

Natural Language Processing with Deep Learning

CS224N/Ling284



Machine Translation,
Sequence-to-sequence and Attention
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Overview

- Introduce a new task: Machine Translation

is a major use-case of



- Introduce a new neural architecture: sequence-to-sequence

is improved by



- Introduce a new neural technique: attention

Section 1: Pre-Neural Machine Translation

Machine Translation

Machine Translation (MT) is the task of translating a sentence x from one language (the **source language**) to a sentence y in another language (the **target language**).

x : *L'homme est né libre, et partout il est dans les fers*



y : *Man is born free, but everywhere he is in chains*

- Rousseau

1950s: Early Machine Translation

Machine Translation research began in the early 1950s.

- Russian → English
(motivated by the Cold War!)



1 minute video showing 1954 MT:
<https://youtu.be/K-HfpsHPmvw>

- Systems were mostly rule-based, using a bilingual dictionary to map Russian words to their English counterparts

1990s-2010s: Statistical Machine Translation

- Core idea: Learn a **probabilistic model** from **data**
- Suppose we're translating French \rightarrow English.
- We want to find **best English sentence y** , given French sentence x

$$\operatorname{argmax}_y P(y|x)$$

- Use Bayes Rule to break this down into **two components** to be learnt separately:

$$= \operatorname{argmax}_y \underbrace{P(x|y)}_{\text{Translation Model}} \underbrace{P(y)}_{\text{Language Model}}$$

Translation Model

Models how words and phrases should be translated (*fidelity*).
Learnt from parallel data.

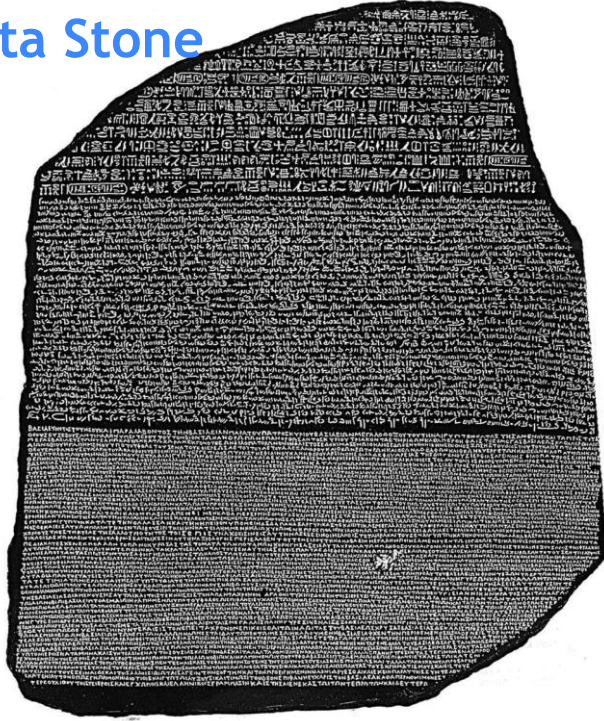
Language Model

Models how to write good English (*fluency*).
Learnt from monolingual data.

1990s-2010s: Statistical Machine Translation

- Question: How to learn translation model $P(x|y)$?
- First, need large amount of **parallel data**
(e.g. pairs of human-translated French/English sentences)

The Rosetta Stone



Ancient Egyptian

Demotic

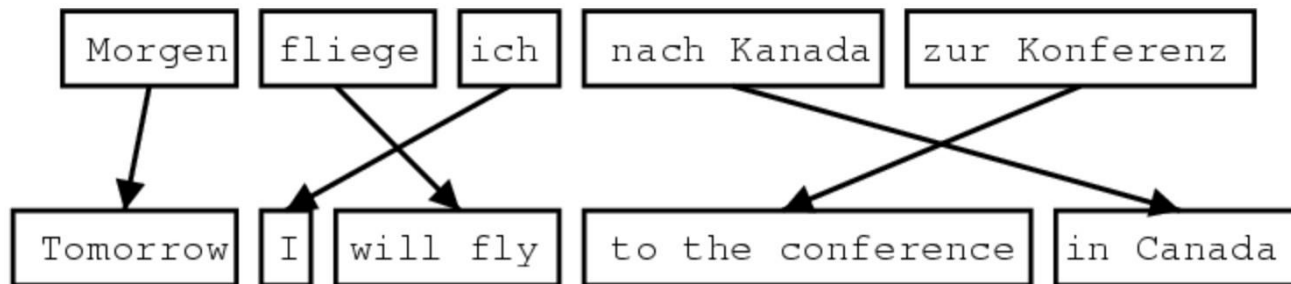
Ancient Greek

Learning alignment for SMT

- Question: How to learn translation model $P(x|y)$ from the parallel corpus?
- Break it down further: Introduce latent a variable into the model:

$$P(x, a|y)$$

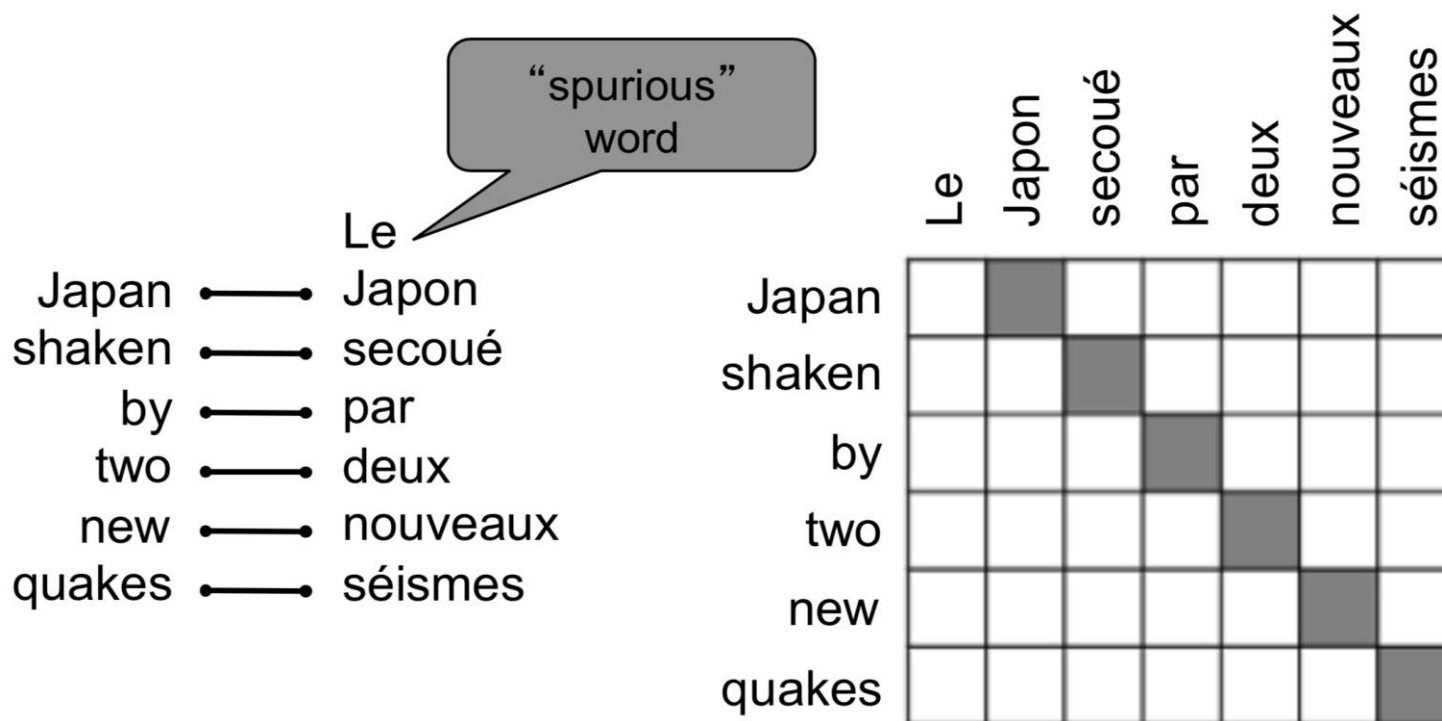
where a is the **alignment**, i.e. word-level correspondence between source sentence x and target sentence y



What is alignment?

Alignment is the **correspondence between particular words** in the translated sentence pair.

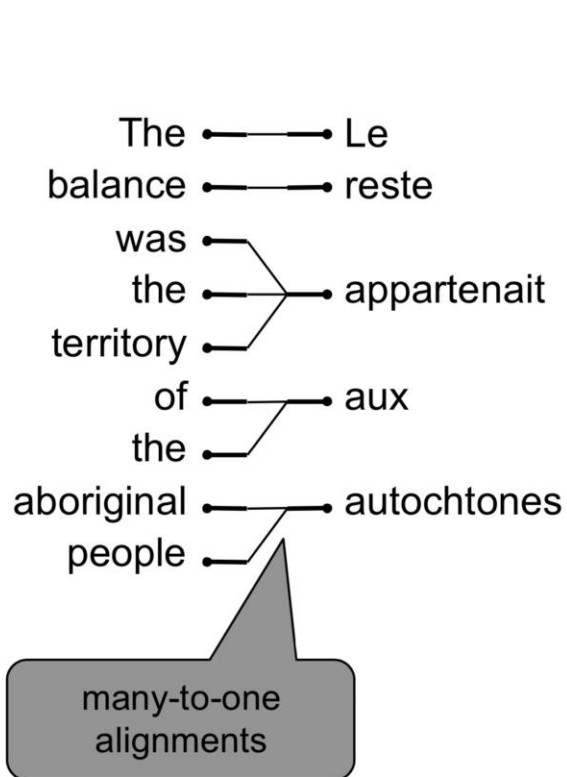
- **Typological differences** between languages lead to complicated alignments!
 - Note: Some words have **no counterpart**



Examples from: "The Mathematics of Statistical Machine Translation: Parameter Estimation", Brown et al, 1993.

<http://www.aclweb.org/anthology/J93-2003>

Alignment can be many-to-one

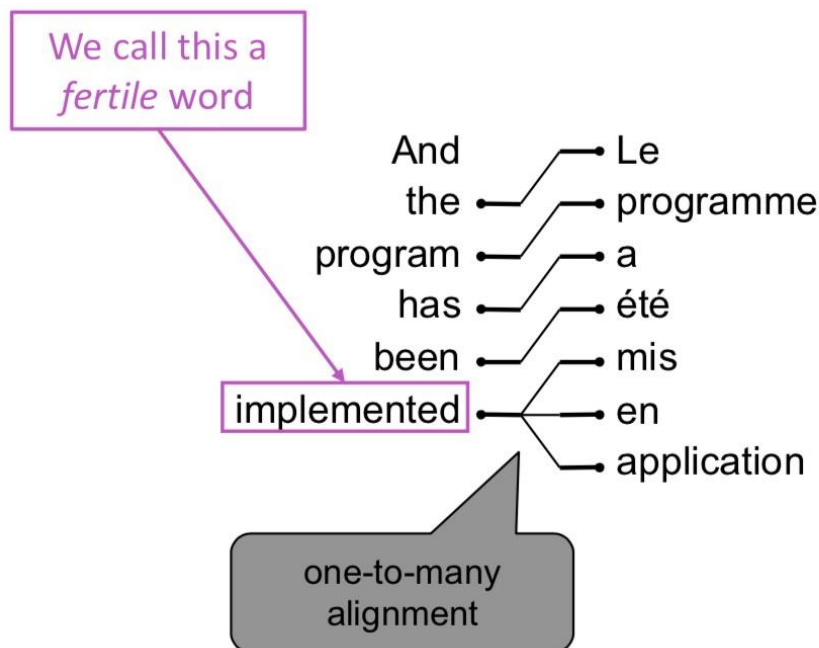


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balance		■			
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territory			■		
of				■	
the				■	
aboriginal					■
people					■

Examples from: "The Mathematics of Statistical Machine Translation: Parameter Estimation", Brown et al, 1993.

<http://www.aclweb.org/anthology/J93-2003>

Alignment can be **one-to-many**



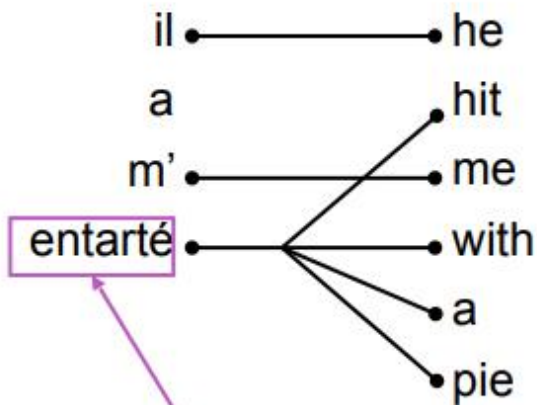
	Le	programme	a	été	mis	en	application
And							
the							
program							
has							
been							
implemented							

Examples from: "The Mathematics of Statistical Machine Translation: Parameter Estimation", Brown et al, 1993.

<http://www.aclweb.org/anthology/J93-2003>

Alignment is complex

Some words are very fertile!

