# Transformer

Wei Xu

(many slides from Greg Durrett)

# This Lecture

- Transformer architecture

# Attention is All You Need

## Attention Is All You Need

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### Abstract

The dominant sequence transduction models are based on complex recurrent or convolutional neural networks that include an encoder and a decoder. The best performing models also connect the encoder and decoder through an attention mechanism. We propose a new simple network architecture, the Transformer, based solely on attention mechanisms, dispensing with recurrence and convolutions entirely. Experiments on two machine translation tasks show these models to be superior in quality while being more parallelizable and requiring significantly less time to train. Our model achieves 28.4 BLEU on the WMT 2014 English-to-German translation task, improving over the existing best results, including ensembles, by over 2 BLEU. On the WMT 2014 English-to-French translation task, our model establishes a new single-model state-of-the-art BLEU score of 41.8 after training for 3.5 days on eight GPUs, a small fraction of the training costs of the best models from the literature. We show that the Transformer generalizes well to other tasks by applying it successfully to English constituency parsing both with large and limited training data.

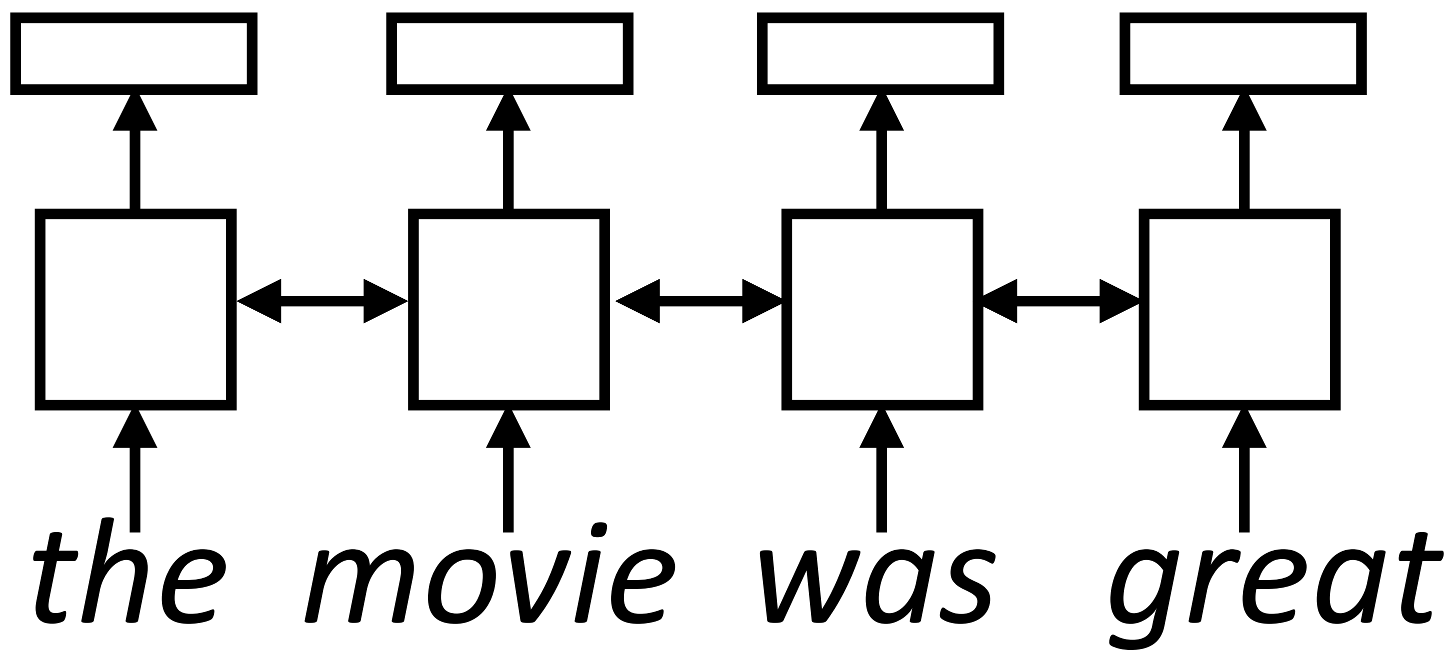
Vaswani et al. (2017)

# Readings

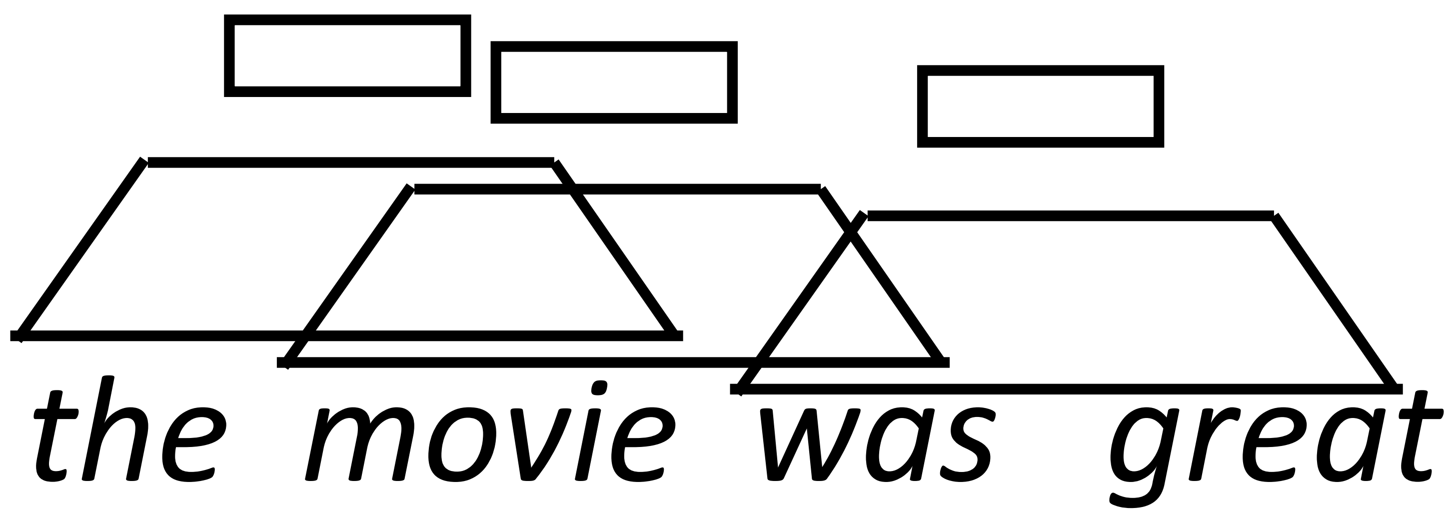
- “The Annotated Transformer” by Sasha Rush
  https://nlp.seas.harvard.edu/2018/04/03/attention.html
- “The Illustrated Transformer” by Jay Lamar
  http://jalammar.github.io/illustrated-transformer/
- Jurafsky+Martin Chapter 8

# Sentence Encoders

- LSTM abstraction: maps each vector in a sentence to a new, context-aware vector




- CNNs do something similar with filters




- Attention can give us a third way to do this

Vaswani et al. (2017)

# Self-Attention

# Self-Attention

- Assume we're using GloVe/word2vec embeddings — what do we want our neural network to do?

*The ballerina is very excited that she will dance in the show.*

- Q: What words need to be contextualized here?

Vaswani et al. (2017)

# Self-Attention

- Assume we're using GloVe/word2vec embeddings — what do we want our neural network to do?

*The ballerina is very excited that she will dance in the show.*

- What words need to be contextualized here?
  - Pronouns need to look at antecedents
  - Ambiguous words should look at context
  - Words should look at syntactic parents/children
- Problem: LSTMs and CNNs don't do this

Vaswani et al. (2017)

# Self-Attention

- Want:

*The ballerina is very excited that she will dance in the show.*

- LSTMs/CNNs: tend to look at local context

*The ballerina is very excited that she will dance in the show.*

- To appropriately contextualize embeddings, we need to pass information over long distances dynamically for each word

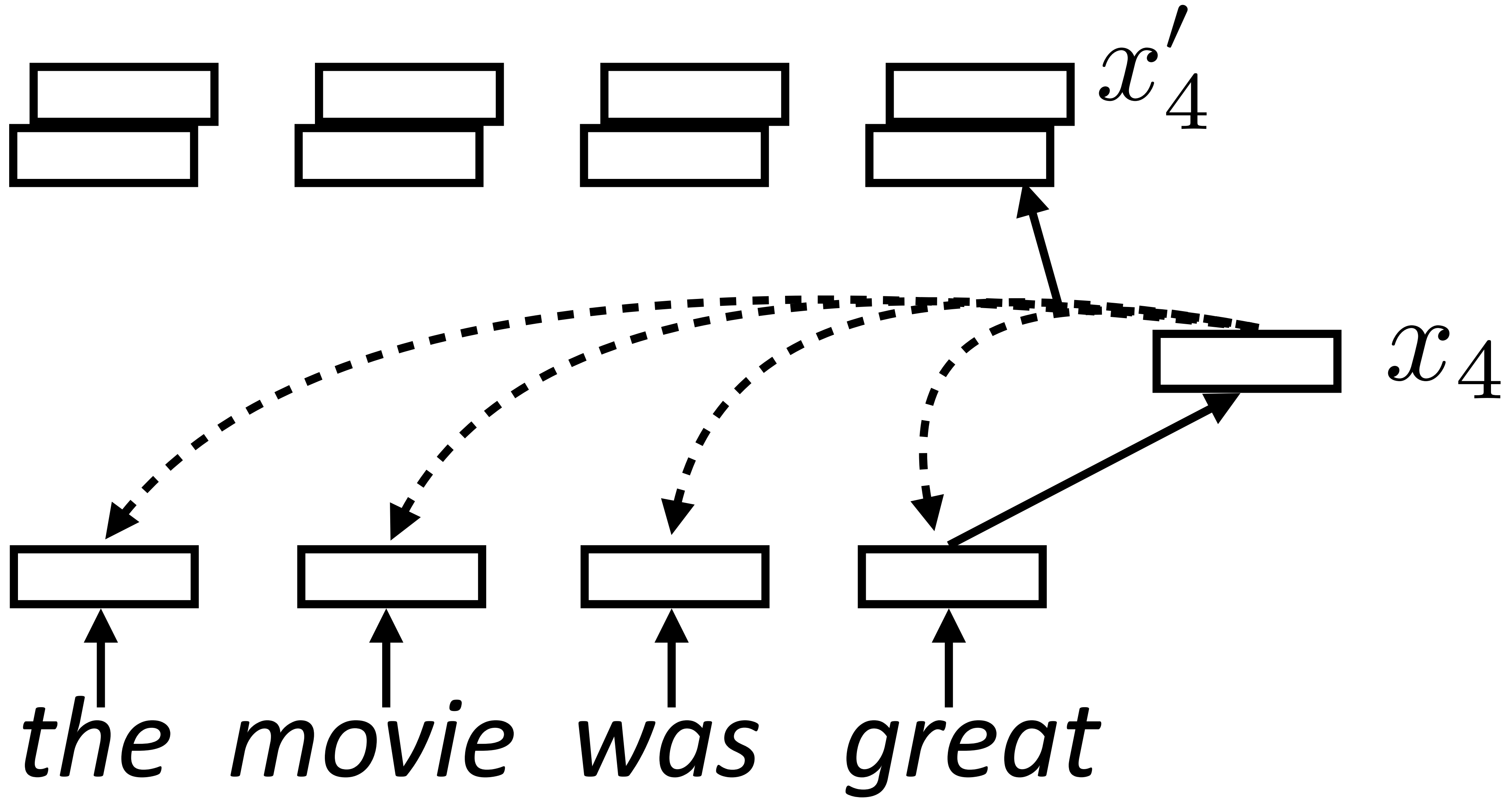
Vaswani et al. (2017)

# Self-Attention

- Each word forms a "query" which then computes attention over each word

$$\alpha_{i,j} = \text{softmax}(x_i^\top x_j) \quad \text{scalar}$$

$$x'_i = \sum_{j=1}^{n} \alpha_{i,j} x_j \quad \text{vector = sum of scalar * vector}$$




- Multiple "heads" use different sets of parameters $W_k$ and $V_k$ to get different attention values + transform vectors

$$\alpha_{k,i,j} = \text{softmax}(x_i^\top W_k x_j) \qquad x'_{k,i} = \sum_{j=1}^{n} \alpha_{k,i,j} V_k x_j$$

Vaswani et al. (2017)

# What can self-attention do?

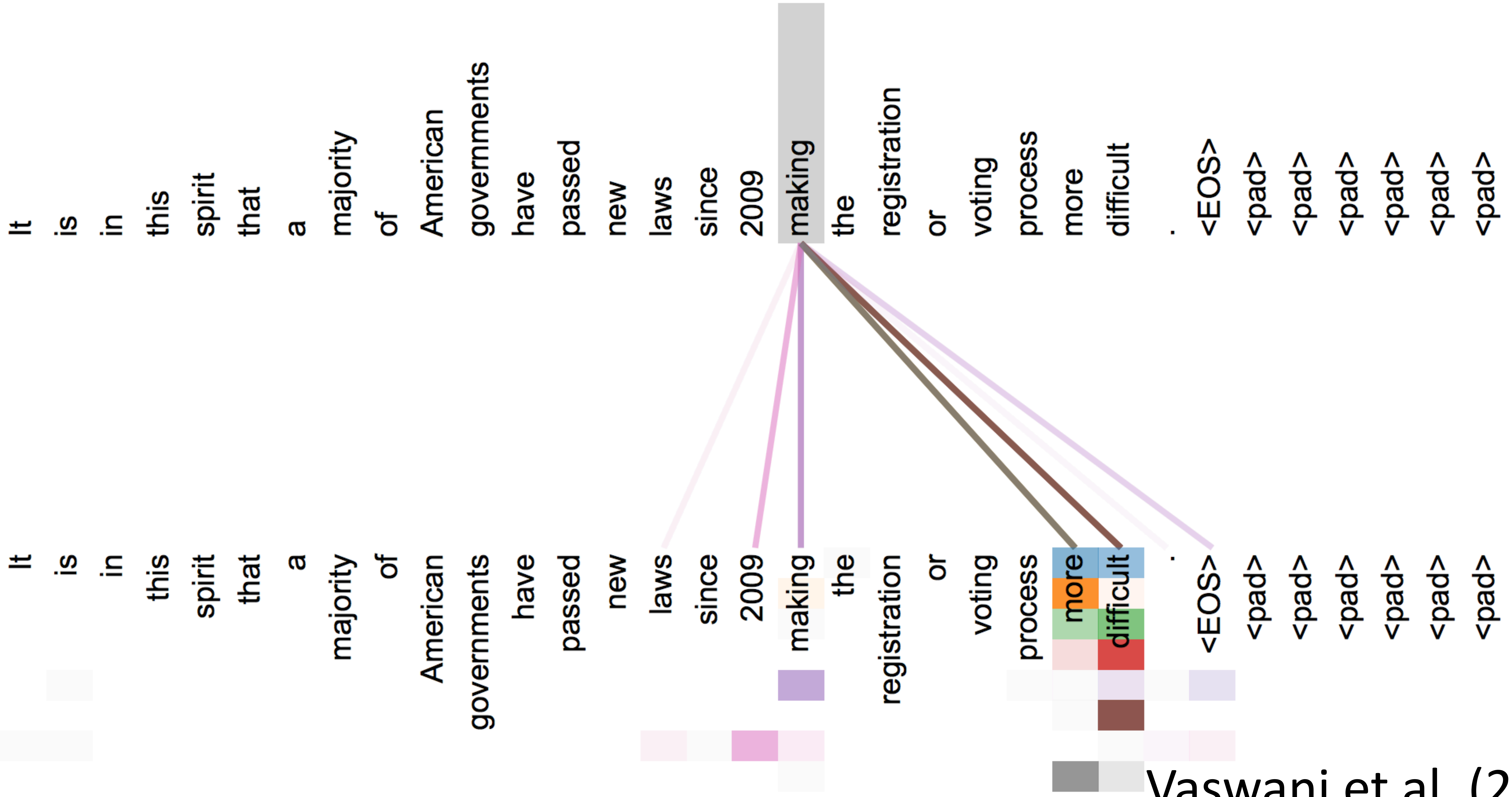
*The ballerina is very excited that she will dance in the show.*

| | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 0 | 0.5 | 0 | 0 | 0.1 | 0.1 | 0 | 0.1 | 0.2 | 0 | 0 | 0 |
| 0 | 0.1 | 0 | 0 | 0 | 0 | 0 | 0 | 0.5 | 0 | 0.4 | 0 |

- Attend nearby + to semantically related terms
- Why multiple heads? Softmaxes end up being peaked, single distribution cannot easily put weight on multiple things

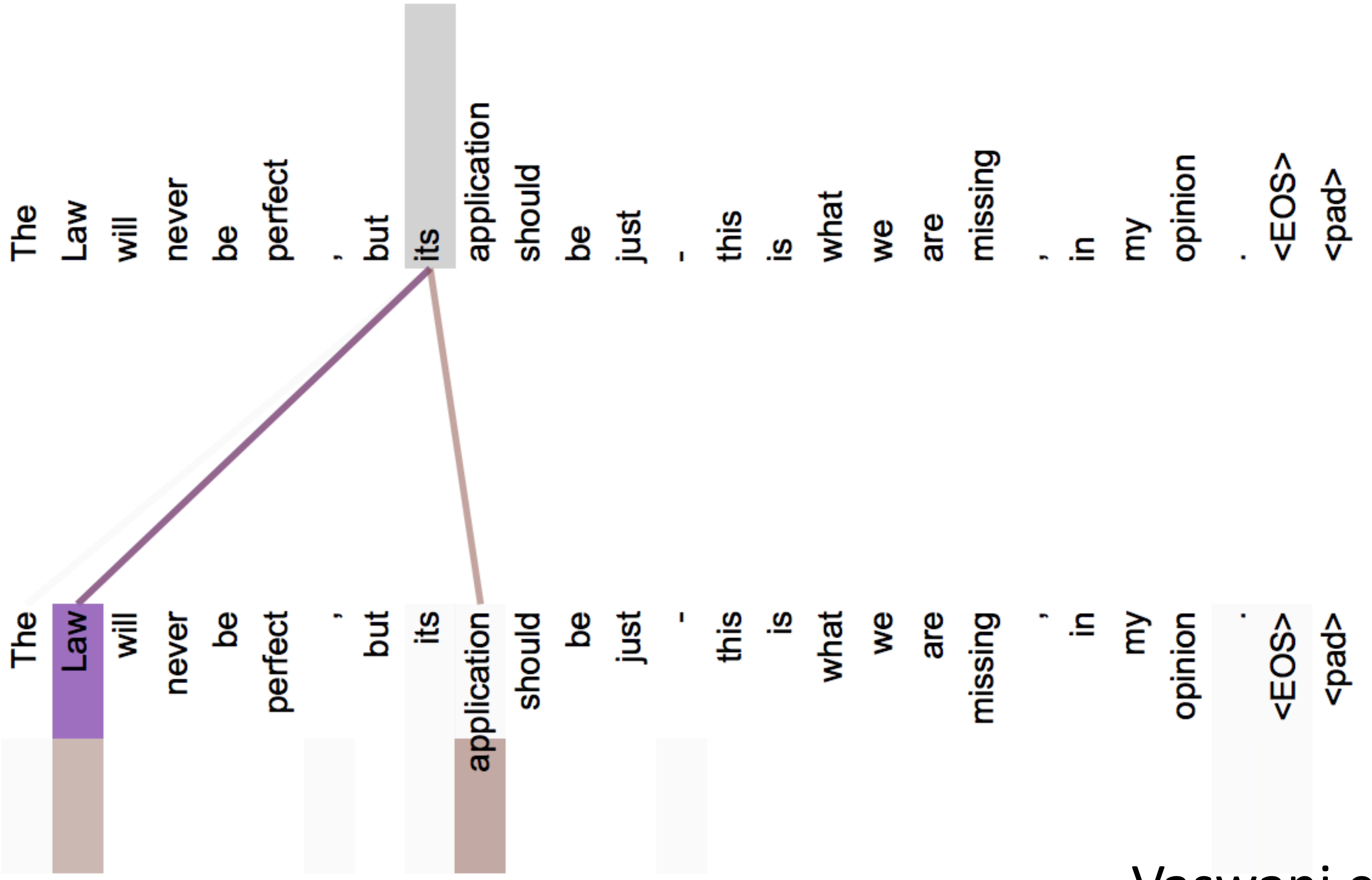
Vaswani et al. (2017)

