CSCI 544: Applied Natural Language Processing

Seq2seq Generation & Neural Machine Translation

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Course Organization

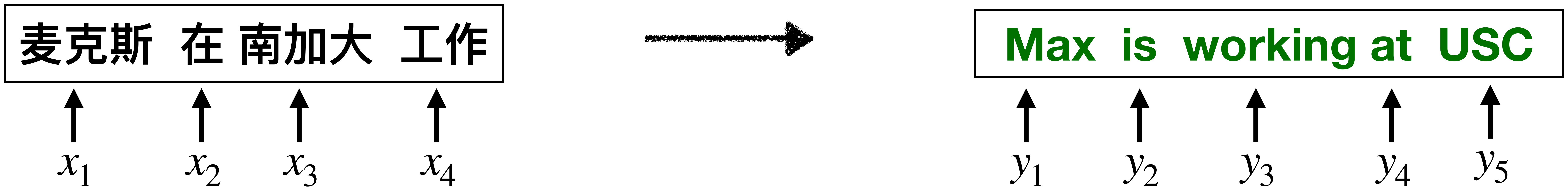
NLP Tasks

Models

Text Classification	Sequence Labeling	Syntactic Parsing	Seq2seq & MT	Language Modeling & Generation
Naive Bayes Logistic Regression SVM …	HMMs MEMMs CRFs	Tree-structured Models/Algorithms	……	……
Word Embedding & Neural Networks	RNN LSTM	Neural Structured Networks	Attention & Transformers	Generative Models & LLMs

Seq2seq Generation

- **Sequence-to-Sequence (Seq2seq) Generation**
  - Input: $X = \{x_1, x_2, \ldots, x_L\}, x_i \in \mathcal{X}$
  - Output: $Y = \{y_1, y_2, \ldots, y_T\}, y_i \in \mathcal{Y}$
  - Model: $p_\theta(Y|X)$



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Input X	Output Y (**Text**)	Task
English	Japanese	Translation
Document	Short Description	Summarization
Utterance	Response	Response Generation
Image	Text	Image Captioning
Speech	Transcript	Speech Recognition

Seq2seq Generation

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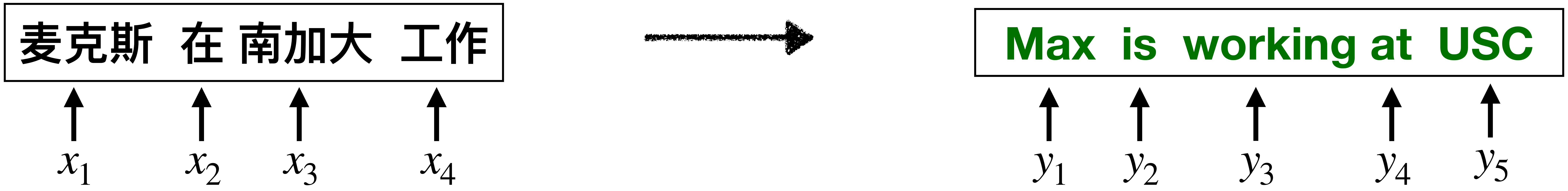
  - Model: $p_\theta(Y|X)$ **How?**
- **Difference from Sequence Labeling**
  - The length of Y can be different from the length of X
  - The size of $\mathcal{Y}$ is often much larger



Statistic Machine Translation

Statistical Machine Translation

- **IBM Translation Models**
  - Word-level alignment model
  - EM algorithm
- **Phrase-based Translation Models**
  - Phrase-based alignment model
- **Heavy Engineering**
  - Moses system
  - 360 pages manual

Statistical Machine Translation

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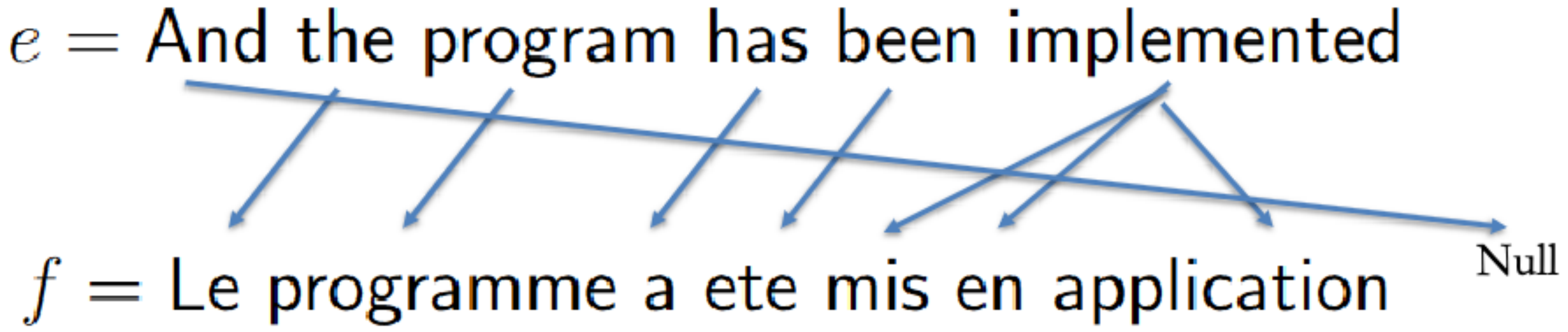
Word-Alignment Model in SMT

- Key Idea: two words are more likely to be aligned when they occur more frequently in translation pairs

我 不 知道	I	don’t	know	
我 是 学生	I	am	a	student
我 爱 喝 茶	I	love	drinking	tea

Word-Alignment Model in SMT

- e is an English sentence with l words
- f is a foreign sentence with m words
- An alignment $a = \{a_1, a_2, \ldots, a_m\}$, $a_j \in \{0, \ldots, l\}$
- Hence there are $(l+1)^m$ possible alignments



Word-Alignment Model in SMT

- **IBM Model 1:**

$$p(a \mid e, m) = \frac{1}{(l+1)^m}$$

- **IBM Model 2:**

$$p(a \mid e, m) = q(a_j \mid j, l, m)$$

- **IBM Model 3, 4, 5, 6…**

Translation Model

$$p(f \mid e) = \sum_{a \in \mathcal{A}} p(a \mid e, m) p(f \mid a, e, m)$$

Statistical Machine Translation

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Neural Machine Translation

Seq2seq Generation

- **Sequence-to-Sequence (Seq2seq) Generation**
  - Input: $X = \{x_1, x_2, \ldots, x_L\}, x_i \in \mathcal{X}$
  - Output: $Y = \{y_1, y_2, \ldots, y_T\}, y_i \in \mathcal{Y}$
  - Model: $p_\theta(Y|X)$ **How?**
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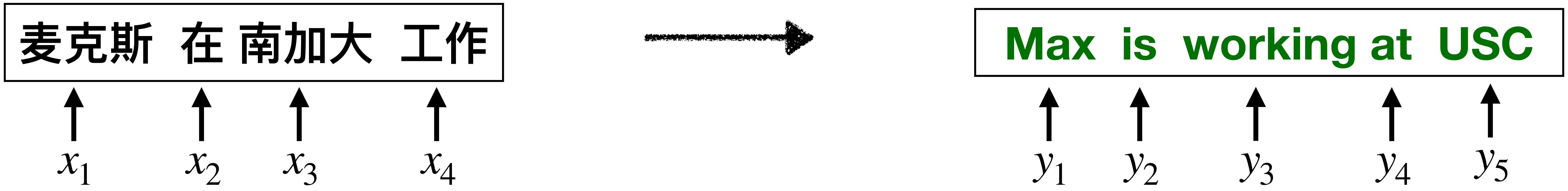
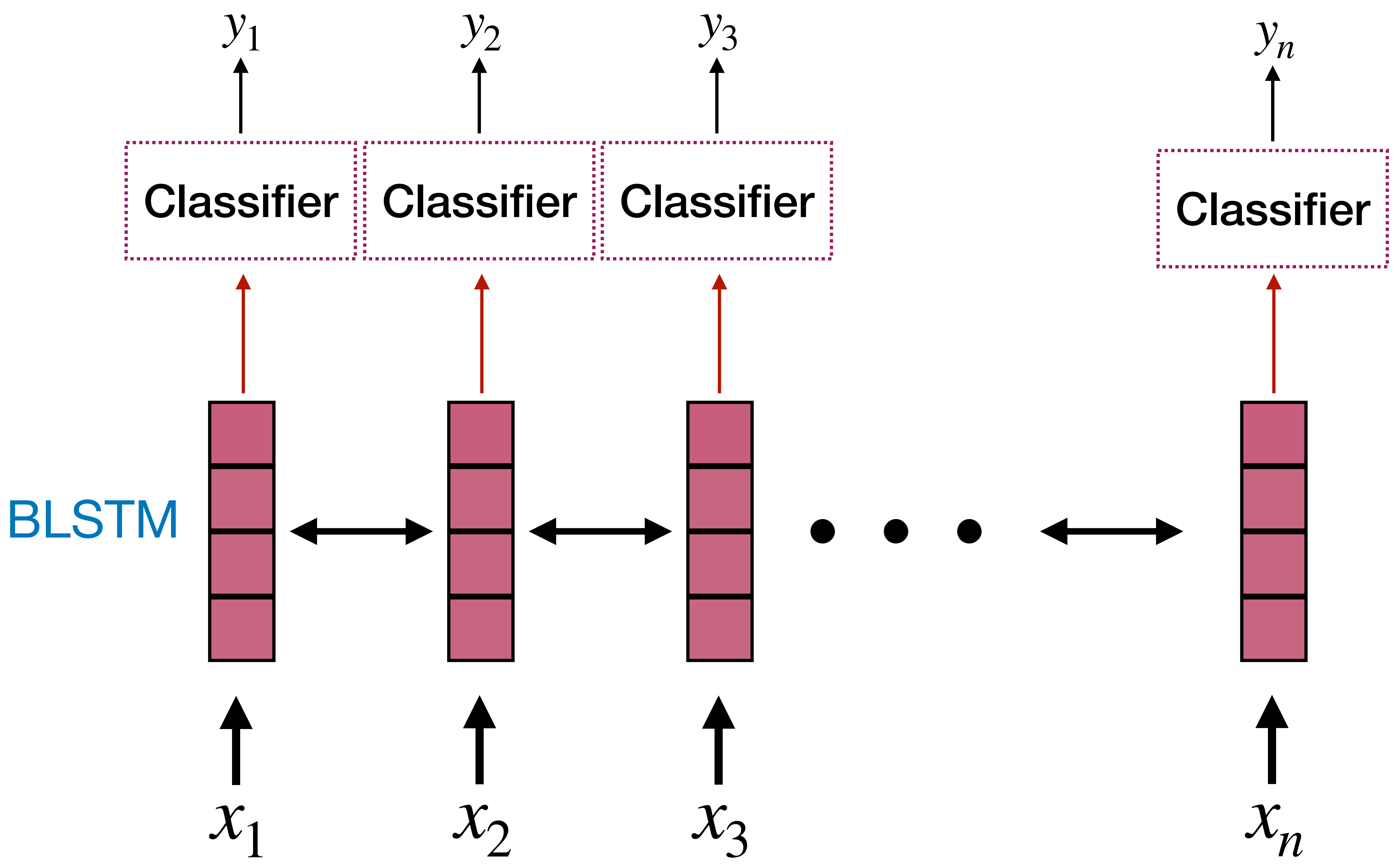


Autoregressive Seq2seq Generation

- **Sequence labeling vs. Seq2seq Generation**

Sequence labeling

$$p_\theta(Y|X) = \prod_{t=1}^{T} p_\theta(y_t|X)$$



Why not for seq2seq generation?

Autoregressive Seq2seq Generation

$$p_\theta(Y|X) = \prod_{t=1}^{T} p_\theta(y_t|X)$$

Not a good choice!