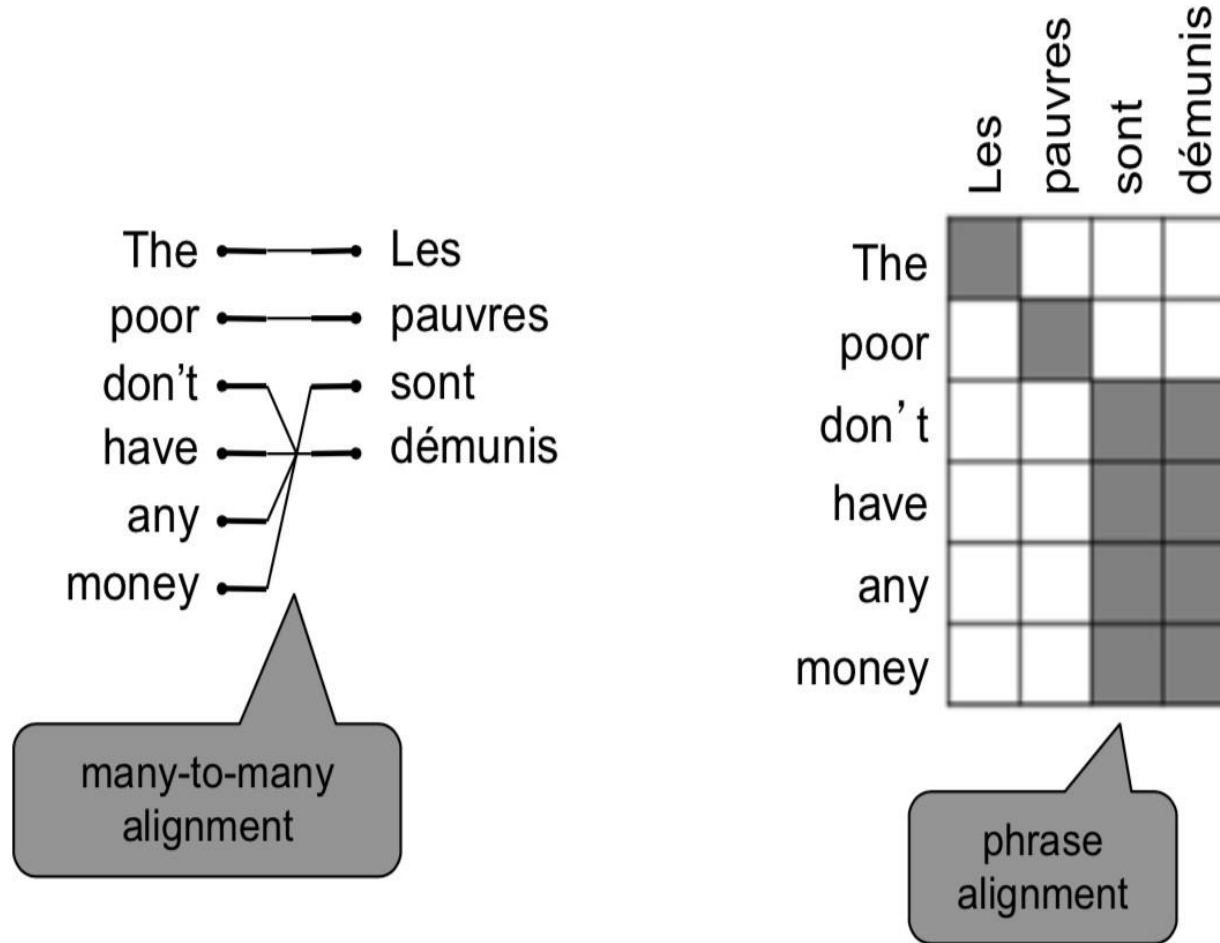


This word has no single-word equivalent in English

	he	hit	me	with	a	pie
il						
a						
m'						
entarté						



Alignment can be many-to-many (phrase-level)

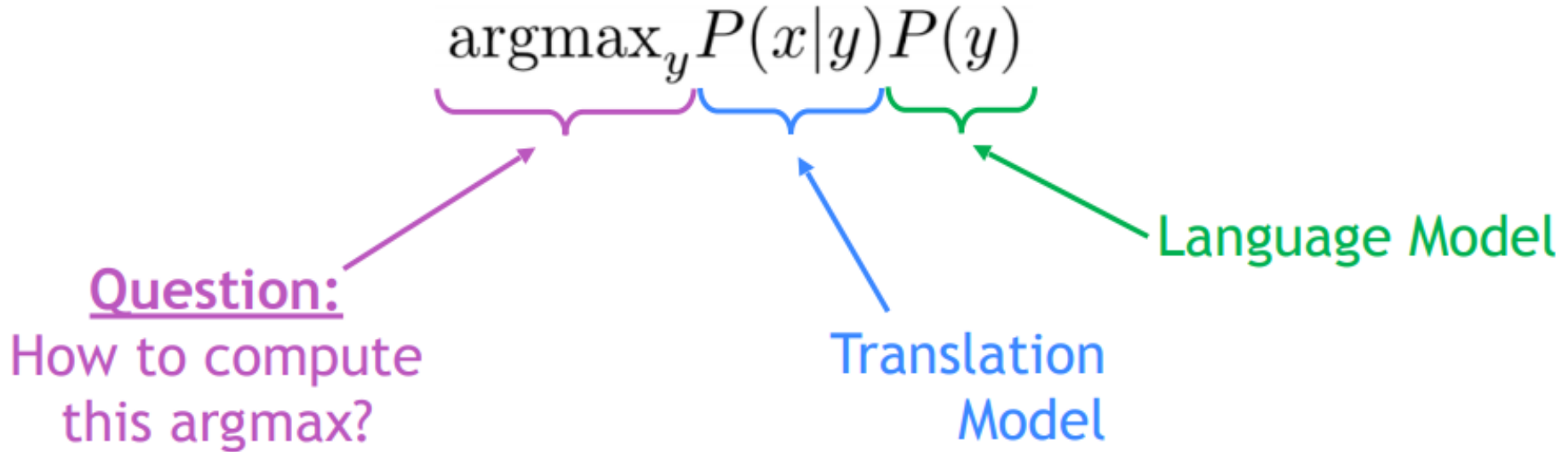


Examples from: "The Mathematics of Statistical Machine Translation: Parameter Estimation", Brown et al, 1993.
<http://www.aclweb.org/anthology/J93-2003>

Learning alignment for SMT

- We learn $P(x, a|y)$ as a combination of many factors, including:
 - Probability of particular words aligning (also depends on position in sent)
 - Probability of particular words having particular fertility (number of corresponding words)
 - etc.
- Alignments a are **latent variables**: They aren't explicitly specified in the data!
 - Require the use of special learning algos (like ExpectationMaximization) for learning the parameters of distributions with latent variables

Decoding for MT

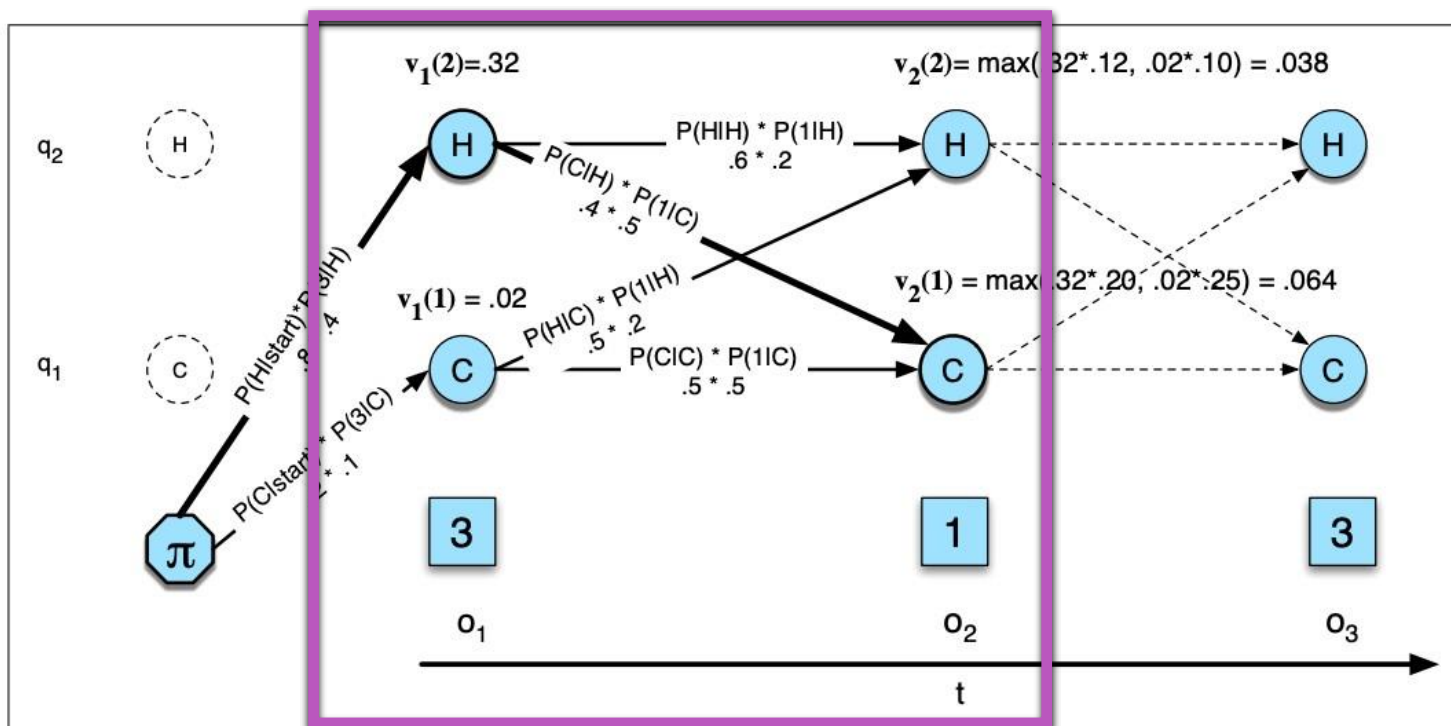


- We could enumerate every possible y and calculate the probability?
→ Too expensive!
- Answer: Impose strong **independence assumptions** in model, use dynamic programming for globally optimal solutions (e.g. Viterbi algorithm).
- This process is called **decoding**

Viterbi: Decoding with Dynamic Programming

- Impose strong **independence assumptions** in model:

$$p(x, a|y) = \prod_{j=1}^{l_x} p(x_j | f_{a(j)})$$



Source: "Speech and Language Processing", Chapter A, Jurafsky and Martin, 2019.

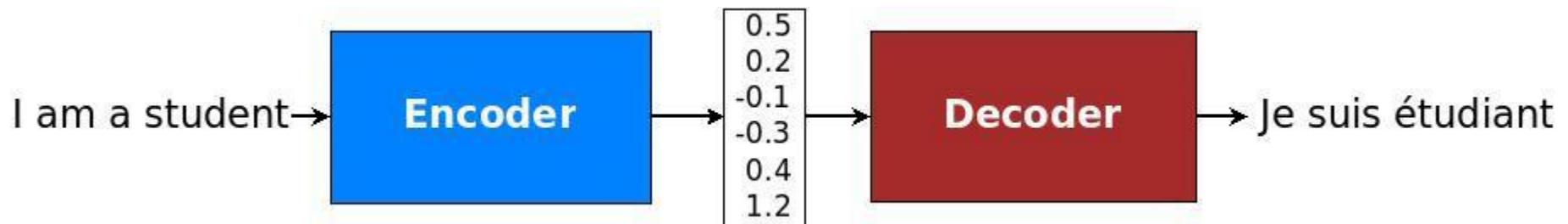
1990s-2010s: Statistical Machine Translation

- SMT was a huge research field
- The best systems were extremely complex
- Hundreds of important details we haven't mentioned here
- Systems had many separately designed subcomponents
- Lots of feature engineering
- Need to design features to capture particular language phenomena
- Require compiling and maintaining extra resources
 - Like tables of equivalent phrases
- Lots of human effort to maintain
 - Repeated effort for each language pair!

Section 2: Neural Machine Translation

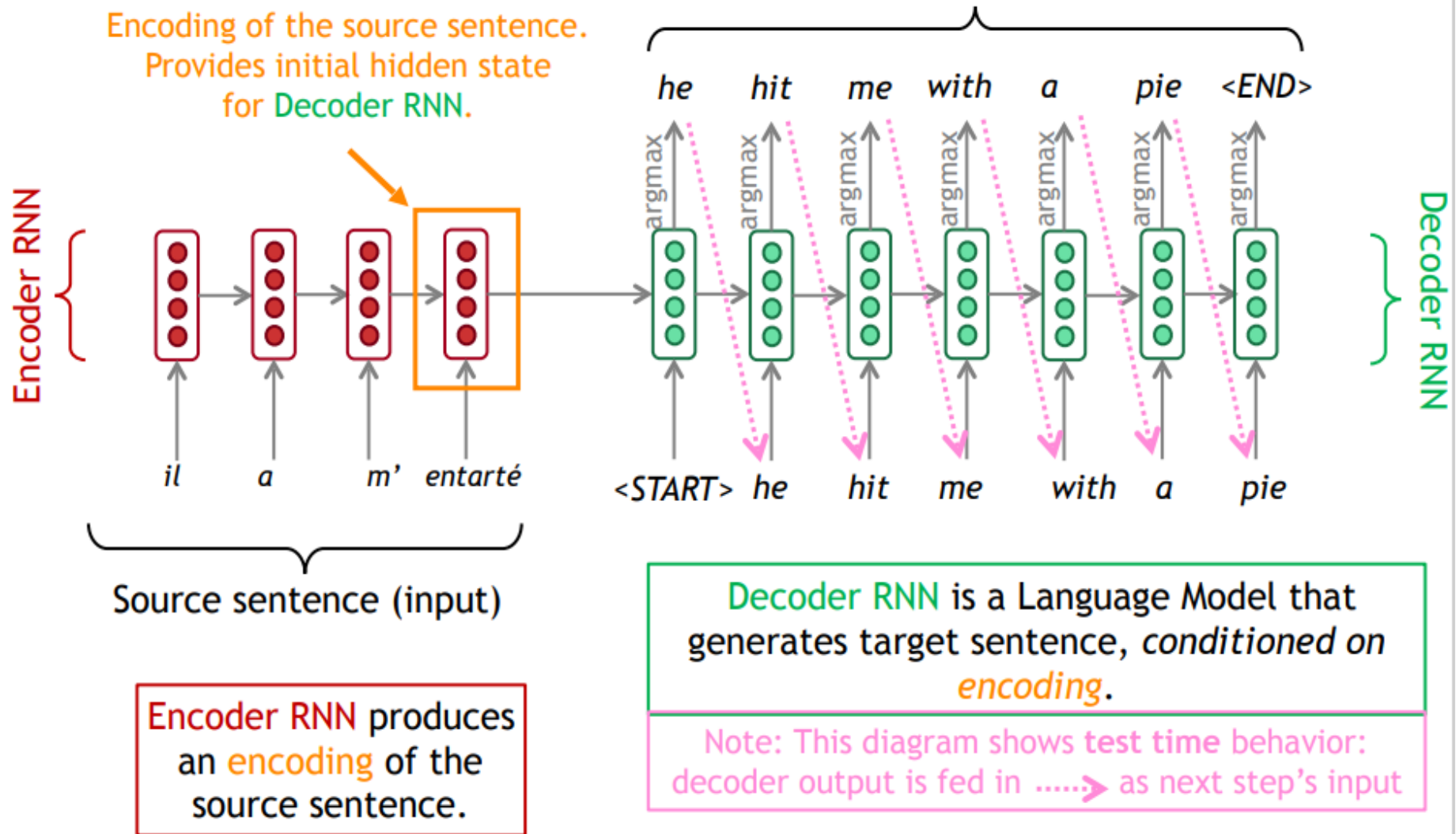
What is Neural Machine Translation?

