Transformers I

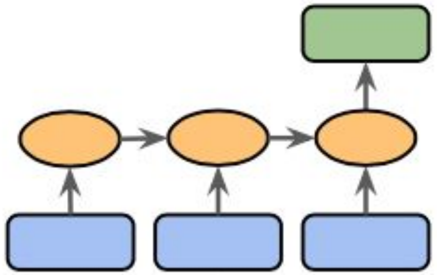
Dr. Parlett-Pelleriti

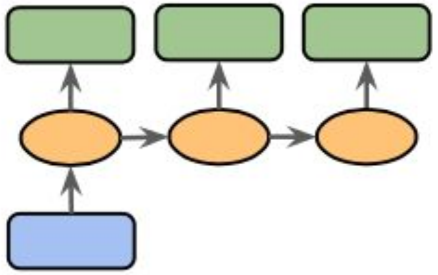
Transformers

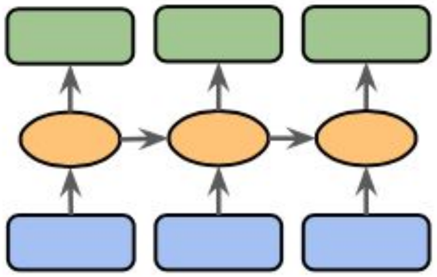
Outline

- Encoder/Decoder Structure
- Transformer Intro
- Word Embeddings
- Positional Encoding

Sequence Models


many-to-one


one-to-many


many-to-many

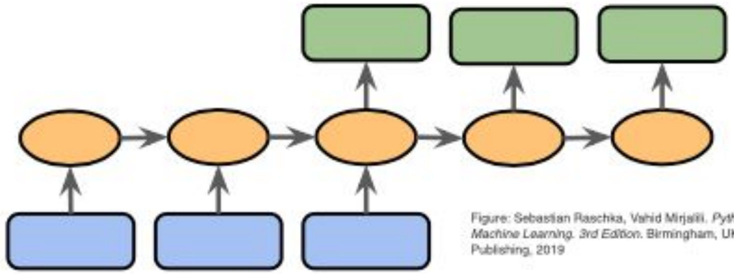

many-to-many

Figure: Sebastian Raschka, Vahid Mirjalili. *Python Machine Learning. 3rd Edition*. Birmingham, UK: Packt Publishing, 2019

Seq-to-Seq Models

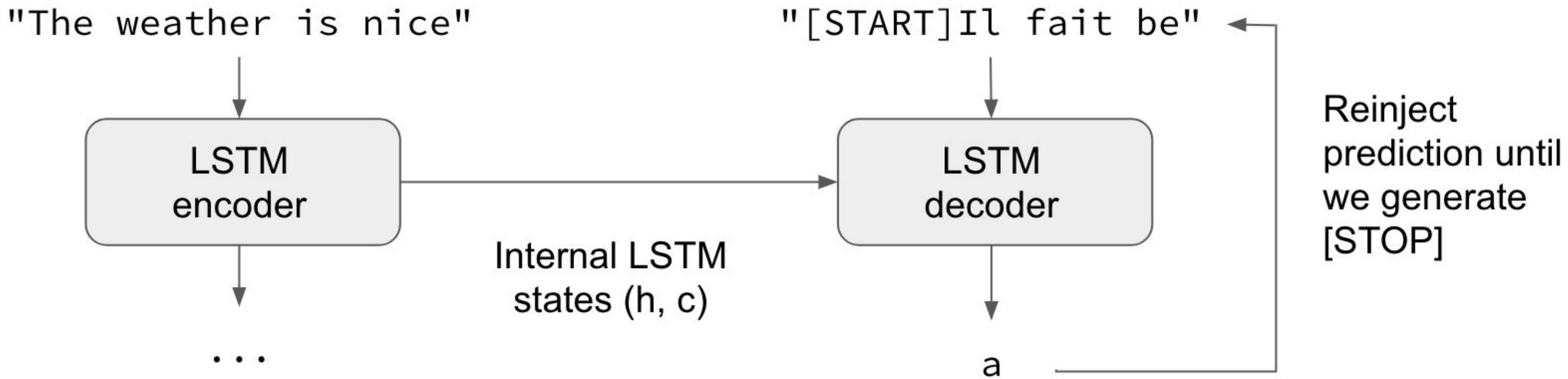
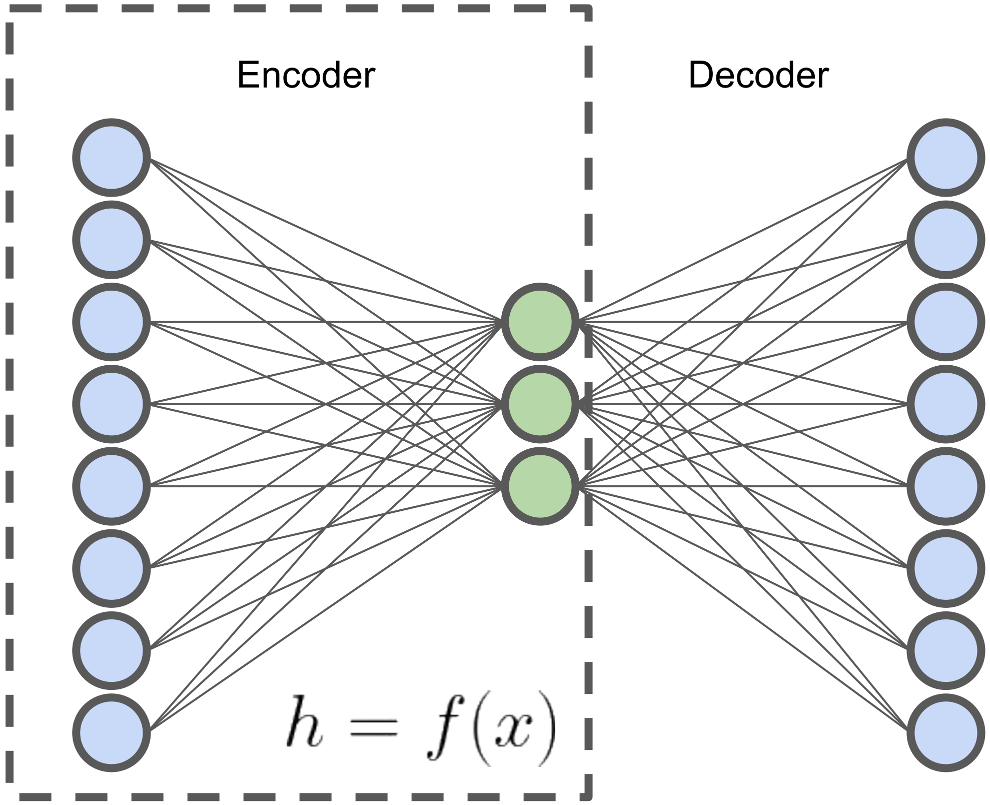
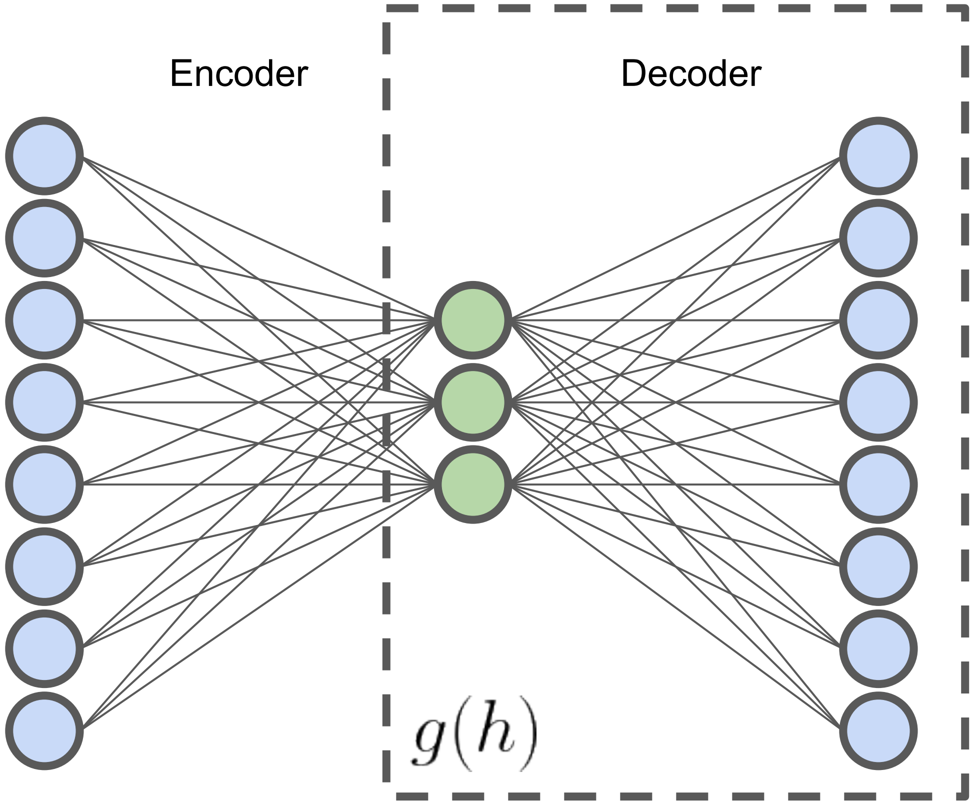

"The weather is nice"
LSTM encoder
...
Internal LSTM states (h, c)
"[START]Il fait be"
LSTM decoder
a
Reinject prediction until we generate [STOP]

Image from: https://blog.keras.io/a-ten-minute-introduction-to-sequence-to-sequence-learning-in-keras.html