# Visualization



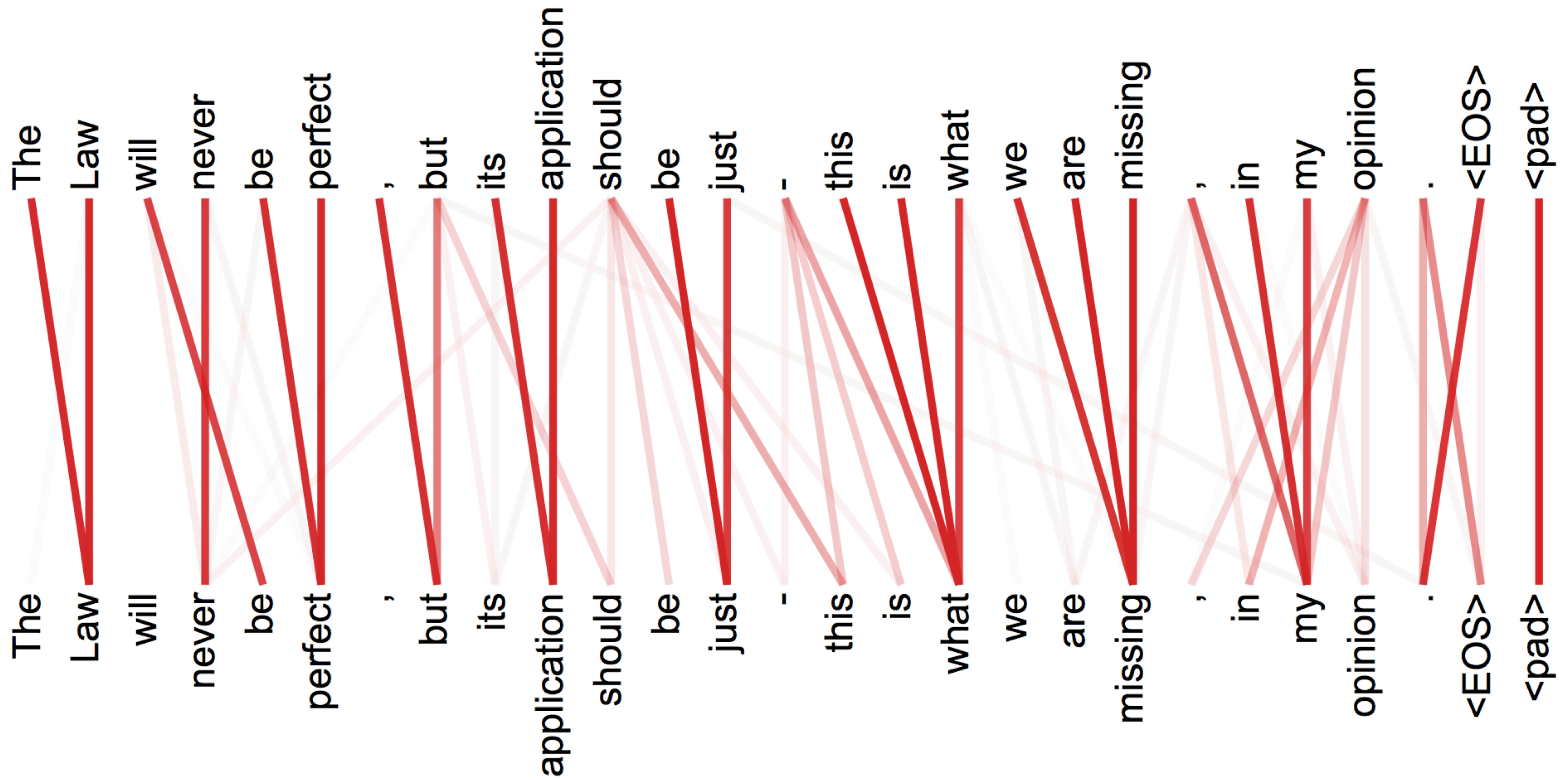

Vaswani et al. (2017)

# Visualization




Vaswani et al. (2017)

# Visualization




Vaswani et al. (2017)

# Self-Attention

- Each word forms a "query" which then computes attention over each word

$$\alpha_{i,j} = \text{softmax}(x_i^\top x_j) \quad \text{scalar}$$

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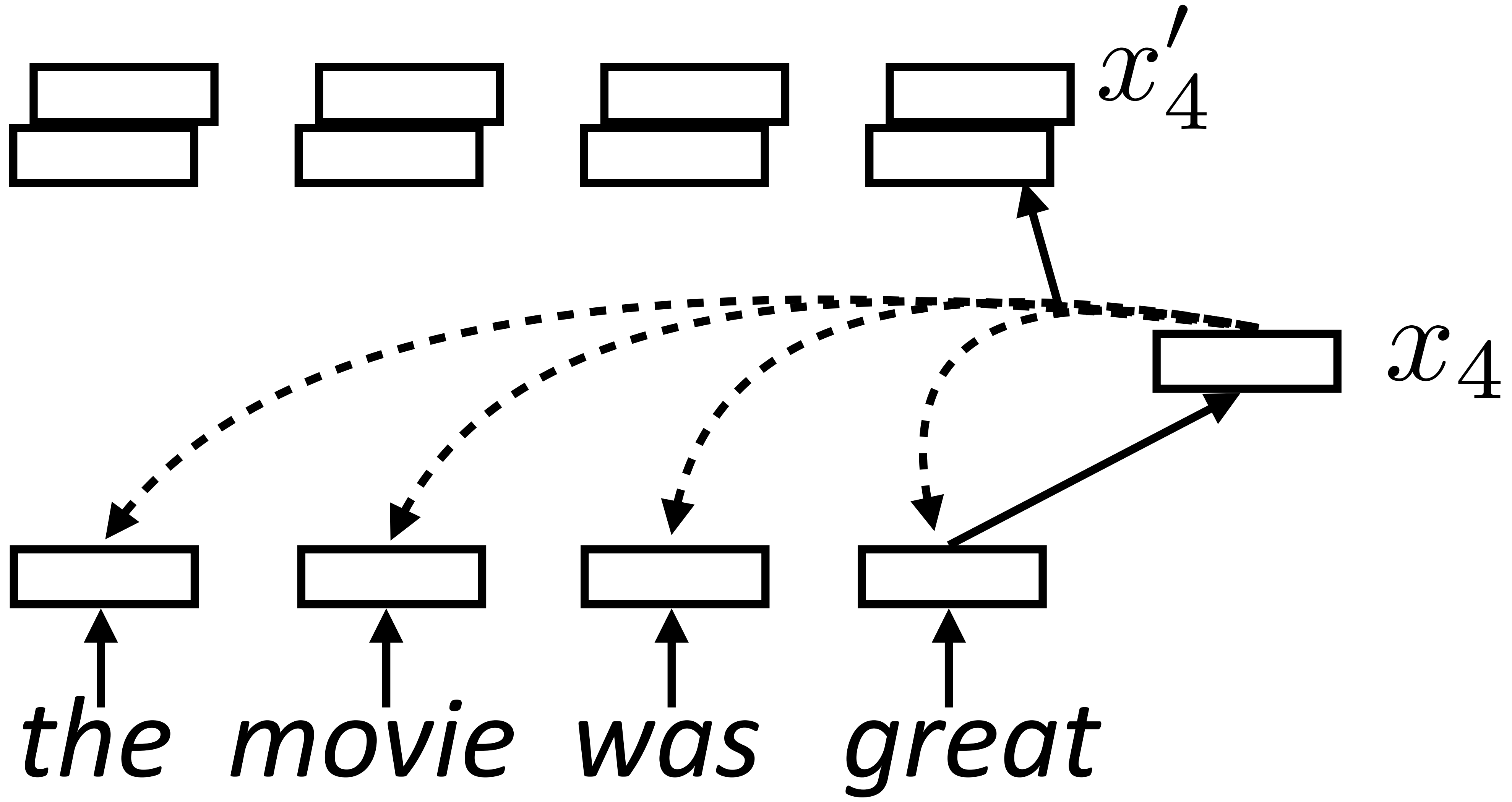



- Multiple "heads" analogous to different convolutional filters. Use parameters $W_k$ and $V_k$ to get different attention values + transform vectors

$$\alpha_{k,i,j} = \text{softmax}(x_i^\top W_k x_j) \quad x'_{k,i} = \sum_{j=1}^{n} \alpha_{k,i,j} V_k x_j$$

Vaswani et al. (2017)

# Multi-Head Self Attention

- Multiple "heads" - actual implementation that uses matrix operations
- Let $X$ = [sent len, embedding dim] be the input sentence
- Query $Q = XW^Q$: these are like the **decoder hidden state** in attention
- Keys $K = XW^K$: these control what gets attended to, along with the query
- Values $V = XW^V$: these vectors get summed up to form the output

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

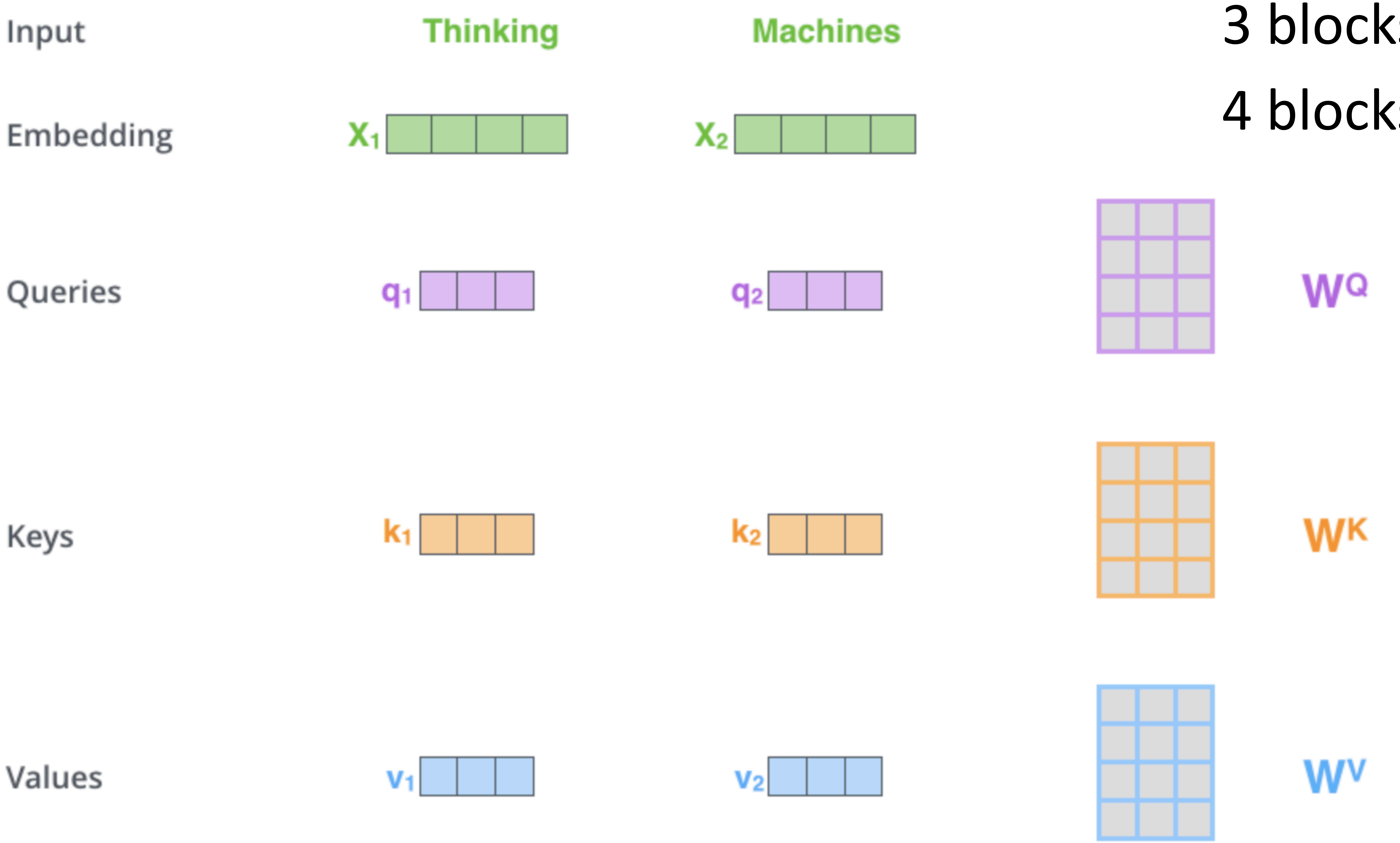
dim of keys

Vaswani et al. (2017)

# Multi-Head Self Attention

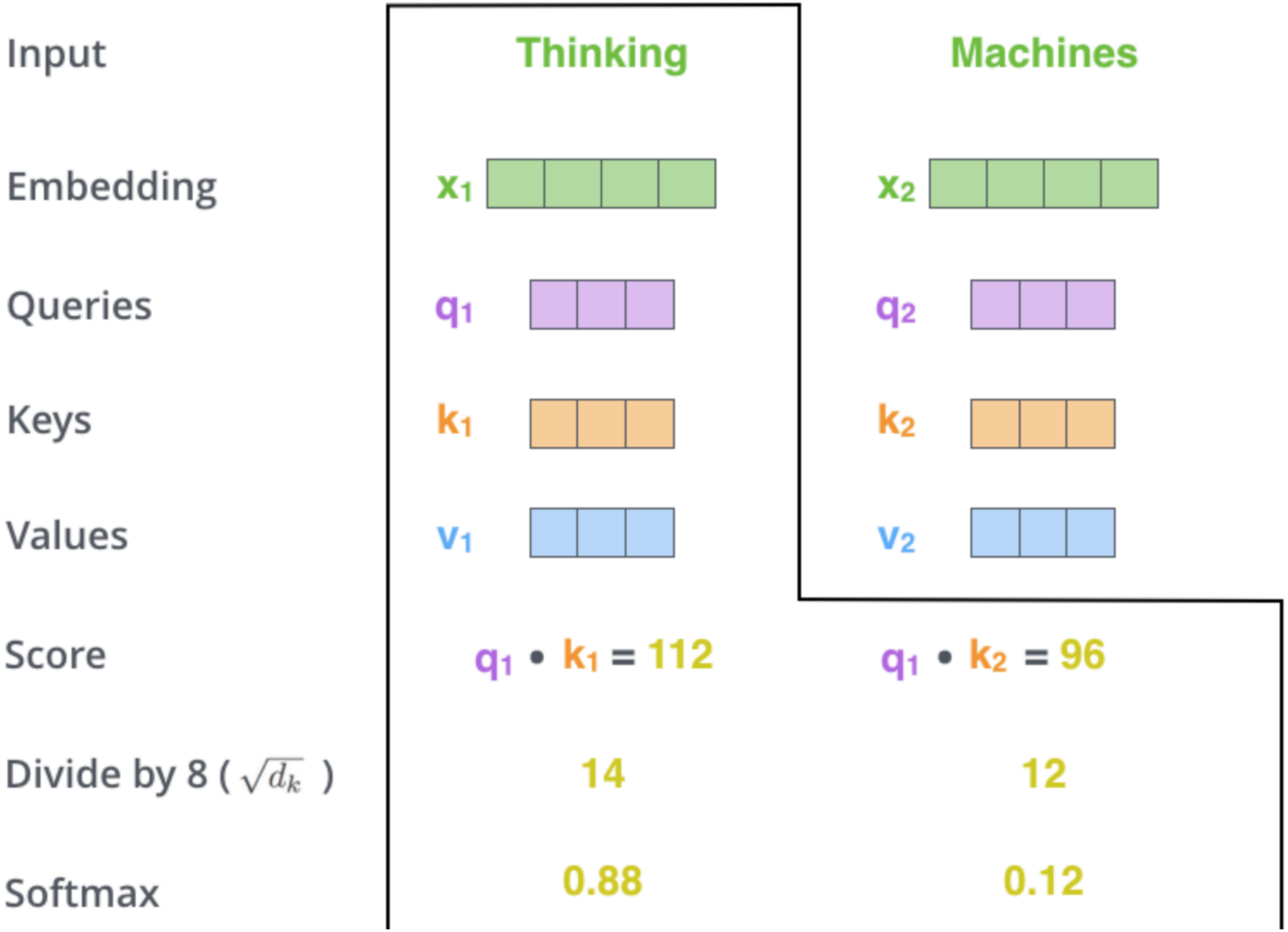
3 blocks - 64 dim ($d_k$)

4 blocks - 512 dim ($d_x$)