我 不 知道

I	don't	know	
I	do	not	know
I	have	no	idea

Autoregressive Seq2seq Generation

- **Autoregressive Factorization:**

$$p_\theta(Y|X) = \prod_{t=1}^{T} p_\theta(\underbrace{y_t}_{\text{Next Token}} | \underbrace{y_{\boxed{<t}}}_{\text{history}}, X)$$

- Autoregressive factorization is just chain-rule (HMMs, MEMMs)
- Autoregressive factorization does NOT assume any independence
- With autoregressive factorization, we need to model each $p_\theta(y_t | y_{<t}, X)$

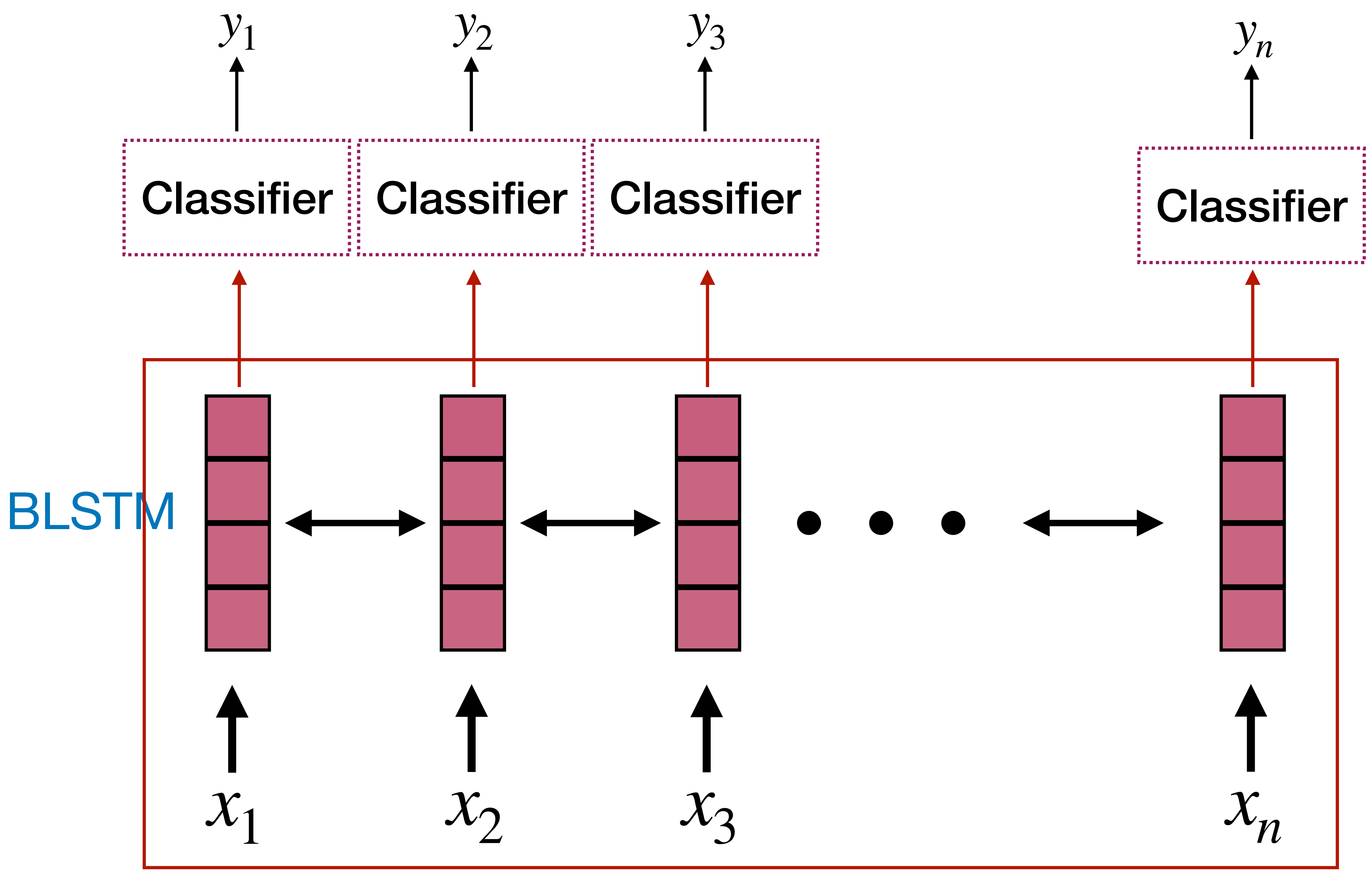
麦克斯	在	南加大	工作	→	Max	is	working	at	USC
x_1	x_2	x_3	x_4		y_1	y_2	y_3	y_4	y_5

Encoder-Decoder Architecture

- **Sequence labeling vs. Seq2seq Generation**

Sequence labeling

$$p_\theta(Y|X) = \prod_{t=1}^{T} p_\theta(y_t|\boxed{X})$$



Seq2seq Generation

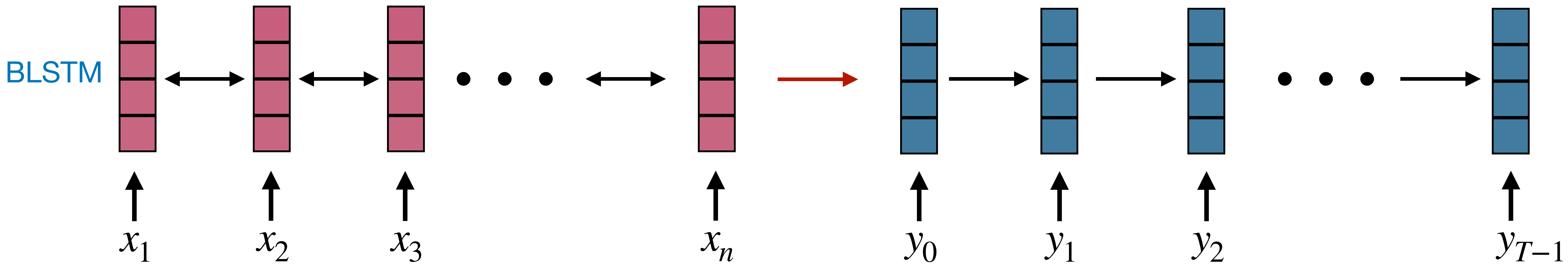
$$p_\theta(Y|X) = \prod_{t=1}^{T} p_\theta(\boxed{y_t|y_{<t}}, \boxed{X})$$

Encoder: encode a sentence into a sequence of vectors

Decoder: use another LSTM?

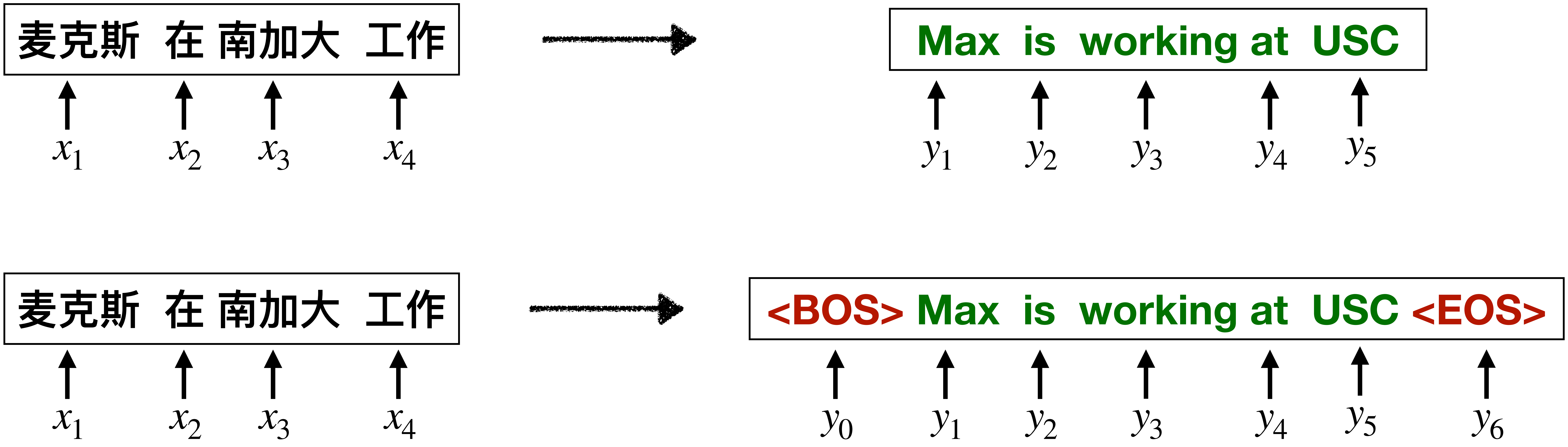
Encoder-Decoder Architecture

- **Two Components:**
  - Encoder: Convert input sequence into a sequence of vectors
  - Decoder: Convert encoding into a sequence in the output space



Special Tokens in Seq2seq

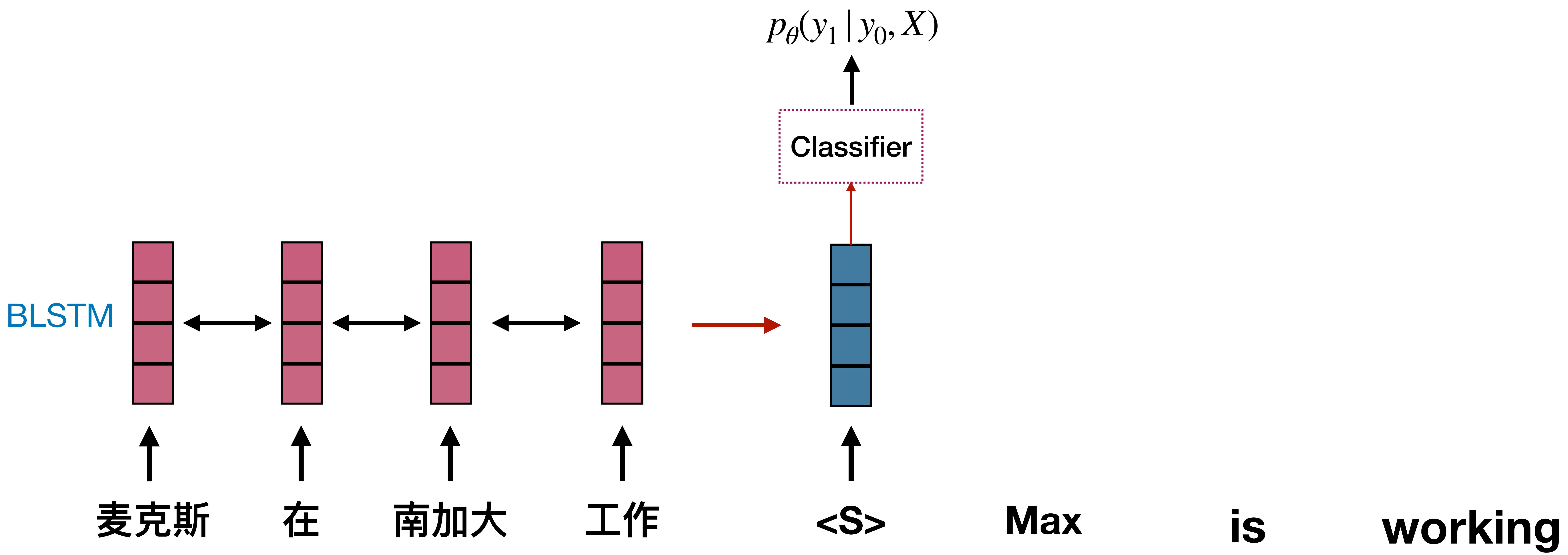
- **<BOS>**: start of the target sentence
- **<EOS>**: end of the target sentence



Seq2seq Training

- **Model Training:**

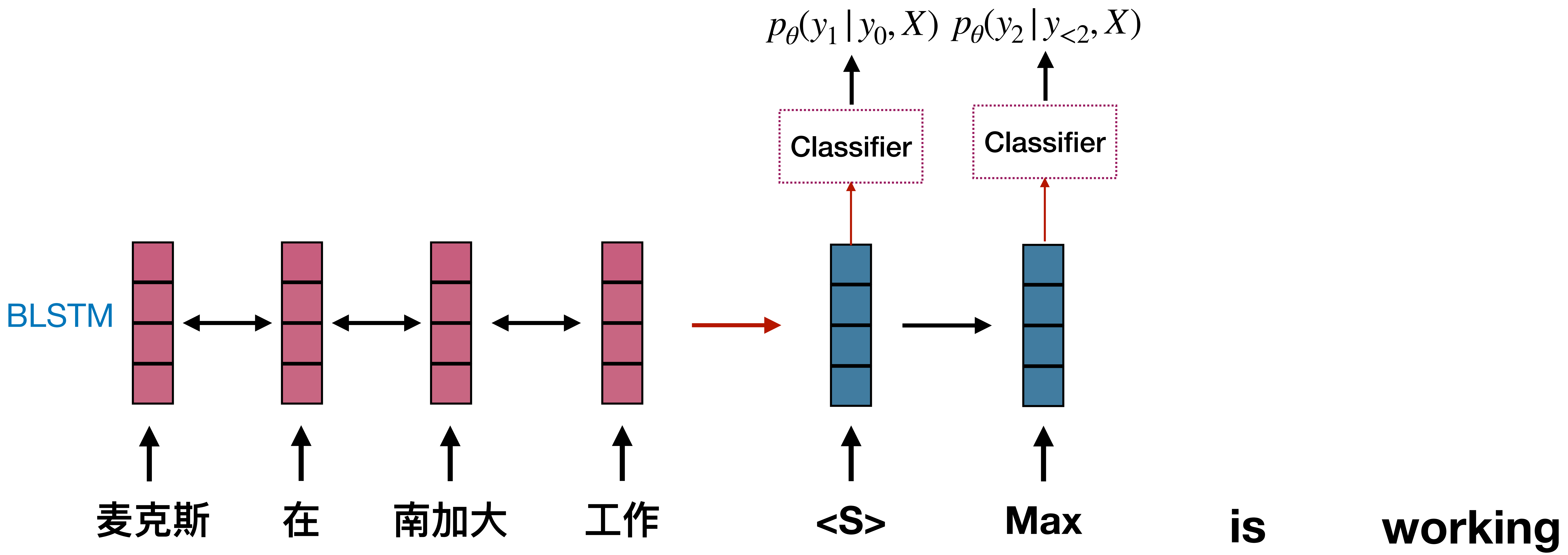
$$p_\theta(Y|X) = \prod_{t=1}^{T} \boxed{p_\theta(y_t|y_{<t}, X) \quad t = 1}$$