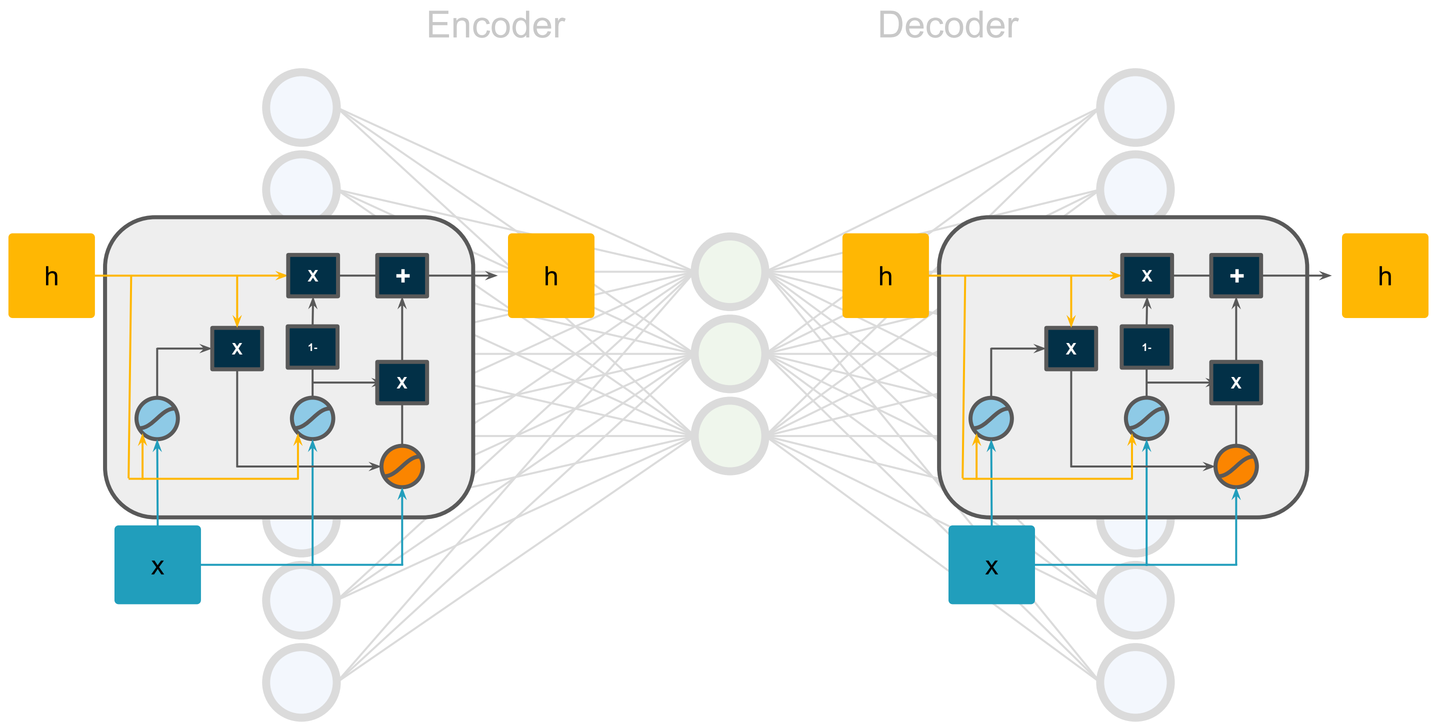
Autoencoder Architecture



Autoencoder Architecture

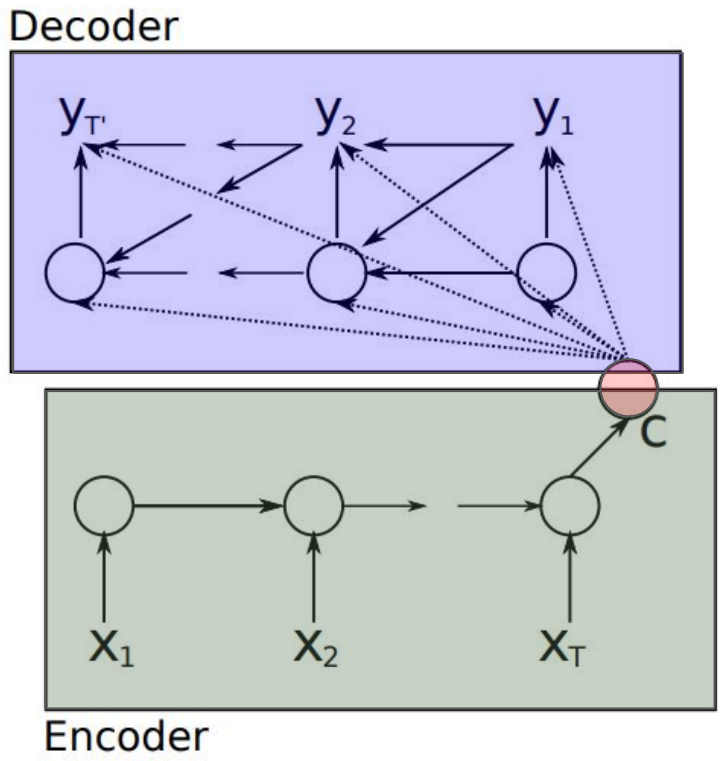


Autoencoder Architecture



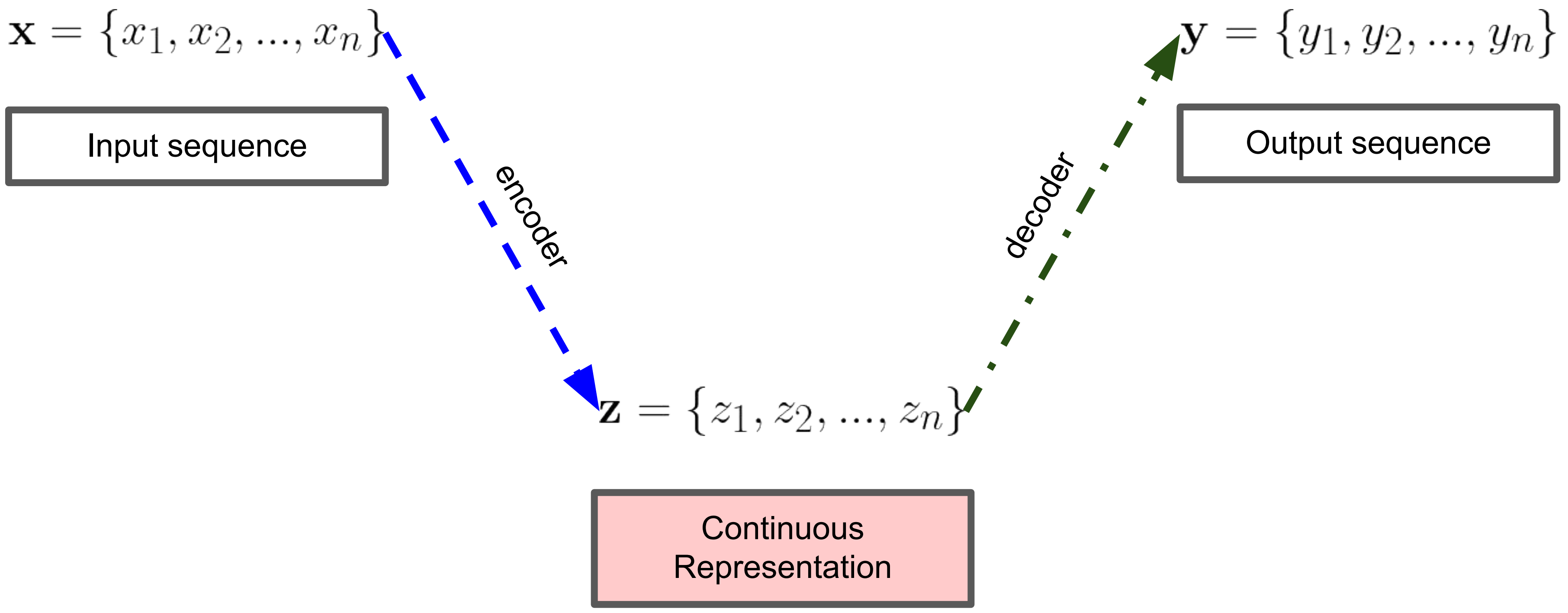
Cho et. al
2014

GRU Machine Translation



Cho et. al
2014

General Encoder/Decoder Model



$\mathbf{x} = \{x_1, x_2, ..., x_n\}$
Input sequence
encoder
$\mathbf{z} = \{z_1, z_2, ..., z_n\}$
Continuous Representation
decoder
$\mathbf{y} = \{y_1, y_2, ..., y_n\}$
Output sequence

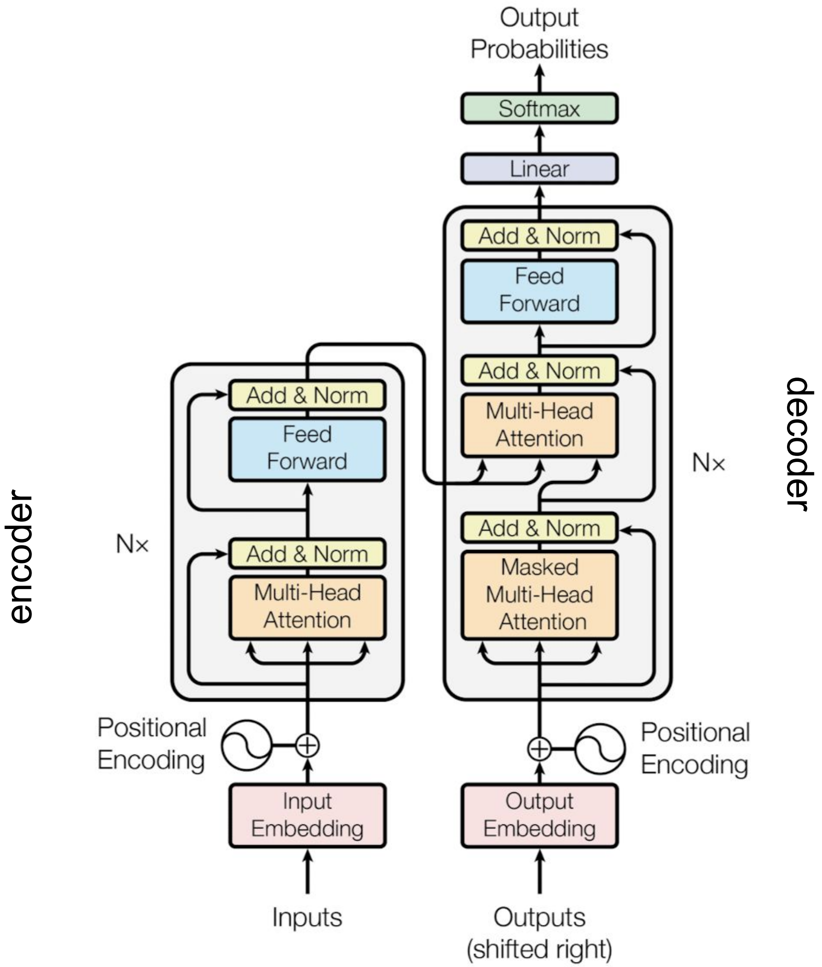
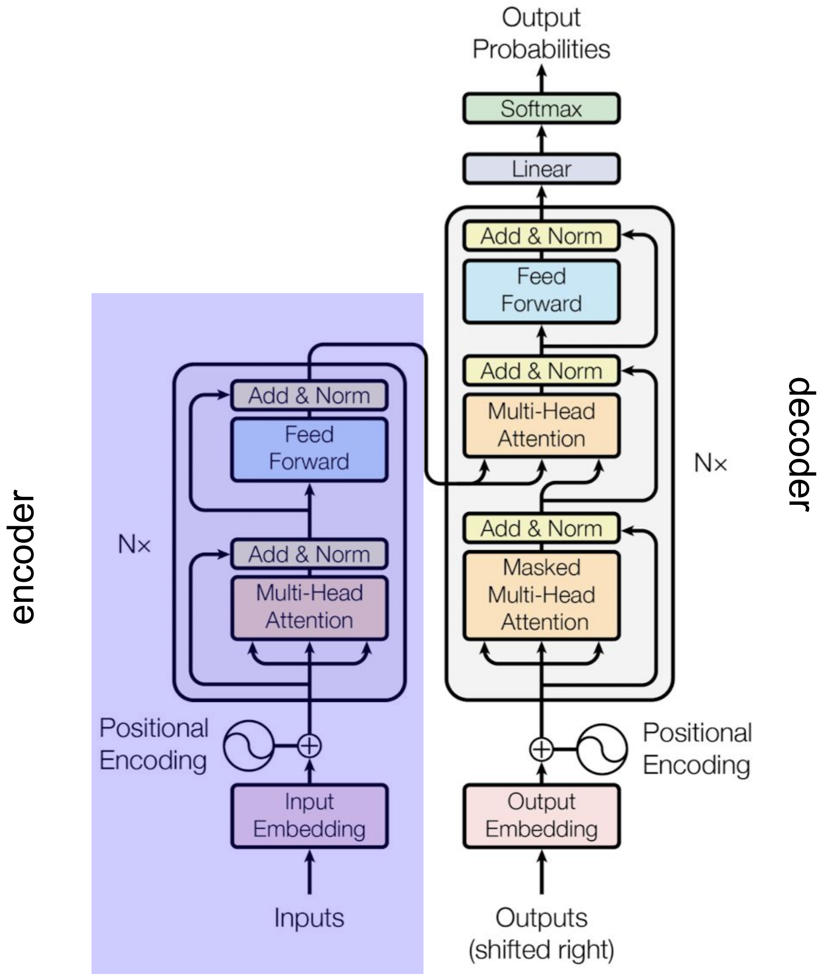


Figure 1: The Transformer - model architecture.

Image from: Attention is all you Need (Vaswani et. al 2017)



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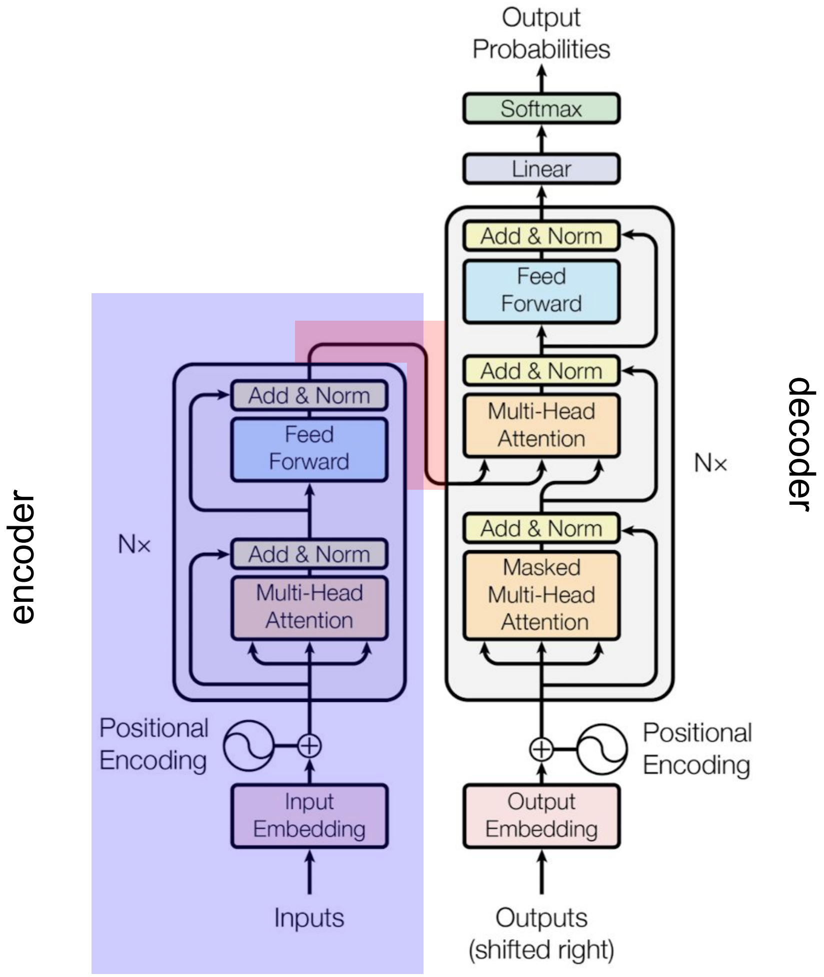

Figure 1: The Transformer - model architecture.

Image from: Attention is all you Need (Vaswani et. al 2017)

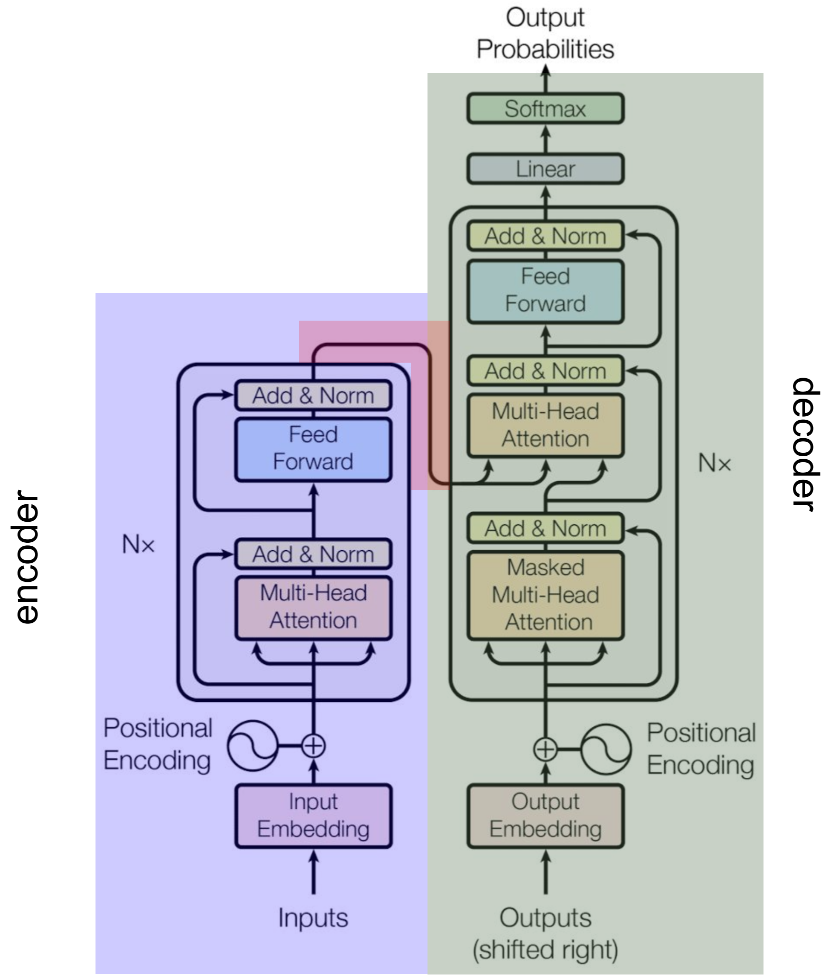

Figure 1: The Transformer - model architecture.