Credit: Alammar, *The Illustrated Transformer*

# Multi-Head Self Attention



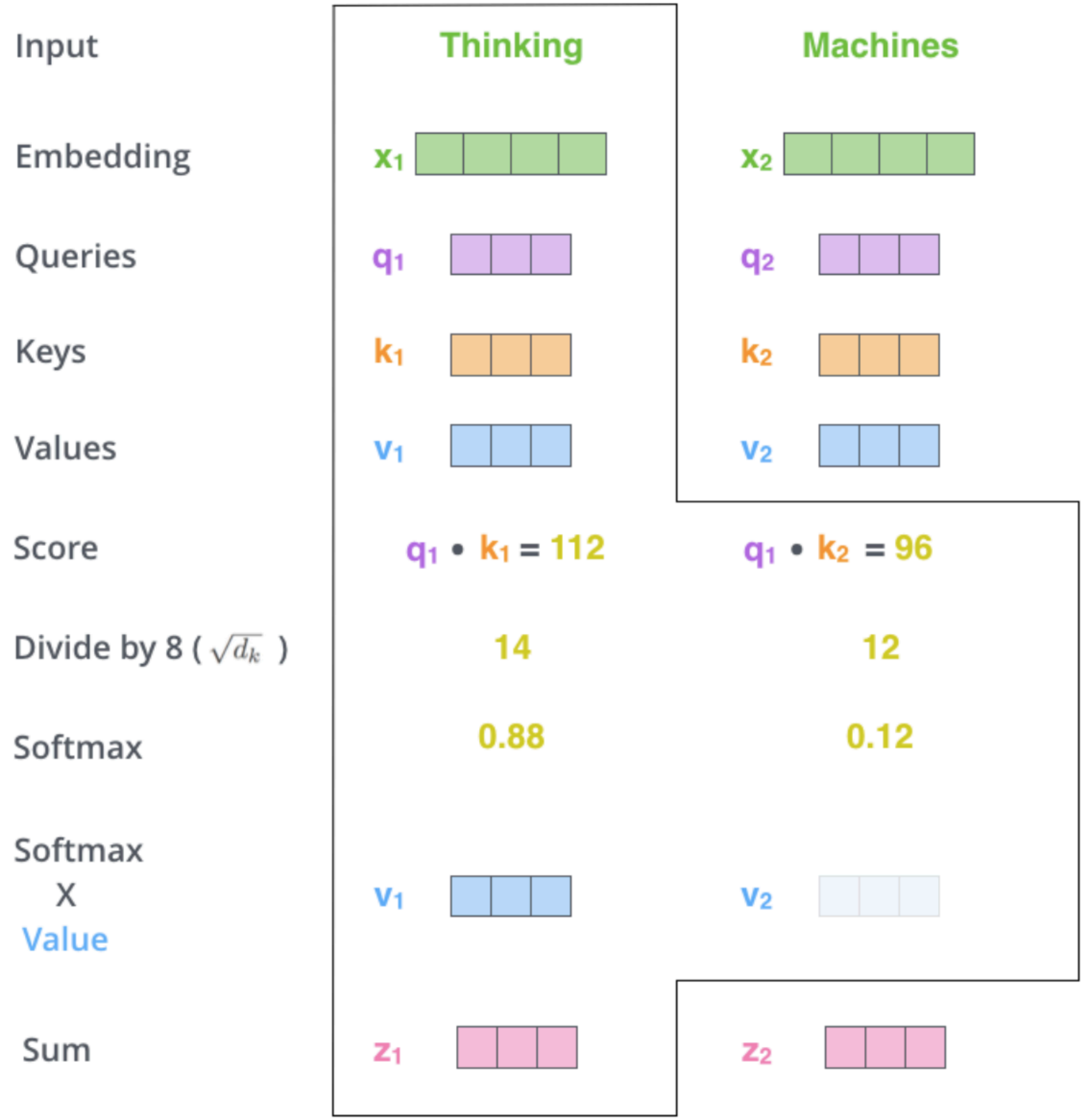

3 blocks - 64 dim ($d_k$)

4 blocks - 512 dim ($d_x$)

$$\mathrm{Attention}(Q, K, V) = \mathrm{softmax}(\frac{QK^T}{\sqrt{d_k}})V$$

Credit: Alammar, *The Illustrated Transformer*

# Multi-Head Self Attention




3 blocks - 64 dim ($d_k$)

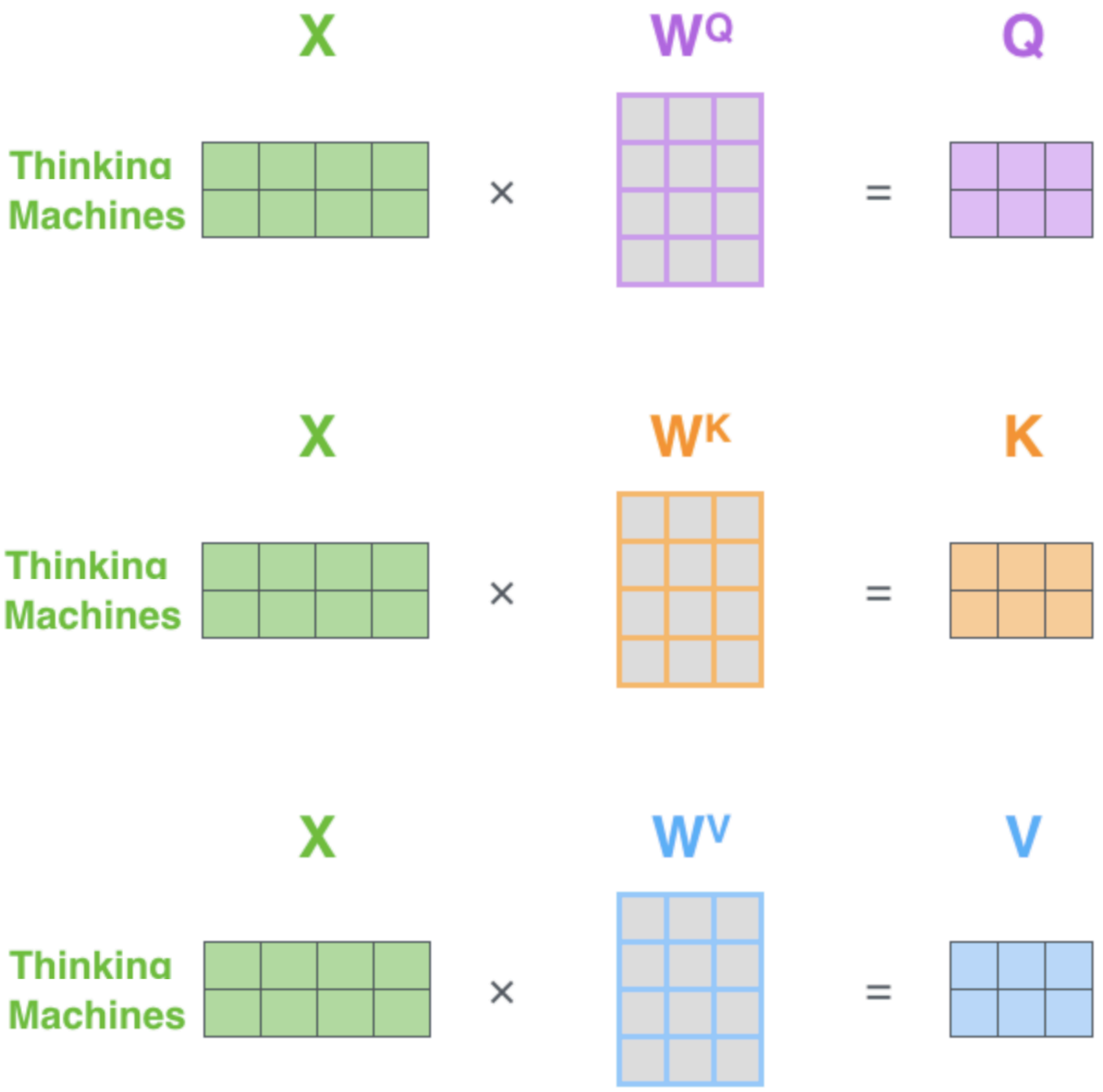
4 blocks - 512 dim ($d_x$)

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

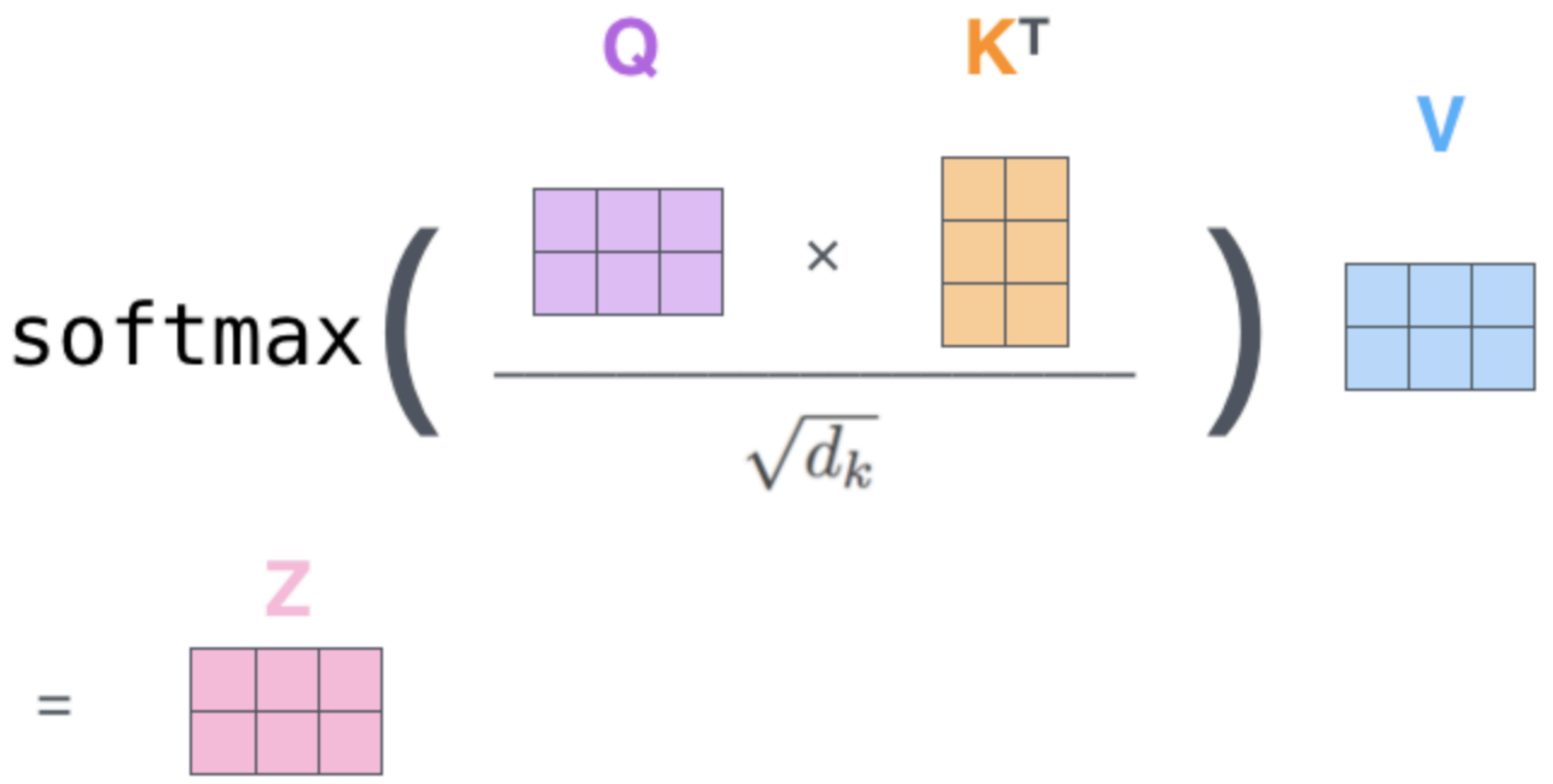
Credit: Alammar, *The Illustrated Transformer*

# Multi-Head Self Attention

every row in X is a word in input sent




sent len x sent len (attn for each word to each other)

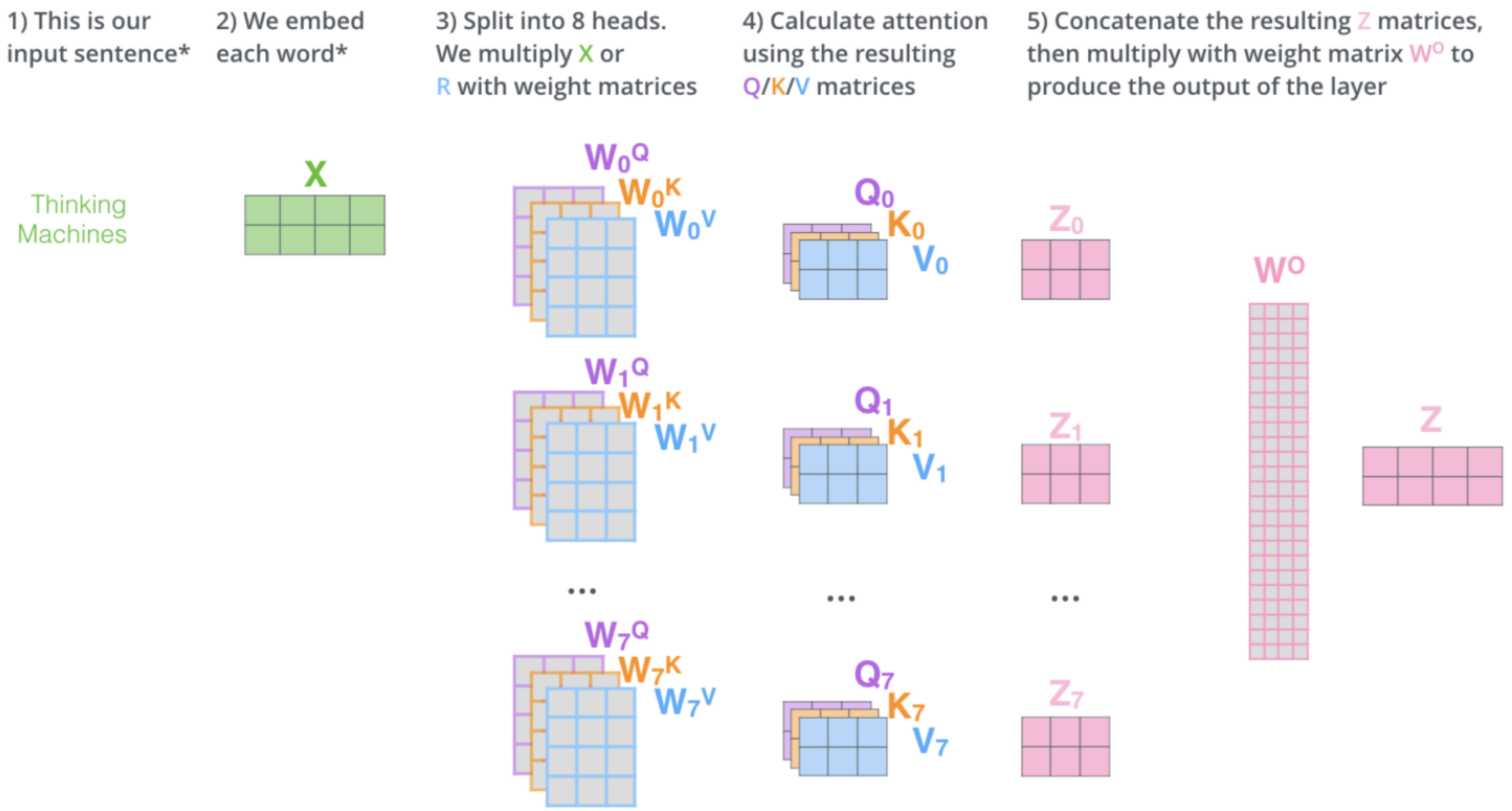



sent len x hidden dim

Z is a weighted combination of V rows

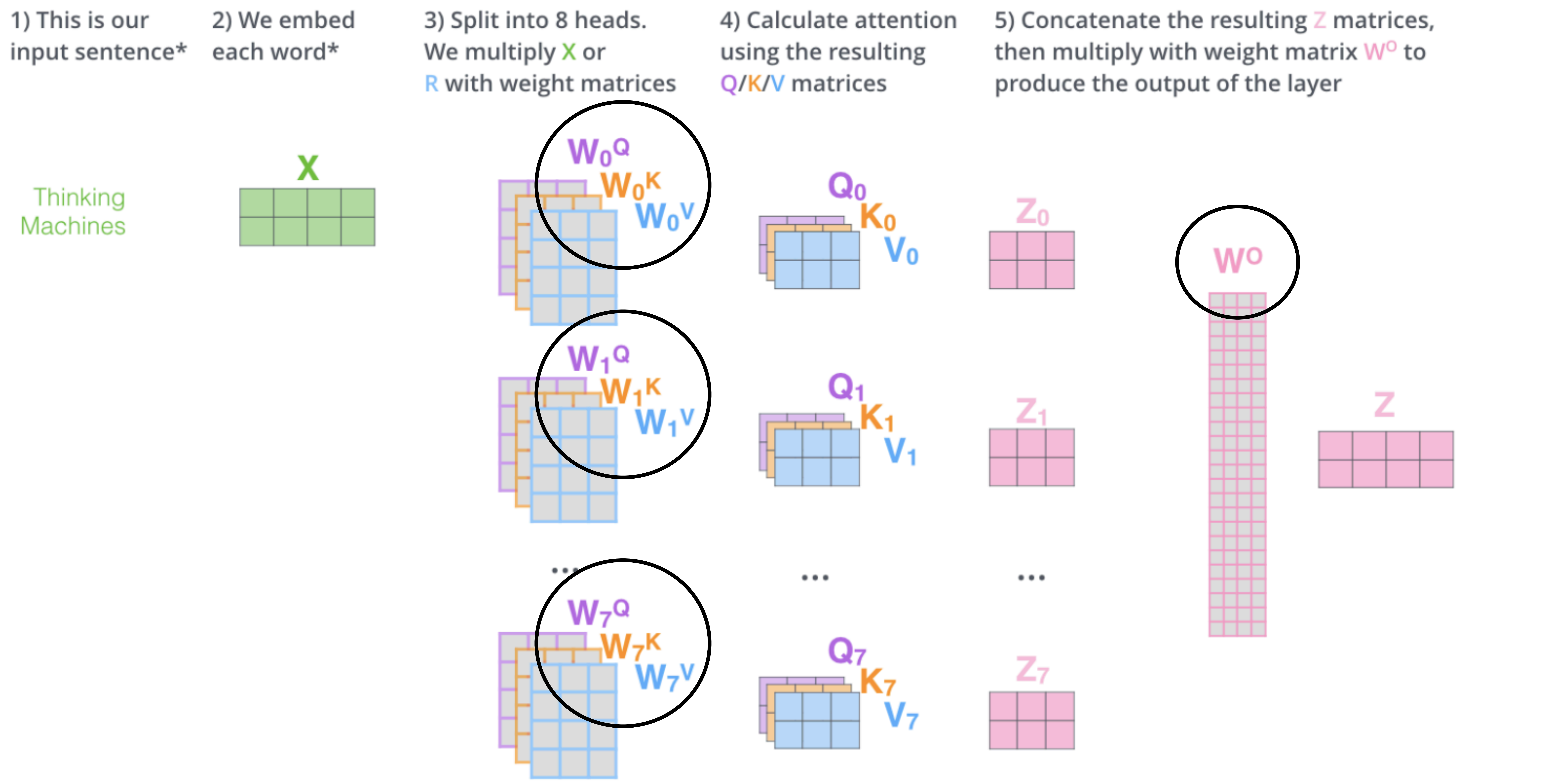
Credit: Alammar, *The Illustrated Transformer*