- Neural Machine Translation (NMT) is a way to do Machine Translation with a *single neural network*
- The neural network architecture is called **sequence-to-sequence** (aka **seq2seq**) and it involves *two* RNNs.



Neural Machine Translation (NMT)

The sequence-to-sequence model



Sequence-to-sequence is versatile!

- Sequence-to-sequence is useful for *more than just MT*
- Many NLP tasks can be phrased as sequence-to-sequence:
 - **Summarization** (long text → short text)
 - **Dialogue** (previous utterances → next utterance)
 - **Parsing** (input text → output parse as sequence)
 - **Code generation** (natural language → Python code)

Neural Machine Translation (NMT)

- The **sequence-to-sequence** model is an example of a **Conditional Language Model**.
 - **Language Model** because the decoder is predicting the next word of the target sentence y
 - **Conditional** because its predictions are *also* conditioned on the source sentence x

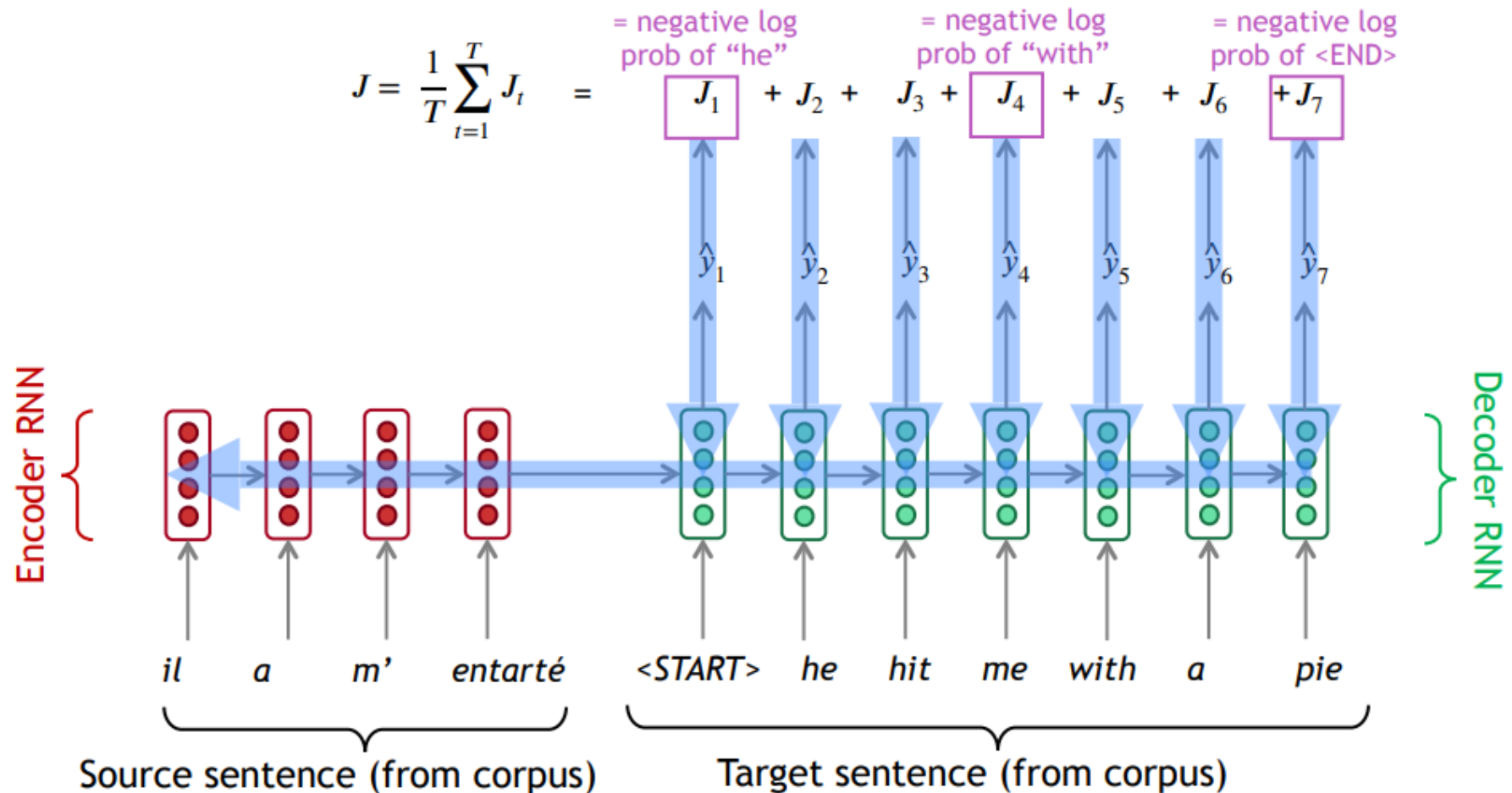
- NMT directly calculates $P(y|x)$:

$$P(y|x) = P(y_1|x) P(y_2|y_1, x) P(y_3|y_1, y_2, x) \dots P(y_T|y_1, \dots, y_{T-1}, x)$$

Probability of next target word, given
target words so far and source
sentence x

- **Question:** How to **train** a NMT system?
- **Answer:** Get a big parallel corpus...

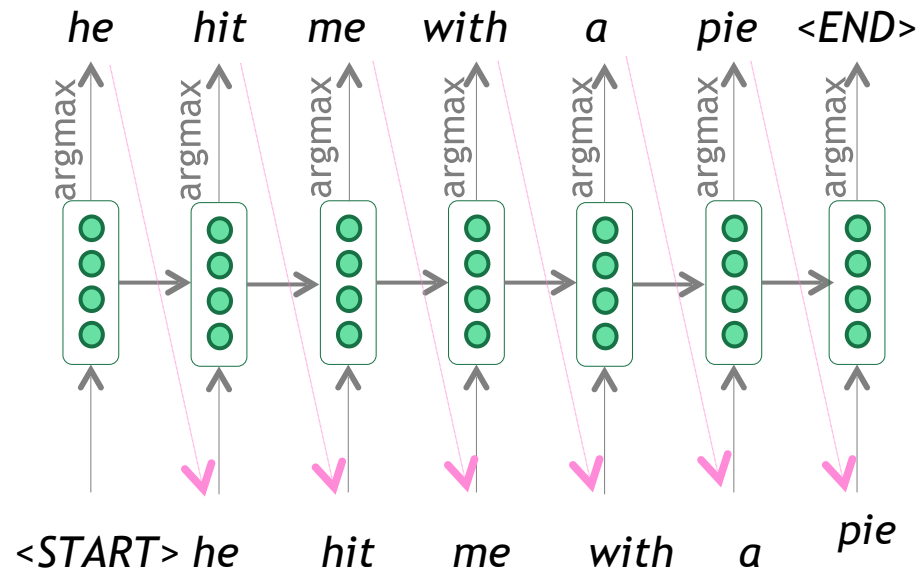
Training a Neural Machine Translation system



Seq2seq is optimized as a single system.
Backpropagation operates "end-to-end".

Greedy decoding

- We saw how to generate (or “decode”) the target sentence by taking argmax on each step of the decoder



- This is **greedy decoding** (take most probable word on each step)
- **Problems with this method?**

Problems with greedy decoding

- Greedy decoding has no way to undo decisions!
- Input: *il a m'entarté* (he hit me with a pie)
- → *he* _____
- → *he hit* _____
- → *he hit a* _____ (whoops! no going back now...)
- How to fix this?

Exhaustive search decoding

- Ideally, we want to find a (length T) translation y that maximizes

$$\begin{aligned} P(y|x) &= P(y_1|x) P(y_2|y_1, x) P(y_3|y_1, y_2, x) \dots, P(y_T|y_1, \dots, y_{T-1}, x) \\ &= \prod_{t=1}^T P(y_t|y_1, \dots, y_{t-1}, x) \end{aligned}$$

- We could try computing all possible sequences y
- This means that on each step t of the decoder, we're tracking V_t possible partial translations, where V is vocab size
- This $O(V_T)$ complexity is far too expensive!

Beam search decoding

- Core idea: On each step of decoder, keep track of the *k most probable* partial translations (which we call *hypotheses*)
- *k* is the *beam size* (in practice around 5 to 10)

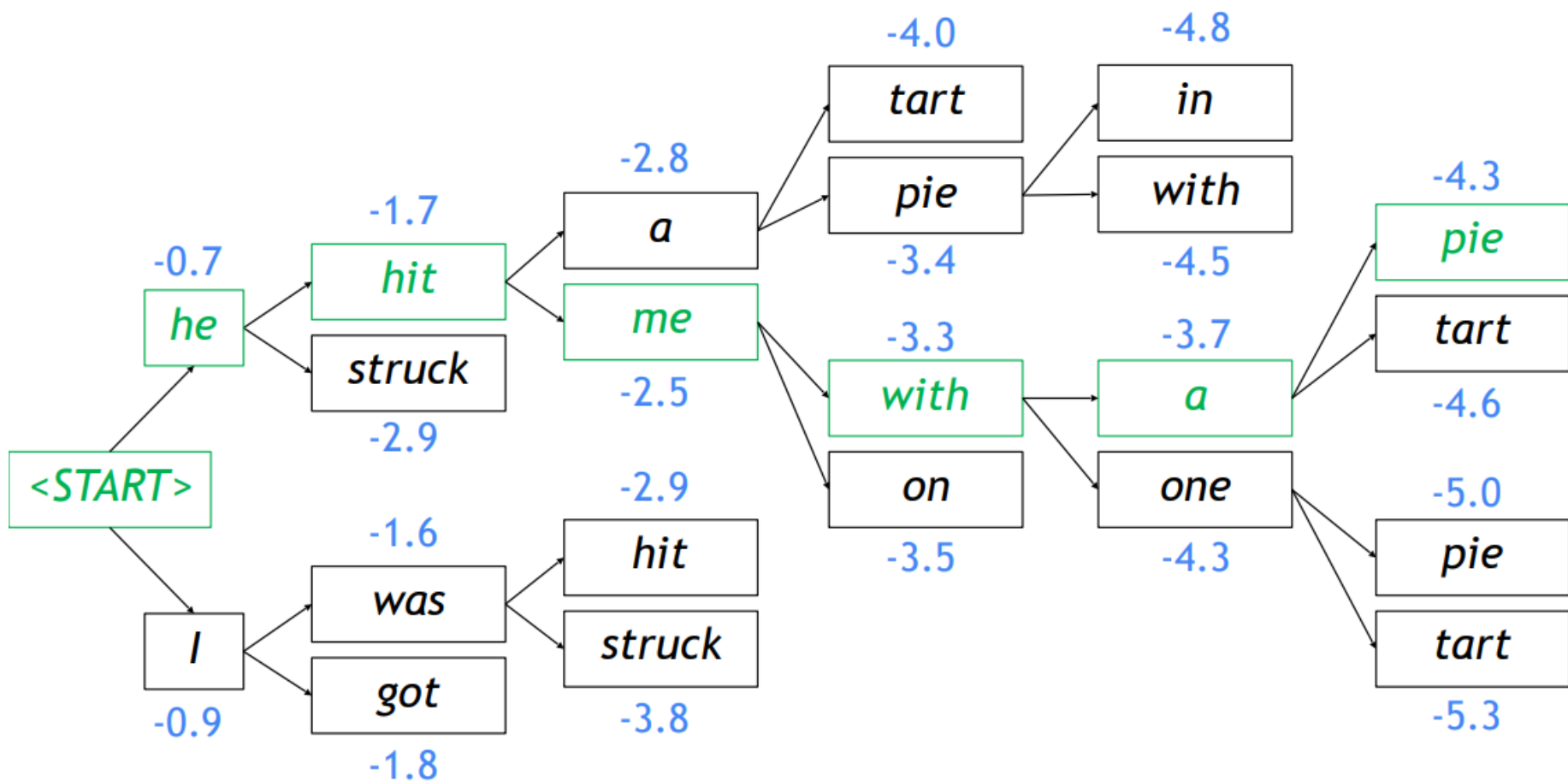
- A hypothesis y_1, \dots, y_t has a *score* which is its log probability:

$$\text{score}(y_1, \dots, y_t) = \log P_{\text{LM}}(y_1, \dots, y_t | x) = \sum_{i=1}^t \log P_{\text{LM}}(y_i | y_1, \dots, y_{i-1}, x)$$

- Scores are all negative, and higher score is better
- We search for high-scoring hypotheses, tracking top *k* on each step
- Beam search is *not guaranteed* to find optimal solution
- But *much more efficient* than exhaustive search!