Image from: Attention is all you Need (Vaswani et. al 2017)

Attention Is All You Need

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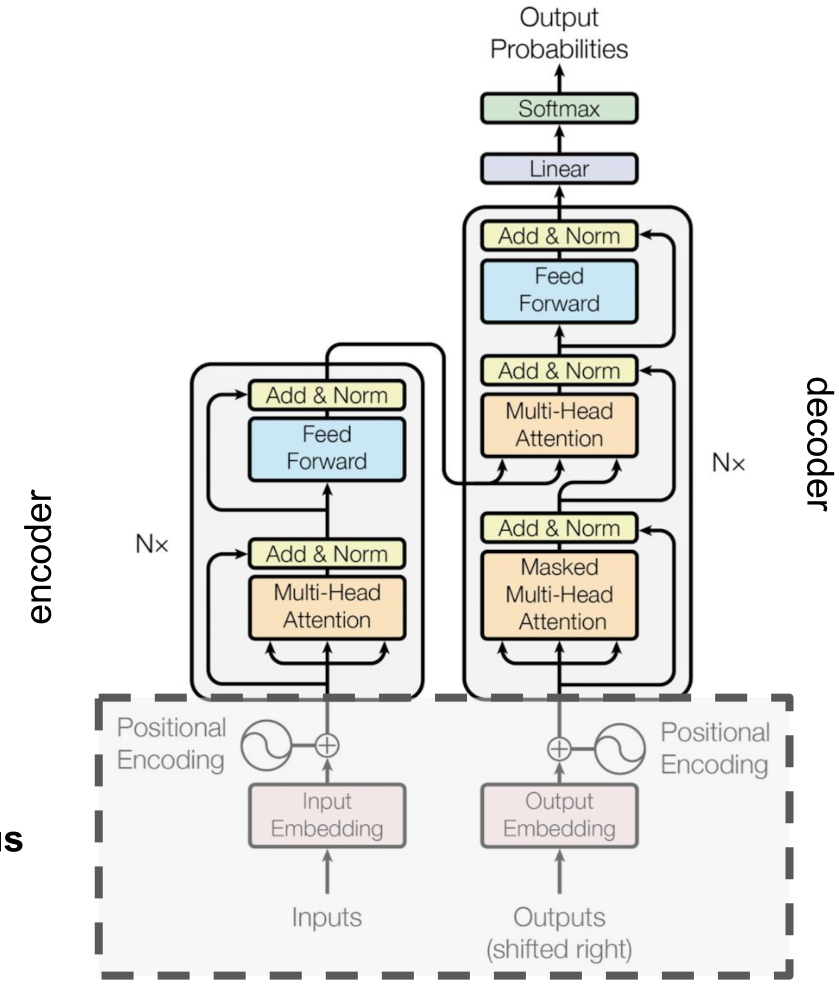

Today's Focus

Figure 1: The Transformer - model architecture.

Image from: Attention is all you Need (Vaswani et. al 2017)

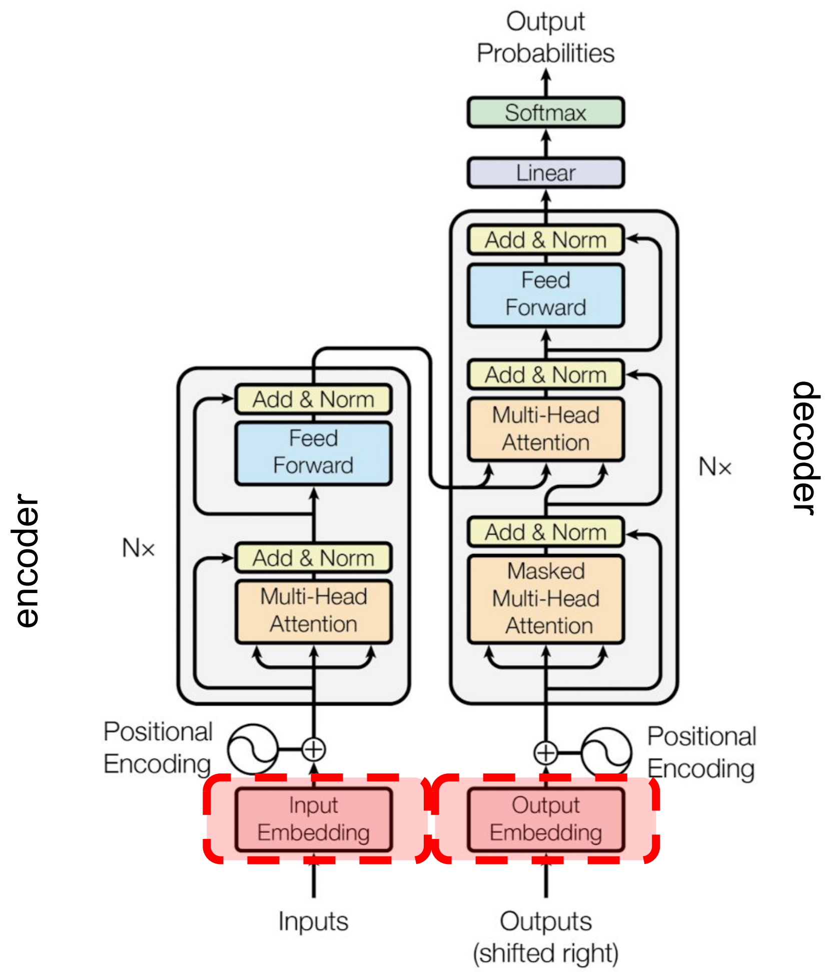

Figure 1: The Transformer - model architecture.

Image from: Attention is all you Need (Vaswani et. al 2017)

Word Embeddings

$$\begin{bmatrix} 0.1 \\ 0.2 \\ 0.4 \\ 0.2 \\ 0.6 \\ 0.1 \end{bmatrix}$$

gorgeous

$$\begin{bmatrix} 0.2 \\ 0.4 \\ 0.5 \\ 0.9 \\ 0.3 \\ 0.1 \end{bmatrix}$$

python

Word Embeddings

$$d_{model} \left\{ \underset{\text{gorgeous}}{\begin{bmatrix} 0.1 \\ 0.2 \\ 0.4 \\ 0.2 \\ 0.6 \\ 0.1 \end{bmatrix}} \right. \qquad d_{model} \left\{ \underset{\text{python}}{\begin{bmatrix} 0.2 \\ 0.4 \\ 0.5 \\ 0.9 \\ 0.3 \\ 0.1 \end{bmatrix}} \right.$$

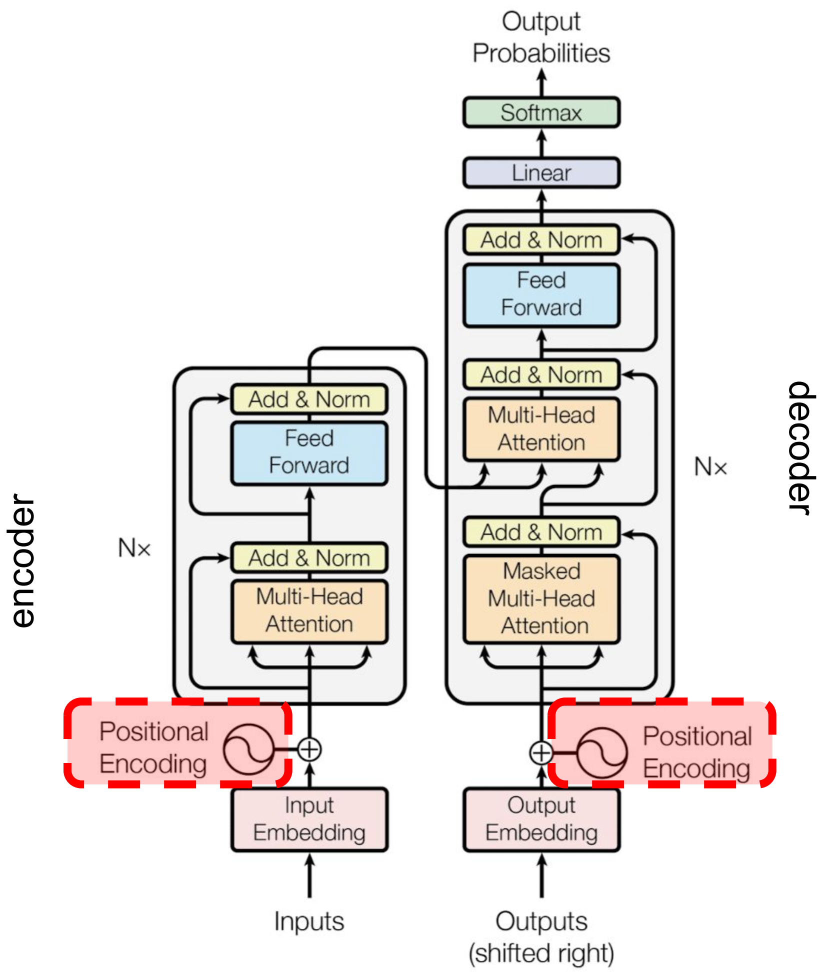

Figure 1: The Transformer - model architecture.

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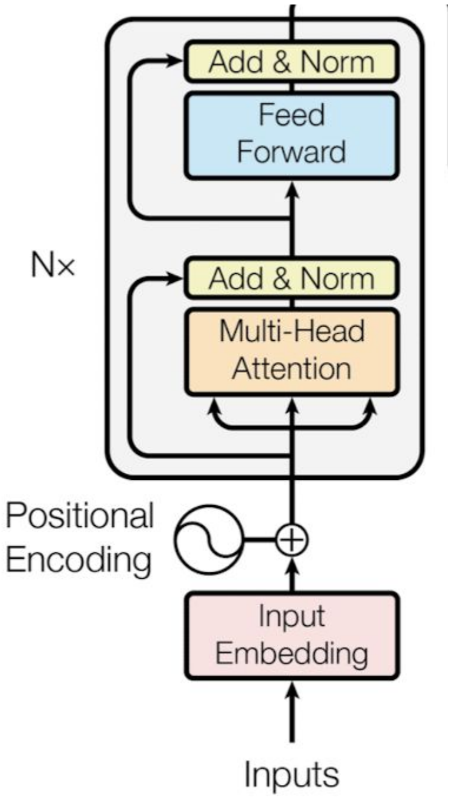
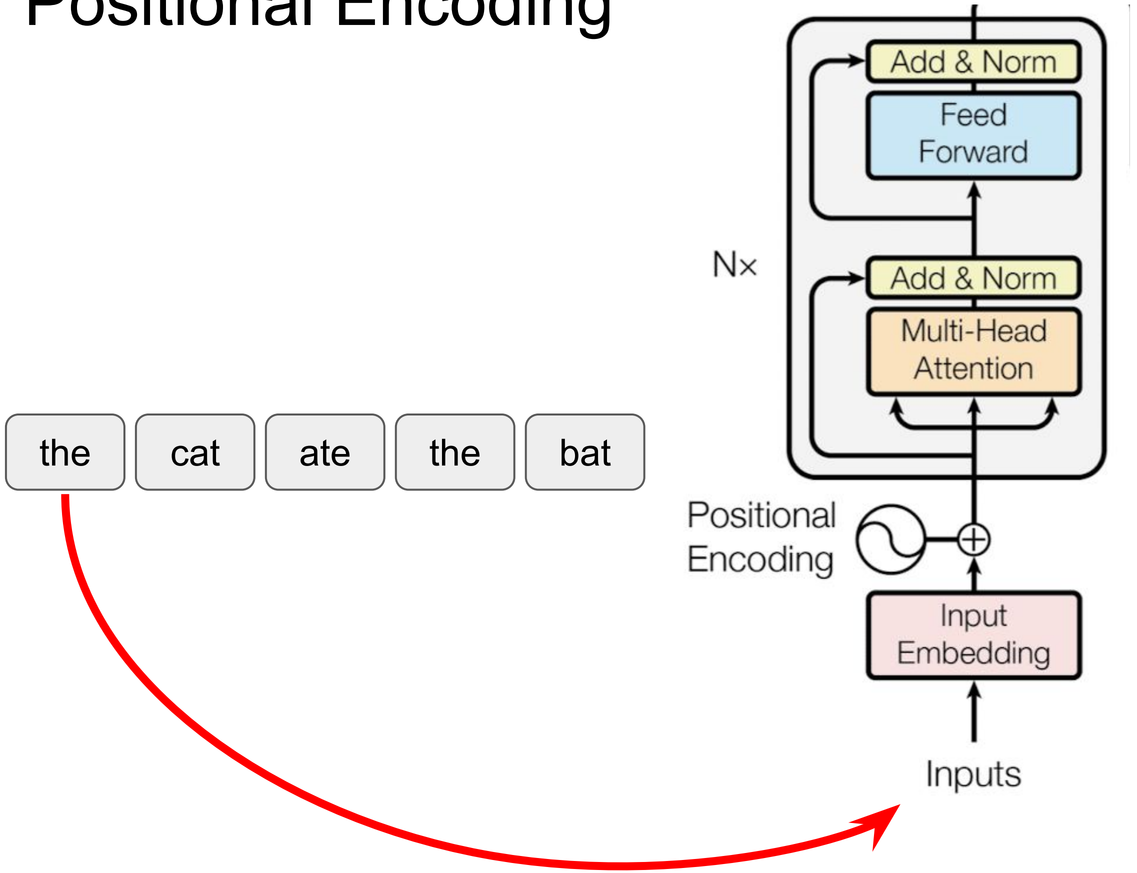
Positional Encoding