# Multi-Head Self Attention




Credit: Alammar, *The Illustrated Transformer*

# Multi-Head Self Attention




Credit: Alammar, *The Illustrated Transformer*

# Properties of Self-Attention

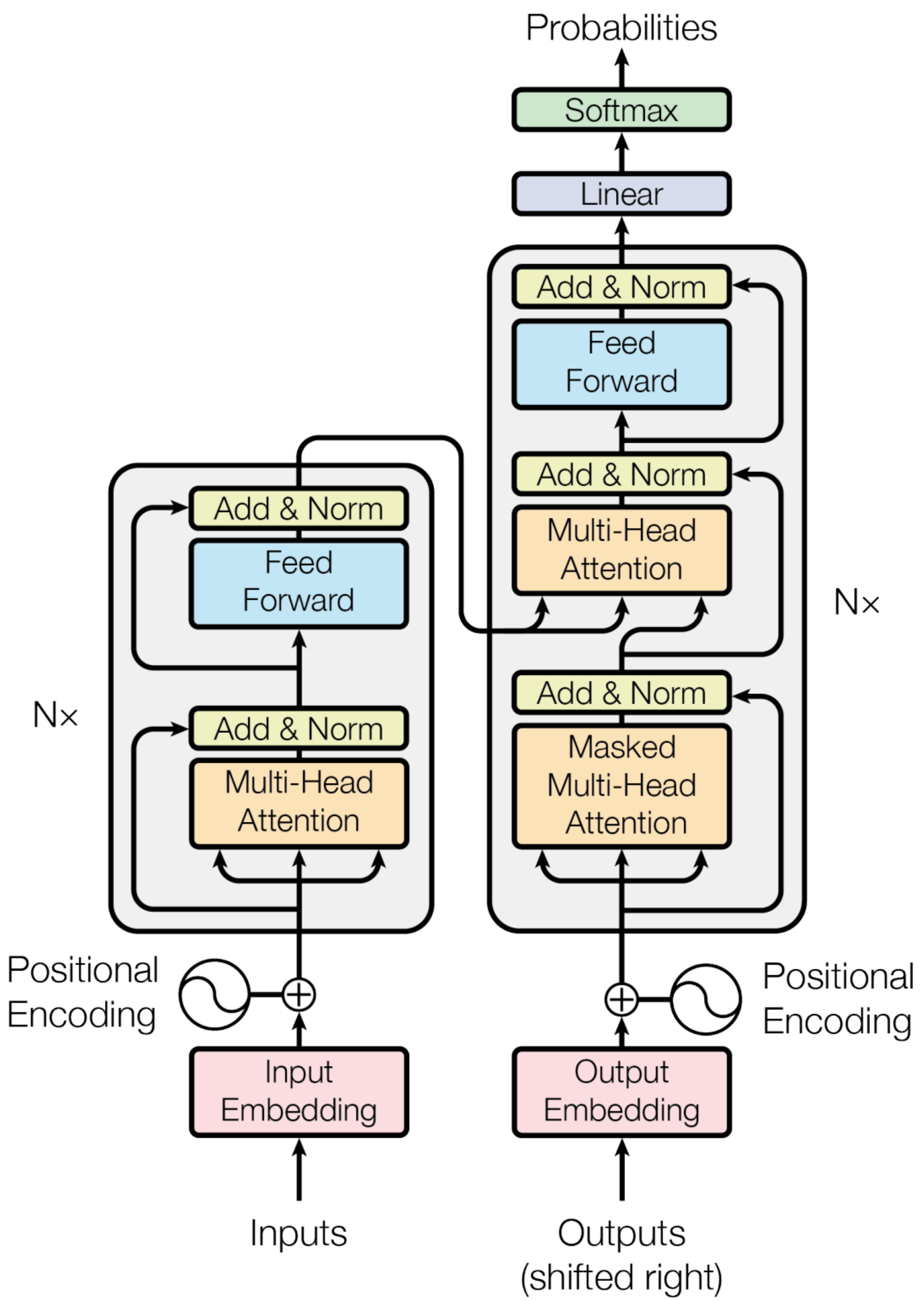
| Layer Type | Complexity per Layer | Sequential Operations | Maximum Path Length |
|---|---|---|---|
| Self-Attention | $O(n^2 \cdot d)$ | $O(1)$ | $O(1)$ |
| Recurrent | $O(n \cdot d^2)$ | $O(n)$ | $O(n)$ |
| Convolutional | $O(k \cdot n \cdot d^2)$ | $O(1)$ | $O(log_k(n))$ |
| Self-Attention (restricted) | $O(r \cdot n \cdot d)$ | $O(1)$ | $O(n/r)$ |

- *n* = sentence length, *d* = hidden dim, *k* = kernel size, *r* = restricted neighborhood size
- **Quadratic complexity**, but O(1) sequential operations (not linear like in RNNs) and O(1) “path” for words to inform each other

Vaswani et al. (2017)

# Transformer

# Transformers for MT: Complete Model




- Encoder and decoder are both transformers
- Decoder alternates attention over the output and attention over the input as well
- Decoder consumes the previous generated tokens but has *no recurrent state*

Vaswani et al. (2017)

# Self-Attention vs. Cross-Attention

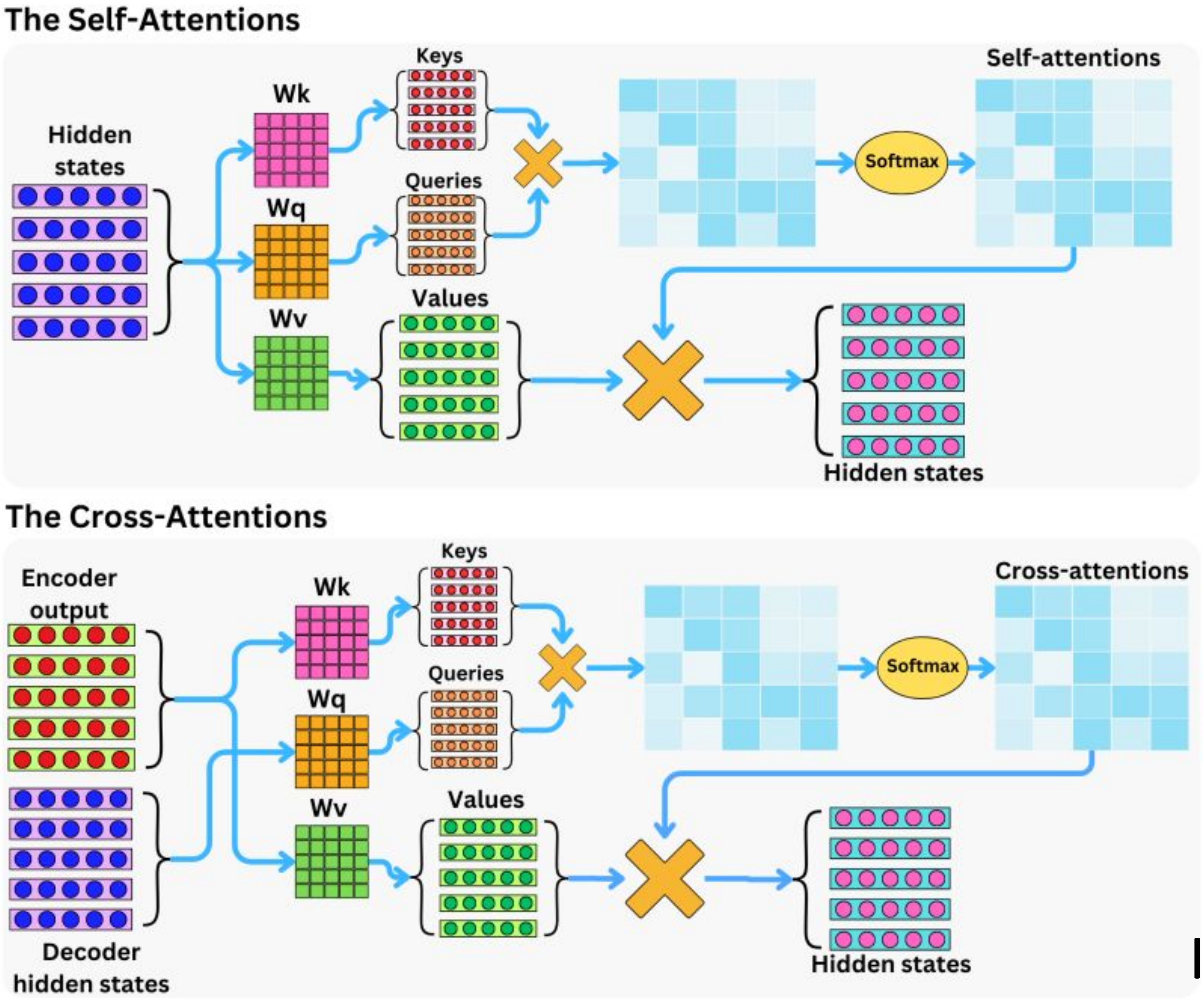
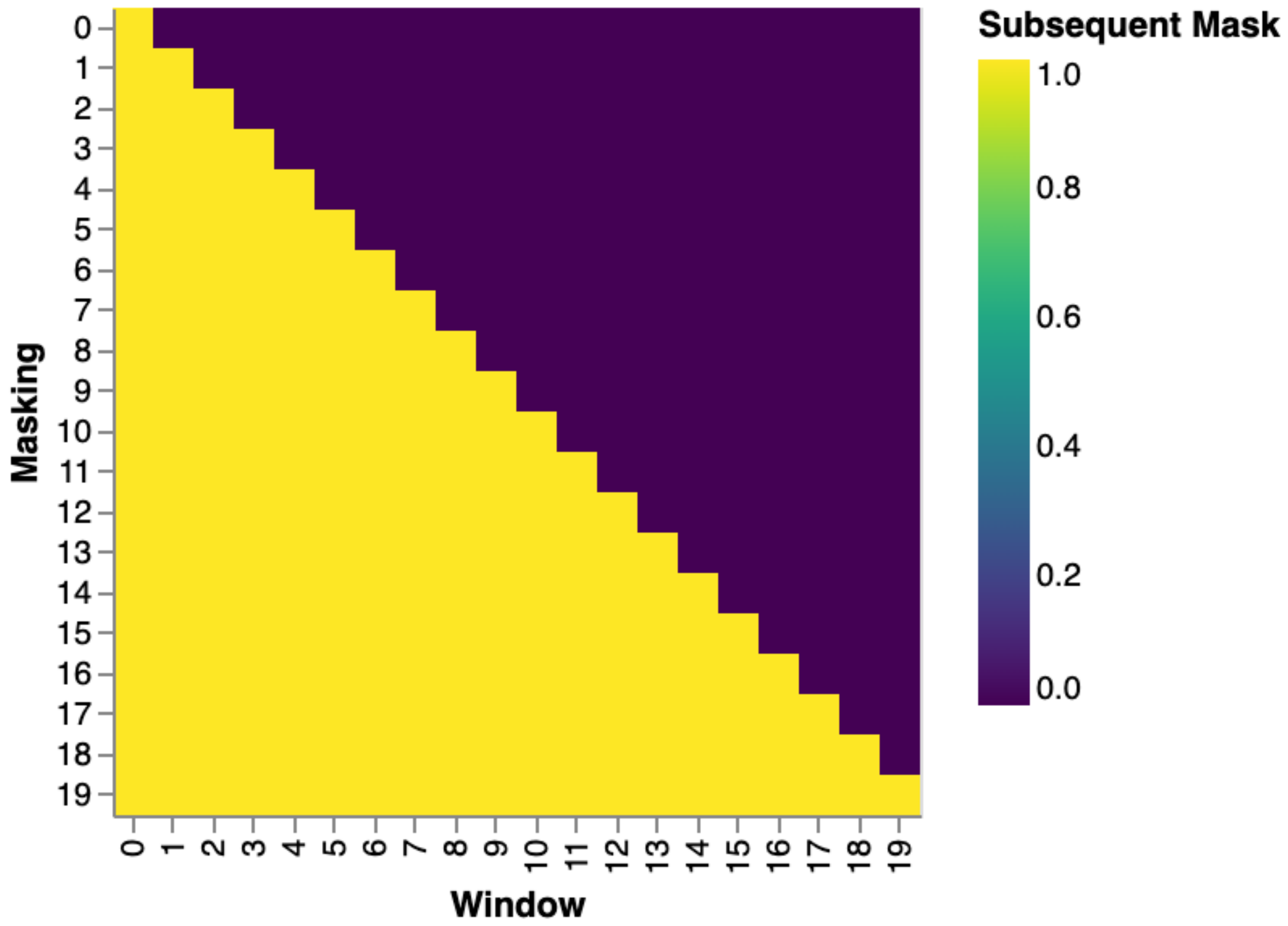


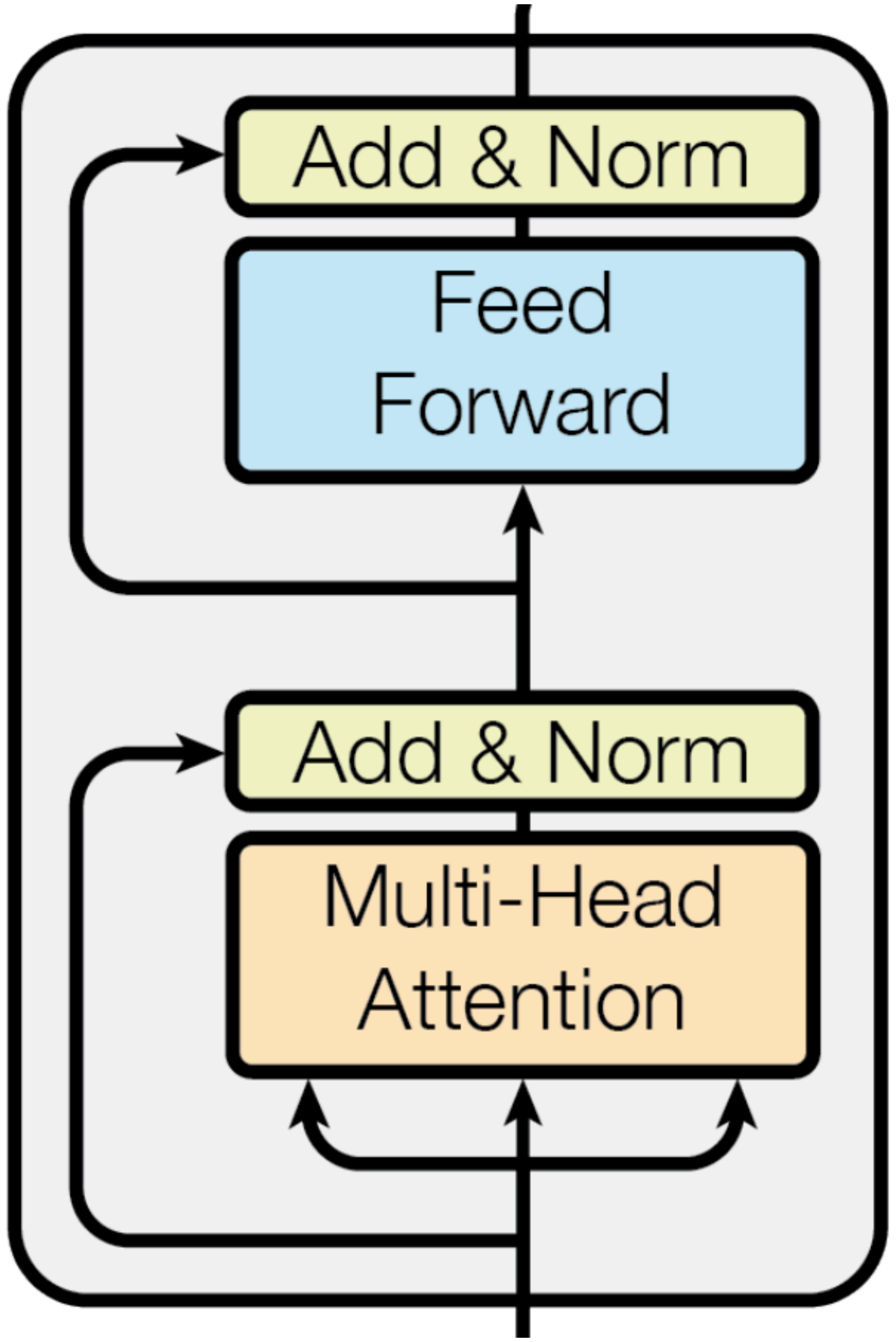

Image Credit: TheAiEdge.io

# Casual Self-Attention Mask

- Decoder (by default) is autoregressive, making prediction word by word
- It should not peek at the right side of the output sentence



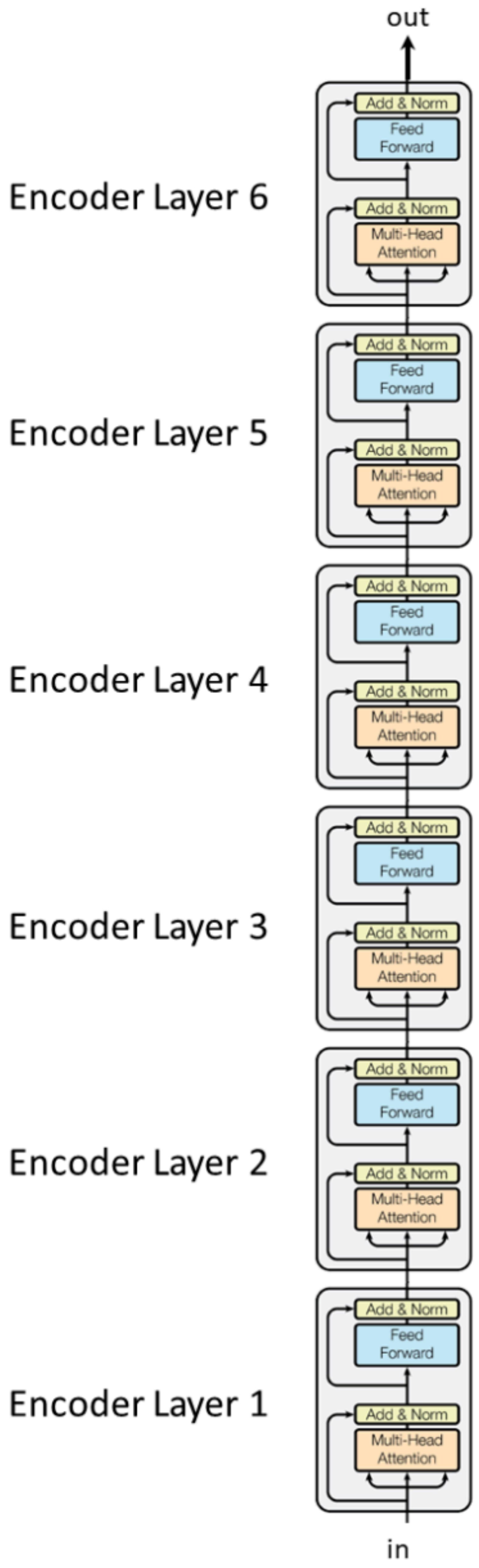
# Transformers




- Alternate multi-head self-attention layers and feedforward layers (w/ ReLU activation) that operate over each word individually

