



Natural Language Processing

Transformer and Self-Attention



Outline

1. Issues with RNNs
2. Attention as a Solution
3. Self-Attention
4. Transformer Encoder-Decoder
5. Transformer's Achievements
6. Transformer Variants

Issues with RNNs: Linear Interaction Distance

- In RNNs, the degree of words interact with each other is decided by their **distance**, but we already know that linear importance is not the right way to understand a sentence...

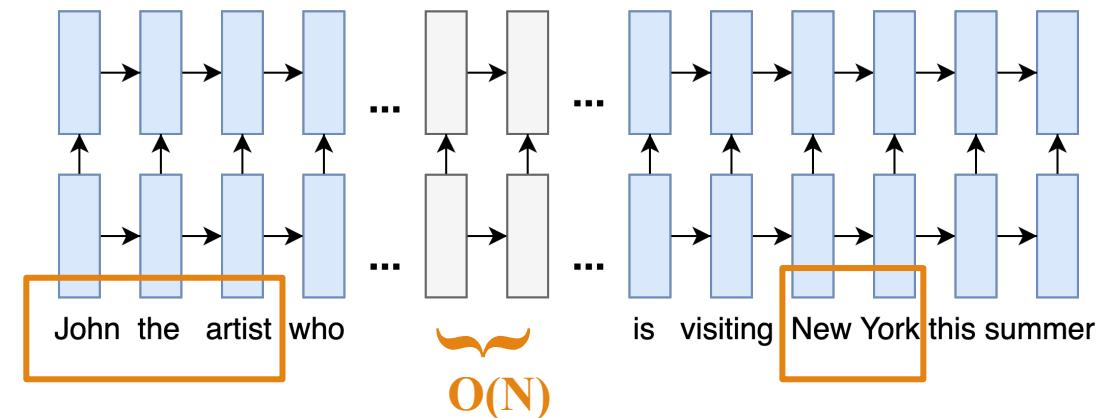
A Long Relative Clause

John, the artist **who has painted many Murals in Vienna**, is visiting New York this summer.

Where is John the artist visiting this summer?

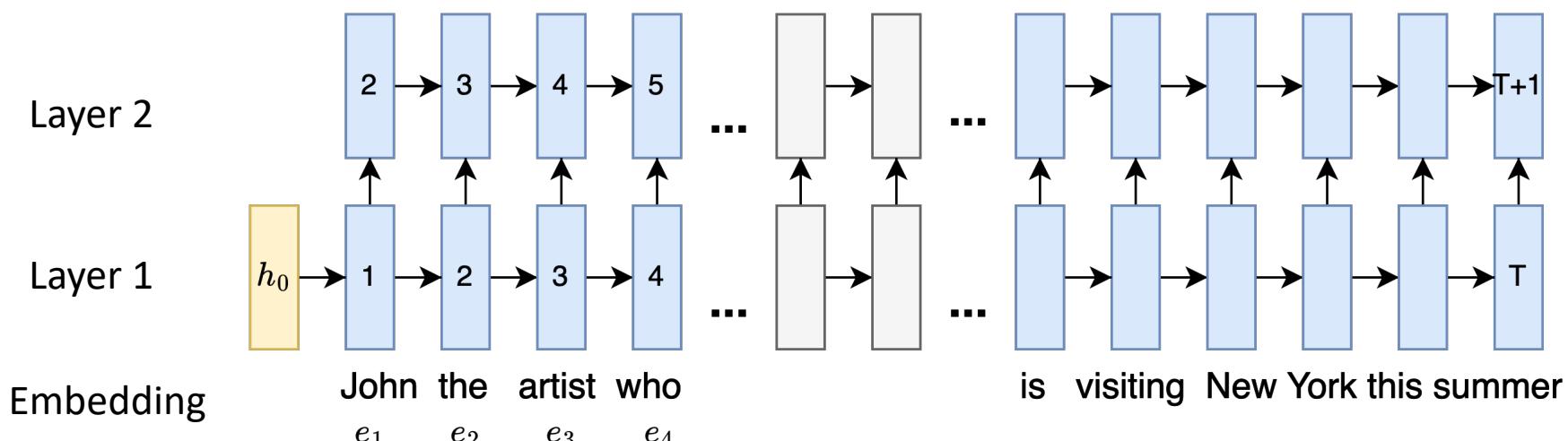
- A) Vienna
- B) New York**

▷ But the RNN may fail to identify **New York** as the correct answer since **the info of "John"** has been propagated for almost **$O(N)$** (N : sequence length).



Issues with RNNs: No Parallelizability

- Past hidden states need to be **fully** computed **before** the next hidden state to be ready for computation, which means it is **unparallelizable** between each timestep. This prevents RNN's use on large corpus or long text.

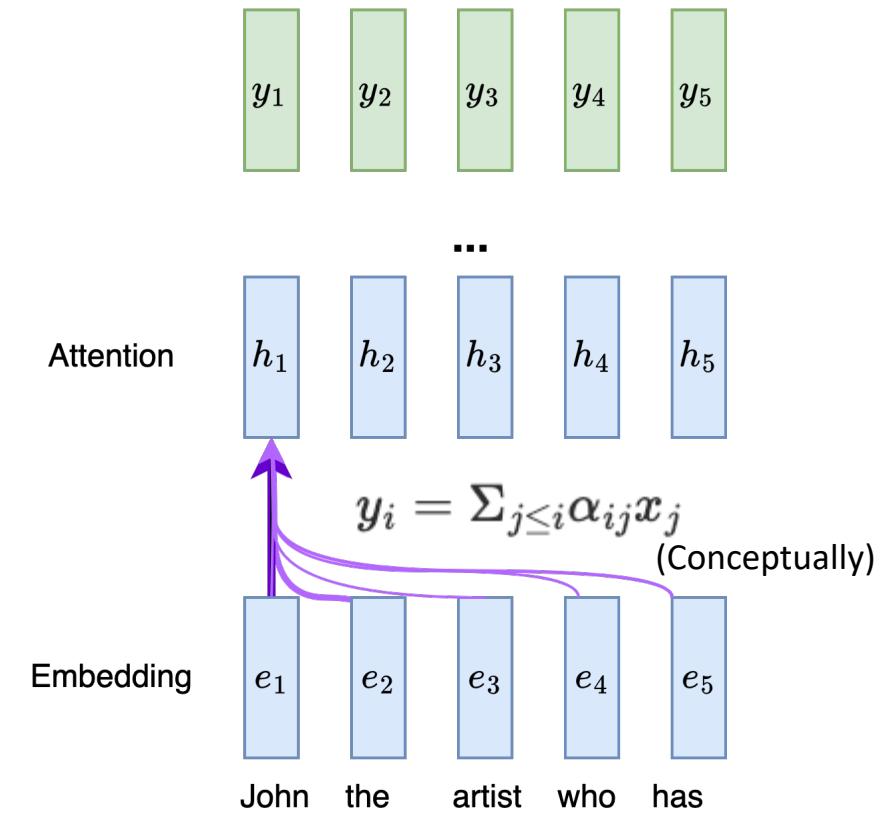


△ This is a 2-layer, uni-directional RNN. Each blue rectangle is a hidden state at the time-step of the layer. The number indicates the **min # of steps required for the hidden state to be computed**.

Attention as a Solution

- Attention within a sentence
- Every word attend to all words in the sentence between layers (solving **linear interaction distance** issue).
- α_{ij} : importance score/attention score of word i to word j.

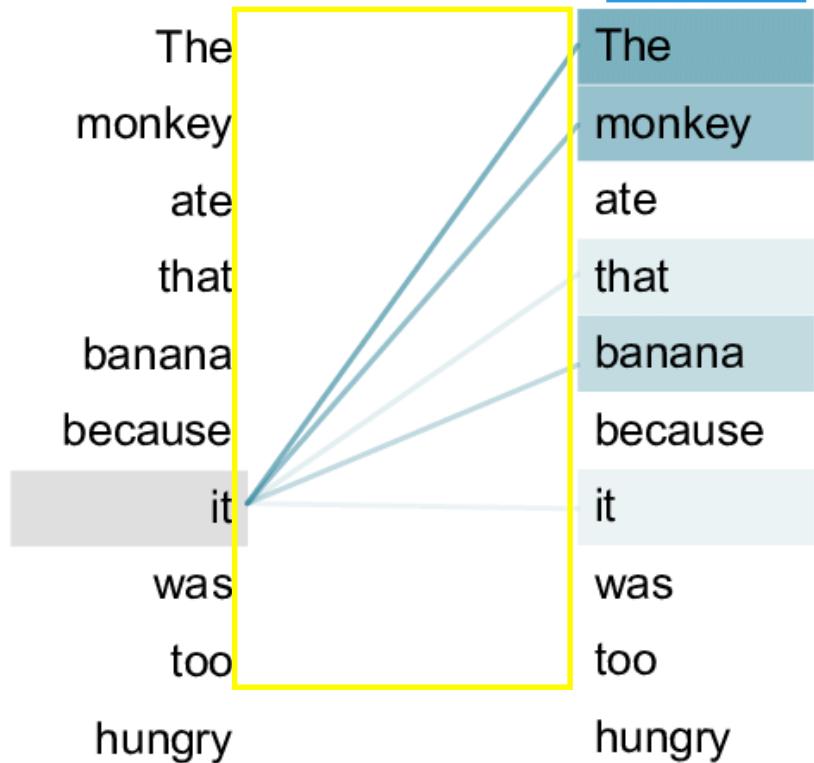
▷ We train the weight matrix α for each layer to learn “the attention score to be placed for each word on one another word.” Width of the arrow (roughly) denote how large or small each α_{ij} is.



Self-Attention

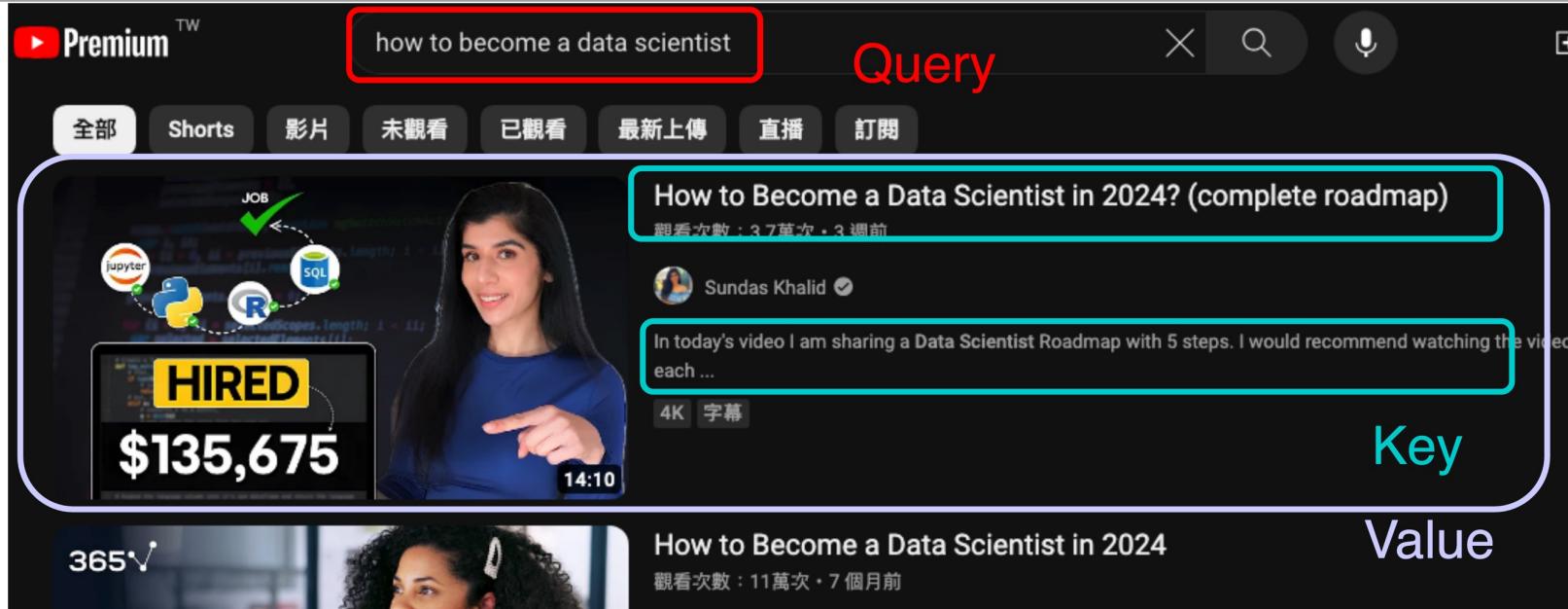
- Attention within a sentence
 - Every word attend to all words in the same sentence.
- 每個字都會將自己和句子中的其他文字算出一個權重

Source: [An example of the self-attention mechanism following long-distance...](#) | Download Scientific Diagram ([researchgate.net](#))



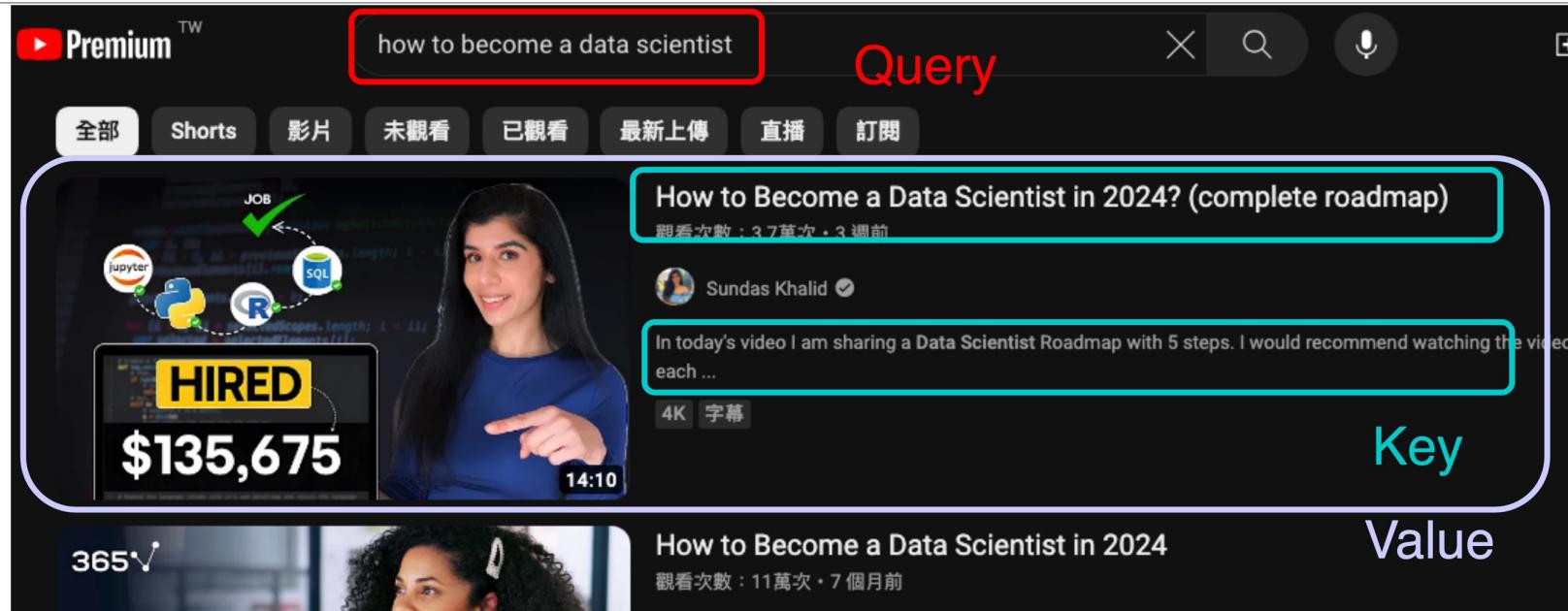
QKV Attention

Vaswani, Ashish, et al. "Attention is all you need." *Advances in neural information processing systems* 30 (2017).



- The self-attention proposed in Vaswani et al. 2017 is **query-key-value attention (QKV attention)**.
- What is **query-key-value attention**?

QKV Attention



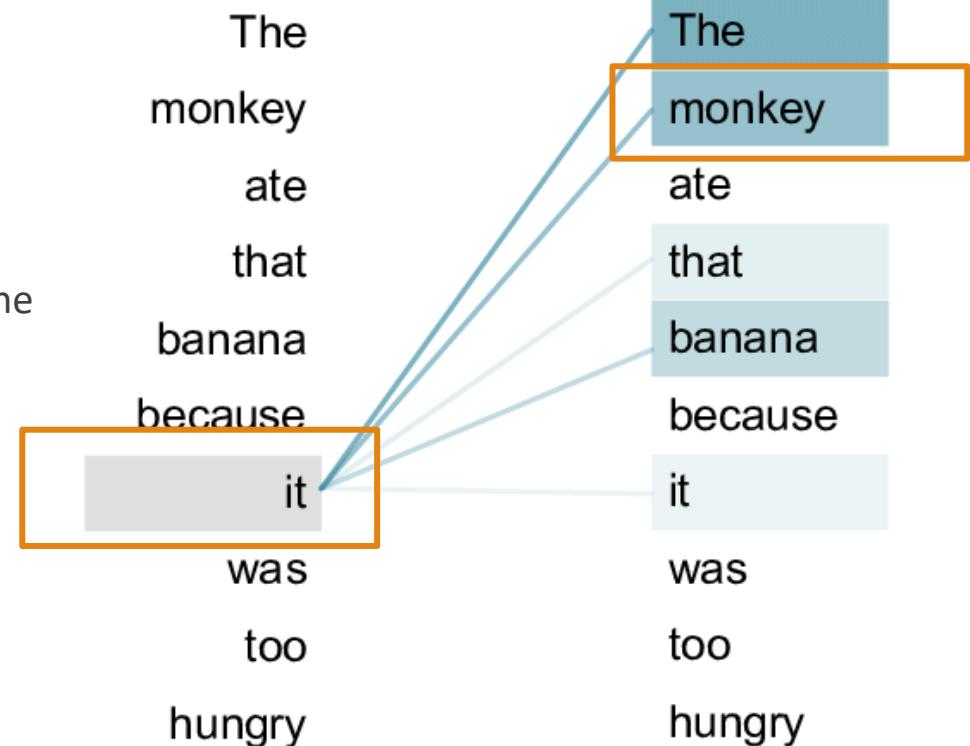
- The self-attention proposed in Vaswani et al. 2017 is **query-key-value attention (QKV attention)**.
- What is **query-key-value attention**?
 - The whole process is analogous to a **retrieval system**.
 - We **query** the search engine (eg. Youtube), which tries to map our query to the **keys** such as video title and video descriptions in its database, and then return some best matched videos (**values**).