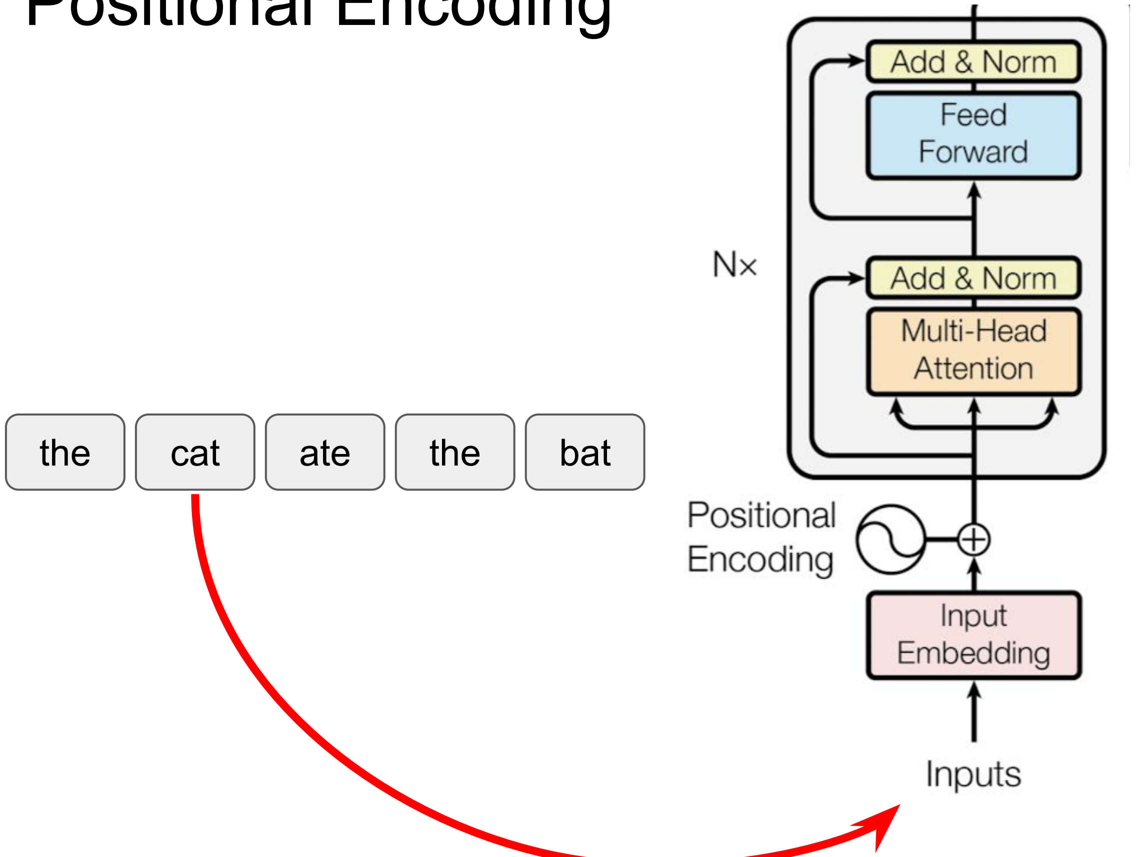
the	cat	ate	the	bat



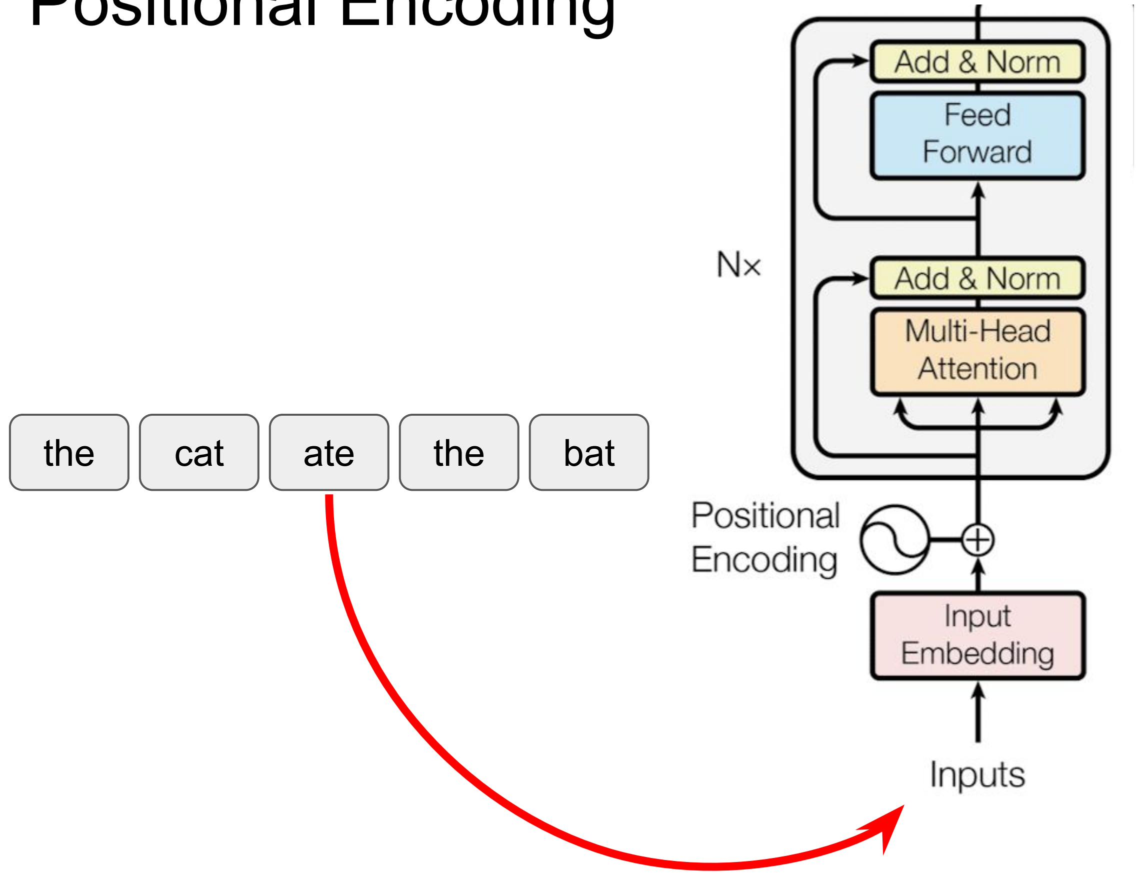
Positional Encoding



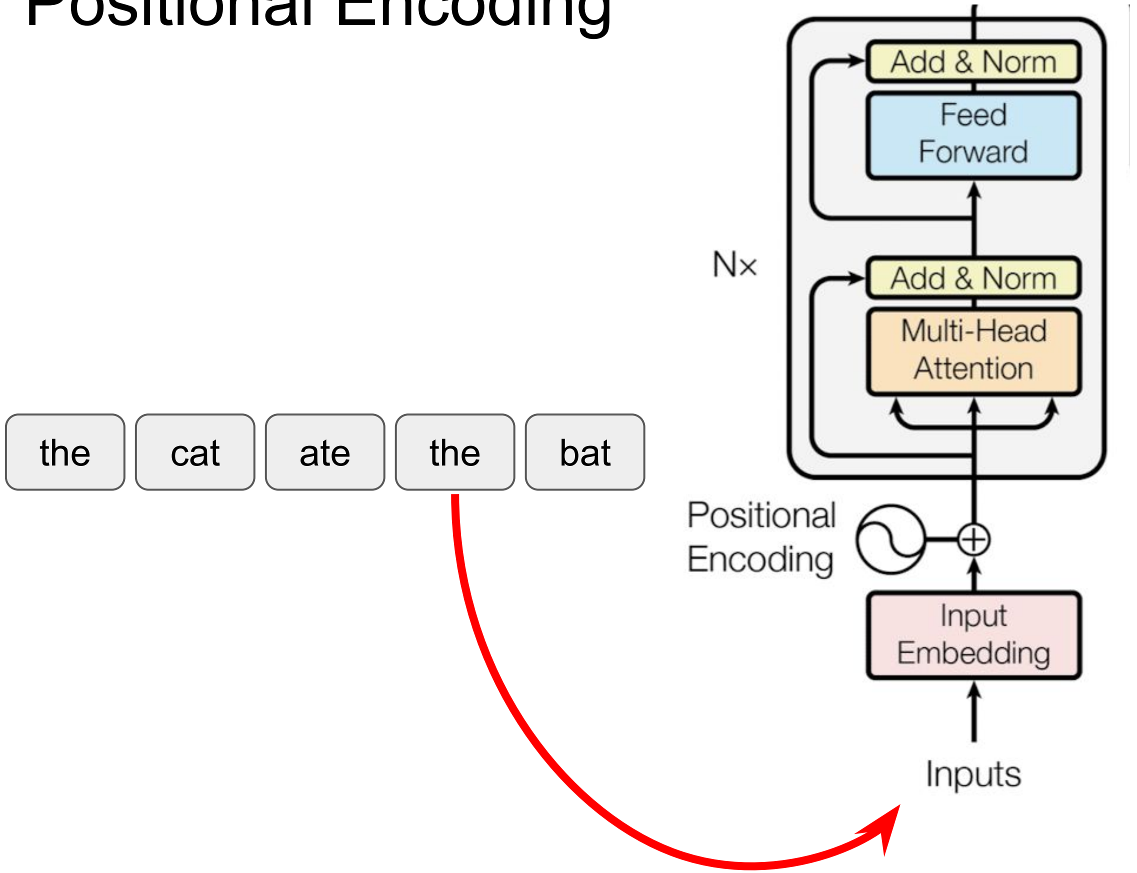
Positional Encoding



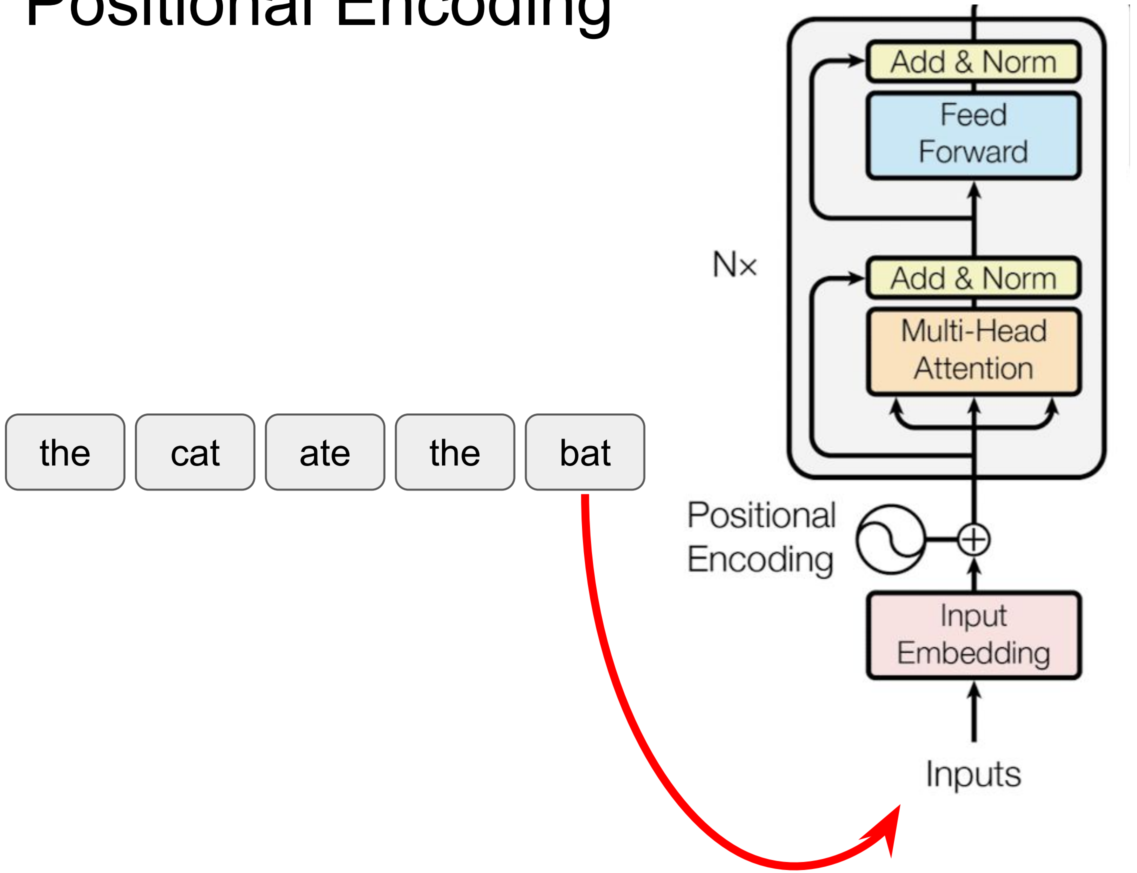
Positional Encoding



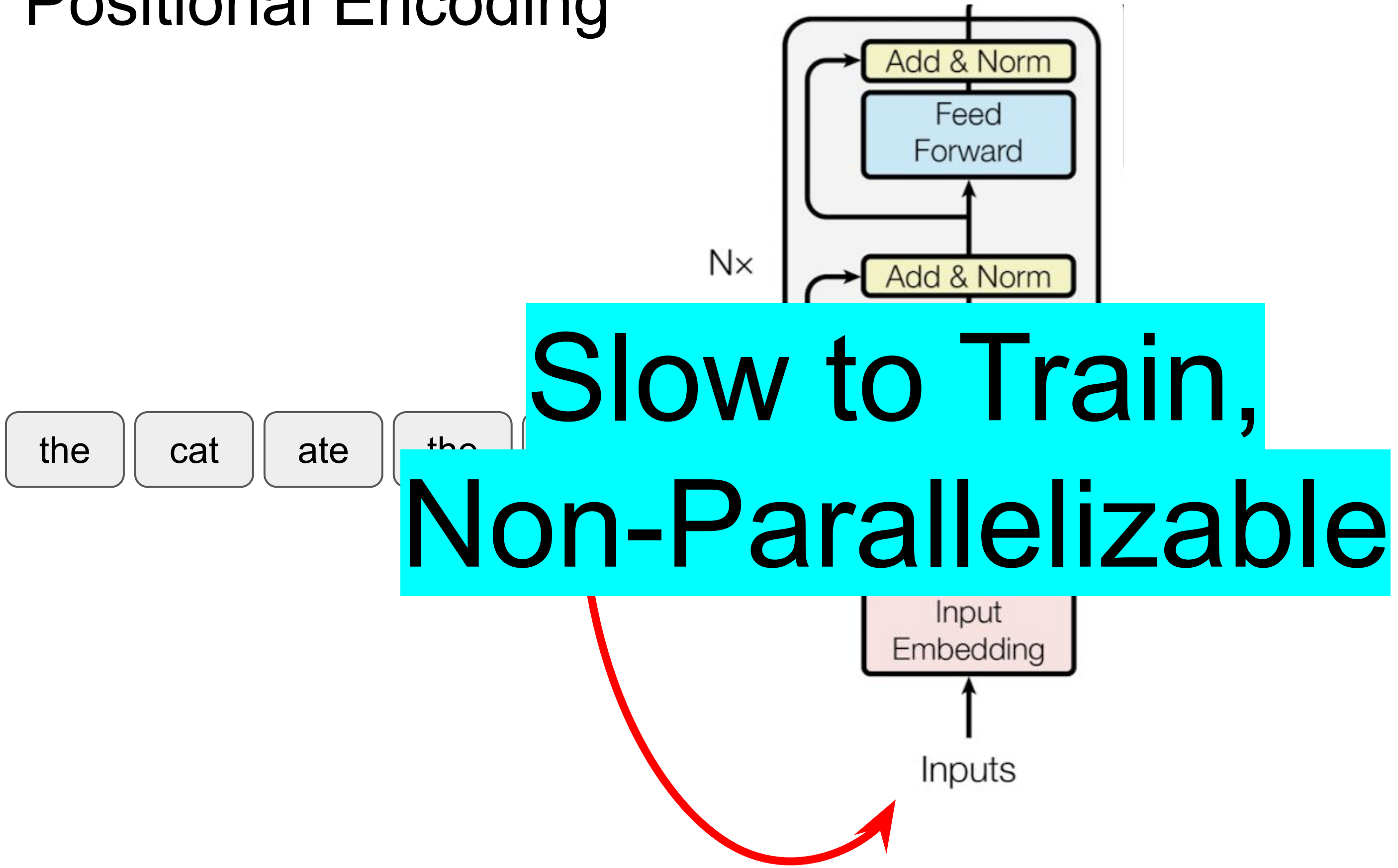
Positional Encoding



Positional Encoding



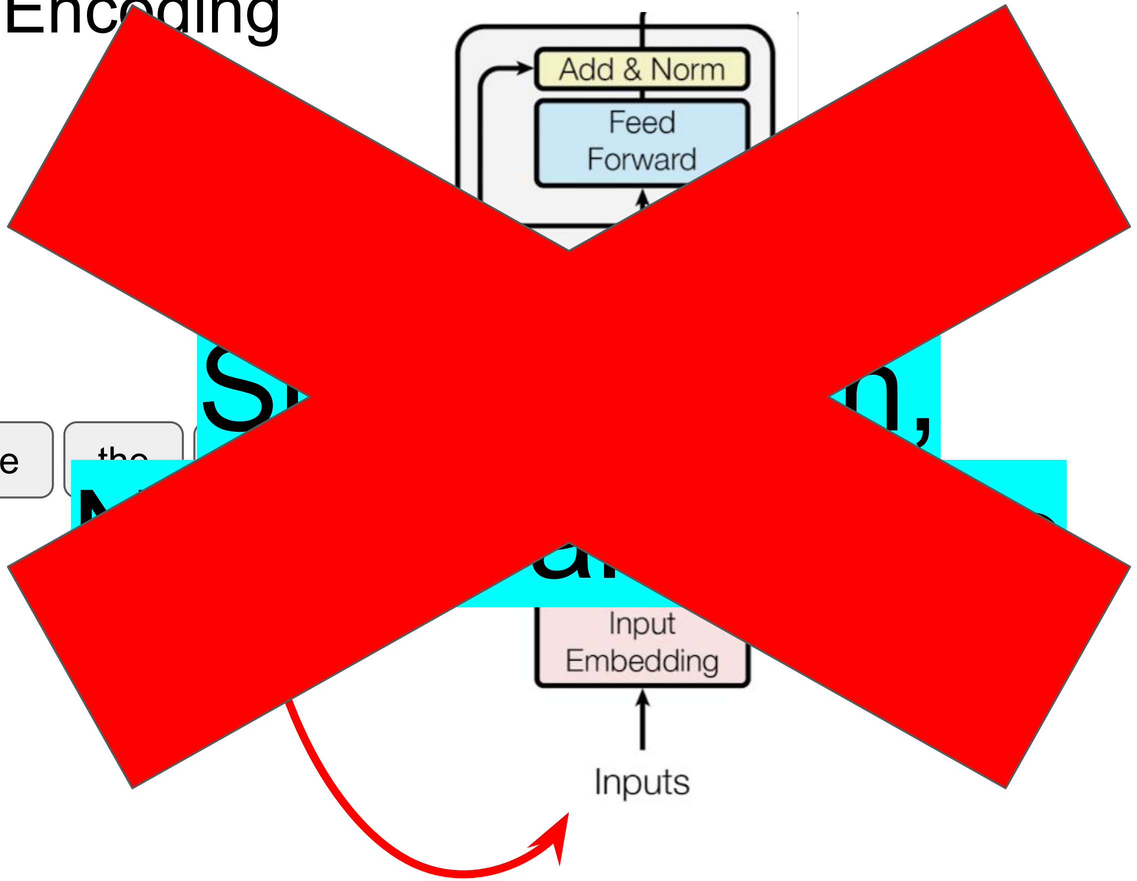
Positional Encoding



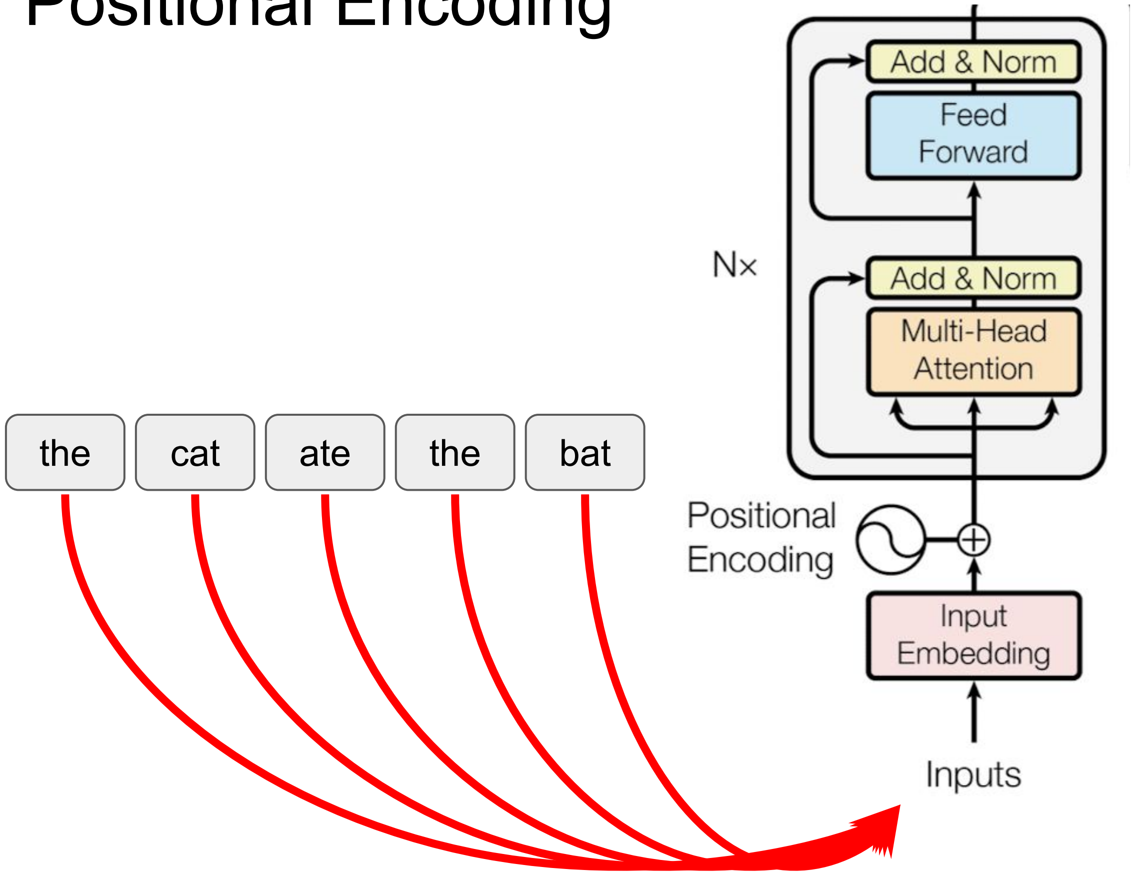
Slow to Train,
Non-Parallelizable

Positional Encoding

the cat ate the



Positional Encoding



Word Embeddings + Positional Encoding

$$d_{model}\left\{\underset{\text{gorgeous}}{\begin{bmatrix}0.1\\0.2\\0.4\\0.2\\0.6\\0.1\end{bmatrix}}\right. + \begin{bmatrix}?\\?\\?\\?\\?\\?\end{bmatrix} \qquad d_{model}\left\{\underset{\text{python}}{\begin{bmatrix}0.2\\0.4\\0.5\\0.9\\0.3\\0.1\end{bmatrix}}\right. + \begin{bmatrix}?\\?\\?\\?\\?\\?\end{bmatrix}$$

Word Embeddings + Positional Encoding

$$d_{model}\left\{\underset{\text{gorgeous}}{\begin{bmatrix}0.1\\0.2\\0.4\\0.2\\0.6\\0.1\end{bmatrix}}\right. + \begin{bmatrix}?\\?\\?\\?\\?\\?\end{bmatrix} \qquad d_{model}\left\{\underset{\text{python}}{\begin{bmatrix}0.2\\0.4\\0.5\\0.9\\0.3\\0.1\end{bmatrix}}\right. + \begin{bmatrix}?\\?\\?\\?\\?\\?\end{bmatrix}$$

Generating Positional Encodings

Positional Encodings

your python code is gorgeous

$$\begin{array}{ccccc}
\begin{bmatrix}0.1\\0\\0.2\\0.1\\0.6\\0.2\end{bmatrix} & \begin{bmatrix}0.2\\0.4\\0.5\\0.9\\0.3\\0.1\end{bmatrix} & \begin{bmatrix}0.2\\0.4\\0.6\\1\\0.2\\0.1\end{bmatrix} & \begin{bmatrix}0.1\\0.3\\0.1\\0\\0\\0.7\end{bmatrix} & \begin{bmatrix}0.1\\0.2\\0.4\\0.2\\0.6\\0.1\end{bmatrix} \\
\text{your} & \text{python} & \text{code} & \text{is} & \text{gorgeous}
\end{array}$$

$$\begin{array}{ccccc}
\begin{bmatrix}0.1\\0\\0.2\\0.1\\0.6\\0.2\end{bmatrix} & + & \begin{bmatrix}0\\0\\0\\0\\0\\0\end{bmatrix} & = & \begin{bmatrix}0.1\\0\\0.2\\0.1\\0.6\\0.2\end{bmatrix} \\
\text{your} & & \textit{position} & &
\end{array}$$

Positional Encodings

your python code is gorgeous

$$\begin{array}{ccccc}
\begin{bmatrix} 0.1 \\ 0 \\ 0.2 \\ 0.1 \\ 0.6 \\ 0.2 \end{bmatrix} &
\begin{bmatrix} 0.2 \\ 0.4 \\ 0.5 \\ 0.9 \\ 0.3 \\ 0.1 \end{bmatrix} &
\begin{bmatrix} 0.2 \\ 0.4 \\ 0.6 \\ 1 \\ 0.2 \\ 0.1 \end{bmatrix} &
\begin{bmatrix} 0.1 \\ 0.3 \\ 0.1 \\ 0 \\ 0 \\ 0.7 \end{bmatrix} &
