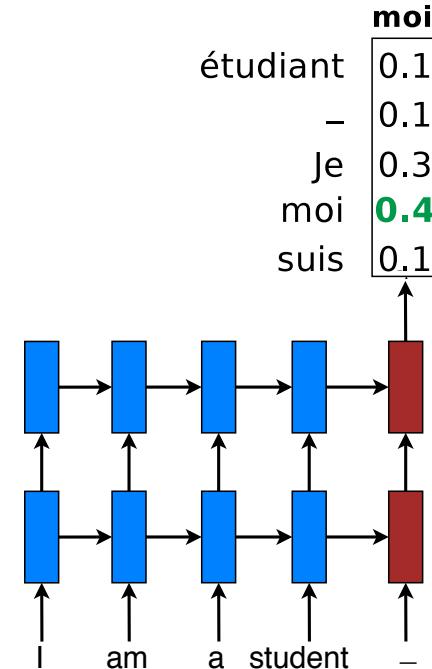
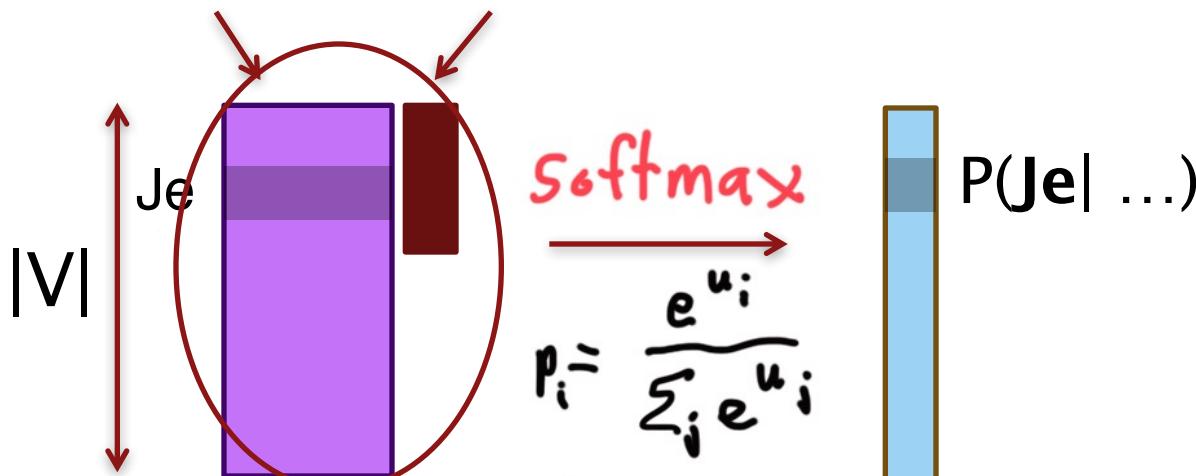
Softmax      Hidden  
parameters    state



# The word generation problem

- Word generation problem

Softmax      Hidden  
parameters    state



Softmax computation is expensive.

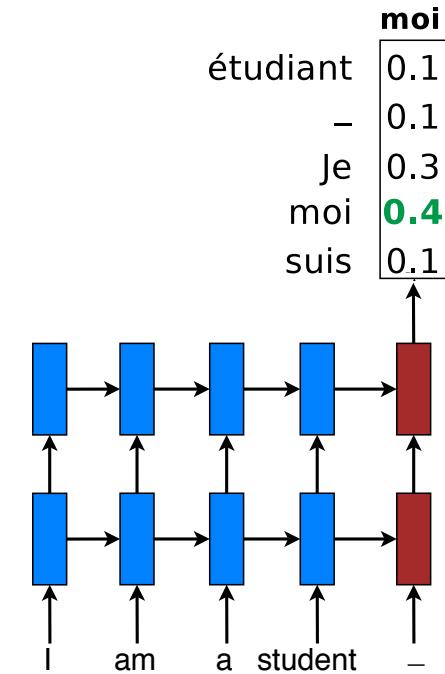
# The word generation problem

- Word generation problem
  - Vocabs are modest: 50K.

The ecotax portico in Pont-de-Buis  
Le portique écotaxe de Pont-de-Buis



The <unk> portico in <unk>  
Le <unk> <unk> de <unk>

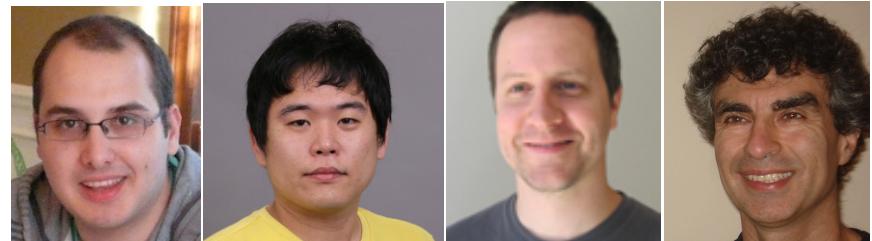


# **First thought: scale the softmax**

- Lots of ideas from the neural LM literature!
- *Hierarchical models*: tree-structured vocabulary
  - [Morin & Bengio, AISTATS'05], [Mnih & Hinton, NIPS'09].
  - Complex, sensitive to tree structures.
- *Noise-contrastive estimation*: binary classification
  - [Mnih & Teh, ICML'12], [Vaswani et al., EMNLP'13].
  - Different noise samples per training example.\*

Not GPU-friendly

# Large-vocab NMT



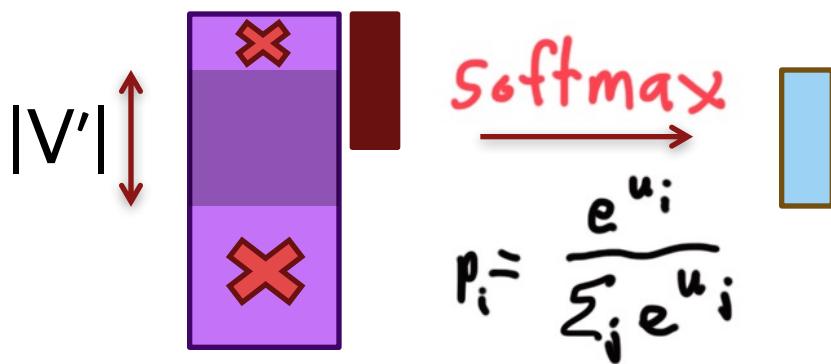
- GPU-friendly.
- *Training*: a subset of the vocabulary at a time.
- *Testing*: smart on the set of possible translations.

Fast at both train & test time.

Sébastien Jean, Kyunghyun Cho, Roland Memisevic, Yoshua Bengio. **On Using Very Large Target Vocabulary for Neural Machine Translation**. ACL'15.

# Training

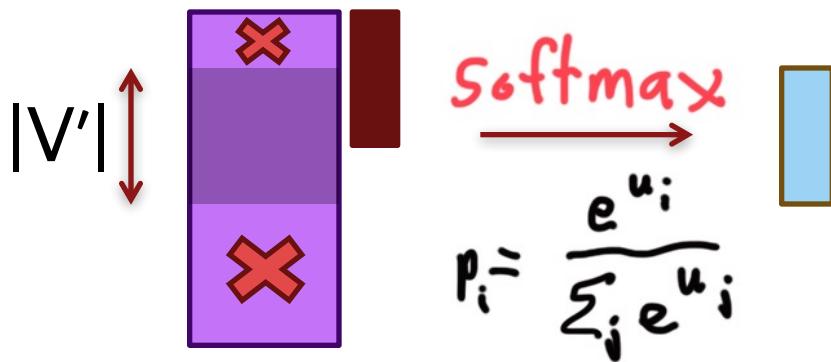
- Each time train on a smaller vocab  $V' \ll V$



How do we  
select  $V'$ ?

# Training

- Each time train on a smaller vocab  $V' \ll V$



- Partition training data in subsets:
  - Each subset has  $\tau$  distinct target words,  $|V'| = \tau$ .

# Training - *Segment data*

- Sequentially select examples:  $|V'| = 5$ .

she loves cats  
he likes dogs

cats have tails

dogs have tails

dogs chase cats

she loves dogs

cats hate dogs

$V' = \{\text{she, loves, cats, he, likes}\}$

# Training - *Segment data*

- Sequentially select examples:  $|V'| = 5$ .

she loves cats

he likes dogs

cats have tails

dogs have tails

dogs chase cats

she loves dogs

cats hate dogs

$$V' = \{\text{cats, have, tails, dogs, chase}\}$$

# Training - *Segment data*

- Sequentially select examples:  $|V'| = 5$ .

she loves cats

he likes dogs

cats have tails

dogs have tails

dogs chase cats

she loves dogs

cats hate dogs

$V' = \{\text{she, loves, dogs, cats, hate}\}$

- *Practice*:  $|V| = 500K$ ,  $|V'| = 30K$  or  $50K$ .

# Testing – *Select candidate words*

- **K** most frequent words: unigram prob.

de,  
,  
la  
-  
et  
des  
les  
...

# Testing – Select candidate words

- $K$  most frequent words: unigram prob.
- Candidate target words
  - $K'$  choices per source word.  $K' = 3$ .

de,  
,  
la  
-  
et  
des  
les  
...

elle  
celle  
ceci

aime  
amour  
aimer

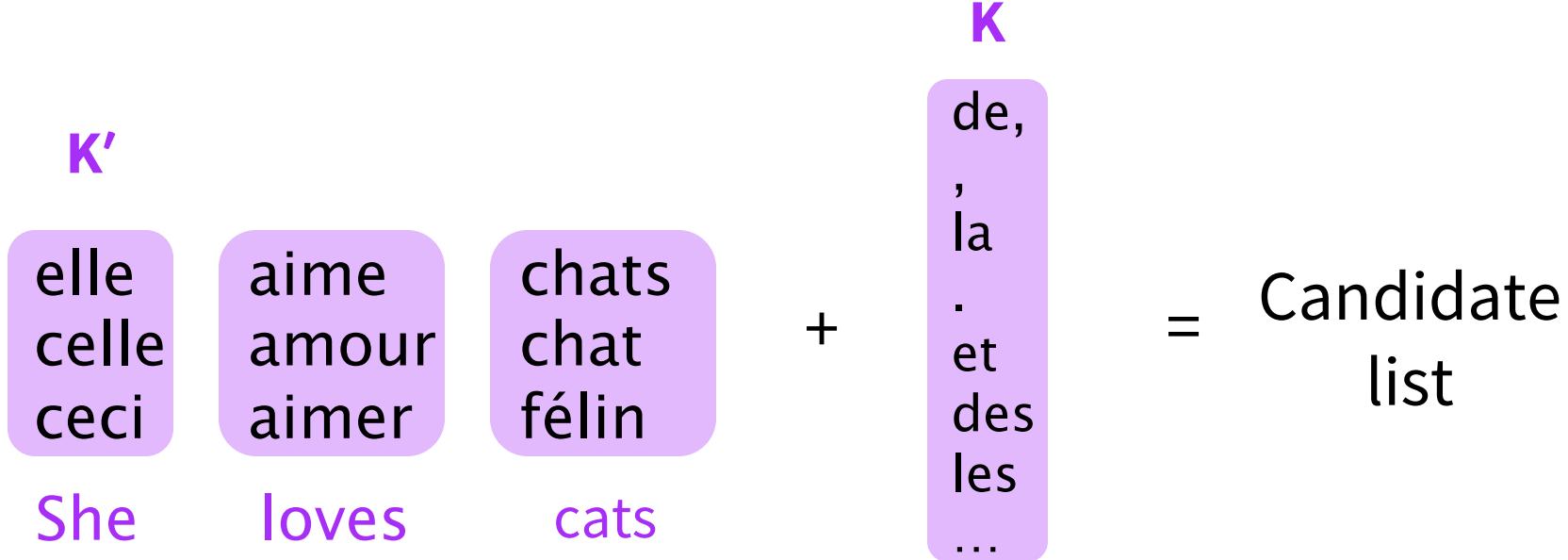
chats  
chat  
félin

She

loves

cats

# Testing – Select candidate words



- Produce translations within the candidate list
- *Practice*:  $K' = 10$  or  $20$ ,  $K = 15k$ ,  $30k$ , or  $50k$ .

# More on large-vocab techniques

- “BlackOut: Speeding up Recurrent Neural Network Language Models with very Large Vocabularies” – [Ji, Vishwanathan, Satis, Anderson, Dubey, ICLR’16].
  - Good survey over many techniques.
- “Simple, Fast Noise Contrastive Estimation for Large RNN Vocabularies” – [Zoph, Vaswani, May, Knight, NAACL’16].
  - Use the same samples per minibatch. GPU efficient.

# 2<sup>nd</sup> thought on word generation

- Scaling softmax is insufficient:
  - New **names**, new **numbers**, etc., at test time.
- But previous MT models can **copy words**.



# Copy Mechanism



- Simple way to track *target <unk>*.
- Treat any NMT as a **black box**.
  - Annotate training data.
  - Post-process translations.

Complementary to softmax scaling!

*Thang Luong, Ilya Sutskever, Quoc Le, Oriol Vinyals, Wojciech Zaremba. **Addressing the Rare Word Problem in Neural Machine Translation.** ACL '15.*

# Training annotation

- Learn alignments

The ecotax portico in Pont-de-Buis  
Le portique écotaxe de Pont-de-Buis

A diagram illustrating word alignment between two sentences. The top sentence is "The ecotax portico in Pont-de-Buis". The bottom sentence is "Le portique écotaxe de Pont-de-Buis". The words "ecotax" and "portico" in the first sentence are crossed out with a large red X. The word "Pont-de-Buis" appears twice in the second sentence, with one arrow pointing to each occurrence.

- Add relative positions

The <unk> portico in <unk>  
Le unk<sub>1</sub> unk<sub>-1</sub> de unk<sub>0</sub>

A diagram illustrating word alignment with relative position markers. The top sentence is "The <unk> portico in <unk>". The bottom sentence is "Le unk<sub>1</sub> unk<sub>-1</sub> de unk<sub>0</sub>". Arrows connect the "unk" markers in the bottom sentence to the corresponding markers in the top sentence.

# Training annotation

- Learn alignments

The ecotax portico in Pont-de-Buis  
Le portique écotaxe de Pont-de-Buis

```
graph LR; A[The ecotax portico in Pont-de-Buis] --- B[Le portique écotaxe de Pont-de-Buis]; B --- C[Pont-de-Buis]; B --- D[Pont-de-Buis]
```

- Add relative positions

The <unk> portico in <unk>  
Le unk<sub>1</sub> unk<sub>-1</sub> de unk<sub>0</sub>

```
graph LR; A[The <unk> portico in <unk>] --- B[Le unk1 unk-1 de unk0]; B --- C[portico]; B --- D[unk1]; B --- E[unk-1]; B --- F[unk0]
```

# Training annotation

- Learn alignments

The ecotax portico in Pont-de-Buis  
Le portique écotaxe de Pont-de-Buis

A diagram illustrating word alignment between two sentences. The top sentence is "The ecotax portico in Pont-de-Buis". The bottom sentence is "Le portique écotaxe de Pont-de-Buis". The words "ecotax" and "portico" in the first sentence are crossed out with a large red X. The word "Pont-de-Buis" appears twice in the second sentence, with one arrow pointing to each occurrence.

- Add relative positions

The <unk> portico in <unk>  
Le unk<sub>1</sub> unk<sub>-1</sub> de unk<sub>0</sub>

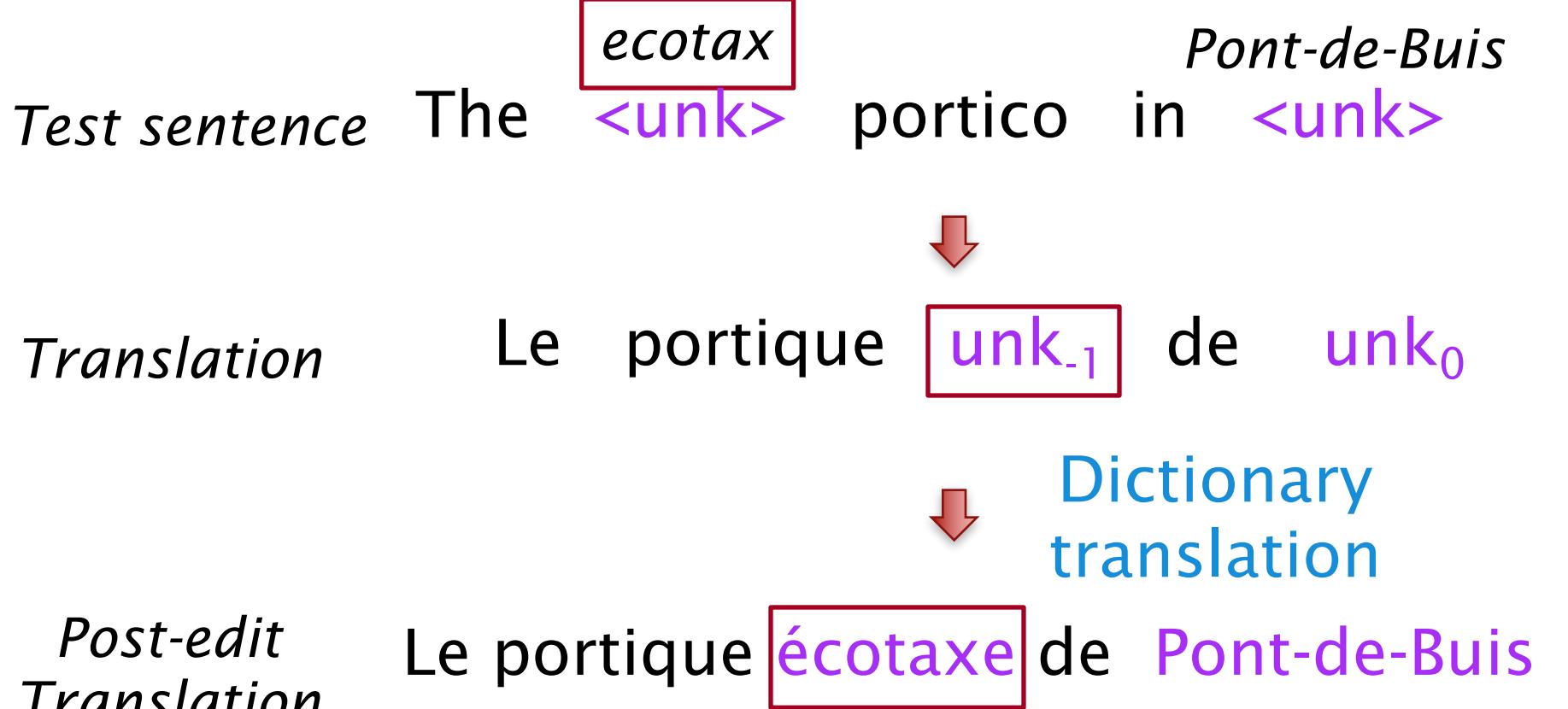
A diagram illustrating word alignment with relative positions. The top sentence is "The <unk> portico in <unk>". The bottom sentence is "Le unk<sub>1</sub> unk<sub>-1</sub> de unk<sub>0</sub>". The first "unk" in the French sentence is enclosed in a red box. Arrows connect the first "unk" in French to the first "unk" in English, and the last "unk" in French to the last "unk" in English.

# Post-processing

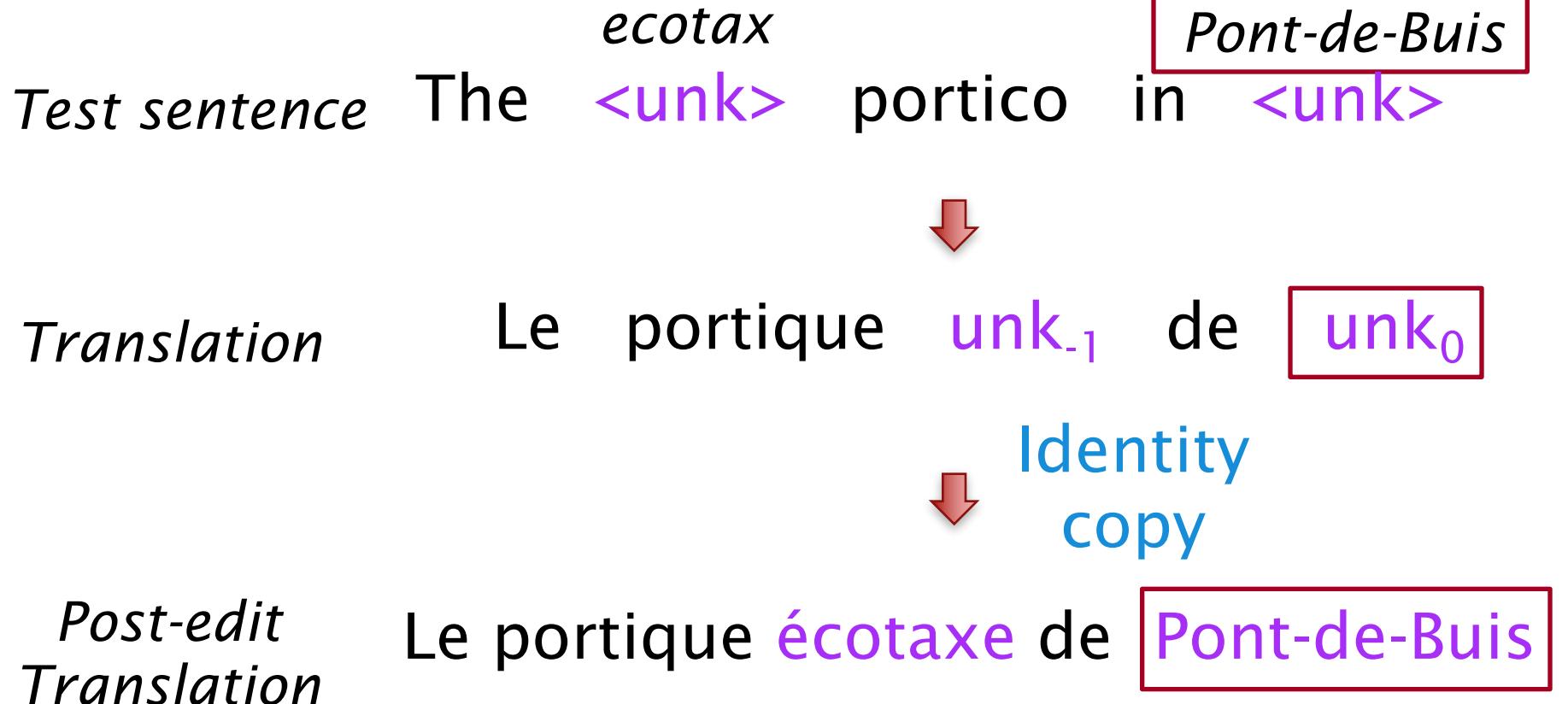
*Test sentence* The *ecotax* portico in *Pont-de-Buis* *<unk>* *<unk>*

*Translation*      Le portique  unk<sub>1</sub> de unk<sub>0</sub>

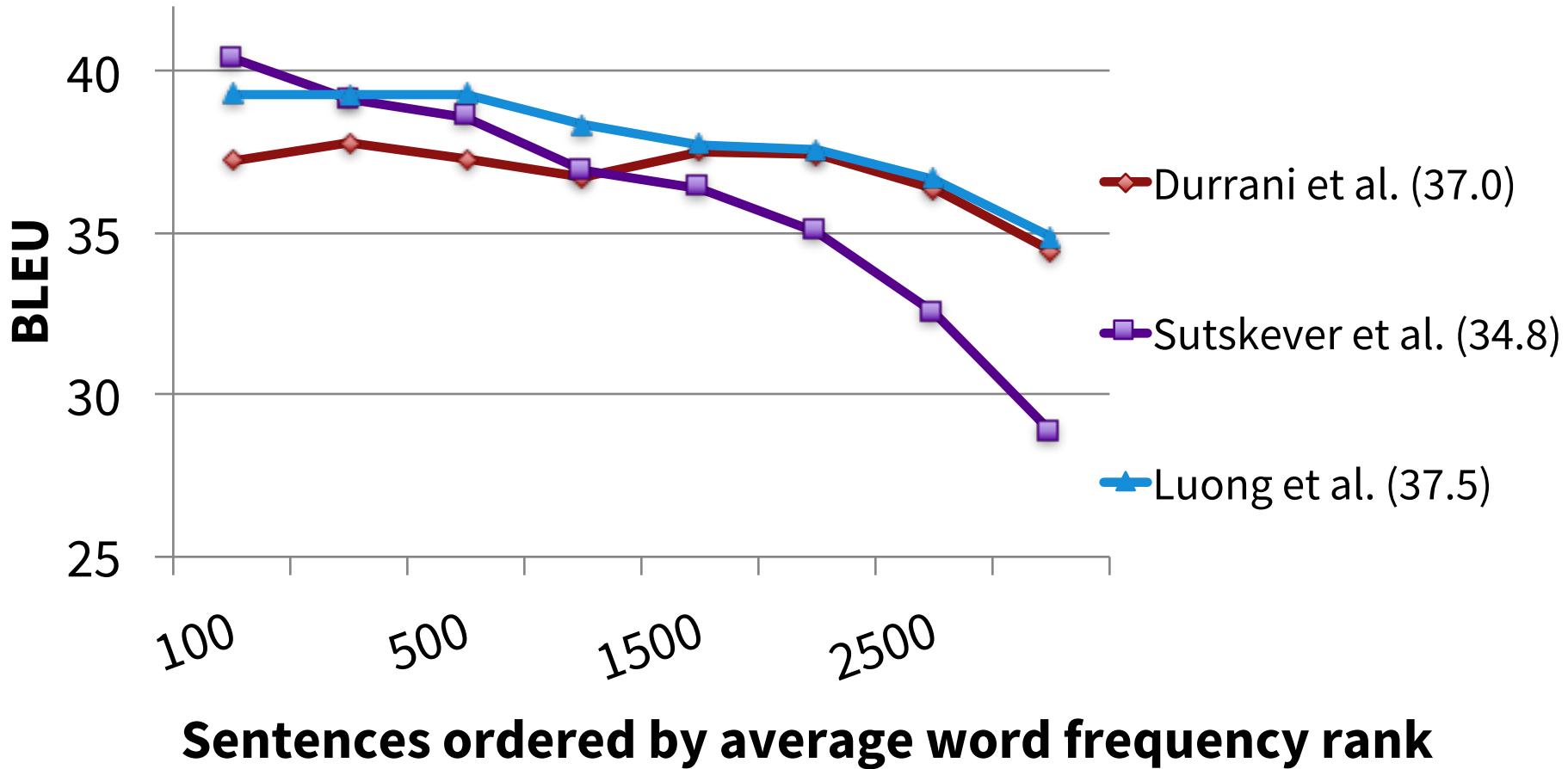
# Post-processing



# Post-processing



# Effects of Translating Rare Words



First SOTA NMT!