Seq2seq Training

- **Model Training:**

$$p_\theta(Y|X) = \prod_{t=1}^{T} p_\theta(y_t | y_{<t}, X) \qquad t = 2$$



Seq2seq Training

- **Model Training:**

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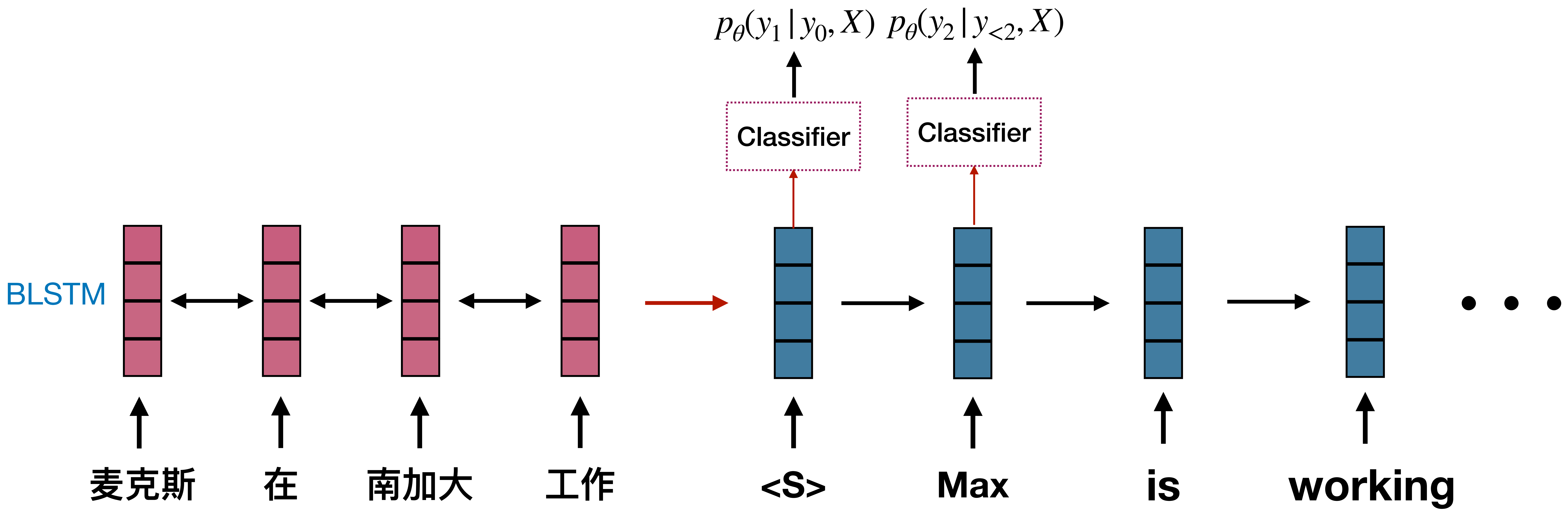


Seq2seq Training

- **Maximum Likelihood Estimation**

$$\max_{\theta} p_{\theta}(Y|X) = \prod_{t=1}^{T} p_{\theta}(y_t | y_{<t}, X)$$

- **Back-propagate gradients through both decoder & encoder**
- **Need a really big training corpus**
  - WMT Russian-English

Seq2seq Decoding

- **Exhaustive Search**
  - Requires computing all possible sequences

$$\arg\max_{Y} p_\theta(Y|X) = \prod_{t=1}^{T} p_\theta(y_t | y_{<t}, X)$$

What is the complexity of doing this search, if $|\mathscr{Y}| = V$ and sequence length T?

(a) $O(VT)$

(b) $\boxed{O(V^T)}$

(c) $O(T^V)$

Seq2seq Decoding

- **Greedy Search**
  - Selects the best current word y_t

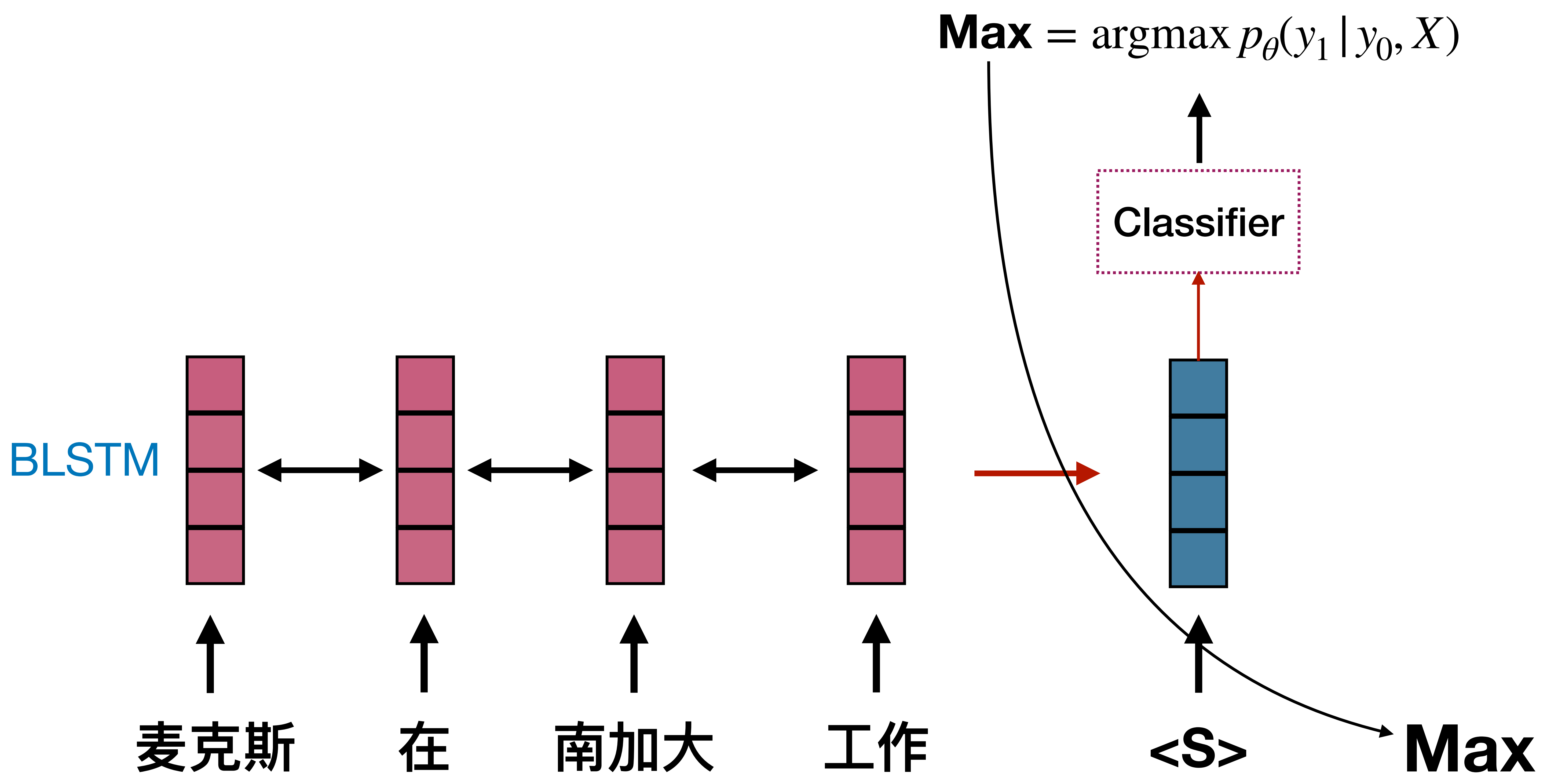
$$\mathrm{arg}\max_{Y} p_\theta(Y|X) = \prod_{t=1}^{T} p_\theta(y_t|y_{<t}, X)$$

$$\approx \mathbf{arg}\max_{y_t} p_\theta(y_t|y_{<t}, X), \forall t$$

Seq2seq Decoding

- **Greedy decoding:**

$$y_t{}^* = \arg\max_{y_t} p_\theta(y_t \mid y_{<t}, X), \forall t$$

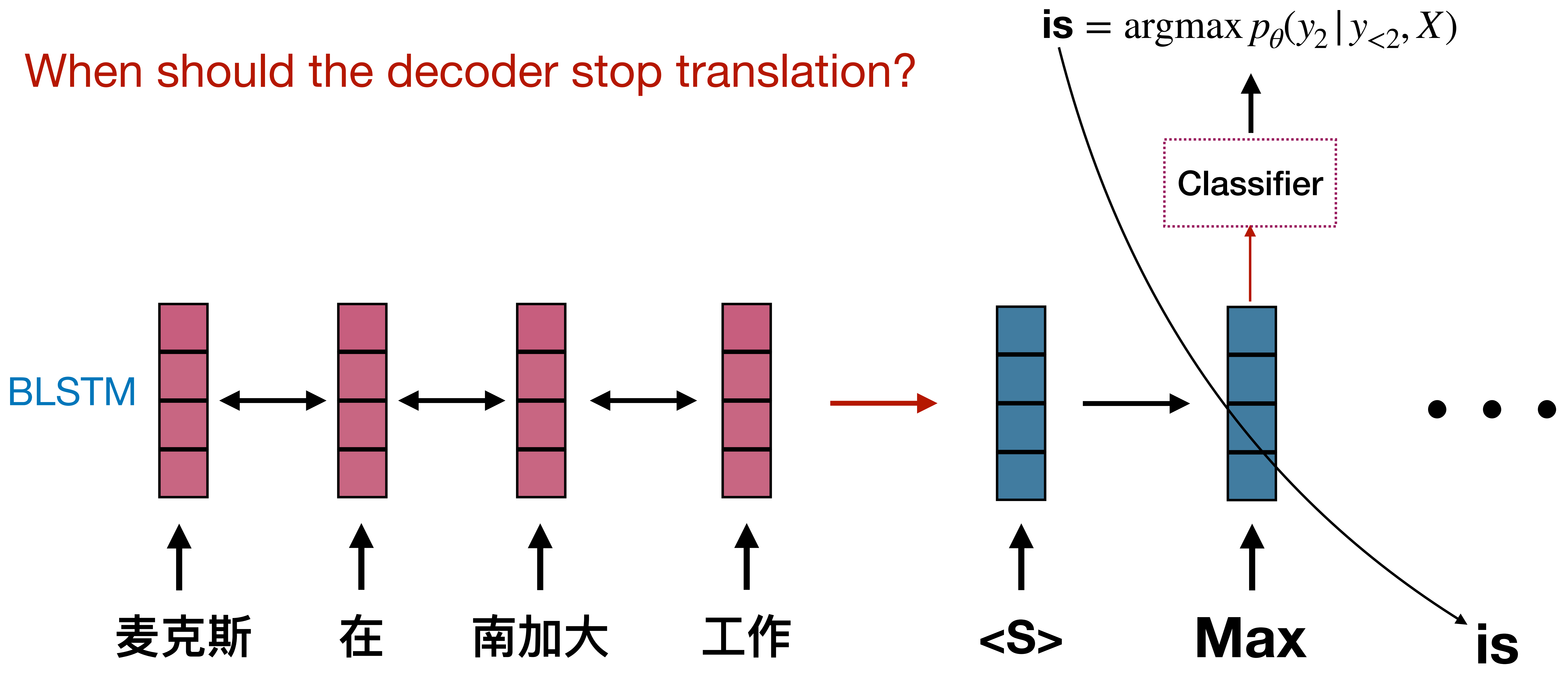


Seq2seq Decoding

- **Greedy decoding:**

$$y_t{}^* = \arg\max_{y_t} p_\theta(y_t \,|\, y_{<t}\,, X), \forall t$$

When should the decoder stop translation?