\begin{bmatrix} 0.1 \\ 0.2 \\ 0.4 \\ 0.2 \\ 0.6 \\ 0.1 \end{bmatrix} \\
\text{your} & \text{python} & \text{code} & \text{is} & \text{gorgeous}
\end{array}$$

$$\begin{array}{ccccc}
\begin{bmatrix} 0.2 \\ 0.4 \\ 0.5 \\ 0.9 \\ 0.3 \\ 0.1 \end{bmatrix} & + &
\begin{bmatrix} 1 \\ 1 \\ 1 \\ 1 \\ 1 \\ 1 \end{bmatrix} & = &
\begin{bmatrix} 1.2 \\ 1.4 \\ 1.5 \\ 1.9 \\ 1.3 \\ 1.1 \end{bmatrix} \\
\text{python} & & \textit{position} & &
\end{array}$$

Positional Encodings

your python code is gorgeous

$$\begin{array}{ccccc} \begin{bmatrix}0.1\\0\\0.2\\0.1\\0.6\\0.2\end{bmatrix} & \begin{bmatrix}0.2\\0.4\\0.5\\0.9\\0.3\\0.1\end{bmatrix} & \begin{bmatrix}0.2\\0.4\\0.6\\1\\0.2\\0.1\end{bmatrix} & \begin{bmatrix}0.1\\0.3\\0.1\\0\\0\\0.7\end{bmatrix} & \begin{bmatrix}0.1\\0.2\\0.4\\0.2\\0.6\\0.1\end{bmatrix} \\ \text{your} & \text{python} & \text{code} & \text{is} & \text{gorgeous} \end{array}$$

$$\begin{array}{ccccc} \begin{bmatrix}0.2\\0.4\\0.6\\1\\0.2\\0.1\end{bmatrix} & + & \begin{bmatrix}2\\2\\2\\2\\2\\2\end{bmatrix} & = & \begin{bmatrix}2.2\\2.4\\2.6\\3\\2.2\\2.1\end{bmatrix} \\ \text{code} & & \textit{position} & & \end{array}$$

Positional Encodings

Instead of:	0	1	2	3	4
Use:	0	0.25	0.5	0.75	1

Positional Encodings

your python code is gorgeous

$$\underset{\text{your}}{\begin{bmatrix}0.1\\0\\0.2\\0.1\\0.6\\0.2\end{bmatrix}}\underset{\text{python}}{\begin{bmatrix}0.2\\0.4\\0.5\\0.9\\0.3\\0.1\end{bmatrix}}\underset{\text{code}}{\begin{bmatrix}0.2\\0.4\\0.6\\1\\0.2\\0.1\end{bmatrix}}\underset{\text{is}}{\begin{bmatrix}0.1\\0.3\\0.1\\0\\0\\0.7\end{bmatrix}}\underset{\text{gorgeous}}{\begin{bmatrix}0.1\\0.2\\0.4\\0.2\\0.6\\0.1\end{bmatrix}}$$

$$\underset{\text{your}}{\begin{bmatrix}0.1\\0\\0.2\\0.1\\0.6\\0.2\end{bmatrix}}+\underset{\textit{position}}{\begin{bmatrix}0\\0\\0\\0\\0\\0\end{bmatrix}}=\begin{bmatrix}0.1\\0\\0.2\\0.1\\0.6\\0.2\end{bmatrix}$$

Positional Encodings

your python code is gorgeous

$$\begin{array}{ccccc}
\begin{bmatrix}0.1\\0\\0.2\\0.1\\0.6\\0.2\end{bmatrix} &
\begin{bmatrix}0.2\\0.4\\0.5\\0.9\\0.3\\0.1\end{bmatrix} &
\begin{bmatrix}0.2\\0.4\\0.6\\1\\0.2\\0.1\end{bmatrix} &
\begin{bmatrix}0.1\\0.3\\0.1\\0\\0\\0.7\end{bmatrix} &
\begin{bmatrix}0.1\\0.2\\0.4\\0.2\\0.6\\0.1\end{bmatrix} \\
\text{your} & \text{python} & \text{code} & \text{is} & \text{gorgeous}
\end{array}$$