# Sample translations

source	This <b>trader</b> , Richard <b>Usher</b> , left RBS in <b>2010</b> and is understand to have be given leave from his current position as European head of forex spot trading at <b>JPMorgan</b> .
human	Ce <b>trader</b> , Richard <b>Usher</b> , a quitté <b>RBS</b> en 2010 et aurait été mis suspendu de son poste de responsable européen du trading au comptant pour les devises chez <b>JPMorgan</b> .
trans	Ce <b>unk<sub>0</sub></b> , Richard <b>unk<sub>0</sub></b> , a quitté <b>unk<sub>1</sub></b> en 2010 et a compris qu' il est autorisé à quitter son poste actuel en tant que leader européen du marché des points de vente au <b>unk<sub>5</sub></b> .
trans+unk	Ce <b>négociateur</b> , Richard <b>Usher</b> , a quitté <b>RBS</b> en 2010 et a compris qu' il est autorisé à quitter son poste actuel en tant que leader européen du marché des points de vente au <b>JPMorgan</b> .

- Translates well long sentences
  - Correct: **JPMorgan** vs. **JPMorgan.**

# Copy Mechanism – Old but useful!

- Later, we'll discuss better techniques!
- But it's useful when adapting to new tasks!
  - Text summarization: [Gu, Lu, Li, Li, ACL'16],  
[Gulcehre, Ahn, Nallapati, Zhou, Bengio, ACL'16]
  - Semantic parsing: [Jia, Liang, ACL'16]

Learn to decide when to copy.

### 3. Advancing NMT

#### a. The **vocabulary** aspect

- *Goal:* extend the vocabulary coverage.

#### b. The **memory** aspect

- *Goal:* translate long sentences better.

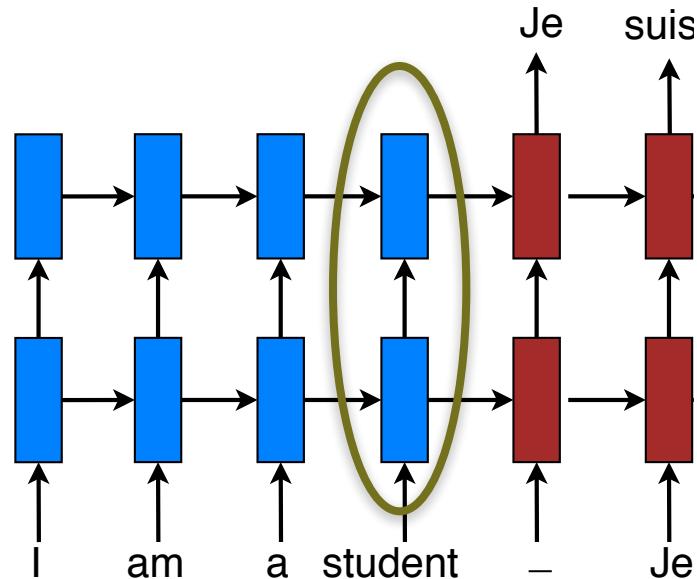
#### c. The **language complexity** aspect

- *Goal:* handle more language variations.

#### d. The **data** aspect

- *Goal:* utilize more data sources.

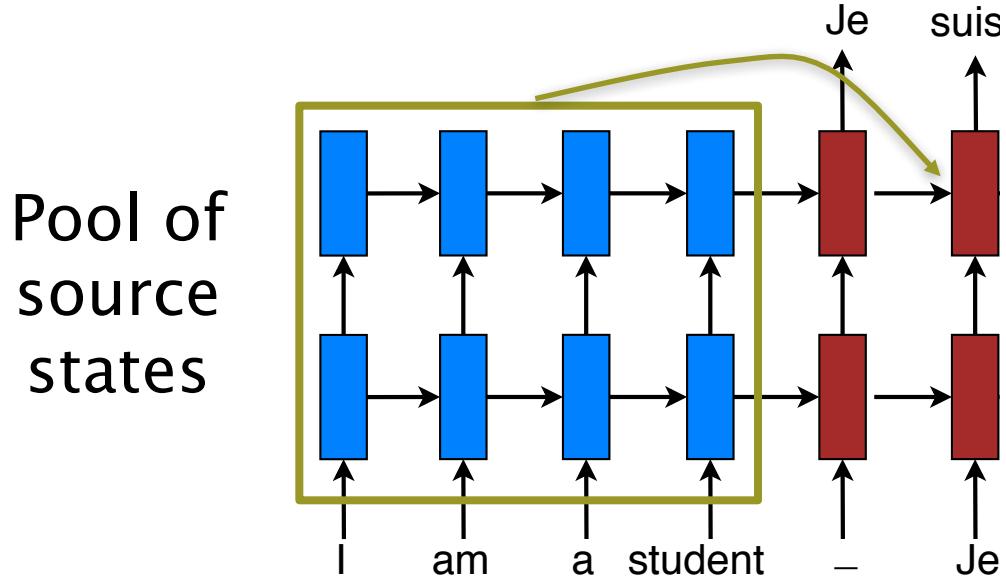
# Vanilla seq2seq & long sentences



Problem: fixed-dimensional representations

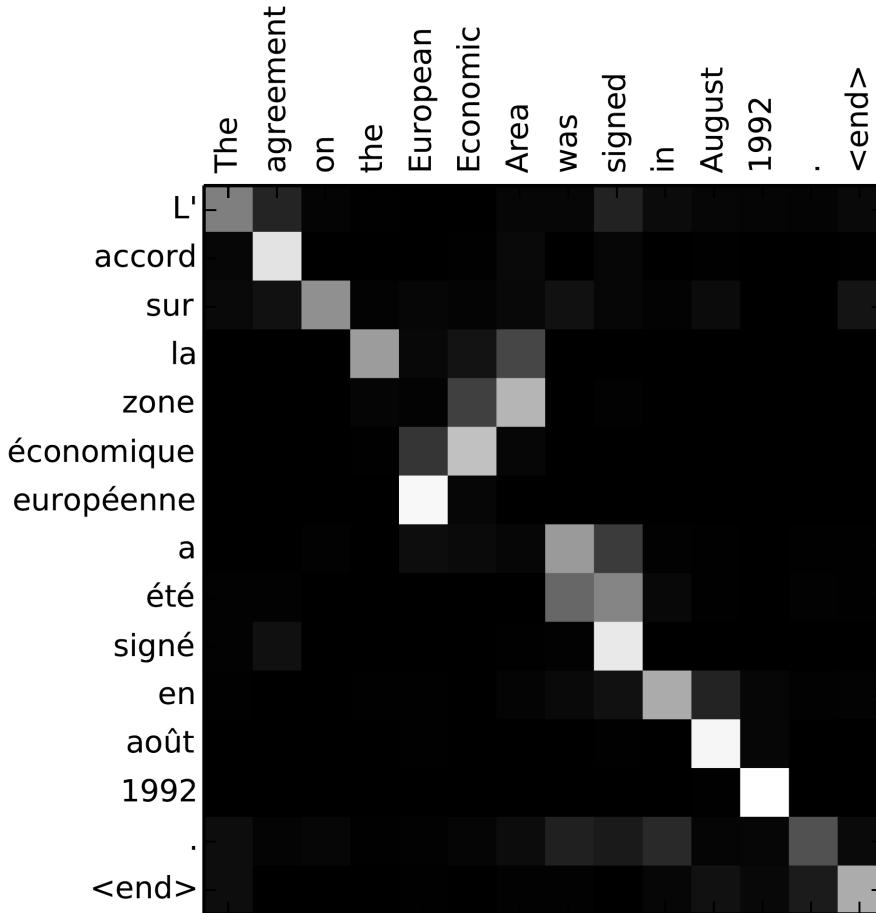
# Attention Mechanism

Started in computer vision!  
[Larochelle & Hinton, 2010],  
[Denil, Bazzani, Larochelle,  
Freitas, 2012]

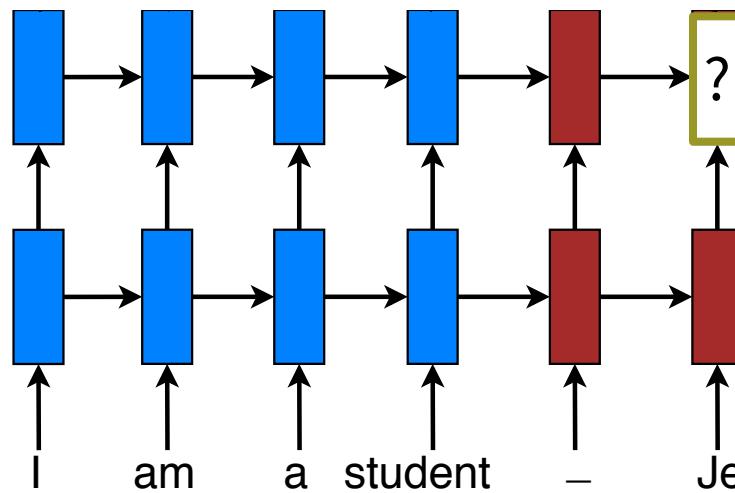


- **Solution:** random access memory
  - Retrieve as needed.

# Learning both translation & alignment



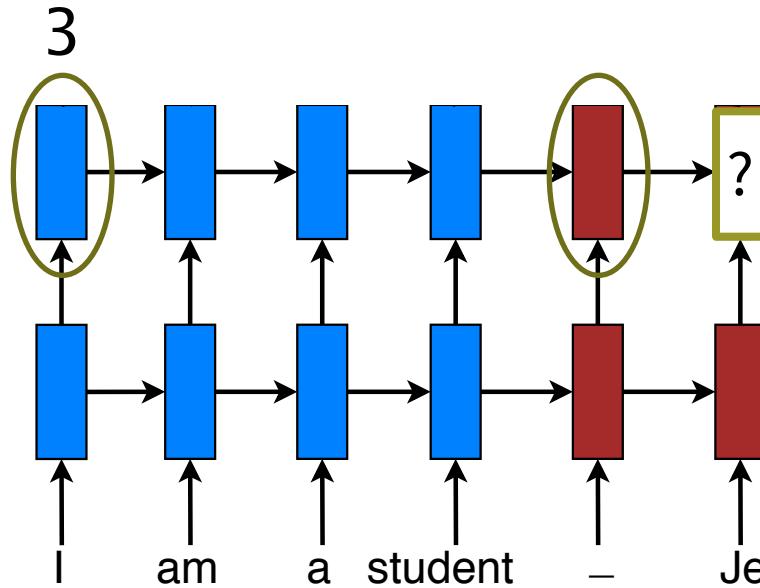
# Attention Mechanism



Simplified version of (Bahdanau et al., 2015)

# Attention Mechanism – Scoring

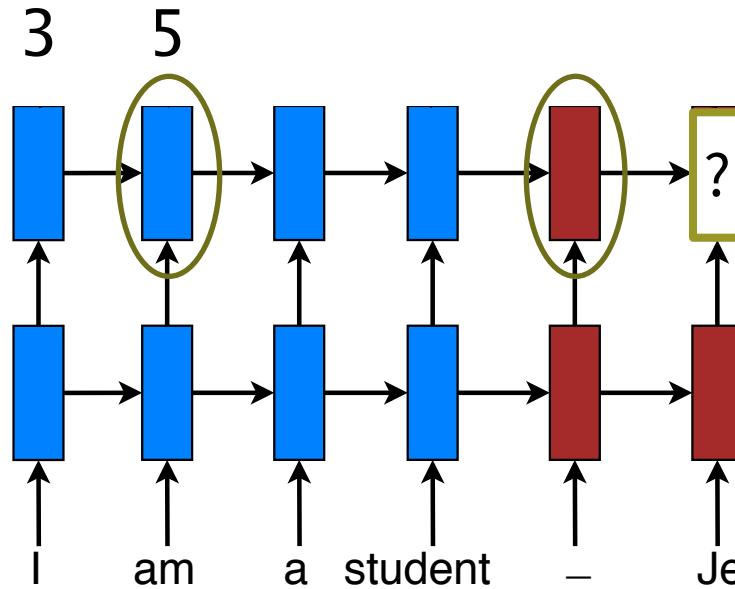
$$\text{score}(\mathbf{h}_{t-1}, \bar{\mathbf{h}}_s)$$



- Compare target and source hidden states.

# Attention Mechanism – Scoring

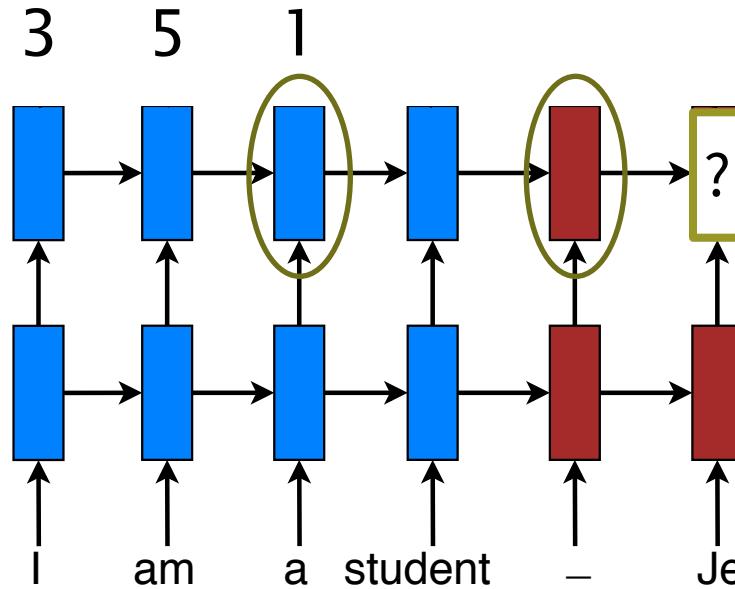
$$\text{score}(\mathbf{h}_{t-1}, \bar{\mathbf{h}}_s)$$



- Compare target and source hidden states.

# Attention Mechanism – Scoring

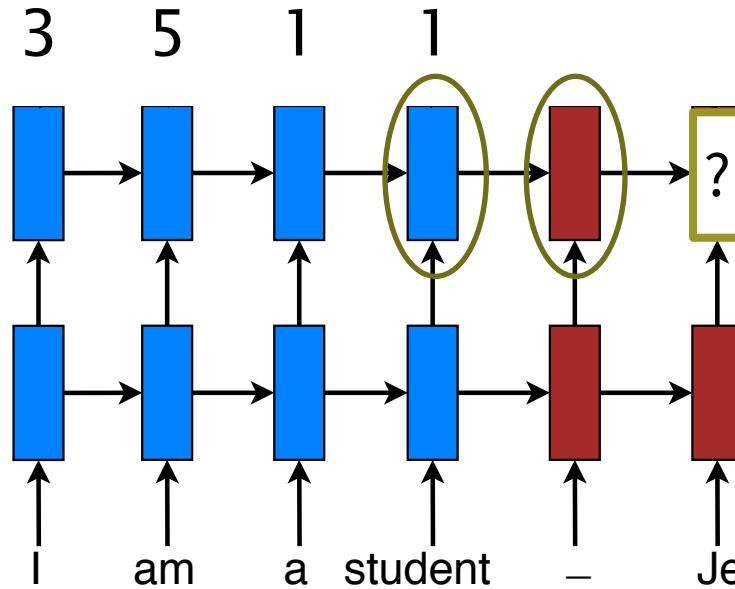
$$\text{score}(\mathbf{h}_{t-1}, \bar{\mathbf{h}}_s)$$



- Compare target and source hidden states.

# Attention Mechanism – Scoring

$$\text{score}(\mathbf{h}_{t-1}, \bar{\mathbf{h}}_s)$$

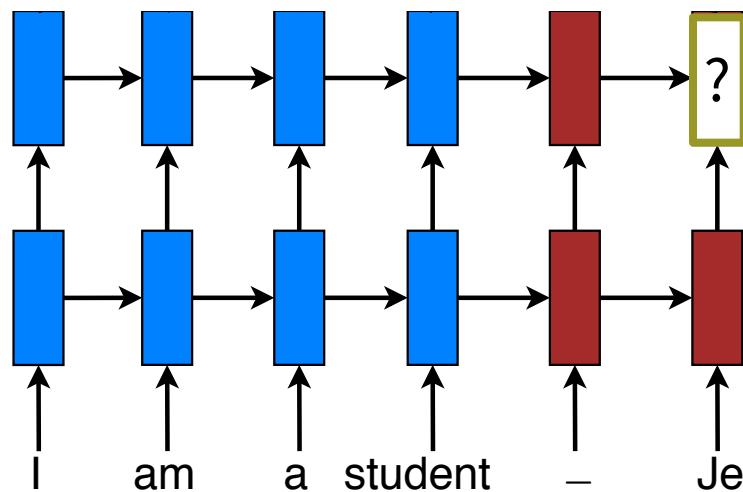


- Compare target and source hidden states.

# Attention Mechanism – Normalization

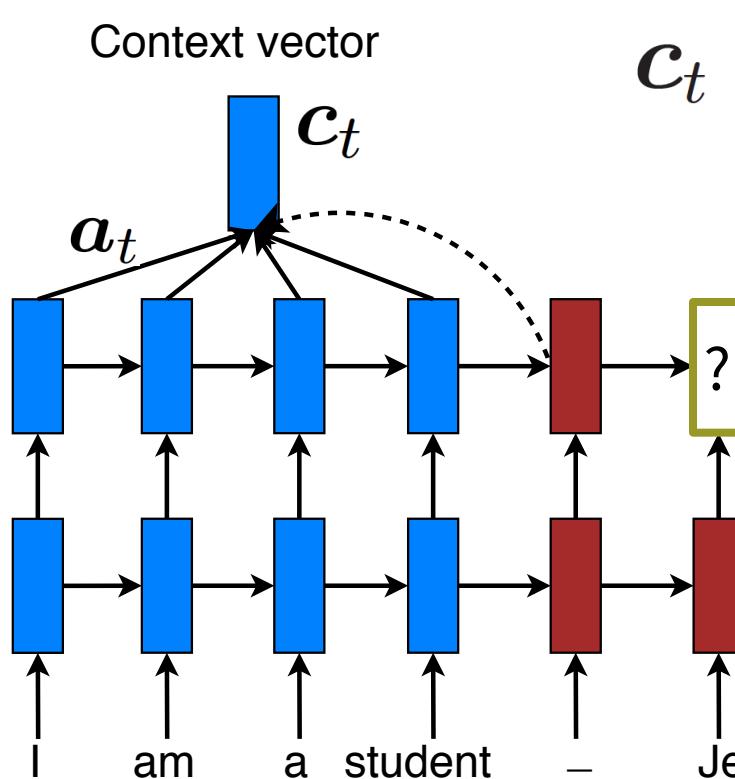
$$a_t(s) = \frac{e^{\text{score}(s)}}{\sum_{s'} e^{\text{score}(s')}}$$

$a_t$  0.3 0.5 0.1 0.1



- Convert into alignment weights.

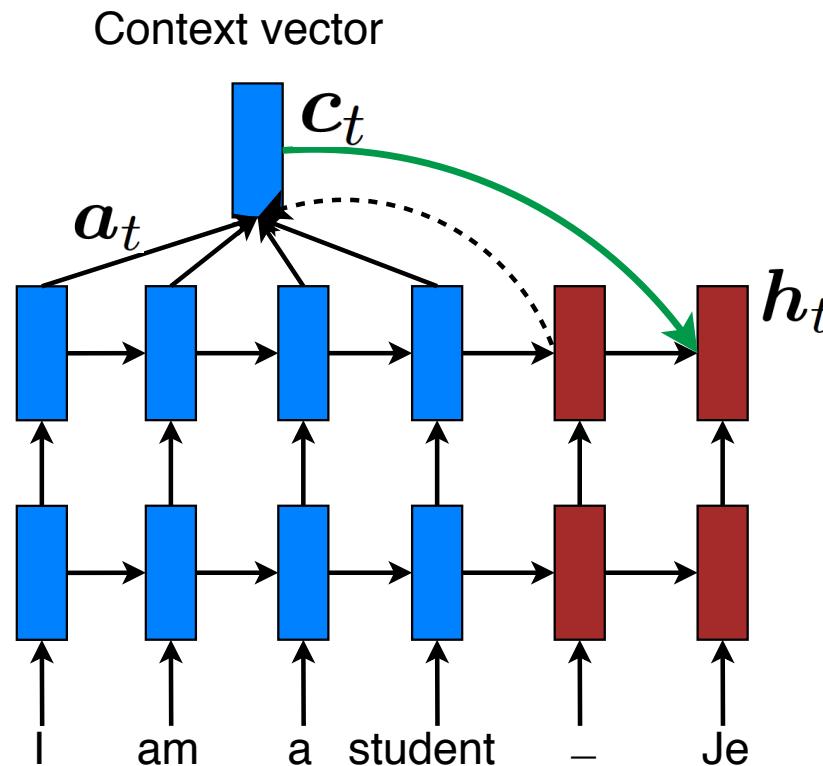
# Attention Mechanism – Context



$$c_t = \sum_s a_t(s) \bar{h}_s$$

- Build **context** vector: weighted average.

# Attention Mechanism – *Hidden State*

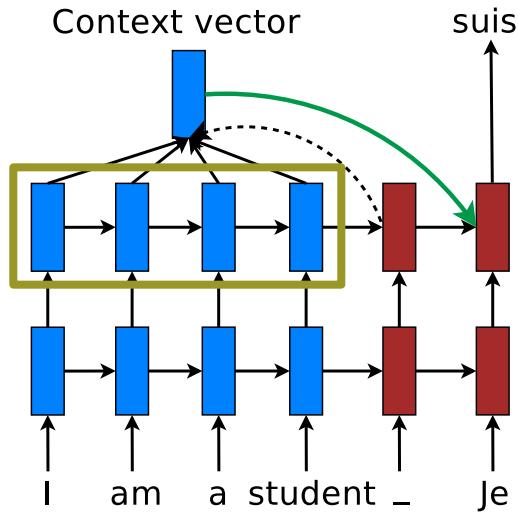


- Compute the next hidden state.

# Attention Mechanisms+



- Simplified mechanism & more functions:



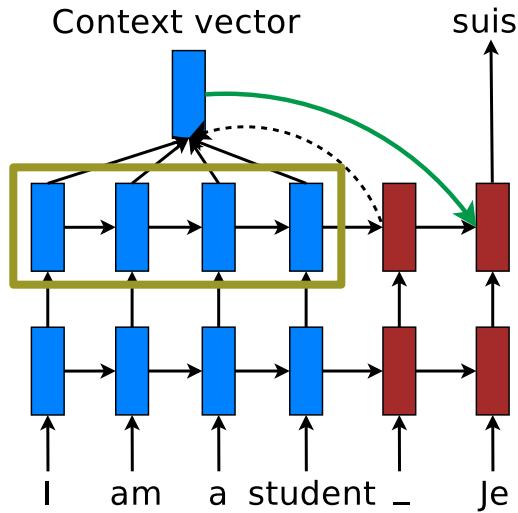
$$\text{score}(\mathbf{h}_t, \bar{\mathbf{h}}_s) = \begin{cases} \mathbf{h}_t^\top \bar{\mathbf{h}}_s \\ \mathbf{h}_t^\top \mathbf{W}_a \bar{\mathbf{h}}_s \\ \mathbf{v}_a^\top \tanh (\mathbf{W}_a [\mathbf{h}_t; \bar{\mathbf{h}}_s]) \end{cases}$$

Thang Luong, Hieu Pham, and Chris Manning. **Effective Approaches to Attention-based Neural Machine Translation.** EMNLP'15.

# Attention Mechanisms+



- Simplified mechanism & more functions:



Bilinear form:  
well-adopted.

$$\text{score}(\mathbf{h}_t, \bar{\mathbf{h}}_s) = \begin{cases} \mathbf{h}_t^\top \bar{\mathbf{h}}_s \\ \mathbf{h}_t^\top \mathbf{W}_a \bar{\mathbf{h}}_s \\ \mathbf{v}_a^\top \tanh (\mathbf{W}_a [\mathbf{h}_t; \bar{\mathbf{h}}_s]) \end{cases}$$

GitHub, Inc. [US] <https://github.com/harvardnlp/seq2seq-attn>

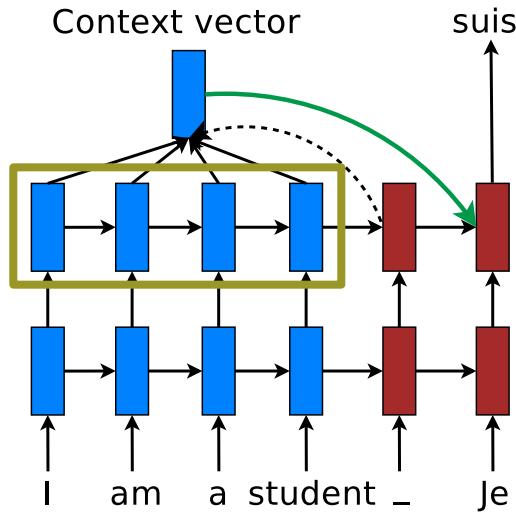
## Sequence-to-Sequence Learning with Attentional Neural Networks

The attention model is from [Effective Approaches to Attention-based Neural Machine Translation](#), Luong et al. EMNLP 2015. We use the *global-general-attention* model with the *input-feeding* approach from the paper. Input-feeding is optional and can be turned off.