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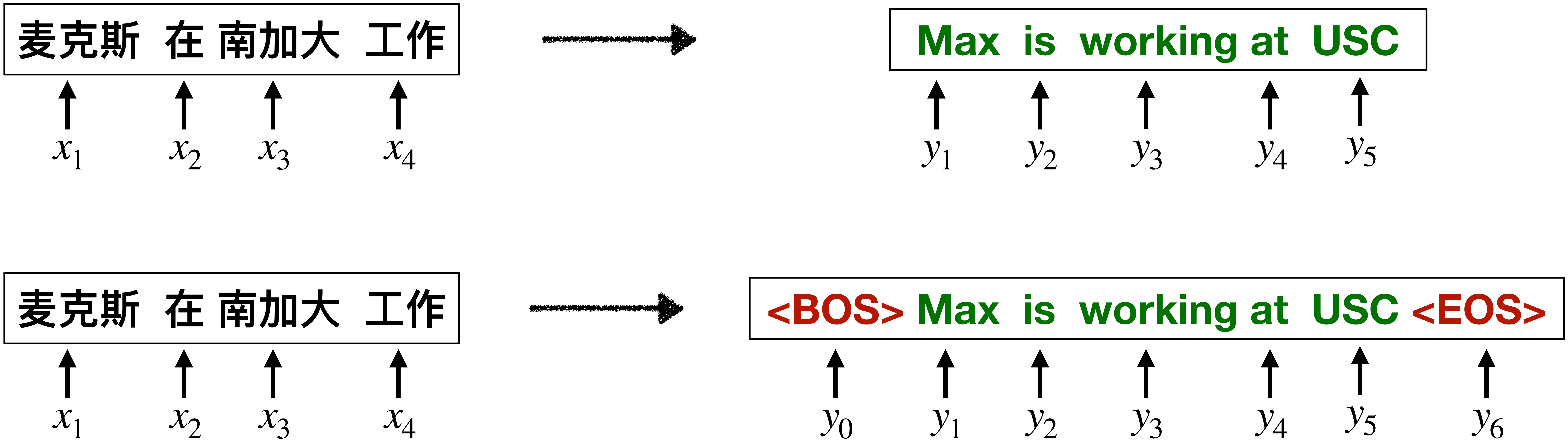
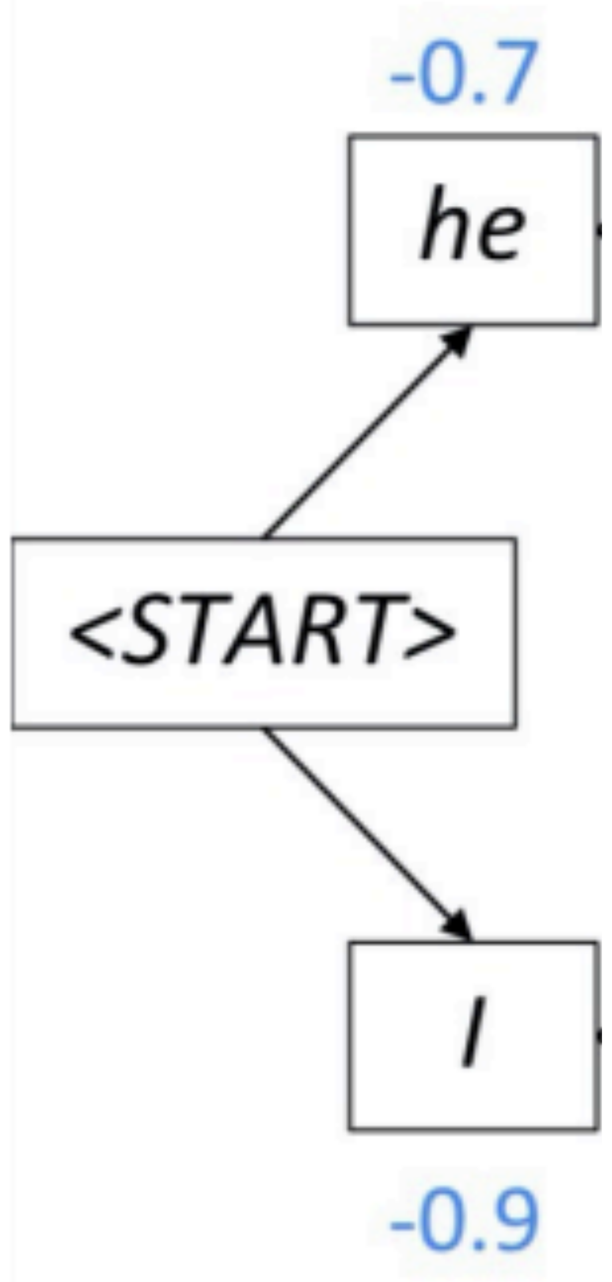


A Middle Ground: Beam Search

- **Key idea:** at every step, keep track of the k most probable partial translations (hypotheses)
- Score of each hypothesis = log probability of sequence so far
- Not guaranteed to be optimal
- More efficient than exhaustive search

Beam Search Decoding

Beam size $K = 2$



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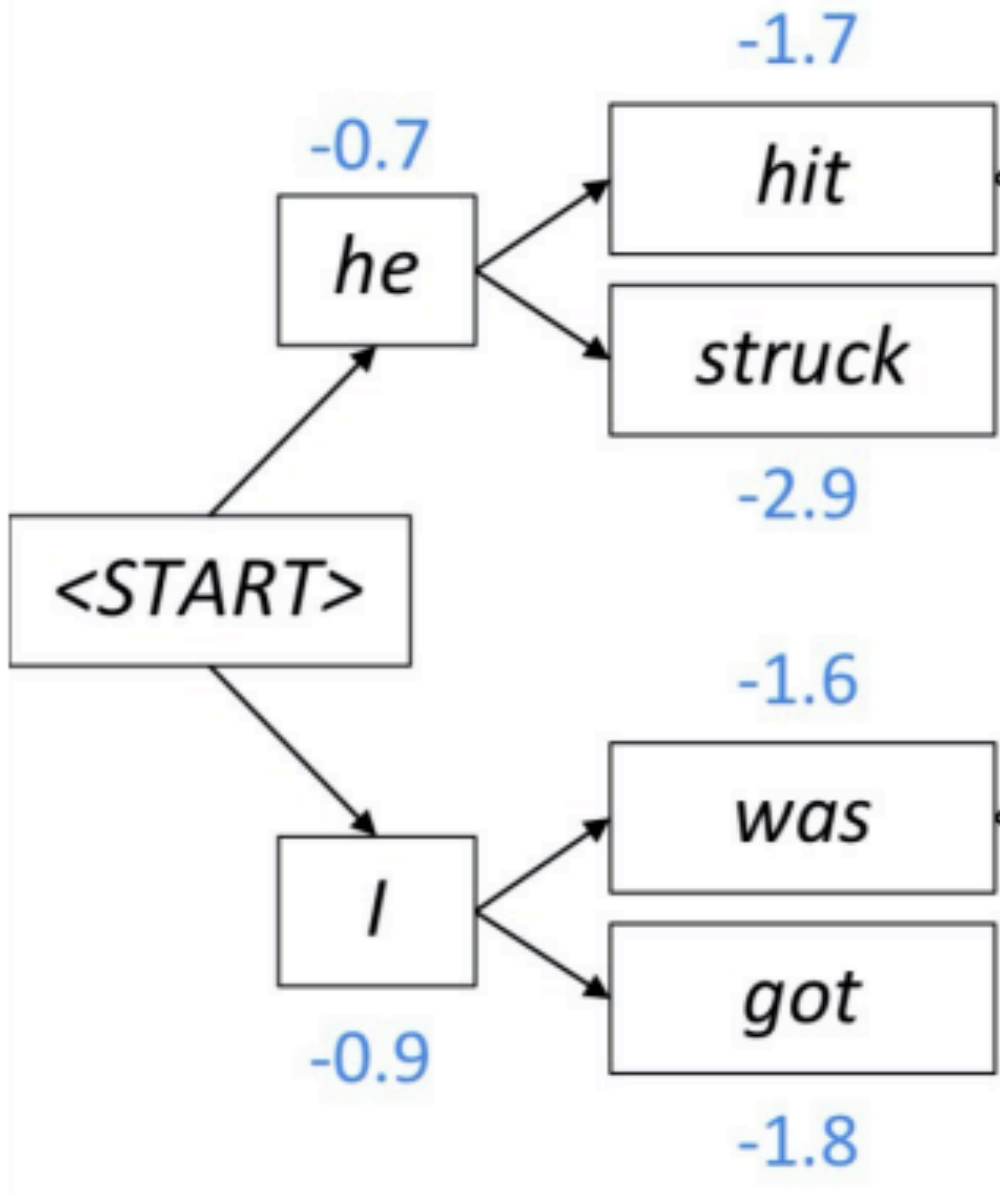

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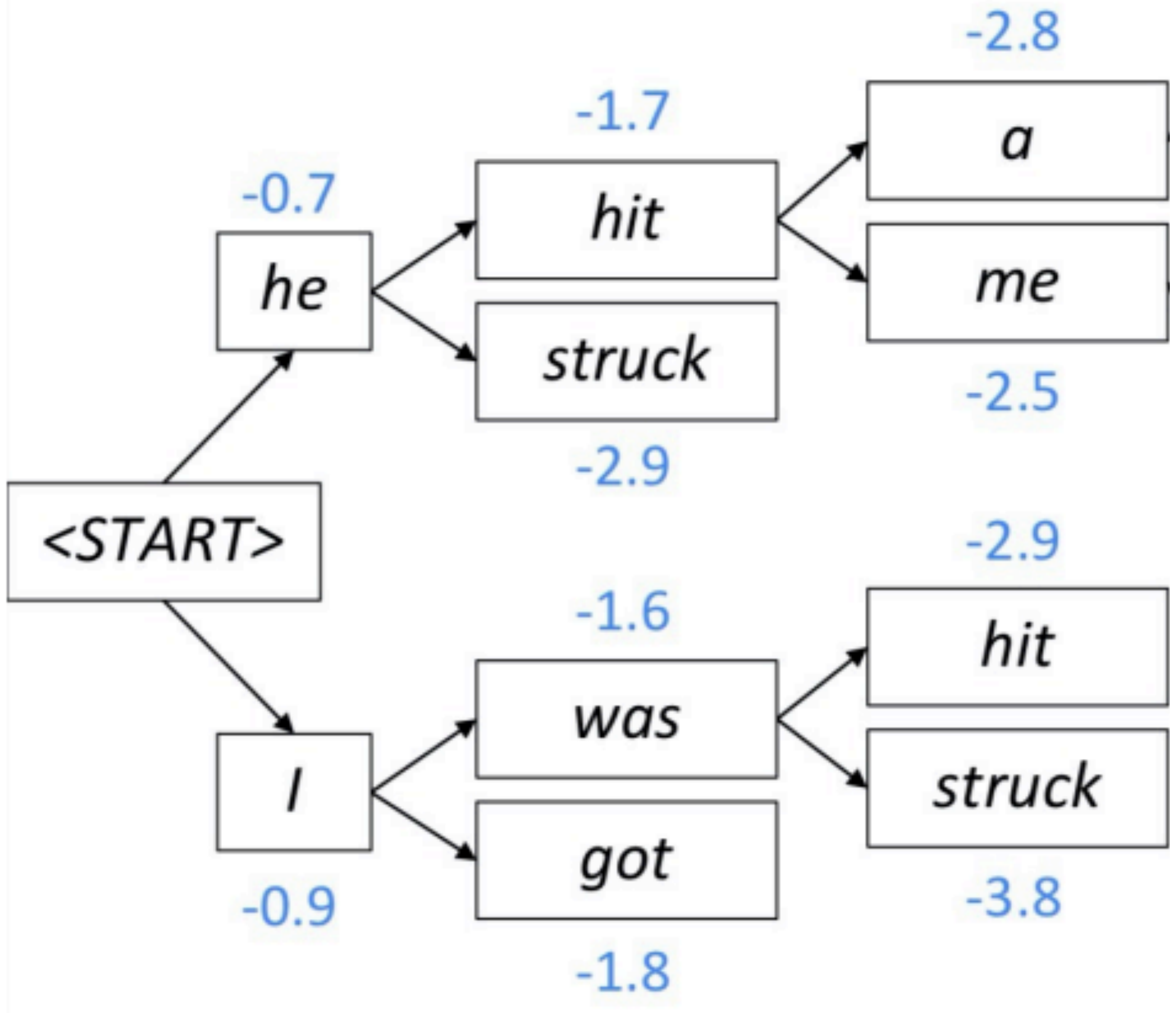