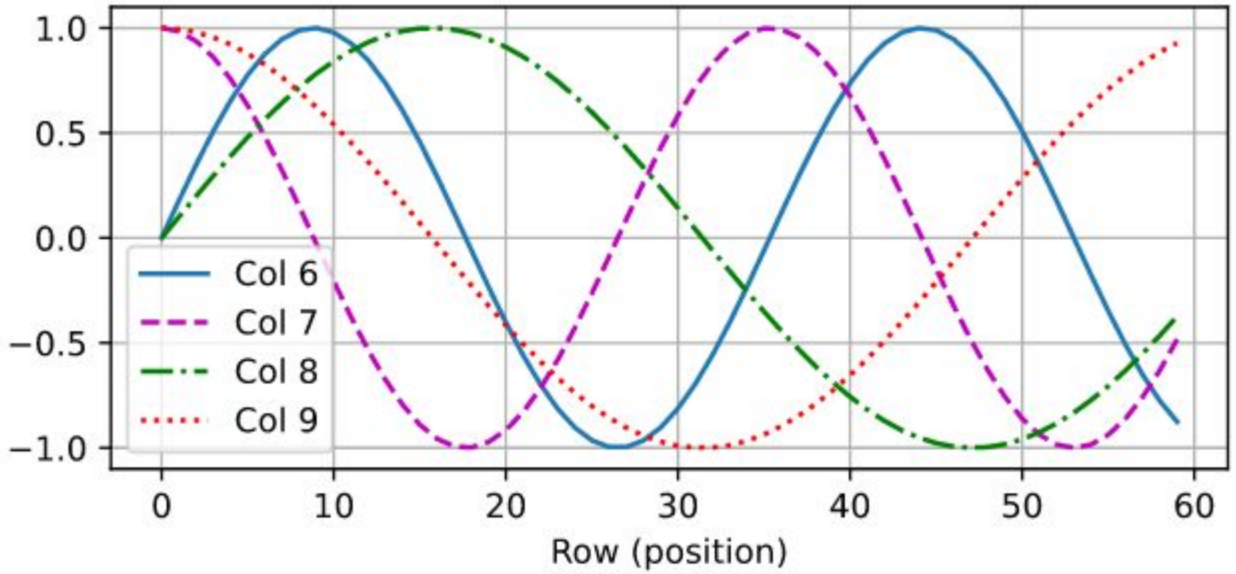
$$\begin{array}{ccccc}
\begin{bmatrix}0.2\\0.4\\0.5\\0.9\\0.3\\0.1\end{bmatrix} & + &
\begin{bmatrix}0.25\\0.25\\0.25\\0.25\\0.25\\0.25\end{bmatrix} & = &
\begin{bmatrix}0.45\\0.65\\0.75\\1.15\\0.55\\0.35\end{bmatrix} \\
\text{python} & & \textit{position} & &
\end{array}$$

Positional Encoding

Things we want:

- Encode position
- No large numbers
- Allow for variable sequence length

Positional Encodings



Positional Encoding

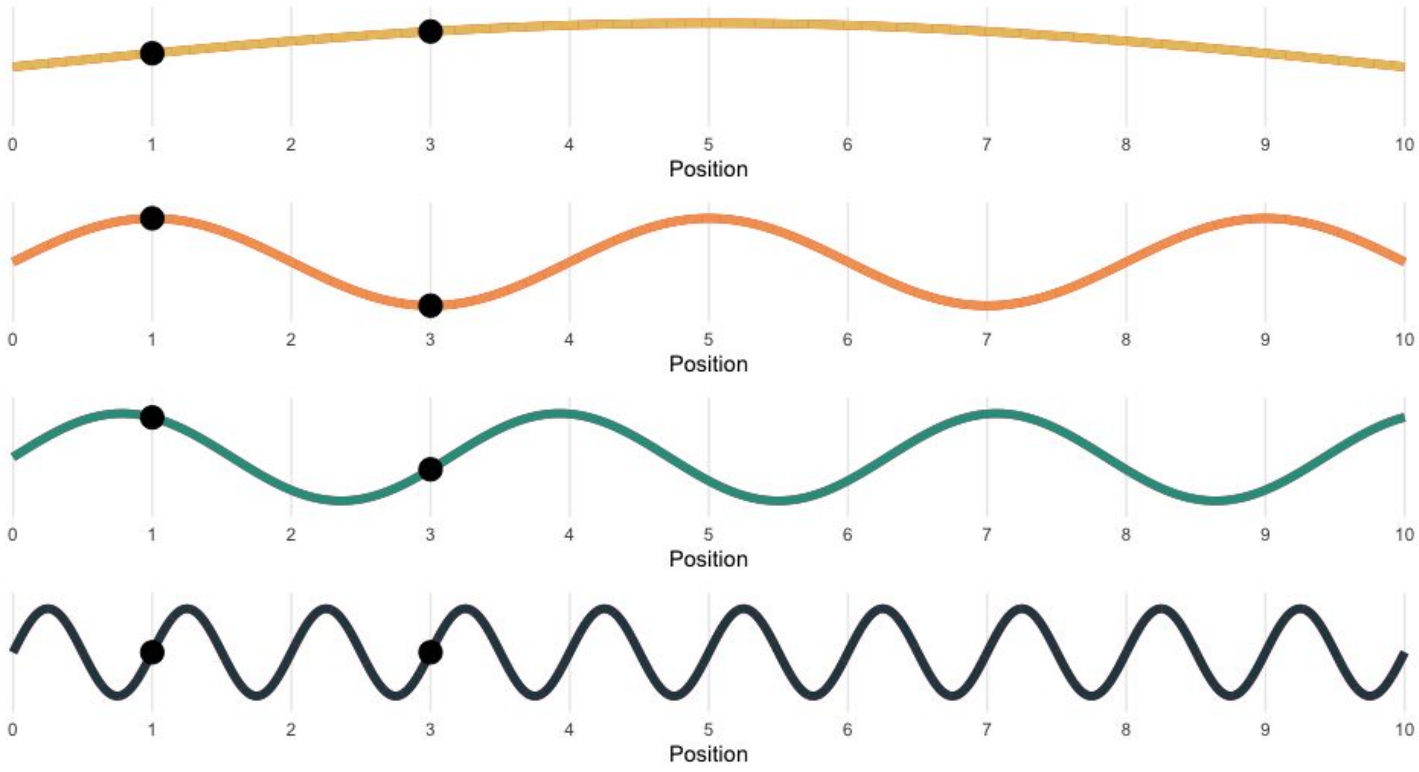
Pros

- sin() and cos() are bounded between -1, 1
- sin() and cos() can go on forever

Cons

- sin() and cos() are periodic

Positional Encoding



Positional Encoding

$$sin(\boxed{pos}/10000^{\frac{2*i}{d}})$$

$$cos(\boxed{pos}/10000^{\frac{2*i}{d}})$$

Positional Encoding

$$sin(pos/10000^{\frac{2*i}{d}})$$

$$cos(pos/10000^{\frac{2*i}{d}})$$

Positional Encoding

$$sin(pos/10000^{\frac{2*i}{d}})$$

$$cos(pos/10000^{\frac{2*i}{d}})$$

Positional Encoding

$$d_{model}\left\{\begin{bmatrix} sin(pos/10000^{\frac{2*0}{d}}) \\ cos(pos/10000^{\frac{2*0}{d}}) \\ \\ sin(pos/10000^{\frac{2*1}{d}}) \\ cos(pos/10000^{\frac{2*1}{d}}) \\ \\ \ldots \\ \\ sin(pos/10000^{\frac{2*j}{d}}) \\ cos(pos/10000^{\frac{2*j}{d}}) \end{bmatrix}\right.$$

$$j = d_{model}//2$$

Positional Encoding

```
pos = 0

d = 6

pos_encoding = np.zeros(d)

for i in range(d//2):

    pos_encoding[2*i]     = sin(pos/10000^{2*i/d})

    pos_encoding[2*i + 1] = cos(pos/10000^{2*i/d})
```

$$\begin{bmatrix} sin(pos/10000^{\frac{2*0}{d}}) \\ cos(pos/10000^{\frac{2*0}{d}}) \\ \\ sin(pos/10000^{\frac{2*1}{d}}) \\ cos(pos/10000^{\frac{2*1}{d}}) \\ \\ \cdots \\ \\ sin(pos/10000^{\frac{2*j}{d}}) \\ cos(pos/10000^{\frac{2*j}{d}}) \end{bmatrix}$$

$$j = d_{model}//2$$

Positional Encoding

```
pos = 0

d = 6

pos_encoding = np.zeros(d)

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    pos_encoding[2*i]     = sin(pos/10000^{2*i/d})

    pos_encoding[2*i + 1] = cos(pos/10000^{2*i/d})
```
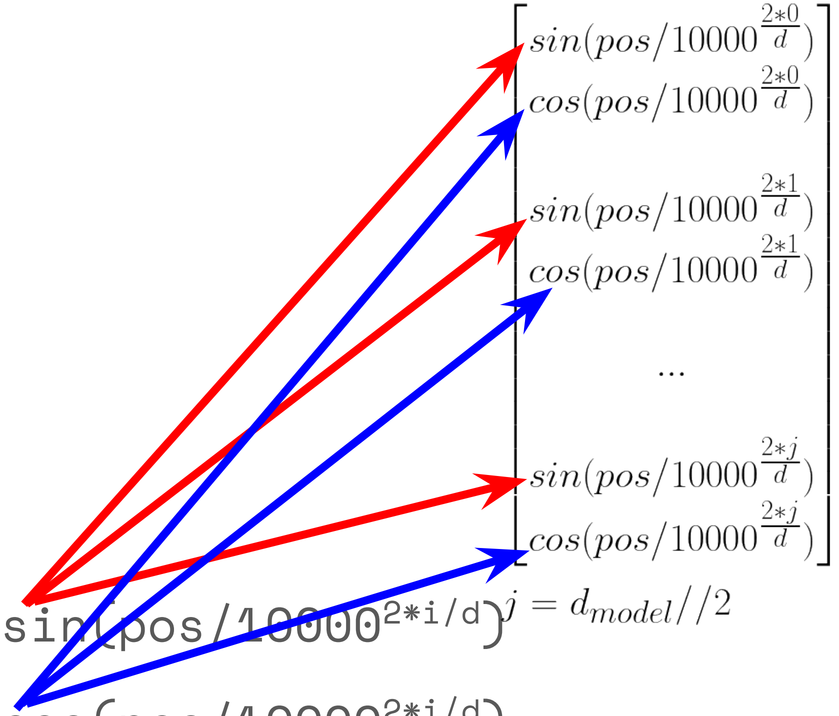
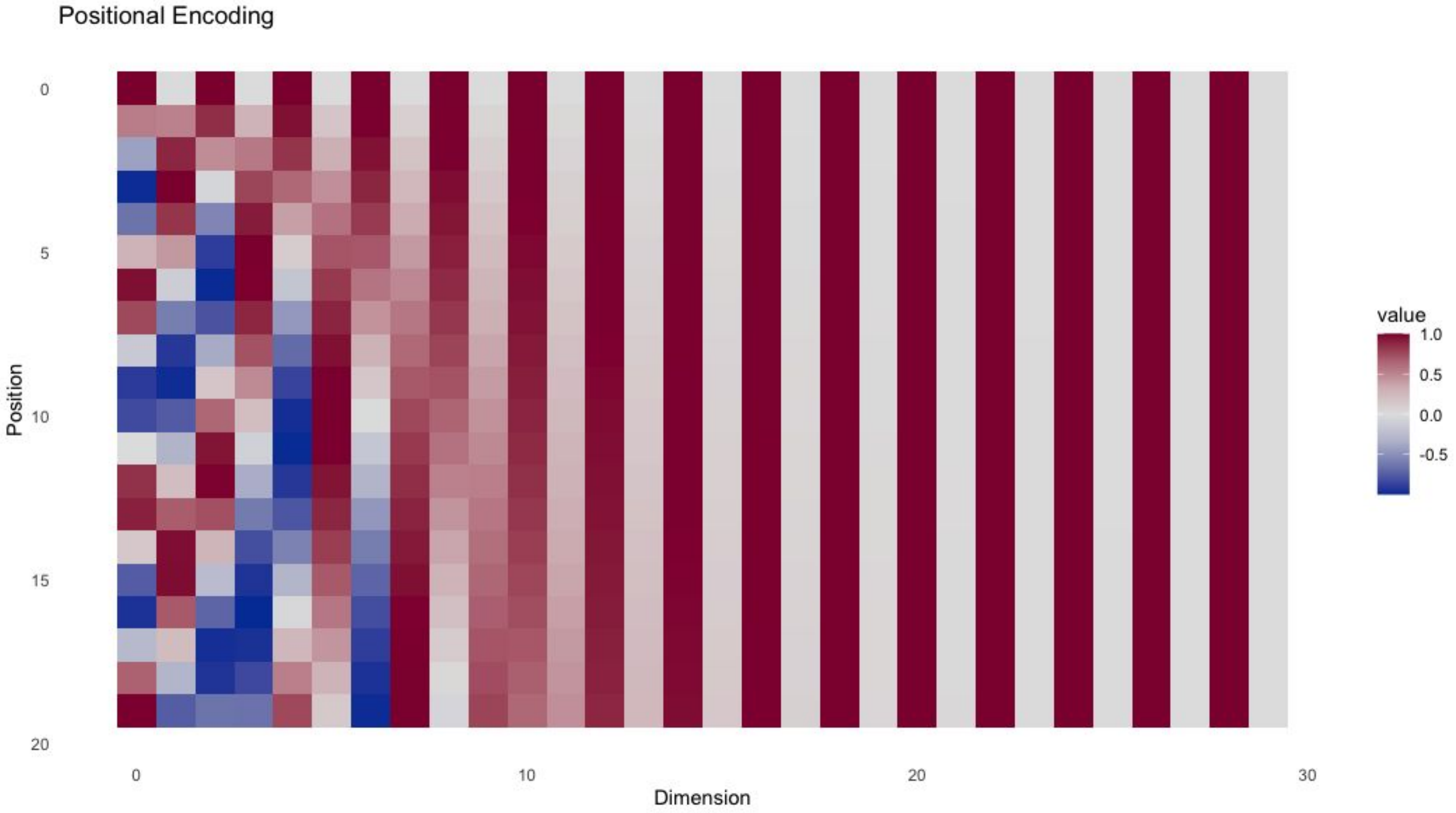