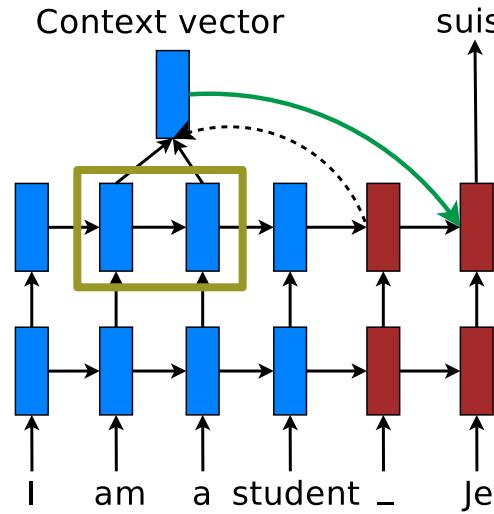
# Global vs. Local



- Avoid focusing on everything at each time



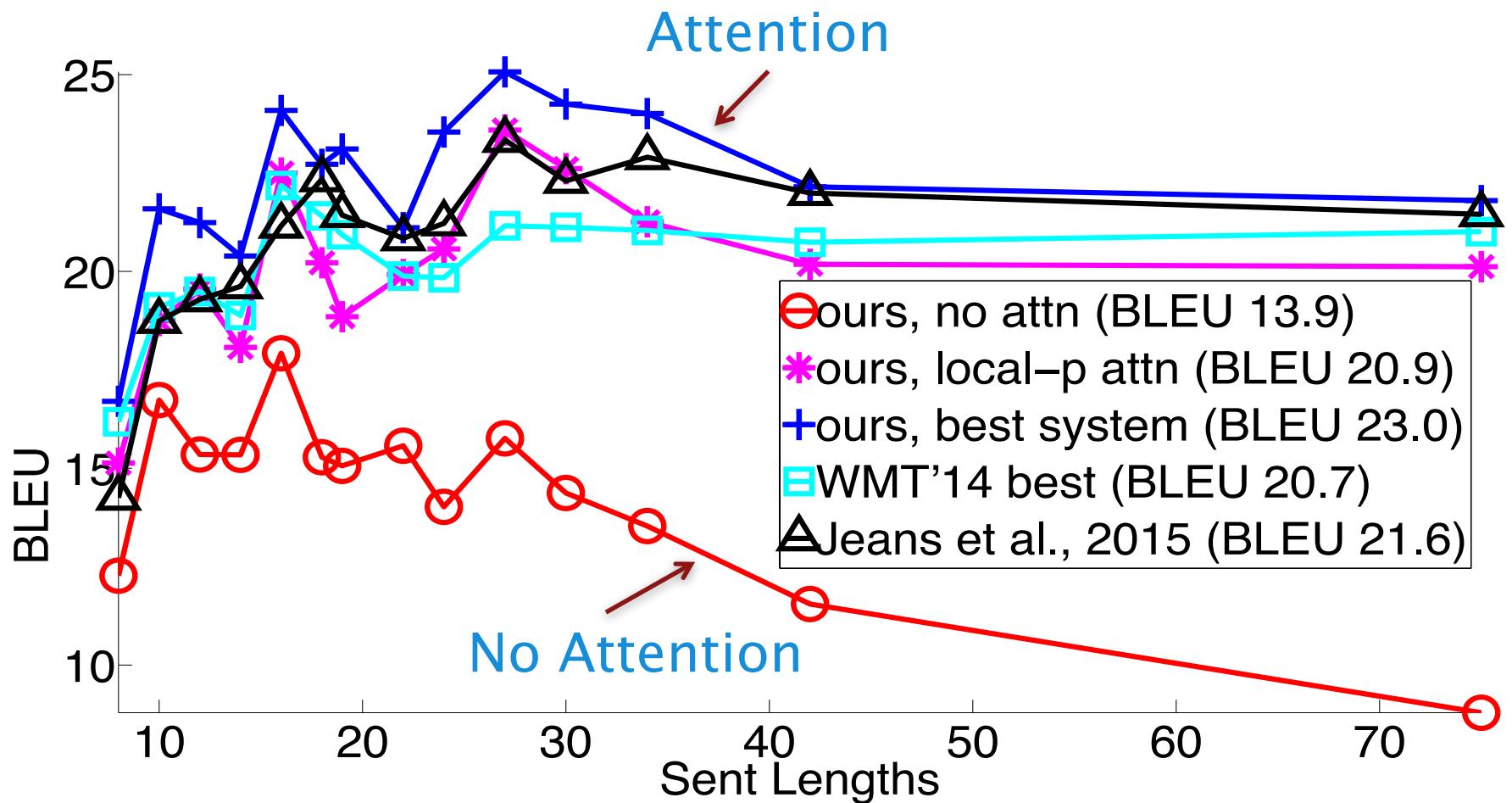
**Global:** **all** source states.



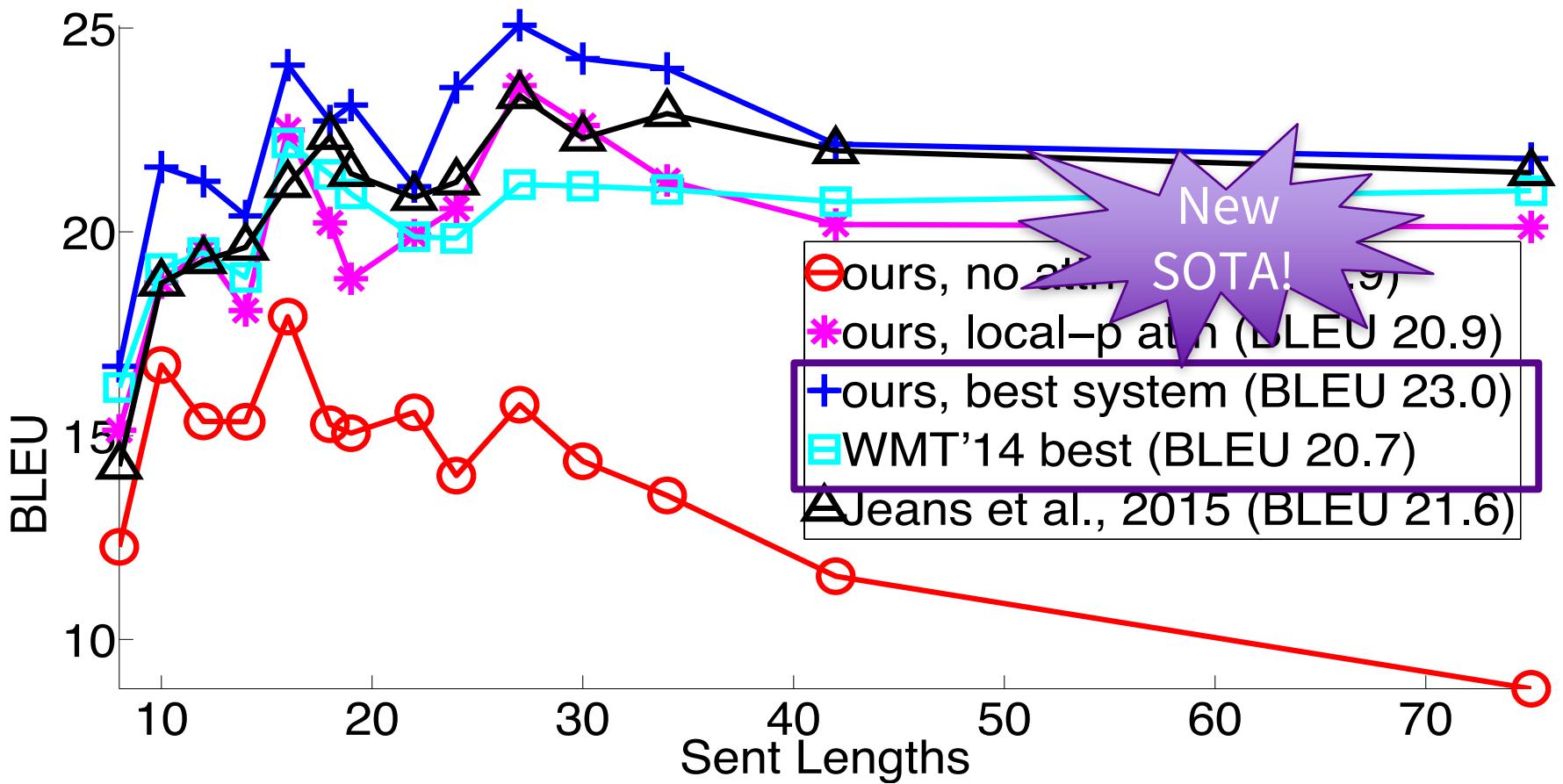
**Local:** **subset** of source states.

Potential for long sequences!

# Better Translation of Long Sentences



# Better Translation of Long Sentences



# Sample English-German translations

source	Orlando Bloom and <i>Miranda Kerr</i> still love each other
human	Orlando Bloom und <b>Miranda Kerr</b> lieben sich noch immer
+attn	Orlando Bloom und <b>Miranda Kerr</b> lieben einander noch immer.
base	Orlando Bloom und <b>Lucas Miranda</b> lieben einander noch immer.

- Translates names correctly.

# Sample English-German translations

source	We're pleased the FAA recognizes that an enjoyable passenger experience is <b>not incompatible</b> with safety and security , said Roger Dow , CEO of the U.S. Travel Association .
human	Wir freuen uns , dass die FAA erkennt , dass ein angenehmes Passagiererlebnis nicht <b>im Wider- spruch zur Sicherheit steht</b> , sagte Roger Dow , CEO der U.S. Travel Association .
+attn	Wir freuen uns , dass die FAA anerkennt , dass ein angenehmes ist nicht mit Sicherheit und Sicherheit <b>unvereinbar</b> ist , sagte Roger Dow , CEO der US - die .
base	Wir freuen uns u'ber die <unk> , dass ein <unk> <unk> mit Sicherheit nicht <b>vereinbar</b> ist mit Sicherheit und Sicherheit , sagte Roger Cameron , CEO der US - <unk> .

- Translates a **doubly-negated phrase** correctly.

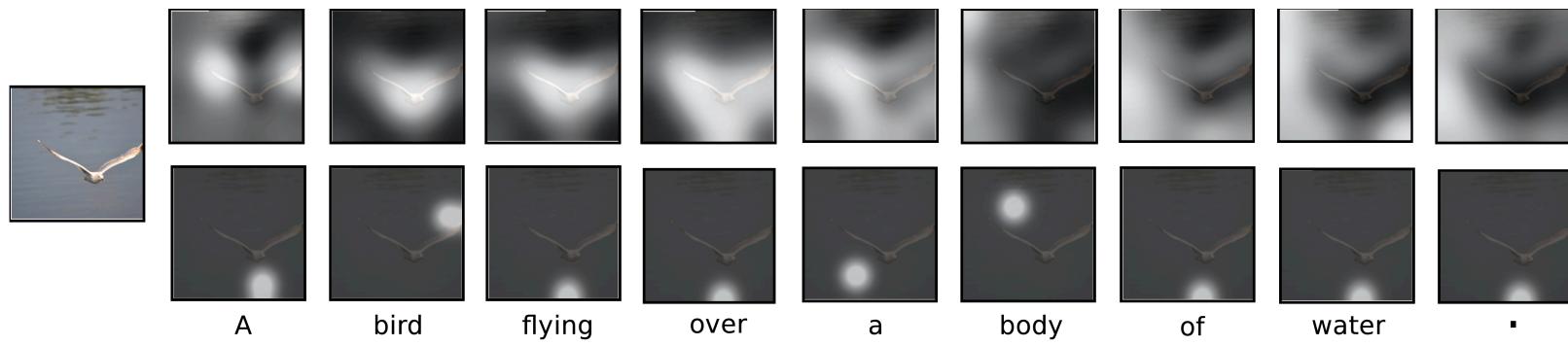
# Sample English-German translations

source	We're pleased the FAA recognizes that an enjoyable passenger experience is <b>not incompatible</b> with safety and security , said Roger Dow , CEO of the U.S. Travel Association .
human	Wir freuen uns , dass die FAA erkennt , dass ein angenehmes Passagiererlebnis nicht <b>im Wider- spruch zur Sicherheit steht</b> , sagte Roger Dow , CEO der U.S. Travel Association .
+attn	Wir freuen uns , dass die FAA anerkennt , dass ein angenehmes ist nicht mit Sicherheit und Sicherheit <b>unvereinbar</b> ist , sagte Roger Dow , CEO der US - die .
base	Wir freuen uns u'ber die <unk> , dass ein <unk> <unk> mit Sicherheit nicht <b>vereinbar</b> ist mit Sicherheit und Sicherheit , sagte Roger Cameron , CEO der US - <unk> .

- Translates a **doubly-negated phrase** correctly.

# More Attention! *The idea of coverage*

- Caption generation



How to not miss an  
important image patch?

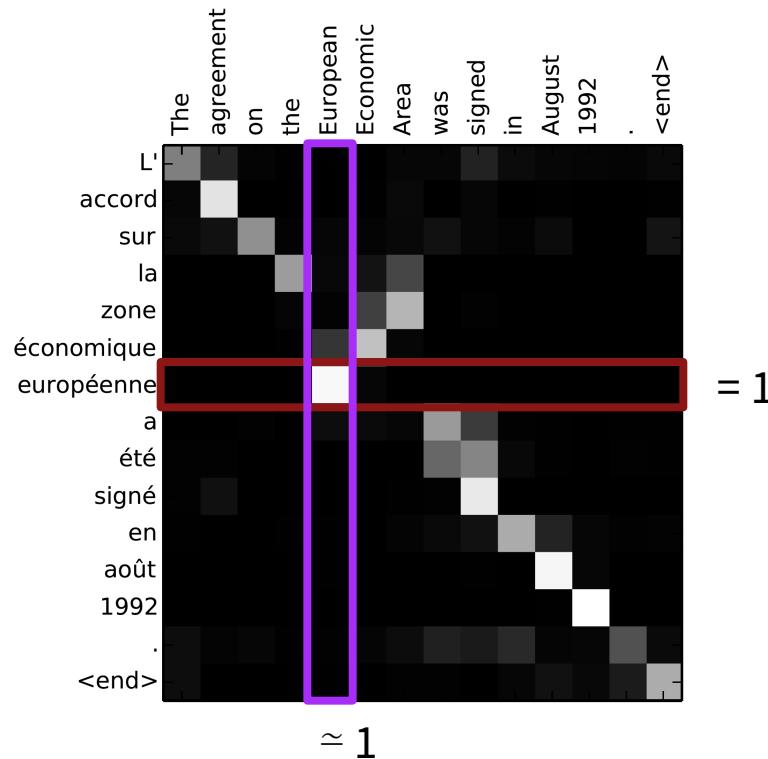
# Doubly attention

$$-\log(P(\mathbf{y}|\mathbf{x})) + \lambda \sum_i^L (1 - \sum_t^C \alpha_{ti})^2$$

Per image patch

Sum across  
caption words

- Sum to 1 in both dimensions

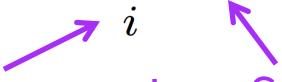


Coverage set  
exists long time  
ago in SMT!

# Extend to NMT – *Linguistic insights*

- [Cohn, Hoang, Vymolova, Yao, Dyer, Haffari, NAACL'16]: position (IBM2) + Markov (HMM) + fertility (IBM3-5) + alignment symmetry (BerkeleyAligner).

$$-\log(P(\mathbf{y}|\mathbf{x})) + \lambda \sum_i^L (1 - \sum_t^C \alpha_{ti})^2$$

  
Per source word      Source word fertility

- [Tu, Lu, Liu, Liu, Li, ACL'16]: linguistic & NN-based coverage models.

# If you feel jetlagged ... see when MT fails



Sale of chicken murder



152

Deep fried baby



Go back toward your behind



Meat muscle stupid bean sprouts

### 3. Advancing NMT

#### a. The **vocabulary** aspect

- *Goal:* extend the vocabulary coverage.

#### b. The **memory** aspect

- *Goal:* translate long sentences better.

#### c. The **language complexity** aspect

- *Goal:* handle more language variations.

#### d. The **data** aspect

- *Goal:* utilize more data sources.

# Extend NMT to more languages

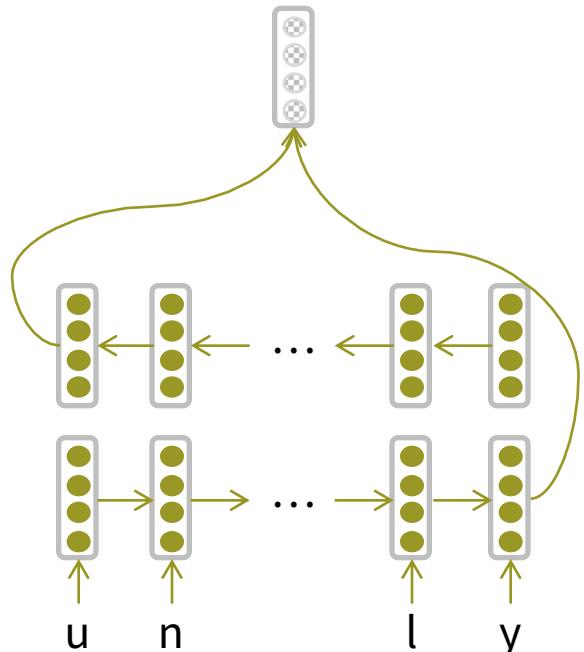
- “Copy” mechanisms are **not sufficient**.
  - Transliteration: Christopher → Kryštof
  - Multi-word alignment: Solar system → Sonnensystem
- Need to handle **large, open vocabulary**
  - Rich morphology: nejneobhospodařovávatelnějšímu (“to the worst farmable one”)
  - Informal spelling: goooooood morning !!!!!

Be able to operate at sub-word levels.

# Sub-word modeling

Again, lots of inspirations  
from neural language modeling!

# Character-based LSTM

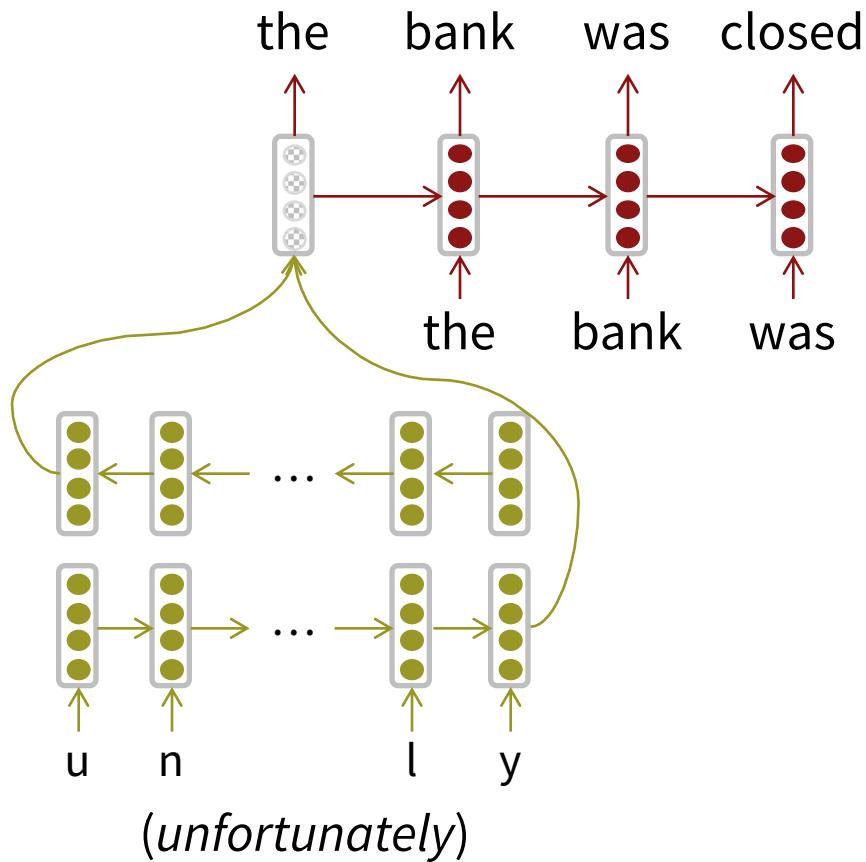


(unfortunately)

Bi-LSTM builds word representations

Ling, Luís, Marujo, Astudillo, Amir, Dyer, Black, Trancoso. **Finding Function in Form: Compositional Character Models for Open Vocabulary Word Representation**. EMNLP'15.

# Character-based LSTM

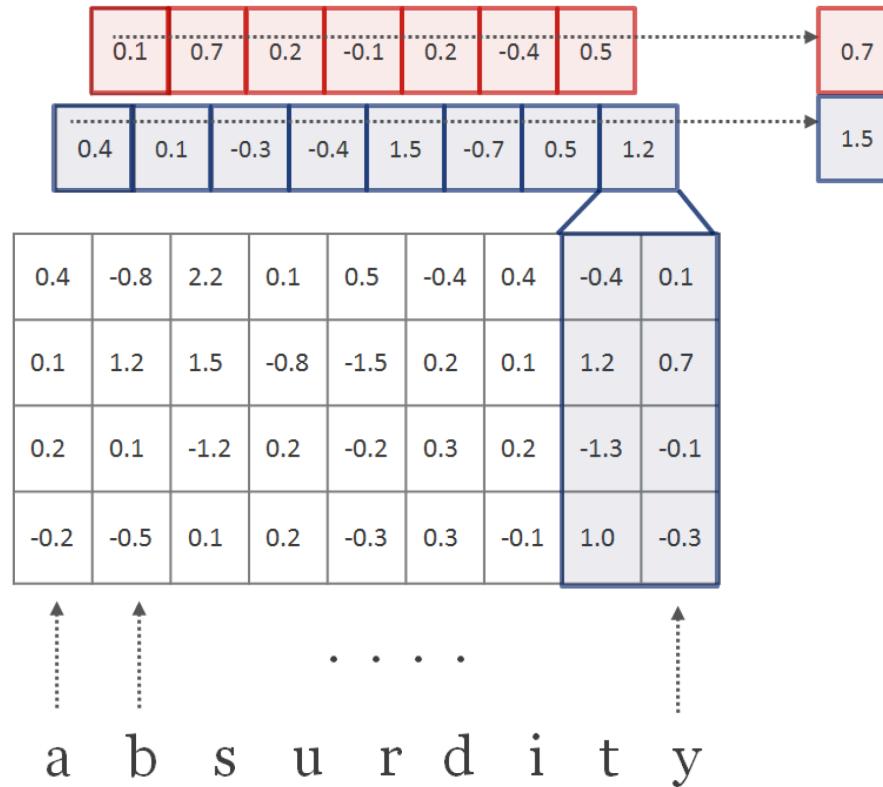


Recurrent Language Model

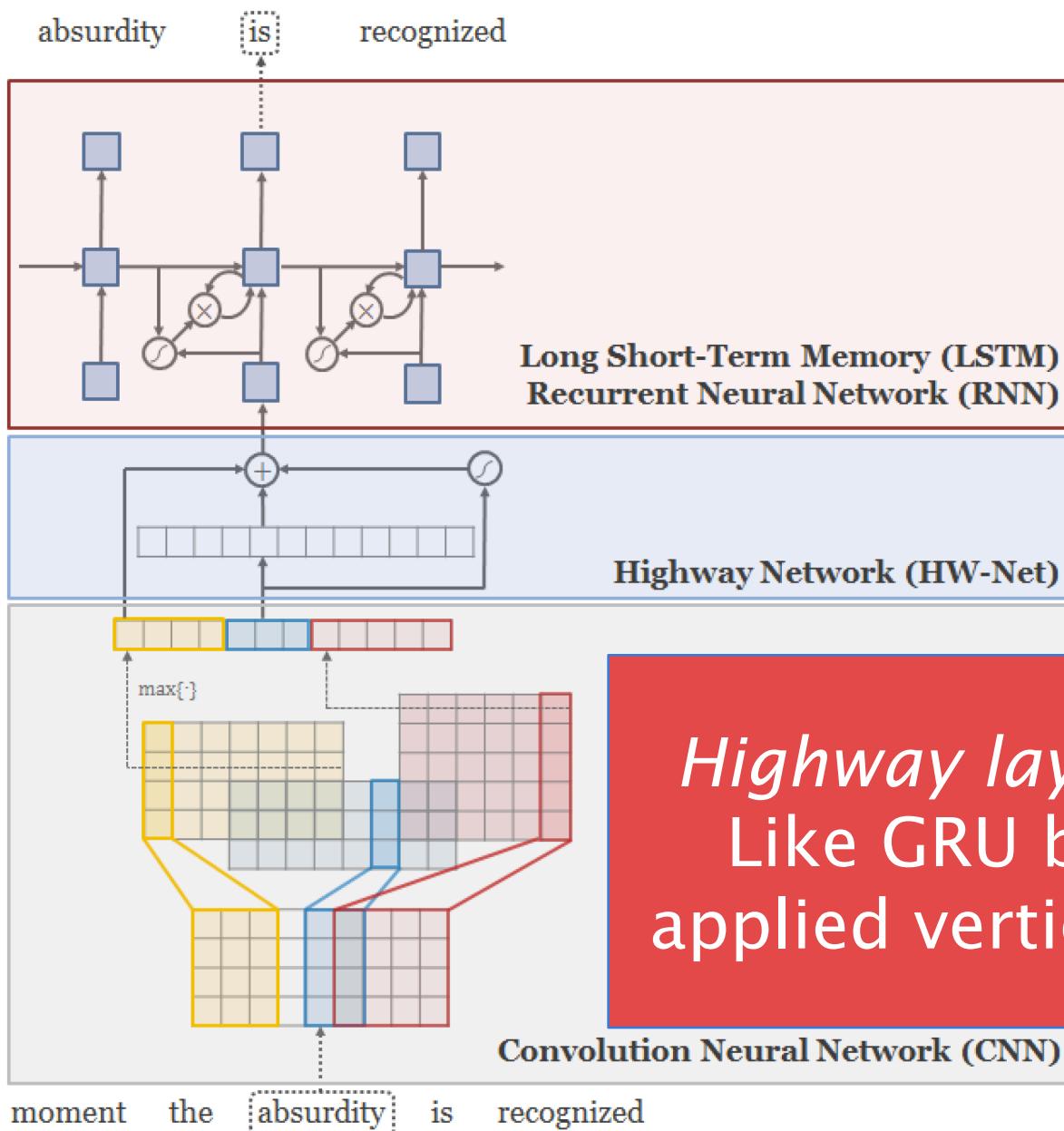
Bi-LSTM builds word representations

Ling, Luís, Marujo, Astudillo, Amir, Dyer, Black, Trancoso. **Finding Function in Form: Compositional Character Models for Open Vocabulary Word Representation**. EMNLP'15.