QKV Attention

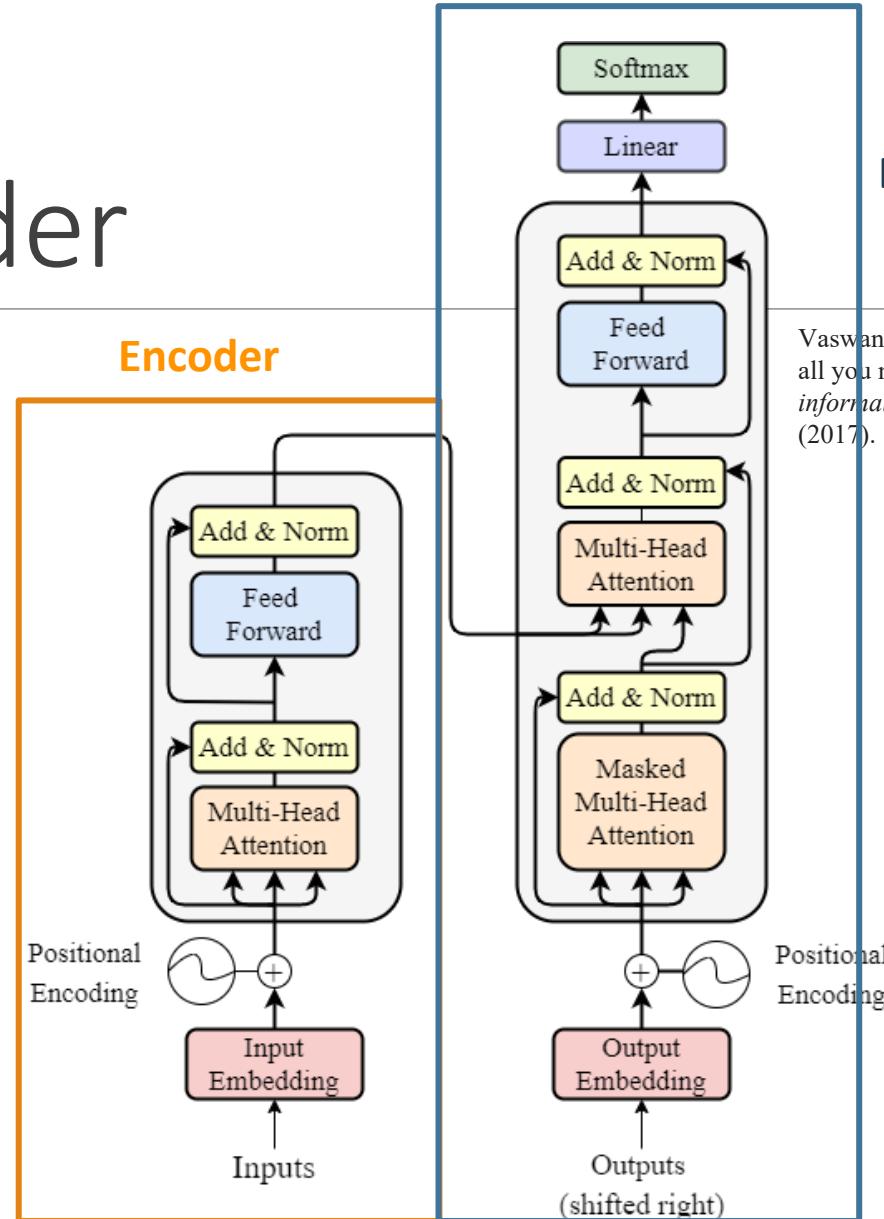
■ Back to the Natural Language example

- The **query** is the information being looked for
 - Coreference Resolution object of “it”
- The **key** is the context or reference
 - This is fairly abstract...
 - Each word w in the sentence gives hints of what “it” could be; eg. the relative distance between w and it, ‘because’, ‘was’ (neighboring) part-of-speech tags, etc.
- The **value** is the content being searched
 - One of the words in the sentence is the answer (monkey)

Source: [An example of the self-attention mechanism following long-distance...](#) | Download Scientific Diagram ([researchgate.net](#))



Transformer Encoder-Decoder

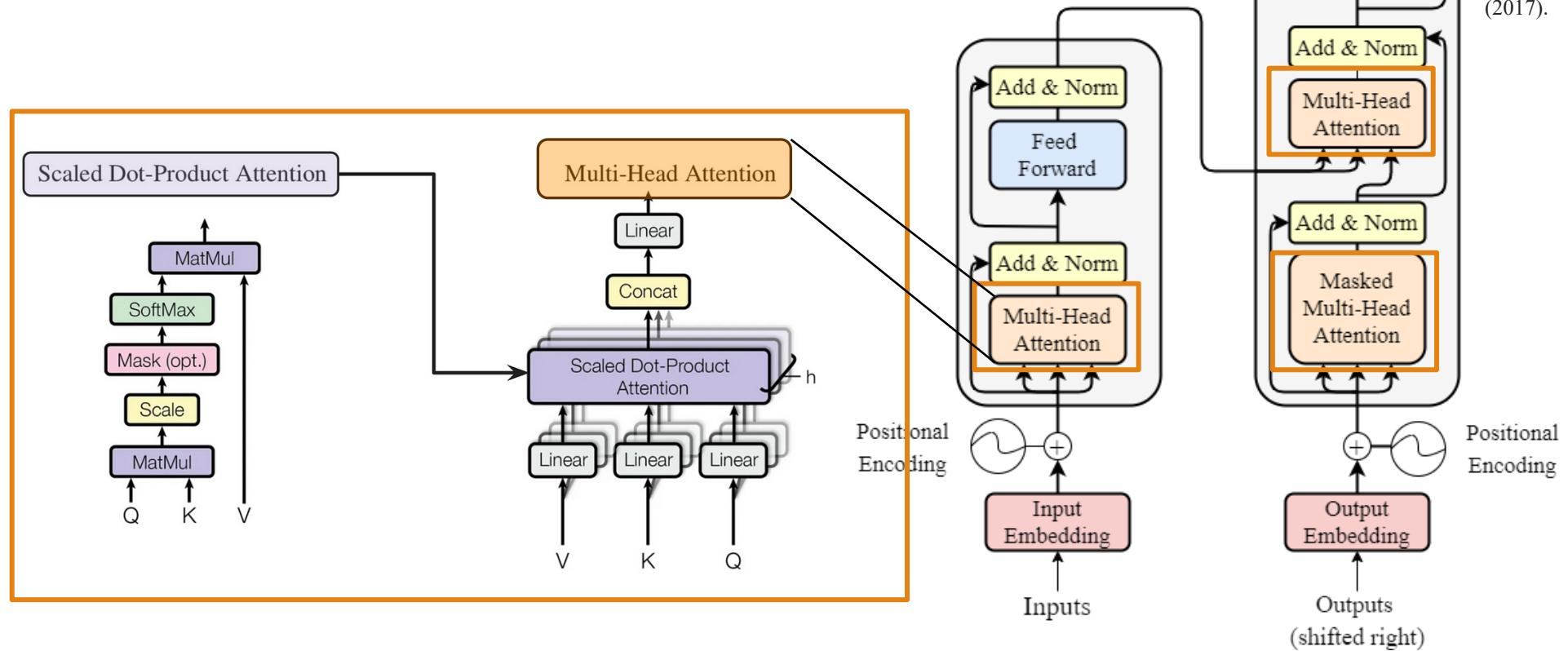


Decoder

Vaswani, Ashish, et al. "Attention is all you need." *Advances in neural information processing systems* 30 (2017).

Self-Attention

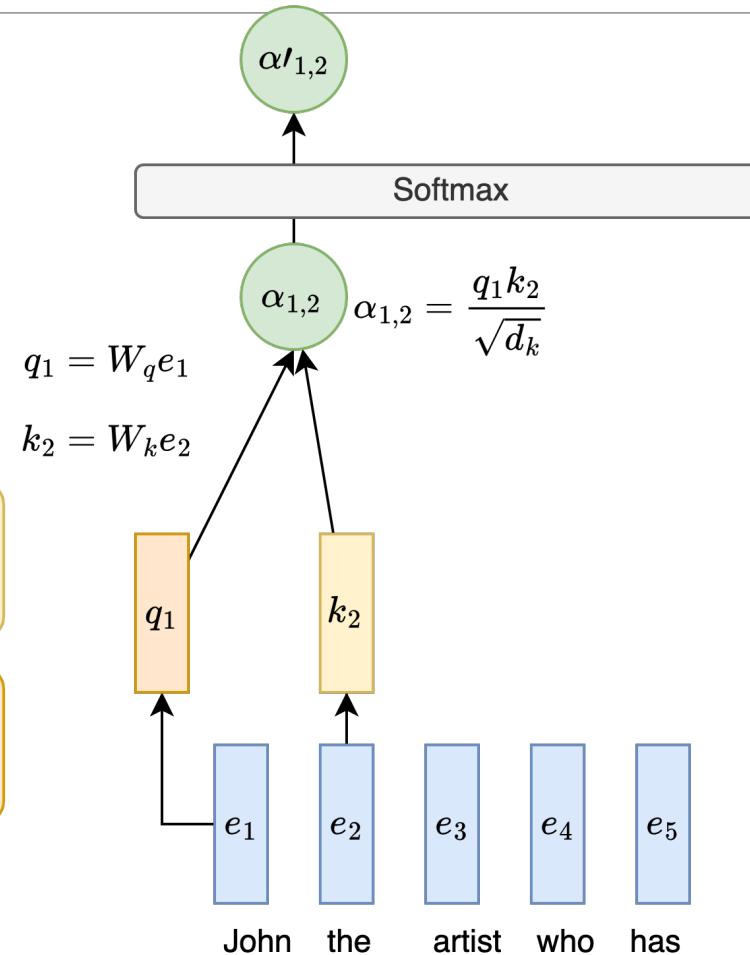
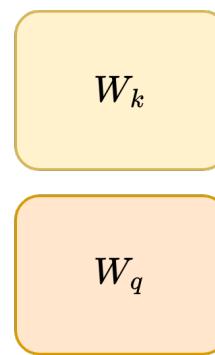
■ Where is self-attention in Transformer?



Vaswani, Ashish, et al. "Attention is all you need." *Advances in neural information processing systems 30* (2017).

Self-Attention

- Let $e_1, \dots, e_N; e_i \in \mathbb{R}^d$ be input embeddings of the text sequence.
- Initialize 3 matrices W_q, W_k, W_v .
 - The matrices are used to project the input from e_1, \dots, e_N to $q_1, \dots, q_N, k_1, \dots, k_N$ and v_1, \dots, v_N respectively.
- Do a **scaled dot product** to get a scalar $\alpha_{1,2}$, meaning “**attention score from word 1 to 2**.”



Attention Score

- The original Transformer uses **scaled dot product** (there are many others).

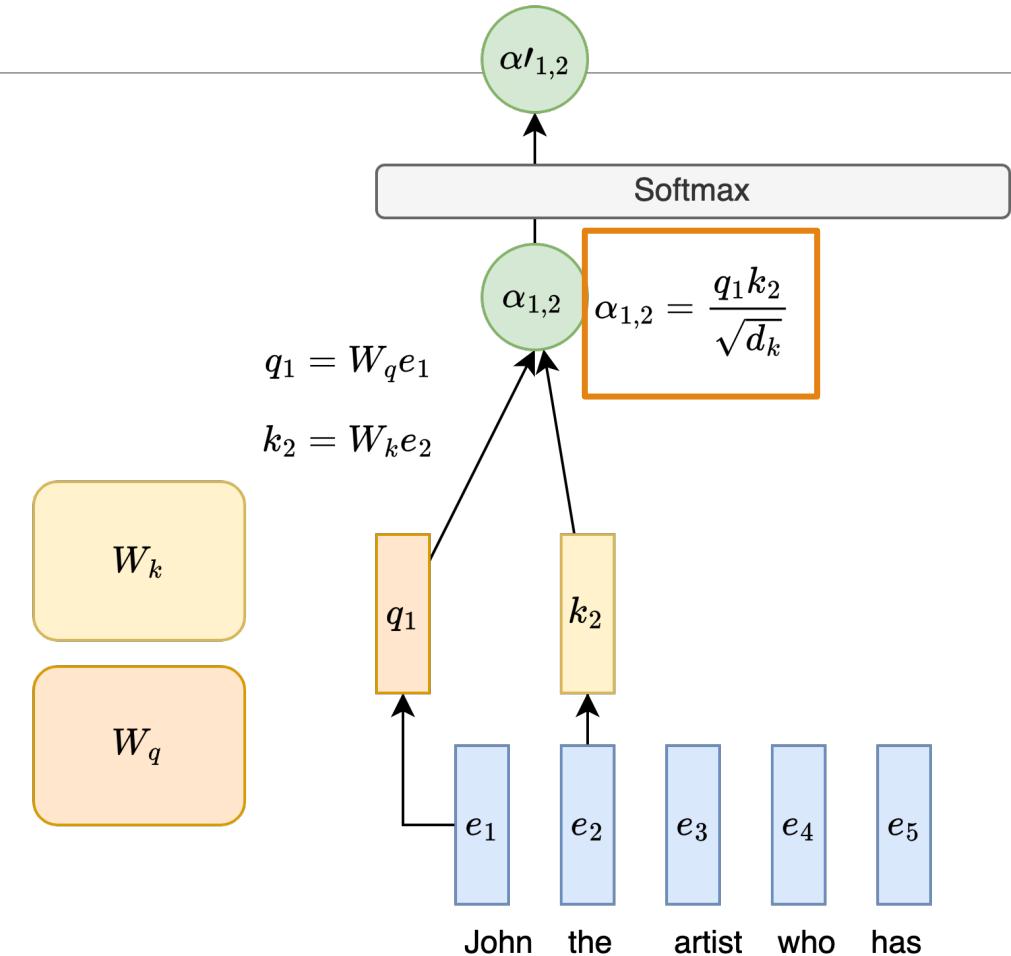
- $score(e_i, e_j) = \frac{q_i k_j}{\sqrt{d_k}}$

- d_k (= dim of keys = dim of queries)

- Why Scaling?**

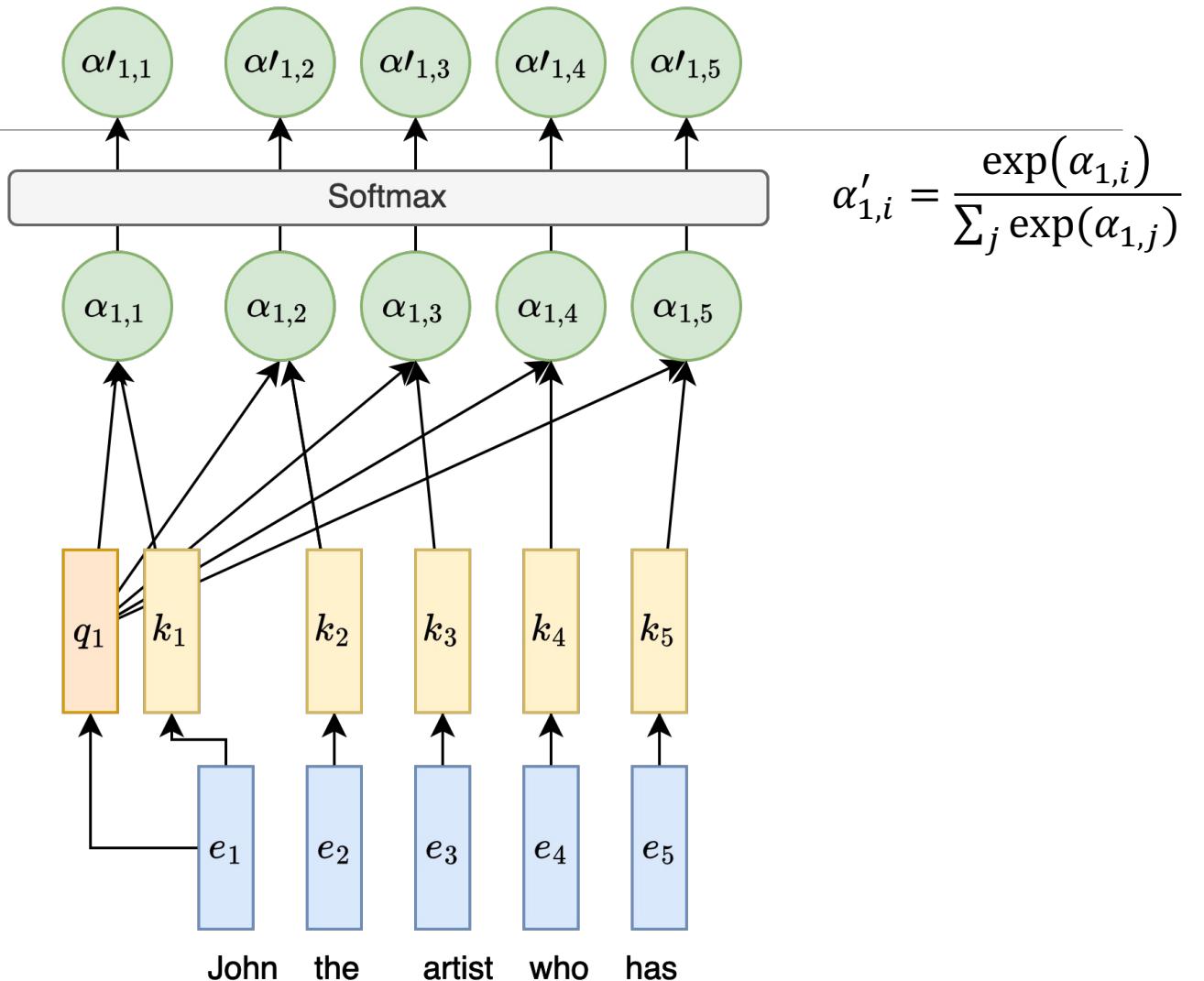
- Because **greater d_k with Softmax() results in vanishing gradients.**

- By initializing all queries and keys to have $\mu = 0, \sigma = 1$, we can ensure $score(e_i, e_j)$ to be numerically stable, as long as we scaled by $\sqrt{d_k}$.



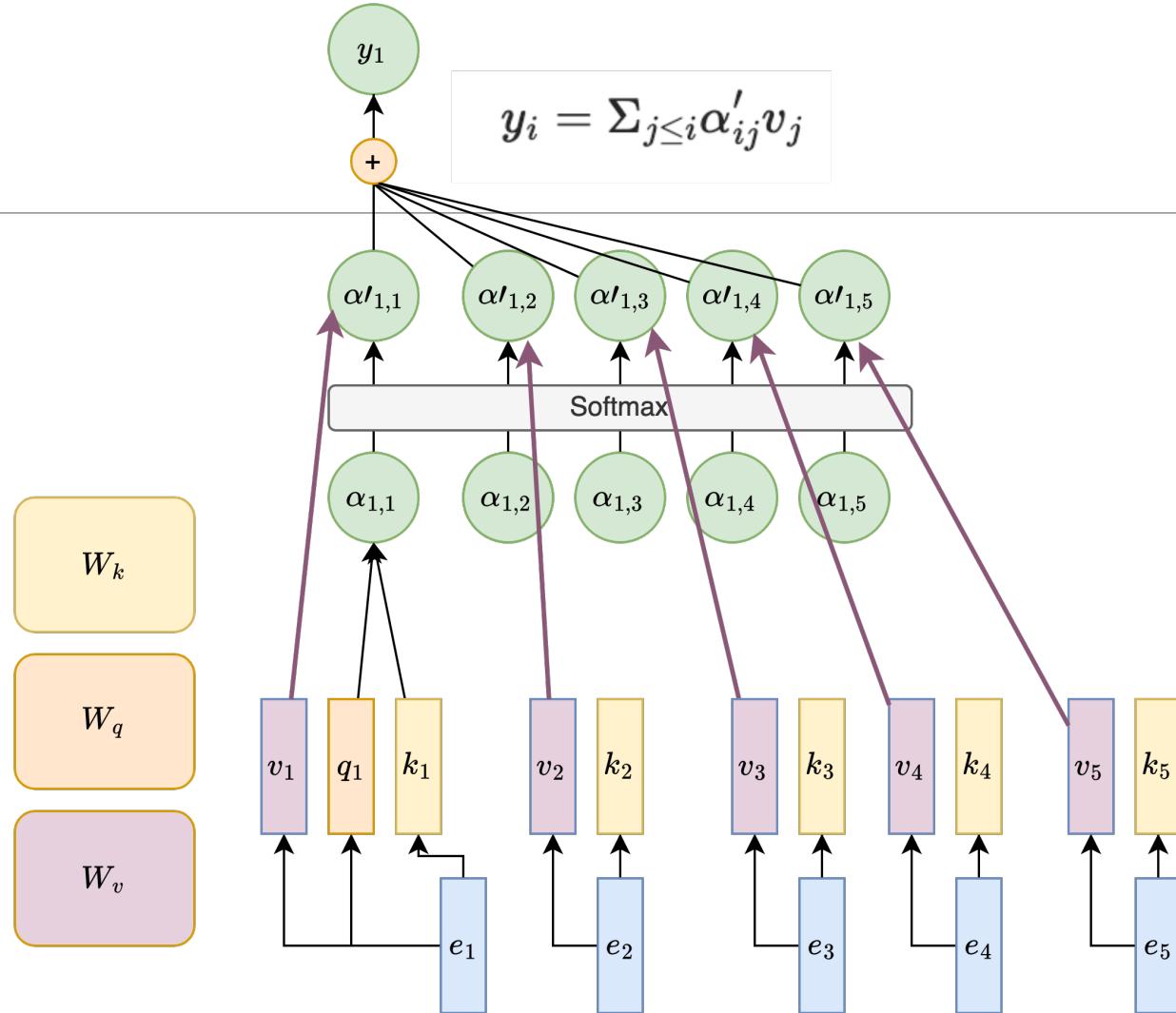
Attention Score

- For every pair of i, j , We calculate the scores. The figure illustrates $q = 1$.



Self-Attention

- The figure illustrates when $q = 1$.
- The → indicates scalar vector multiplication.