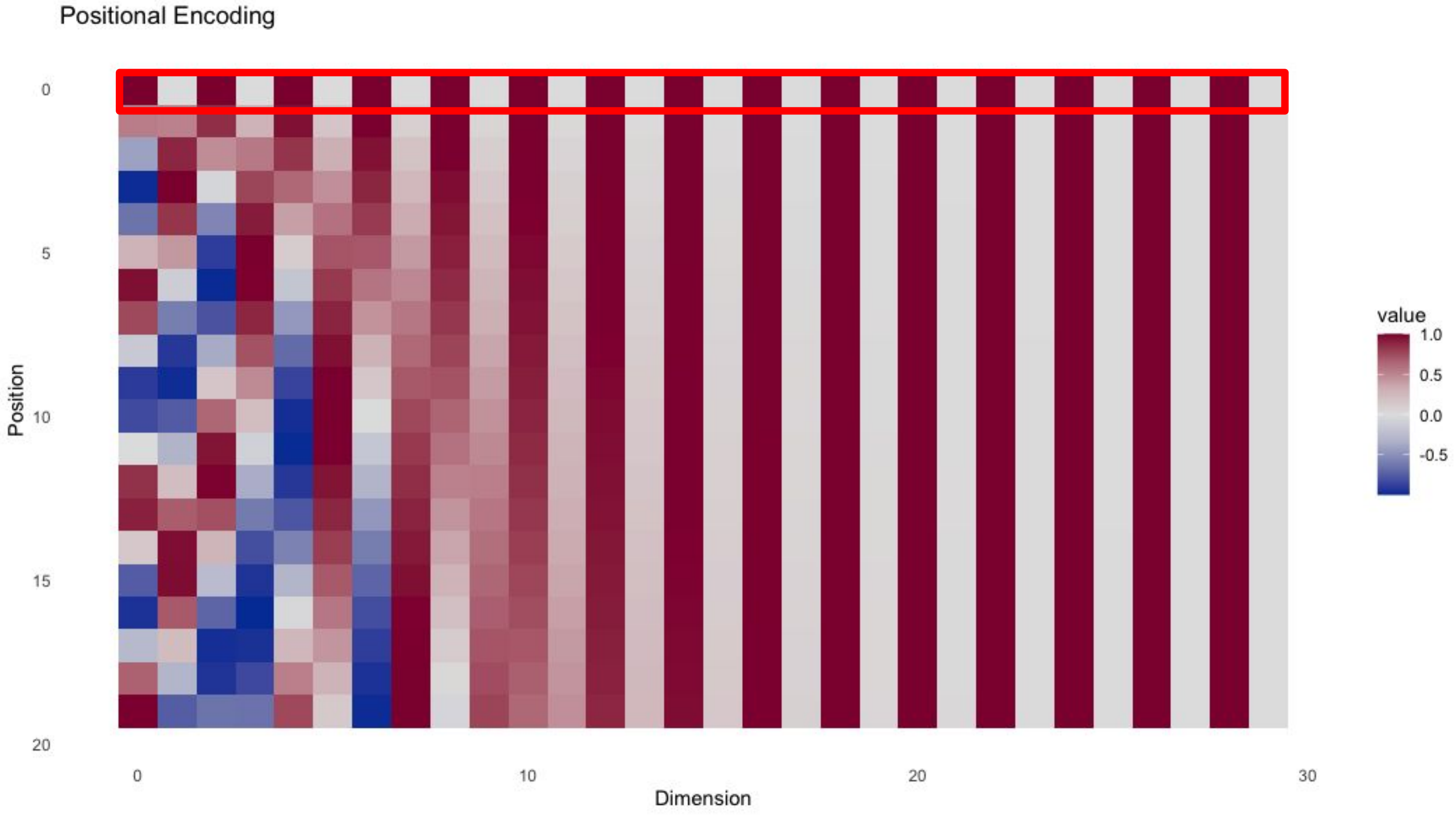
$$\begin{bmatrix} sin(pos/10000^{\frac{2*0}{d}}) \\ cos(pos/10000^{\frac{2*0}{d}}) \\ sin(pos/10000^{\frac{2*1}{d}}) \\ cos(pos/10000^{\frac{2*1}{d}}) \\ \cdots \\ sin(pos/10000^{\frac{2*j}{d}}) \\ cos(pos/10000^{\frac{2*j}{d}}) \end{bmatrix}$$