# Character ConvNet



*Yoon Kim, Yacine Jernite, David Sontag, and Alexander M. Rush.  
Character-Aware Neural Language Models. AAAI 2016.*



# Sub-word NMT: two trends

- Same seq2seq architecture:
  - Use smaller units.
  - [Sennrich, Haddow, Birch, ACL'16a], [Chung, Cho, Bengio, ACL'16].
- Hybrid architectures:
  - RNN for *words* + something else for *characters*.
  - [Costa-Jussà & Fonollosa, ACL'16], [Luong & Manning, ACL'16].

# Byte Pair Encoding



- A compression algorithm:
  - Most frequent byte pair  $\mapsto$  a new byte.

Replace bytes with character ngrams

*Rico Sennrich, Barry Haddow, and Alexandra Birch. Neural Machine Translation of Rare Words with Subword Units. ACL 2016.*

# Byte Pair Encoding



- A word segmentation algorithm:
  - Start with a vocabulary of characters.
  - Most frequent ngram pairs  $\mapsto$  a new ngram.

# Byte Pair Encoding



- A word segmentation algorithm:
  - Start with a vocabulary of characters.
  - Most frequent ngram pairs  $\mapsto$  a new ngram.

*Dictionary*

5 low  
2 lower  
6 newest  
3 widest

*Vocabulary*

l, o, w, e, r, n, w, s, t, i, d

Start with all characters  
in vocab

# Byte Pair Encoding



- A word segmentation algorithm:
  - Start with a vocabulary of characters.
  - Most frequent ngram pairs  $\mapsto$  a new ngram.

*Dictionary*

5 low  
2 lower  
6 new es t  
3 wi d es t

*Vocabulary*

I, o, w, e, r, n, w, s, t, i, d, es

Add a pair (e, s) with freq 9

# Byte Pair Encoding



- A word segmentation algorithm:
  - Start with a vocabulary of characters.
  - Most frequent ngram pairs  $\mapsto$  a new ngram.

*Dictionary*

5 low  
2 lower  
6 new est  
3 wid est

*Vocabulary*

I, o, w, e, r, n, w, s, t, i, d, es, est

Add a pair (es, t) with freq 9

# Byte Pair Encoding



- A word segmentation algorithm:
  - Start with a vocabulary of characters.
  - Most frequent ngram pairs  $\mapsto$  a new ngram.

*Dictionary*

5 low  
2 lower  
6 newest  
3 widest

*Vocabulary*

I, o, w, e, r, n, w, s, t, i, d, es, est, lo

Add a pair (l, o) with freq 7

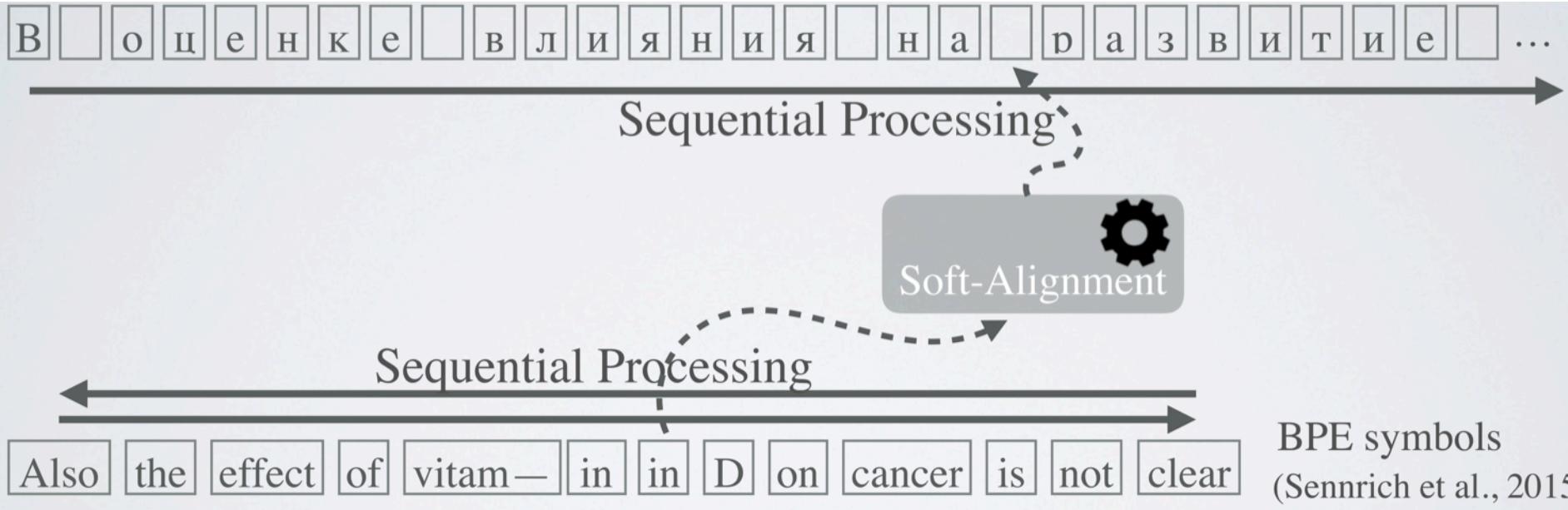
# Byte Pair Encoding



- A word segmentation algorithm:
  - Start with a vocabulary of characters.
  - Most frequent ngram pairs  $\mapsto$  a new ngram.
- Automatically decide vocabs for NMT
  - *Word-level*: asinine situation  $\mapsto$  Asinin-Situation
  - *BPE-level*: as in ine situation  $\mapsto$  As in in- Situation

Top places in WMT 2016!

# BPE $\mapsto$ Characters



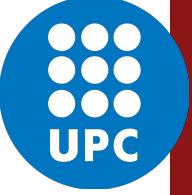
Works for many language pairs.

*Junyoung Chung, Kyunghyun Cho, Yoshua Bengio. A Character-Level Decoder without Explicit Segmentation for Neural Machine Translation. ACL 2016.*

# Sub-word NMT: two trends

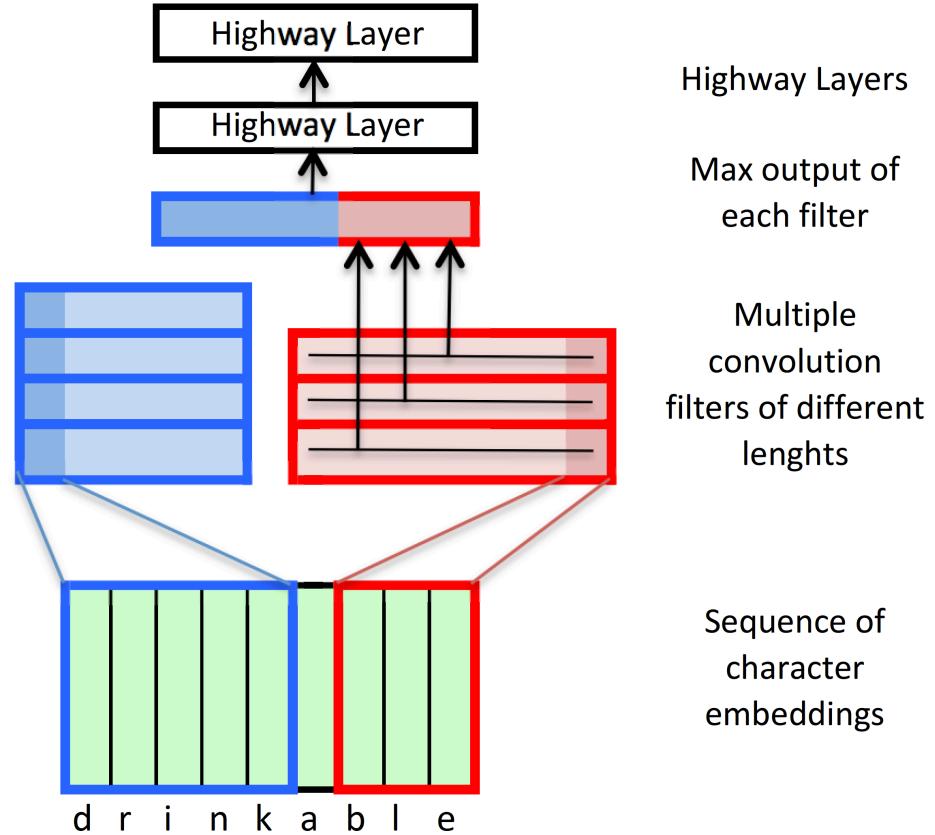
- Same seq2seq architecture:
  - Use smaller units.
  - (Sennrich et al., ACL'16), (Chung et al., ACL'16).
- Hybrid architectures:
  - RNN for *words* + something else for *characters*.
  - [Costa-Jussà & Fonollosa, ACL'16], [Luong & Manning, ACL'16].

# Character-level Encoder



- Useful when **source language is complex**:
  - Similar architecture [Kim, Jernite, Sontag, Rush, AAAI'15].

+3 BLEU for German-English translation.



# Hybrid NMT

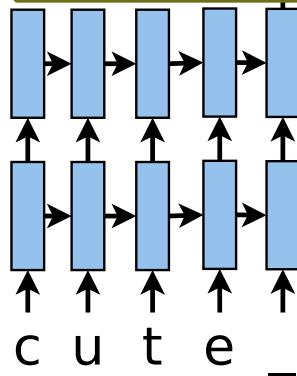
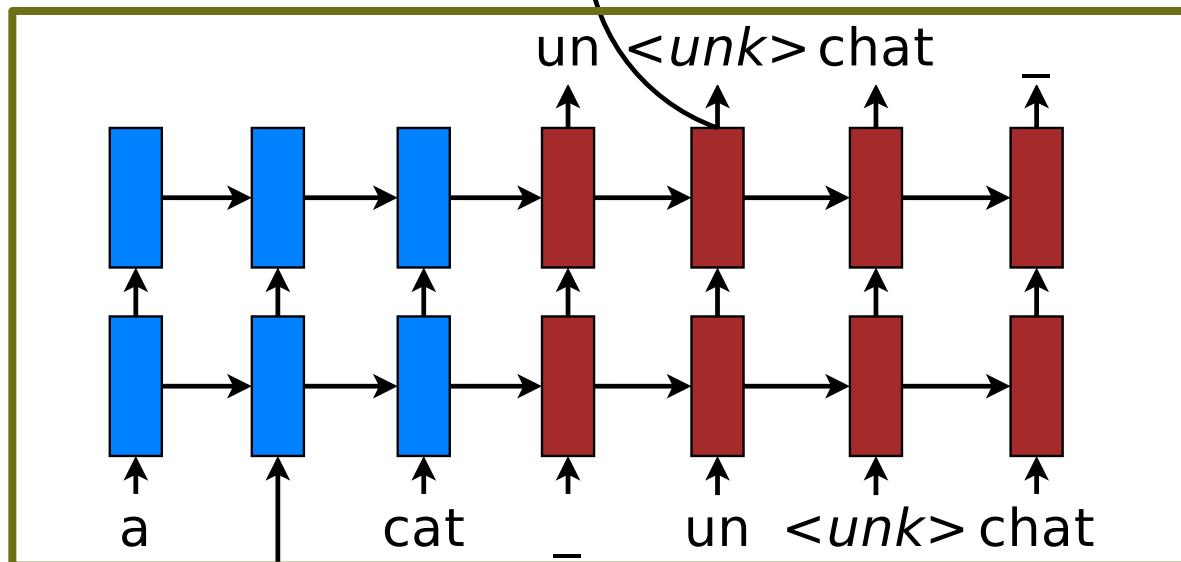


- A *best-of-both-worlds* architecture:
  - Translate mostly at the **word** level
  - Only go the **character** level when needed.
- More than **2 BLEU** improvement over copy mechanism.

*Thang Luong and Chris Manning. Achieving Open Vocabulary Neural Machine Translation with Hybrid Word-Character Models. ACL 2016.*

# Hybrid NMT

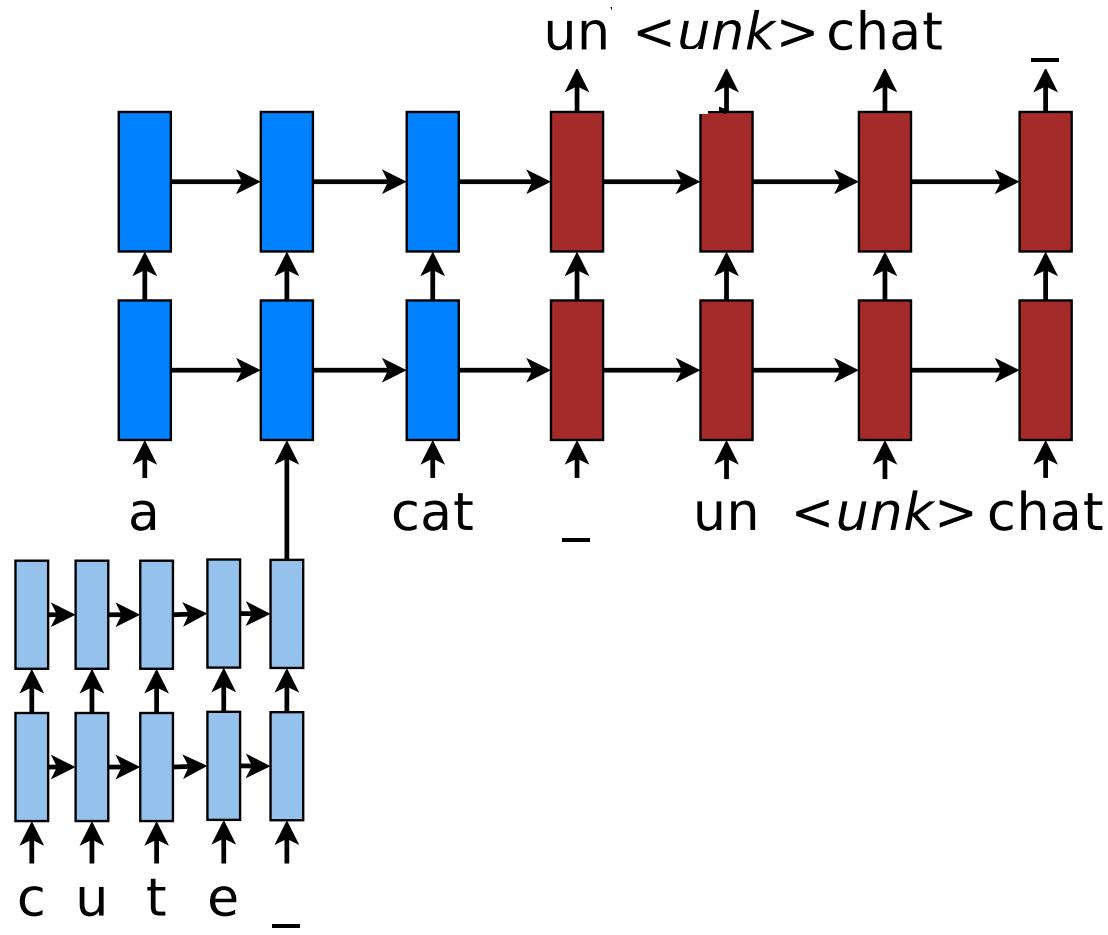
Word-level  
(4 layers)



End-to-end training  
8-stacking LSTM layers.

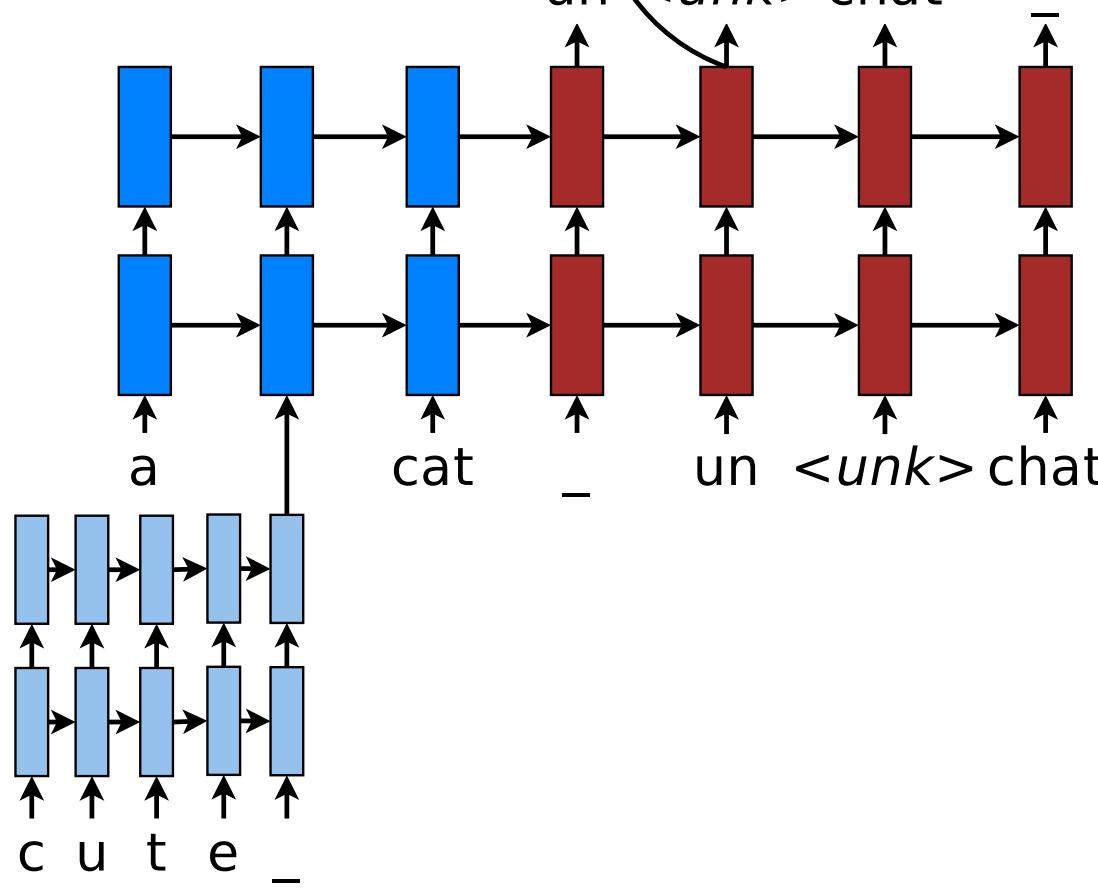
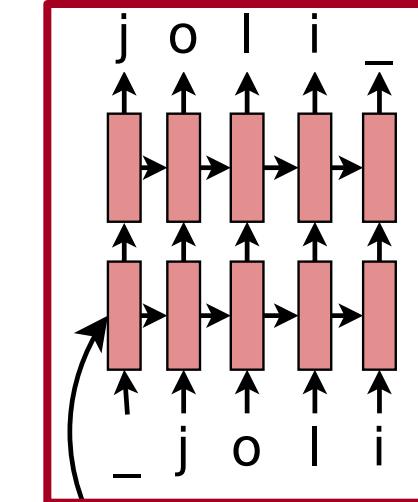
# 2-stage Decoding

- Word-level beam search



# 2-stage Decoding

- Word-level beam search
- Char-level beam search for  $\langle unk \rangle$ .



# English-Czech Results

- Train on WMT'15 data (12M sentence pairs)
  - newstest2015

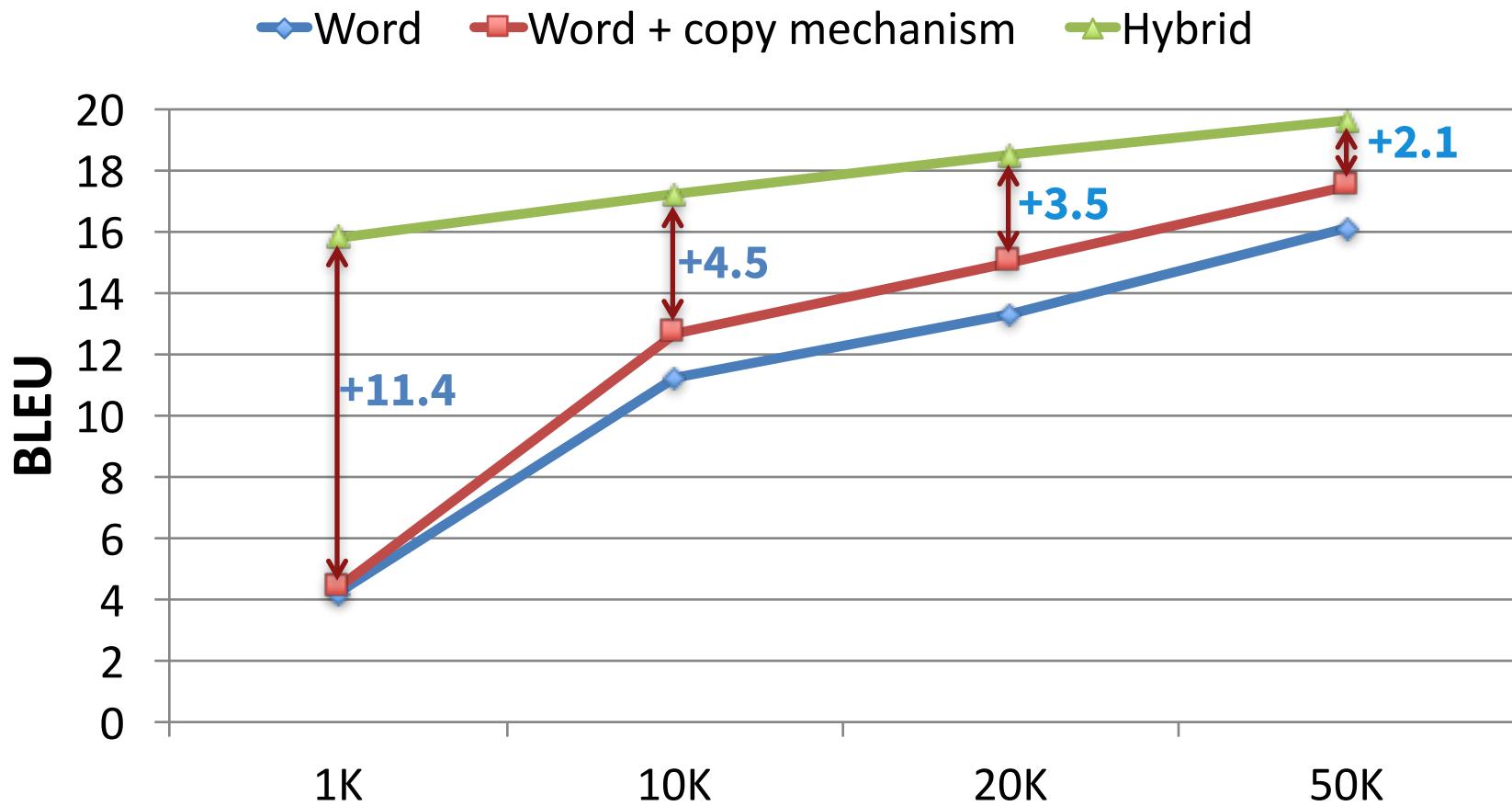
Systems	BLEU	
Winning WMT'15 (Bojar & Tamchyna, 2015)	18.8	30x data 3 systems
<b>Word-level</b> NMT (Jean et al., 2015)	18.3	Large vocab + copy mechanism

# English-Czech Results

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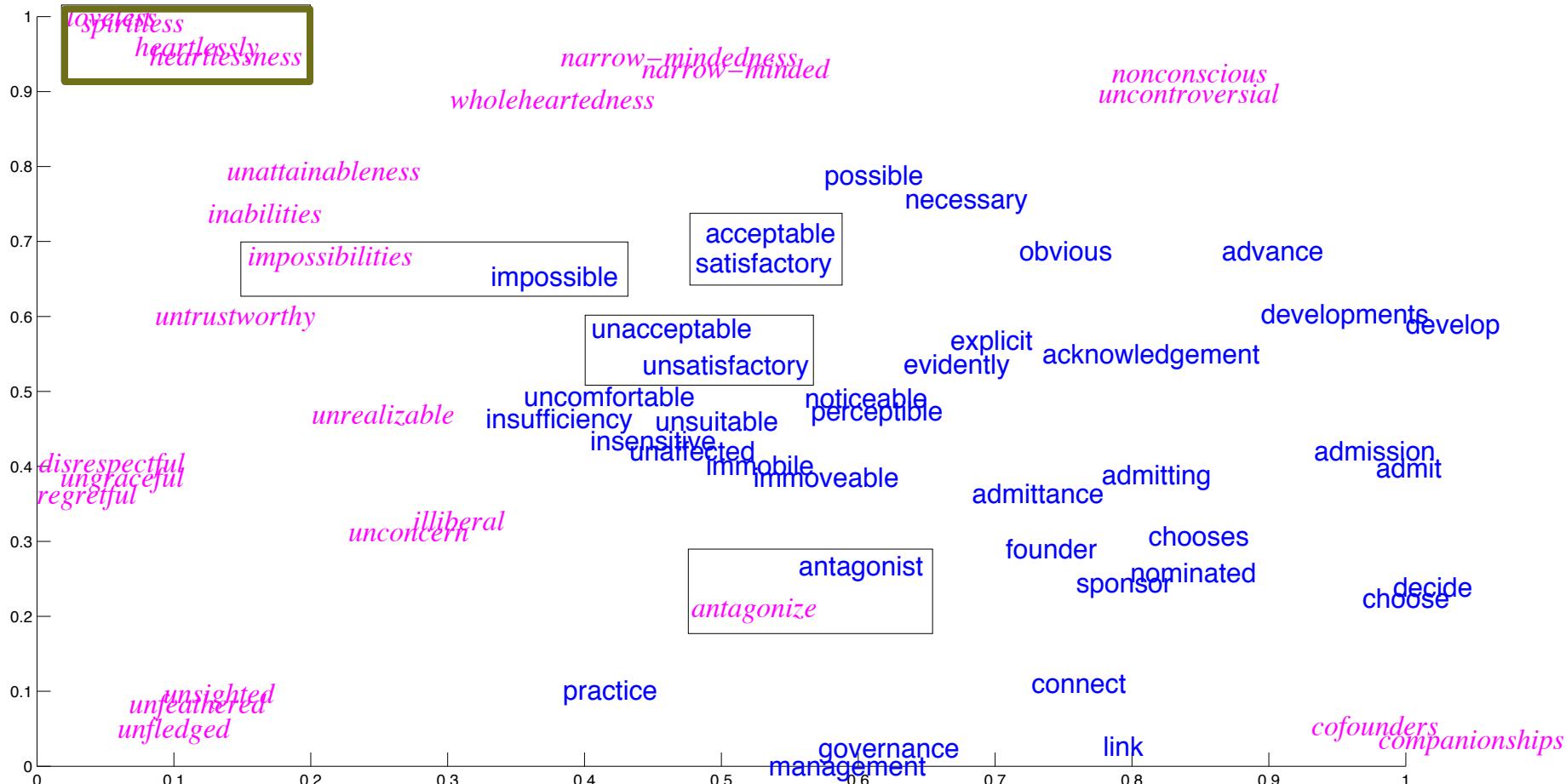
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<b>Word-level</b> NMT (Jean et al., 2015)	18.3	Large vocab + copy mechanism
<b>Hybrid</b> NMT (Luong & Manning, 2016)*	<b>20.7</b>	New SOTA!