Self-Attention

- Mathematically, in terms of a pair of indices i, j : **Project the sequence vectors to q, k, v .**

$$q_i = W^Q x_i; k_i = W^K x_i; v_i = W^V x_i$$

$$\text{score}(x_i, x_j) = \frac{q_i \cdot k_j}{\sqrt{d_k}}$$

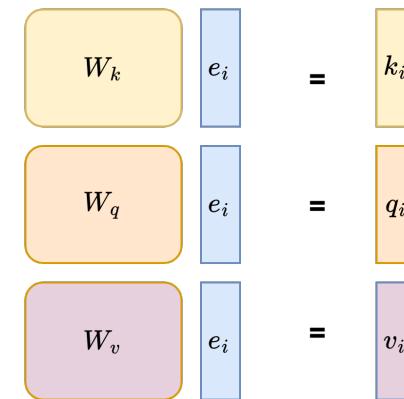
$$\alpha_{ij} = \text{score}(x_i, x_j) \quad \forall j \leq i$$

$$\alpha'_{ij} = \text{softmax}(\alpha_{ij}) = \frac{\exp(\text{score}(x_i, x_j))}{\sum_{k=1}^i \exp(\text{score}(x_i, x_k))} \quad \forall j \leq i$$

$$y_i = \sum_{j \leq i} \alpha'_{ij} v_j$$

Project the

sequence vectors
to q, k, v .



Self-Attention

- Mathematically, in terms of a pair of indices i, j :

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Calculate Attention
Score/Weight

Self-Attention

- Mathematically, in terms of a pair of indices i, j :

$$q_i = W^Q x_i; k_i = W^K x_i; v_i = W^V x_i$$

$$\text{score}(x_i, x_j) = \frac{q_i \cdot k_j}{\sqrt{d_k}}$$

$$\alpha_{ij} = \text{score}(x_i, x_j) \quad \forall j \leq i$$

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$$y_i = \sum_{j \leq i} \alpha'_{ij} v_j$$

Calculate Attn-Weighted
Average on v

Self-Attention

- Mathematically, in matrix notation:
 - N : sequence length
 - d : hidden dimension, original Transformer uses $d = 1024$.
- Solves the parallelizability problem!!

$$X \in \mathbb{R}^{N \times d}; W^Q, W^K, W^V \in \mathbb{R}^{d \times d}$$
$$Q = XW^Q; K = XW^K, V = XW^V$$

$$A' = \text{Softmax}\left(\frac{QK^T}{\sqrt{d_k}}\right)$$
$$Y = A'V$$

Self-Attention

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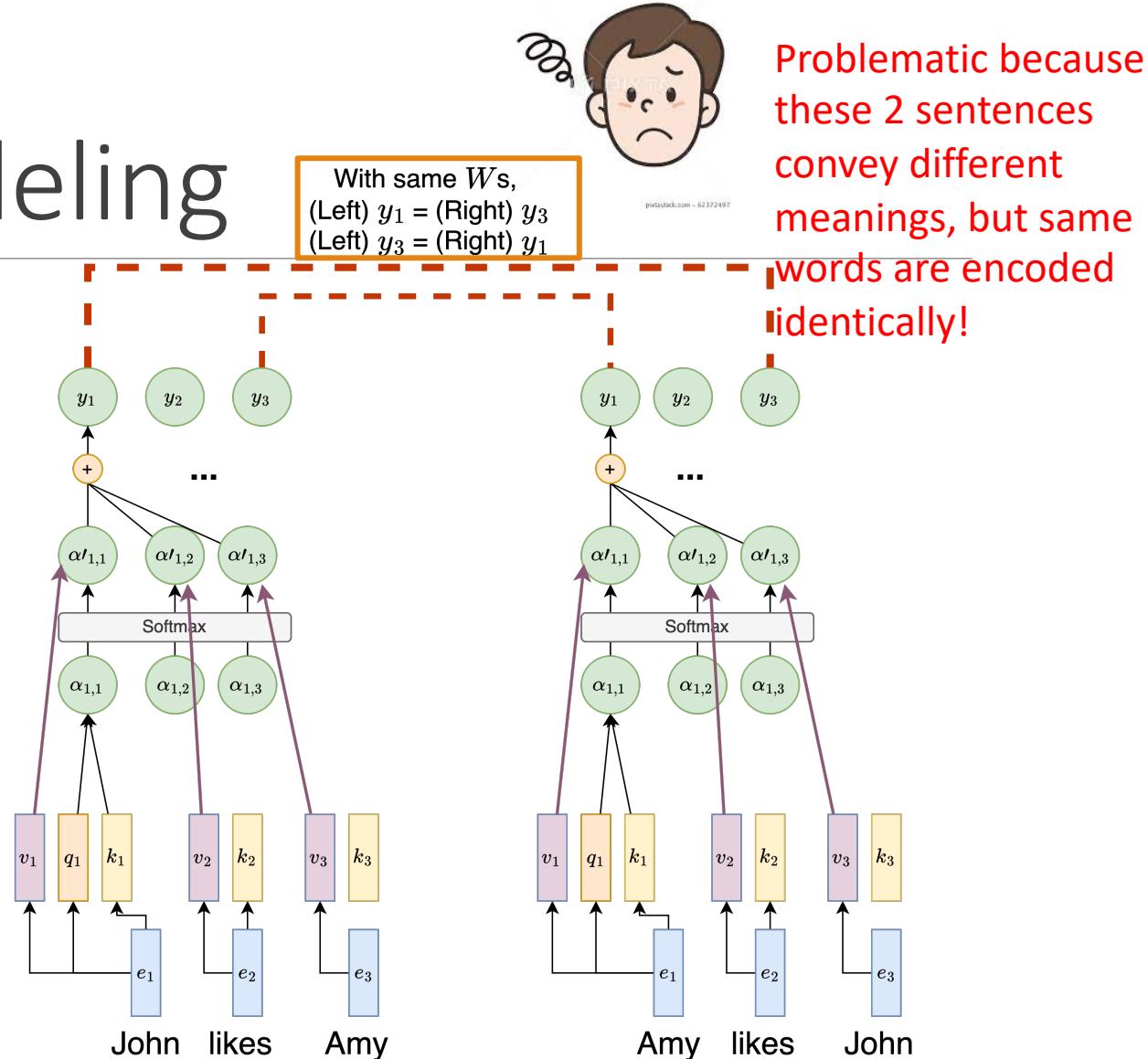
$$A' = \text{Softmax}\left(\frac{QK^T}{\sqrt{d_k}}\right)$$
$$Y = A'V$$

$$\text{Attention}(Q, K, V) = \text{softmax}\left(\frac{QK^T}{\sqrt{d_k}}\right)V = Y$$

$$Y \in \mathbb{R}^{N \times d}$$

Lack of Position Modeling

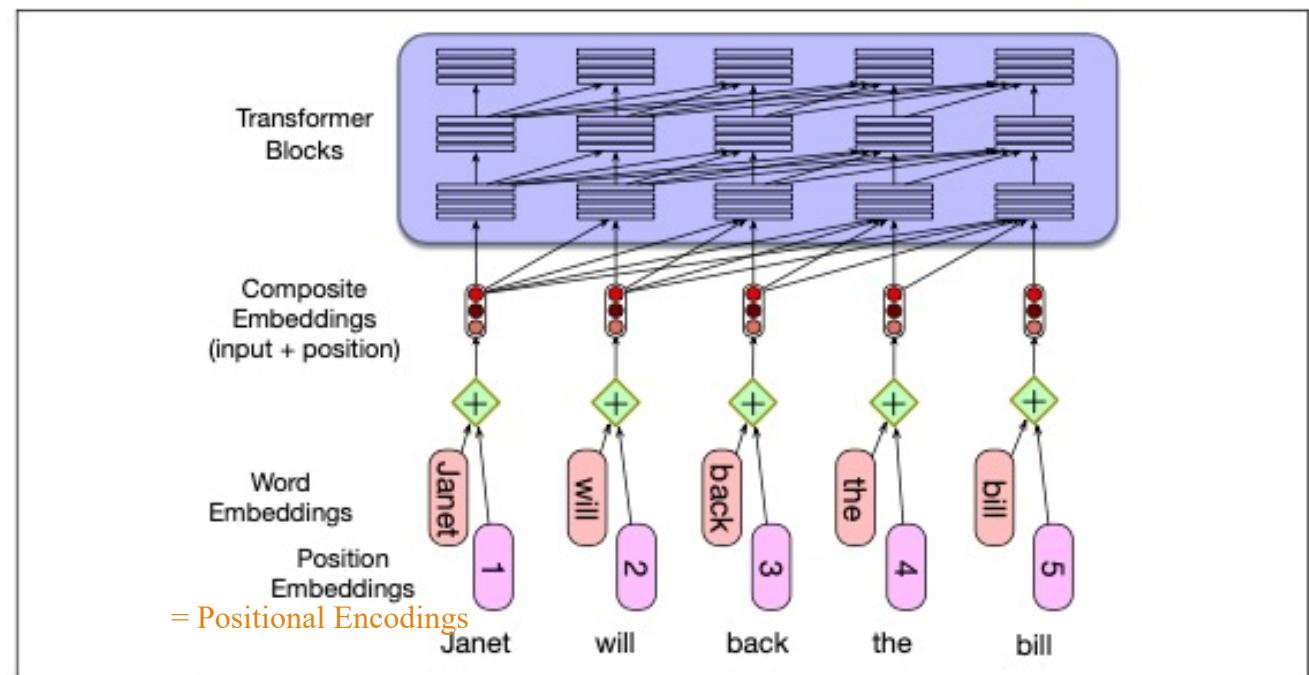
- Recall the 2 issues of RNNs:
 - Linear interaction distance
 - [solved] by directly learning attention weight instead of decaying the degree by distance.
 - Lack of parallelizability
 - [solved] by using matrix multiplication.
- But ... **We have no way to know the relative distance of one word to another!**
 - The same word, eg. “Amy”, in the 2 sentences are encoded to the same y (with the same weight matrices).



Positional Encoding

Vaswani, Ashish, et al. "Attention is all you need." *Advances in neural information processing systems* 30 (2017).

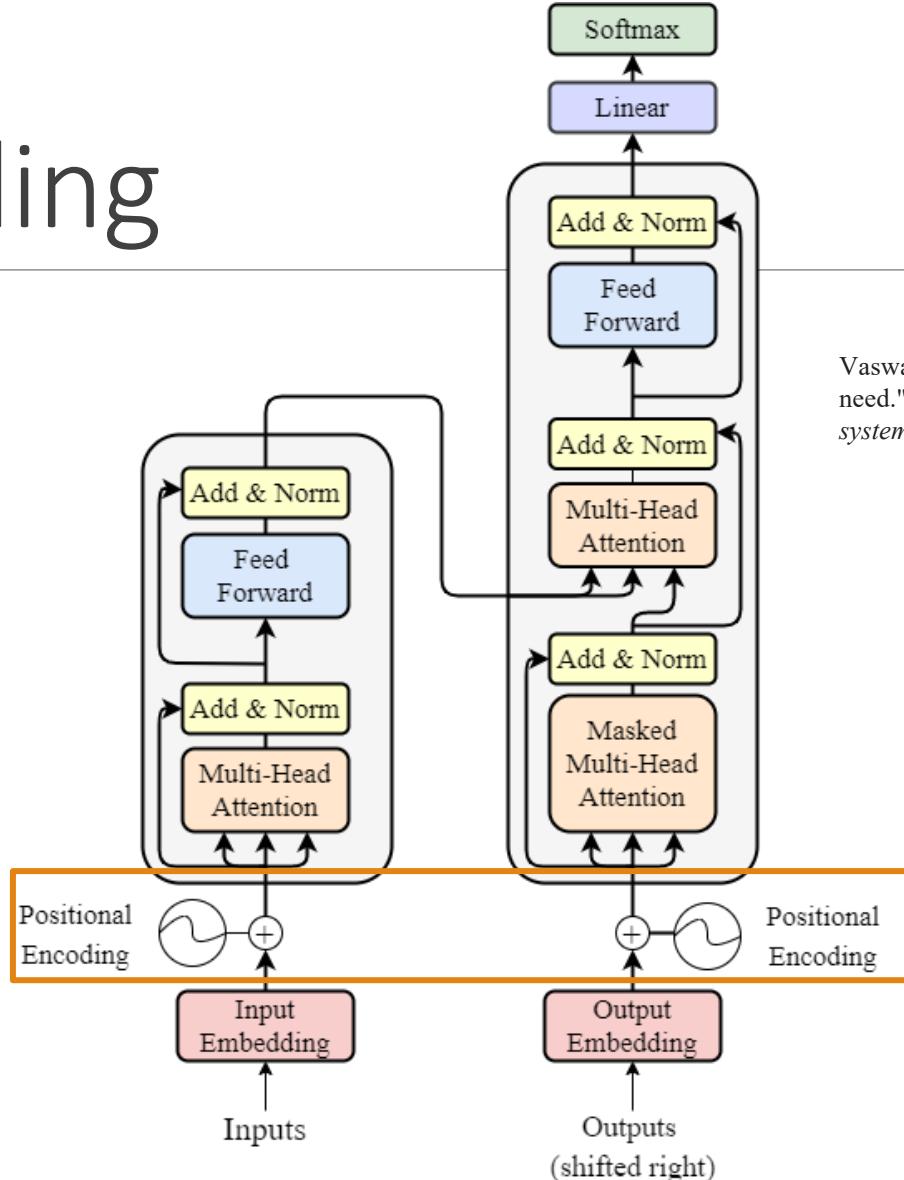
- The solution is to add some values to tell the model the positional info of each token.
- The RHS figure does not work, why?
 - **Lack of Magnitude Boundary:** The value could get very large as sequence length increases.
 - **Lack of Length Boundary:** Suppose maximum length 50 in training set, maximum length 53 in tst set → positional embedding 51, 52, 53 are NOT trained.



Source: Jurafsky, D. & Martin, J. Speech and language processing : an introduction to natural language processing, computational linguistics, and speech recognition. 3rd Edition draft (2020). Figure 10.6 in Chapter 10.

Positional Encoding

- Where is the Positional Encoding inside the transformer?
- In brief, it is a way to tell the model the position of each token in a sequence.



Vaswani, Ashish, et al. "Attention is all you need." *Advances in neural information processing systems* 30 (2017).

Positional Encoding

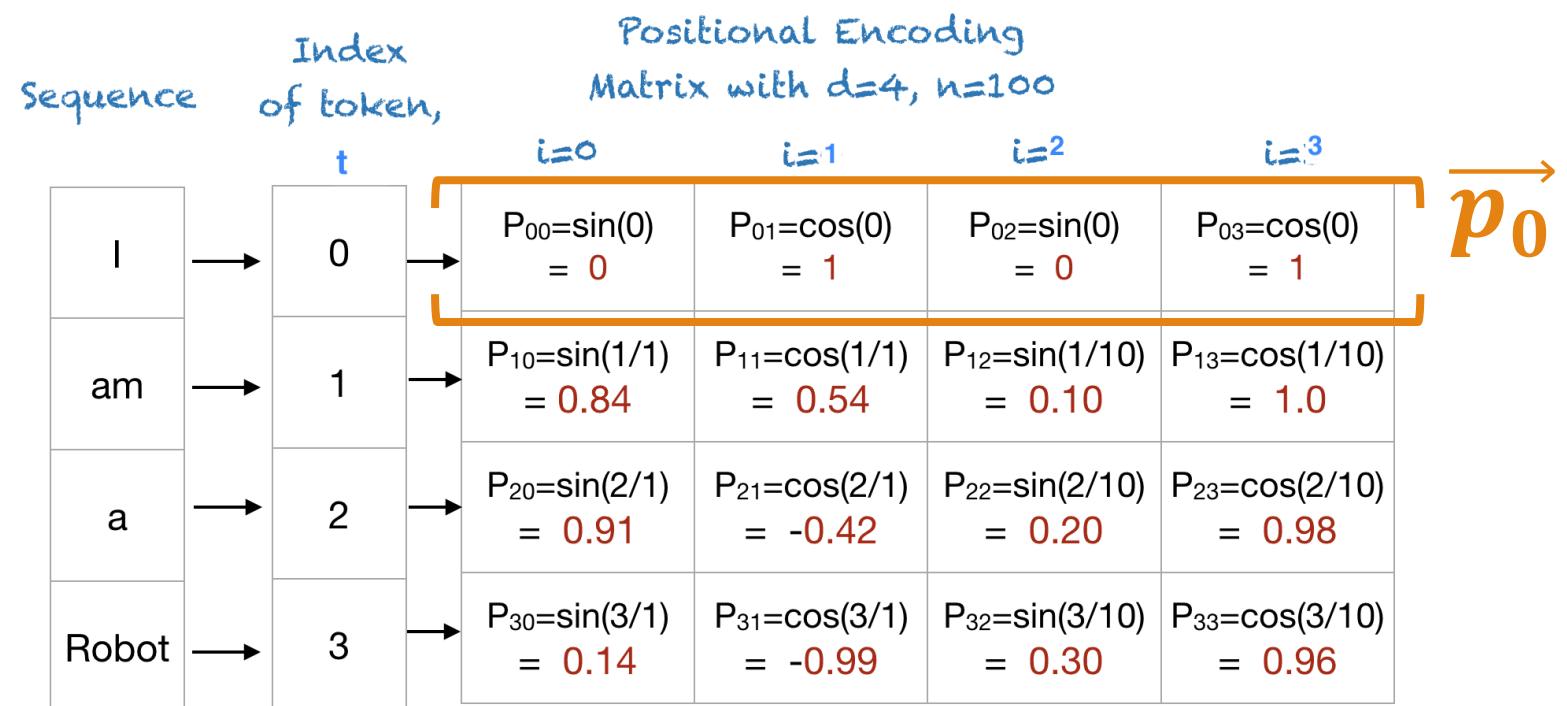
- Again, there are many positional encoding approaches. We only introduce Vaswani's (2017).
- A cyclic/periodic solution
- Do not train positional encodings.
- t : timestep, $\overrightarrow{p_t} \in \mathbb{R}^d$: positional encoding,
 $i < d$: positional encoding element index

$$\overrightarrow{p_t}^{(i)} = f(t)^{(i)} := \begin{cases} \sin(\omega_k \cdot t), & \text{if } i = 2k \\ \cos(\omega_k \cdot t), & \text{if } i = 2k + 1 \end{cases}$$
$$\omega_k = \frac{1}{10000^{2k/d}}$$

$$\overrightarrow{p_t} = \begin{bmatrix} \sin(\omega_1 \cdot t) \\ \cos(\omega_1 \cdot t) \\ \sin(\omega_2 \cdot t) \\ \cos(\omega_2 \cdot t) \\ \vdots \\ \sin(\omega_{d/2} \cdot t) \\ \cos(\omega_{d/2} \cdot t) \end{bmatrix}_{d \times 1}$$

Positional Encoding

$$\vec{p}_t = \begin{bmatrix} \sin(\omega_1 \cdot t) \\ \cos(\omega_1 \cdot t) \\ \sin(\omega_2 \cdot t) \\ \cos(\omega_2 \cdot t) \\ \vdots \\ \sin(\omega_{d/2} \cdot t) \\ \cos(\omega_{d/2} \cdot t) \end{bmatrix}_{d \times 1}$$