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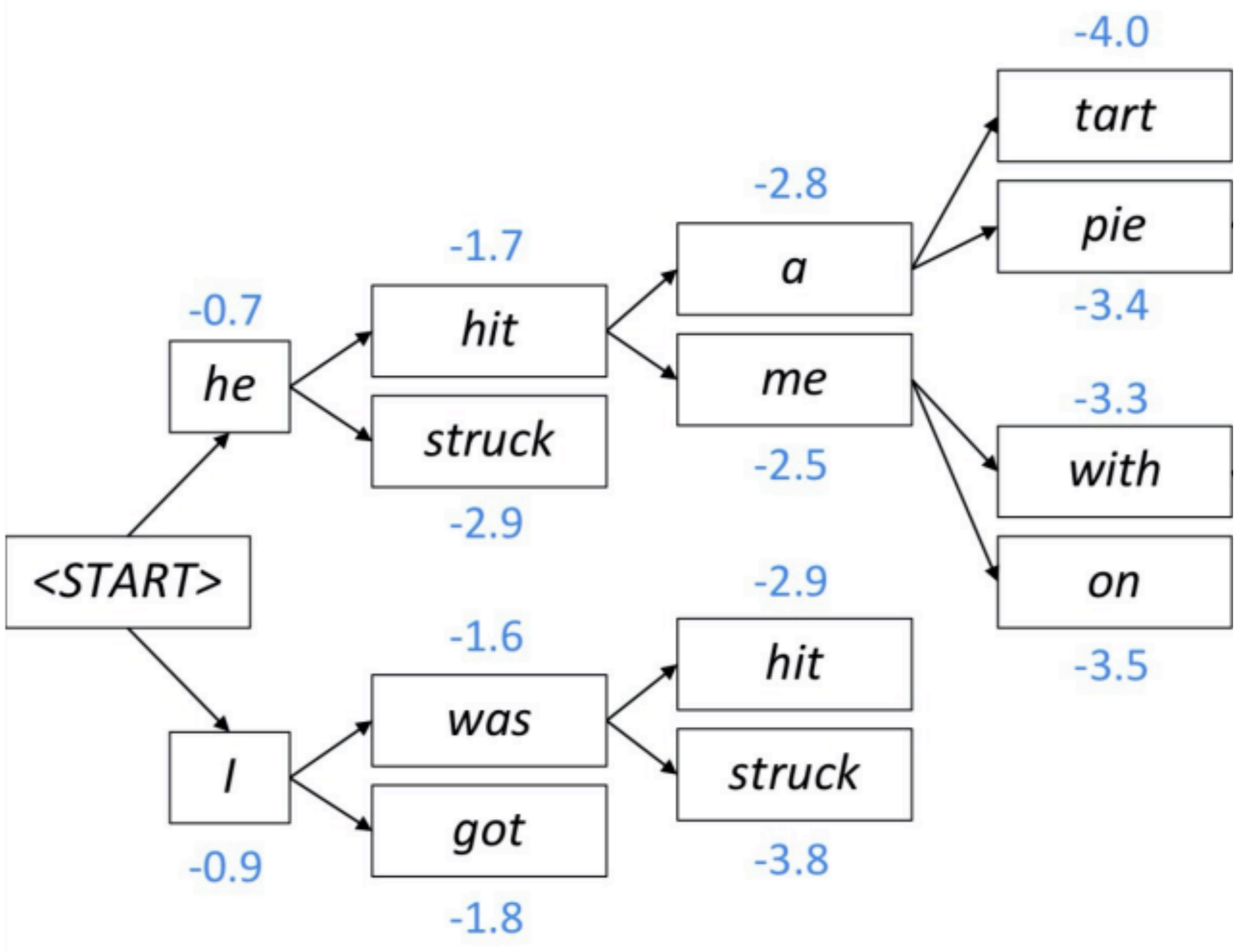

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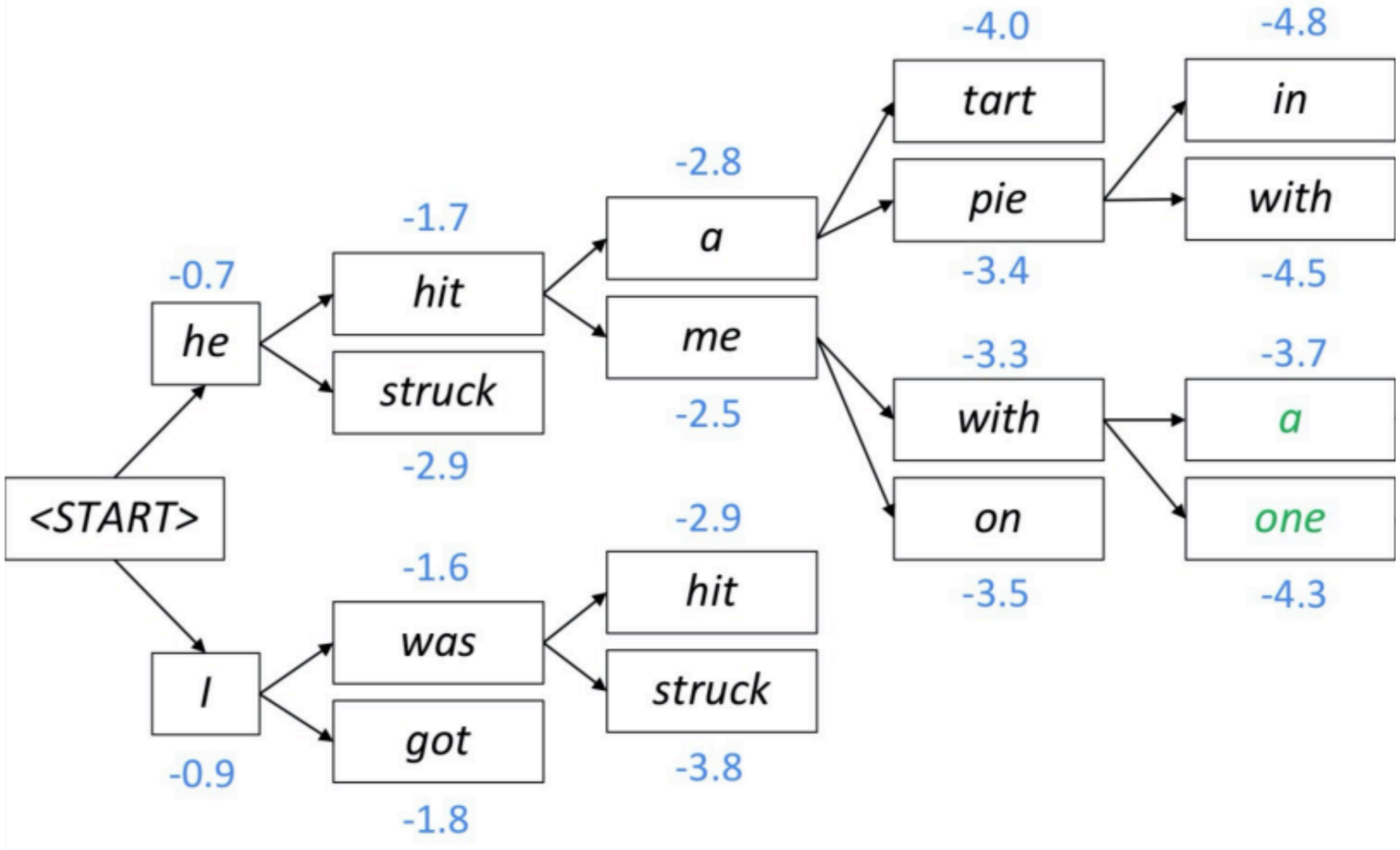

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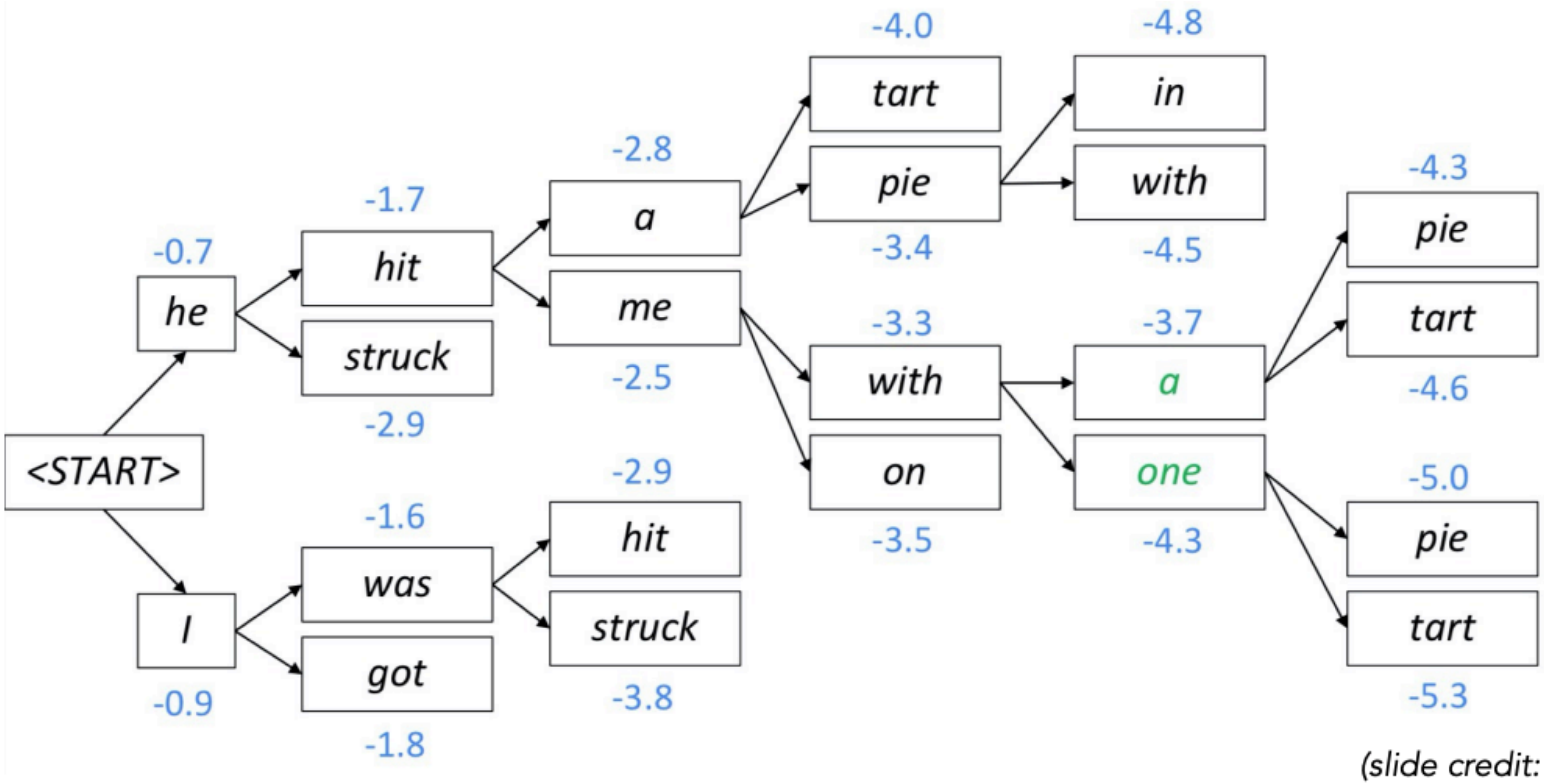
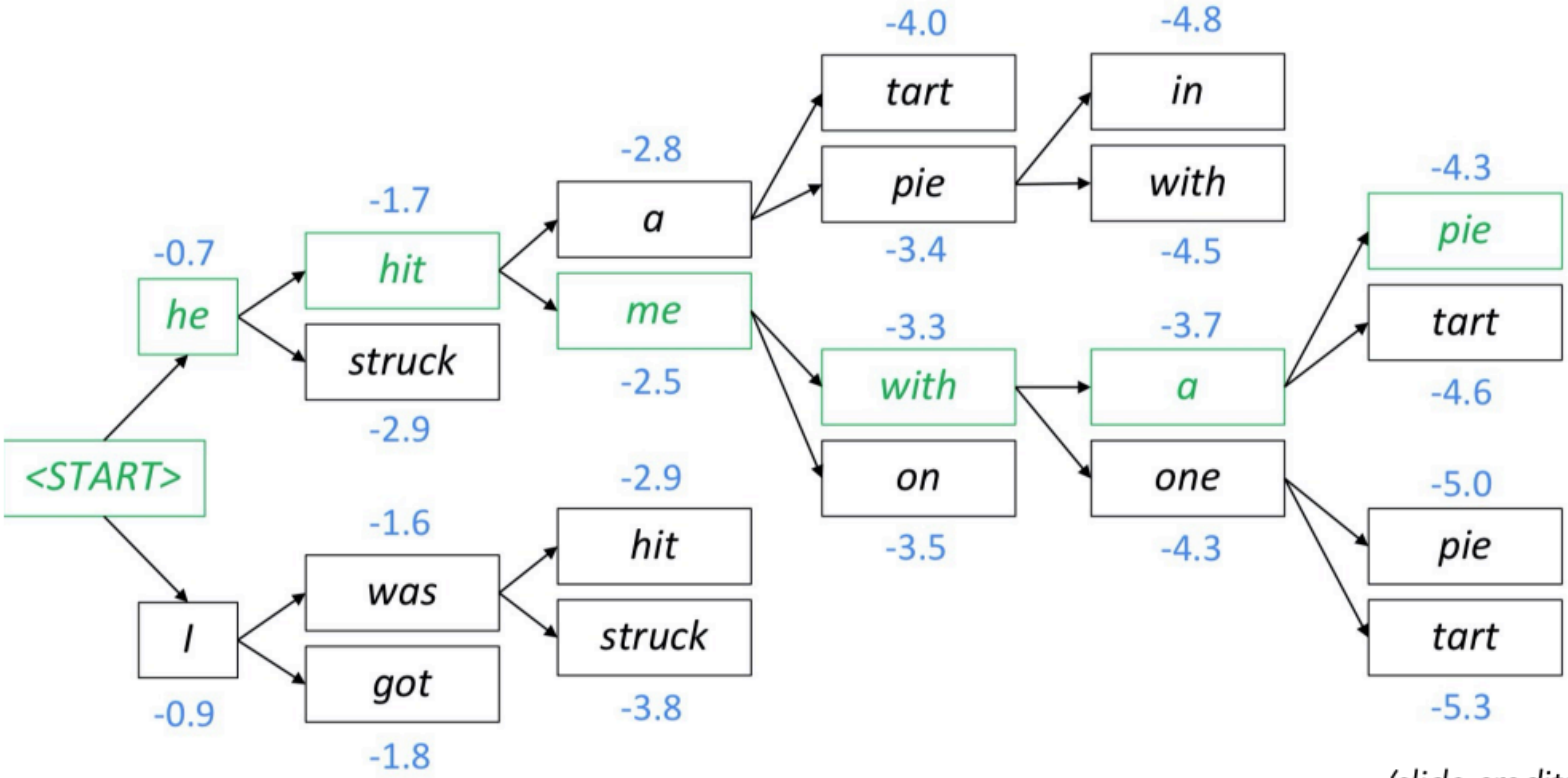