$j = d_{model}//2$

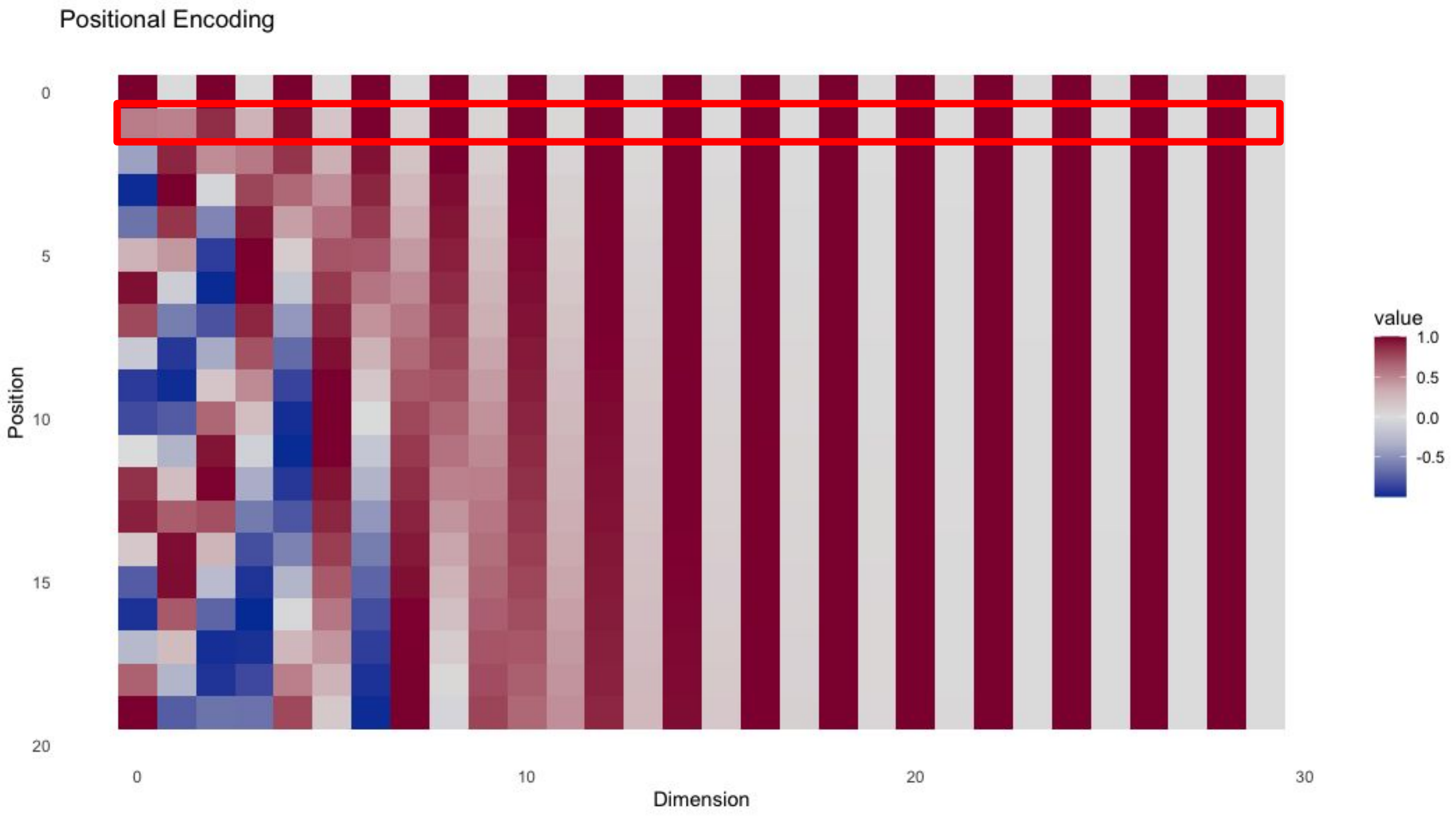
Positional Encoding



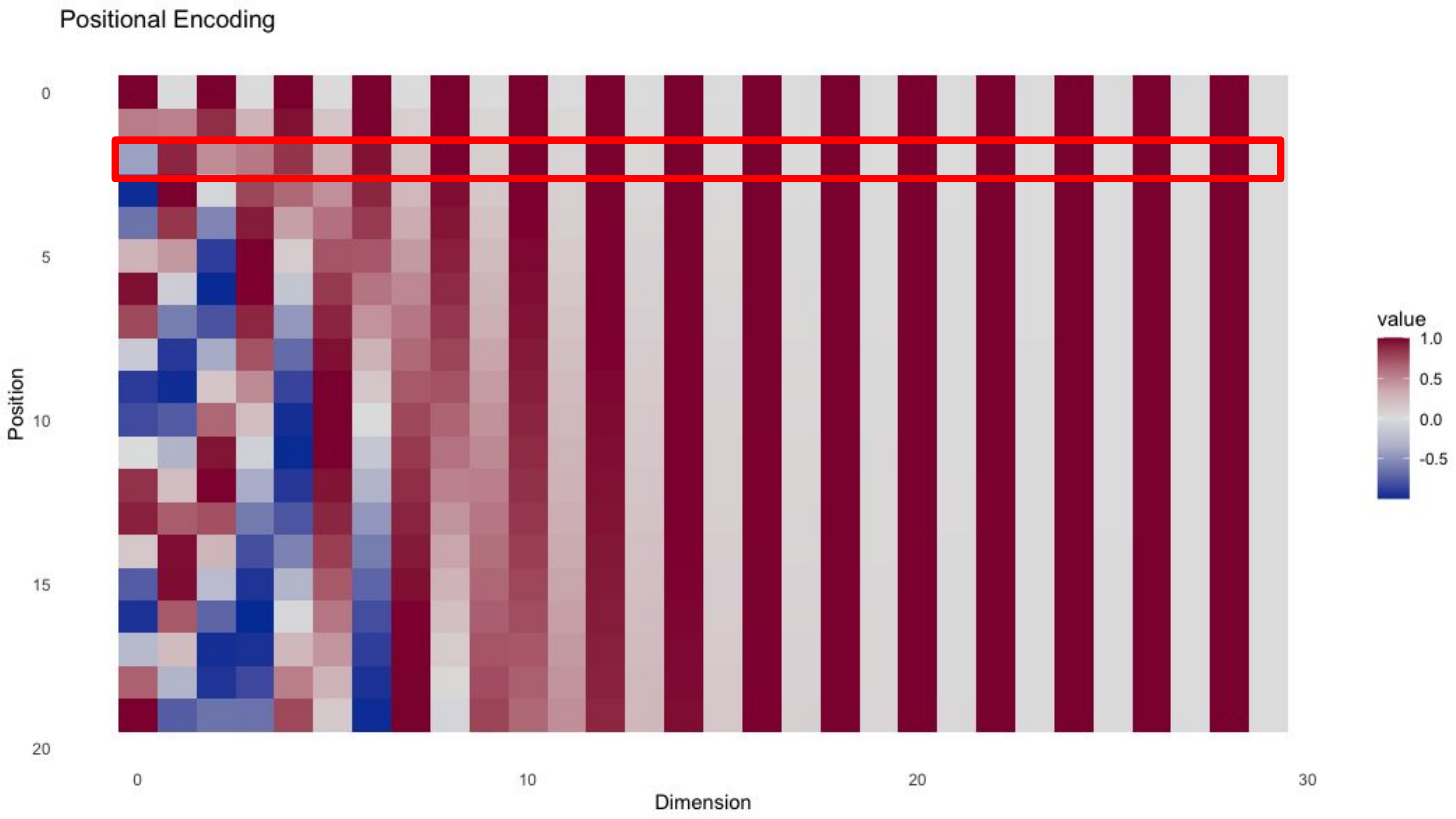
Positional Encoding



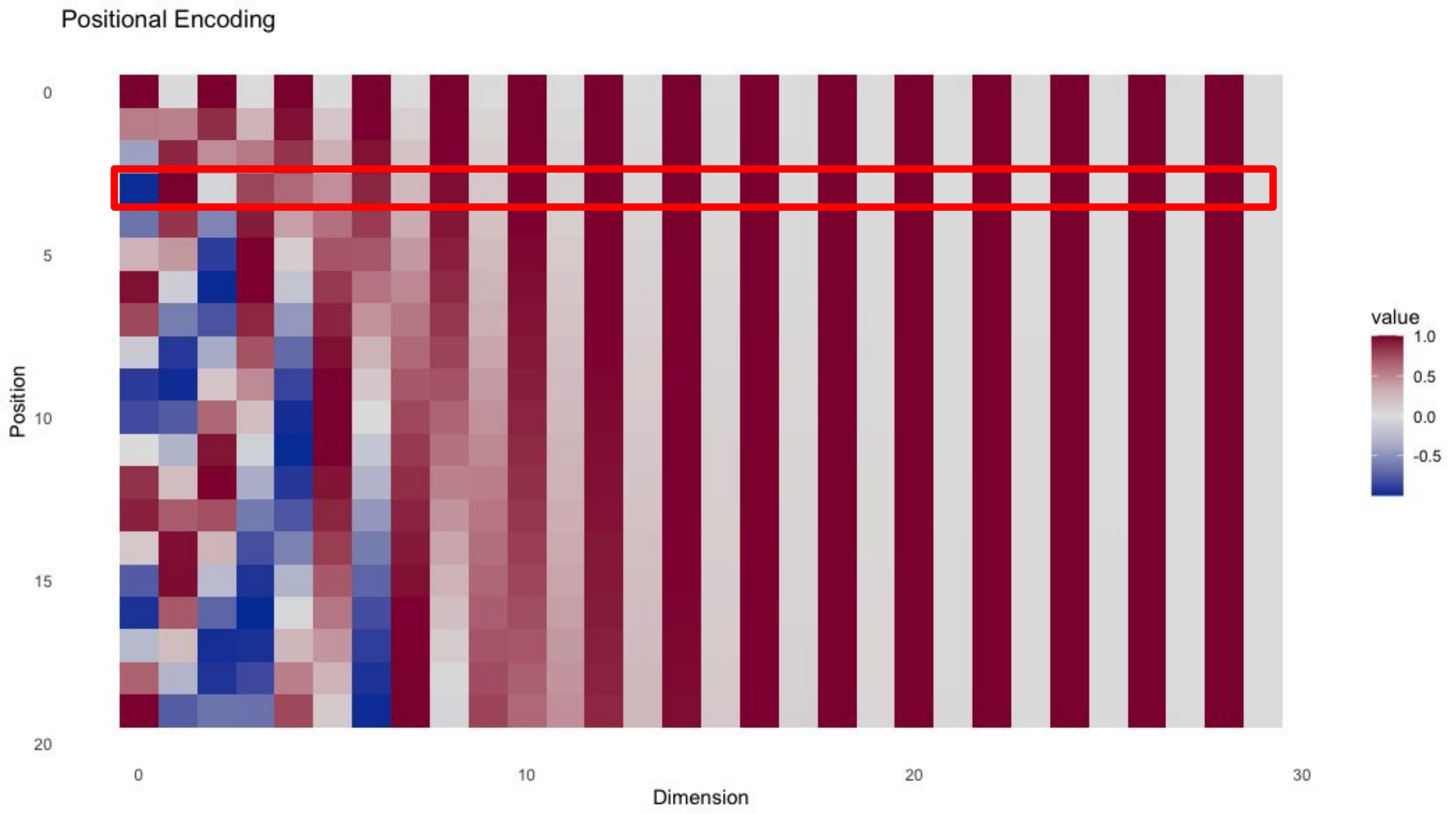
Positional Encoding



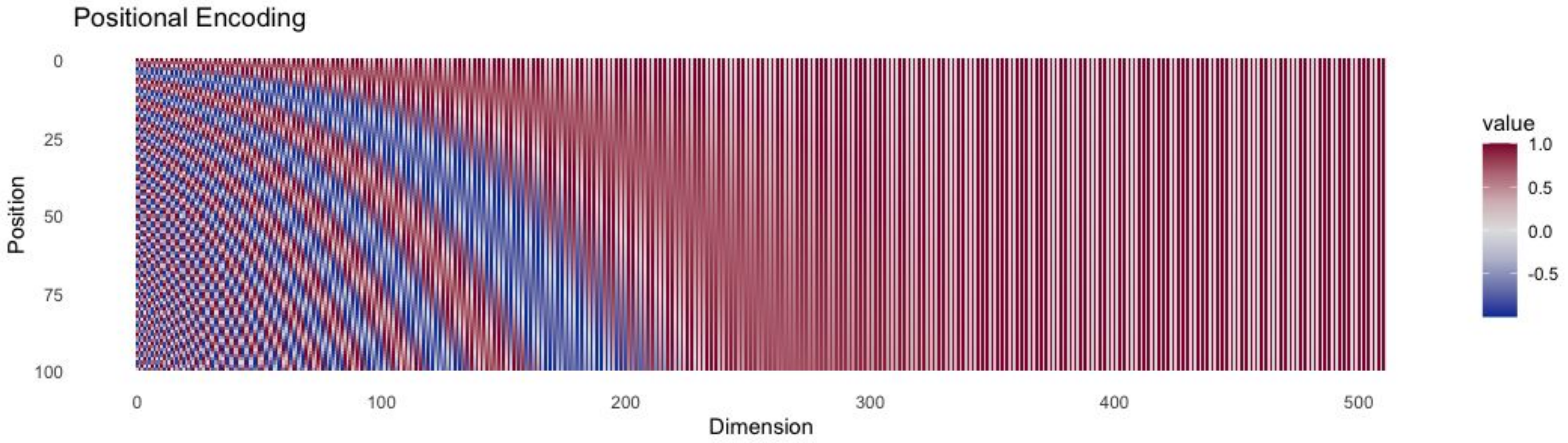
Positional Encoding



Positional Encoding



Positional Encoding



Positional Encodings

your python code is gorgeous

$$\begin{array}{ccccc} \begin{bmatrix}0.1\\0\\0.2\\0.1\\0.6\\0.2\end{bmatrix} & \begin{bmatrix}0.2\\0.4\\0.5\\0.9\\0.3\\0.1\end{bmatrix} & \begin{bmatrix}0.2\\0.4\\0.6\\1\\0.2\\0.1\end{bmatrix} & \begin{bmatrix}0.1\\0.3\\0.1\\0\\0\\0.7\end{bmatrix} & \begin{bmatrix}0.1\\0.2\\0.4\\0.2\\0.6\\0.1\end{bmatrix} \\ \text{your} & \text{python} & \text{code} & \text{is} & \text{gorgeous}\end{array} \longrightarrow \begin{array}{ccc} \begin{bmatrix}0.1\\0\\0.2\\0.1\\0.6\\0.2\end{bmatrix} & + & \begin{bmatrix} sin(0/10000^{\frac{2*1}{6}})\\ cos(0/10000^{\frac{2*1}{6}})\\ sin(0/10000^{\frac{2*2}{6}})\\ cos(0/10000^{\frac{2*2}{6}})\\ sin(0/10000^{\frac{2*3}{6}})\\ cos(0/10000^{\frac{2*3}{6}}) \end{bmatrix} \\ \text{your} & & \textit{position}\end{array}$$

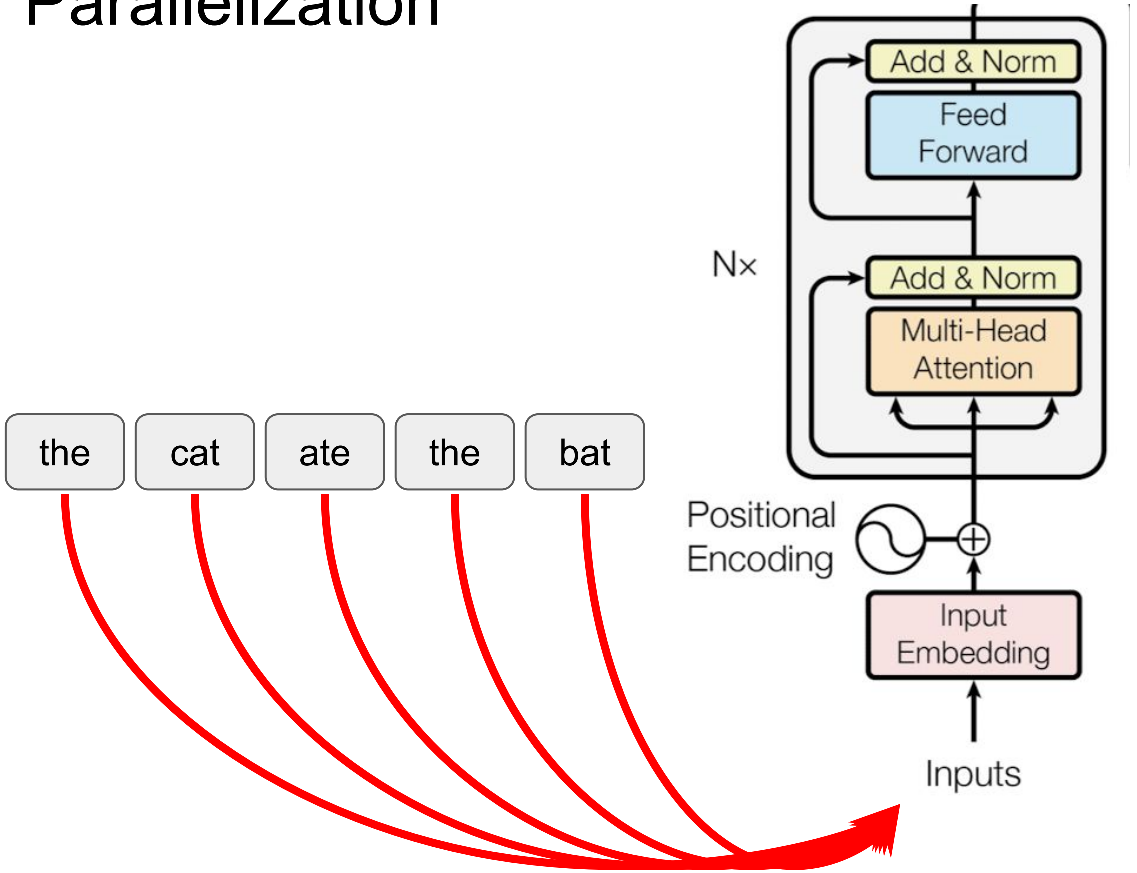
Positional Encodings

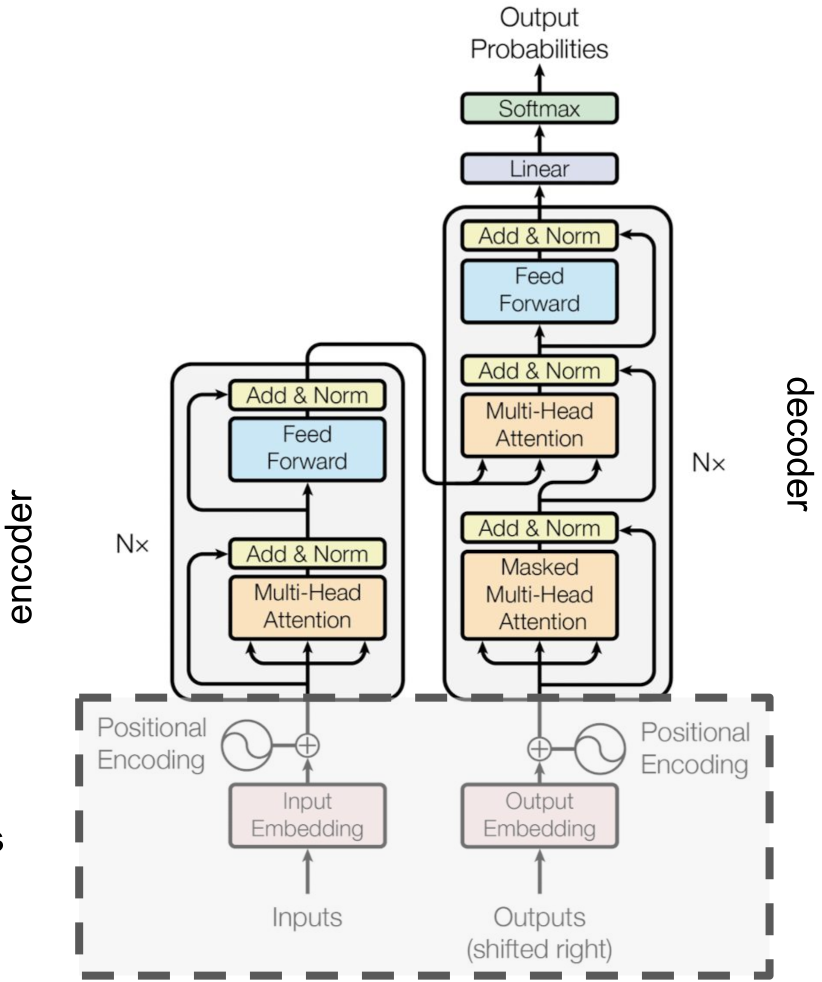
your python code is gorgeous

$$\begin{array}{ccccc} \begin{bmatrix} 0.1 \\ 0 \\ 0.2 \\ 0.1 \\ 0.6 \\ 0.2 \end{bmatrix} & \begin{bmatrix} 0.2 \\ 0.4 \\ 0.5 \\ 0.9 \\ 0.3 \\ 0.1 \end{bmatrix} & \begin{bmatrix} 0.2 \\ 0.4 \\ 0.6 \\ 1 \\ 0.2 \\ 0.1 \end{bmatrix} & \begin{bmatrix} 0.1 \\ 0.3 \\ 0.1 \\ 0 \\ 0 \\ 0.7 \end{bmatrix} & \begin{bmatrix} 0.1 \\ 0.2 \\ 0.4 \\ 0.2 \\ 0.6 \\ 0.1 \end{bmatrix} \\ \text{your} & \text{python} & \text{code} & \text{is} & \text{gorgeous} \end{array}$$

$$\begin{array}{ccc} \begin{bmatrix} 0.2 \\ 0.4 \\ 0.5 \\ 0.9 \\ 0.3 \\ 0.1 \end{bmatrix} & + & \begin{bmatrix} sin(1/10000^{\frac{2*1}{6}}) \\ cos(1/10000^{\frac{2*1}{6}}) \\ sin(1/10000^{\frac{2*2}{6}}) \\ cos(1/10000^{\frac{2*2}{6}}) \\ sin(1/10000^{\frac{2*3}{6}}) \\ cos(1/10000^{\frac{2*3}{6}}) \end{bmatrix} \\ \text{python} & & \textit{position} \end{array}$$

Parallelization





Today's Focus

Figure 1: The Transformer - model architecture.

Image from: Attention is all you Need (Vaswani et. al 2017)

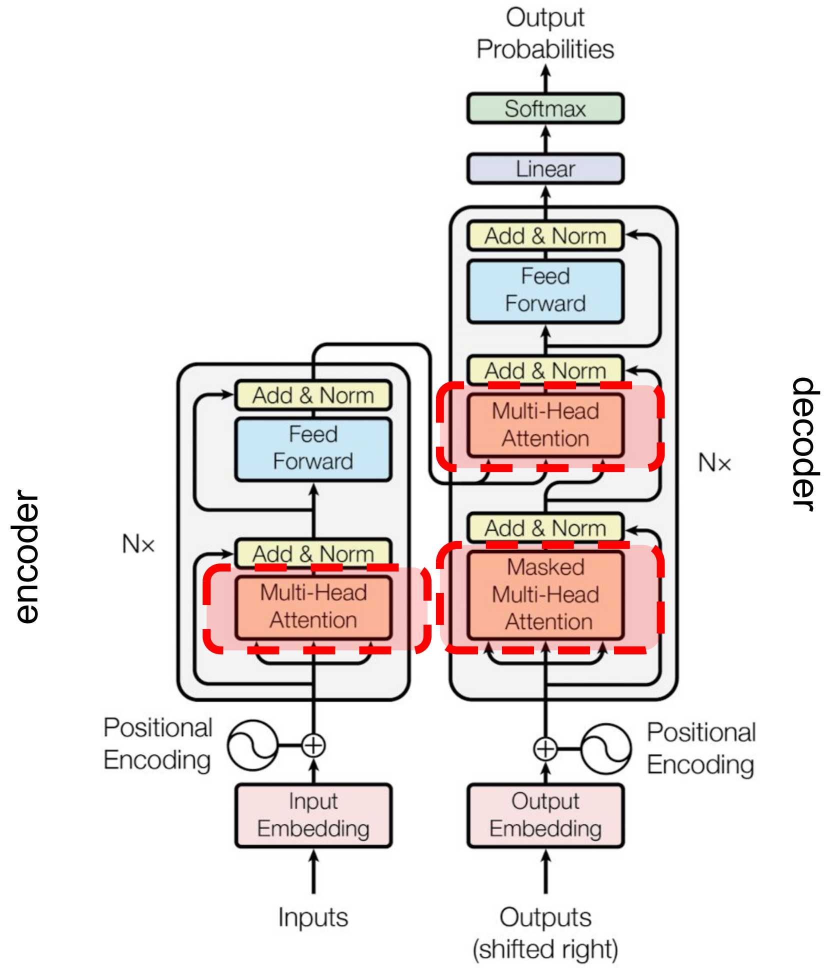


Figure 1: The Transformer - model architecture.

Image from: Attention is all you Need (Vaswani et. al 2017)