CS 839: Foundation Models
Transformers and Attention

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Sept. 11, 2025

Announcements

- **Announcements:** Recordings available on Canvas (under Kaltura tab)
- Class roadmap:

Thursday Sept. 11	**Architectures I: Transformers & Attention**
Tuesday Sept. 16	Architectures II: Subquadratic Architectures
Thursday Sept. 18	Language Models I
Tuesday Sept. 23	Language Models II
Thursday Sept. 25	Prompting

Mostly Language Models

Outline

- **Basic Attention**
  - Notions of attention, self-attention, basic attention layer, QKV setup and intuition
- **Additional Elements**
  - Multi-head attention, positional encodings
- **Transformers**
  - Architecture, encoder and decoder setups

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History of Attention

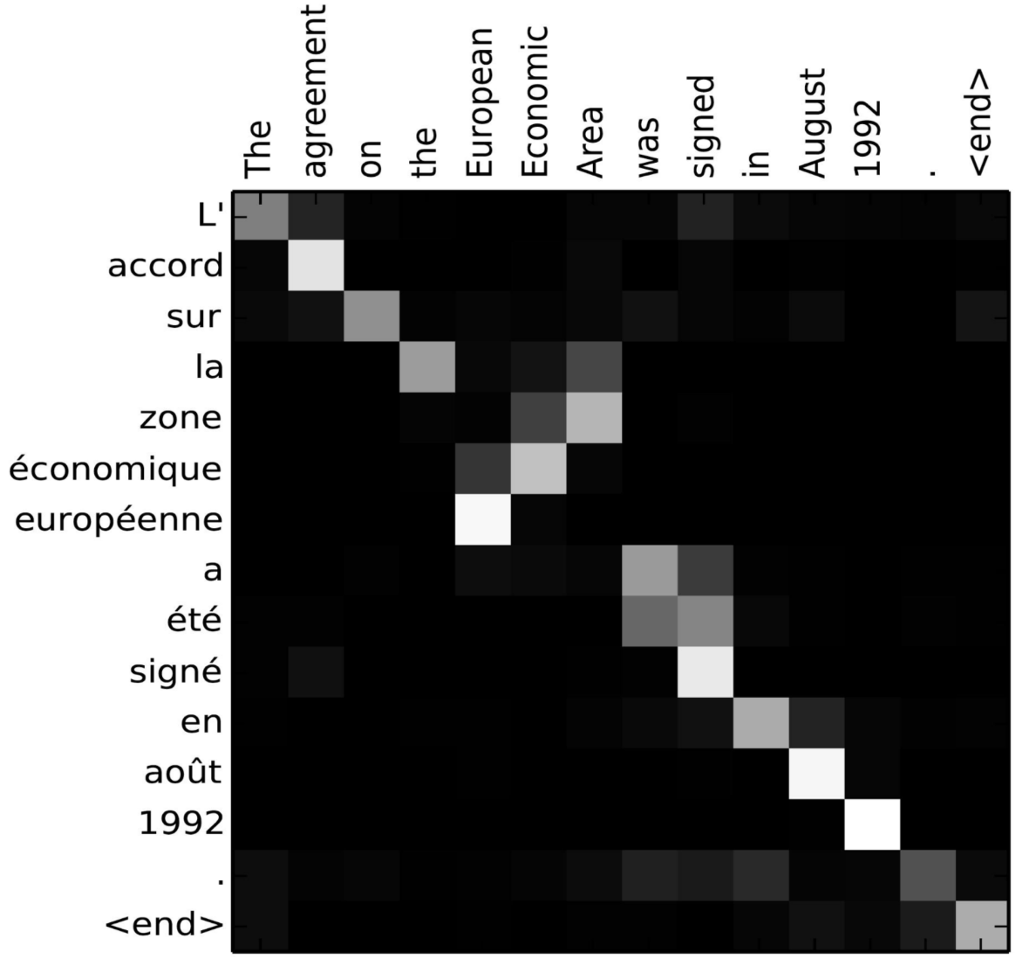
Basic motivation: in NLP *fixed* context vector **not** enough

- Why?
  - Words depend on each other
  - Dependencies are complex

- Need: mechanism to help model **focus** on the right "part"