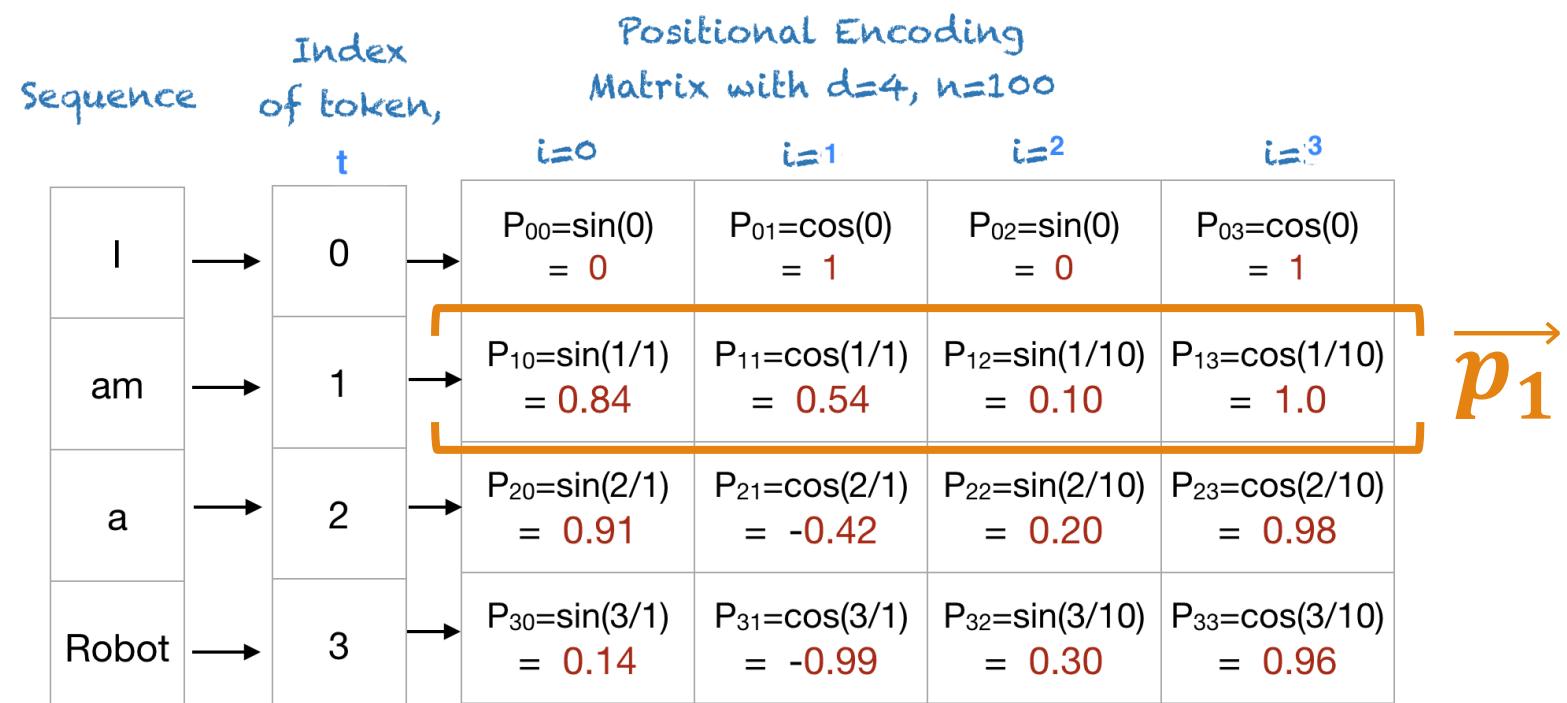


Positional Encoding Matrix for the sequence 'I am a robot'

Source: A Gentle Introduction to Positional Encoding in Transformer Models, Part 1 -
MachineLearningMastery.com

Positional Encoding

$$\vec{p}_t = \begin{bmatrix} \sin(\omega_1 \cdot t) \\ \cos(\omega_1 \cdot t) \\ \sin(\omega_2 \cdot t) \\ \cos(\omega_2 \cdot t) \\ \vdots \\ \sin(\omega_{d/2} \cdot t) \\ \cos(\omega_{d/2} \cdot t) \end{bmatrix}_{d \times 1}$$

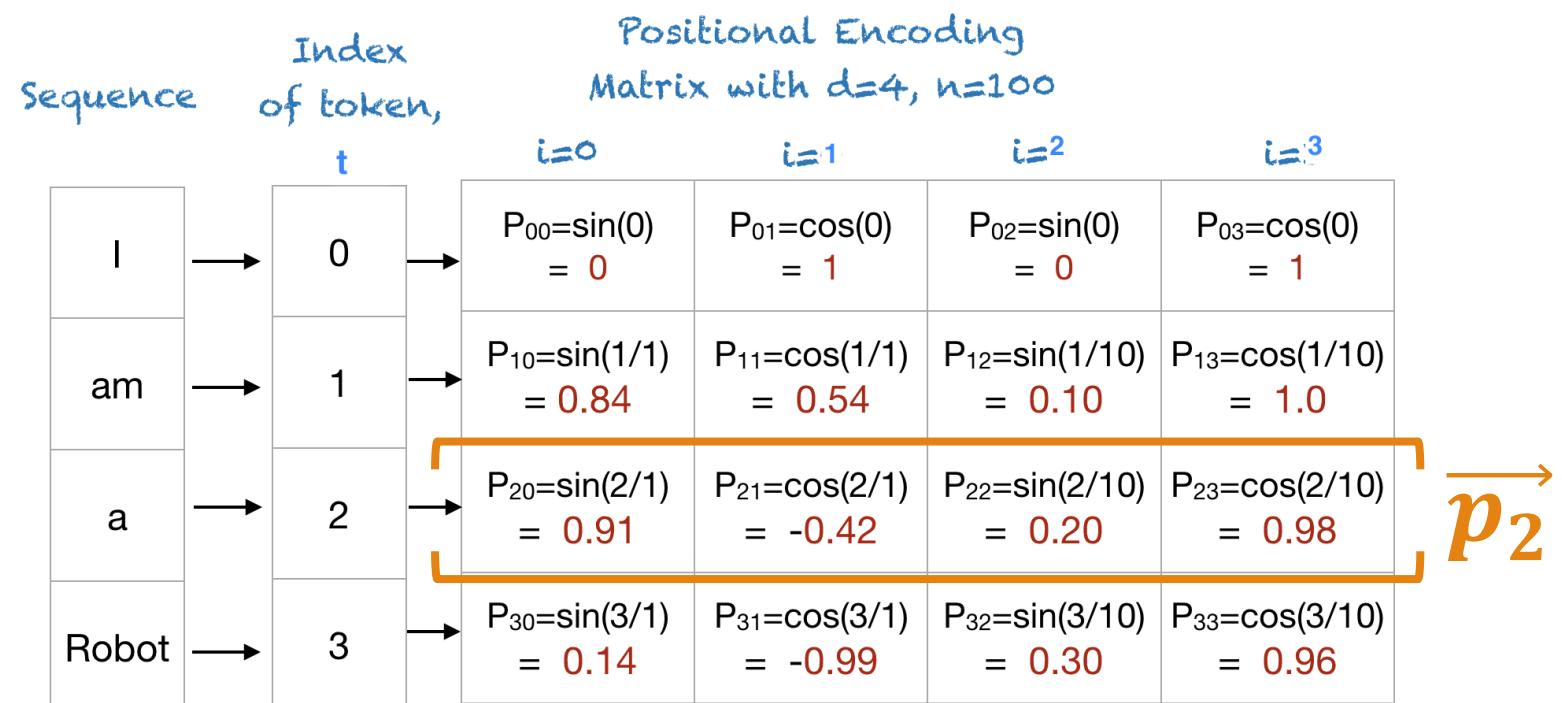


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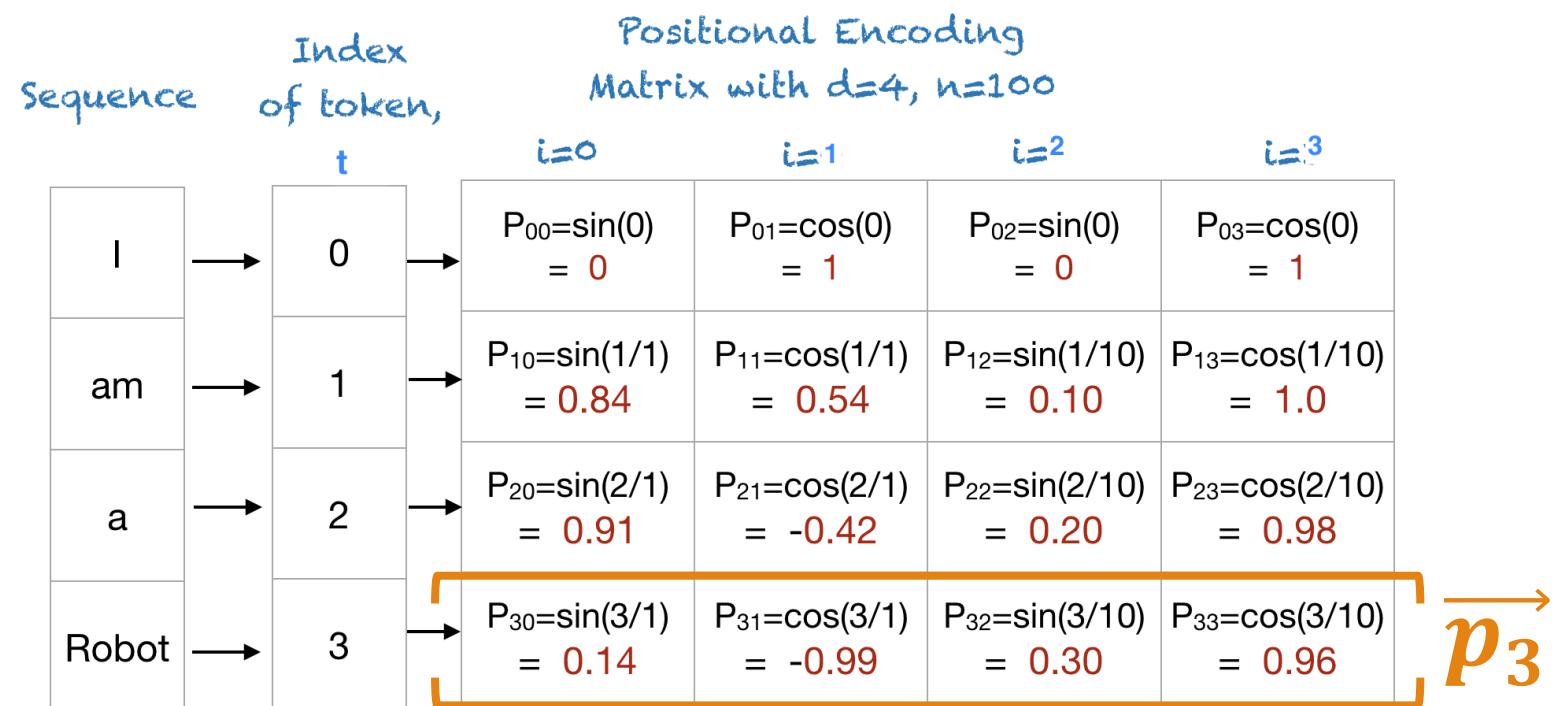


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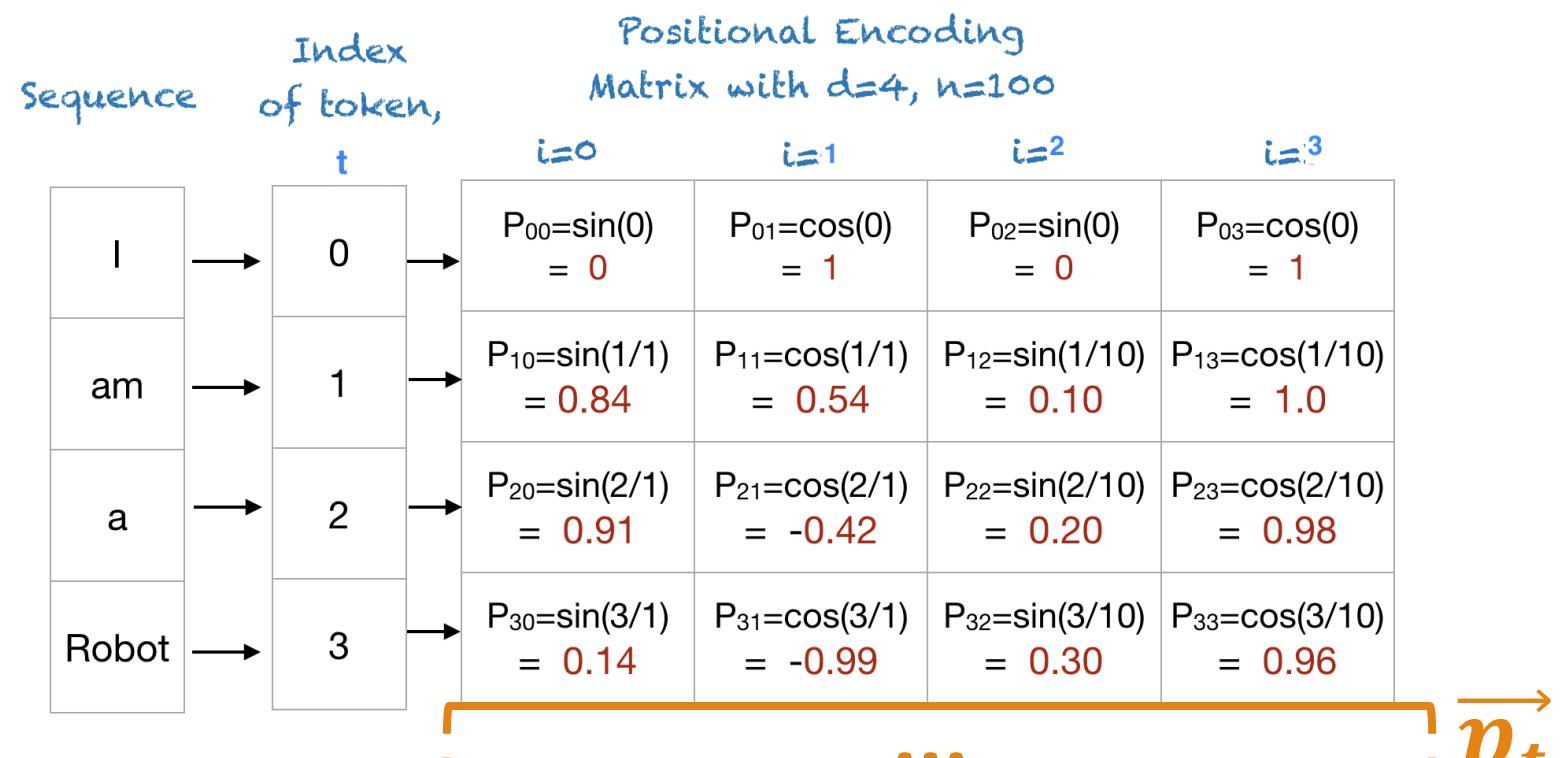


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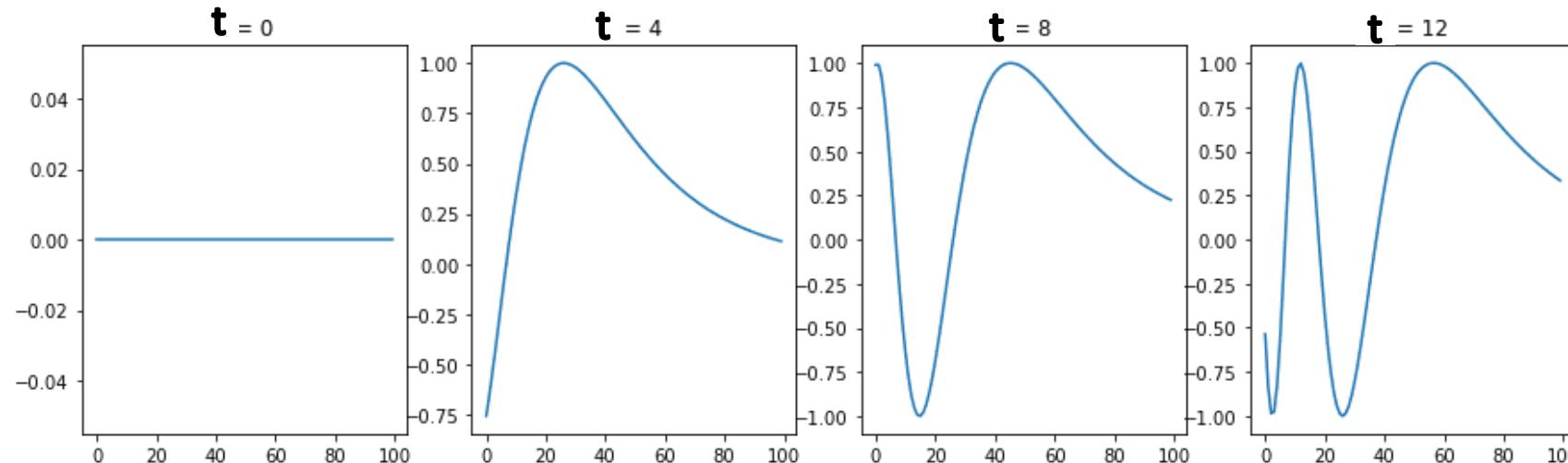
Source: A Gentle Introduction to Positional Encoding in Transformer Models, Part 1 -
MachineLearningMastery.com

In general

Positional Encoding

Vaswani, Ashish, et al. "Attention is all you need." *Advances in neural information processing systems* 30 (2017).

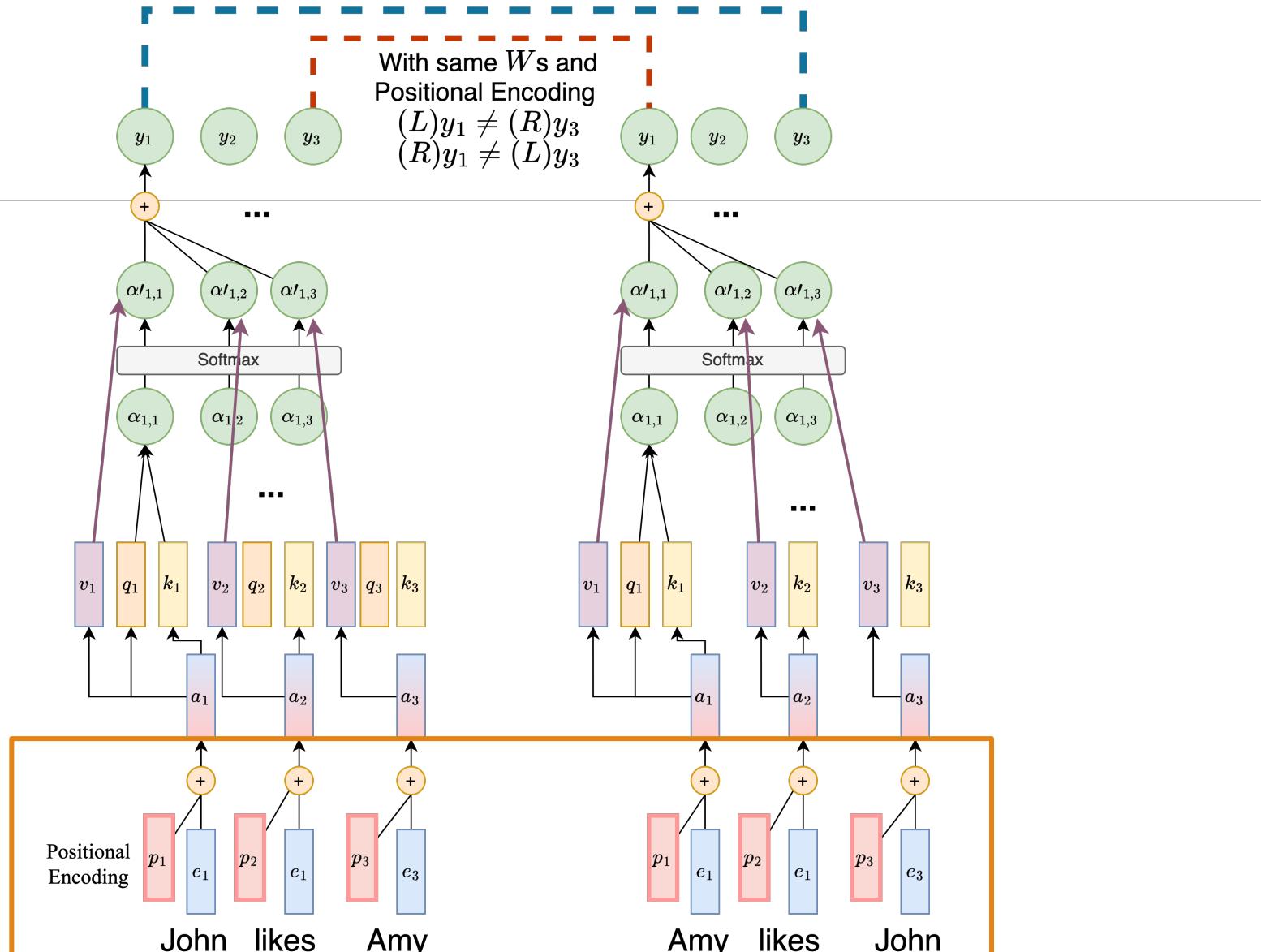
- t : timestep, $\vec{p}_t \in \mathbb{R}^d$: positional encoding
- Each positional embedding at position t is a sinusoidal wave. Closer positions have closer patterns.
- **Solved Lack of Magnitude Boundary:** Numeric range in $[-1, 1]$.
- **Solved Lack of Length Boundary:** Cyclic, can go on forever.