Beam search decoding: example

Beam size = $k = 2$. Blue numbers = $\text{score}(y_1, \dots, y_t) = \sum_{i=1}^t \log P_{\text{LM}}(y_i | y_1, \dots, y_{i-1}, x)$



Backtrack to obtain the full hypothesis

Beam search decoding: stopping criterion

- In **greedy decoding**, usually we decode until the model produces a **<END> token**
 - For example: *<START> he hit me with a pie <END>*
- In **beam search decoding**, different hypotheses may produce **<END> tokens** on **different timesteps**
 - When a hypothesis produces **<END>**, that hypothesis is **complete**.
 - **Place it aside** and continue exploring other hypotheses via beam search.
- Usually we continue beam search until:
 - We reach timestep T (where T is some pre-defined cutoff), or
 - We have at least n completed hypotheses (where n is pre-defined cutoff)

Beam search decoding: finishing up

- We have our list of completed hypotheses.
- How to select top one with highest score?
- Each hypothesis y_1, \dots, y_t on our list has a score

$$\text{score}(y_1, \dots, y_t) = \log P_{\text{LM}}(y_1, \dots, y_t | x) = \sum_{i=1}^t \log P_{\text{LM}}(y_i | y_1, \dots, y_{i-1}, x)$$

- Problem with this: longer hypotheses have lower scores
- Fix: Normalize by length. Use this to select top one instead:

$$\frac{1}{t} \sum_{i=1}^t \log P_{\text{LM}}(y_i | y_1, \dots, y_{i-1}, x)$$

Advantages of NMT

Compared to SMT, NMT has many advantages:

- Better performance
 - More fluent
 - Better use of context
 - Better use of phrase similarities
- A single neural network to be optimized end-to-end
 - No subcomponents to be individually optimized
- Requires much less human engineering effort
 - No feature engineering
 - Same method for all language pairs

Disadvantages of NMT?

Compared to SMT:

- NMT is **less interpretable**
 - Hard to debug
- NMT is **difficult to control**
 - For example, can't easily specify rules or guidelines for translation
 - Safety concerns!

How do we evaluate Machine Translation?

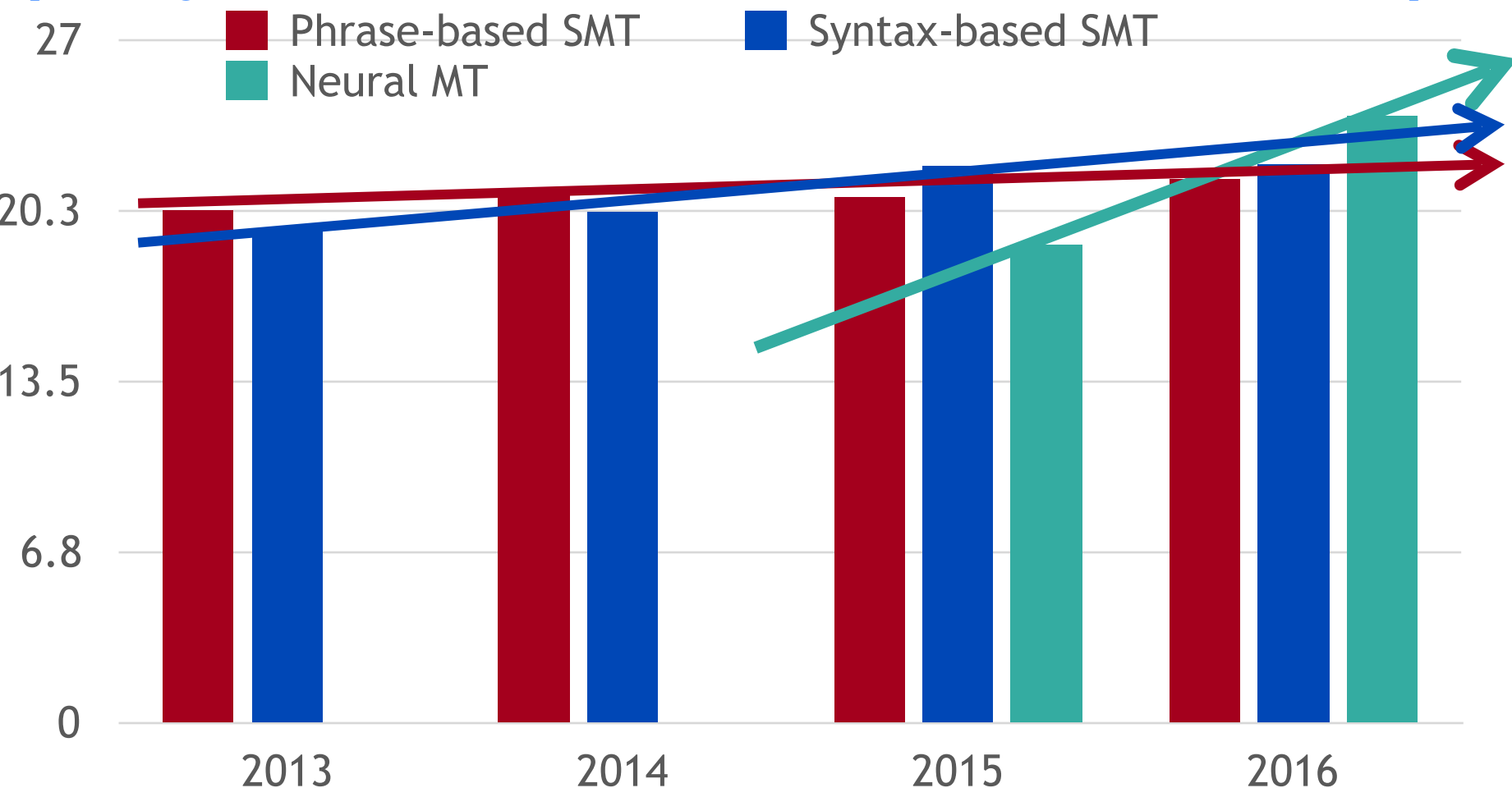
BLEU (Bilingual Evaluation Understudy)

- BLEU compares the machine-written translation to one or several human-written translation(s), and computes a **similarity score** based on:
 - ***n*-gram precision** (usually for 1, 2, 3 and 4-grams)
 - Plus a penalty for too-short system translations
- BLEU is **useful** but **imperfect**
 - There are many valid ways to translate a sentence
 - So a **good** translation can get a **poor** BLEU score because it has low *n*-gram overlap with the human translation 😞

Source: "BLEU: a Method for Automatic Evaluation of Machine Translation", Papineni et al, 2002. <http://aclweb.org/anthology/P02-1040>

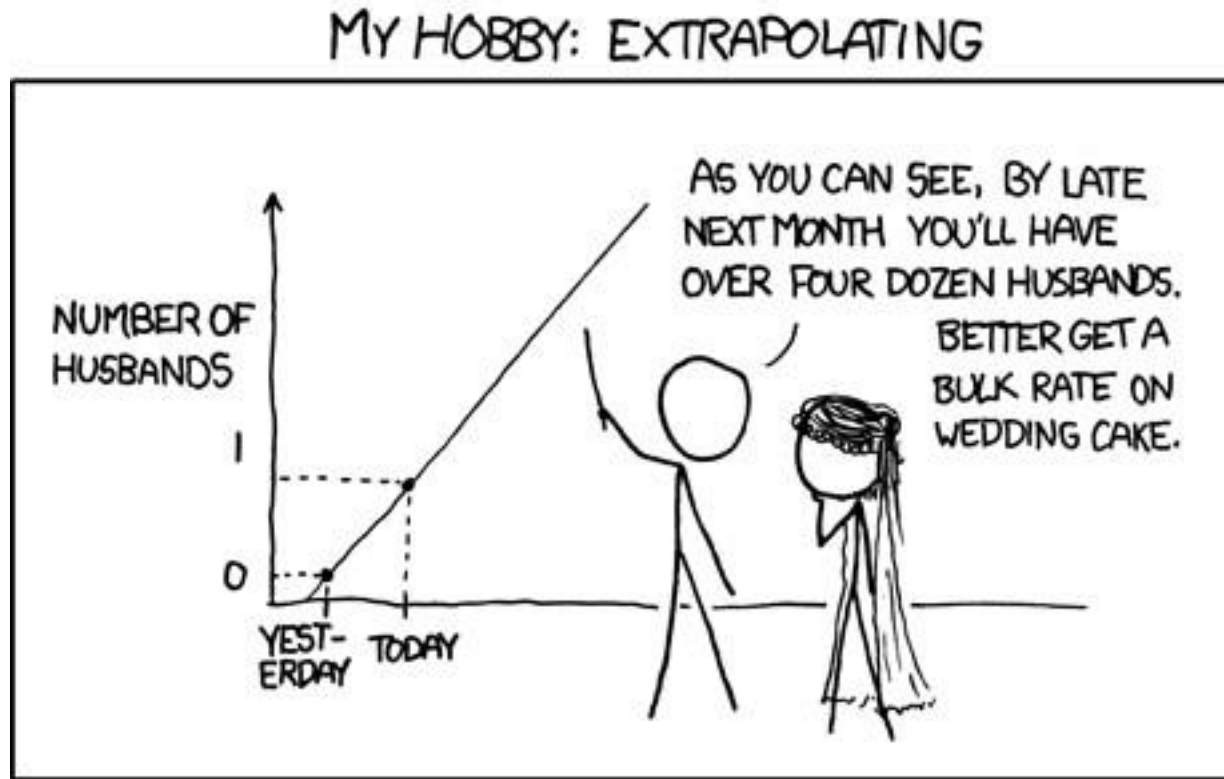
MT progress over time

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



Source: http://www.meta-net.eu/events/meta-forum-2016/slides/09_sennrich.pdf

MT progress over time



NMT: the biggest success story of NLP Deep Learning

Neural Machine Translation went from a fringe research activity in 2014 to the leading standard method in 2016

- 2014: First seq2seq paper published
- 2016: Google Translate switches from SMT to NMT
- This is amazing!
 - SMT systems, built by hundreds of engineers over many years, outperformed by NMT systems trained by a handful of engineers in a few months

So is Machine Translation solved?

- **Nope!**
- Many difficulties remain:
 - Out-of-vocabulary words
 - Domain mismatch between train and test data
 - Maintaining context over longer text
 - Low-resource language pairs

Further reading: *“Has AI surpassed humans at translation? Not even close!”*
https://www.skynettoday.com/editorials/state_of_nmt

So is Machine Translation solved?

- **Nope!**
- Using **common sense** is still hard
- Idioms are difficult to translate

SPANISH - DETECTED HINDI SPANISH ENGLISH ↕ ENGLISH SPANISH ARABIC

Mi amigo no tiene pelos en la lengua × My friend has no hair on the tongue ☆

36/5000 🔊 📄 ✎ 🔗

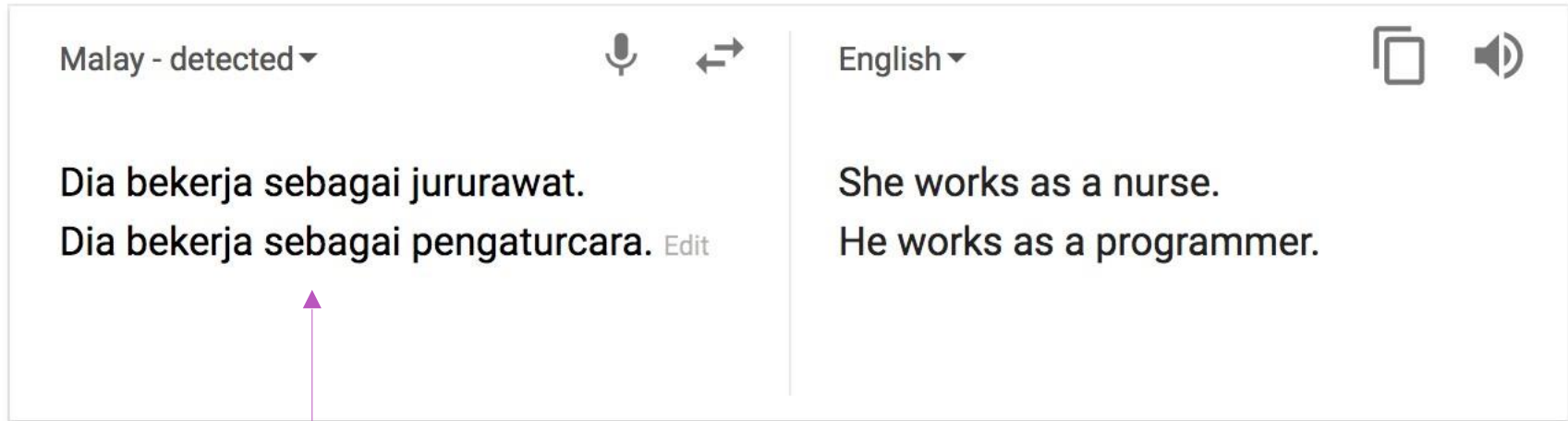
HINDI - DETECTED ENGLISH SPANISH FRENCH ↕ ENGLISH SPANISH ARABIC

जब श्याम को पता चला की वो परीक्षा में विफल हो गया, तब उसका चहरा उतर गया. × When Shyam came to know that he failed the exam, his face went down. ☆

jab shyaam ko pata chala kee vo pareeksha mein viphal ho gaya, tab usaka chahara utar gaya. 72/5000 🔊 📄 ✎ 🔗

So is Machine Translation solved?