Lots of approaches from 2014 on

- Bahdanau et al, 2014

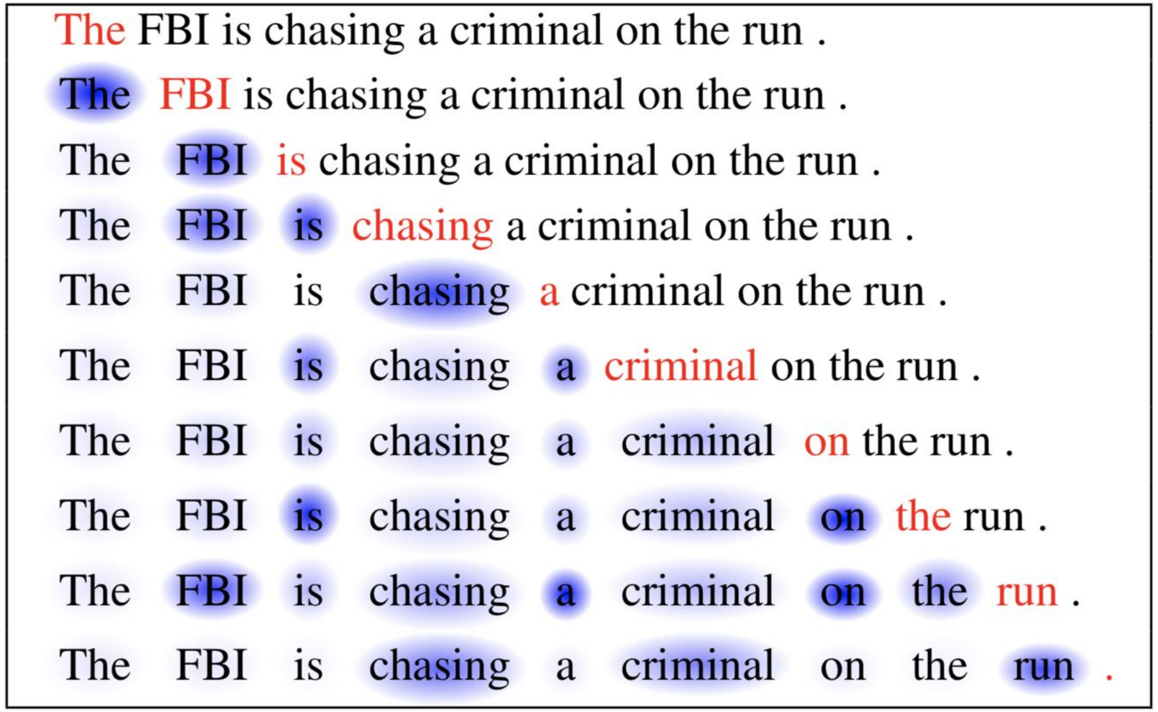


Bahdanau et al, 2014

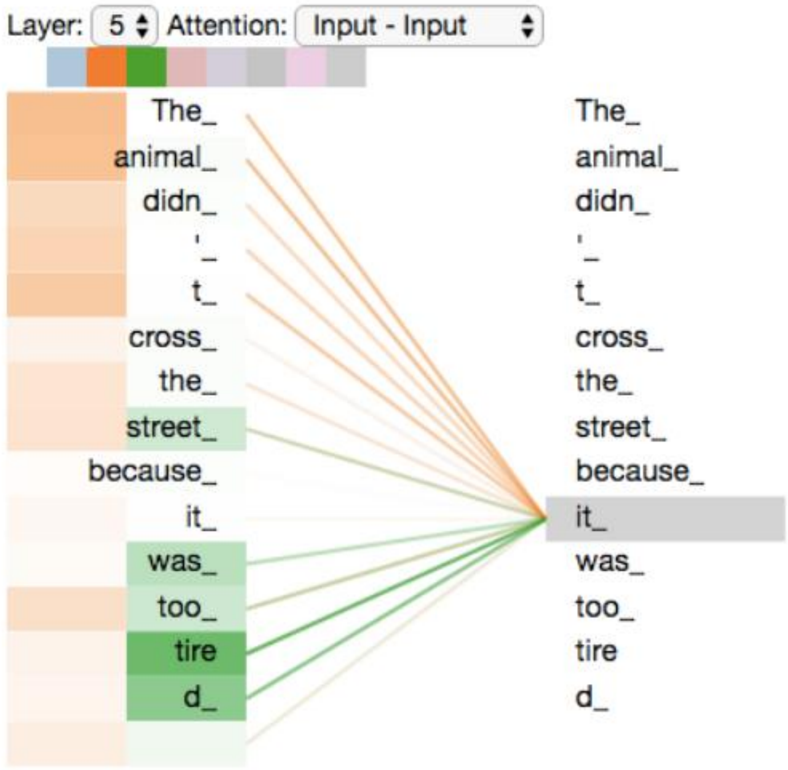
Self-Attention: Motivation

Popularized from 2017 on…

- From bottom-up. Let’s design a basic layer.
  - Intuition: dependencies **within** same sentence



Cheng et al, 2016



Jay Alammar

Self-Attention: Goals and Inputs

From bottom-up. Let’s design a basic layer.

- Two criteria
  - *Transform* incoming word vectors,
  - Enable *interactions* between words

- Input: vectors for words

Note: All visualizations are due to Jay Alammar

Excellent resource: https://jalammar.github.io/illustrated-transformer/

Self-Attention: Retrieval Intuition

- How should we design the interactions?
  - Analogy: **search**

“Which restaurants near me are open at 9:00 pm?”

Query

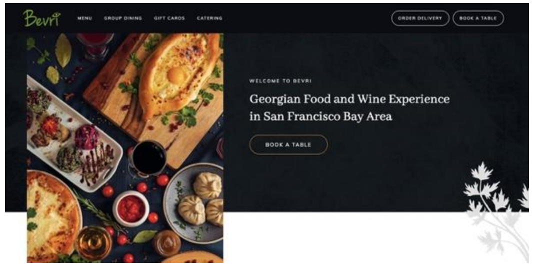
Key

Value

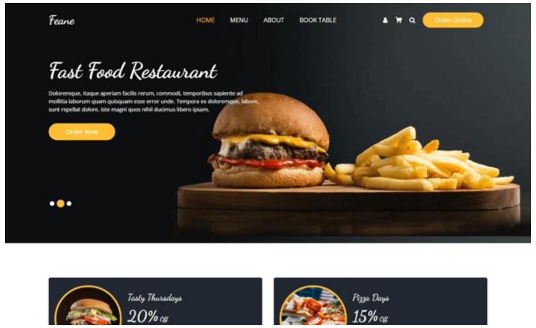
Objects:

Query
Key
Value

Score 0.3



Score 0.7



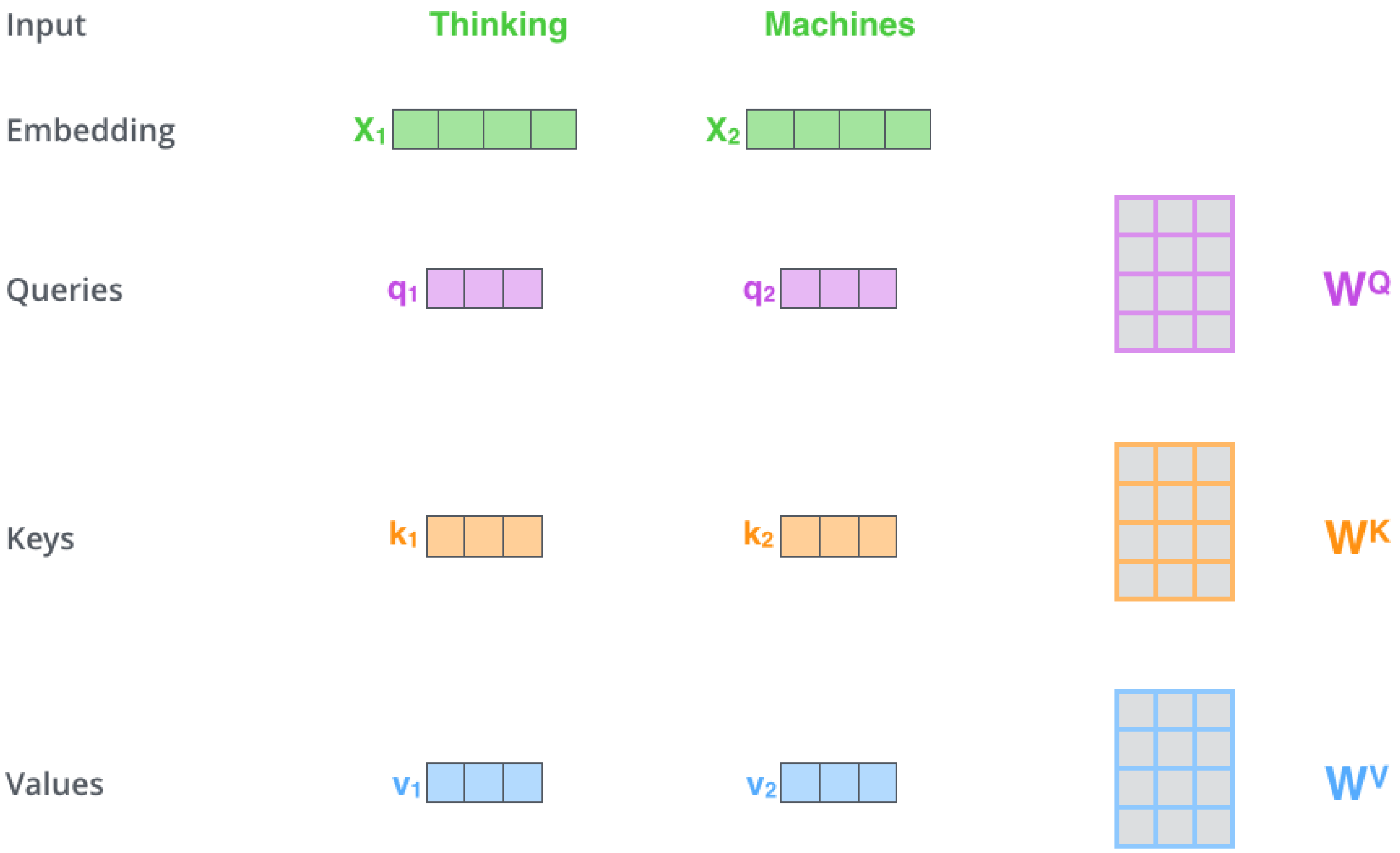
Self-Attention: Query, Key, Value Vectors

- *Transform* incoming word vectors,
- Enable *interactions* between words

- Get our **query,** **key,** **value** vectors via weight matrices: linear transformations!

Objects:

Query
Key
Value



Self-Attention: Score Functions

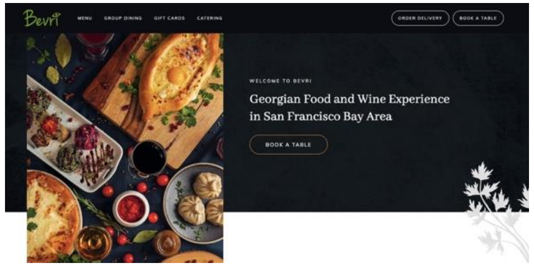
Have **query, key, value** vectors

- Next, get our **score**

q_1 k_2

Query Key

Score 0.3



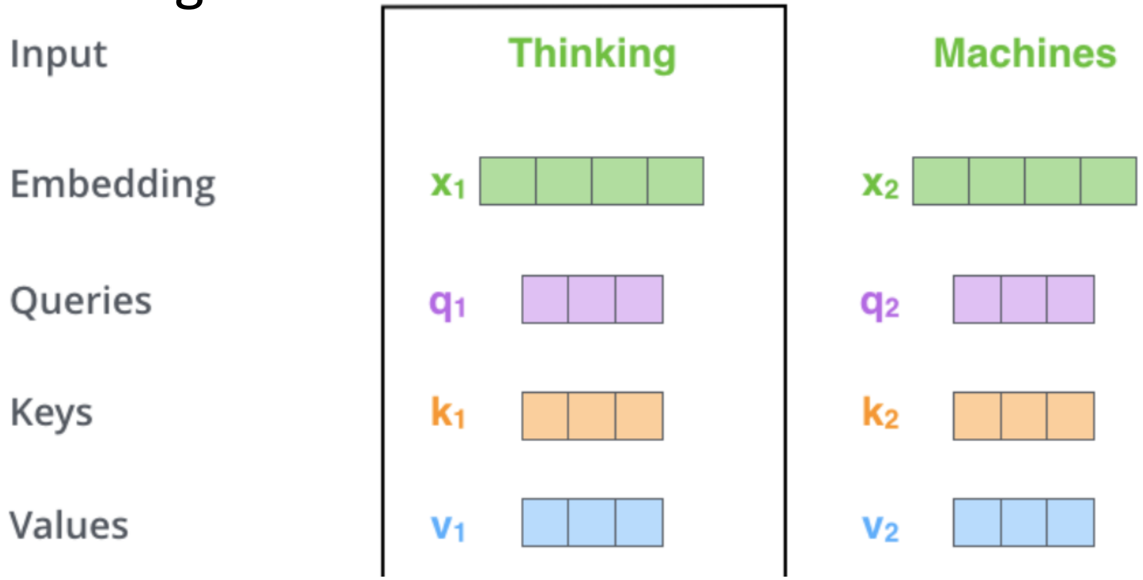
- Lots of things we could do --- **simpler** is usually better!
- Dot product $q_1 \cdot k_2 = 96$