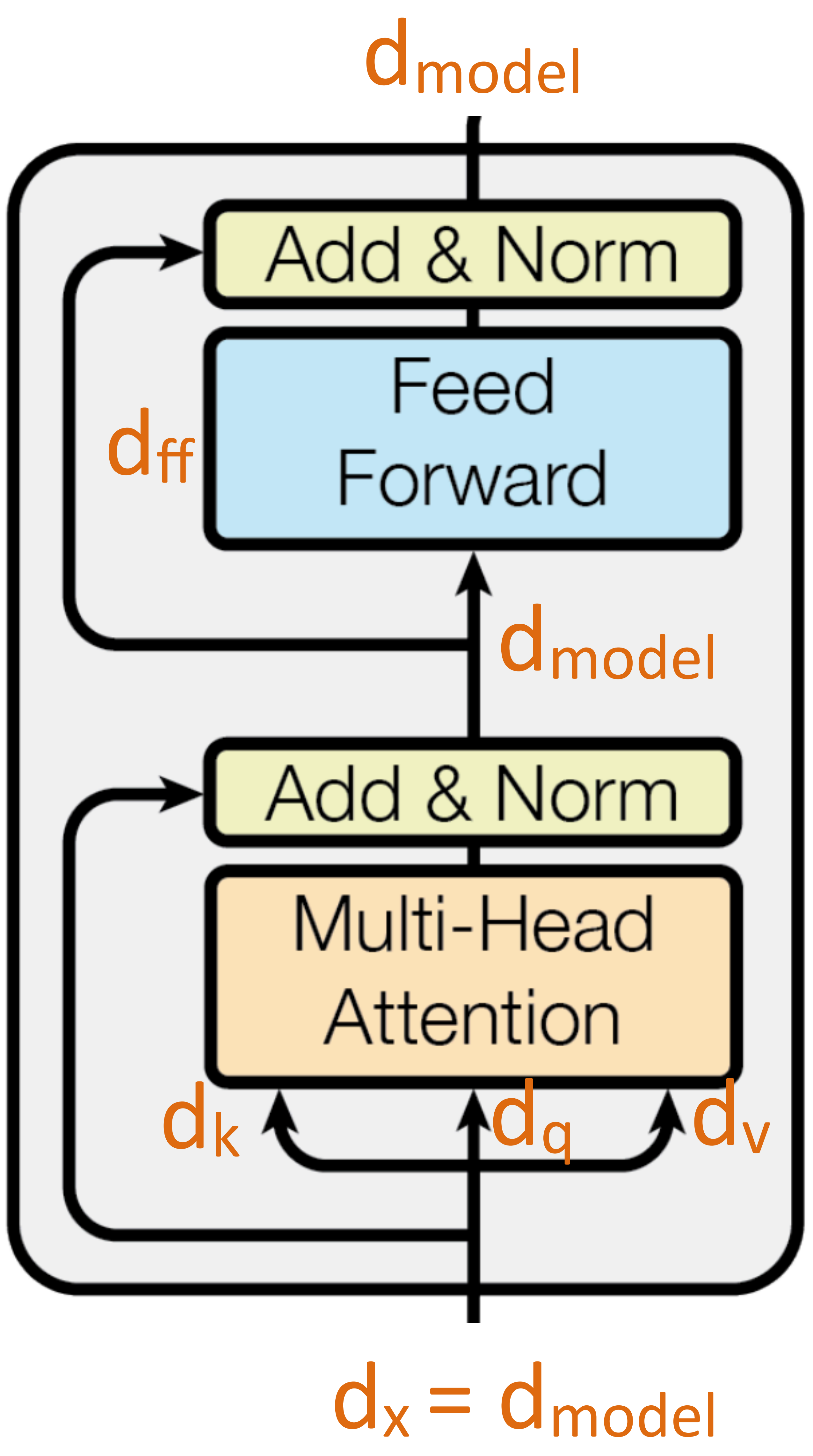
$$\mathrm{FFN}(x) = \max(0, xW_1 + b_1)W_2 + b_2$$

- Most of the parameters are in these feedforward layers




Vaswani et al. (2017)

# Transformers




- Alternate multi-head self-attention layers and feedforward layers (w/ ReLU activation) that operate over each word individually

$$\mathrm{FFN}(x) = \max(0, xW_1 + b_1)W_2 + b_2$$

$h = 8$

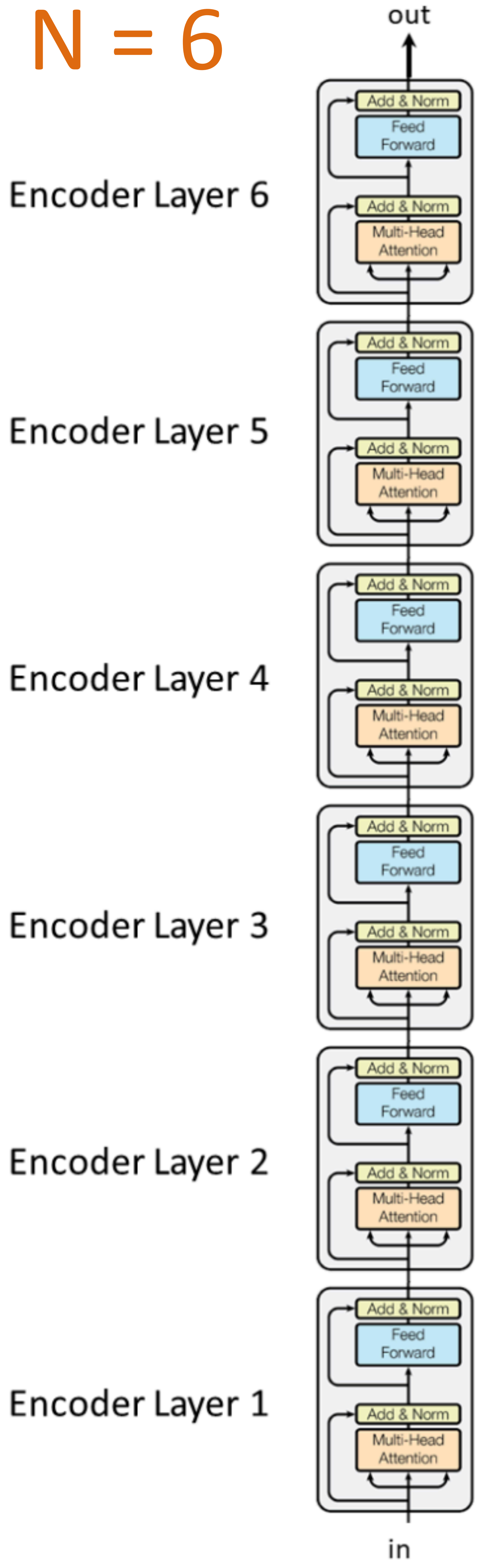
$d_x = 512$

$d_{ff} = 2048$

$d_k = d_q = d_{model} / h = 64$

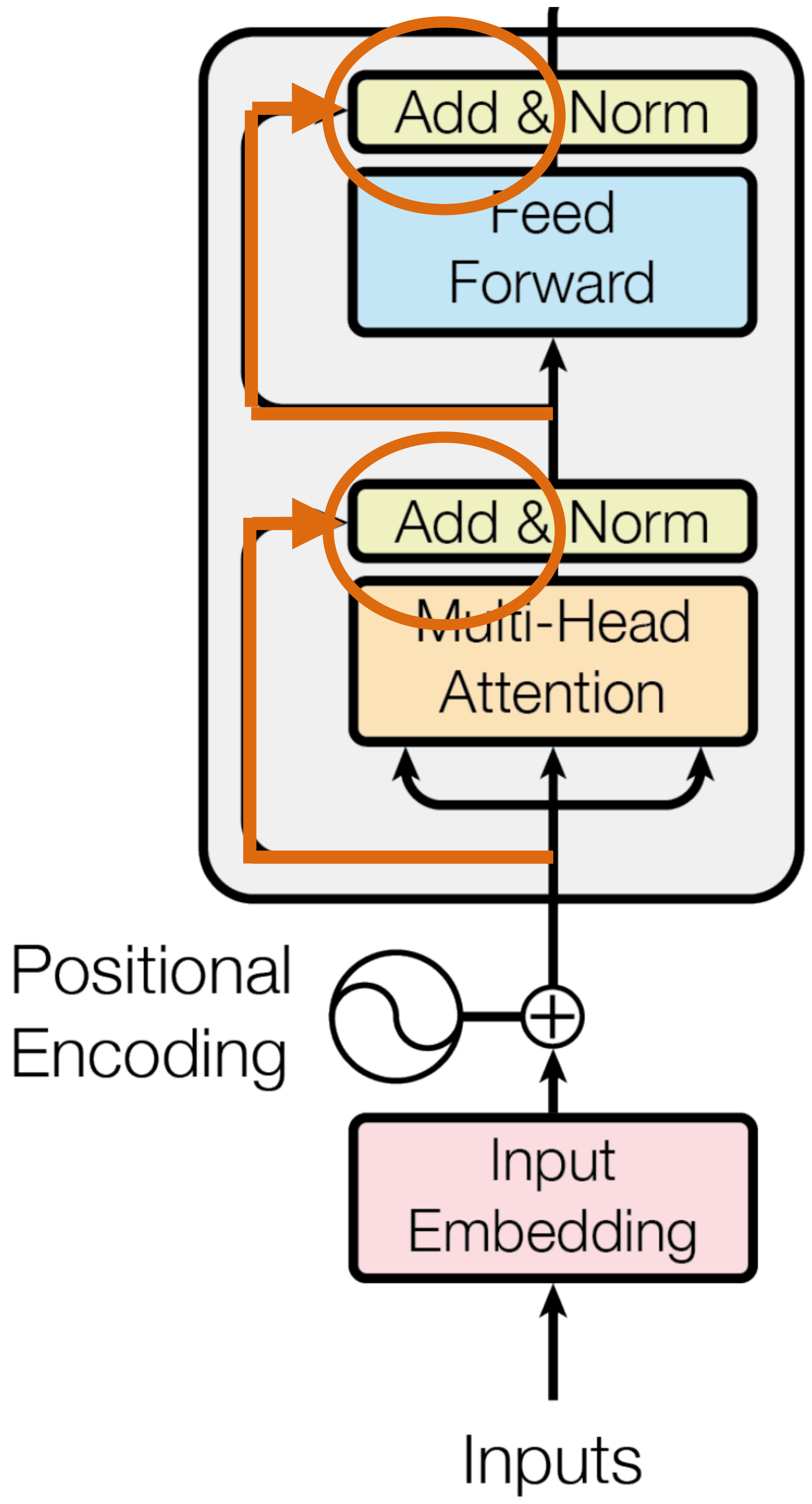
$d_v = d_{model} / h = 64$

N = 6



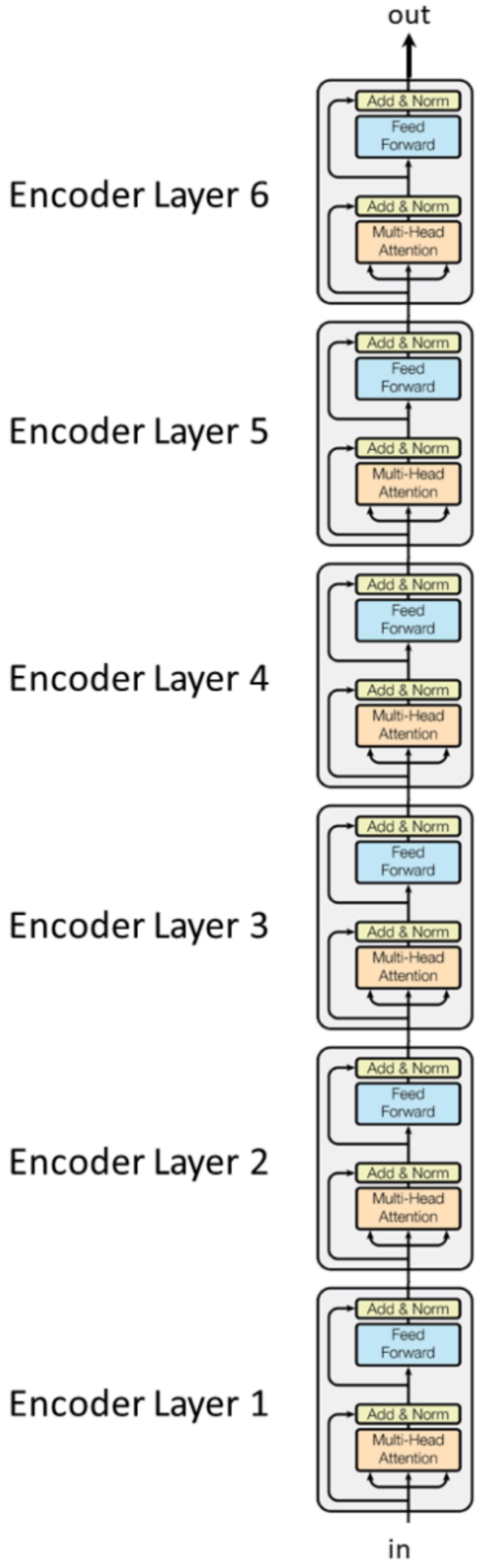

Vaswani et al. (2017)

# Transformers




- Alternate multi-head self-attention layers and feedforward layers

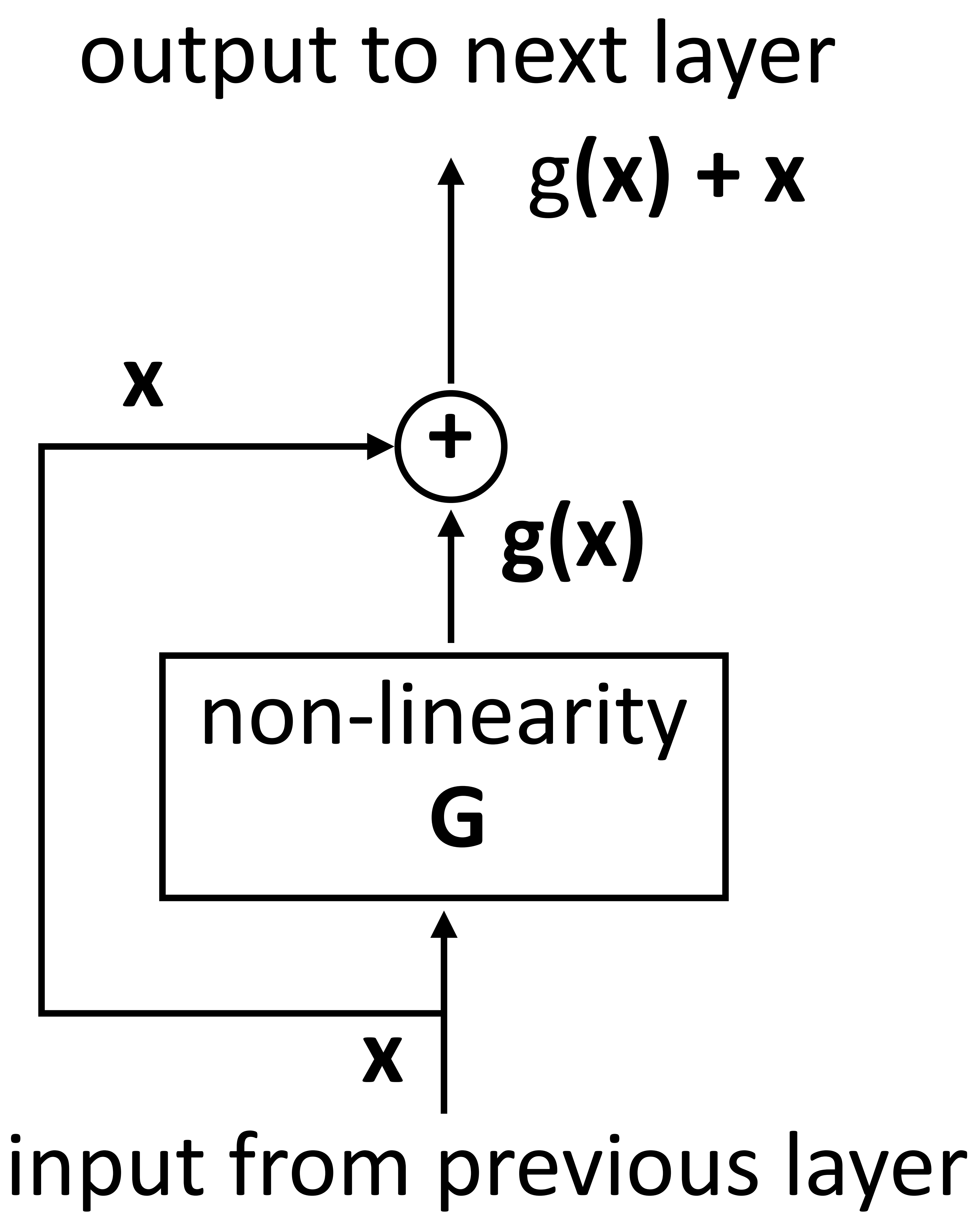
- Residual connections let the model “skip” each layer — these are particularly useful for training deep networks




Vaswani et al. (2017)