- **Nope!**
- NMT picks up **biases** in training data

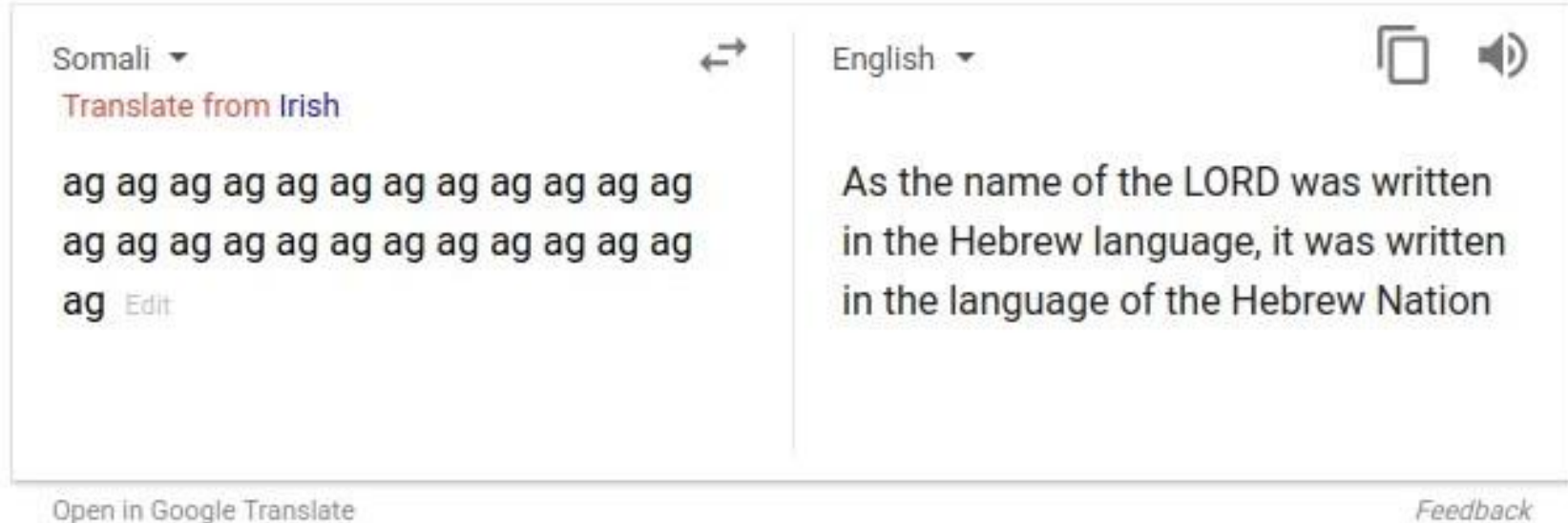


Didn't specify gender

Source: <https://hackernoon.com/bias-sexist-or-this-is-the-way-it-should-bece1f7c8c683c>

So is Machine Translation solved?

- Nope!
- Uninterpretable systems do strange things



Picture source: https://www.vice.com/en_uk/article/j5npeg/why-is-google-translate-spitting-out-sinisterreligious-prophecies

Explanation: <https://www.skynettoday.com/briefs/google-nmt-prophecies>

NMT research continues

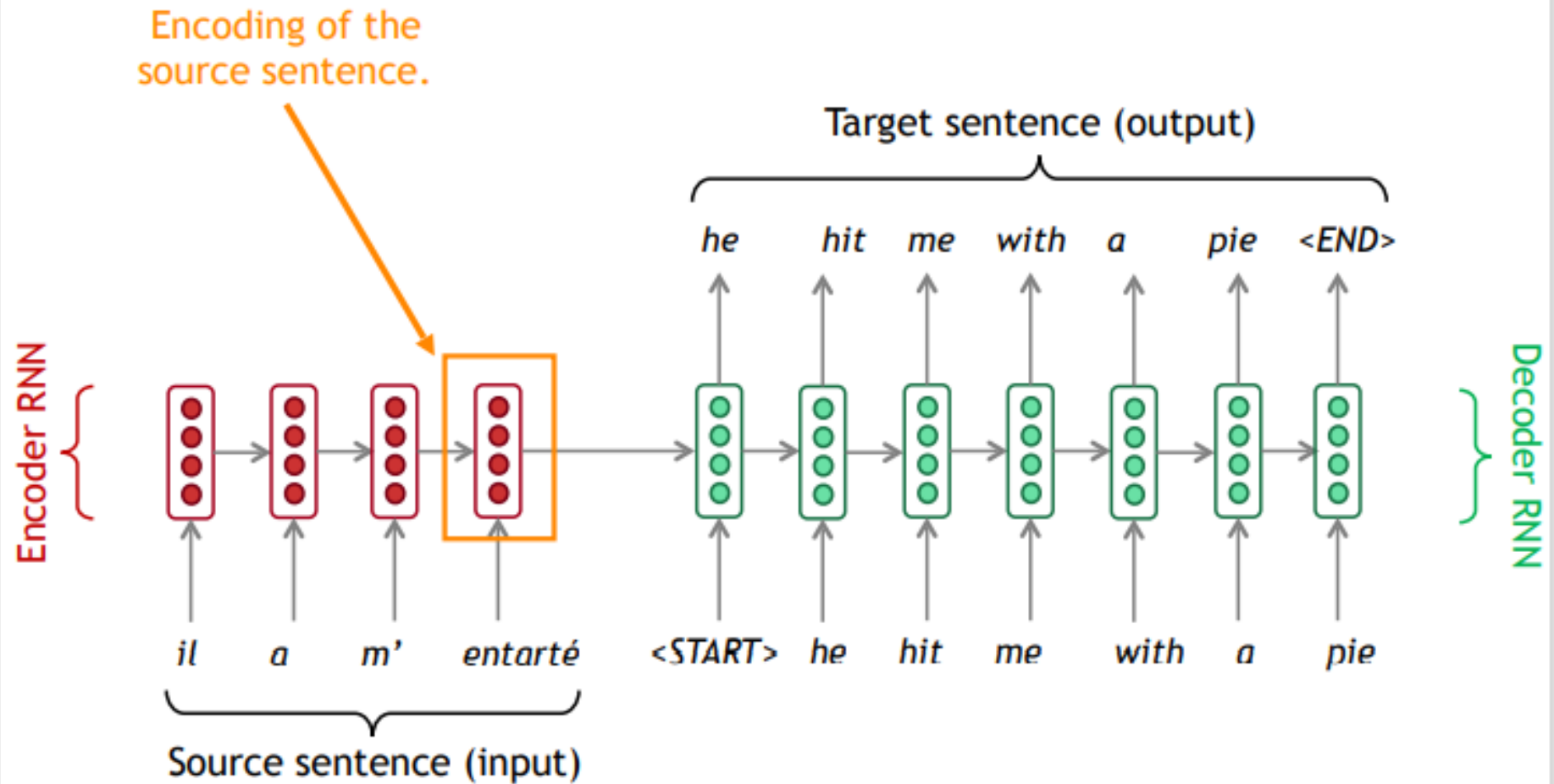
NMT is the **flagship task** for NLP Deep Learning

- NMT research has **pioneered** many of the recent **innovations** of NLP Deep Learning
- In **2019**: NMT research continues to **thrive**
- Researchers have found **many, many improvements** to the “vanilla” seq2seq NMT system we’ve presented today
 - But **one improvement** is so integral that it is the new vanilla...

ATTENTION

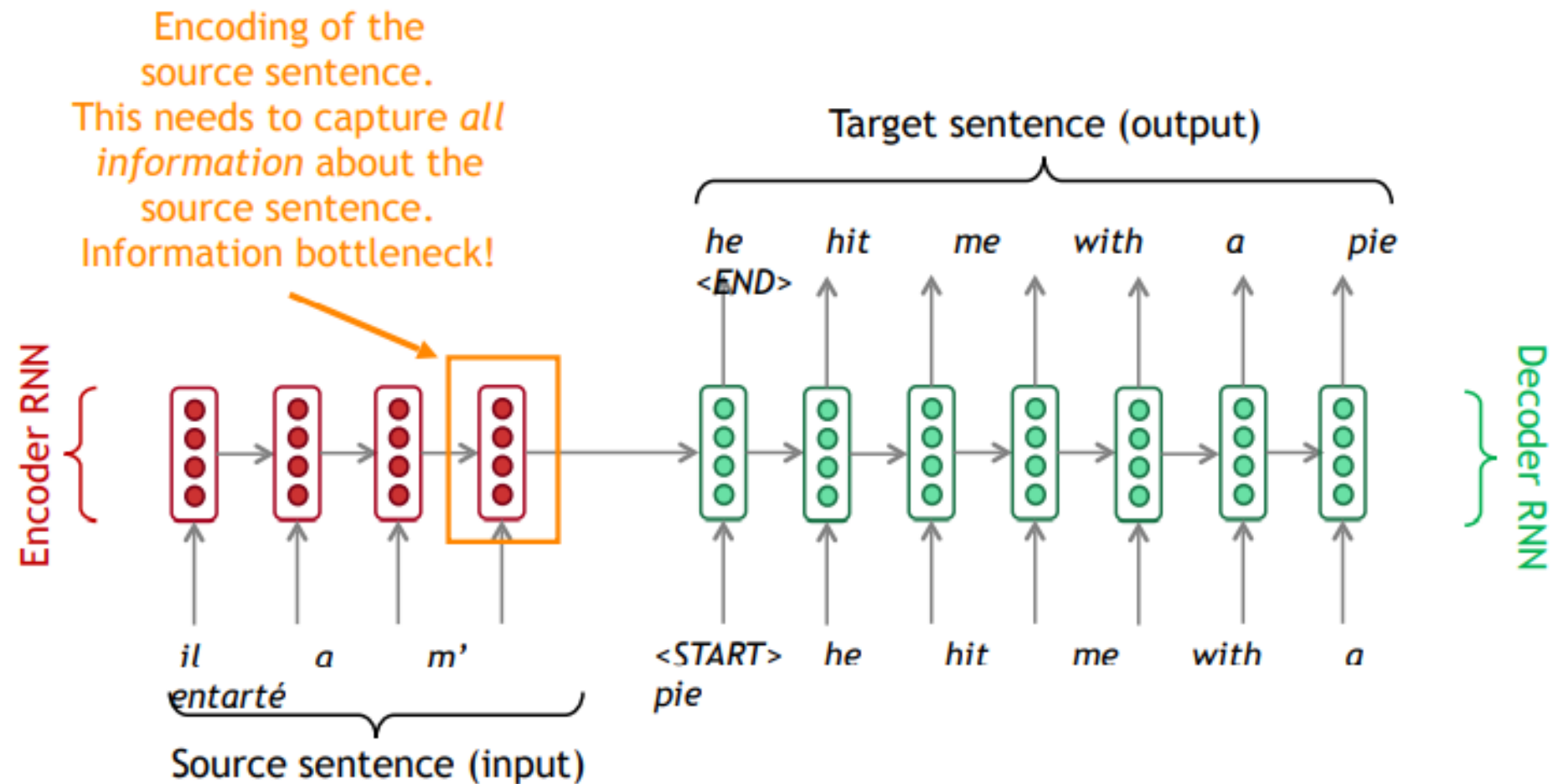
Section 3: Attention

Sequence-to-sequence: the bottleneck problem



Problems with this architecture?

Sequence-to-sequence: the bottleneck problem



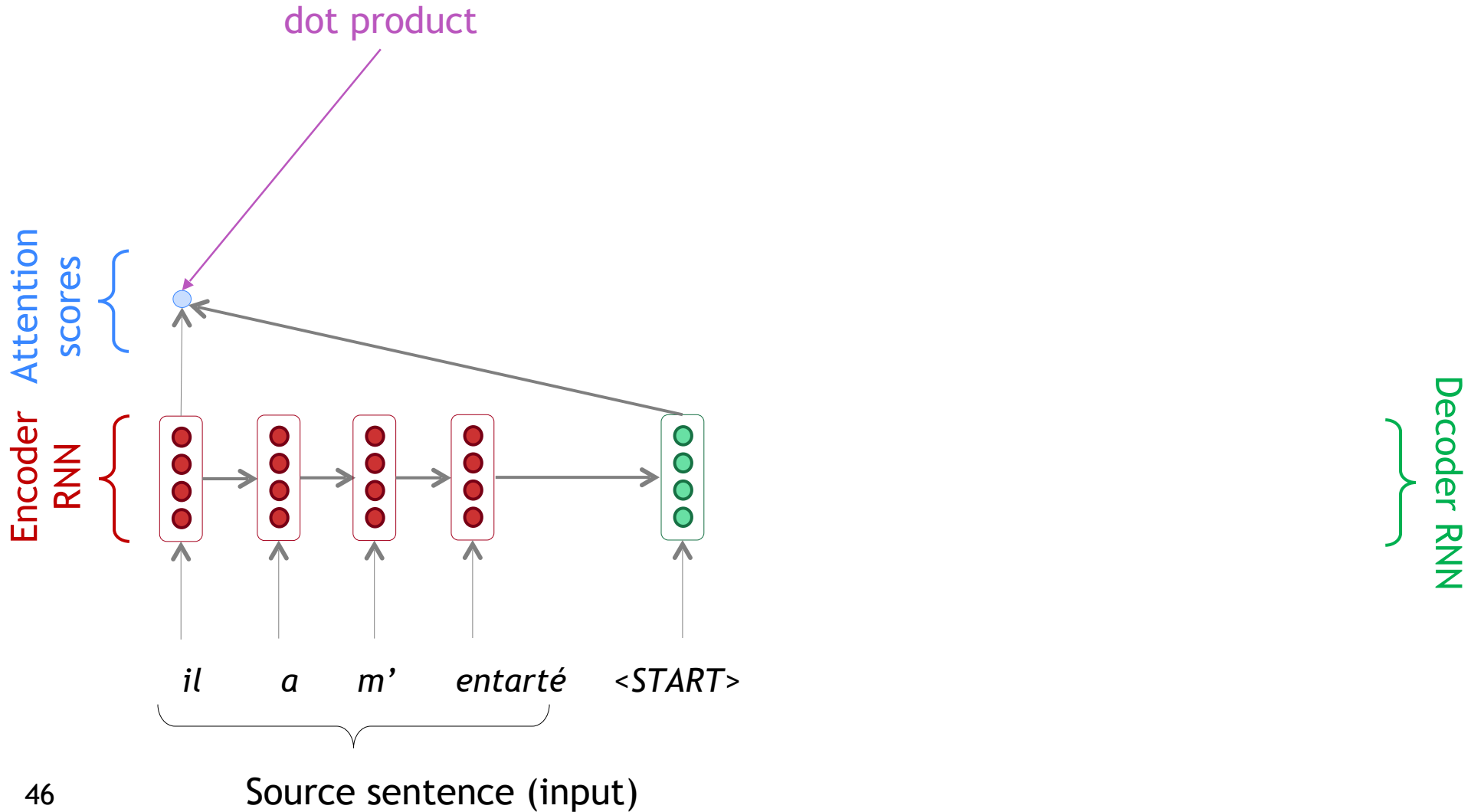
Attention

- **Attention** provides a solution to the bottleneck problem.
- Core idea: on each step of the decoder, use *direct connection to the encoder* to *focus on a particular part* of the source sequence