- Then we'll do **softmax**

Self-Attention: Scoring and Scaling

- *Transform* incoming word vectors,
- Enable *interactions* between words

- Get our **query, key, value** vectors via weight matrices: linear transformations!
- Compute scores

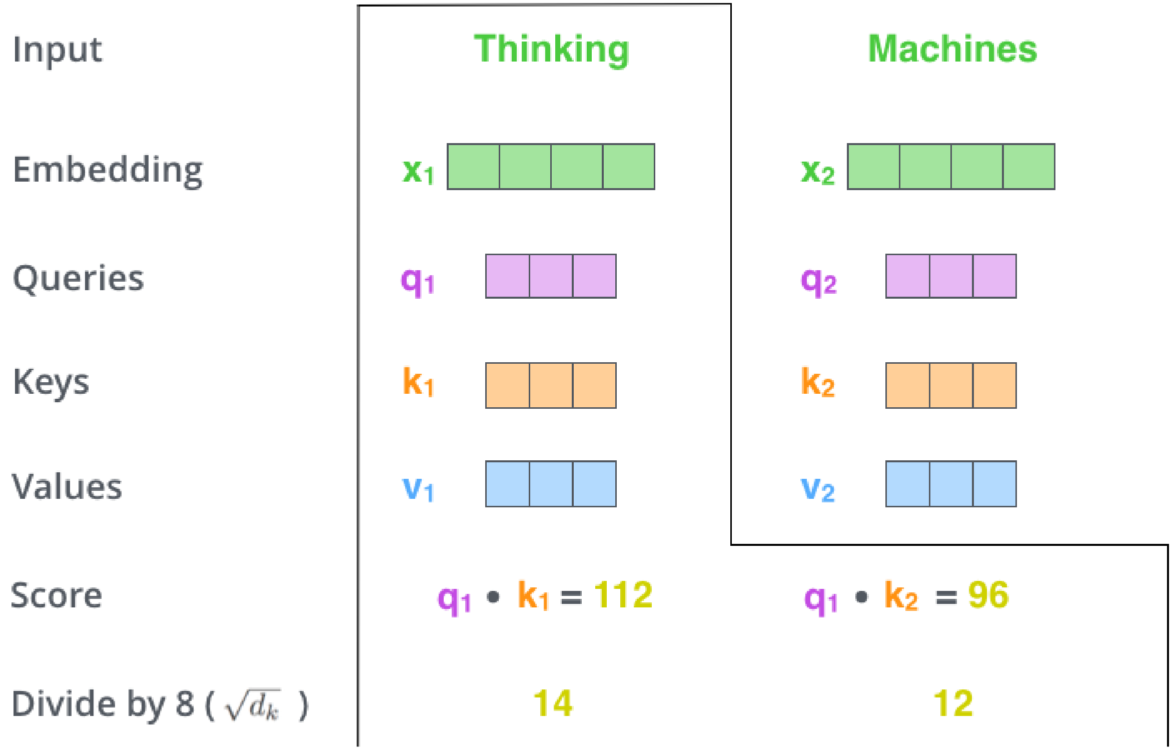


Objects:

Query
Key
Value

Self-Attention: Putting it Together

- Have **query, key, value** vectors via weight matrices: linear transformations!
- Have softmax score outputs (**focus**)
- Add up the values!



Objects:

Query
Key
Value

Self-Attention: Matrix Formulas

- Have **query, key, value** vectors via weight matrices: linear transformations!
- Have softmax score outputs (**focus**)
- Add up the values!

Objects:

Query
Key
Value

$$Q = XW_Q, K = XW_K, V = XW_V$$

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

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

Break & Questions

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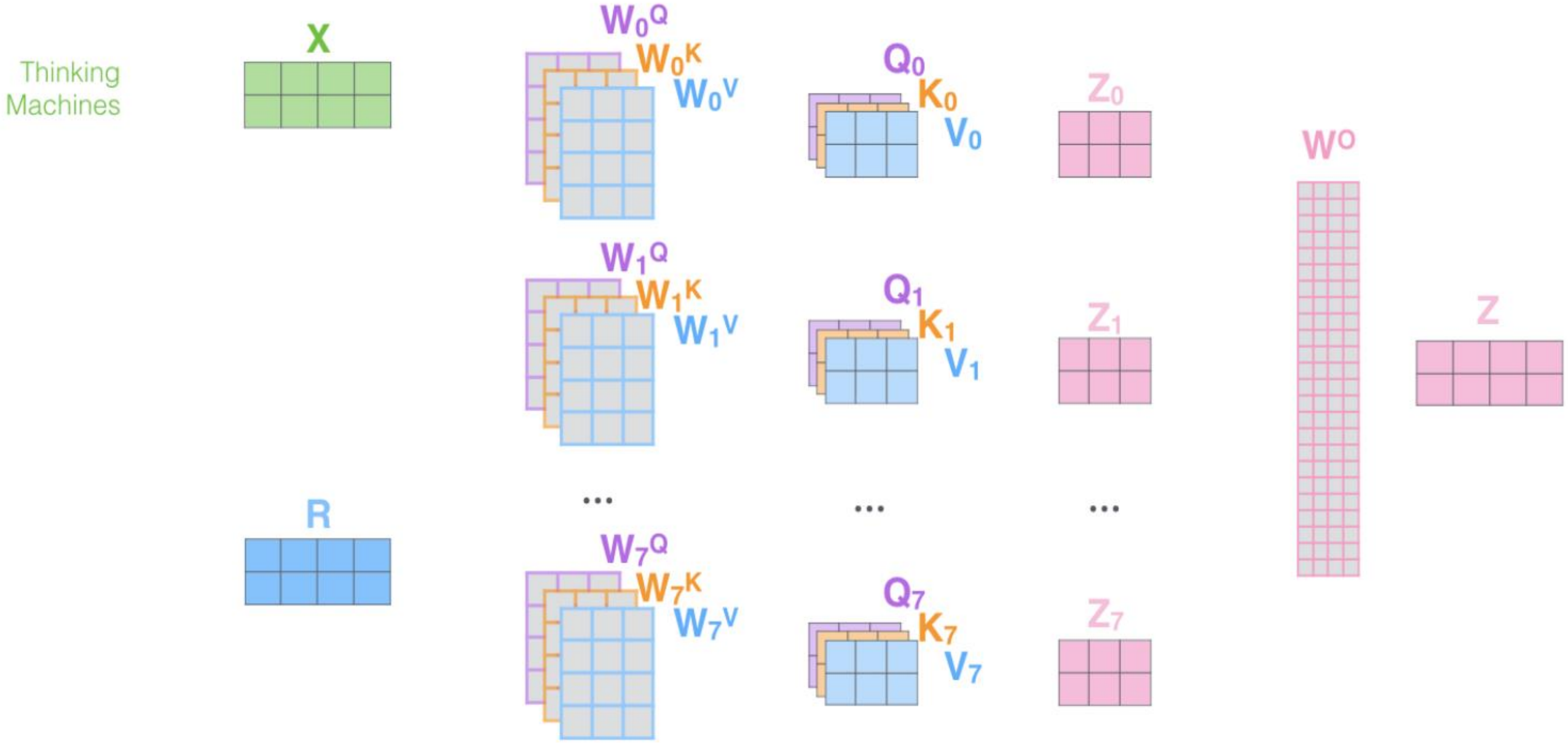
Self-Attention: Multi-head

This is great but will we capture everything in one?

- Do we use just 1 kernel in CNNs? **No!**
- Do it many times in parallel: **multi-headed attention.** Concatenate outputs



Self-Attention: Positional Encodings

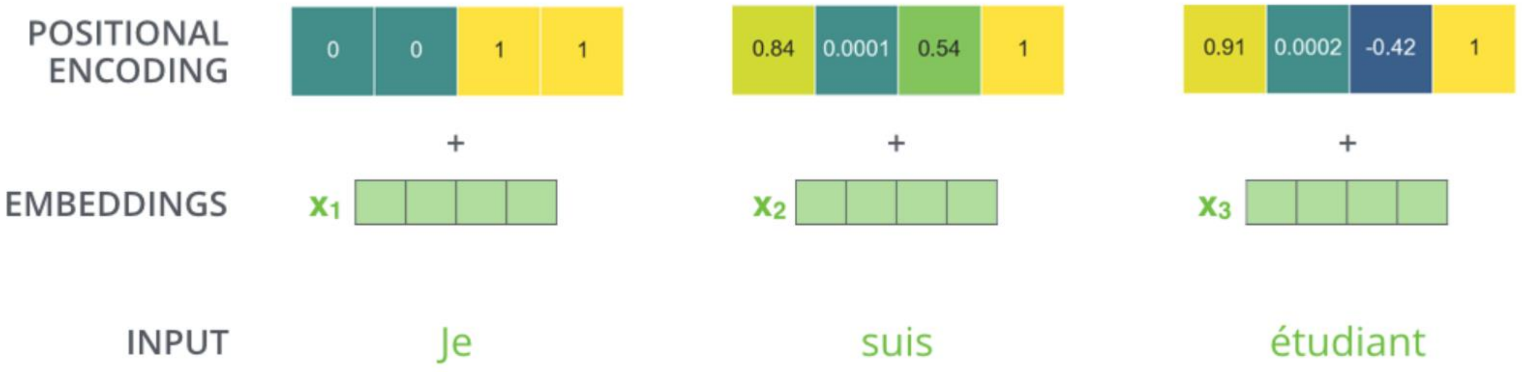
Almost have a full layer designed.

- One annoying issue: so far, order of words **(position) doesn't matter**!
- Solution: add positional encodings