$$\vec{p}_t = \begin{bmatrix} \sin(\omega_1 \cdot t) \\ \cos(\omega_1 \cdot t) \\ \sin(\omega_2 \cdot t) \\ \cos(\omega_2 \cdot t) \\ \vdots \\ \sin(\omega_{d/2} \cdot t) \\ \cos(\omega_{d/2} \cdot t) \end{bmatrix}_{d \times 1}$$

Source: <https://machinelearningmastery.com/a-gentle-introduction-to-positional-encoding-in-transformer-models-part-1/>

Positional Encoding



Multi-head Attention

- In p.9, we describe self-attention as QKV attention, where
 - we **query** the search engine
 - search engine tries to map our query to the **keys**
 - output some best matched videos (**values**)
- What if we want to **have queries focusing on different aspects?**
 - For example, one set of queries focusing on **semantic similarity**, another set focusing on **passive/active voice**.
 - We need **multiple** attention mechanisms, i.e. **multiple (attention) heads!**

Multi-head Attention

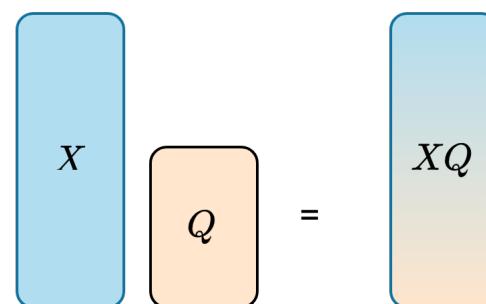
- Recall p.20, where we have explained the **Attention()** function.
- Multi-head Attention is essentially multiple self-attentions...

$$\text{Multihead}(Q, K, V) = \text{Concat}(\text{head}_1, \dots, \text{head}_h)W^O$$

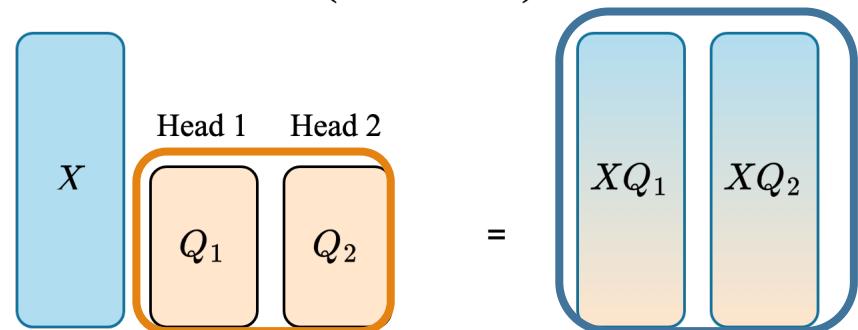
where $\text{head}_i = \text{Attention}(QW_i^Q, KW_i^K, VW_i^V)$

▷ In computation, we can group the Q_1, Q_2, \dots matrices into one Q matrix, hence transform the computation process into single-head attention.

Single-head Attention



Multi-head Attention
(head#=2)



Self-Attention (p.20)

- Mathematically, in matrix notation:
 - N : sequence length
 - d : hyperparameter, hidden dimension, original Transformer uses $d = 1024$.
- Solves the parallelizability problem!!

$$X \in \mathbb{R}^{N \times d}; W^Q, W^K, W^V \in \mathbb{R}^{d \times d}$$
$$Q = XW^Q; K = XW^K, V = XW^V$$

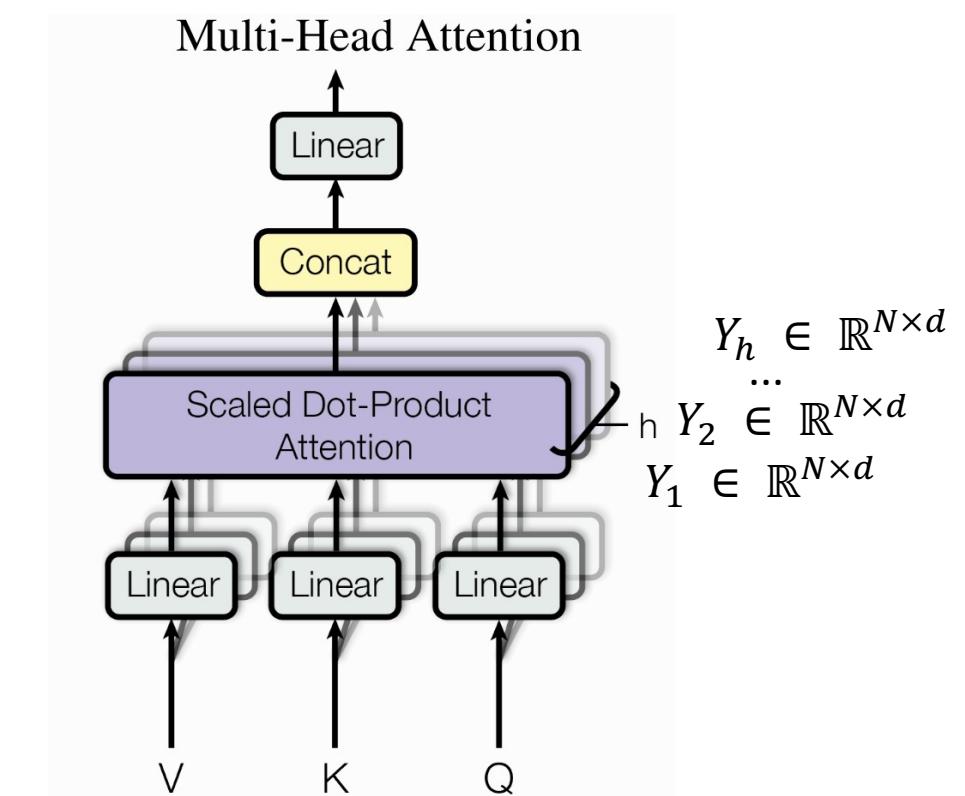
$$A' = \text{Softmax}\left(\frac{QK^T}{\sqrt{d_k}}\right)$$
$$Y = A'V$$

$$\text{Attention}(Q, K, V) = \text{softmax}\left(\frac{QK^T}{\sqrt{d_k}}\right)V = Y$$

$$Y \in \mathbb{R}^{N \times d}$$

Multi-head Attention

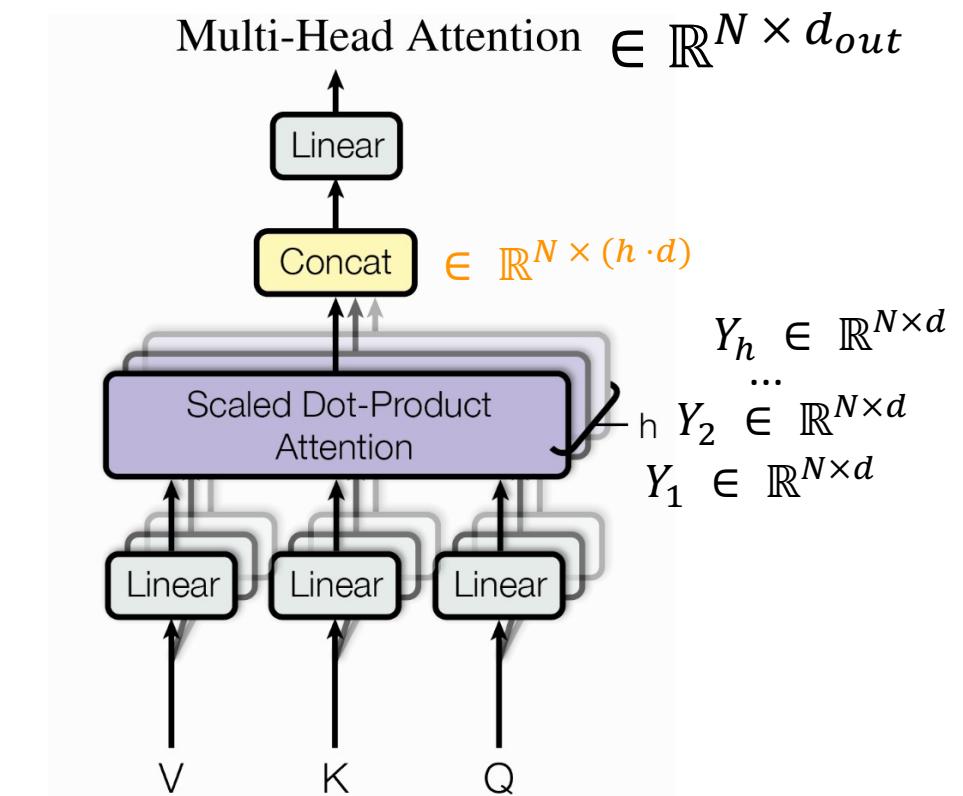
Multihead(Q, K, V) = Concat(head₁, ..., head_h) W^O
 $\in \mathbb{R}^{N \times (h \cdot d)}$



Multi-head Attention

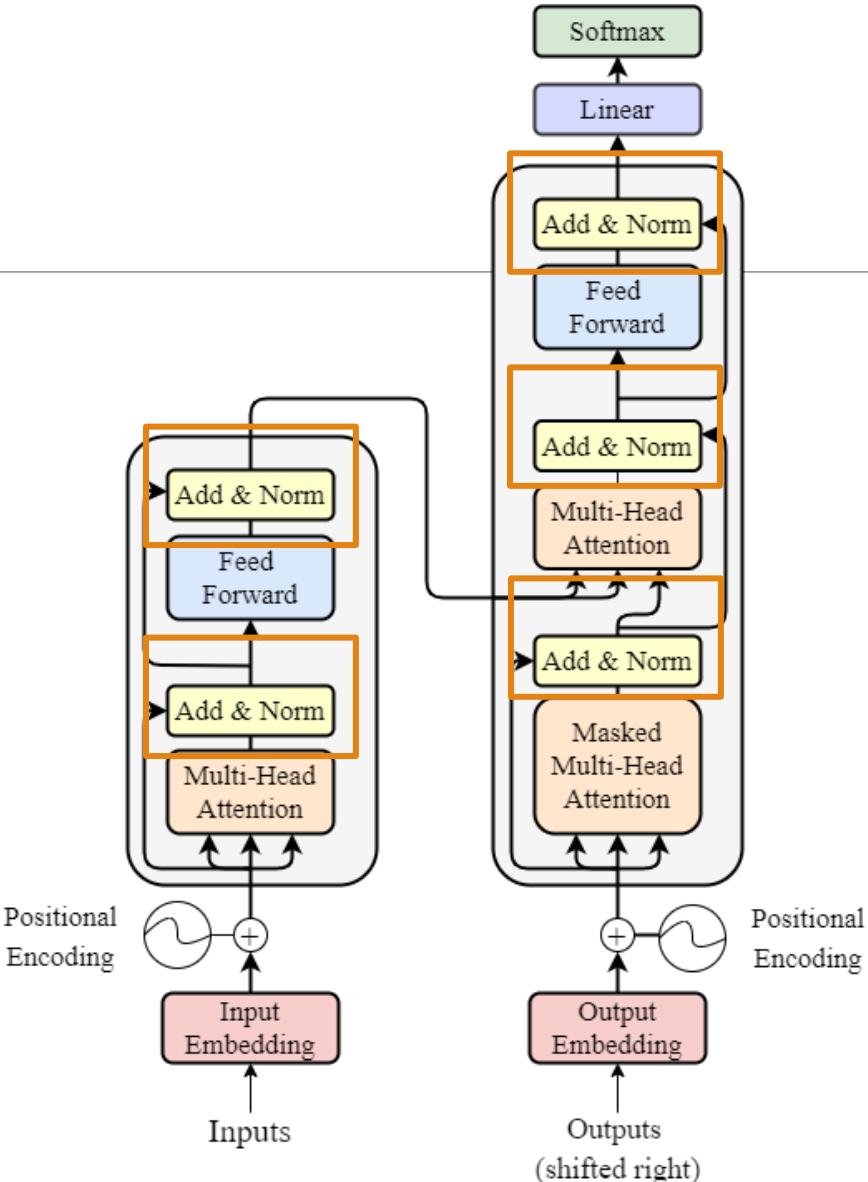
$$\text{Multihead}(Q, K, V) = \text{Concat}(\text{head}_1, \dots, \text{head}_h) W^O$$
$$\in \mathbb{R}^{N \times (h \cdot d)} \quad \in \mathbb{R}^{(h \cdot d) \times d_{out}}$$

- With W^O , the concated head outputs can be projected to a preferred dimension (hyperparameter: d_{out}).
- No worries on how head# changes dimension of outputs!



Add & Norm

- Add: Residual Connection
- Norm: Layer Normalization

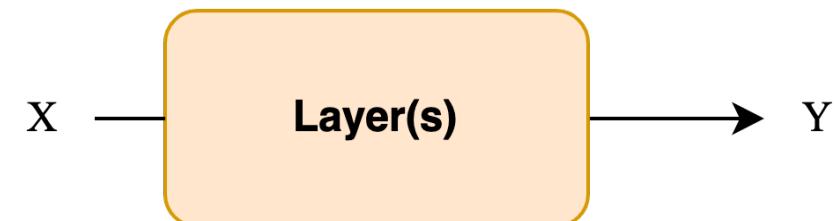


Vaswani, Ashish, et al. "Attention is all you need." *Advances in neural information processing systems 30* (2017).

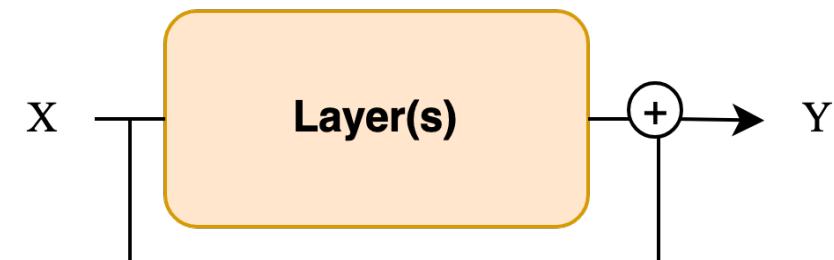
Add & Norm

- Research shows that Residual Connection (He, Kaiming, et al., 2016) **stabilizes training.**
- Let the layers in between learn the residual (i.e. $Y - X$).

Standard



Residual



He, Kaiming, et al. "Deep residual learning for image recognition." *Proceedings of the IEEE conference on computer vision and pattern recognition* (2016).

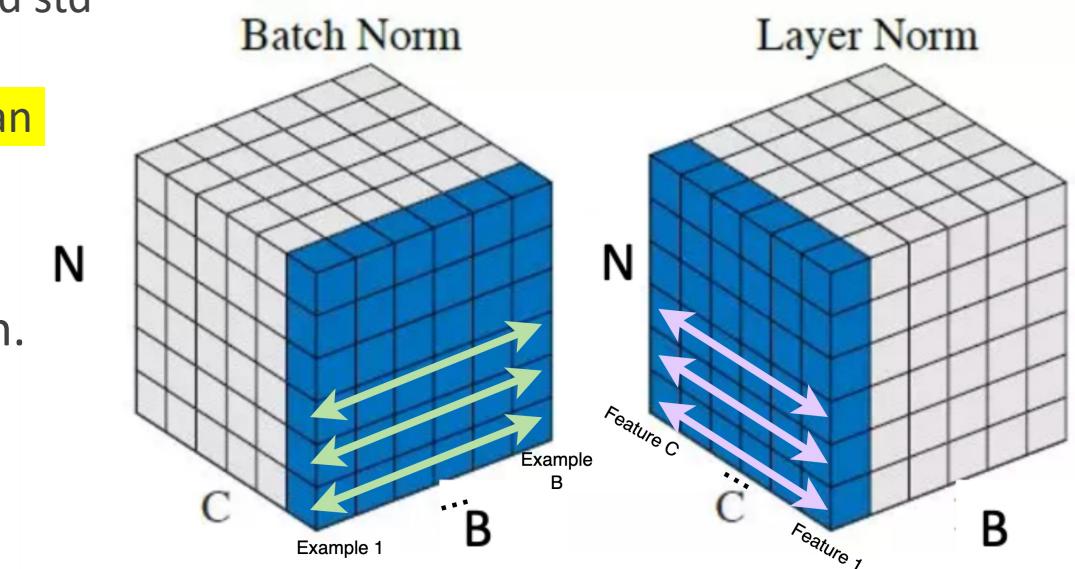
Add & Norm

B: Batch Size

C: Channels / Embedding Feature Dimension

N: Sequence length

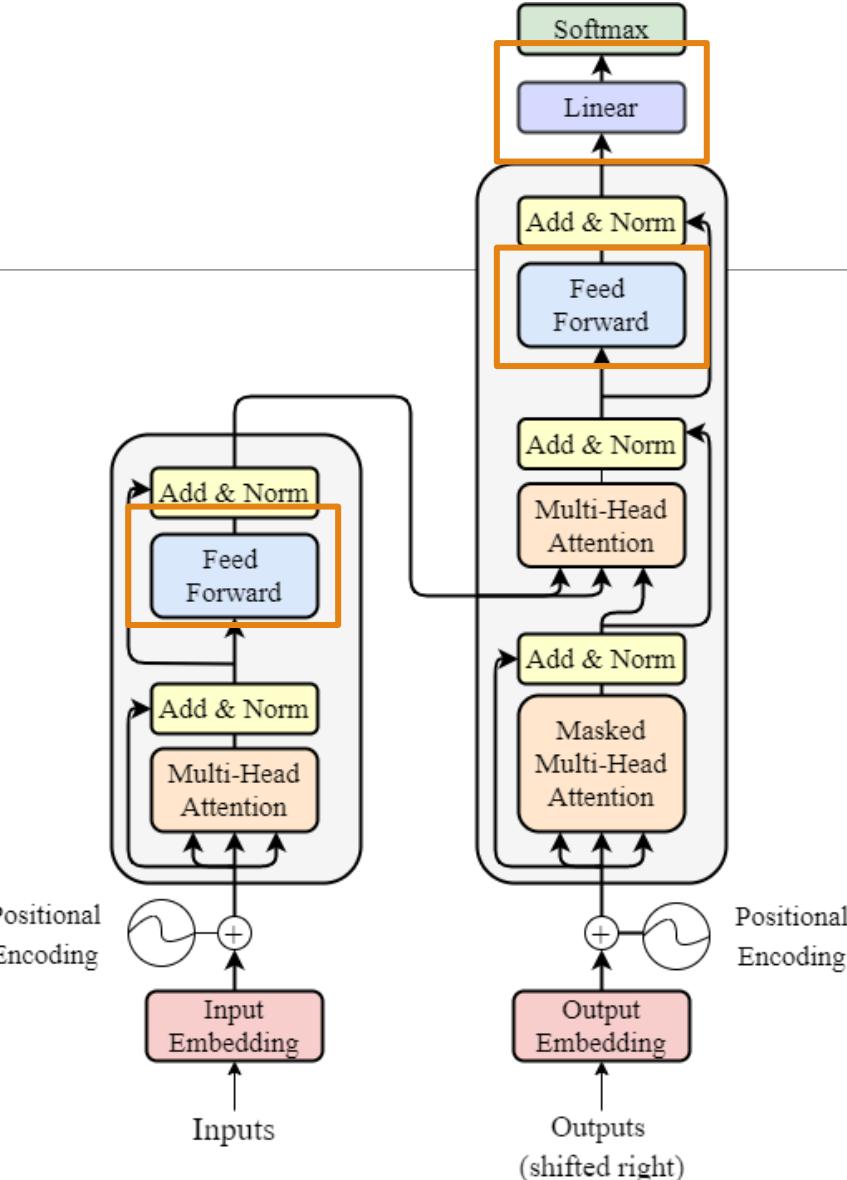
- Normalization is also a way to stabilize training.
 - Batch Norm: For the same embedding dimension in the same sequence index, calculate its mean μ and std σ **across the samples within the same batch.**
 - Layer Norm: For an input vector, calculate its mean and std **across embedding dimension.**
- $\text{norm}(X) = \frac{X - \mu}{\sigma}$
- Vaswani et al. (2017) used Layer Normalization.
Why LN?
 - No specific exp. from Vaswani et al., 2017.
 - BN needs batch mean and std during inference, unsuitable for varying seq length in NLP.
 - LN yields good results.