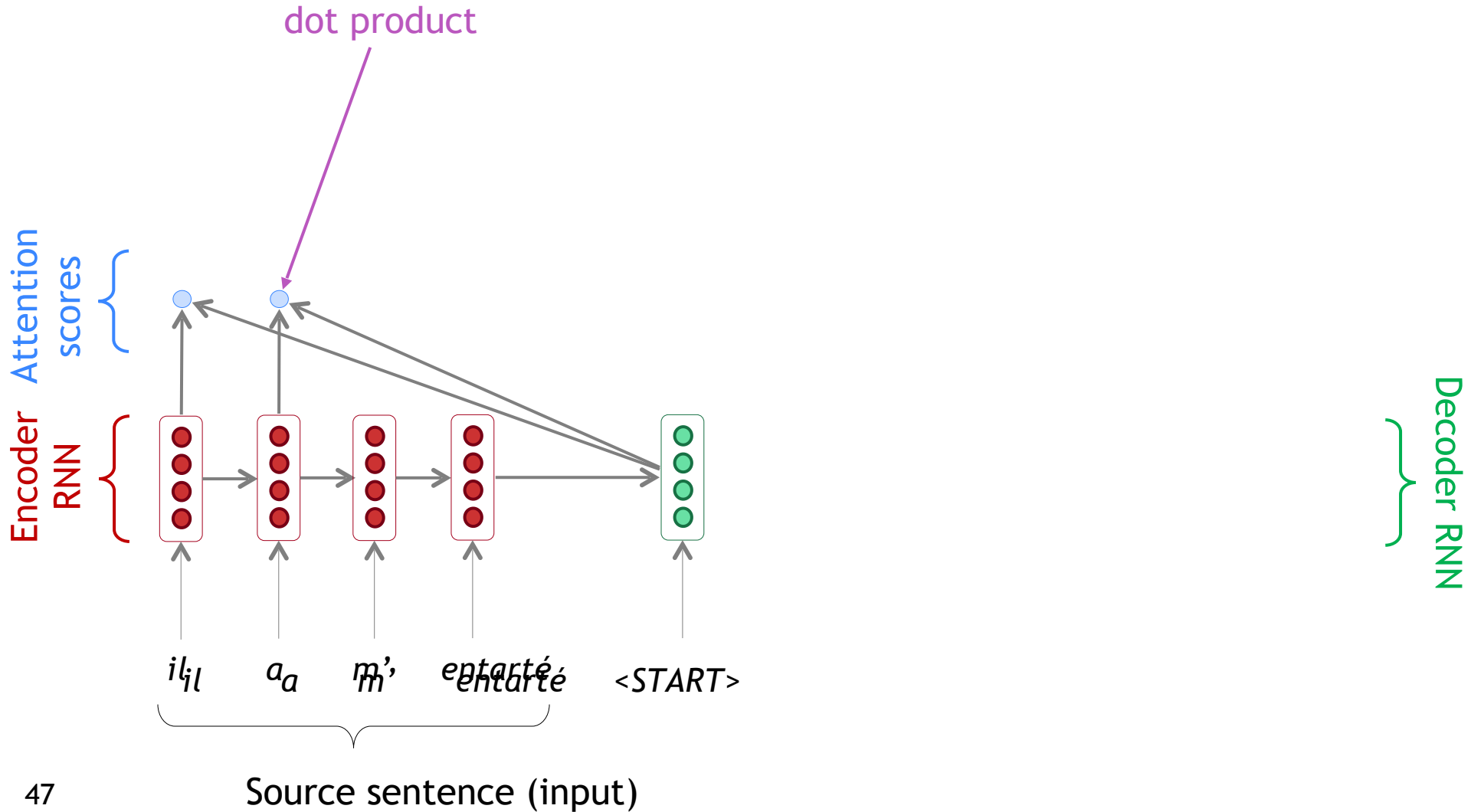


- First we will show via diagram (no equations), then we will show with equations