# Effects of Vocabulary Sizes



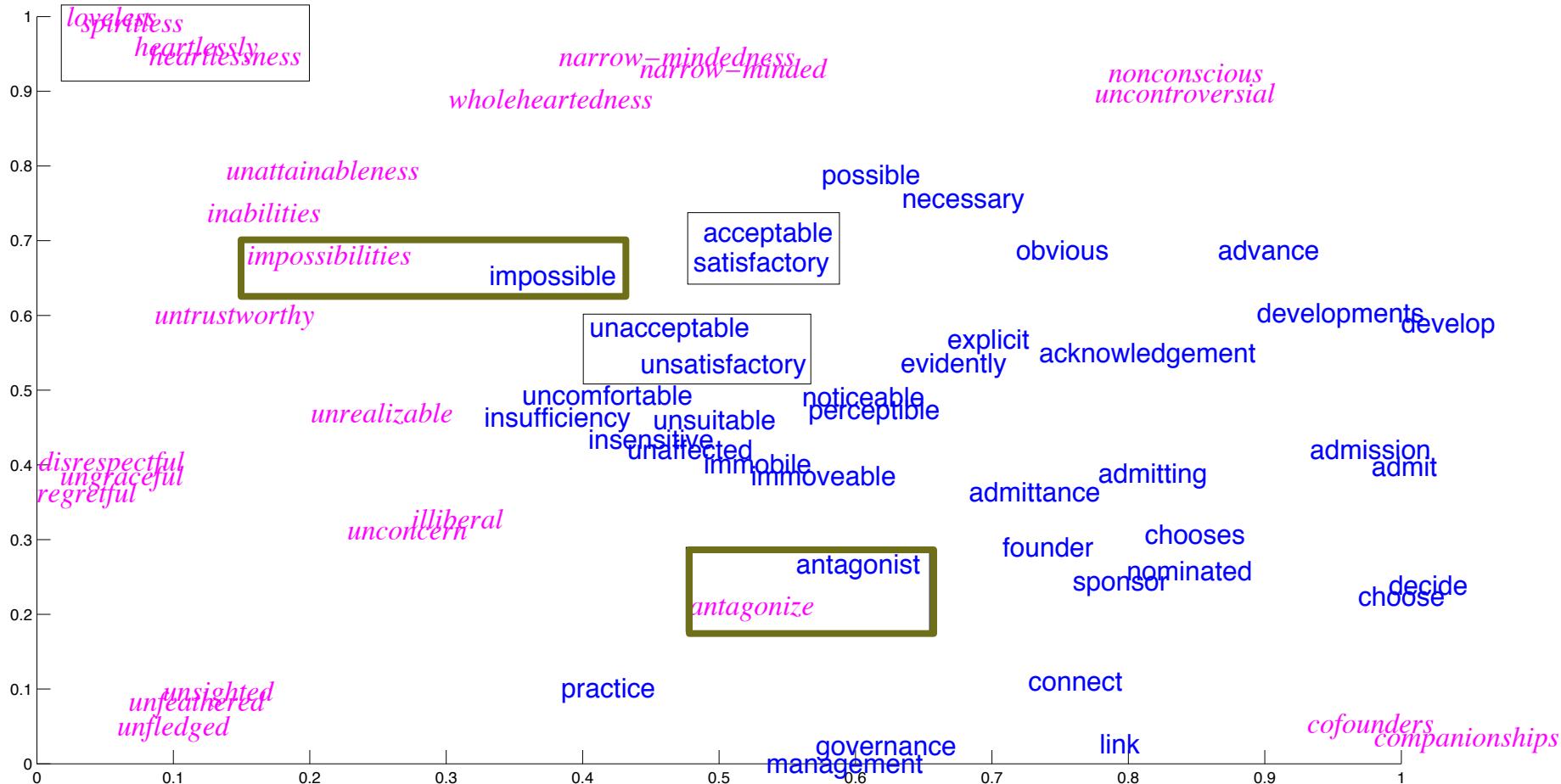
More than +2.0 BLEU over copy mechanism!

# Rare Word Embeddings



- Word & character-based embeddings.

# Rare Word Embeddings



- Word & character-based embeddings.

# Sample English-Czech translations

source	Her <b>11-year-old</b> daughter , <b>Shani Bart</b> , said it felt a little bit <b>weird</b>
human	Její <b>jedenáctiletá</b> dcera <b>Shani Bartová</b> prozradila , že je to trochu <b>zvláštní</b>
word	Její <unk> dcera <unk> <unk> řekla , že je to trochu divné
hybrid	Její <b>11-year-old</b> dcera <b>Shani</b> , řekla , že je to trochu <b>divné</b>
	Její <unk> dcera , <unk> <unk> , řekla , že je to <unk> <unk>
	Její <b>jedenáctiletá</b> dcera , <b>Graham Bart</b> , řekla , že cítí trochu <b>divný</b>

- Hybrid: correct, **11-year-old** – **jedenáctiletá**.

# Sample English-Czech translations

source	Her <b>11-year-old</b> daughter , <b>Shani Bart</b> , said it felt a little bit <b>weird</b>
human	Její <b>jedenáctiletá</b> dcera <b>Shani Bartová</b> prozradila , že je to trochu <b>zvláštní</b>
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hybrid	Její <unk> dcera , <unk> <unk> , řekla , že je to <unk> <unk>
	Její <b>jedenáctiletá</b> dcera , <b>Graham Bart</b> , řekla , že cítí trochu <b>divný</b>

- Word-based: identity copy fails.

### 3. Advancing NMT

#### a. The **vocabulary** aspect

- *Goal:* extend the vocabulary coverage.

#### b. The **memory** aspect

- *Goal:* translate long sentences better.

#### c. The **language complexity** aspect

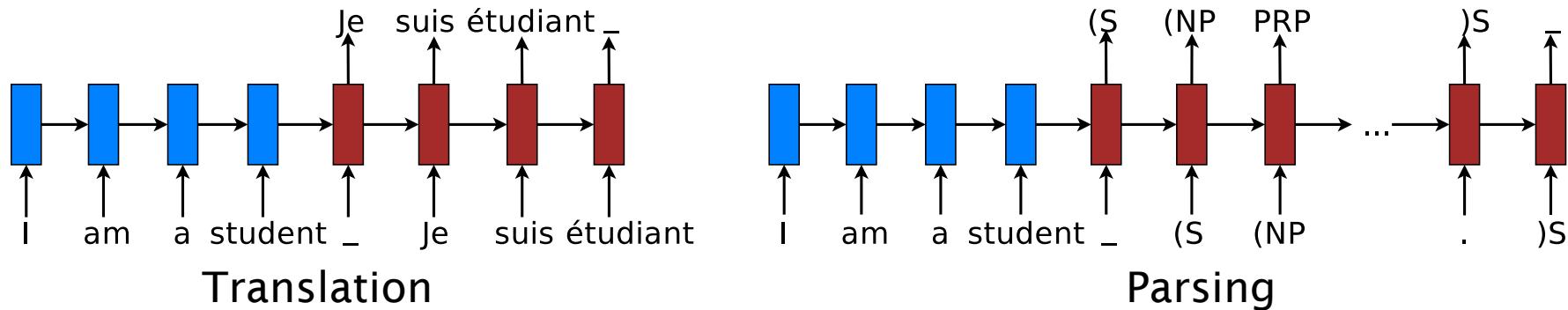
- *Goal:* handle more language variations.

#### d. The **data** aspect

- *Goal:* utilize more data sources.

# Can we utilize other data sources?

- Multi-lingual: learn from many language pairs?
- SMT-inspired: utilize monolingual data?
- Multi-task: combine seq2seq tasks?



# Can we utilize other data sources?

- Multi-lingual: learn from many language pairs?
- **SMT-inspired: utilize monolingual data?**
- Multi-task: combine seq2seq tasks?

More later by Cho!

# Integrating Language Models

- Score interpolation:

$$\log p(\mathbf{y}_t = k) = \log p_{\text{TM}}(\mathbf{y}_t = k) + \beta \log p_{\text{LM}}(\mathbf{y}_t = k)$$

Language model scores  
Hyperparameter

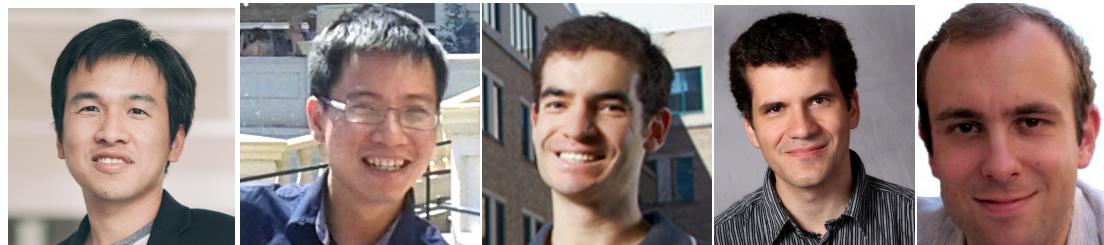
- Deep fusion: combine hidden states instead.
  - Controller learns interpolation weights.
  - Better than *shallow score interpolation*.

Improve low-resource language pairs

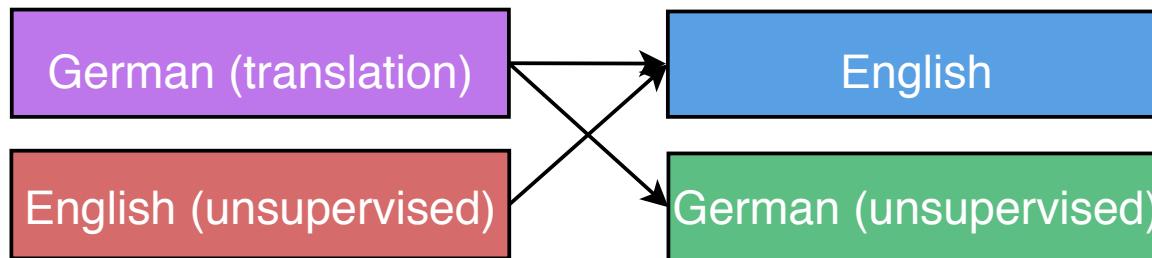
Gulcehre, Firat, Xu, Cho, Barrault, Lin, Bougares, Schwenk, Bengio.

<sup>185</sup>**On Using Monolingual Corpora in Neural Machine Translation.** arXiv 2015.

# Autoencoders



- Shared encoders & decoders: 3 tasks



- Small amount of mono data as regularization.
  - +0.9 BLEU improvements

How to utilize more monolingual data?

*Thang Luong, Quoc Le, Ilya Sutskever, Oriol Vinyals, Lukasz Kaiser.*  
***Multi-task sequence to sequence learning. ICLR 2016.***

# Enriching parallel data



- *Dummy* source sentences

She loves cute cats

Elle aime les chats mignons

(parallel)

<null>

Elle aime les chiens mignons

(mono)

Small gain +0.4-1.0 BLEU.  
Difficult to add more mono data.

# Enriching parallel data



- *Synthetic* source sentences

She loves cute cats

Elle aime les chats mignons

(parallel)

She likes cute cats

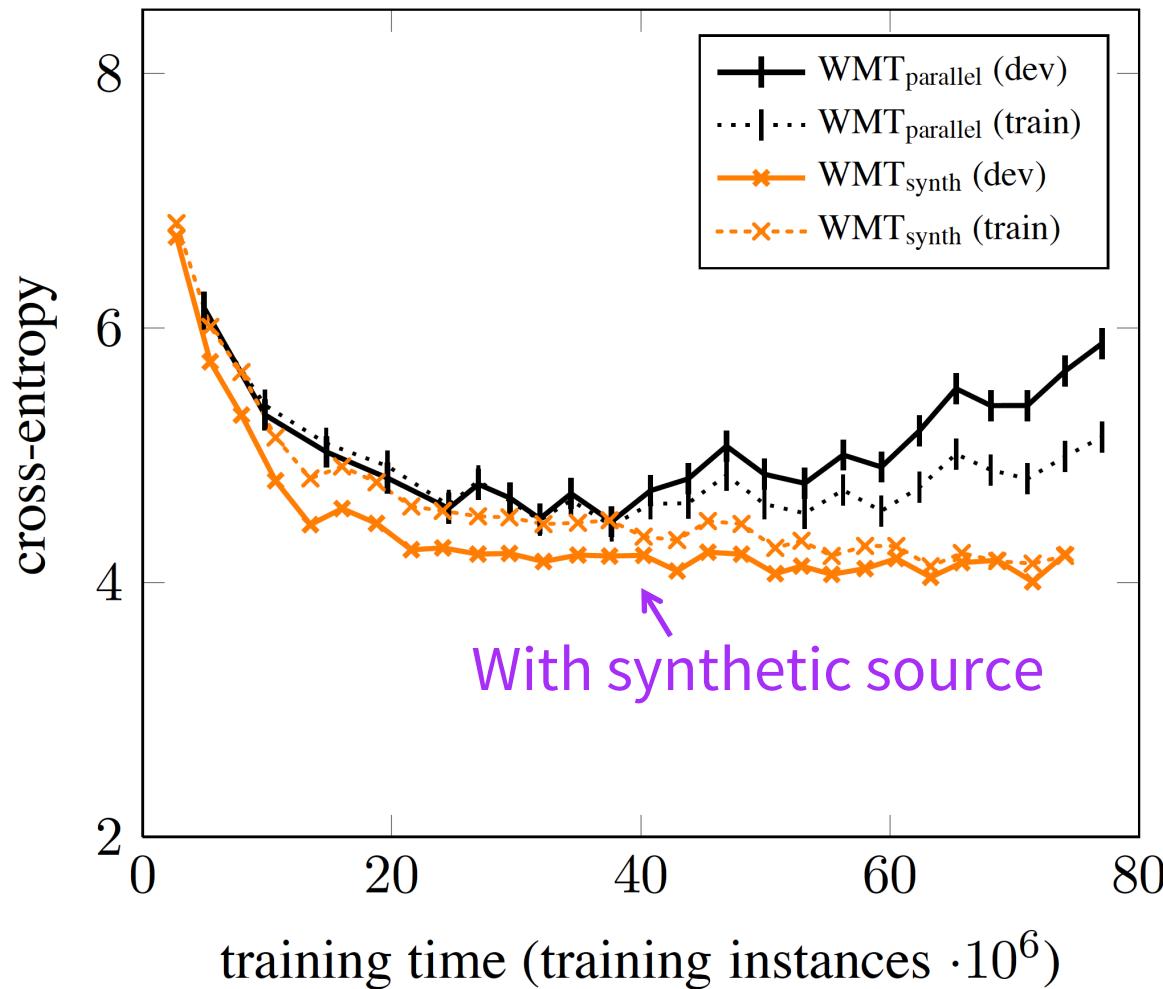
Elle aime les chiens mignons

(mono)

Back translated

Large gain +2.1-3.4 BLEU.

# Prevent Over-fitting



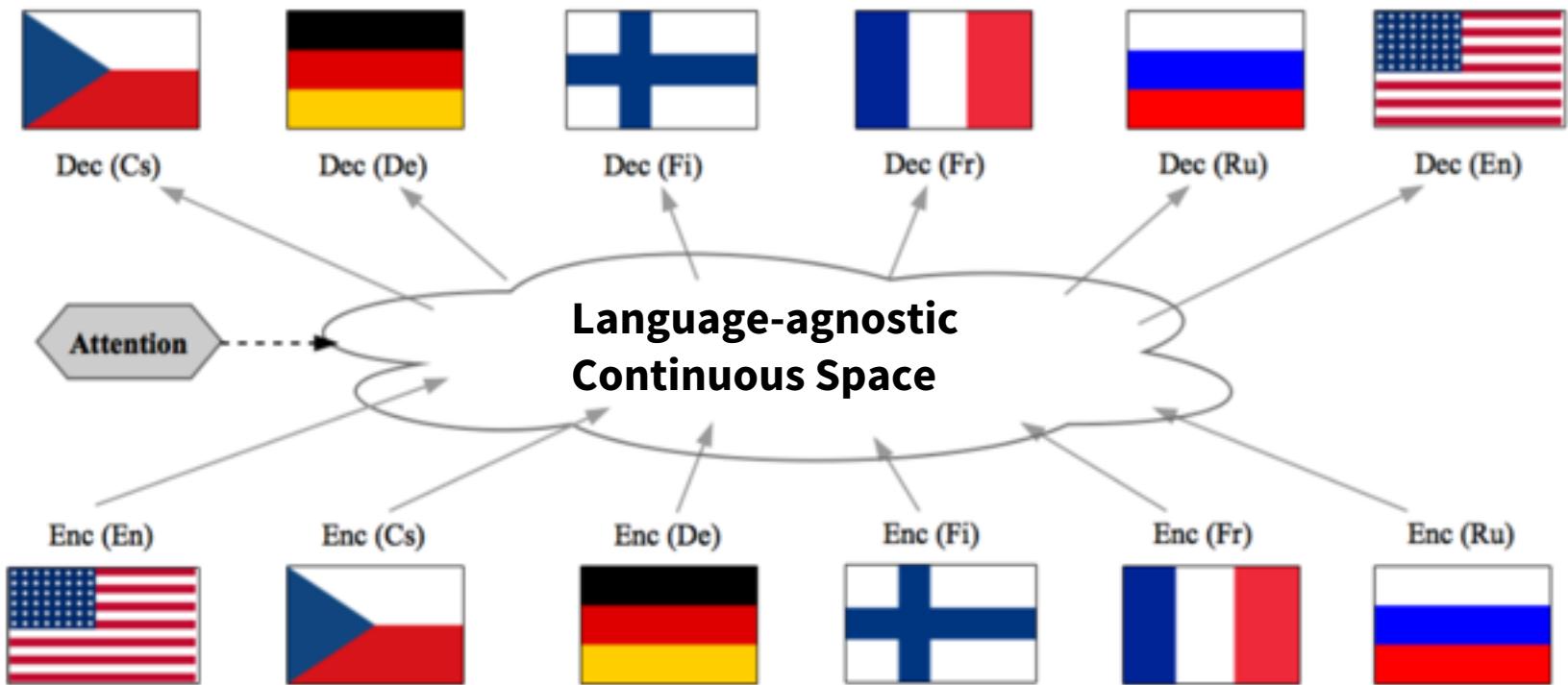
## 4. Future of NMT

- a. Multi-task learning
- b. Larger context
- c. Mobile devices
- d. Beyond Maximum Likelihood Estimation

## 4. Future of NMT

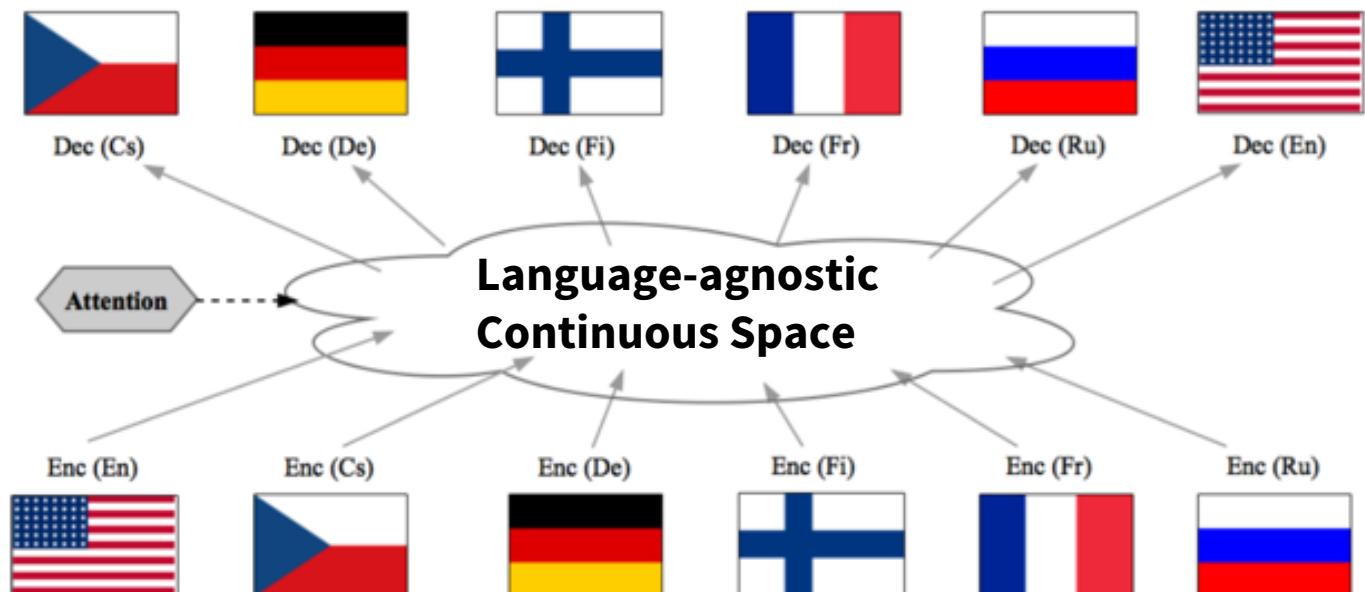
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# Multilingual Translation

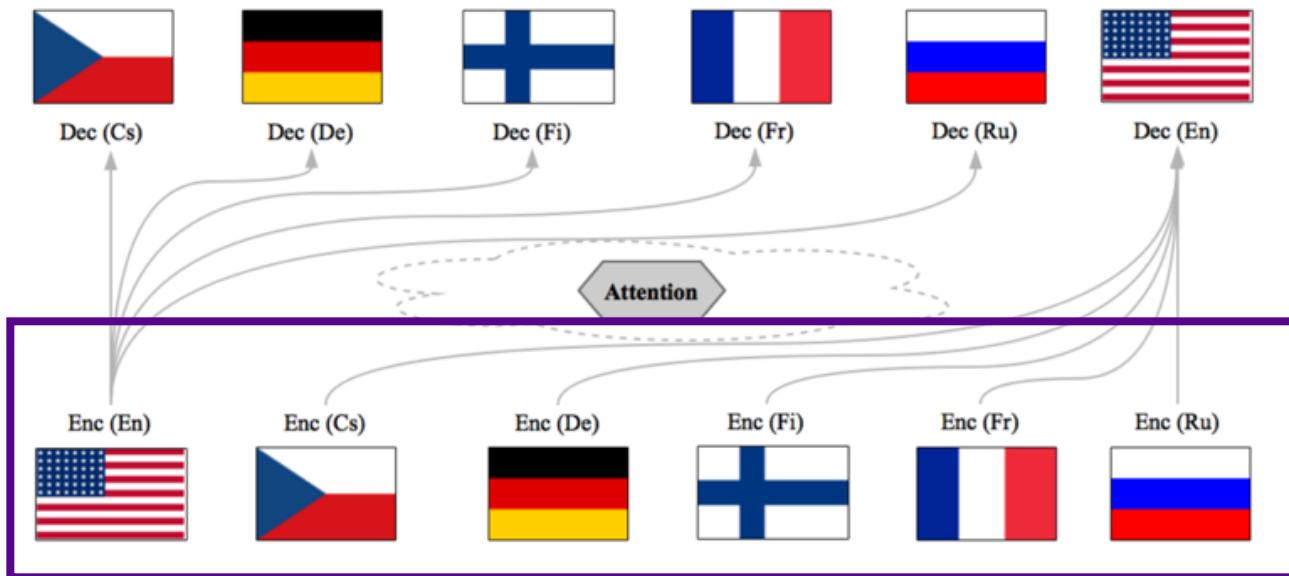


# Multilingual Translation: Expectations

1. Positive language transfer
2. # of parameters grows linearly w.r.t. # of languages
3. Multi-source translation [Zoph&Knight, NAACL2016]