Ba, Jimmy Lei, Jamie Ryan Kiros, and Geoffrey E. Hinton. "Layer normalization." *arXiv preprint arXiv:1607.06450* (2016).

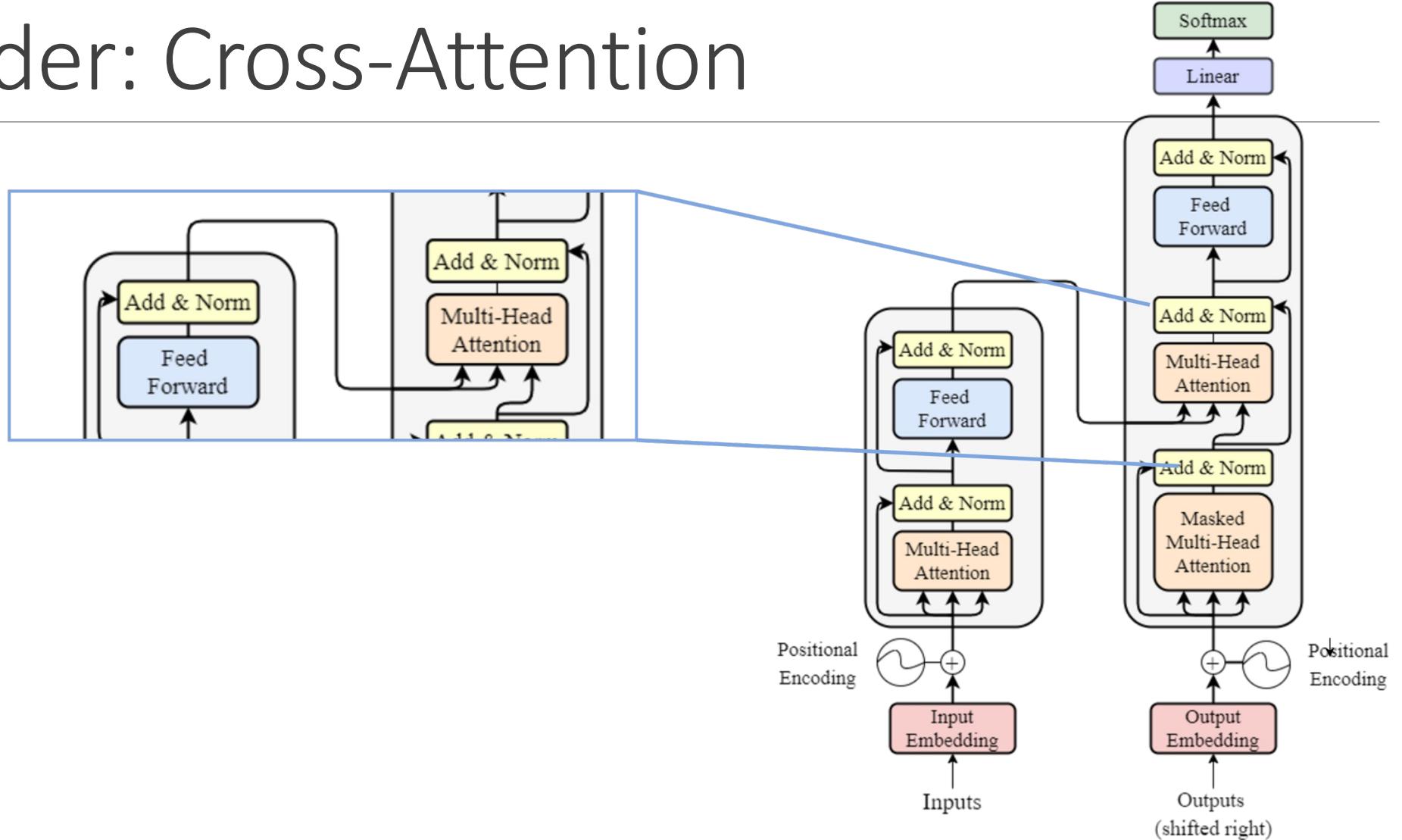
Feed Forward

- Simply multiply by a weight matrix.
- Used to project to a specific dimension.

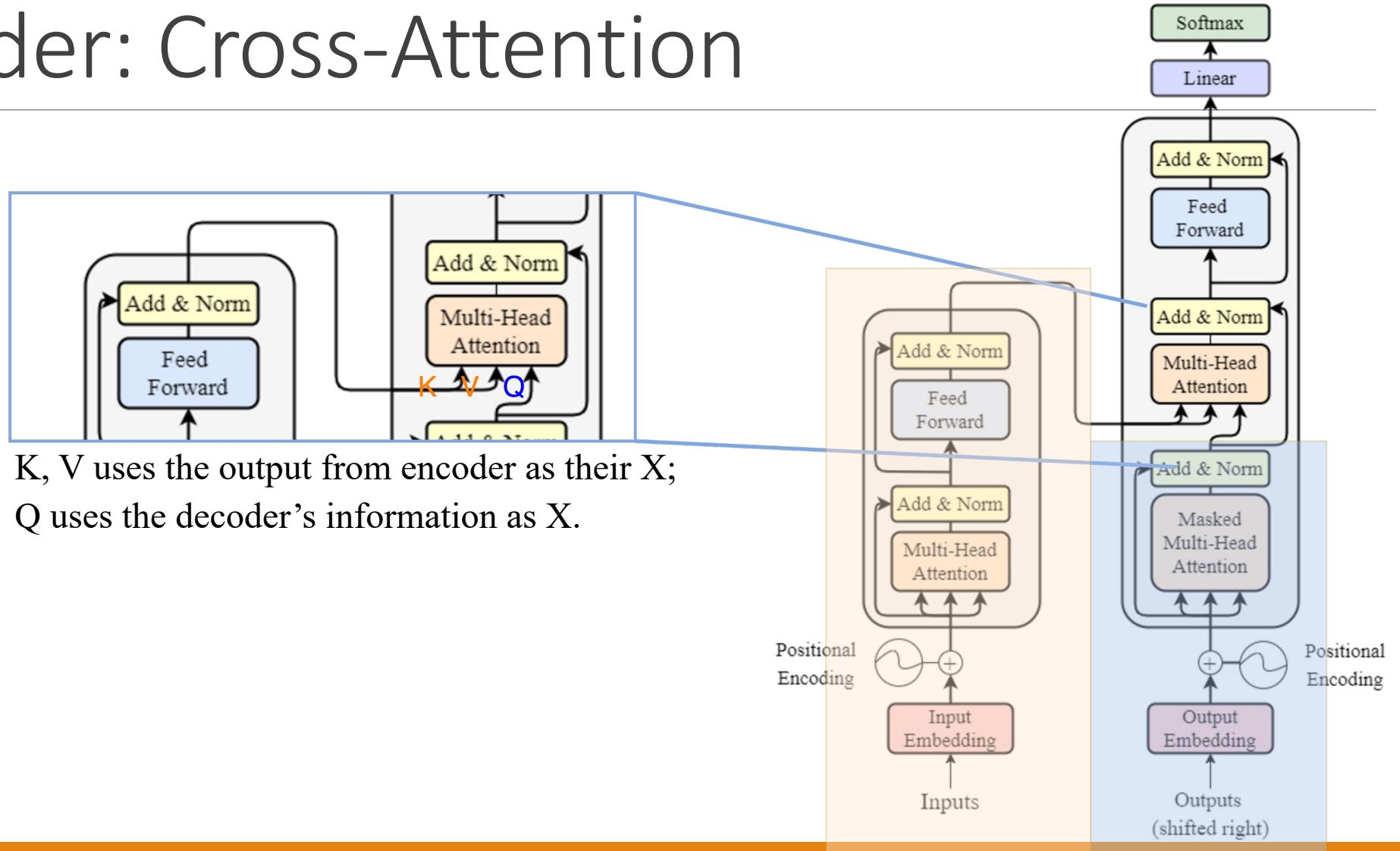


Vaswani, Ashish, et al. "Attention is all you need." *Advances in neural information processing systems 30* (2017).

Decoder: Cross-Attention



Decoder: Cross-Attention

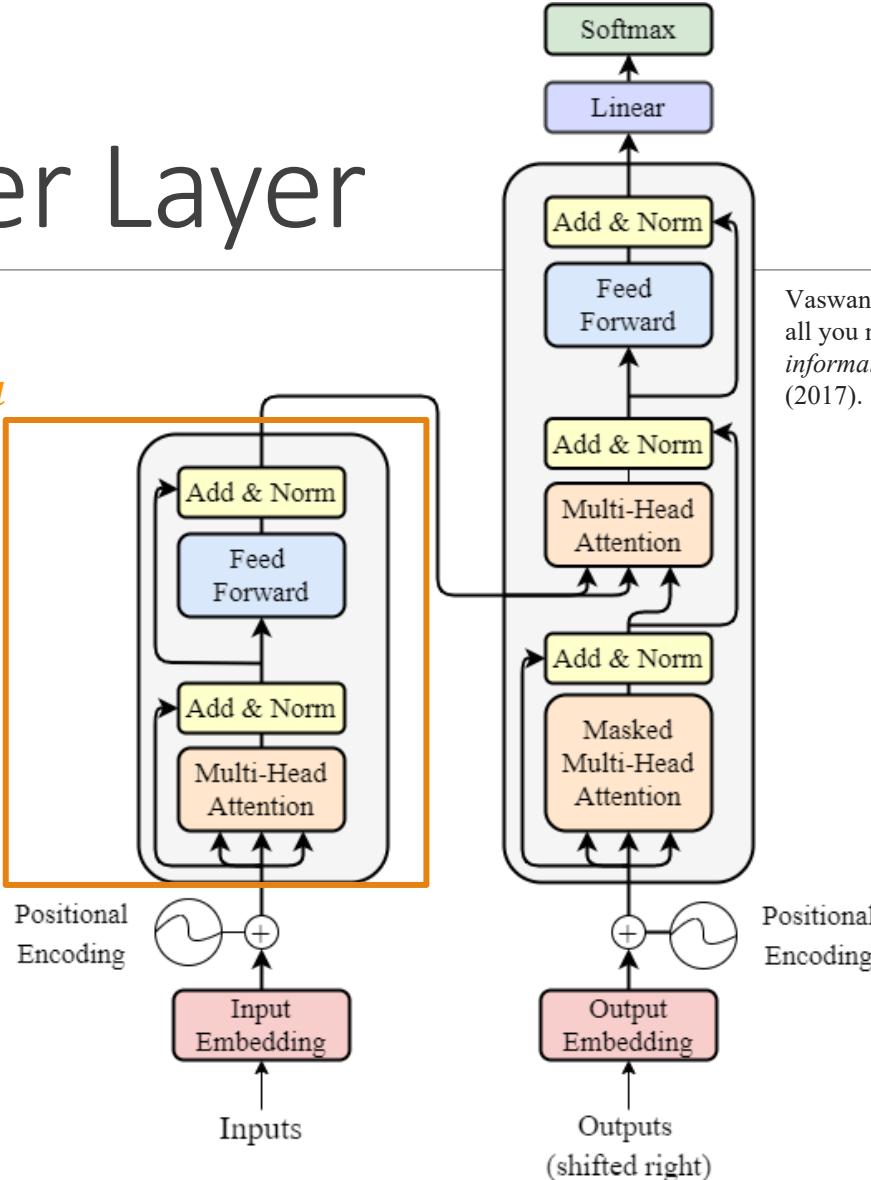


K , V uses the output from encoder as their X ;
 Q uses the decoder's information as X .

of Transformer Layer

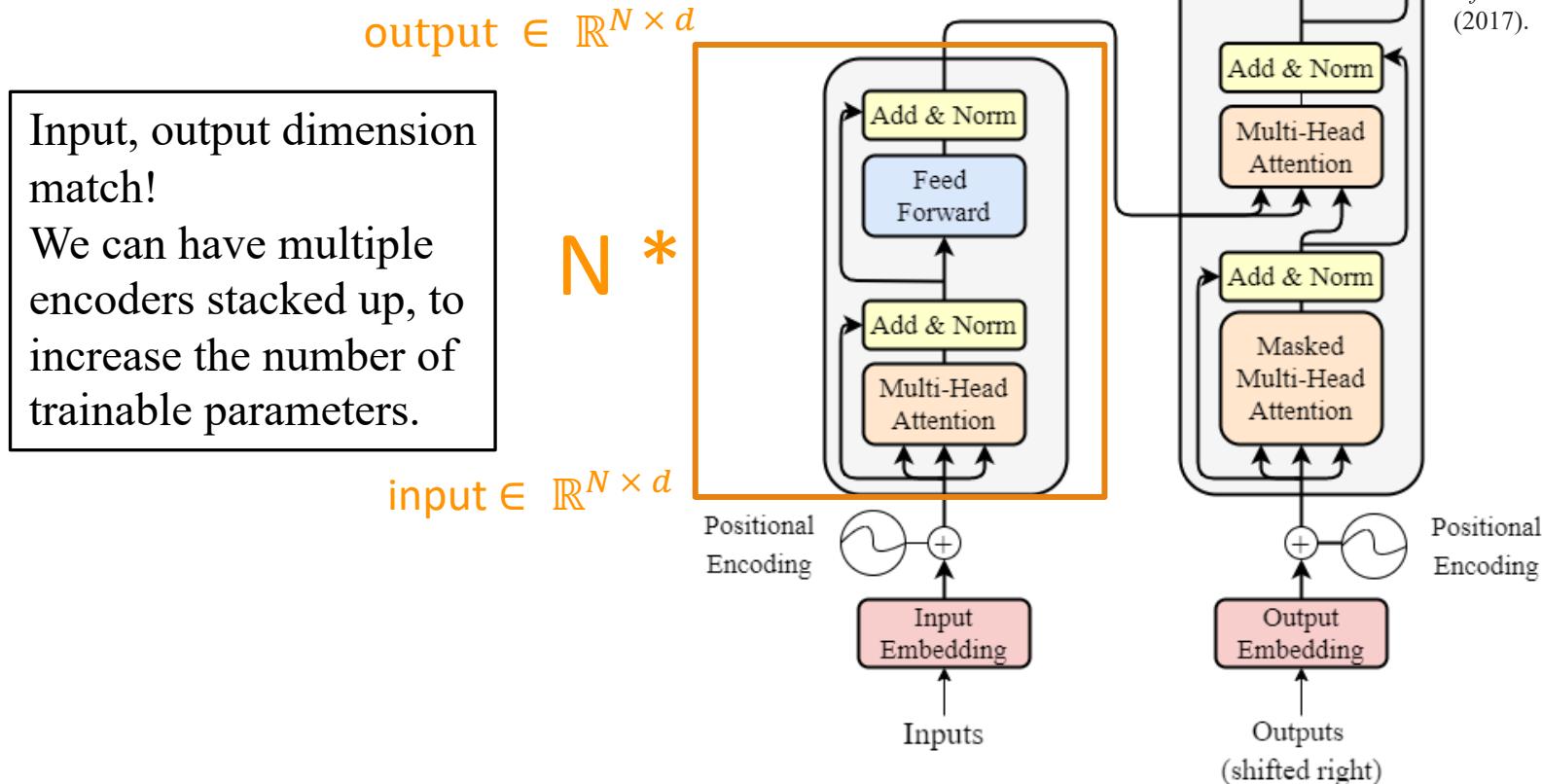
$\text{output} \in \mathbb{R}^{N \times d}$

$\text{input} \in \mathbb{R}^{N \times d}$



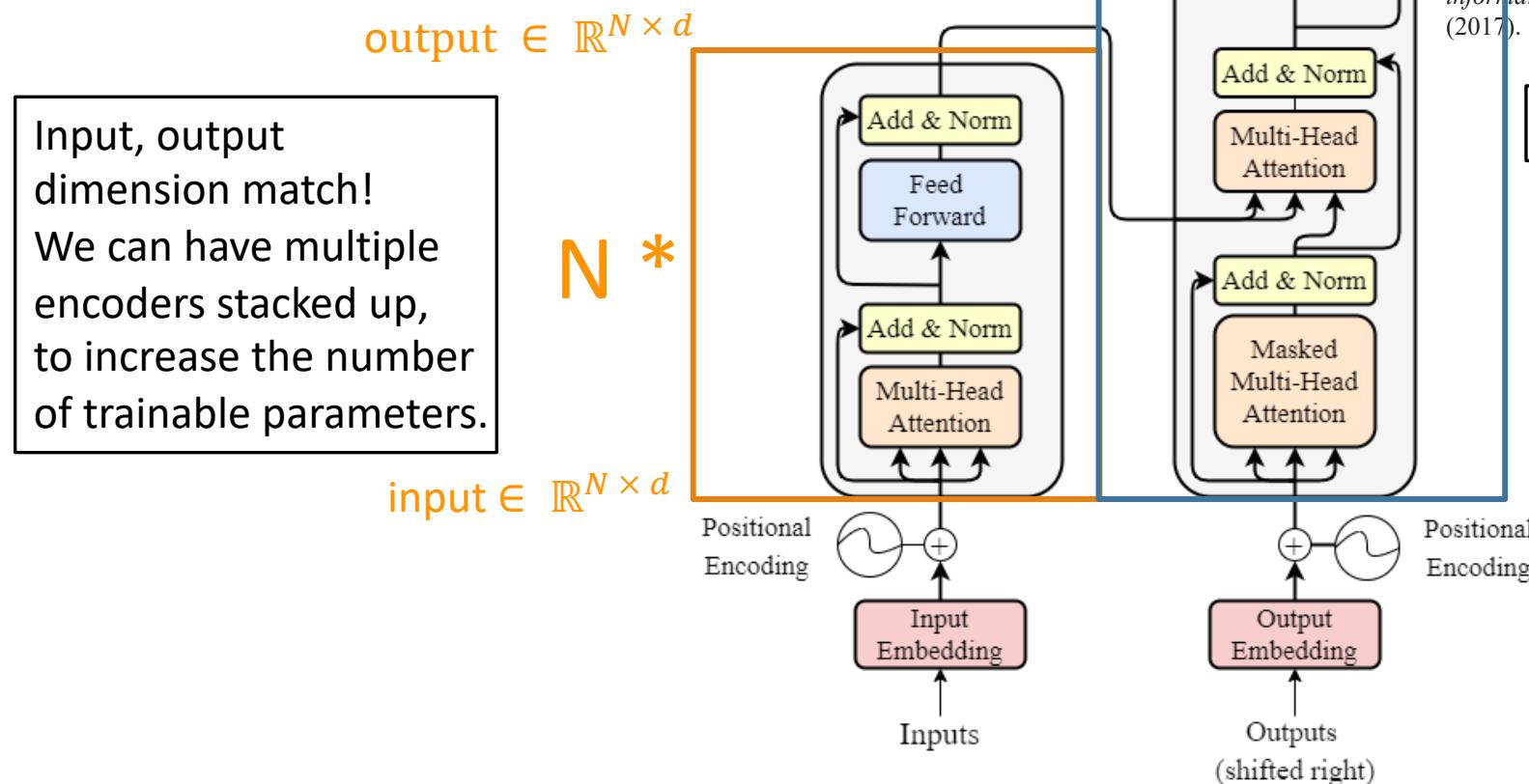
Vaswani, Ashish, et al. "Attention is all you need." *Advances in neural information processing systems* 30 (2017).

of Transformer Layer



Vaswani, Ashish, et al. "Attention is all you need." *Advances in neural information processing systems* 30 (2017).

of Transformer Layer



Vaswani, Ashish, et al. "Attention is all you need." *Advances in neural information processing systems* 30 (2017).

Same for the decoder.