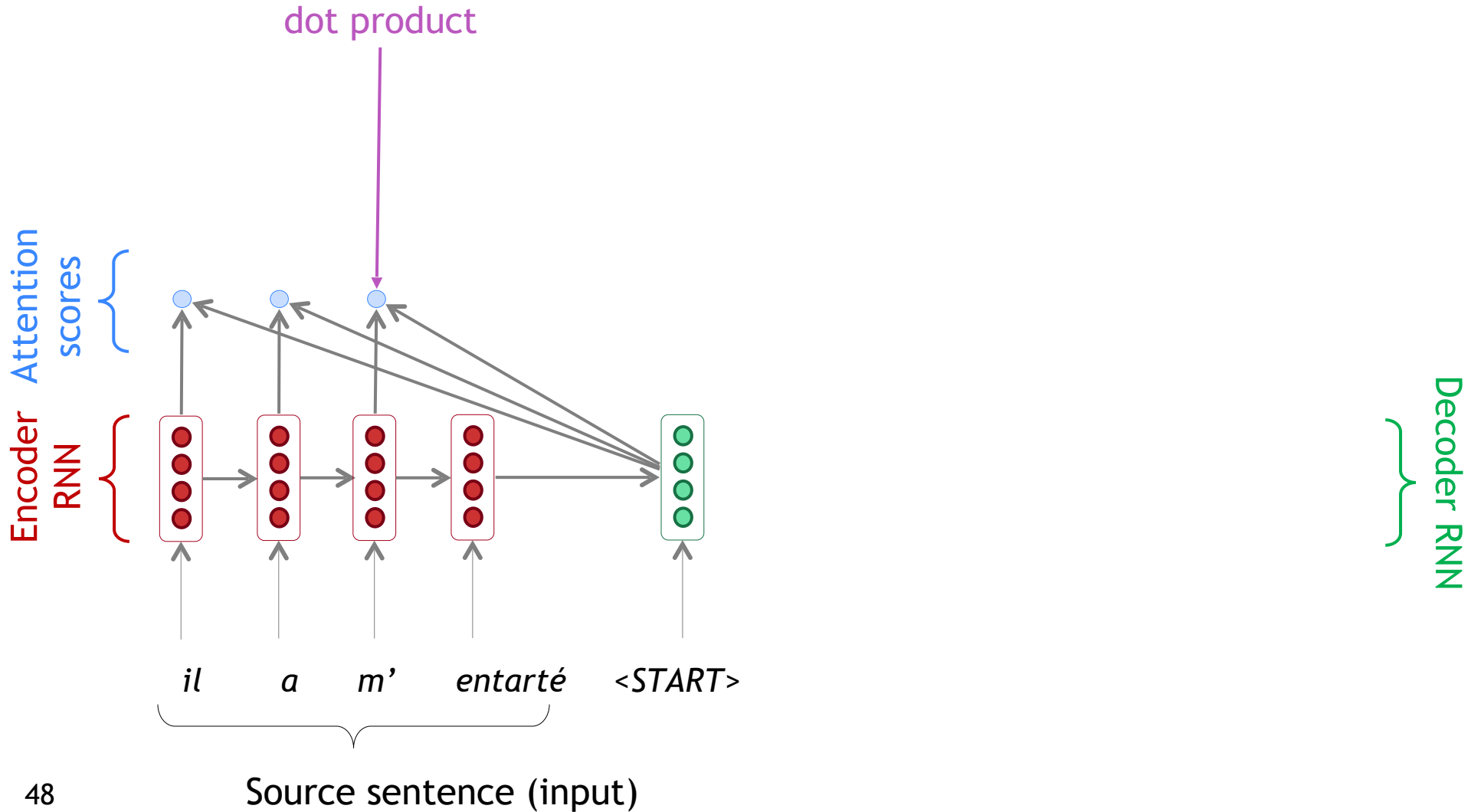
Sequence-to-sequence with attention

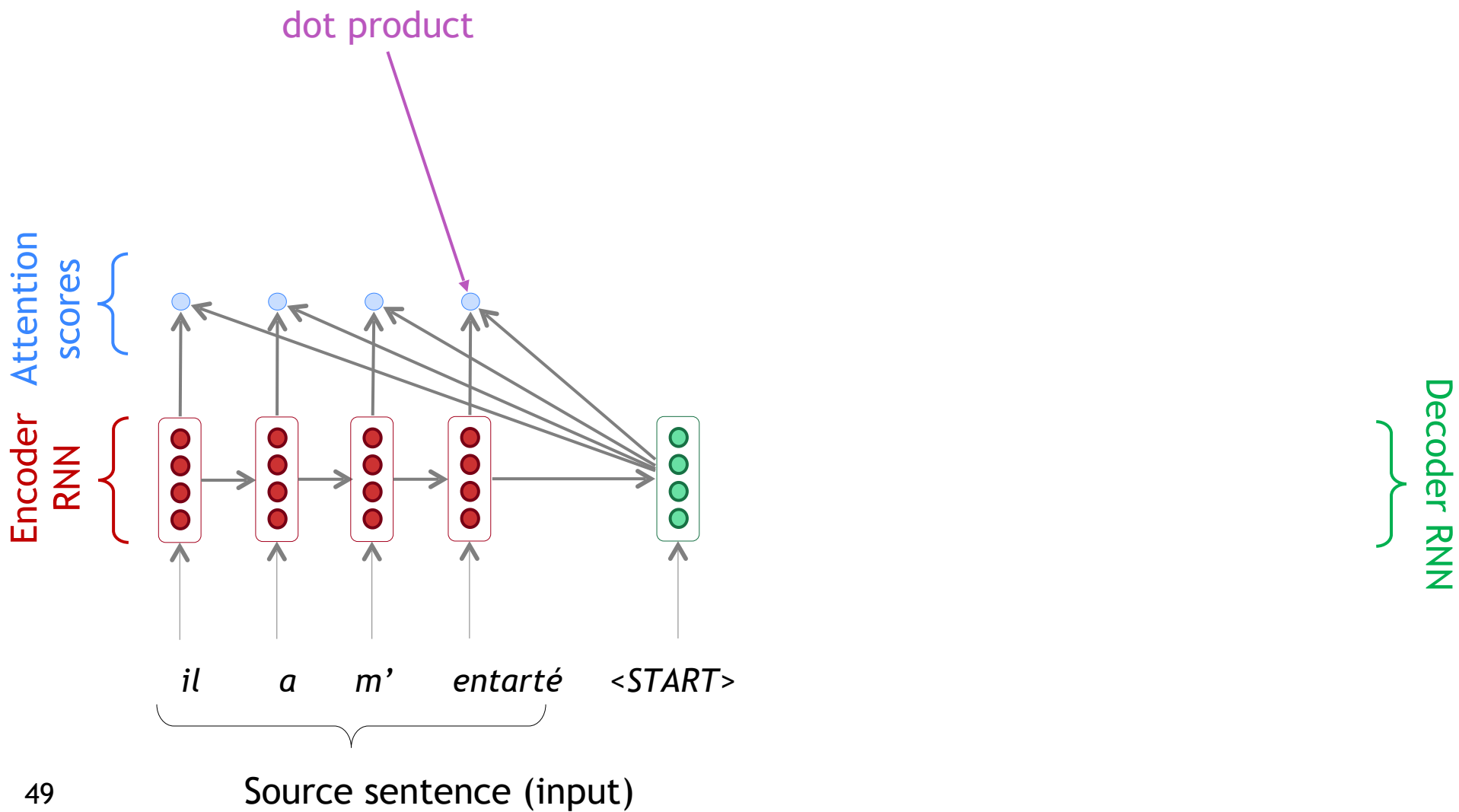


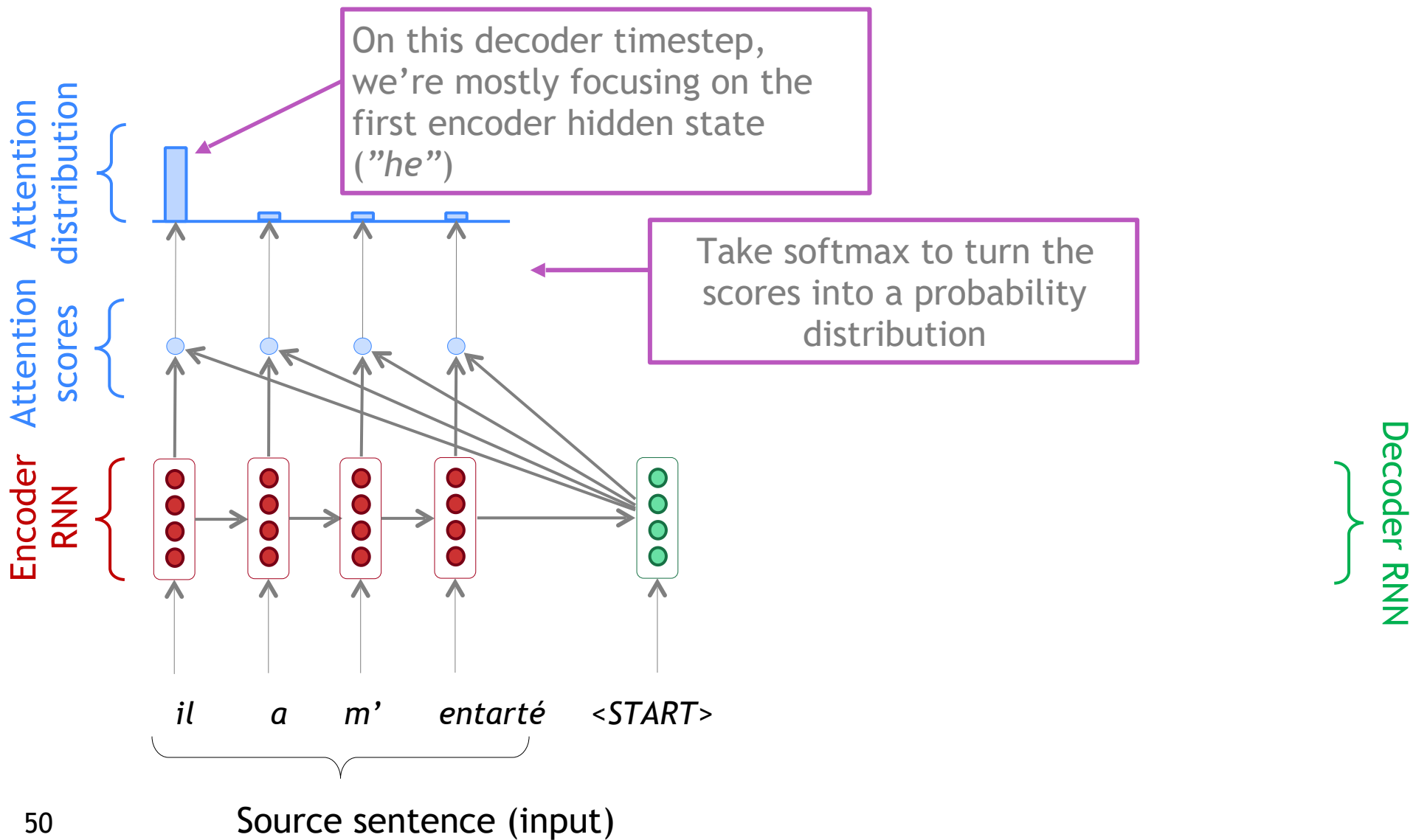
Sequence-to-sequence with attention

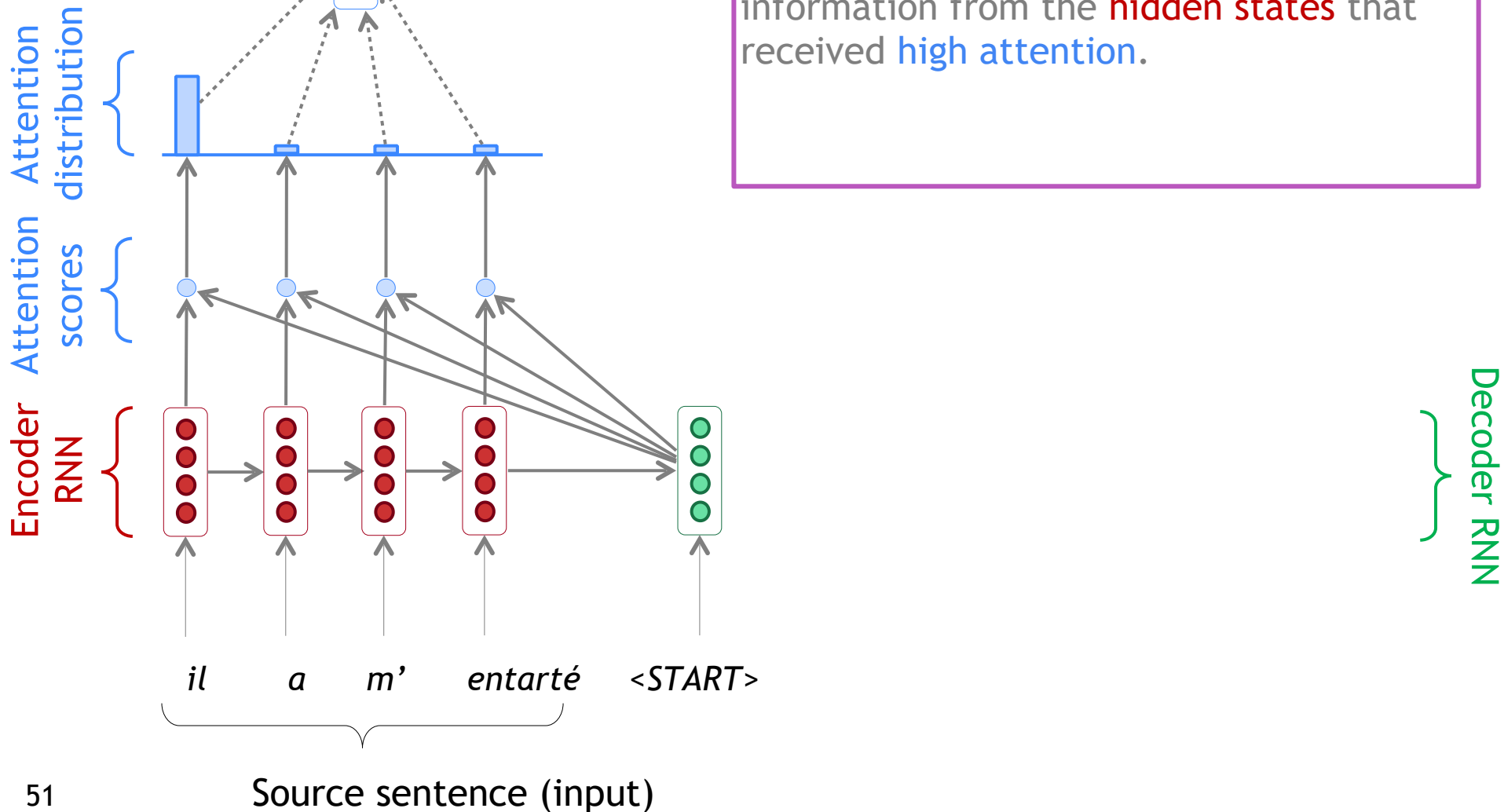


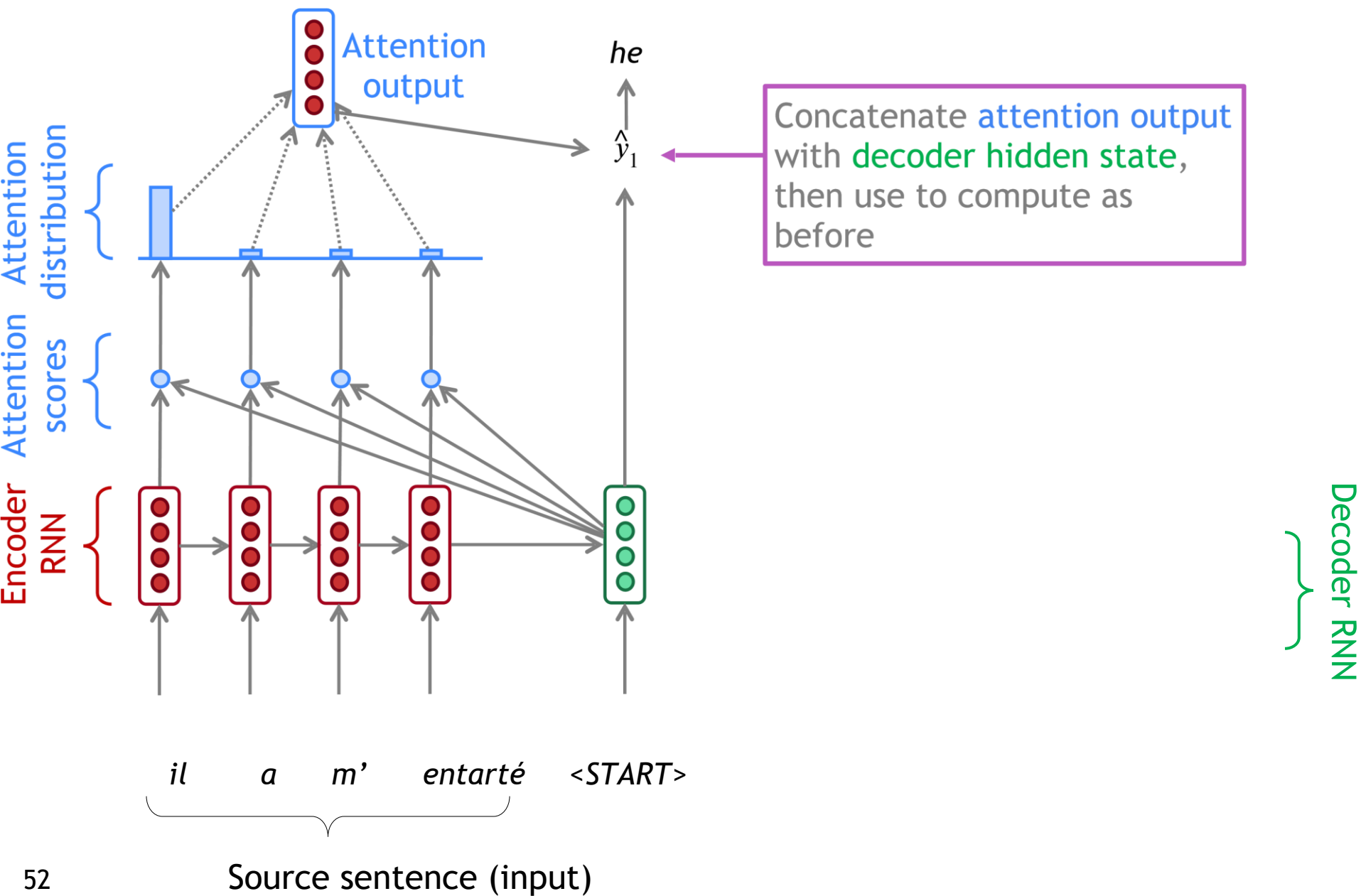
Sequence-to-sequence with attention

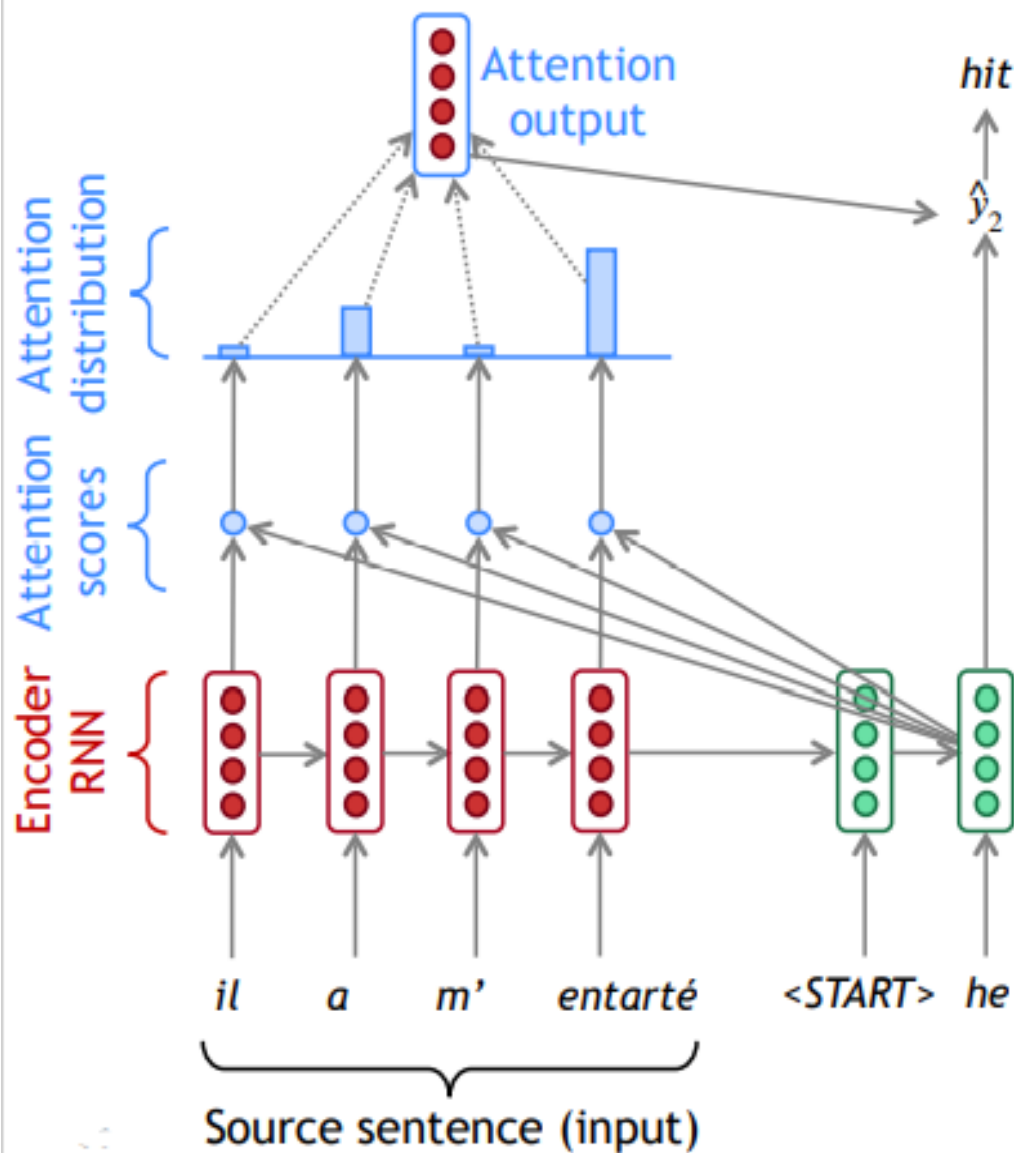






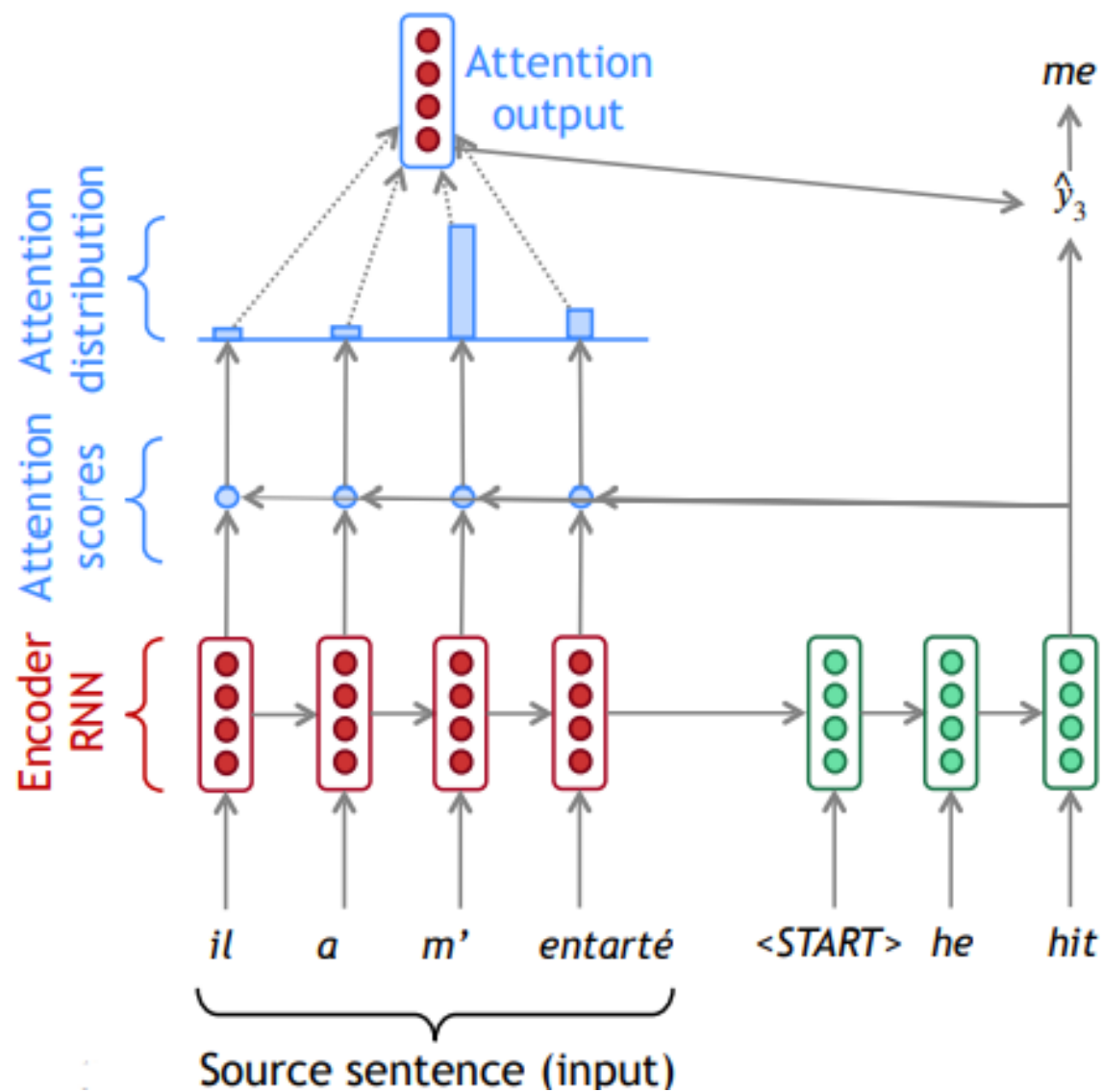






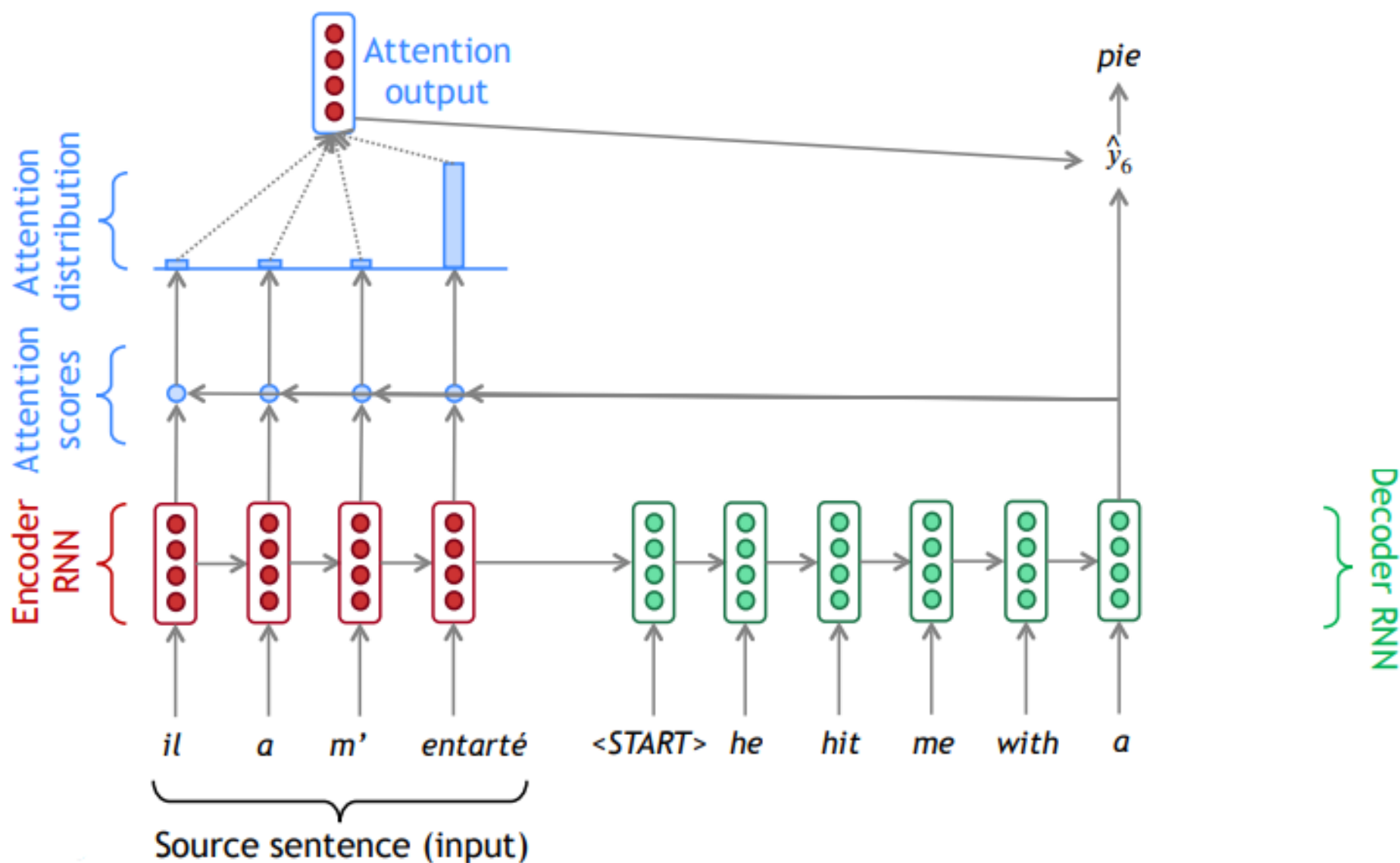
Sometimes we take the **attention output** from the previous step, and also feed it into the decoder (along with the usual decoder input).

Decoder RNN



Decoder RNN

Sequence-to-sequence with attention



Attention: in equations

- We have encoder hidden states $h_1, \dots, h_N \in \mathbb{R}^h$
- On timestep t , we have decoder hidden state $s_t \in \mathbb{R}^h$
- We get the attention scores e^t for this step:

$$e^t = [s_t^T h_1, \dots, s_t^T h_N] \in \mathbb{R}^N$$

- We take softmax to get the attention distribution α^t for this step (this is a probability distribution and sums to 1)

$$\alpha^t = \text{softmax}(e^t) \in \mathbb{R}^N$$

- We use α^t to take a weighted sum of the encoder hidden states to get the attention output

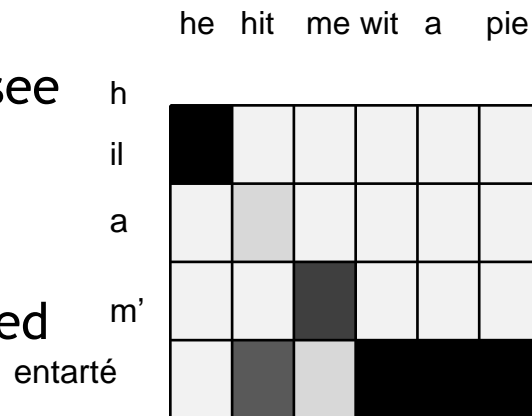
$$a_t = \sum_{i=1}^N \alpha_i^t h_i \in \mathbb{R}^h$$

- Finally we concatenate the attention output a_t with the decoder hidden state s_t and proceed as in the non-attention seq2seq model

$$[a_t; s_t] \in \mathbb{R}^{2h}$$

Attention is great

- Attention significantly **improves NMT performance**
 - It's very useful to allow decoder to focus on certain parts of the source
- Attention **solves the bottleneck problem**
 - Attention allows decoder to look directly at source; bypass bottleneck
- Attention **helps with vanishing gradient problem**
 - Provides shortcut to faraway states
- Attention provides **some interpretability**
 - By inspecting attention distribution, we can see what the decoder was focusing on
 - We get (soft) **alignment for free!**
 - This is cool because we never explicitly trained an alignment system
- The network just learned alignment by itself



Attention is a *general* Deep Learning technique

- We've seen that attention is a great way to improve the sequence-to-sequence model for Machine Translation.
- However: You can use attention in *many architectures* (not just seq2seq) and *many tasks* (not just MT)
- More general definition of attention:
 - Given a set of vector *values*, and a vector *query*, attention is a technique to compute a weighted sum of the values, dependent on the query.