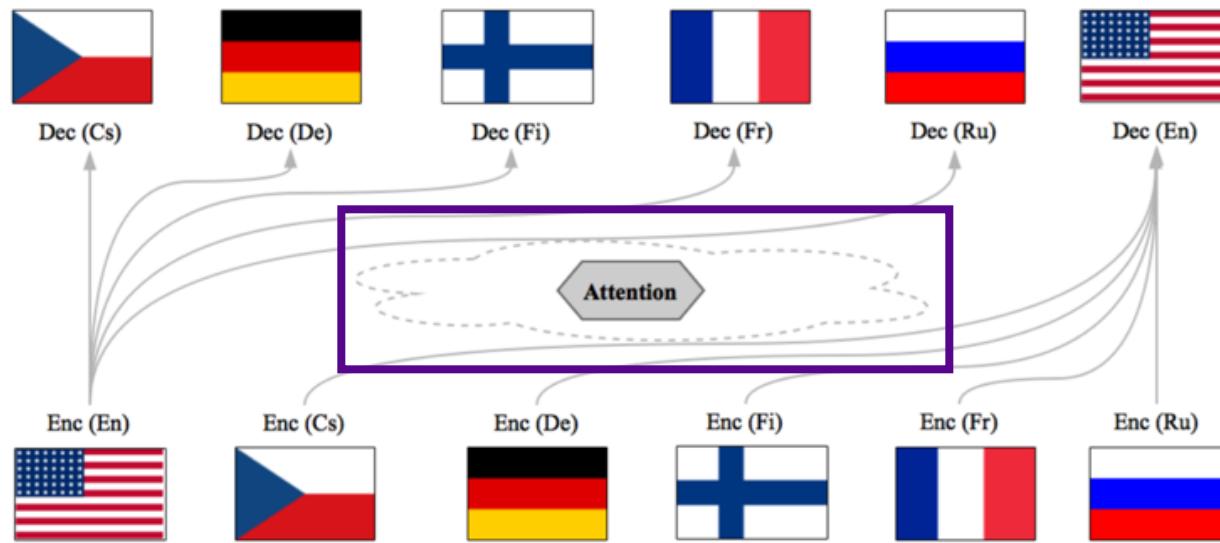


# Multilingual Translation with Shared Alignment



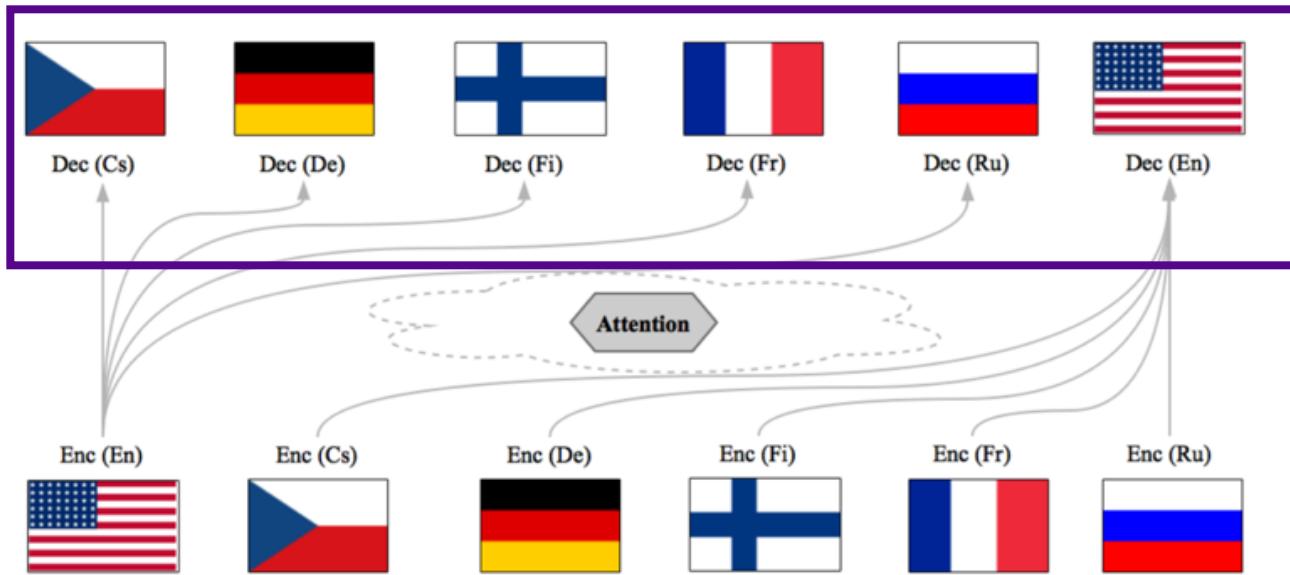
- Encoder *per* source language
  - Seq. of source symbols → Seq. of context vectors

# Multilingual Translation with Shared Alignment



- *Shared Attention Mechanism*
  - Target hidden state, source context vector  
→ Attention weight

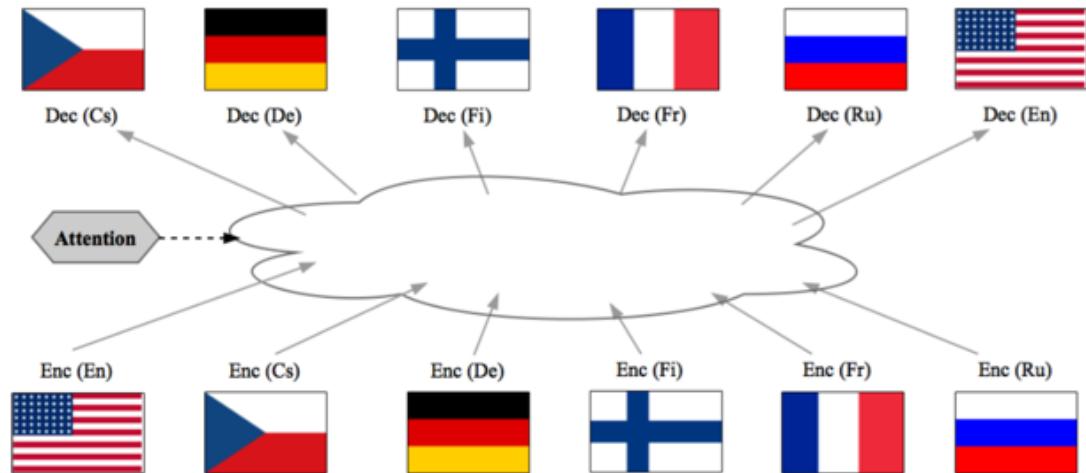
# Multilingual Translation with Shared Alignment



- Decoder *per* target language
  - Aligned context vector → Target symbol

# Multilingual Translation: Training

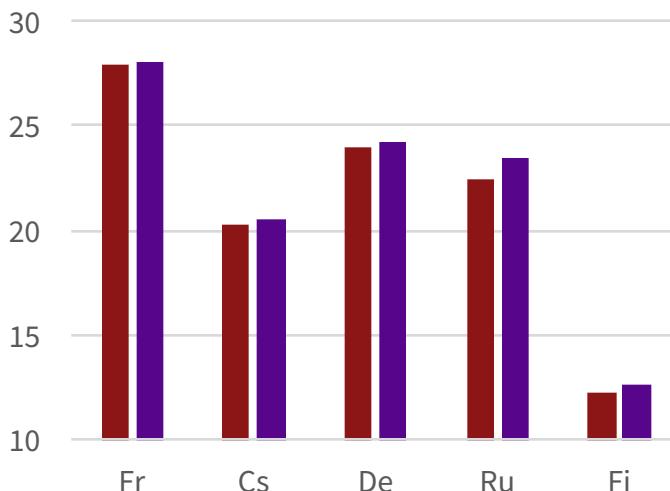
- No multi-way parallel corpus assumed
  - Bilingual sentence pairs only
  - Each sentence pair activates/updates one encoder, decoder and shared attention



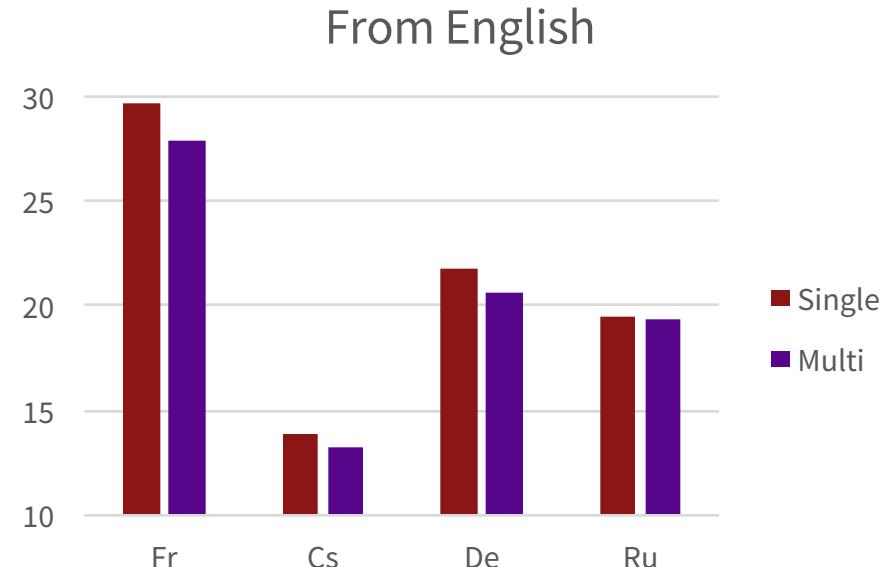
# Multilingual Translation: First Result

- 10 language pair-directions
  - $\text{En} \rightarrow \{\text{Fr}, \text{Cs}, \text{De}, \text{Ru}, \text{Fi}\} + \{\text{Fr}, \text{Cs}, \text{De}, \text{Ru}, \text{Fi}\} \rightarrow \text{En}$
- 60+ million bilingual sentence pairs
- *Comparable to 10 single-pair models*

To English



From English



# Multilingual Translation: Looking Ahead

- Low-resource translation
  - Positive language transfer from high-resource to low-resource language pair-directions

		# Symbols		# Sentence		
		# En	Other	Train	Dev	Test
	En-Uz	1.361m	1.186m	73.66k	948	882
	En-Es	908.1m	924.9m	34.71m	3003	3000
	En-Fr	1.837b	1.911b	65.77m	3003	3000

# Multilingual Translation: Looking Ahead

- Low-resource translation: Example

Uz-En: 6.45

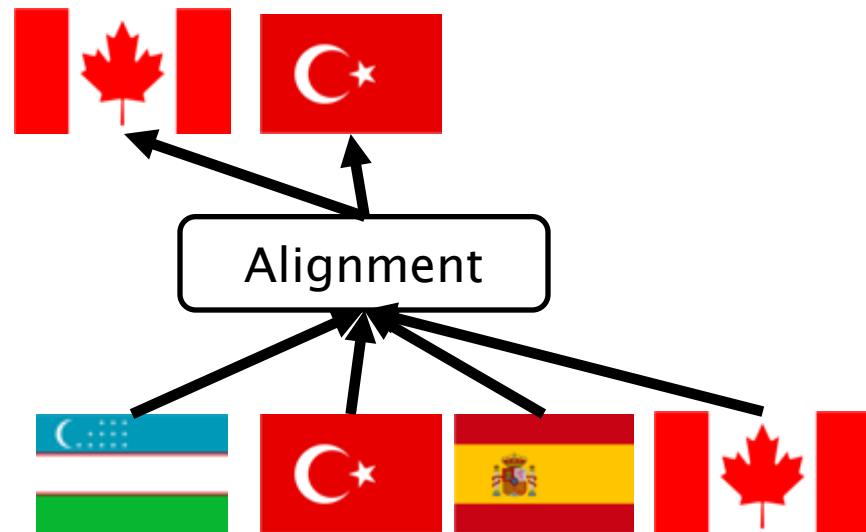
Uz-En + Tr-En: 9.34

Uz-En + Tr-En + Es-En: 10.34

Uz-En + Tr-En + Es-En + En-Tr: 9.41

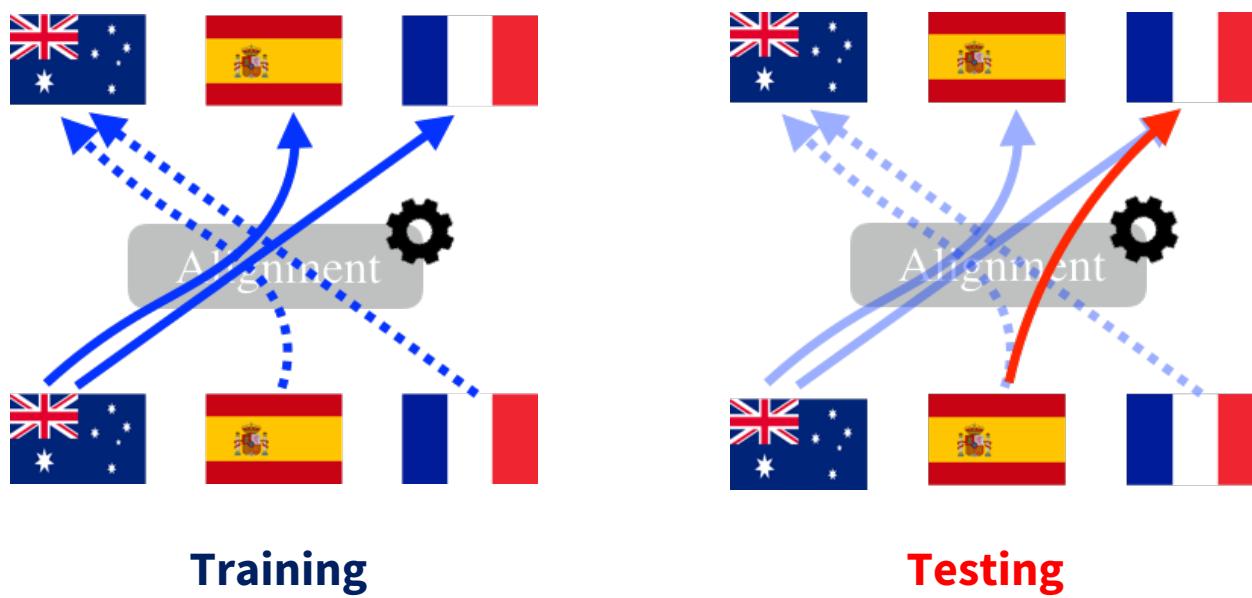
Ensemble: 12.99

- 3x Uz-En + Tr-En + Es-En
- 3x Uz-En + Tr-En + Es-En + En-Tr



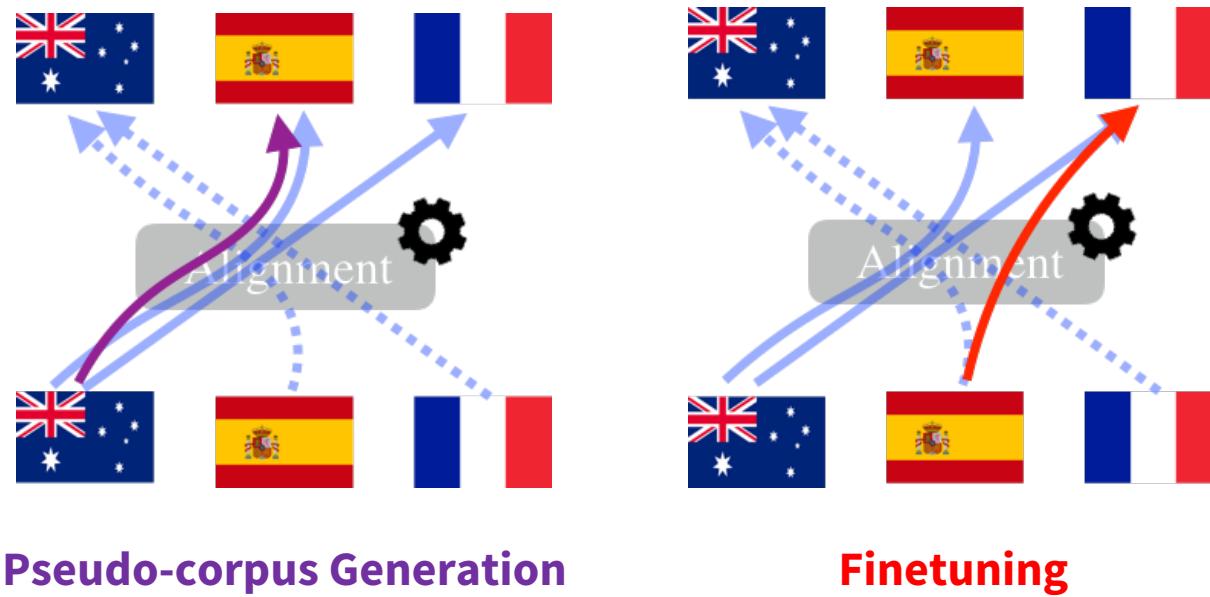
# Multilingual Translation: Looking Ahead

- Zero-resource translation
  - Translation without any direct parallel resource



# Multilingual Translation: Looking Ahead

- Zero-resource translation
  - Finetuning with *pseudo*-parallel corpus  
[Sennrich et al., ACL2016]
  - Closely related to unsupervised learning



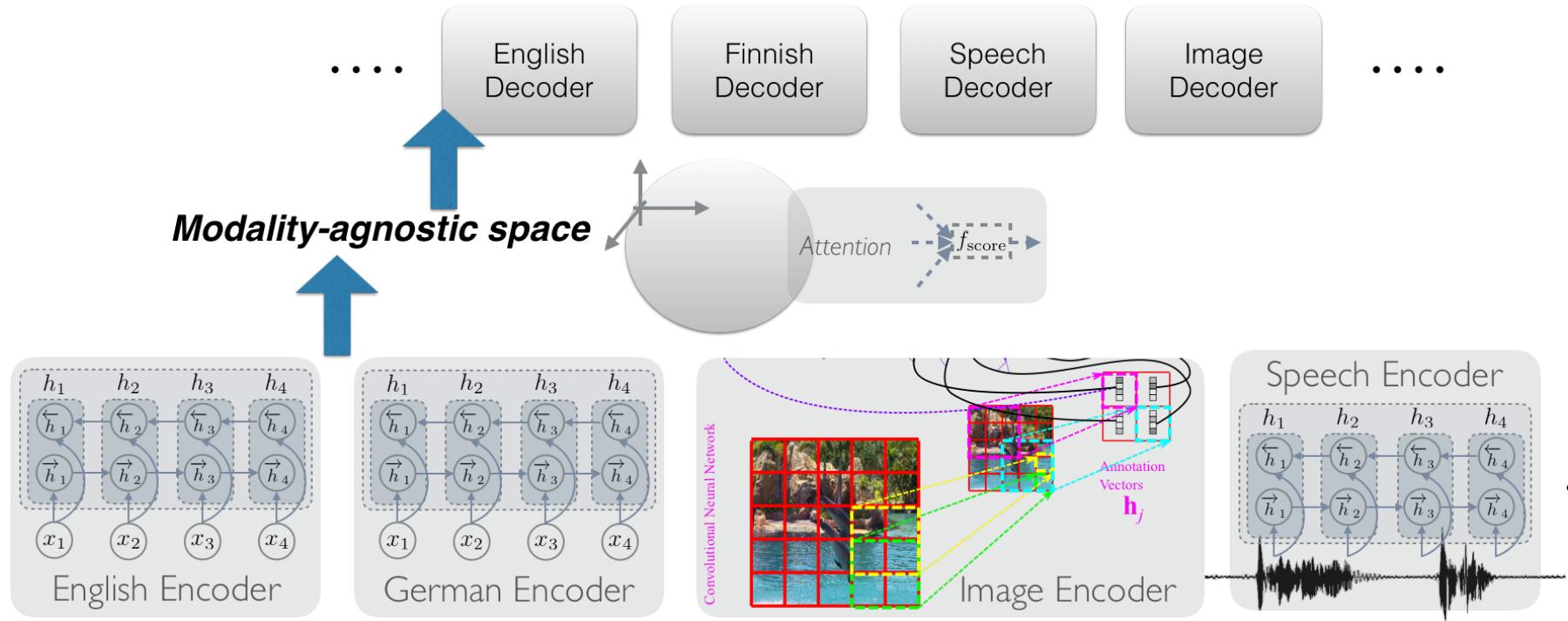
# Multilingual Translation: Looking Ahead

- Zero-resource translation
  - Some initial result, but long way to go...

Pivot	Many-to-1	Pseudo Parallel Corpus				True Parallel Corpus				
		1k	10k	100k	1m	1k	10k	100k	1m	
✓	No Finetuning	Dev: 20.64, Test 20.4				–				
✓	Early	Dev	0.28	10.16	15.61	17.59	0.1	8.45	16.2	20.59
		Test	0.47	10.14	15.41	17.61	0.12	8.18	15.8	19.97
✓	Early+ Late	Dev	19.42	21.08	21.7	21.81	8.89	16.89	20.77	22.08
		Test	19.43	20.72	21.23	21.46	9.77	16.61	20.40	21.7

# Multilingual Translation: Looking Ahead

- Multi-modal, Multitask Translation  
[Luong et al., ICLR2016; Caglayan et al., WMT2016]



## 4. Future of NMT

- a. Multi-task learning
- b. Larger context
- c. Mobile devices
- d. Beyond Maximum Likelihood Estimation

# Larger-context NMT



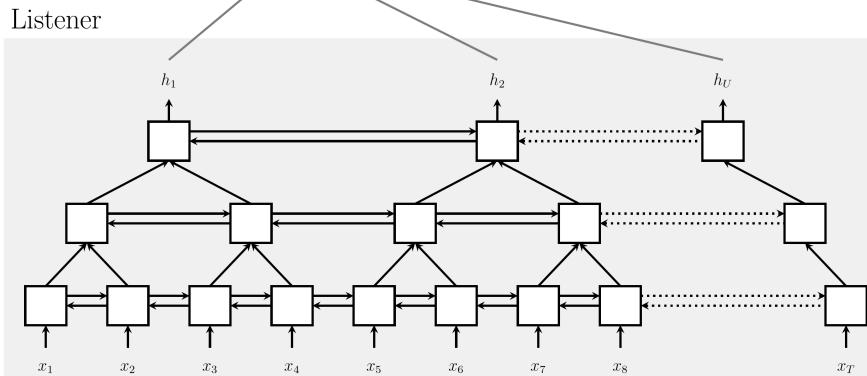
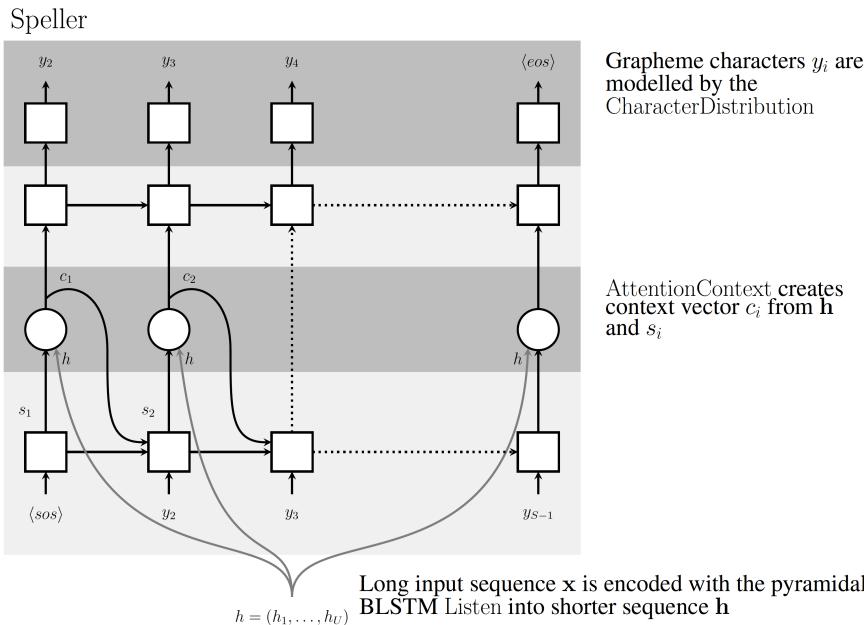
- Beyond sentence level:
  - Paragraphs, articles, books, etc.
- Challenges?
  - Extremely long sequences.
  - Maintain across sentences:
    - Coherent style
    - Discourse structure

# ***Solution: Hierarchical architectures?***

- Effective attention mechanism for long sequences

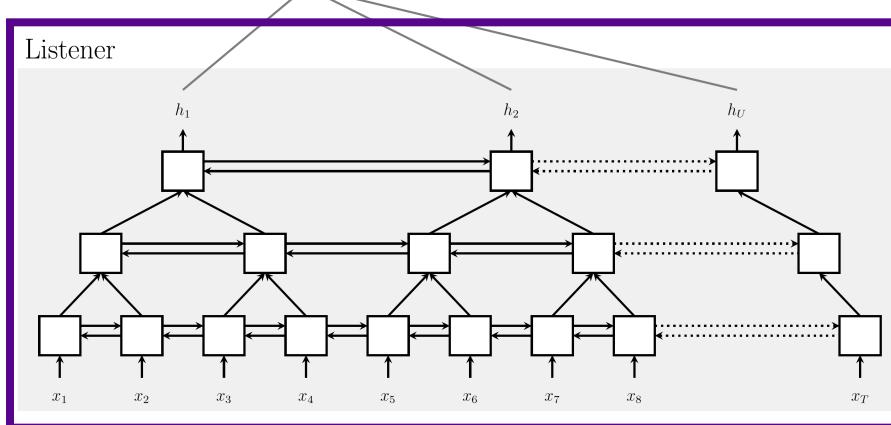
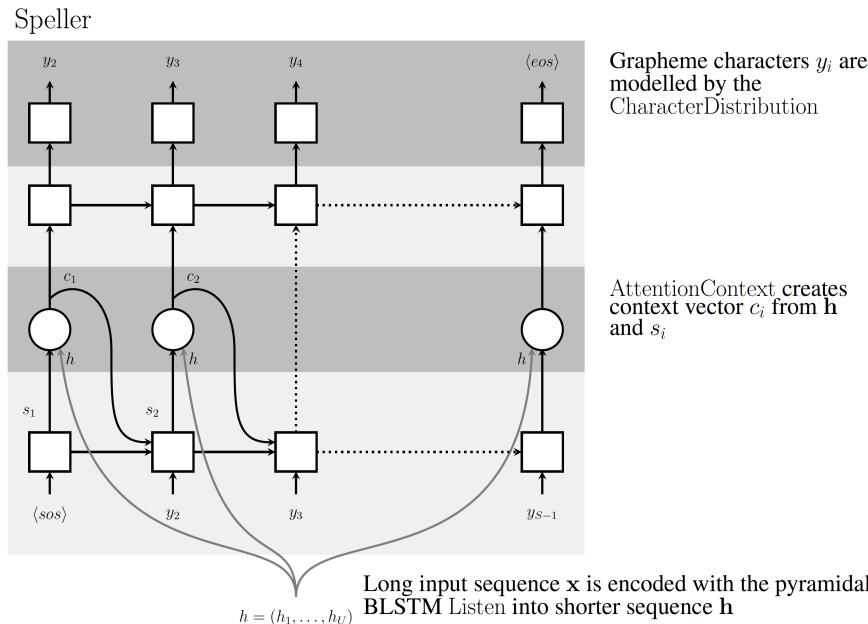
# Solution: Hierarchical architectures?