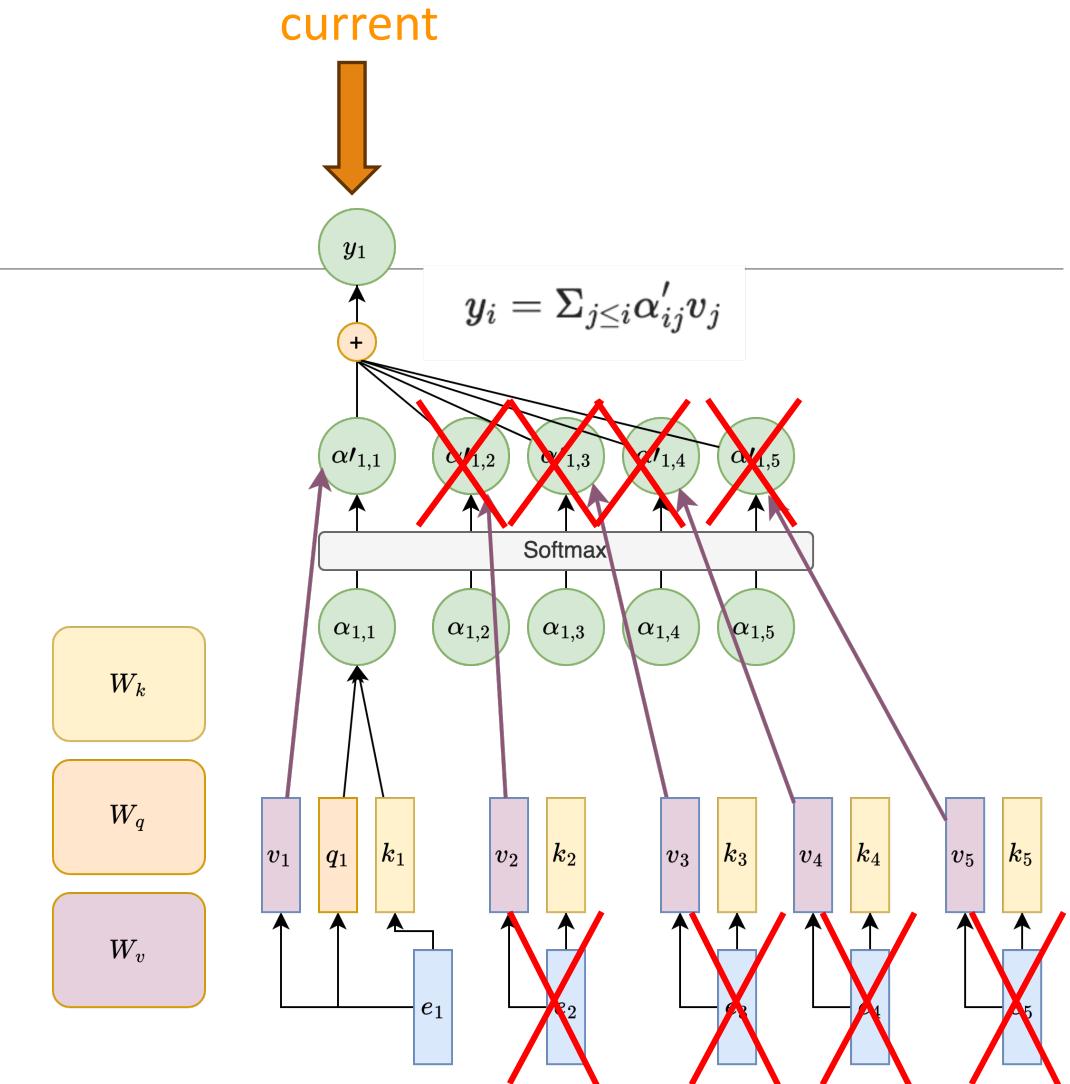
N *

Encoder & Decoder

- Recall that the decoder-encoder architecture accepts a sequence, encodes it, and then outputs another sequence.
 - Encoder sees the input sequence. Decoder **predicts** the output sequence.
- In transformer, both encoder and decoder applies the Multi-head Attention block(s).

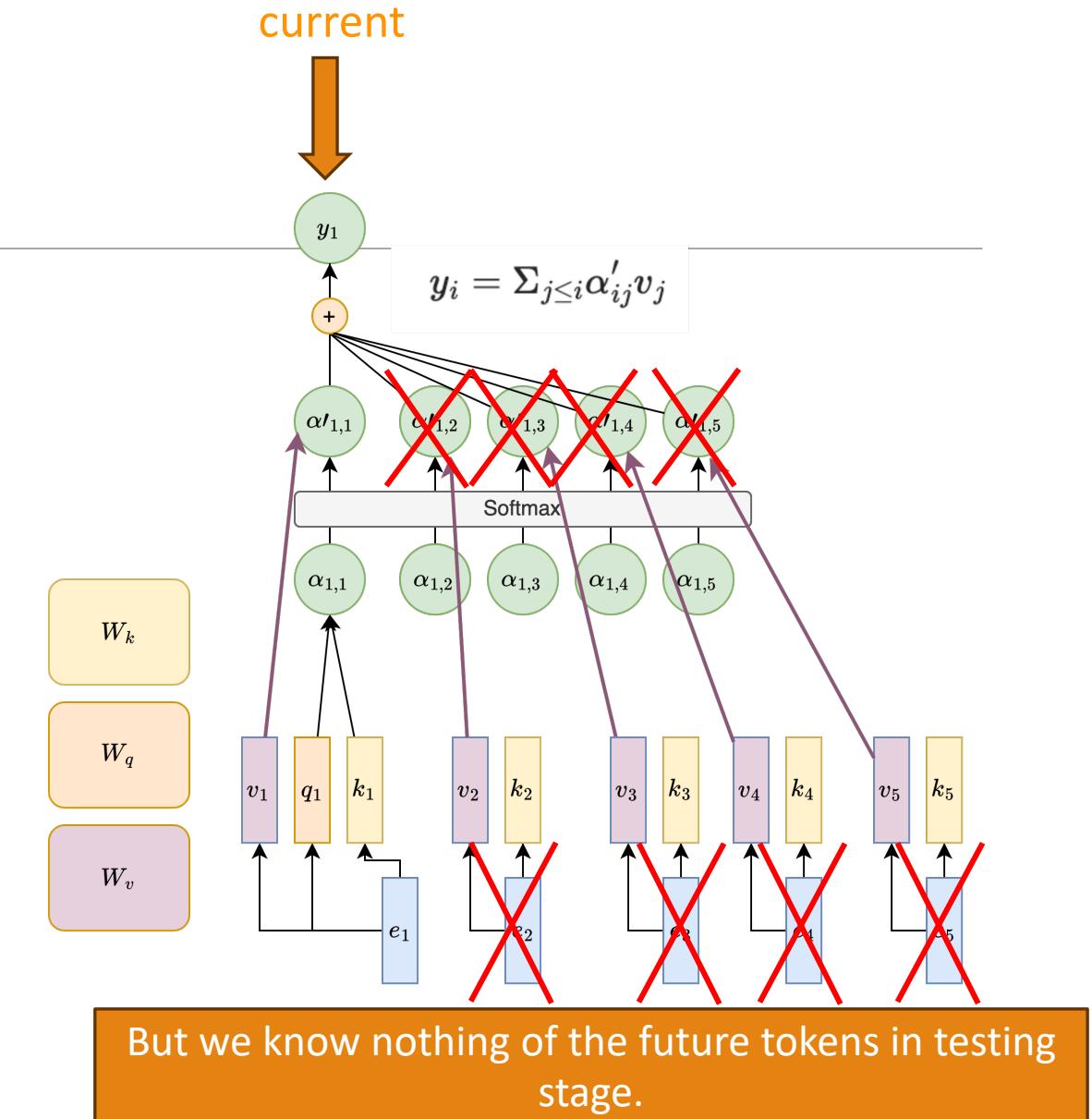
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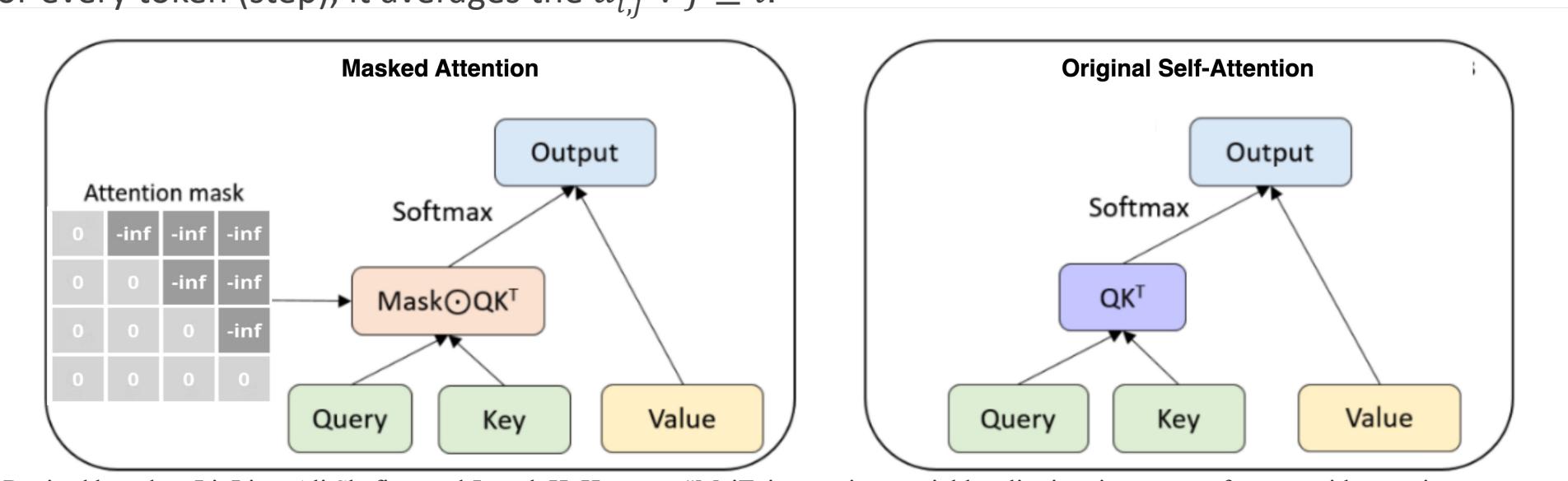
Encoder & Decoder

- Recall that the decoder-encoder architecture accepts a sequence, encodes it, and then outputs another sequence.
- Encoder sees the input sequence. Decoder **predicts** the output sequence.
- In transformer, both encoder and decoder applies the Multi-head Attention block(s).
- However, according to the calculation of self-attention, **we need future tokens to calculate attention score for the current token**.



Decoder: Masked-Attention

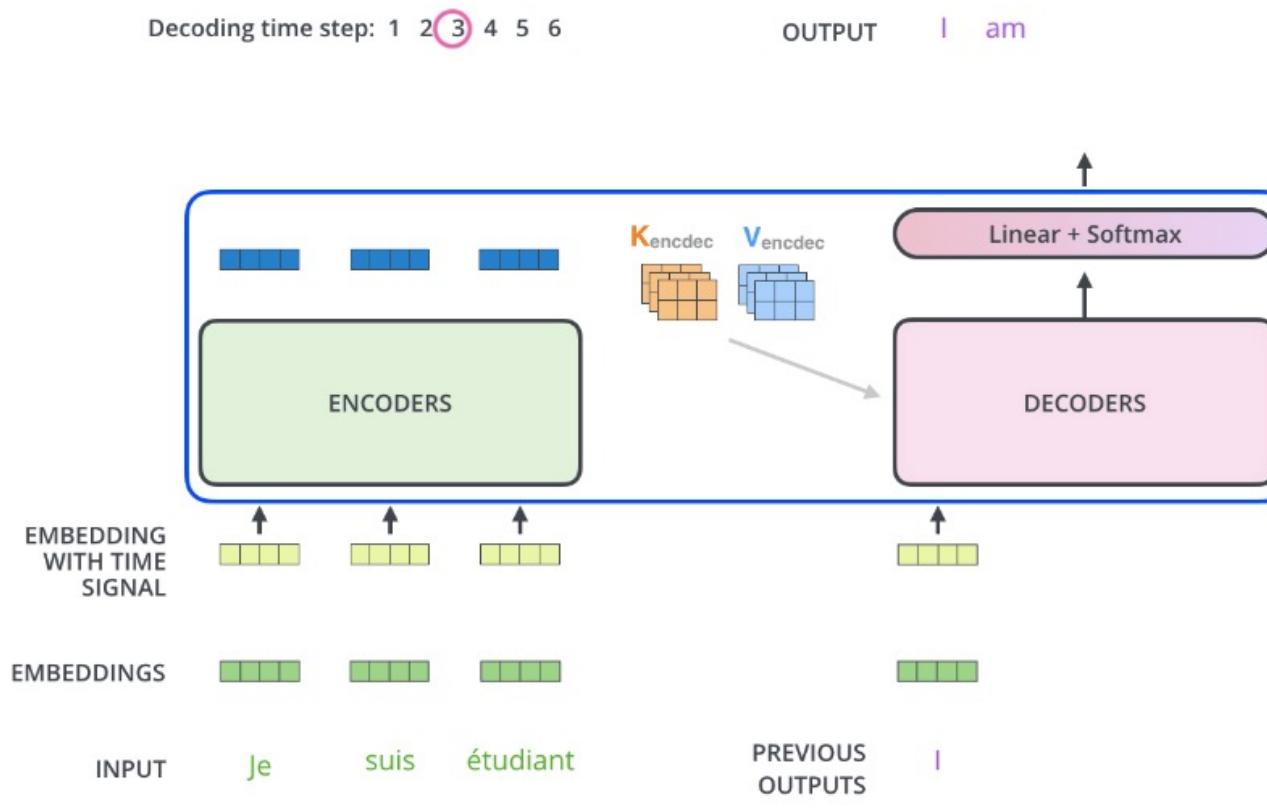
- We mask the future tokens position in QK attention before Softmax().
- By masking the right-upper triangle, the decoder calculates attention scores only on the tokens it can see (since $\text{Softmax}(-\infty) = 0$).
- For every token (step), it averages the $\alpha'_{i,j} \forall j \leq i$.



Revised based on Li, Ling, Ali Shafiee, and Joseph H. Hassoun. "MaIT: integrating spatial locality into image transformers with attention masks." (2021).

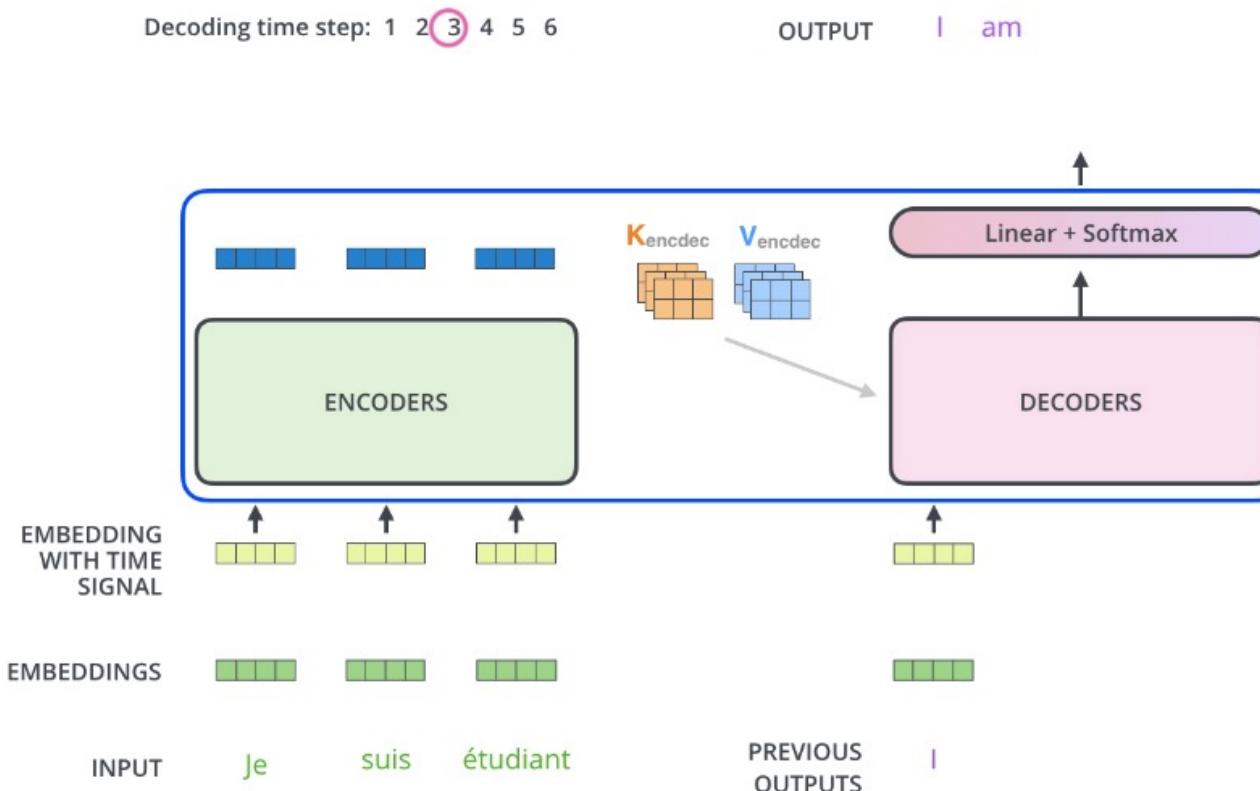
Decoder: Autoregressive Decoding

- In seq2seq problem, the decoder works by generating a token at one step.



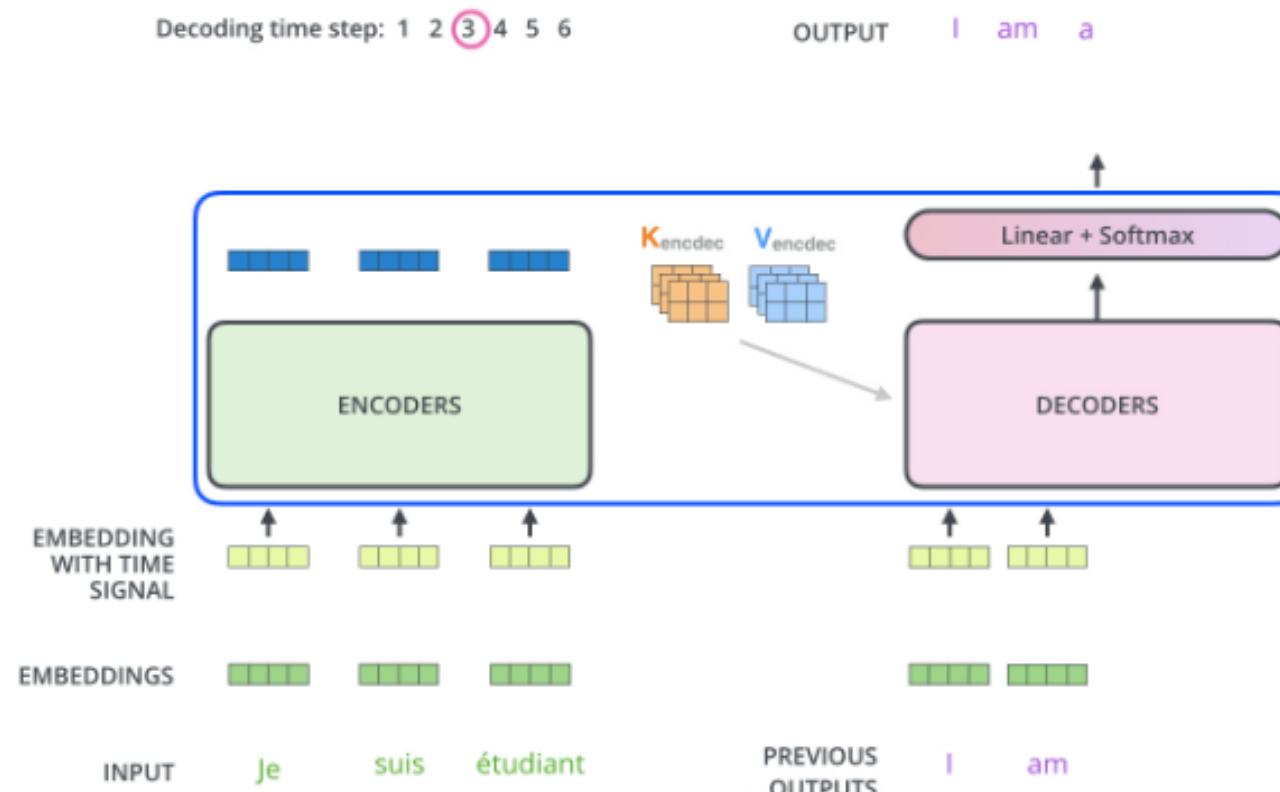
<https://jalammar.github.io/illustrated-transformer/>