$$PE_{(pos,2i)} = sin(pos/10000^{2i/d_{\text{model}}})$$

$$PE_{(pos,2i+1)} = cos(pos/10000^{2i/d_{\text{model}}})$$

Location index



Self-Attention: Positional Encodings

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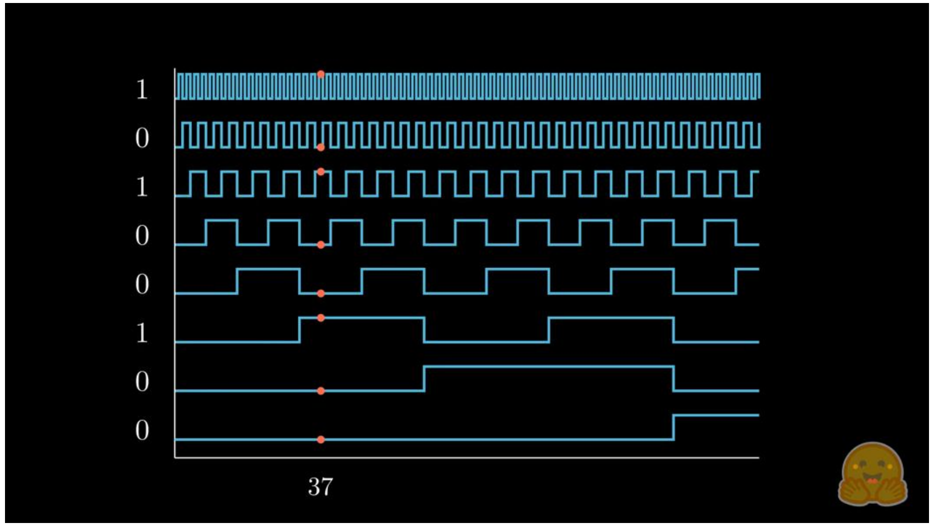
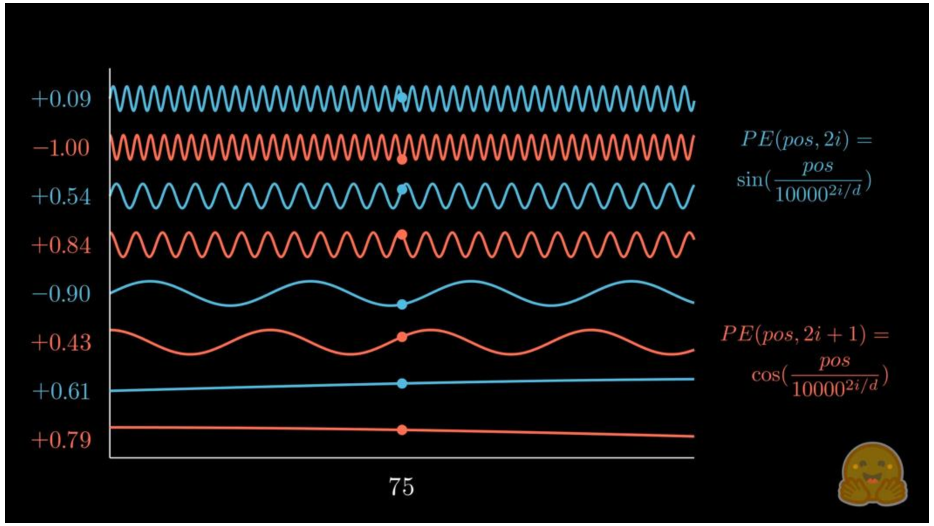


Why these **mysterious formulas**? Want properties:

- Consistent encoding
- Smooth
- Linearity across positions
  - Alternating sin and cos: can multiply by rotation matrix to obtain shifts



https://huggingface.co/blog/designing-positional-encoding

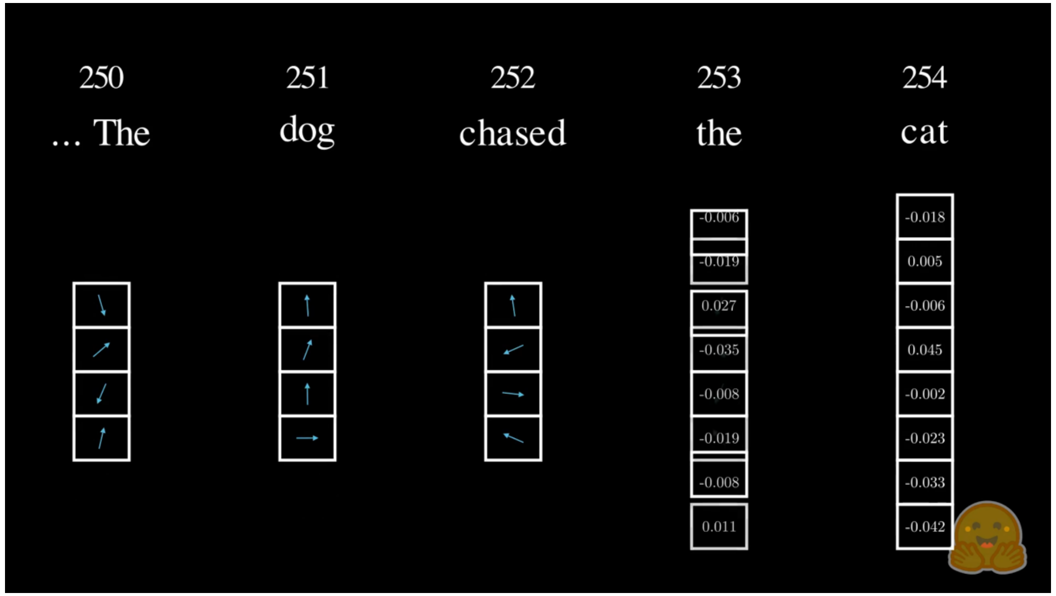
Self-Attention: Modern Positional Encodings

These ***sinusoidal*** embeddings were defined in the original Transformers paper,

- Added once (as we saw) prior to the first layer

Many new variants of positional encodings that behave slightly differently

- Example: ***multiplicative*** instead of ***additive***
- Popular: **Rotary Positional Encoding (RoPE)**
- Note: perform in every attention layer