- Speech recognition [Chan, Jaity, Le, Vinyals, ICASSP'15].

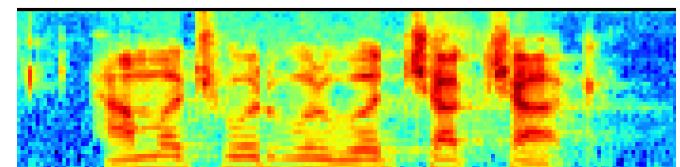


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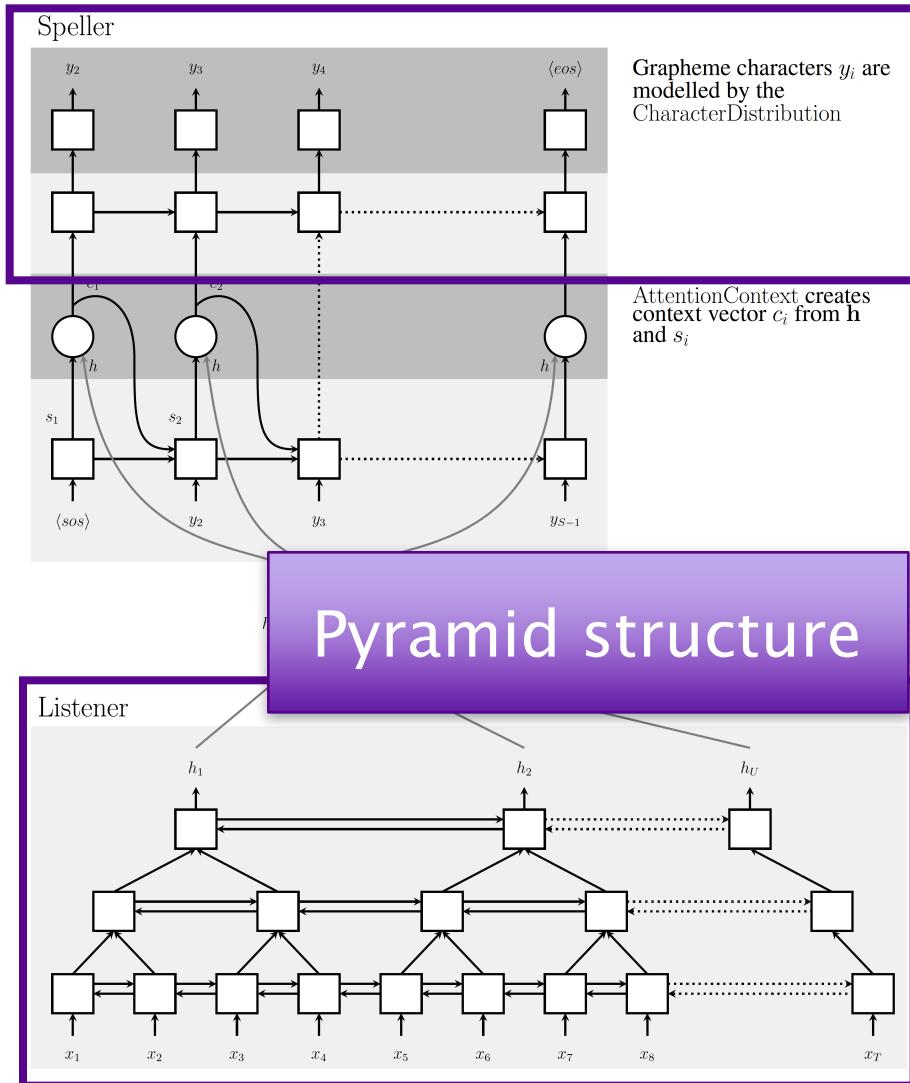


Speech signals:  
thousands of frames



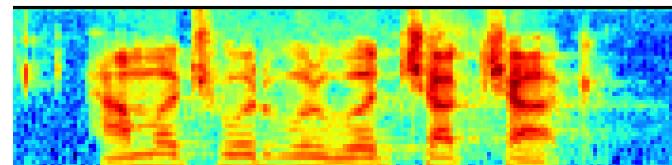
# Solution: Hierarchical architectures?

- Speech recognition [Chan, Jaity, Le, Vinyals, ICASSP'15].



Speech transcription:  
“*how much would a  
woodchuck chuck*”

Speech signals:  
thousands of frames

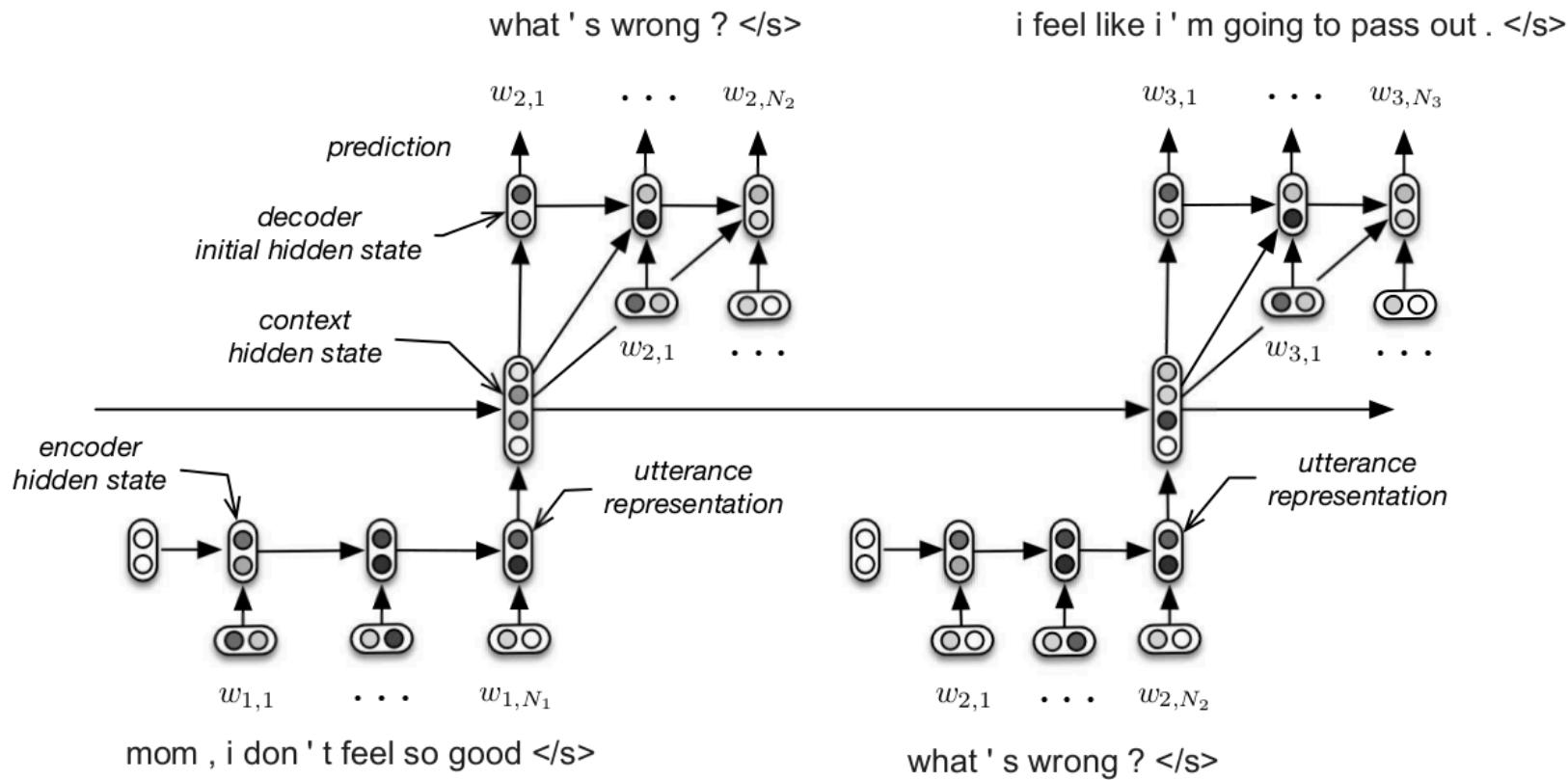


# **Solution: Hierarchical architectures?**

- Effective attention mechanism for long sequences
  - Speech recognition [Chan, Jaity, Le, Vinyals, ICASSP'15].
- Tracking states over time

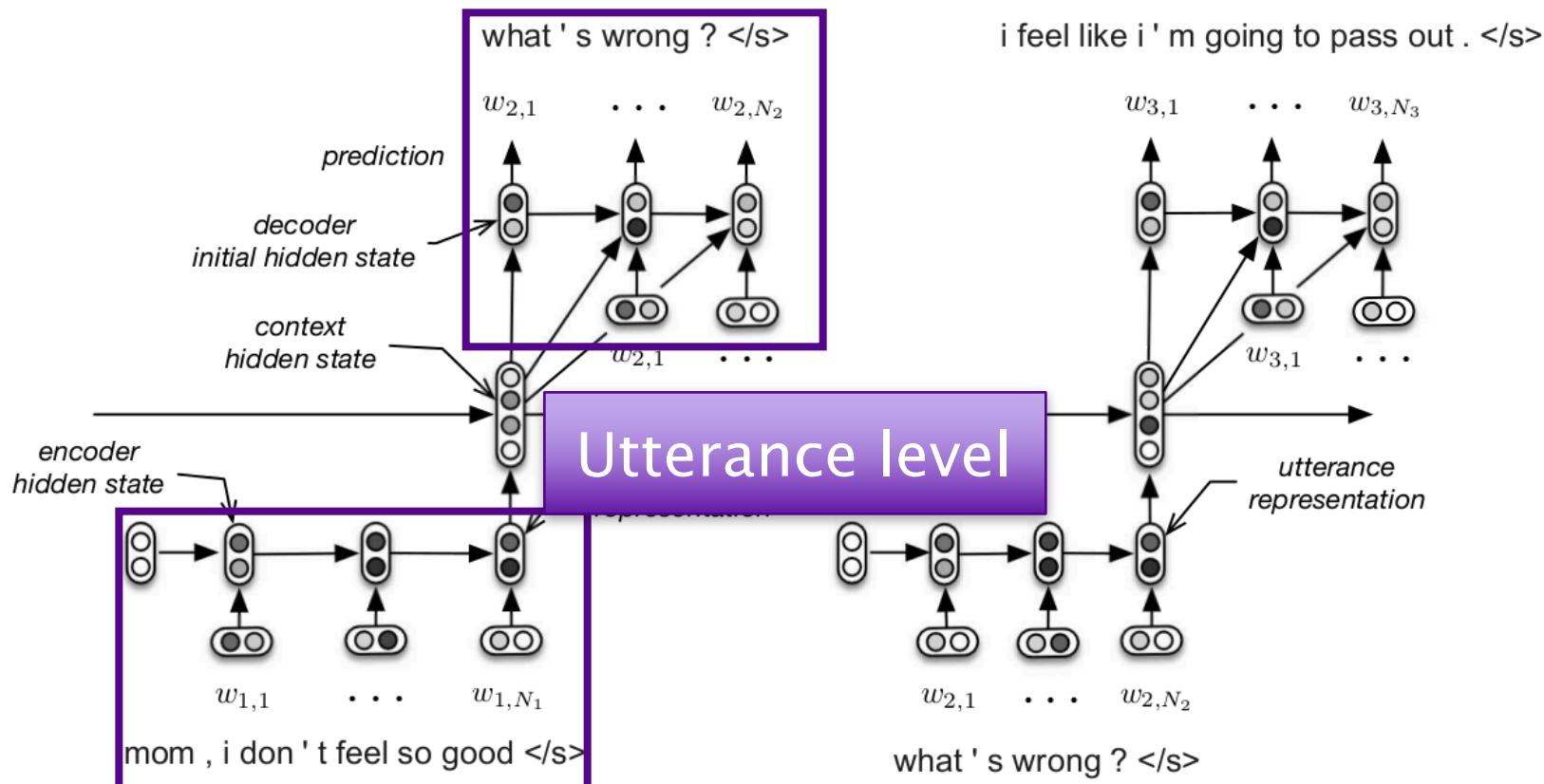
# Solution: Hierarchical architectures?

- Dialogue systems [Serban, Sordoni, Bengio, Courville, Pineau , AAAI'15].



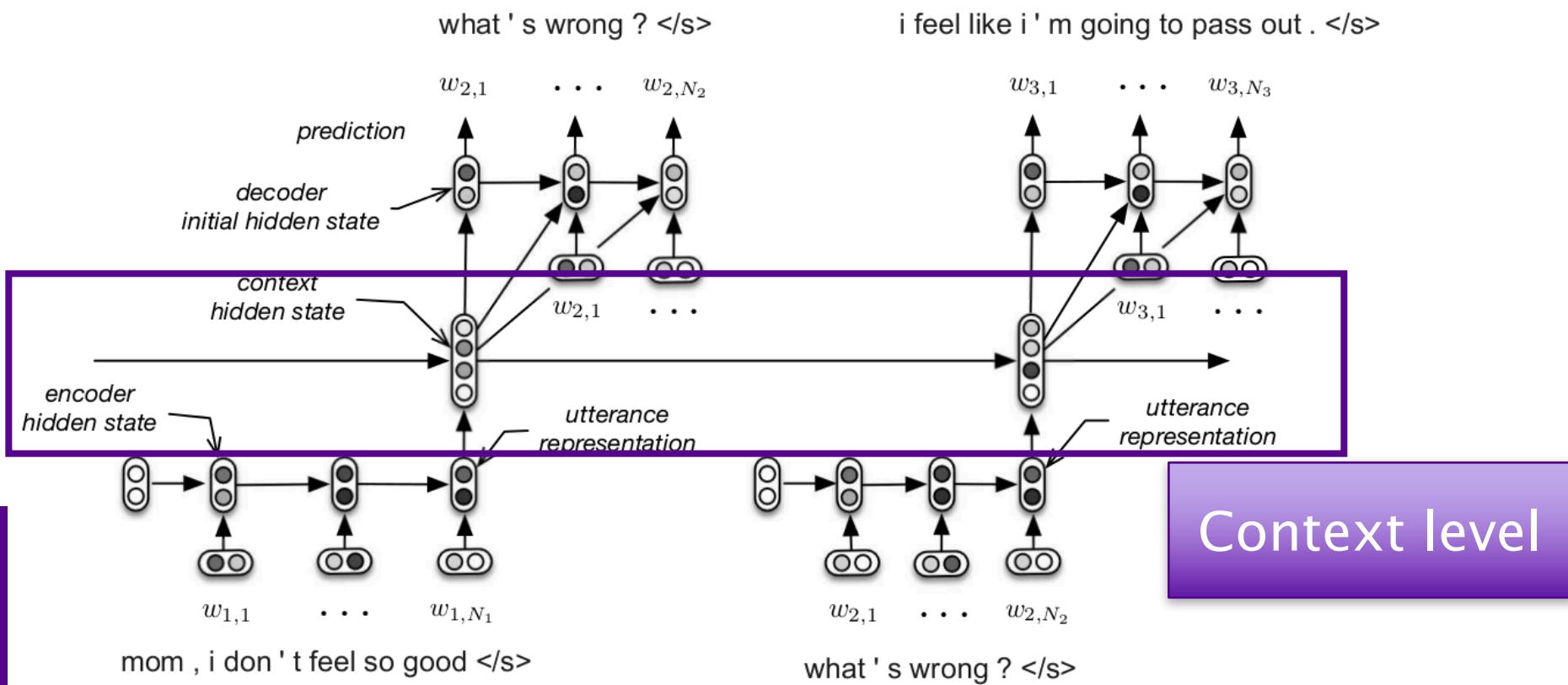
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# Solution: Hierarchical architectures

- Dialogue systems [Serban, Sordoni, Bengio, Courville, Pineau , AAAI'15].



# **Solution: Hierarchical architectures?**

- Effective attention mechanism for long sequences
  - Speech recognition [Chan, Jaity, Le, Vinyals, ICASSP'15].
- Tracking states over many sentences
  - Dialogue systems [Serban, Sordoni, Bengio, Courville, Pineau , AAAI'15].



What else?

## 4. Future of NMT

- a. Multi-task learning
- b. Larger context
- c. Mobile devices
- d. Beyond Maximum Likelihood Estimation

# Mobile devices



INDEPENDENT

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## There are officially more mobile devices than people in the world

The world is home to 7.2 billion gadgets, and they're multiplying five times faster than we are

- NMT has **small memory footprint**:
  - No gigantic phrase tables & LMs compared to SMT.
- Still, require **large NNs** for SOTA results

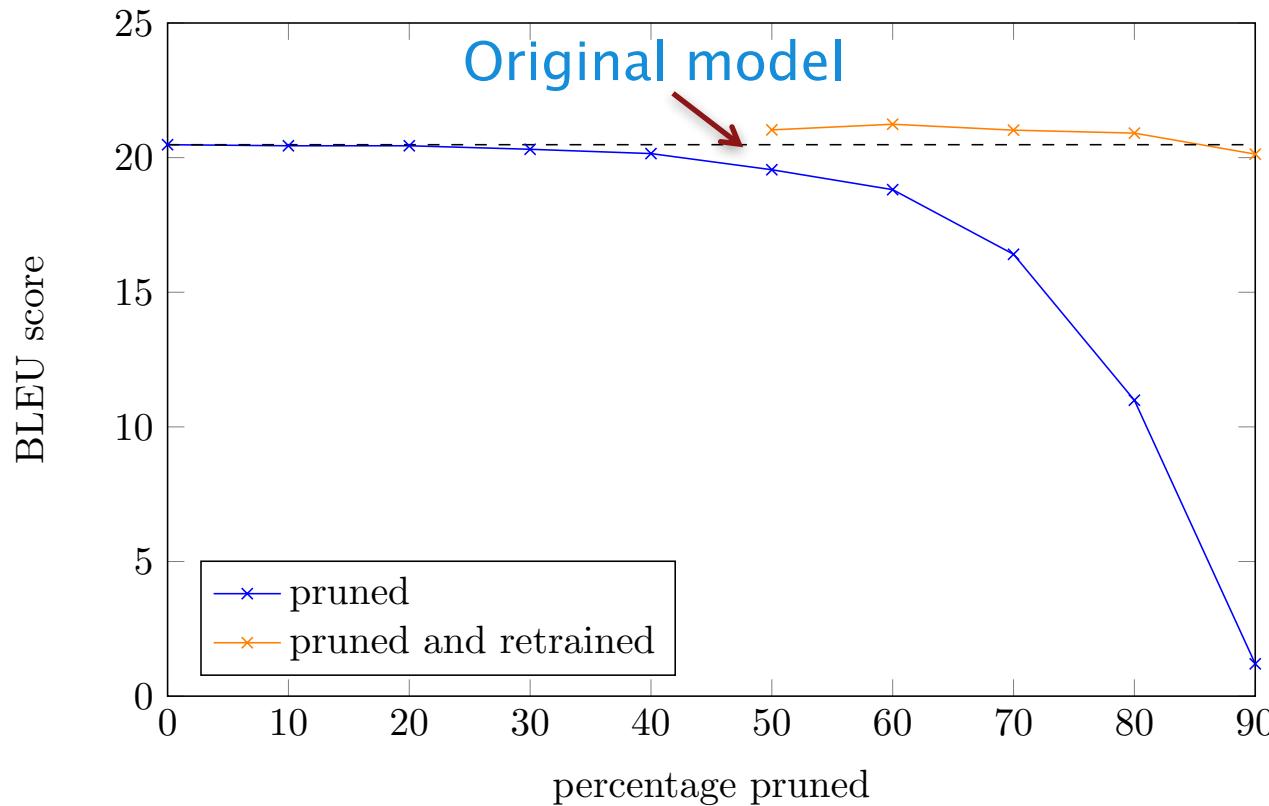


Can we address this?