(slide credit: Abigail See)

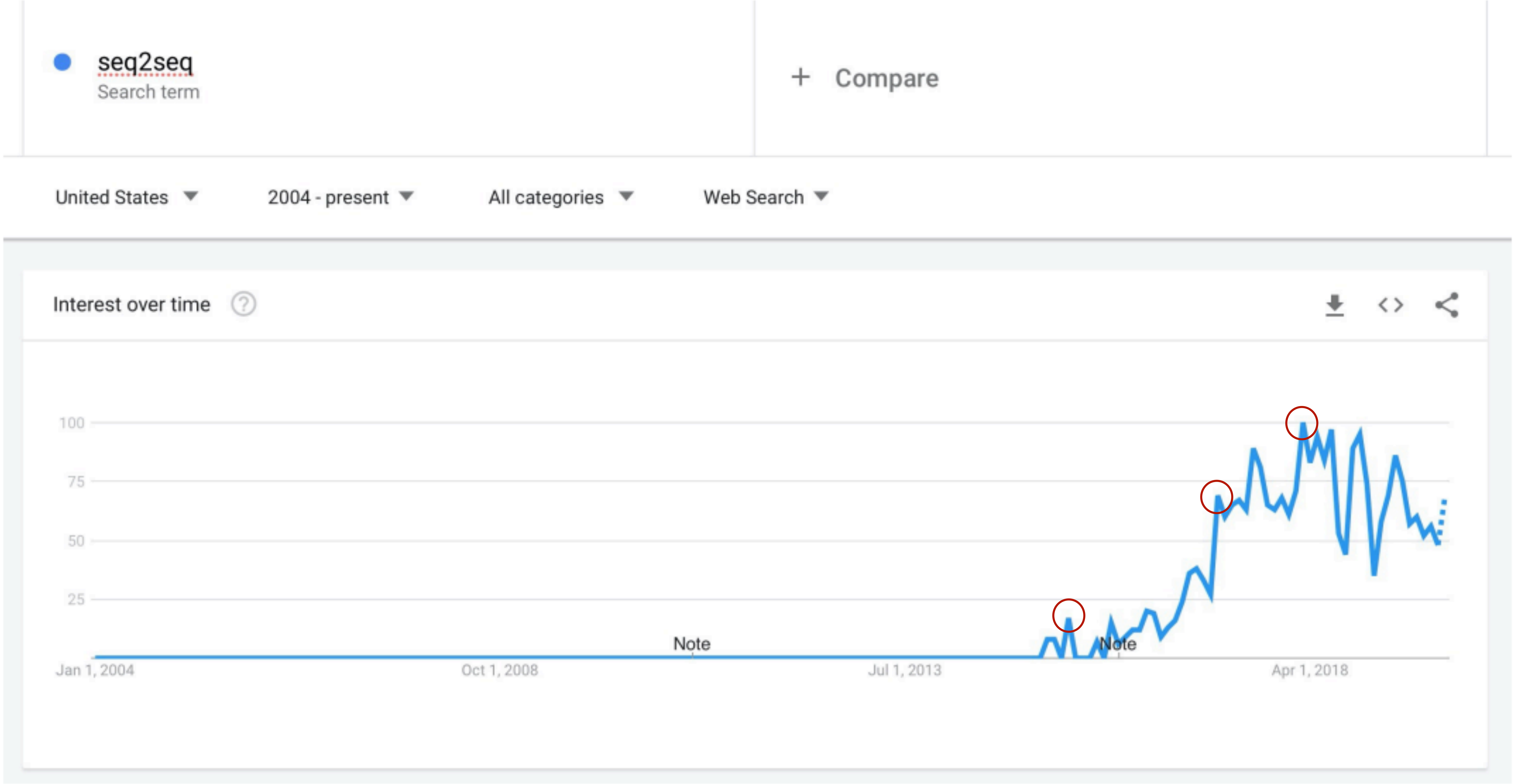
Backtrack

Beam size $K = 2$

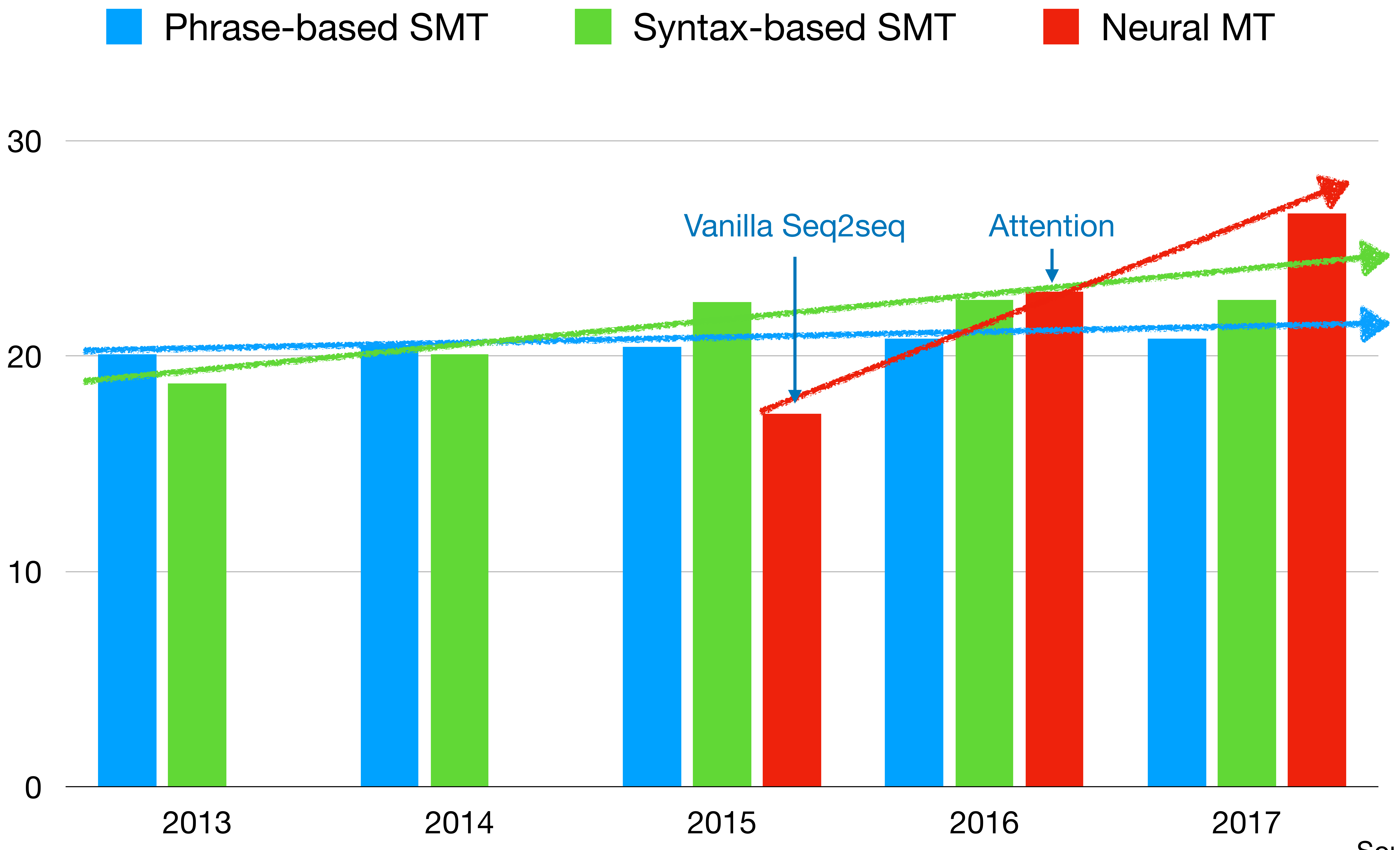


(slide credit: Abigail See)