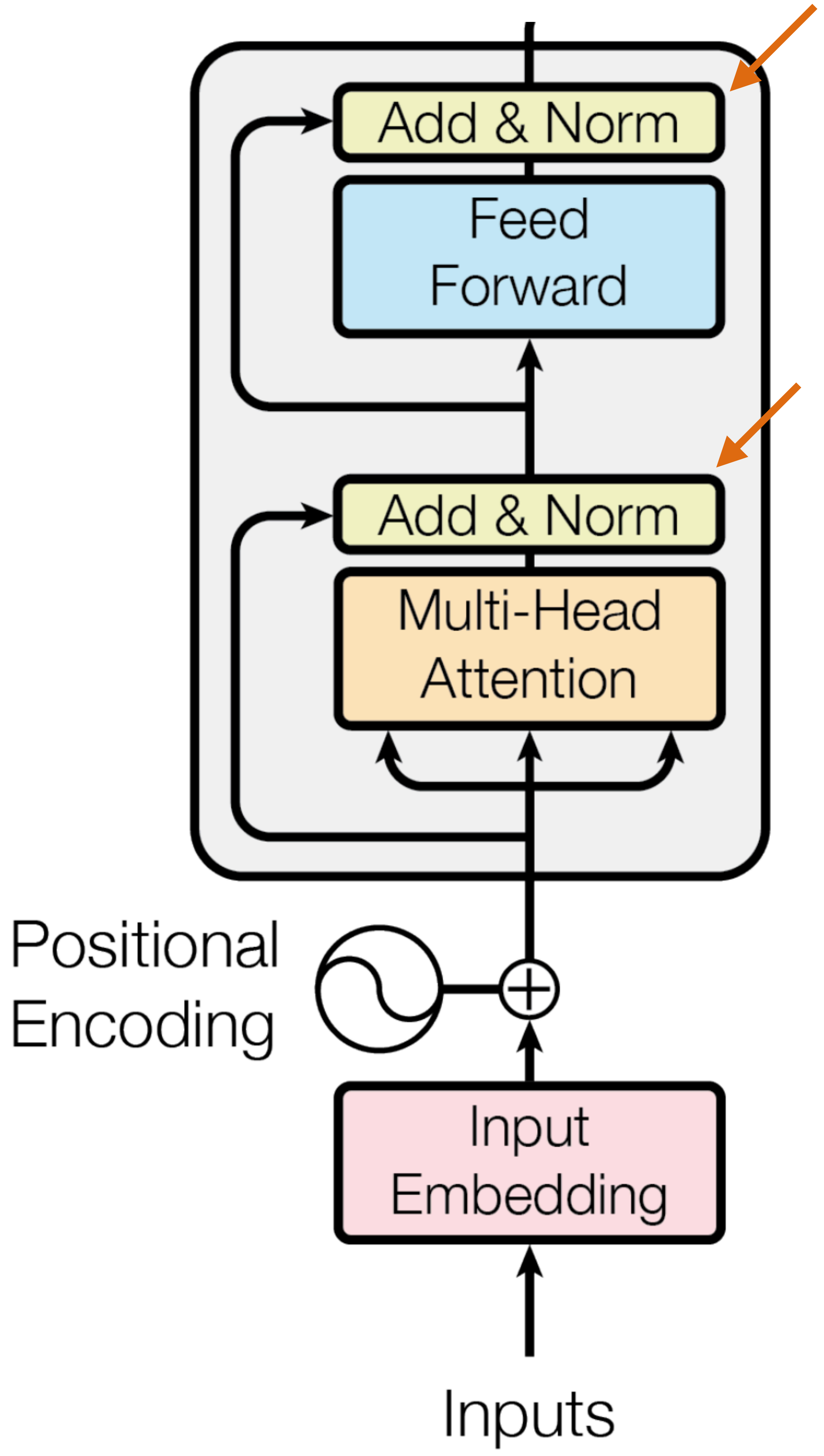
# Residual Connections

- allow gradients to flow through a network directly, without passing through non-linear activation functions




He et al. (2015)

# Layer Normalization




- subtract mean, divide by variance

Ba et al. (2016) Ioffe & Szegedy (2015)

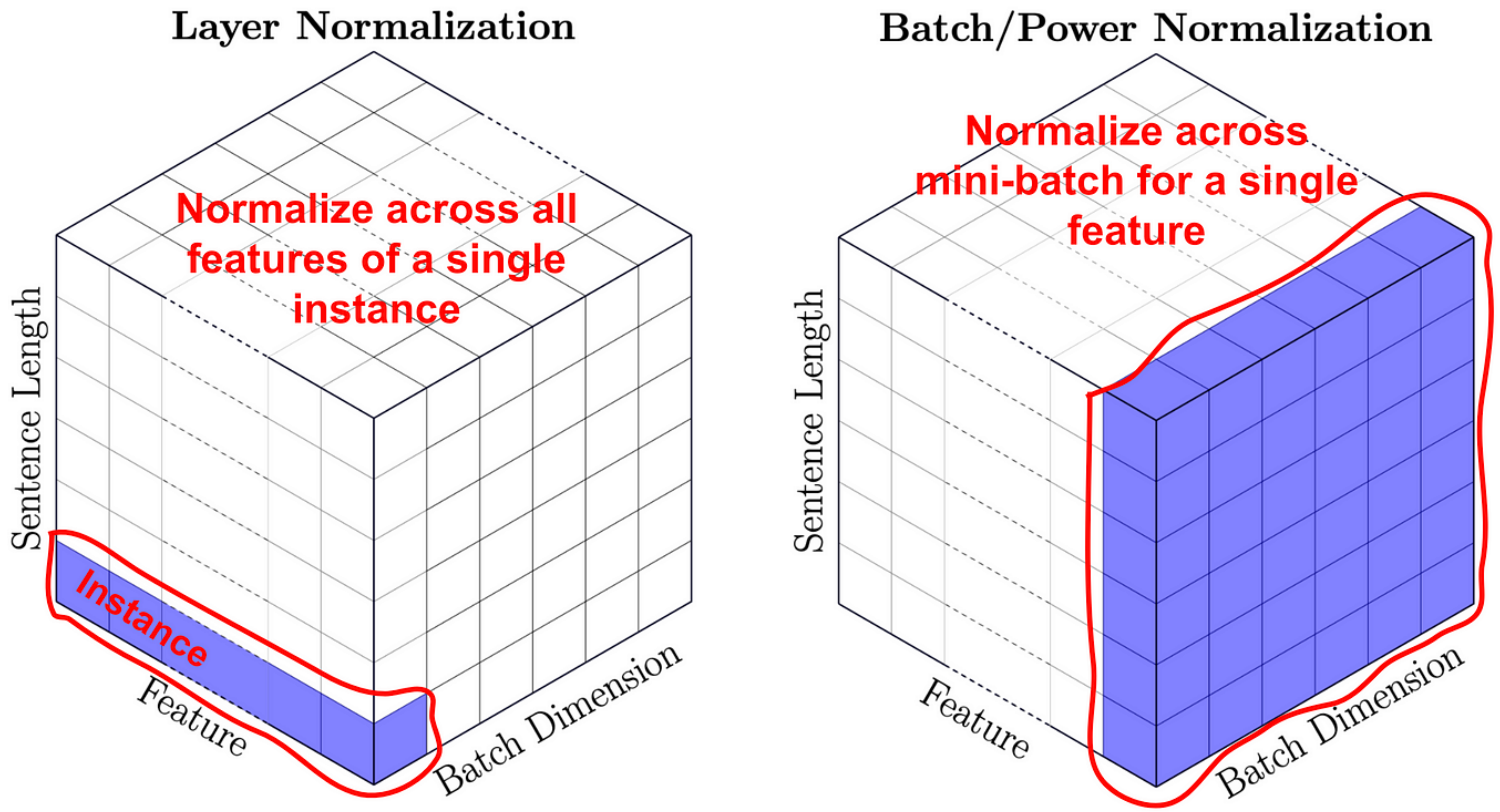



Image Credit: Shen et al. (2020)

# Batch Normalization

**Input:** Values of $x$ over a mini-batch: $\mathcal{B} = \{x_{1...m}\}$;
Parameters to be learned: $\gamma$, $\beta$

**Output:** $\{y_i = \text{BN}_{\gamma,\beta}(x_i)\}$

$$\mu_{\mathcal{B}} \leftarrow \frac{1}{m}\sum_{i=1}^{m} x_i \qquad \text{// mini-batch mean}$$

$$\sigma_{\mathcal{B}}^2 \leftarrow \frac{1}{m}\sum_{i=1}^{m}(x_i - \mu_{\mathcal{B}})^2 \qquad \text{// mini-batch variance}$$

$$\widehat{x}_i \leftarrow \frac{x_i - \mu_{\mathcal{B}}}{\sqrt{\sigma_{\mathcal{B}}^2 + \epsilon}} \qquad \text{// normalize}$$

$$y_i \leftarrow \gamma\widehat{x}_i + \beta \equiv \text{BN}_{\gamma,\beta}(x_i) \qquad \text{// scale and shift}$$

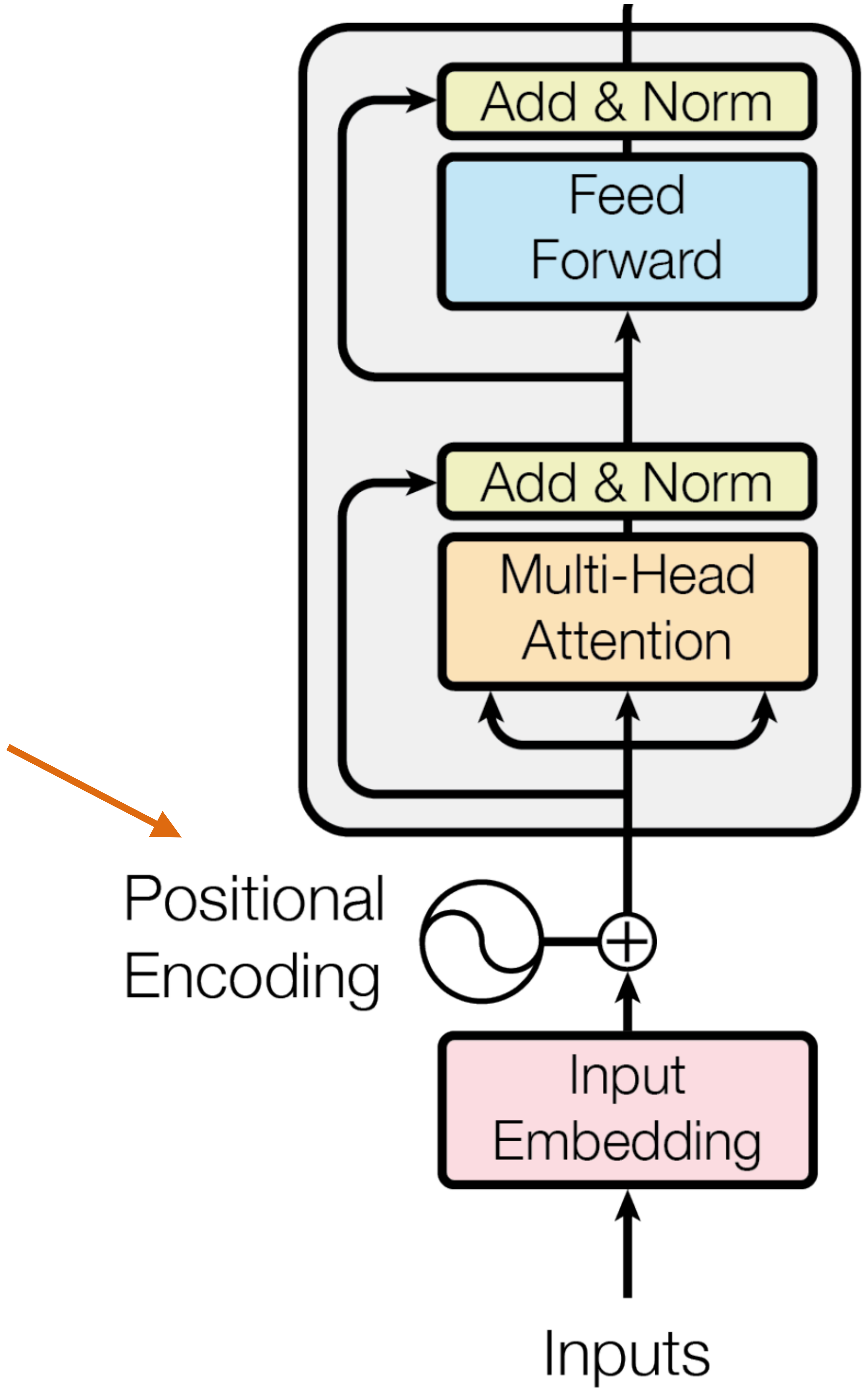
# Transformers: Position Sensitivity

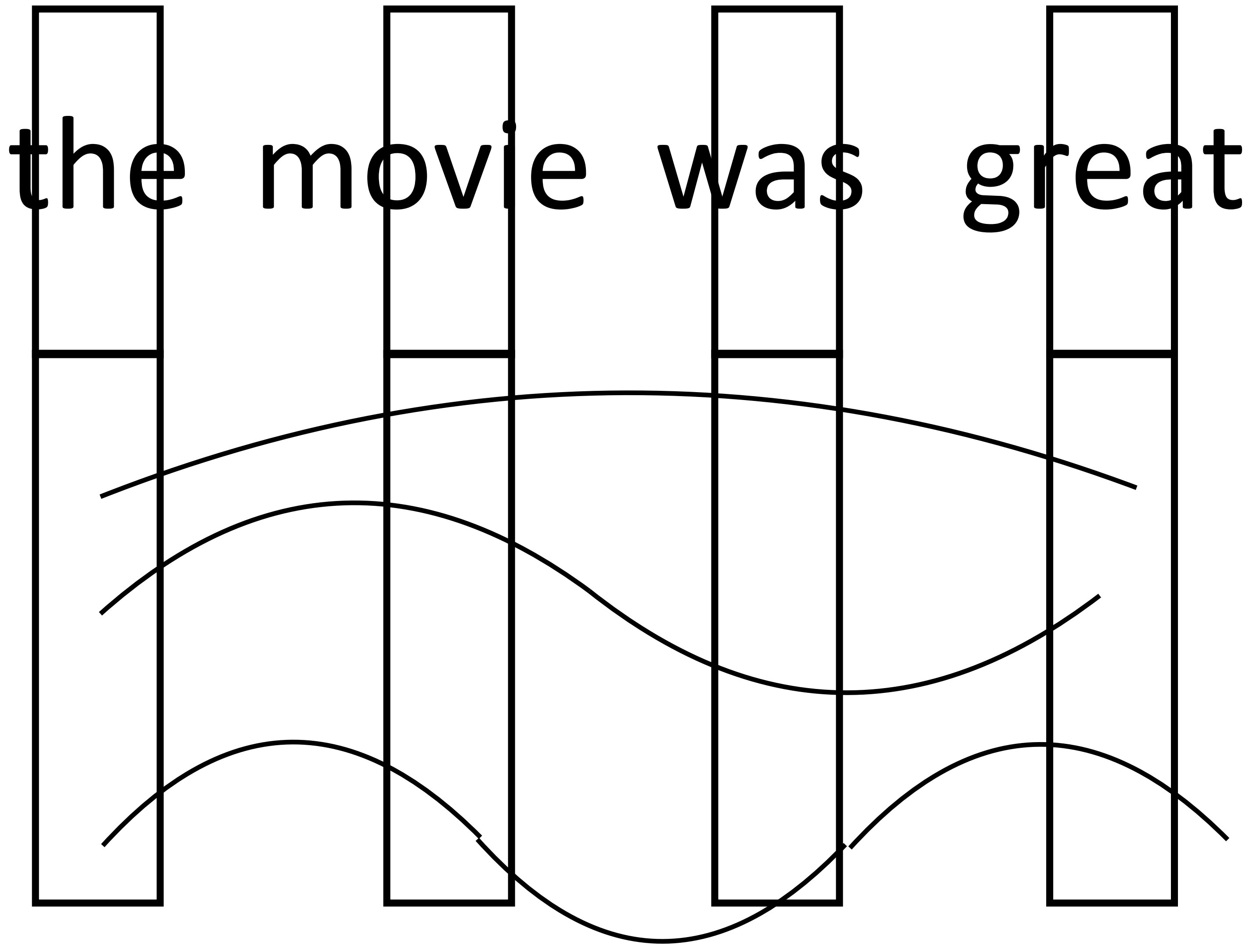
*The ballerina is very excited that she will dance in the show.*

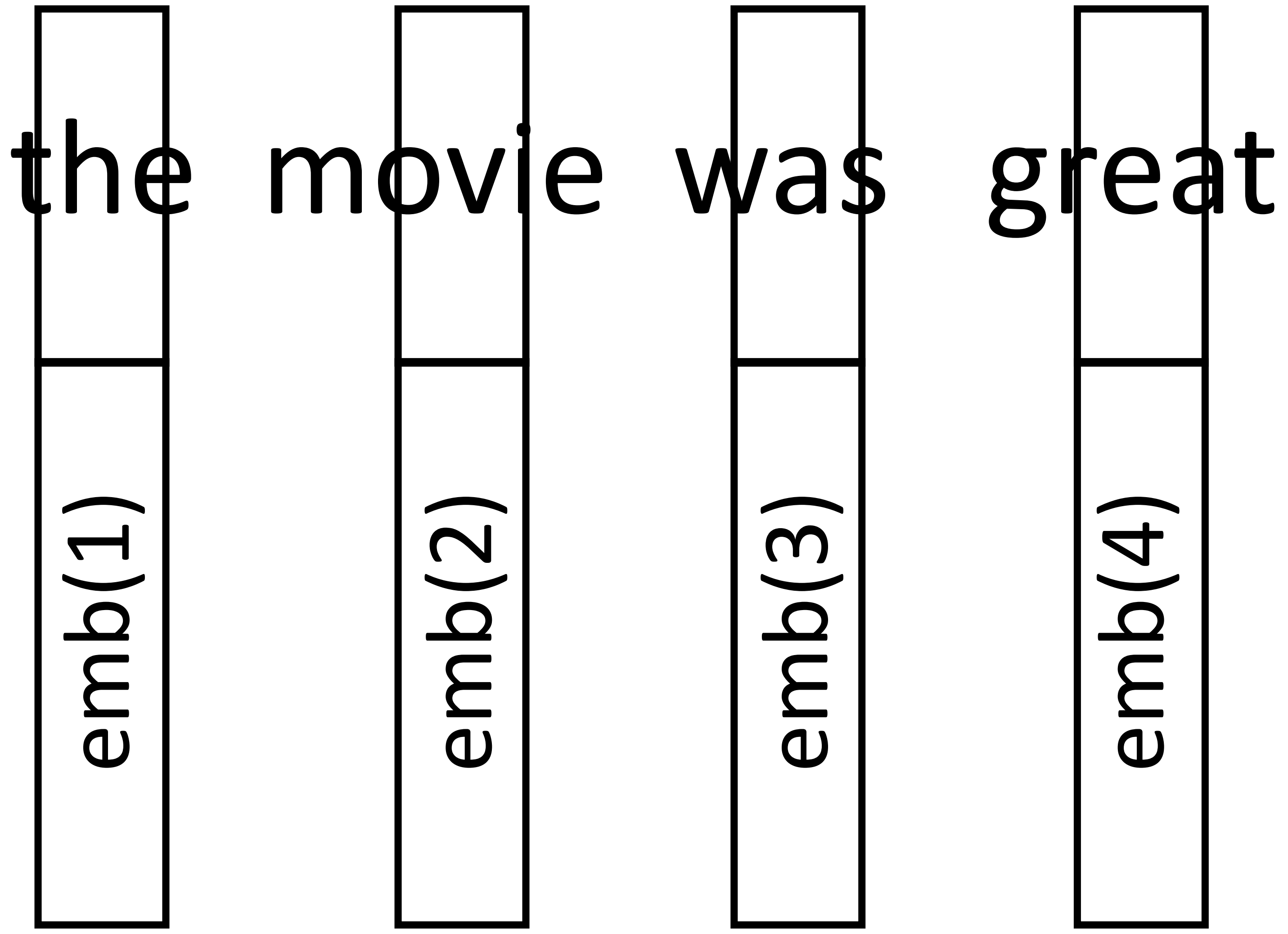
- If this is in a longer context, we want words to attend *locally*
- But transformers have *no notion of position* by default