- We sometimes say that the *query attends to the values*.
- For example, in the seq2seq + attention model, each decoder hidden state (query) *attends to* all the encoder hidden states (values).

Attention is a *general* Deep Learning technique

More general definition of attention:

Given a set of vector *values*, and a vector *query*, attention is a technique to compute a weighted sum of the values, dependent on the query.

Intuition:

- The weighted sum is a *selective summary* of the information contained in the values, where the query determines which values to focus on.
- Attention is a way to obtain a *fixed-size representation of an arbitrary set of representations* (the values), dependent on some other representation (the query).

There are *several* attention variants

- We have some *values* $\mathbf{h}_1, \dots, \mathbf{h}_N \in \mathbb{R}^{d_1}$ and a $\mathbf{s} \in \mathbb{R}^{d_2}$

- Attention always involves:

1. Computing the *attention scores* $\mathbf{e} \in \mathbb{R}^N$
2. Taking softmax to get *attention distribution* α :

There are multiple ways to do this

$$\alpha = \text{softmax}(\mathbf{e}) \in \mathbb{R}^N$$

3. Using attention distribution to take weighted sum of values:

$$\mathbf{a} = \sum_{i=1}^N \alpha_i \mathbf{h}_i \in \mathbb{R}^{d_1}$$

thus obtaining the *attention output* \mathbf{a} (sometimes called the *context vector*)

Attention variants

There are **several ways** you can compute $e \in \mathbb{R}^N$ and $s \in \mathbb{R}^{d_2}$ $h_1, \dots, h_N \in \mathbb{R}^{d_1}$

- Basic dot-product $e_i = s^T h_i \in \mathbb{R}$ attention:
- Note: this $d_1 = d_2$ assumes
- This is the version we saw earlier
- Multiplicative attention: $e_i = s^T W h_i \in \mathbb{R}$
- Where $W \in \mathbb{R}^{d_2 \times d_1}$ is a weight matrix
- Additive attention: $e_i = v^T \tanh(W_1 h_i + W_2 s) \in \mathbb{R}$
- Where $W_1 \in \mathbb{R}^{d_3 \times d_1}, W_2 \in \mathbb{R}^{d_3 \times d_2}$ are weight matrices: $v \in \mathbb{R}^{d_3}$ is a weight vector.
- d_3 (the attention dimensionality) is a hyperparameter

More information:

“Deep Learning for NLP Best Practices”, Ruder, 2017. <http://ruder.io/deep-learning-nlp-best-practices/index.html#attention>
 “Massive Exploration of Neural Machine Translation Architectures”, Britz et al, 2017, <https://arxiv.org/pdf/>

Summary

- We learned some history of Machine Translation (MT)
- Since 2014, **Neural MT** rapidly replaced intricate Statistical MT
- **Sequence-to-sequence** is the architecture for NMT (uses 2 RNNs)
- **Attention** is a way to *focus on particular parts* of the input
- Improves sequence-to-sequence a lot!