How Seq2seq changed the MT Landscape



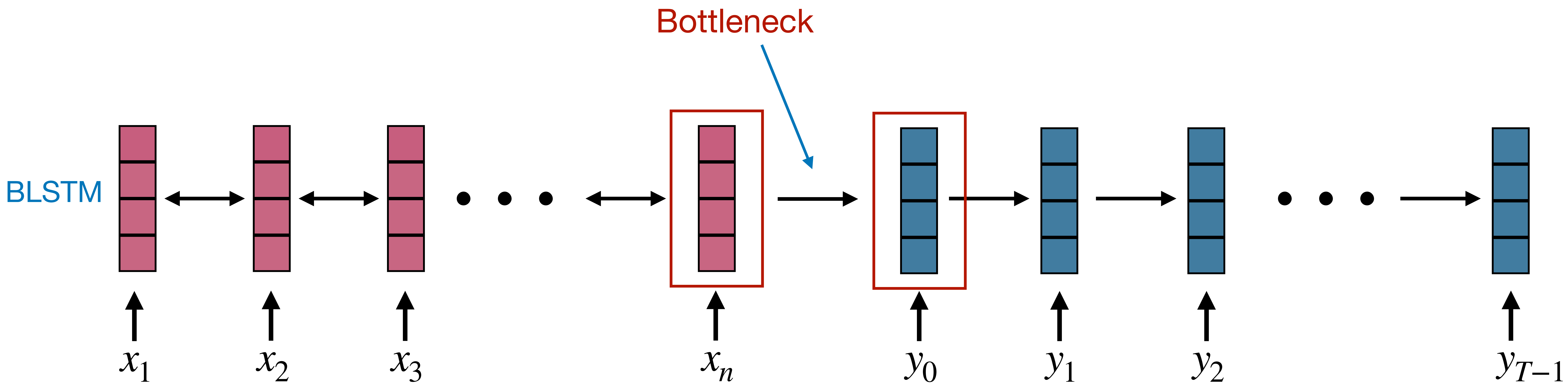
MT Progress



Source: Rico Sennrich

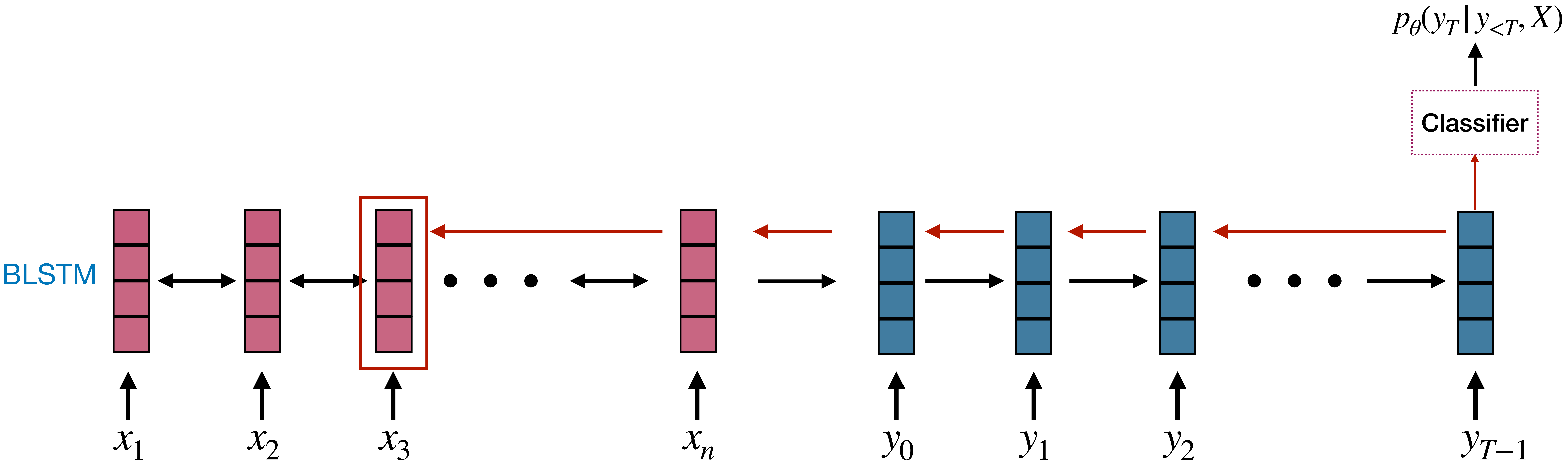
Issues with Vanilla Encoder-Decoder Architecture

- A single encoding vector needs to capture **all the information** about source sentence



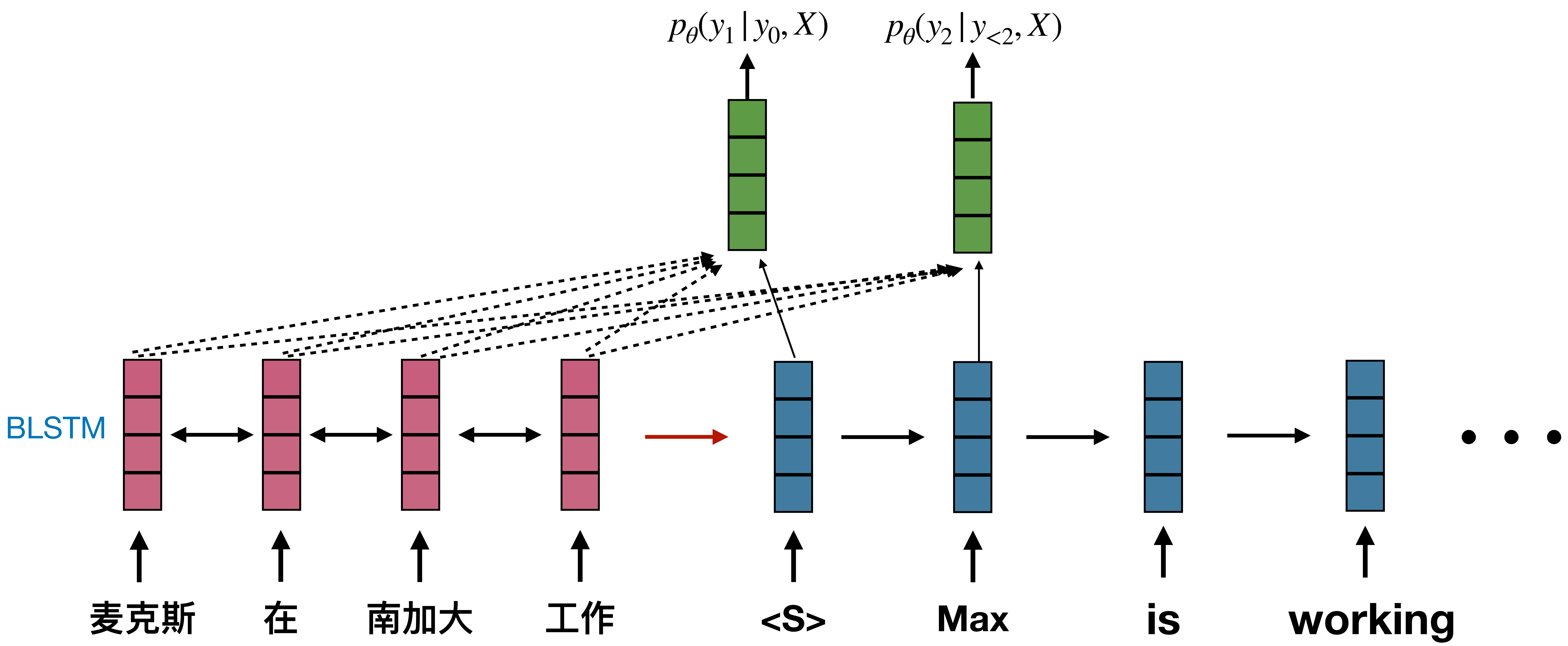
Issues with Vanilla Encoder-Decoder Architecture

- A single encoding vector needs to capture **all the information** about source sentence
- Longer sequences can lead to **vanishing gradients**



Attention Mechanism

- **Key idea:** At each time step, use all parts of source sentence



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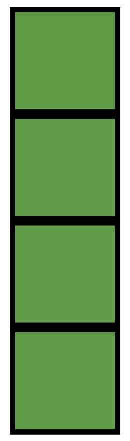
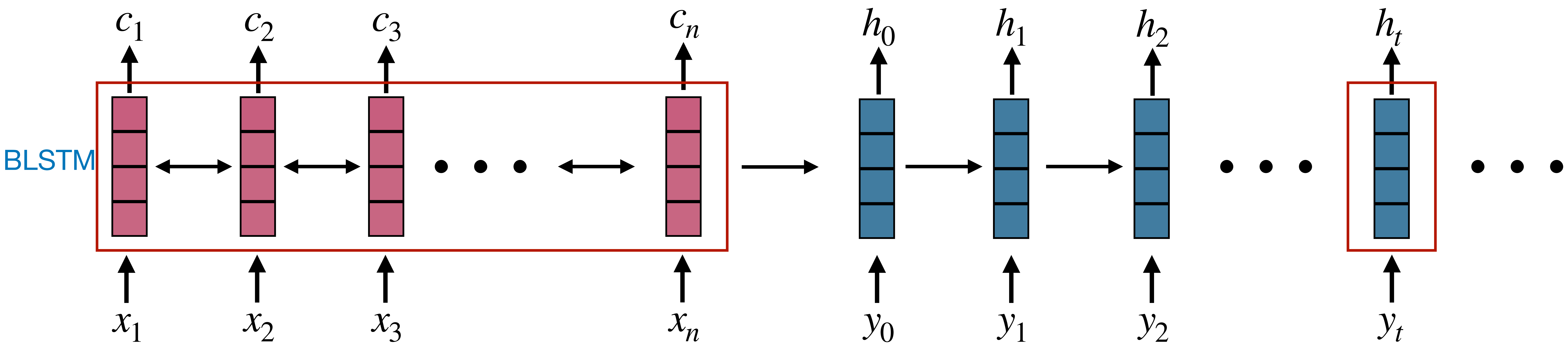
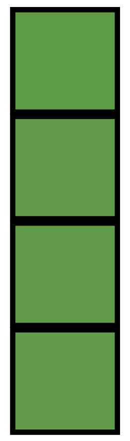


$$= \text{attn}([c_1, c_2, \ldots, c_n], h_t)$$



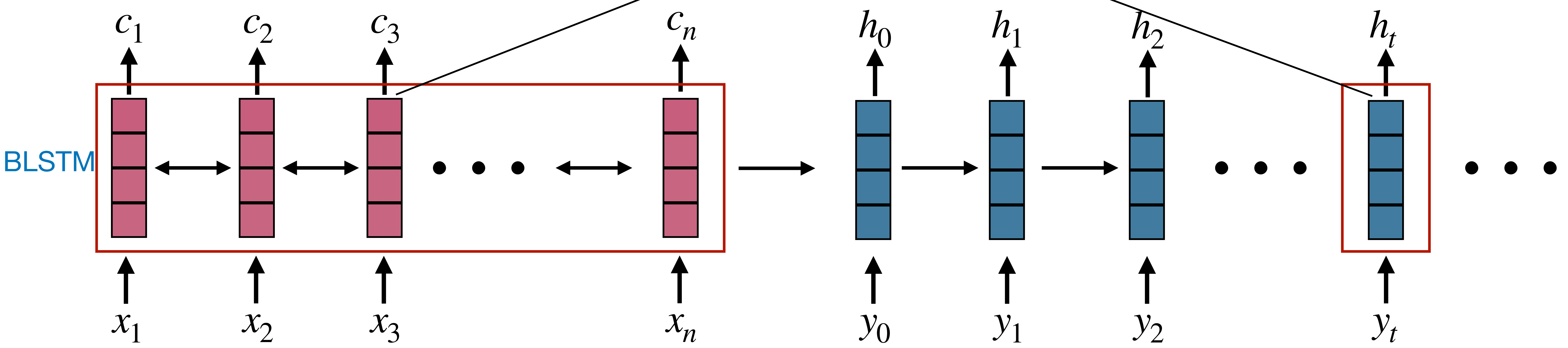
Attention Mechanism



$$= \mathrm{attn}([c_1, c_2, \ldots, c_n], h_t)$$

$$e_j^t = \mathrm{sim}(c_j, h_t),\ \forall j \in \{1, \ldots, n\}$$

Attention scores



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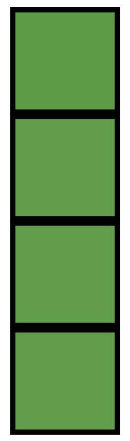


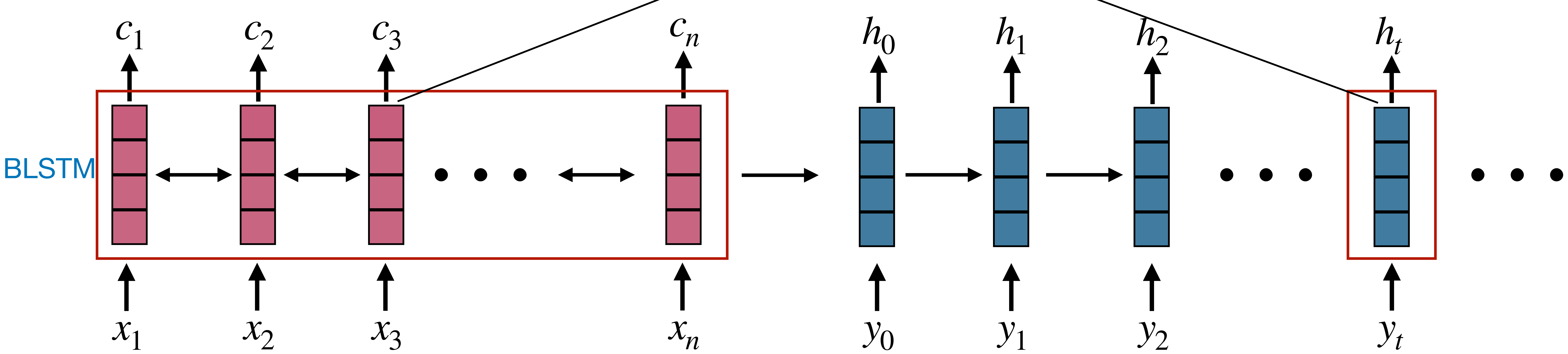
$$= \operatorname{attn}([c_1, c_2, \ldots, c_n], h_t)$$

$$a^t = \operatorname{softmax}(e^t) \in (0,1)^n$$

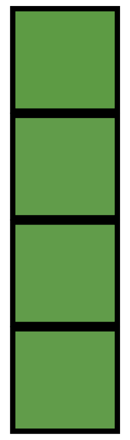
Attention distribution

$$e_j^t = \operatorname{sim}(c_j, h_t), \ \forall j \in \{1, \ldots, n\}$$

Attention scores



Attention Mechanism



$$= \mathrm{attn}([c_1, c_2, \ldots, c_n], h_t) = \sum_{j=1}^{n} a_j^t c_j \in \mathbb{R}^d$$