Vaswani et al. (2017)

# Transformers



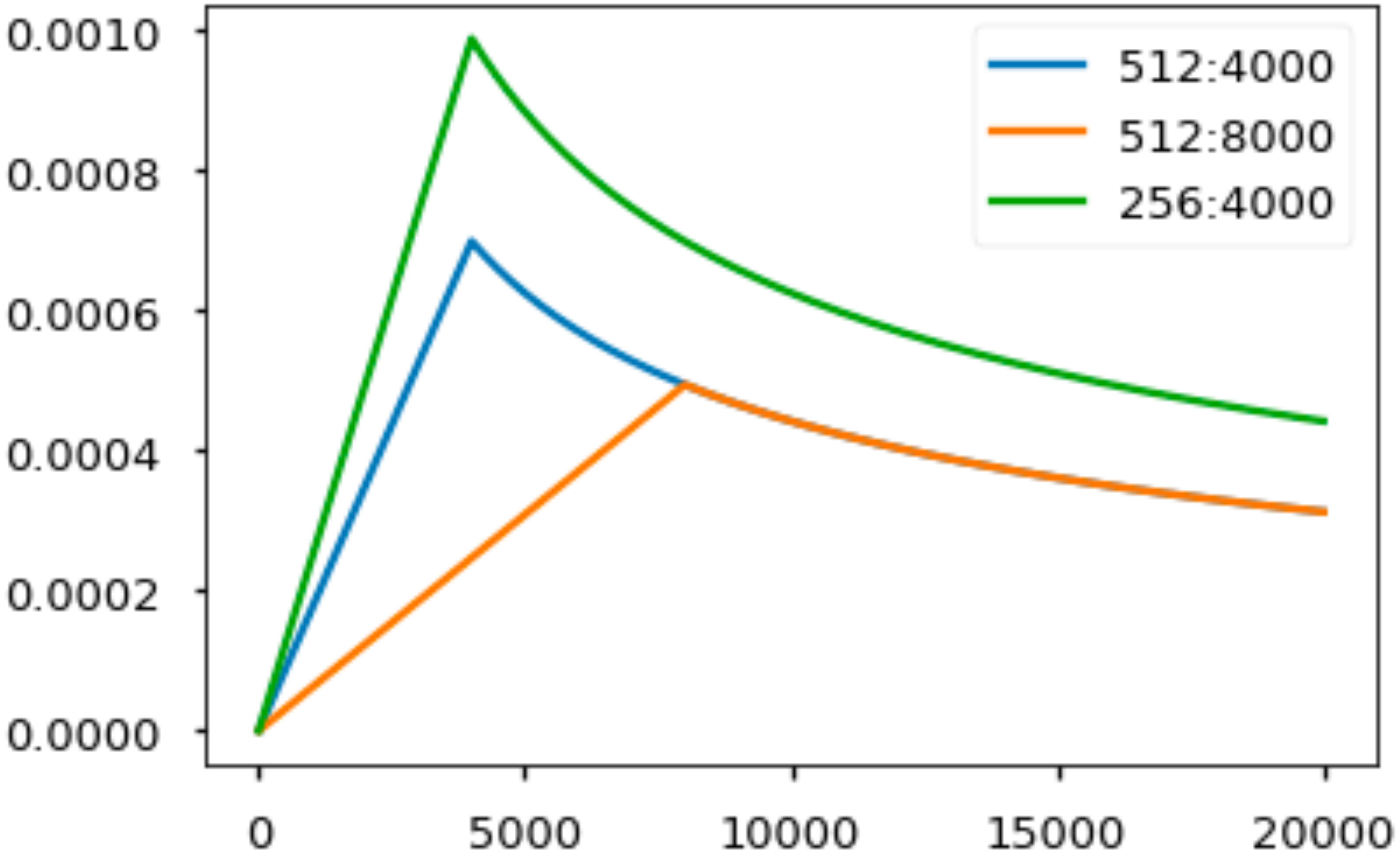




- Augment word embedding with position embeddings, each dim is a sine/cosine wave of a different frequency. Closer points = higher dot products
- Works essentially as well as just encoding position as a one-hot vector

Vaswani et al. (2017)

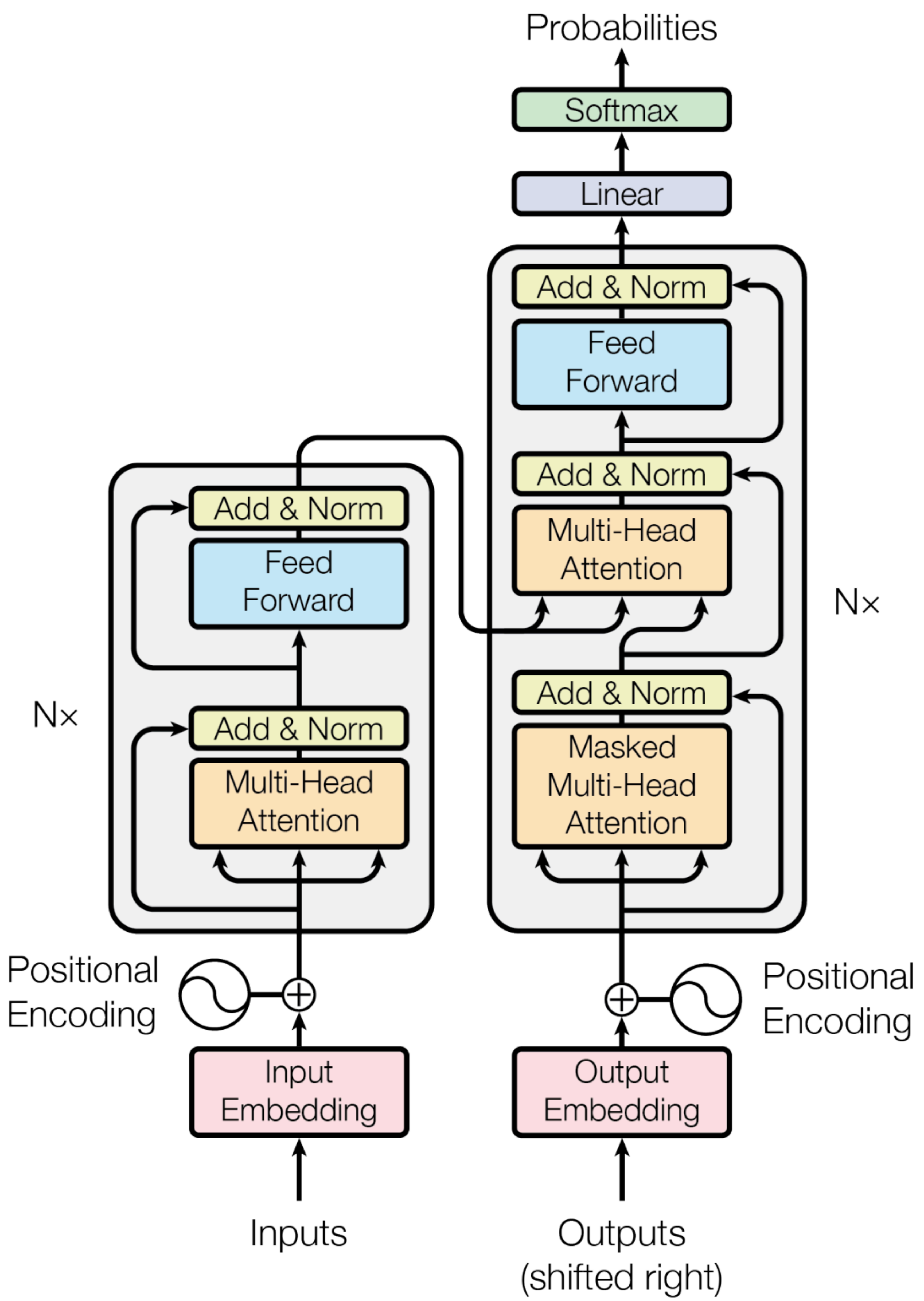
# Transformers




- Adam optimizer with varied learning rate over the course of training
- Linearly increase for warmup, then decay proportionally to the inverse square root of the step number
- This part is very important!

Vaswani et al. (2017)

# Transformers for MT: Complete Model




- Many other details to get it to work: residual connections, layer normalization, positional encoding, optimizer with learning rate schedule, label smoothing ….

Vaswani et al. (2017)

# Transformers

| Model | BLEU | |
|---|---|---|
| | EN-DE | EN-FR |
| ByteNet [18] | 23.75 | |
| Deep-Att + PosUnk [39] | | 39.2 |
| GNMT + RL [38] | 24.6 | 39.92 |
| ConvS2S [9] | 25.16 | 40.46 |
| MoE [32] | 26.03 | 40.56 |
| Deep-Att + PosUnk Ensemble [39] | | 40.4 |
| GNMT + RL Ensemble [38] | 26.30 | 41.16 |
| ConvS2S Ensemble [9] | 26.36 | **41.29** |
| Transformer (base model) | 27.3 | 38.1 |
| Transformer (big) | **28.4** | **41.8** |

- big = 6 layers, 1000 dim for each token, 16 heads, base = 6 layers + other params halved

Vaswani et al. (2017)

# Useful Resources

## nn.Transformer:

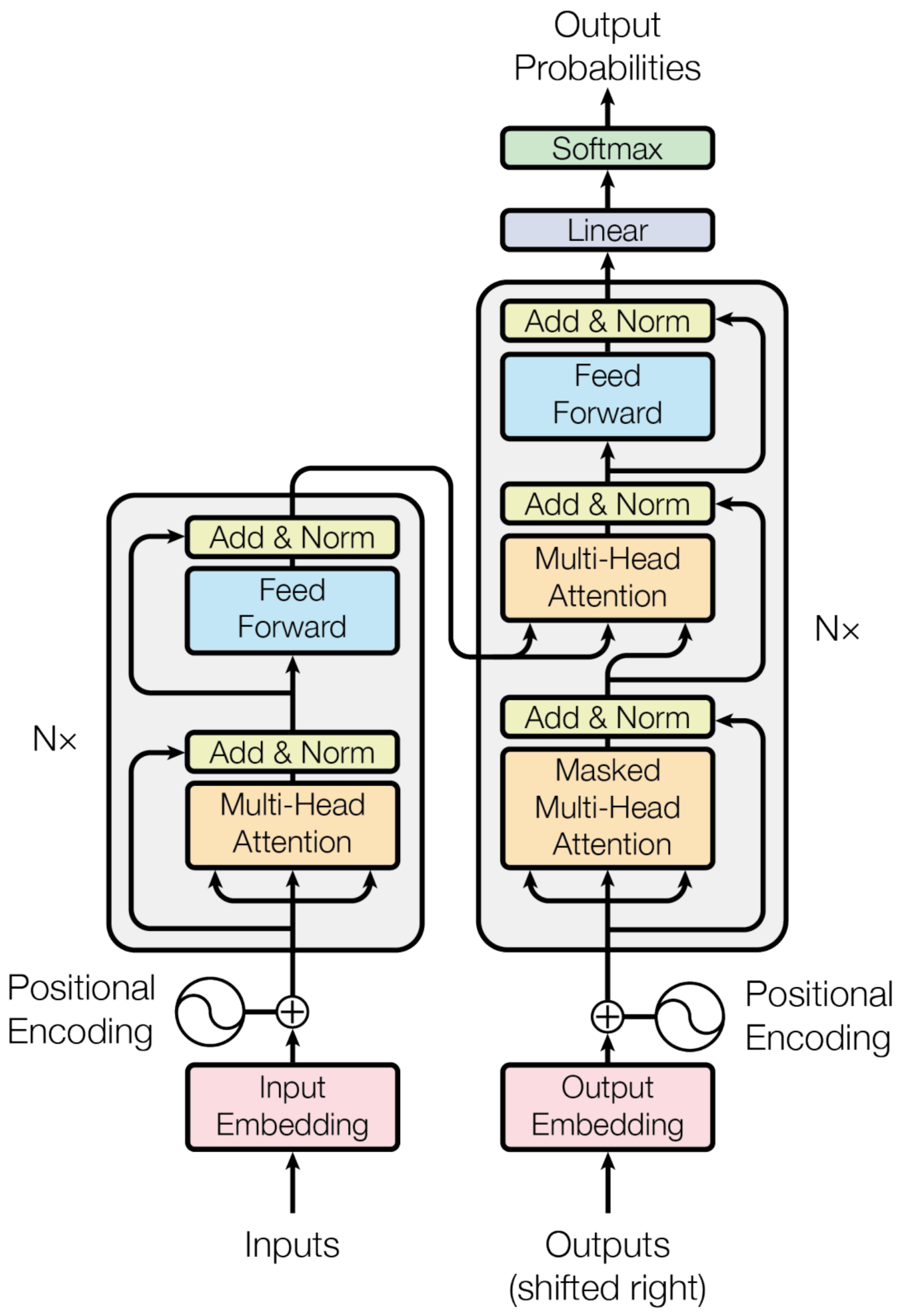
```
>>> transformer_model = nn.Transformer(nhead=16, num_encoder_layers=12)
>>> src = torch.rand((10, 32, 512))
>>> tgt = torch.rand((20, 32, 512))
>>> out = transformer_model(src, tgt)
```

## nn.TransformerEncoder:

```
>>> encoder_layer = nn.TransformerEncoderLayer(d_model=512, nhead=8)
>>> transformer_encoder = nn.TransformerEncoder(encoder_layer, num_layers=6)
>>> src = torch.rand(10, 32, 512)
>>> out = transformer_encoder(src)
```

# Summary: Transformer Uses

- Supervised: transformer can replace LSTM as encoder, decoder, or both; such as in machine translation and natural language generation tasks.

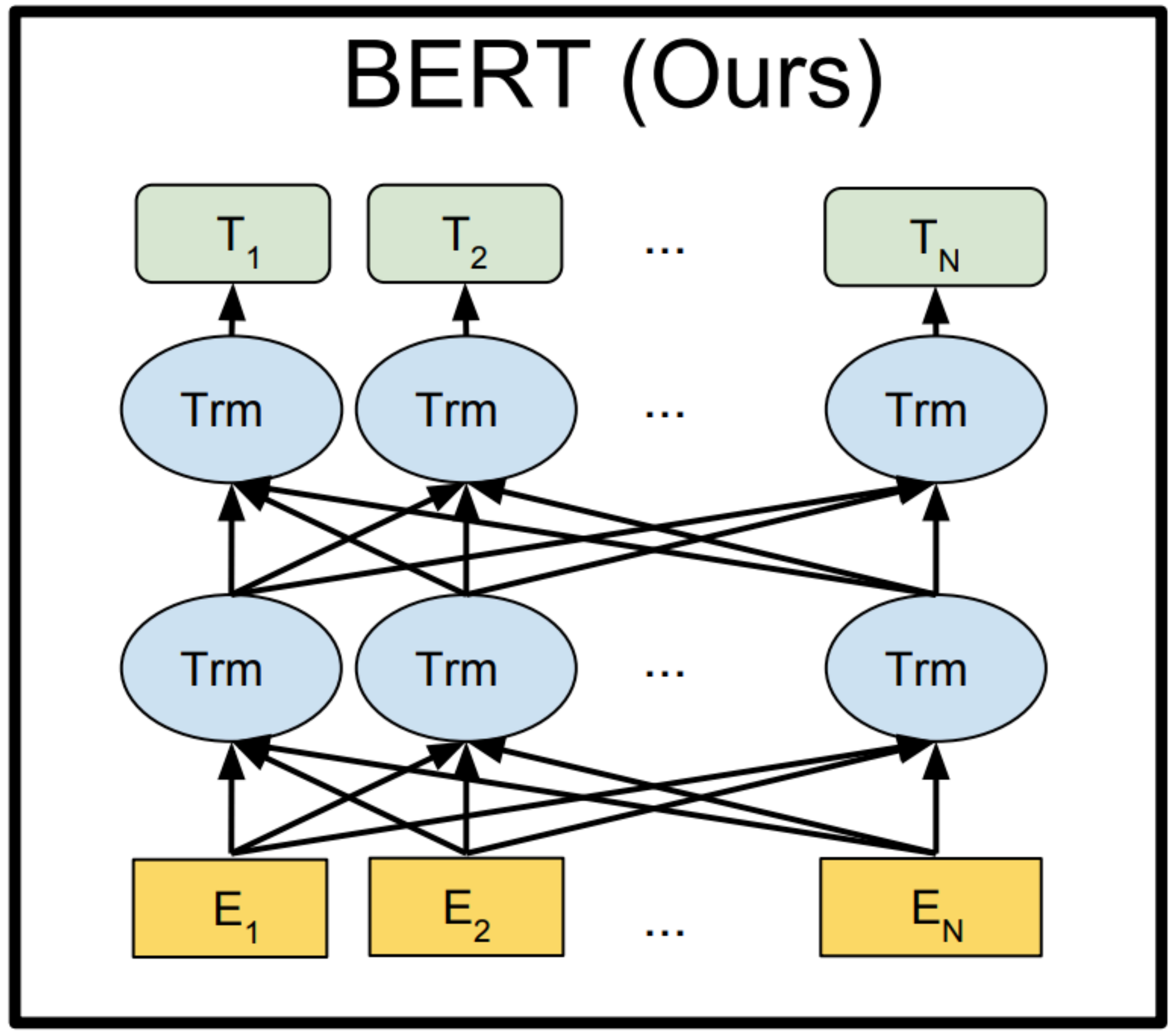



- Encoder and decoder are both transformers
- Decoder consumes the previous generated token (and attends to input), but has *no recurrent state*