Decoder: Autoregressive Decoding



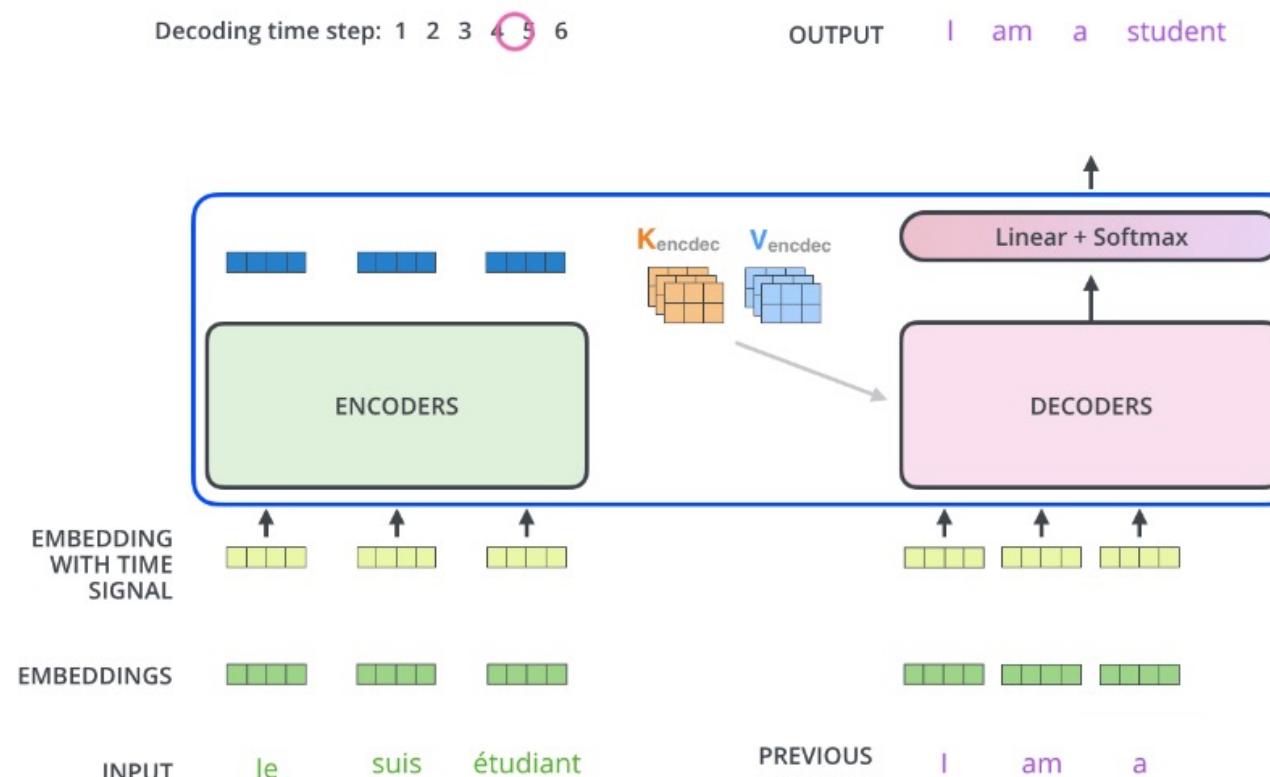
<https://jalammar.github.io/illustrated-transformer/>

Decoder: Autoregressive Decoding



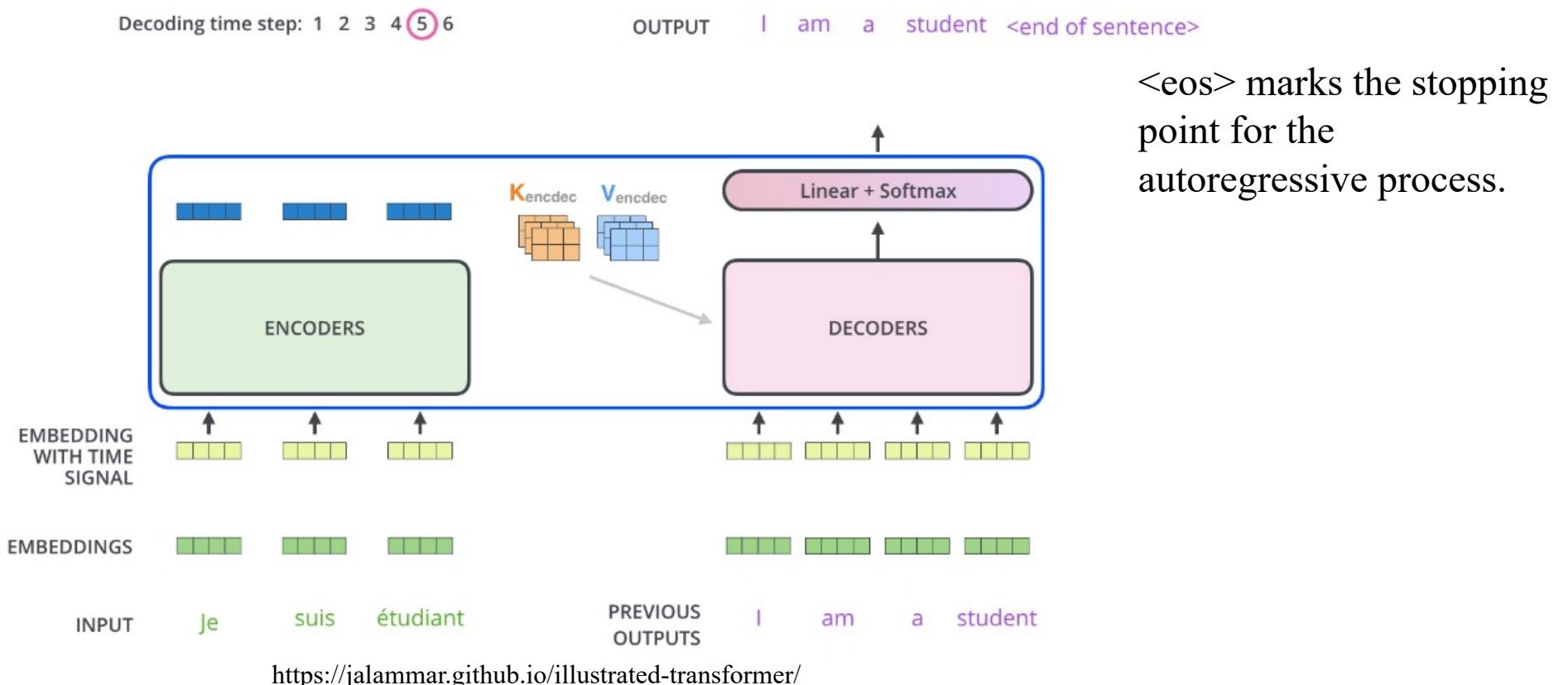
<https://jalammar.github.io/illustrated-transformer/>

Decoder: Autoregressive Decoding



<https://jalammar.github.io/illustrated-transformer/>

Decoder: Autoregressive Decoding

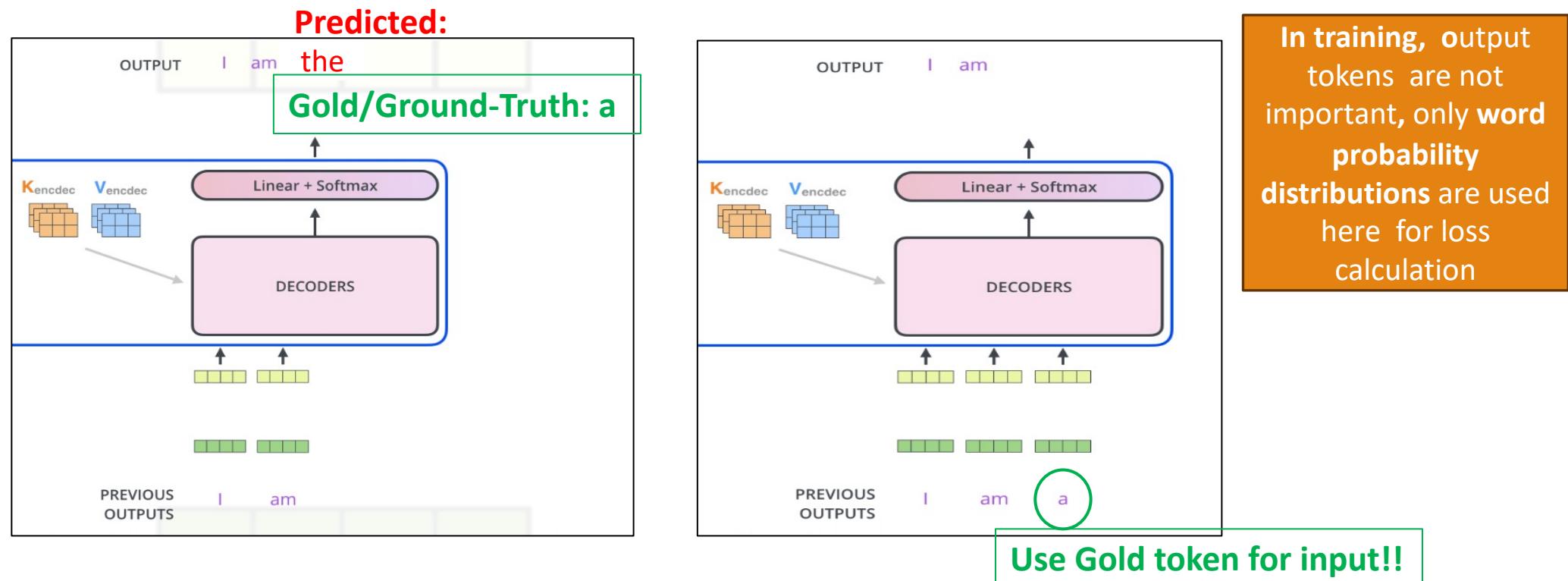


Decoder: Autoregressive Decoding

- In **testing stage**, generated token at i is then concated with previous tokens and fed into the model to predict token at $i + 1$.
- In **training stage**, **teacher forcing** is used (i.e. no matter what token is generated at step i , the gold token at i is used; it is concatenated and fed into the model to predict).

Decoding in Training Stage: Teacher-Forcing

Suppose at step 2 (0-indexed), the predicted highest-prob token is “the” instead of ground-truth “a” ...



Transformer's Achievements

1. In original paper, State-of-The-Art (SoTA) of machine translation.

Table 2: The Transformer achieves better BLEU scores than previous state-of-the-art models on the English-to-German and English-to-French newstest2014 tests at a fraction of the training cost.

Model	BLEU		Training Cost (FLOPs)	
	EN-DE	EN-FR	EN-DE	EN-FR
ByteNet [18]	23.75			
Deep-Att + PosUnk [39]		39.2		$1.0 \cdot 10^{20}$
GNMT + RL [38]	24.6	39.92	$2.3 \cdot 10^{19}$	$1.4 \cdot 10^{20}$
ConvS2S [9]	25.16	40.46	$9.6 \cdot 10^{18}$	$1.5 \cdot 10^{20}$
MoE [32]	26.03	40.56	$2.0 \cdot 10^{19}$	$1.2 \cdot 10^{20}$
Deep-Att + PosUnk Ensemble [39]		40.4		$8.0 \cdot 10^{20}$
GNMT + RL Ensemble [38]	26.30	41.16	$1.8 \cdot 10^{20}$	$1.1 \cdot 10^{21}$
ConvS2S Ensemble [9]	26.36	41.29	$7.7 \cdot 10^{19}$	$1.2 \cdot 10^{21}$
Transformer (base model)	27.3	38.1		$3.3 \cdot 10^{18}$
Transformer (big)	28.4	41.8		$2.3 \cdot 10^{19}$

6 encoders,
6 decoders,
 $h = 512$, 100K train
steps.

6 encoders,
6 decoders,
 $h = 1024$, 300K train
steps.

Vaswani, Ashish, et al. "Attention is all you need." *Advances in neural information processing systems* 30 (2017).
<https://arxiv.org/abs/1706.03762>

Transformer's Achievements

- (Chat)GPT is just a **pretrained** transformer (it is just n layers of transformer decoders).
- **Pretraining** is similar to let the model read through a lot of books, and get a sense of the context word distribution so that it can infer the meaning.
 - For more on **linguistic theory**, check “distributional hypothesis.”
 - For more on **pretraining**, wait till next week (W7) ’s topic of BERT and its Family!

I saw a sentence
“I found a special
restaurant and I
like it” before...

The word
“extraordinary” must
share a similar meaning
with “special”!

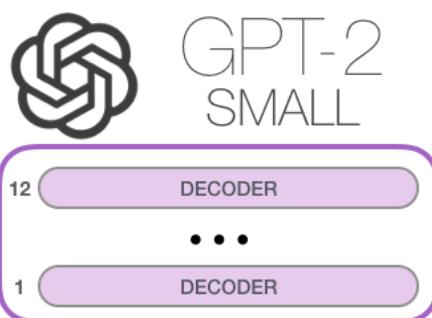


(On the book)
“I found an **extraordinary**
restaurant and I love it!”

Source:
https://stock.adobe.com/tw/search?k=robot+reading&asset_id=570899814

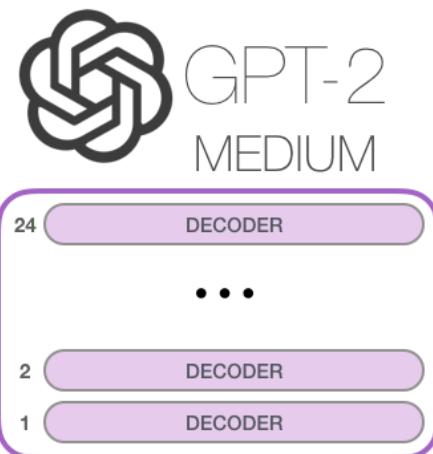
GPT-2

- GPT-2 are just a lot of transformer decoders!
- We will not talk about GPT series right now, wait till Week 9 or search about it by yourself!

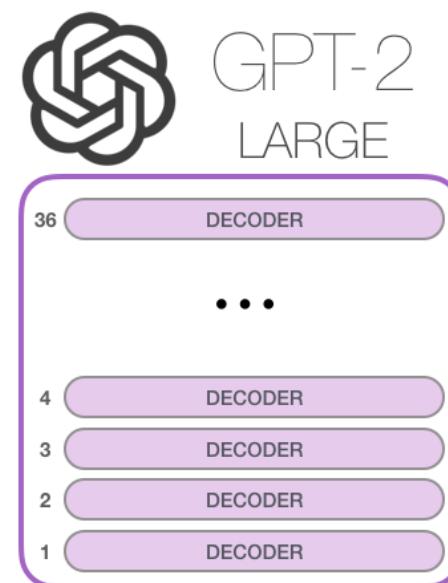


Model Dimensionality: 768

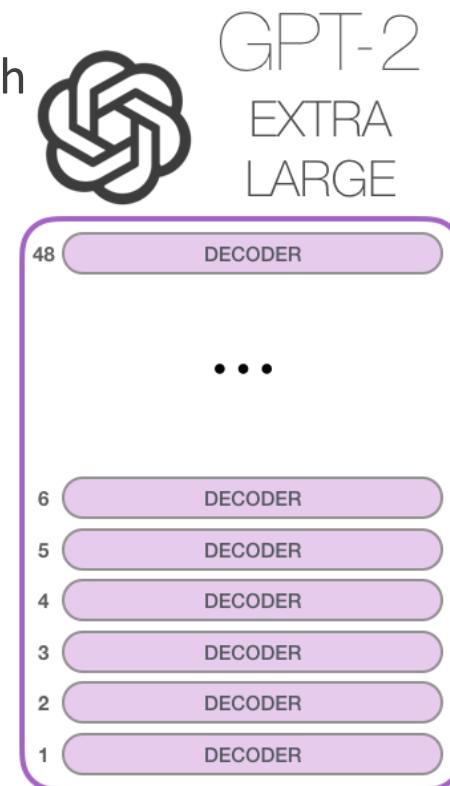
Source: <https://jalammar.github.io/illustrated-gpt2/>



Model Dimensionality: 1024



Model Dimensionality: 1280

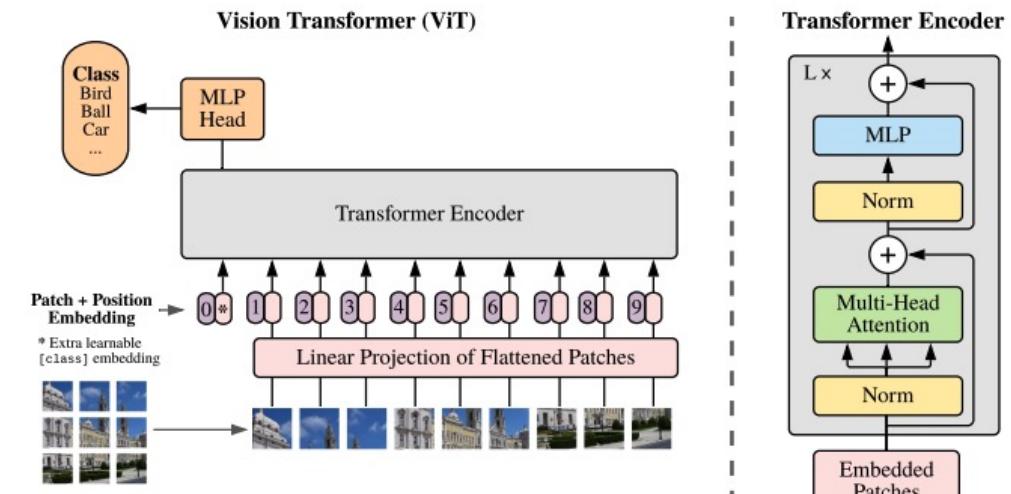


Model Dimensionality: 1600

Vision Transformer (ViT)

- Google Research
- Apply transformer on vision tasks...
 - Split an image into image pathes.
 - Concat the pathes into a sequence.
 - Add positional encoding
 - Send the sequence to our transformer encoder. That's it!
- Outperform BiTL (ResNet with some improvements).
- Learn well on large-scale datasets.

Testing on
which
dataset



Alexey Dosovitskiy, et al. "An Image is Worth 16x16 Words: Transformers for Image Recognition at Scale." *International Conference on Learning Representations*. 2021.

Pretrained on which

dataset	Ours-JFT (ViT-H/14)	Ours-JFT (ViT-L/16)	Ours-I21k (ViT-L/16)	BiT-L (ResNet152x4)	Noisy Student (EfficientNet-L2)
ImageNet	88.55 ± 0.04	87.76 ± 0.03	85.30 ± 0.02	87.54 ± 0.02	88.4/88.5*
ImageNet ReaL	90.72 ± 0.05	90.54 ± 0.03	88.62 ± 0.05	90.54	90.55
CIFAR-10	99.50 ± 0.06	99.42 ± 0.03	99.15 ± 0.03	99.37 ± 0.06	—
CIFAR-100	94.55 ± 0.04	93.90 ± 0.05	93.25 ± 0.05	93.51 ± 0.08	—
Oxford-IIIT Pets	97.56 ± 0.03	97.32 ± 0.11	94.67 ± 0.15	96.62 ± 0.23	—
Oxford Flowers-102	99.68 ± 0.02	99.74 ± 0.00	99.61 ± 0.02	99.63 ± 0.03	—
VTAB (19 tasks)	77.63 ± 0.23	76.28 ± 0.46	72.72 ± 0.21	76.29 ± 1.70	—
TPUv3-core-days	2.5k	0.68k	0.23k	9.9k	12.3k

Transformer Variants (there are many more)

■ Universal Transformer

- Adds Adaptive Computation Time
- Dehghani, Mostafa, et al. "Universal transformers." arXiv preprint arXiv:1807.03819 (2018).

■ Longformer

- Tackles long documents
- Iz Beltagy, et al. (2020). Longformer: The Long-Document Transformer. arXiv:2004.05150.

■ Roformer

- Changes the design of positional encoding
- Su, Jianlin, et al. "RoFormer: Enhanced Transformer with Rotary Position Embedding. CoRR abs/2104.09864 (2021)." arXiv preprint arXiv:2104.09864 (2021).

■ Vision Transformer

- Tackles vision tasks
- Alexey Dosovitskiy, et al. "An Image is Worth 16x16 Words: Transformers for Image Recognition at Scale." *International Conference on Learning Representations*. 2021.



Q & A