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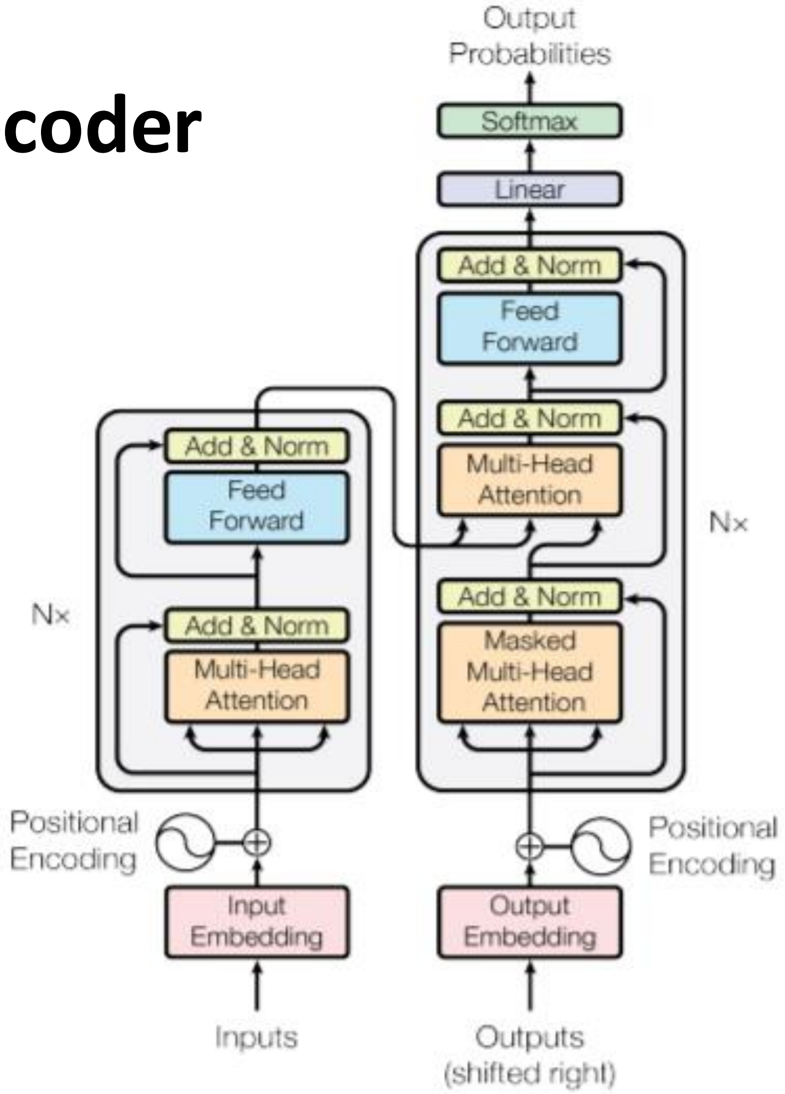
Transformers: Model Architecture

- Initial goal for an architecture: **encoder-decoder**
  - Get **rid of recurrence**
  - Replace with **self-attention**

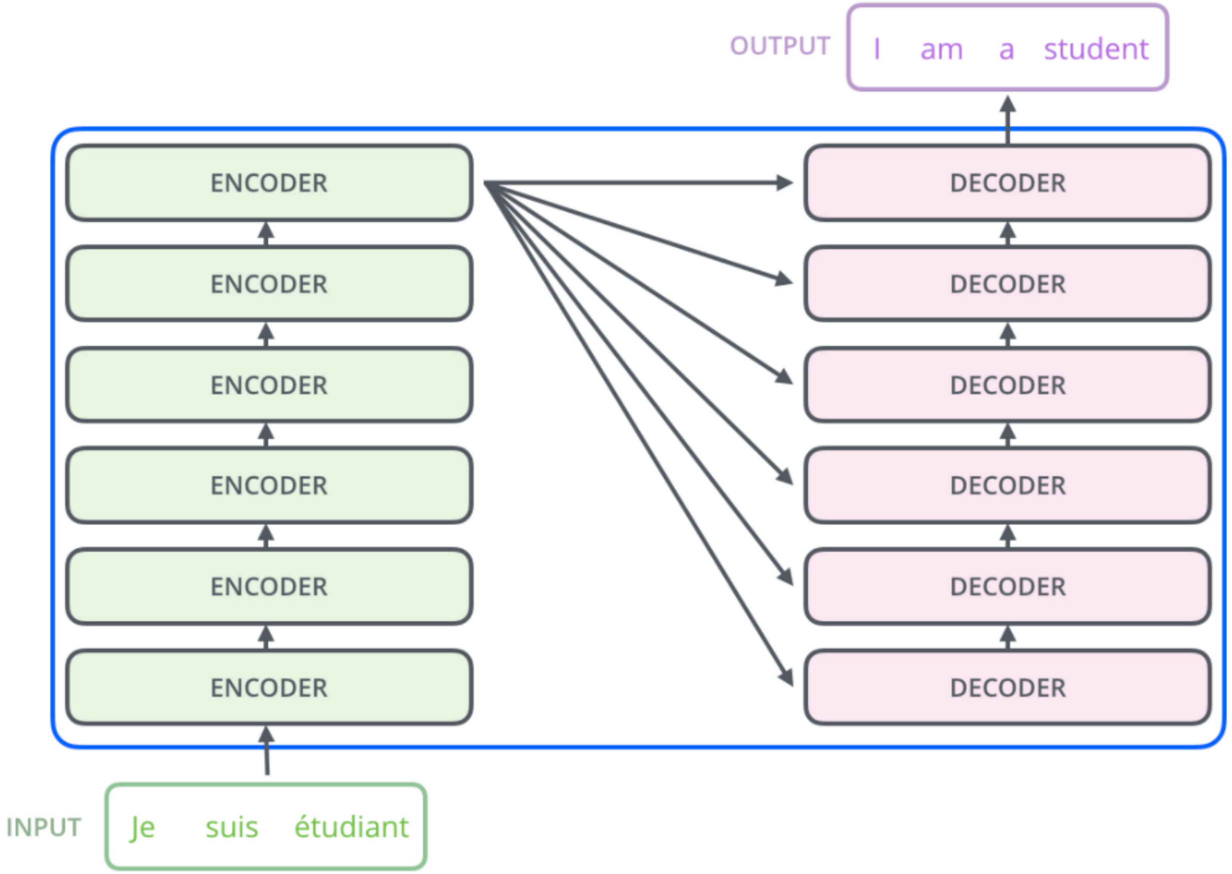
- Architecture
  - The famous picture you've seen
  - Centered on self-attention blocks