Vaswani et al. (2017)

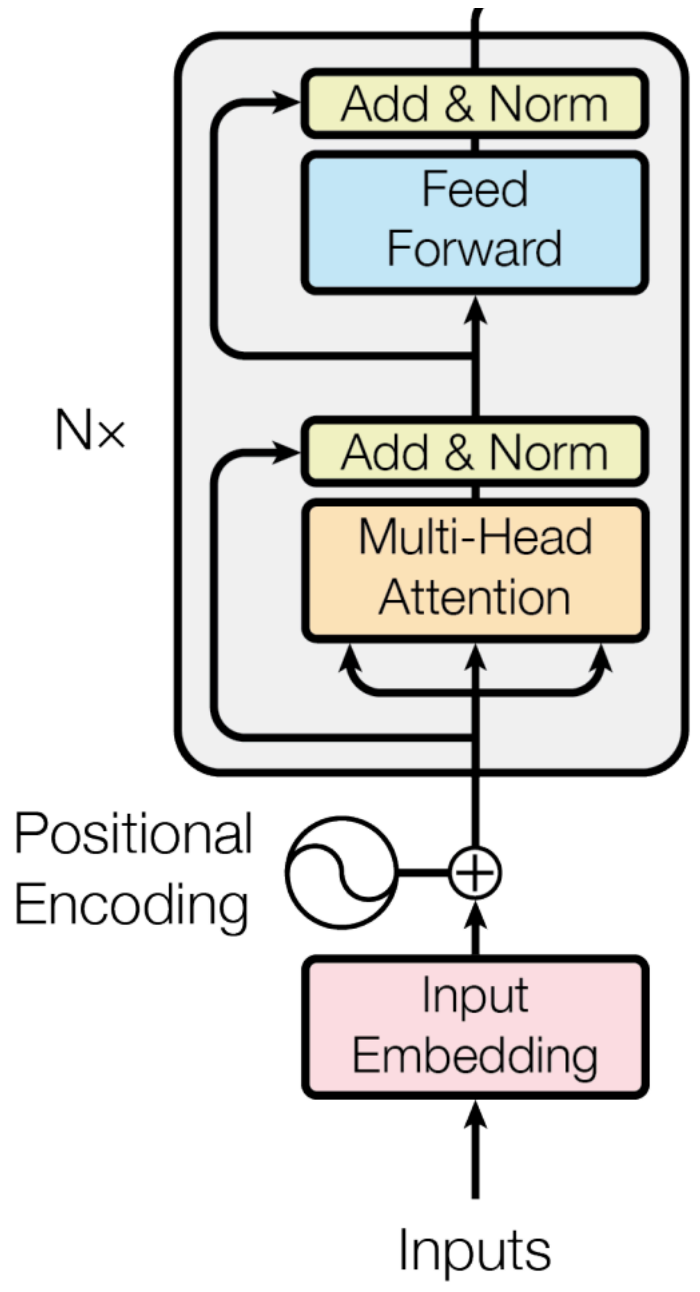
# Summary: Transformer Uses

- Unsupervised: transformers work better than LSTM for unsupervised pre-training of embeddings — predict word given context words
- BERT (Bidirectional Encoder Representations from Transformers): pretraining transformer language models similar to ELMo (based on LSTM)
- Stronger than similar methods, SOTA on ~11 tasks (including NER — 92.8 F1)



# Other Transformer Variations

- Multilayer transformer networks consist of interleaved self-attention and feedforward sublayers.
- Could ordering the sublayers in a different pattern lead to better performance?



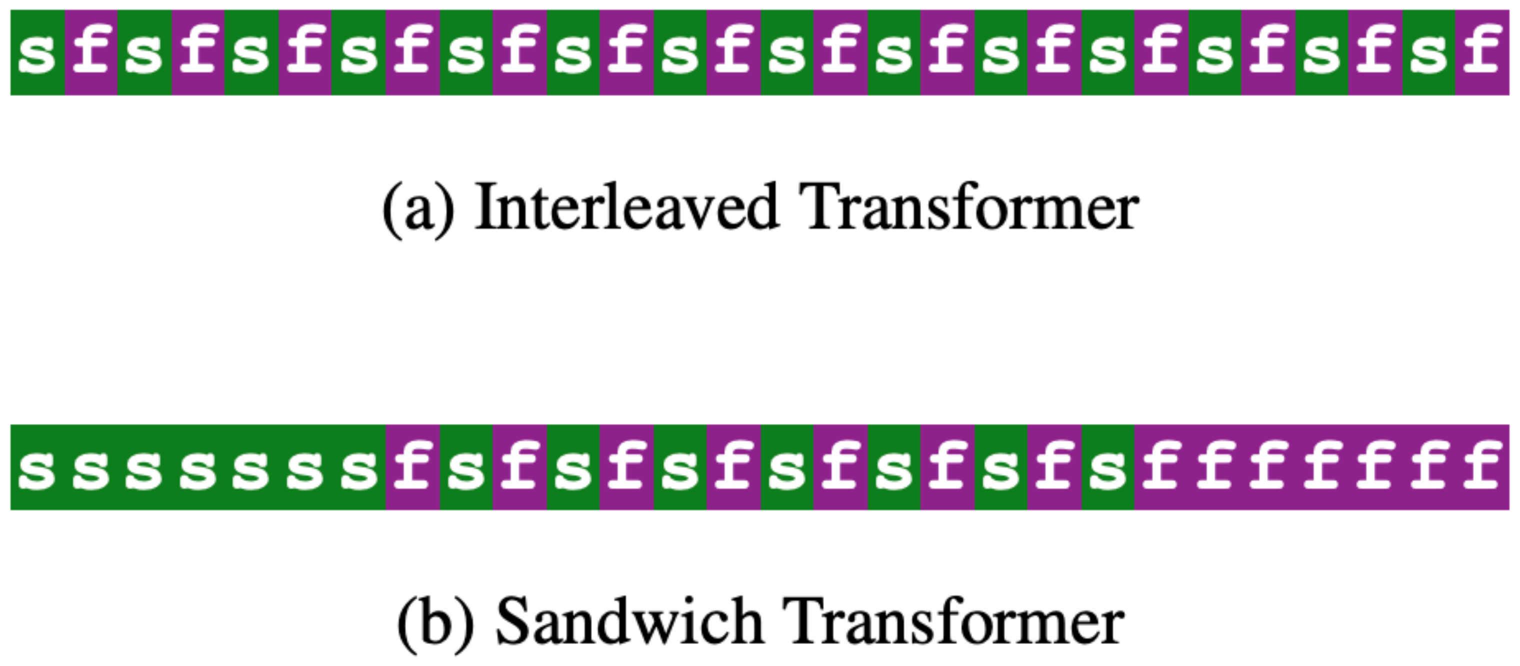




Figure 1: A transformer model (a) is composed of interleaved self-attention (green) and feedforward (purple) sublayers. Our sandwich transformer (b), a reordering of the transformer sublayers, performs better on language modeling. Input flows from left to right.

Press et al. (2020)

# Other Transformer Variations

- Mixture of Expert (MoE) Transformer, e.g., used in massively multilingual MT

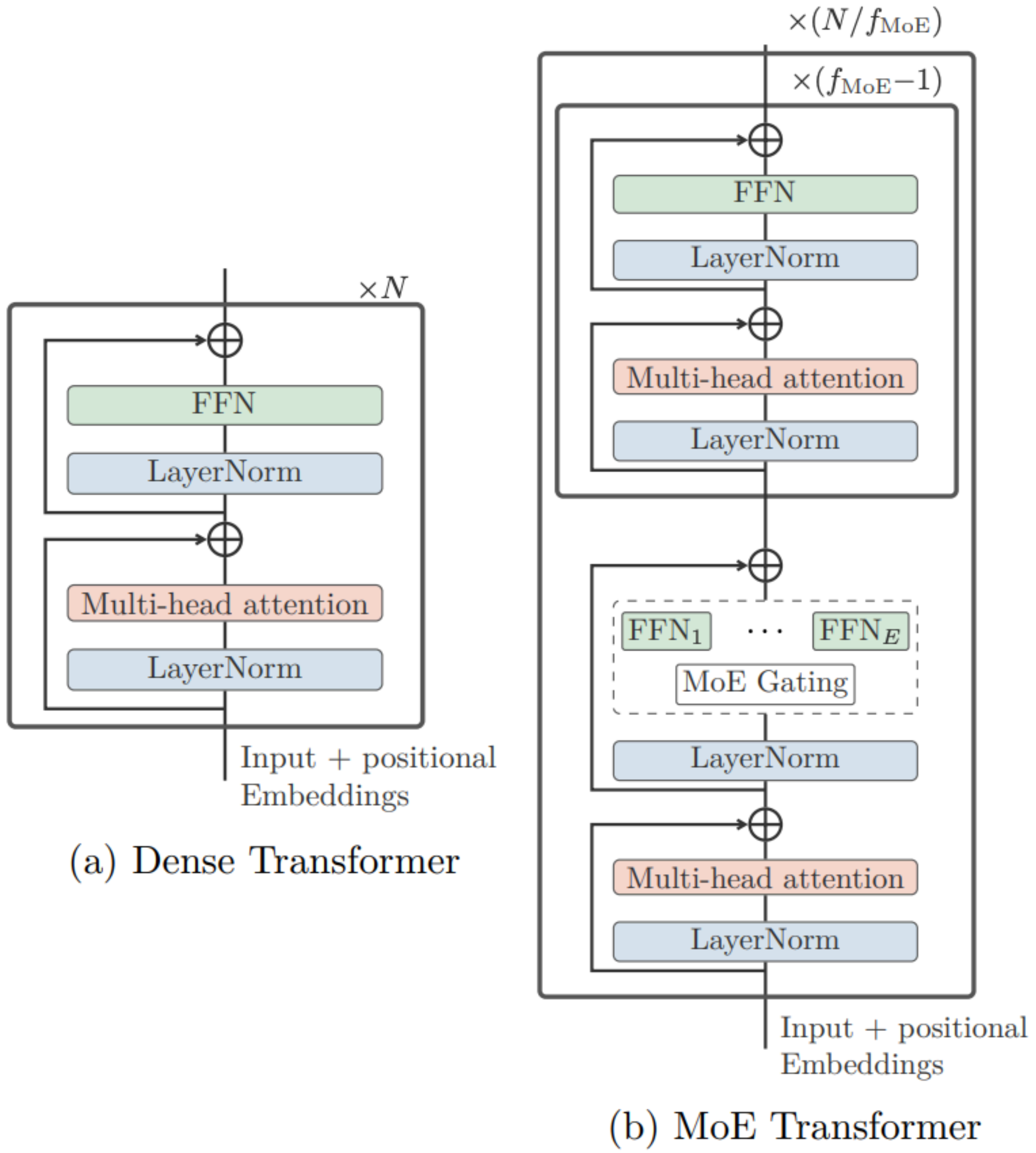
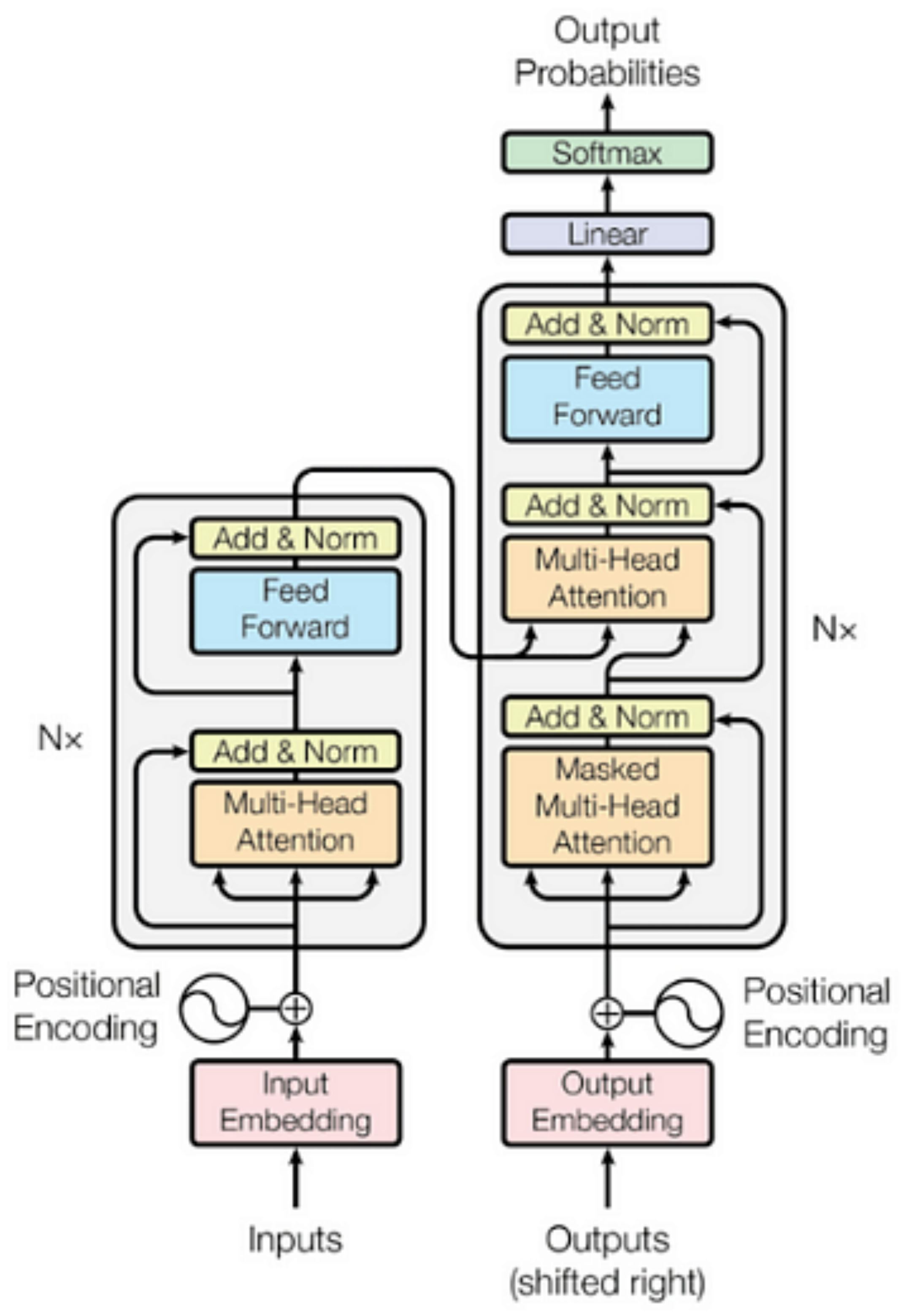


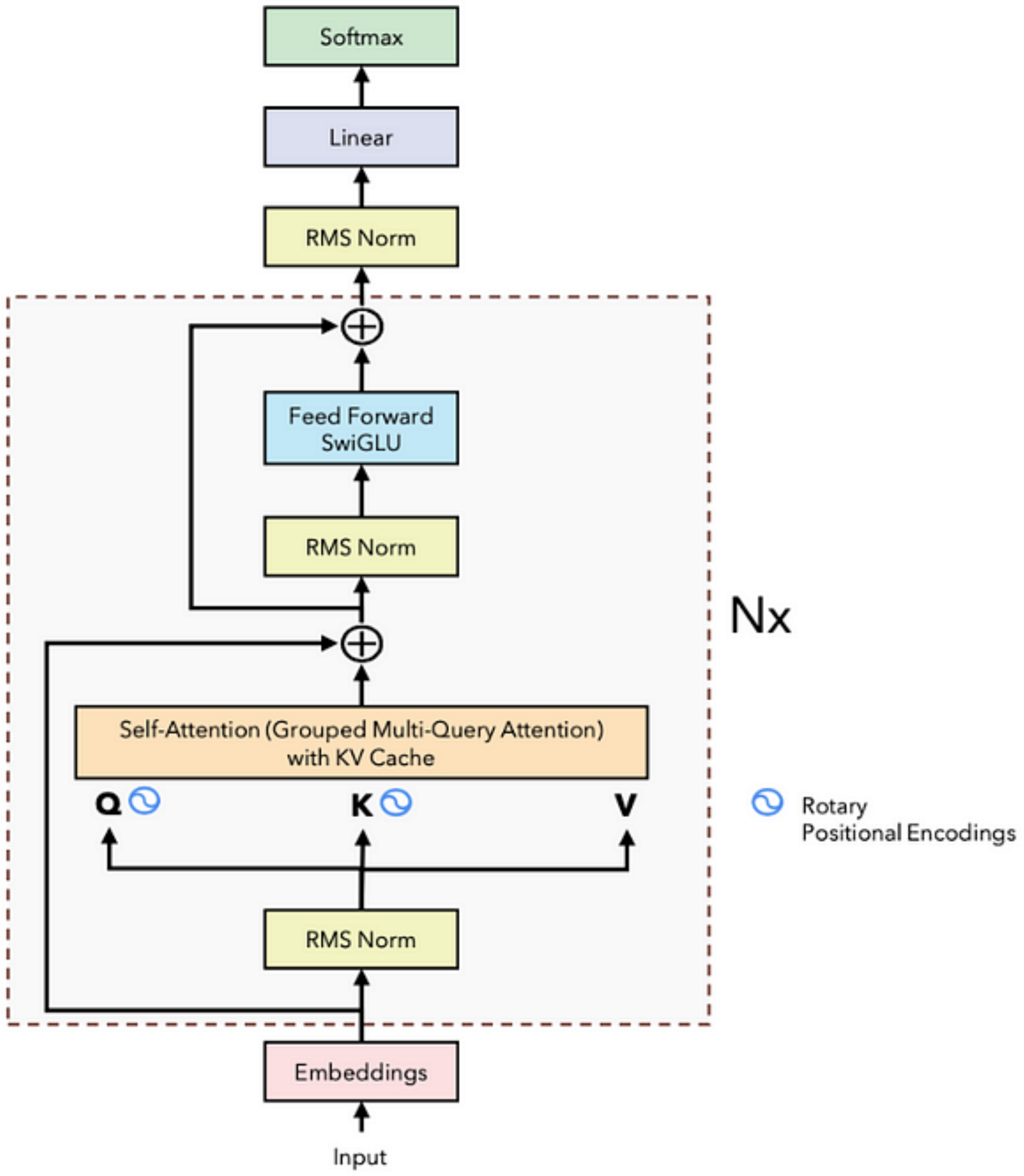

Figure 16: **Illustration of a Transformer encoder with MoE layers** inserted at a 1:$f_{\mathrm{MoE}}$ frequency. Each MoE layer has $E$ experts and a gating network responsible for dispatching tokens.

Eigen el al. (2013), Shazeer et al. (2017), NLLB (2022)

# Transformer as in LLaMA-3




**Transformer**




**LLaMA**