# Model Pruning



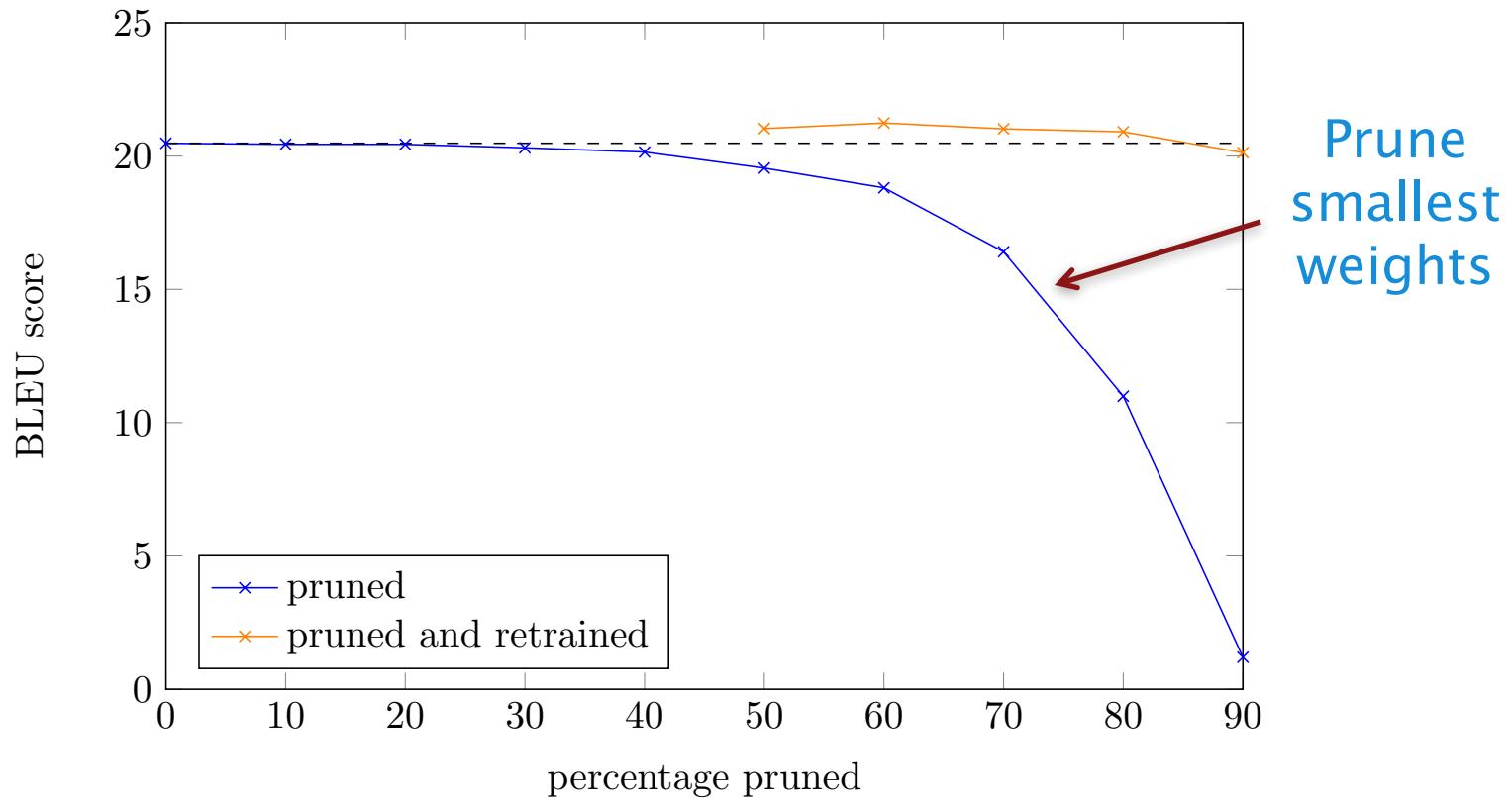
- Explore the redundancy structure in NMT



# Model Pruning



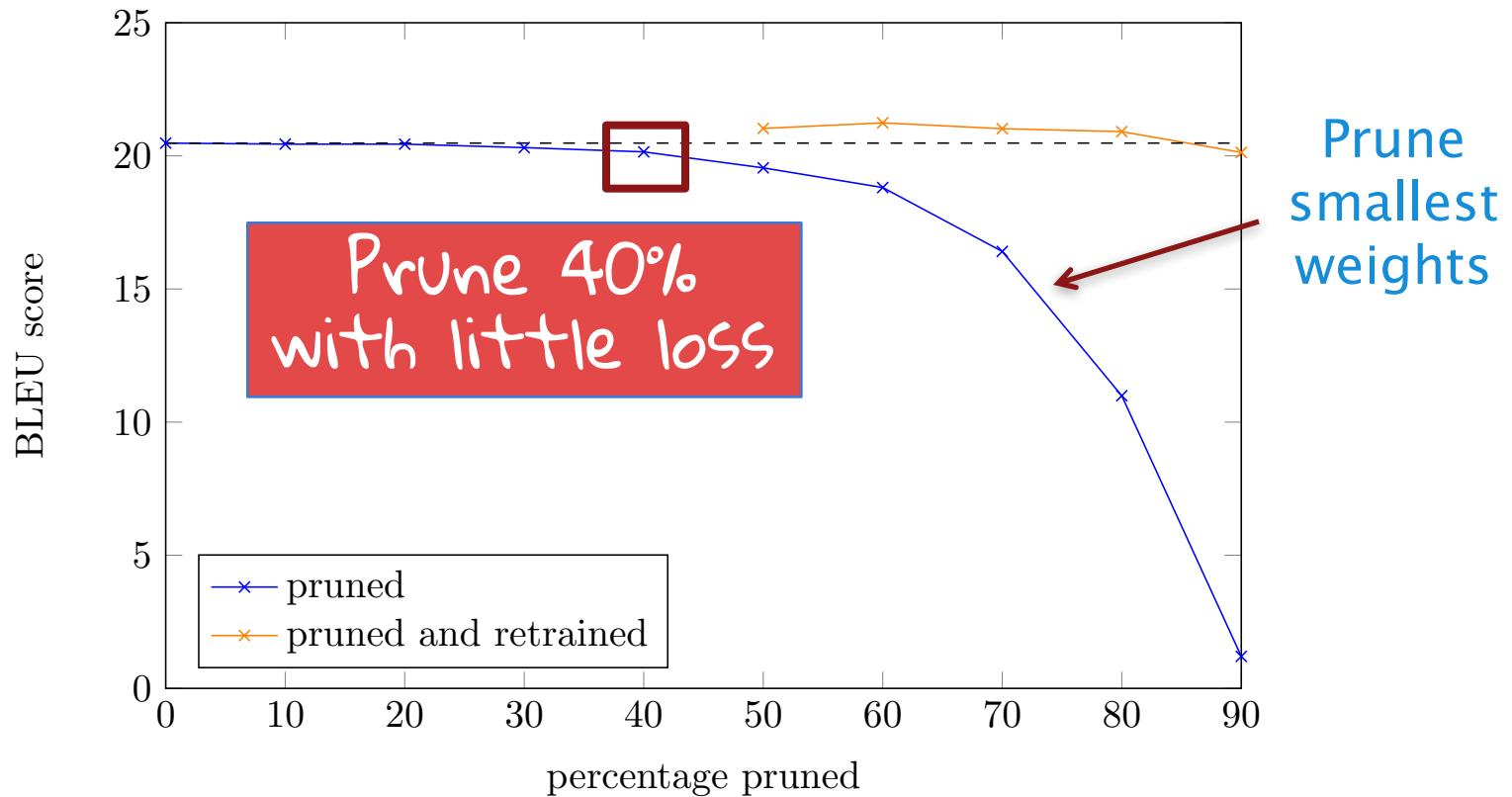
- NMT redundancy via **pruning & retraining**:



# Model Pruning



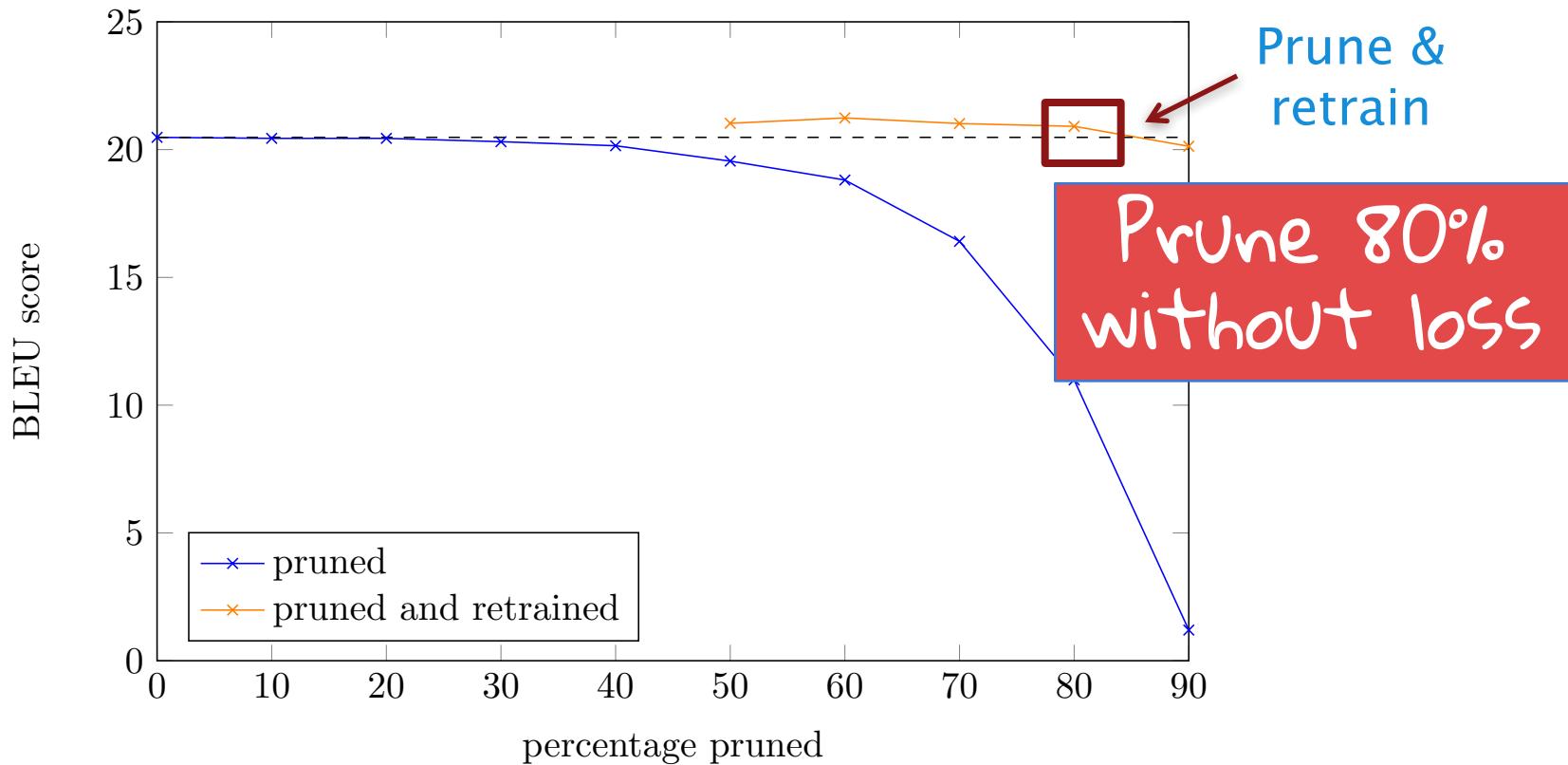
- NMT redundancy via pruning & retraining:



# Model Pruning



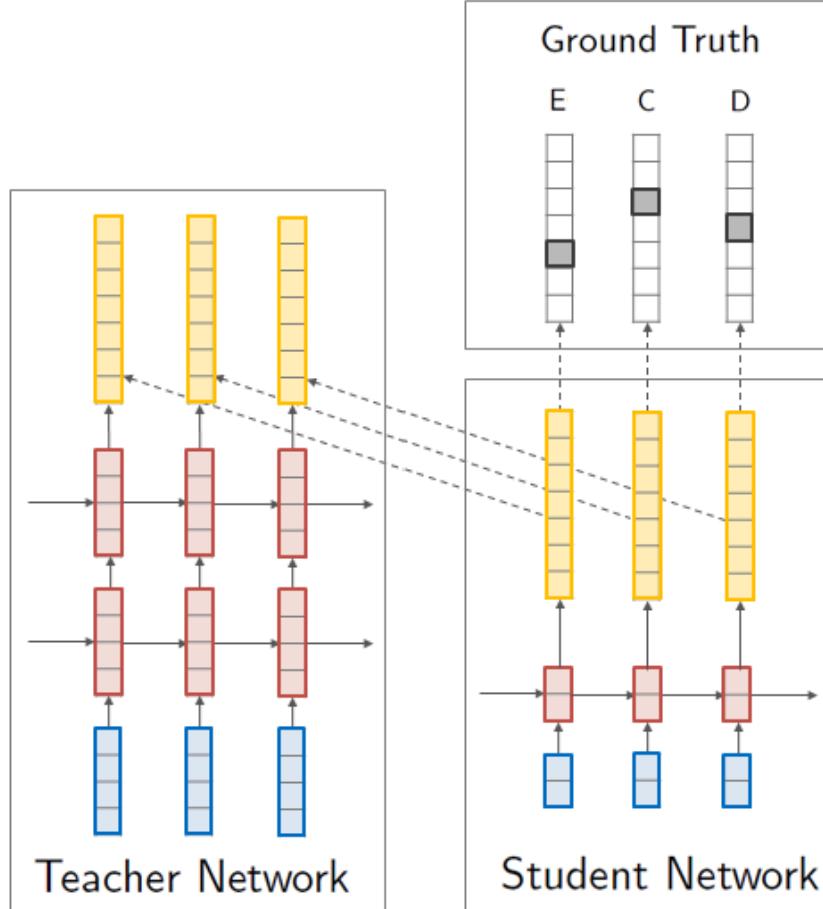
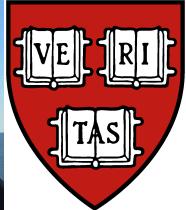
- NMT redundancy via **pruning & retraining**:



# **It was just a baby!**

Next, really putting NMT  
onto mobile devices!

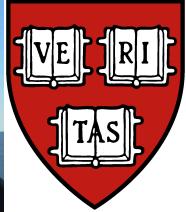
# Knowledge Distillation



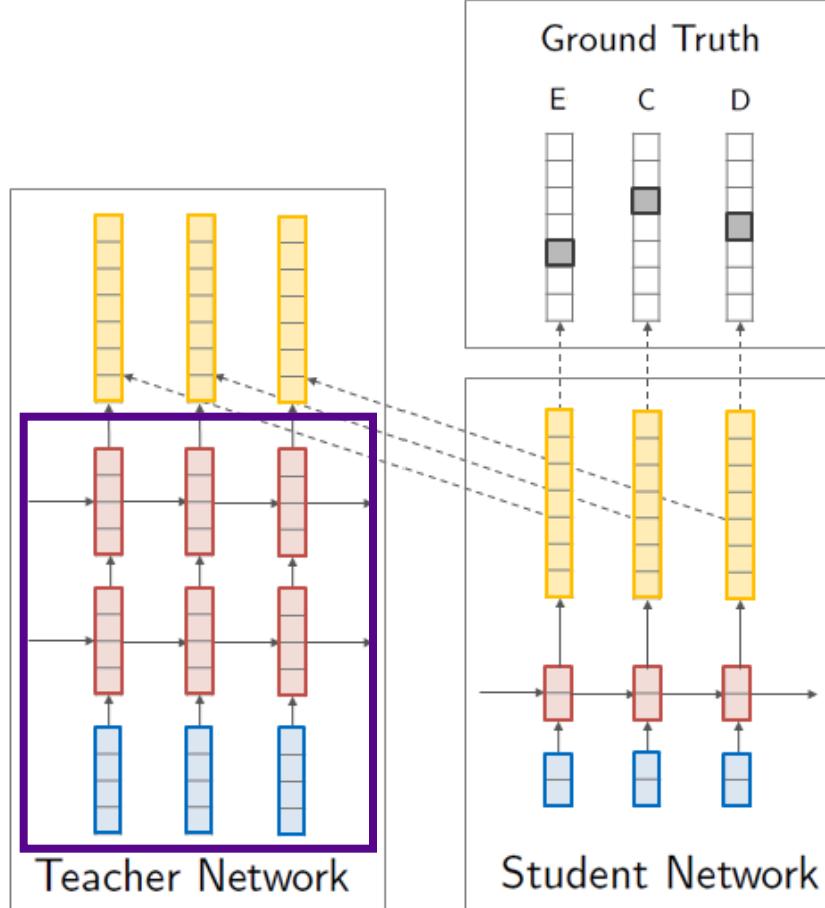
Yoon Kim, Alexander M. Rush.

**Sequence-level knowledge distillation.** EMNLP'16.

# Knowledge Distillation



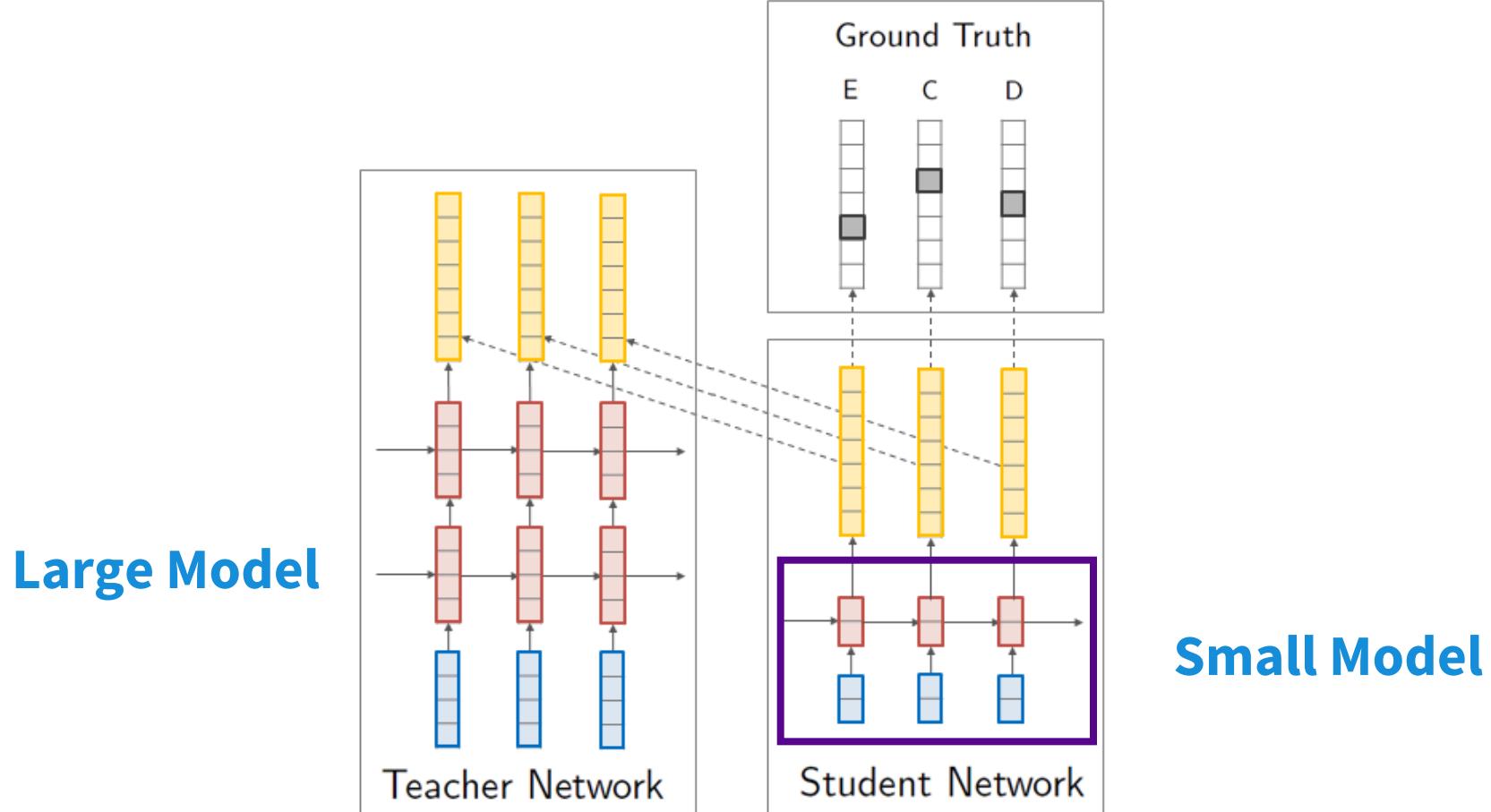
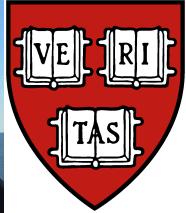
Large Model



Yoon Kim, Alexander M. Rush.

***Sequence-level knowledge distillation. EMNLP'16.***

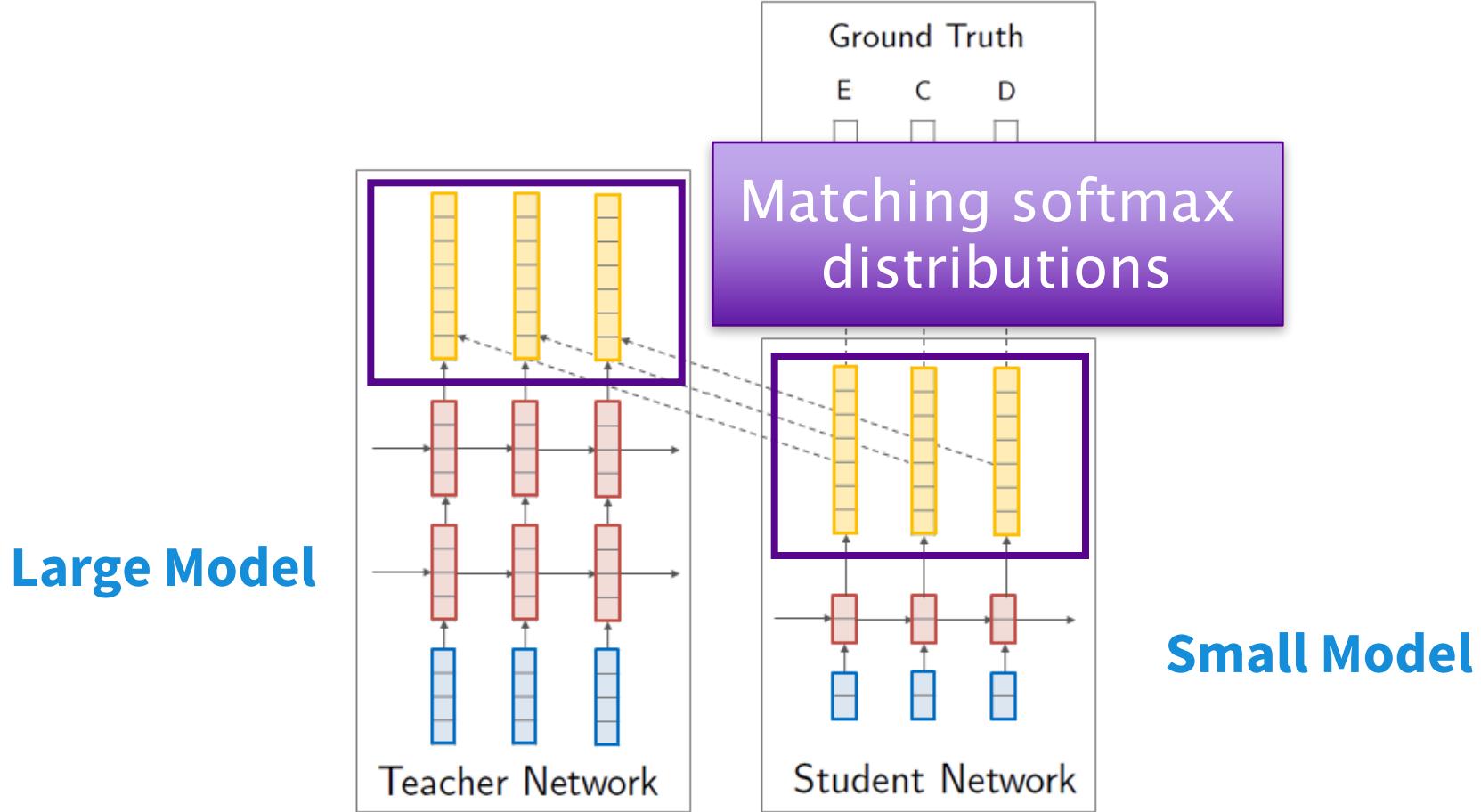
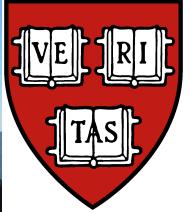
# Knowledge Distillation



Yoon Kim, Alexander M. Rush.

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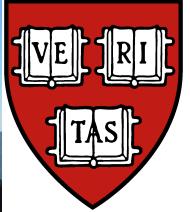
# Knowledge Distillation



Yoon Kim, Alexander M. Rush.

***Sequence-level knowledge distillation. EMNLP'16.***

# Knowledge Distillation



- Sequence-level knowledge distillation:
  - Match the final distribution over sequences
  - Beam search to create new training data
- Student model: no need beam search.

10 times faster with only 0.2 BLEU loss!

<https://github.com/harvardsnlp/nmt-android>

Yoon Kim, Alexander M. Rush.

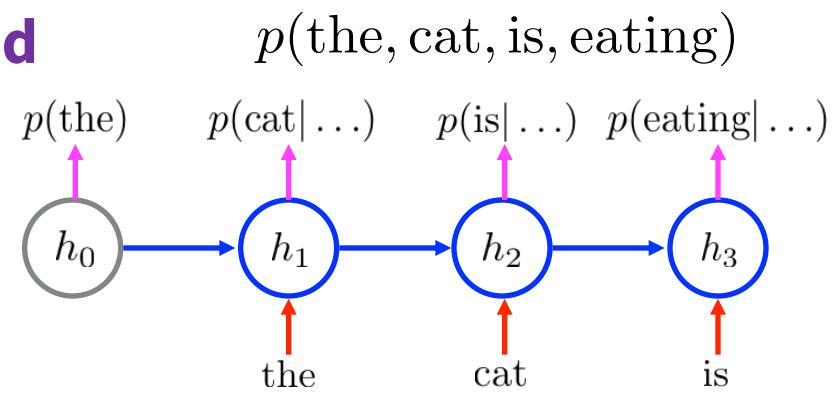
**Sequence-level knowledge distillation.** EMNLP'16.

## 4. Future of NMT

- a. Multi-task learning
- b. Larger context
- c. Mobile devices
- d. Beyond Maximum Likelihood Estimation

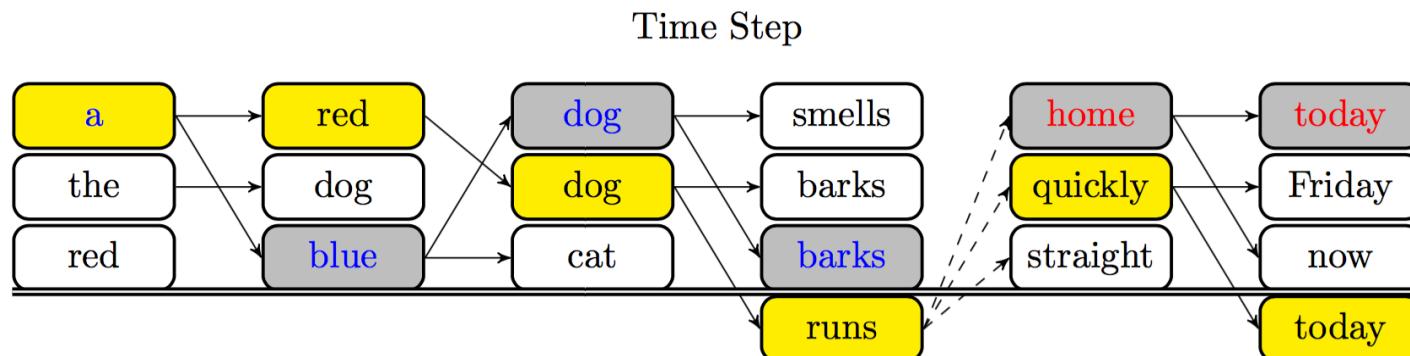
# Maximum Likelihood Estimation for Sequence Modelling

- Given a ground-truth trajectory, maximize the predictability of a next action:  $\max \log p(x_t | x_{<t})$
- Maximum (log-)likelihood estimation
- Two issues
  - Weak correlation with a true reward
  - Mismatch between training and inference**



# Beyond Maximum Likelihood

- Maximize the sequence-wise global loss
- Incorporate inference into training
  - Stochastic inference
    - Policy gradient [Ranzato et al., ICLR2016; Bahdanau et al., arXiv2016]
    - Minimum risk training [Shen et al., ACL2016]
  - Deterministic inference
    - Learning to search [Wiseman & Rush, arXiv2016]



# What have we learnt today?

1. History of MT and where Neural MT fits in
2. Language modelling & Neural Machine Translation
  - a. Feedforward and recurrent language models
  - b. Recurrent neural network and its learning
  - c. Conditional language model: learning and decoding
3. Advanced Neural machine translation
  - a. Scaling softmax and copy mechanism
  - b. Attention-based models
  - c. Subword-level translation
  - d. Incorporating monolingual corpora
4. And, the future!

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



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