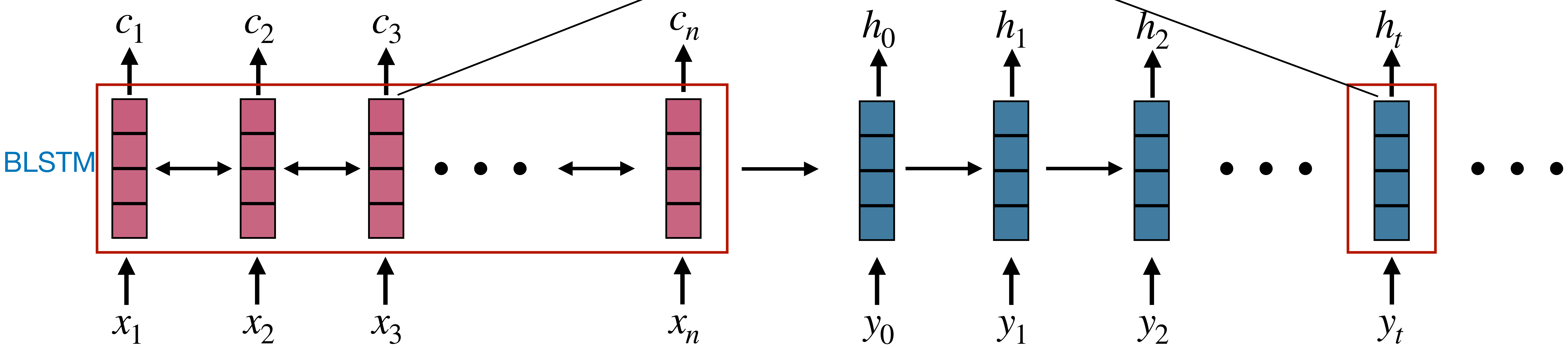
Attention output

$$a^t = \mathrm{softmax}(e^t) \in (0,1)^n$$

Attention distribution

$$e_j^t = \mathrm{sim}(c_j, h_t), \ \forall j \in \{1, \ldots, n\}$$

Attention scores



Softmax Function

$$e^t = [e_1^t, e_2^t, \ldots, e_n^t]$$

$$\text{softmax}(e^t) = [\frac{\exp(e_1^t)}{\sum_{j=1}^{n} \exp(e_j^t)}, \frac{\exp(e_2^t)}{\sum_{j=1}^{n} \exp(e_j^t)}, \ldots, \frac{\exp(e_n^t)}{\sum_{j=1}^{n} \exp(e_j^t)}]$$

Types of Attention

- **Dot-product attention** (assumes equal dimensions for c and h)

$$\mathrm{sim}(c_j, h_t) = c_j^T h_t$$

- **Multiplicative attention**

$\mathrm{sim}(c_j, h_t) = c_j^T W h_t$, where W is learnable weight matrix

- **Additive attention**

$$\mathrm{sim}(c_j, h_t) = v^T \tanh(W_c c_j + W_h h_t)$$

where W_c and W_h are learnable weight matrices and v is a learnable weight vector

Attention Improves Translation Performance

System	Ppl	BLEU
Winning WMT'14 system – *phrase-based + large LM* (Buck et al., 2014)		20.7
Existing NMT systems		
RNNsearch (Jean et al., 2015)		16.5
RNNsearch + unk replace (Jean et al., 2015)		19.0
RNNsearch + unk replace + large vocab + *ensemble* 8 models (Jean et al., 2015)		**21.6**
Our NMT systems		
Base	10.6	11.3
Base + reverse	9.9	12.6 (+*1.3*)
Base + reverse + dropout	8.1	14.0 (+*1.4*)
Base + reverse + dropout + global attention (*location*)	7.3	16.8 (+*2.8*)
Base + reverse + dropout + global attention (*location*) + feed input	6.4	18.1 (+*1.3*)
Base + reverse + dropout + local-p attention (*general*) + feed input	5.9	19.0 (+*0.9*)
Base + reverse + dropout + local-p attention (*general*) + feed input + unk replace		20.9 (+*1.9*)
Ensemble 8 models + unk replace		**23.0** (+*2.1*)

(Luong et al., 2015)

RESEARCH › PUBLICATIONS ›

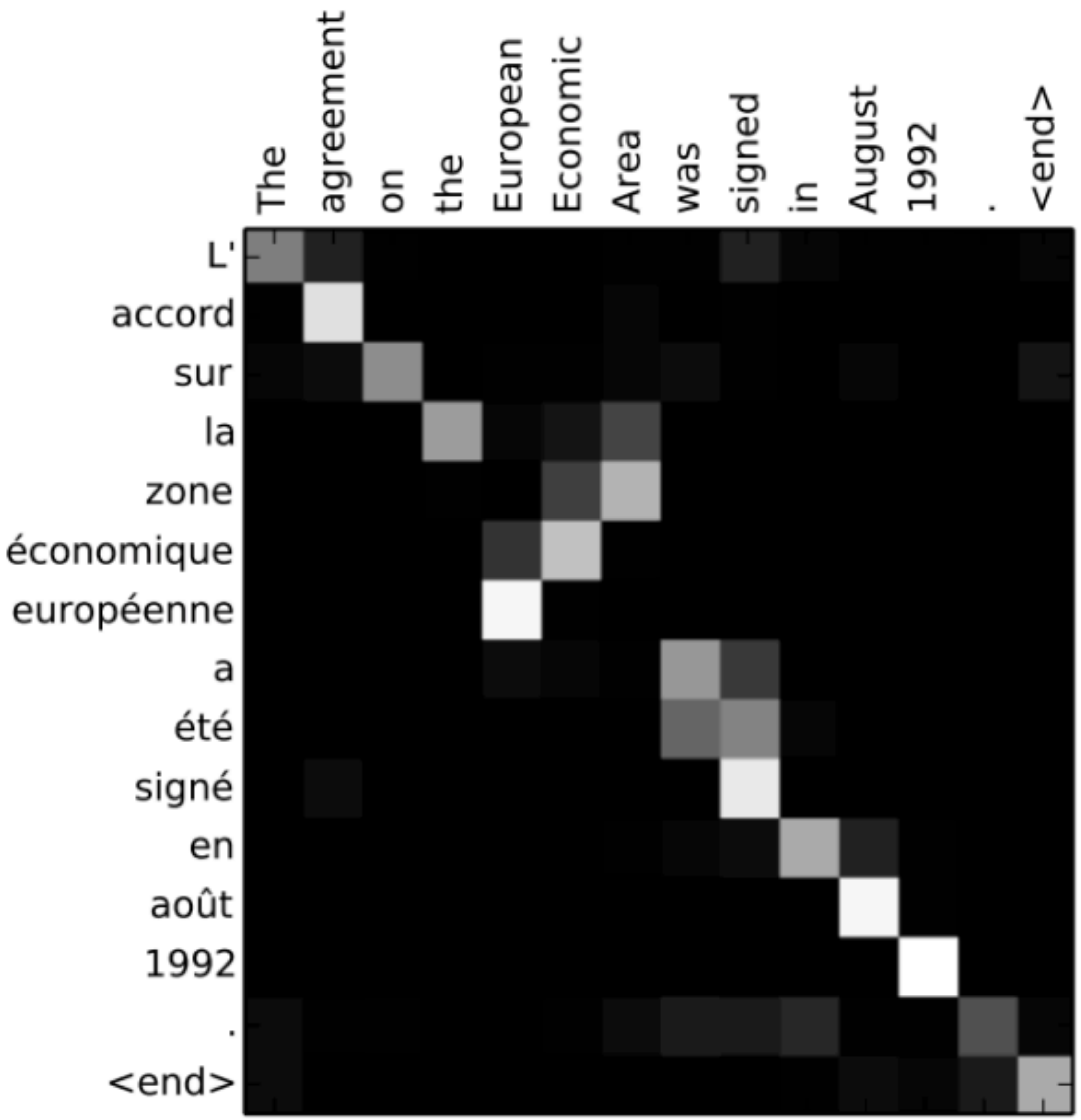
Google's Neural Machine Translation System: Bridging the Gap between Human and Machine Translation

Table 10: Mean of side-by-side scores on production data

	PBMT	GNMT	Human	Relative Improvement
English → Spanish	4.885	5.428	5.504	87%
English → French	4.932	5.295	5.496	64%
English → Chinese	4.035	4.594	4.987	58%
Spanish → English	4.872	5.187	5.372	63%
French → English	5.046	5.343	5.404	83%
Chinese → English	3.694	4.263	4.636	60%

(Wu et al., 2016)

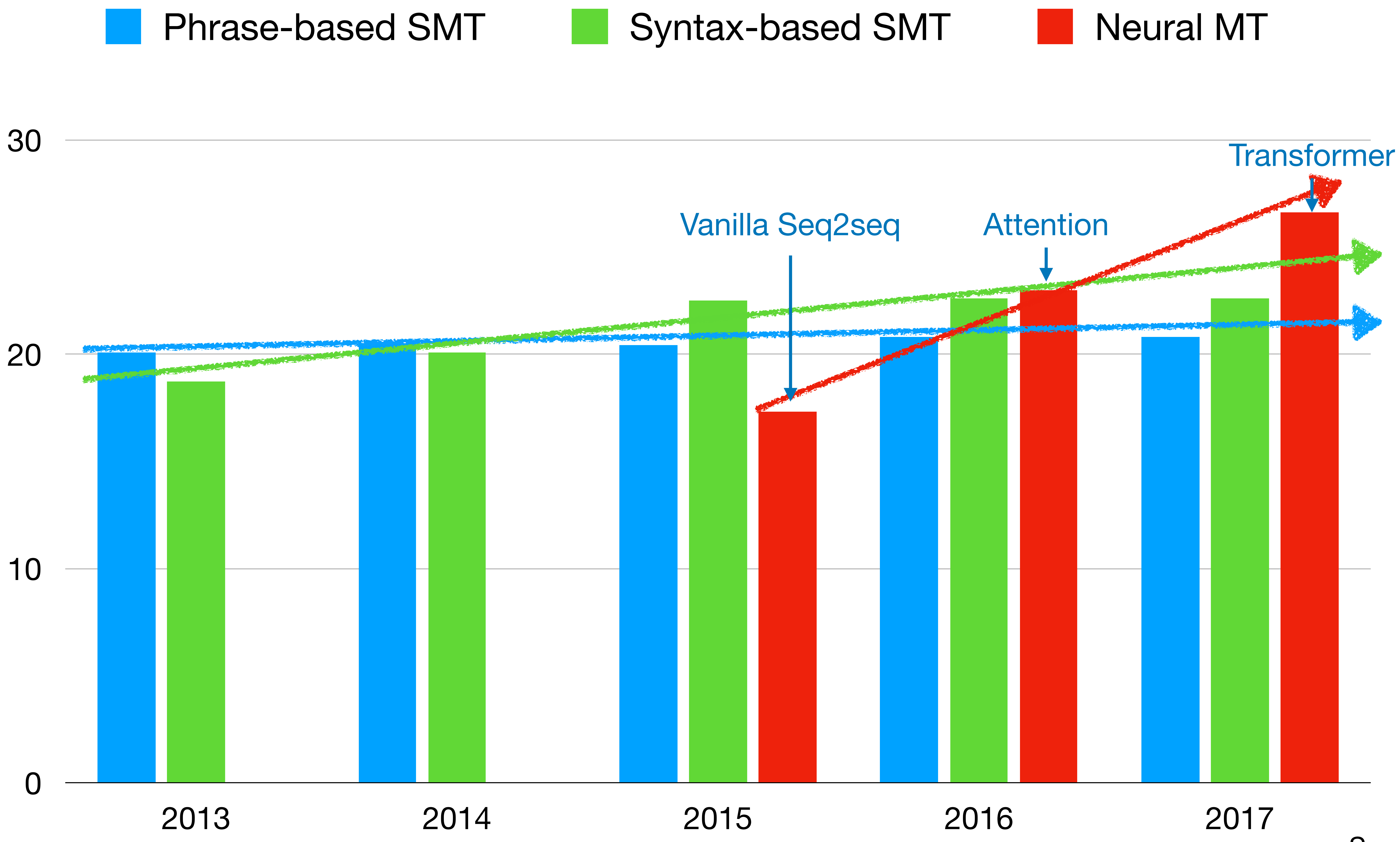
Visualizing Attention



Highly correlated with alignment

credits: Jay Alammar

MT Progress



Source: Rico Sennrich

Reading Materials

- **Reading Materials**
  - Sequence to Sequence Learning with Neural Networks
  - Neural Machine Translation by Jointly Learning to Align and Translate