Vaswani et al. '17

Transformers: Architecture

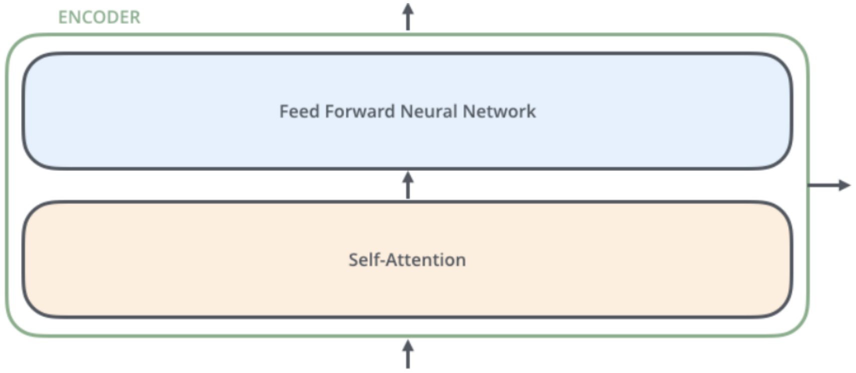
- **Sequence-sequence** model with **stacked** encoders/decoders:
  - For example, for French-English translation:

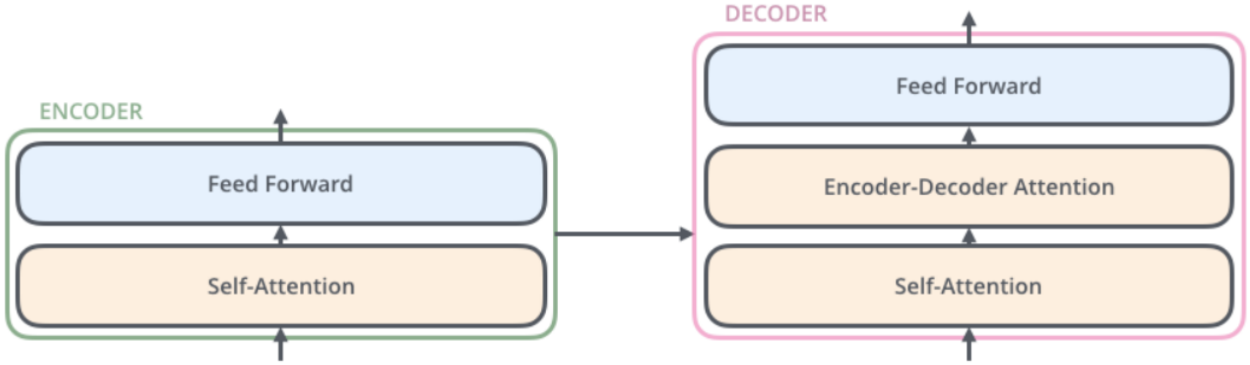


Transformers: Architecture

- Sequence-sequence model with **stacked** encoders/decoders:
  - What's inside each encoder/decoder unit?

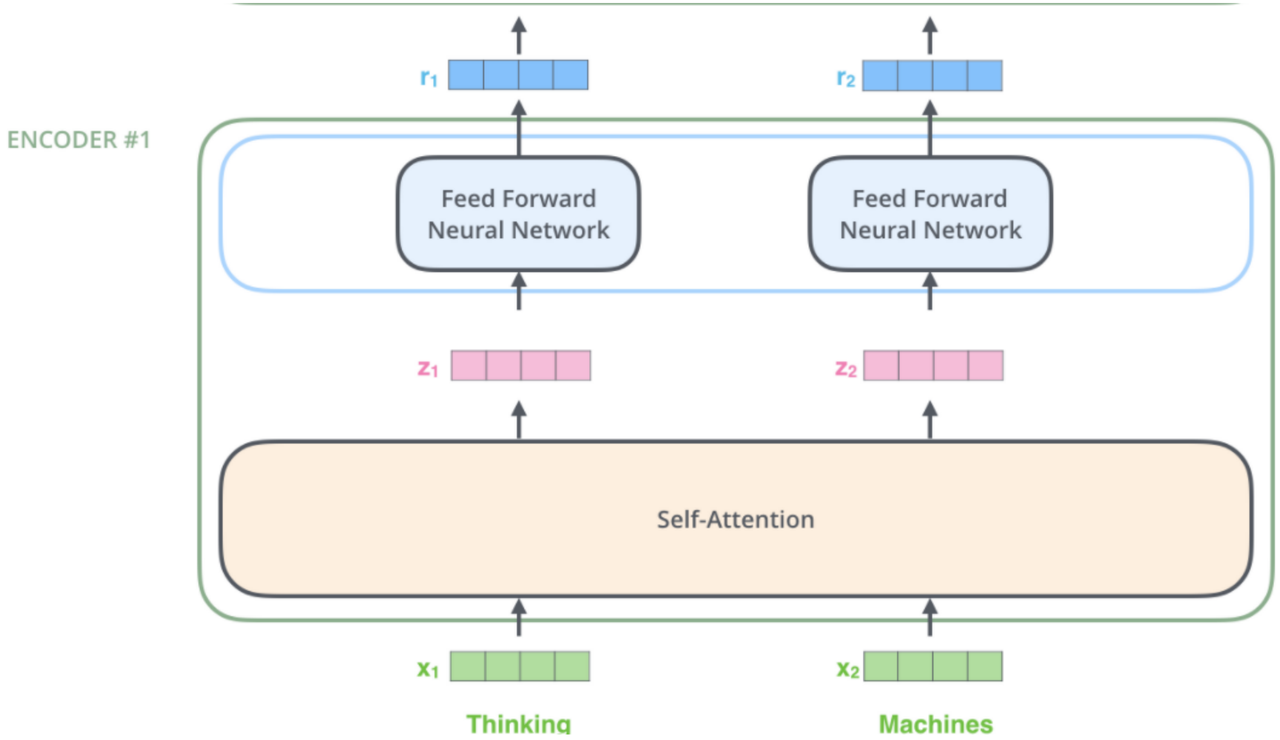
  - Focus encoder first: **pretty simple**! 2 components:
    - Self-attention block
    - Fully-connected layers (i.e., an MLP)





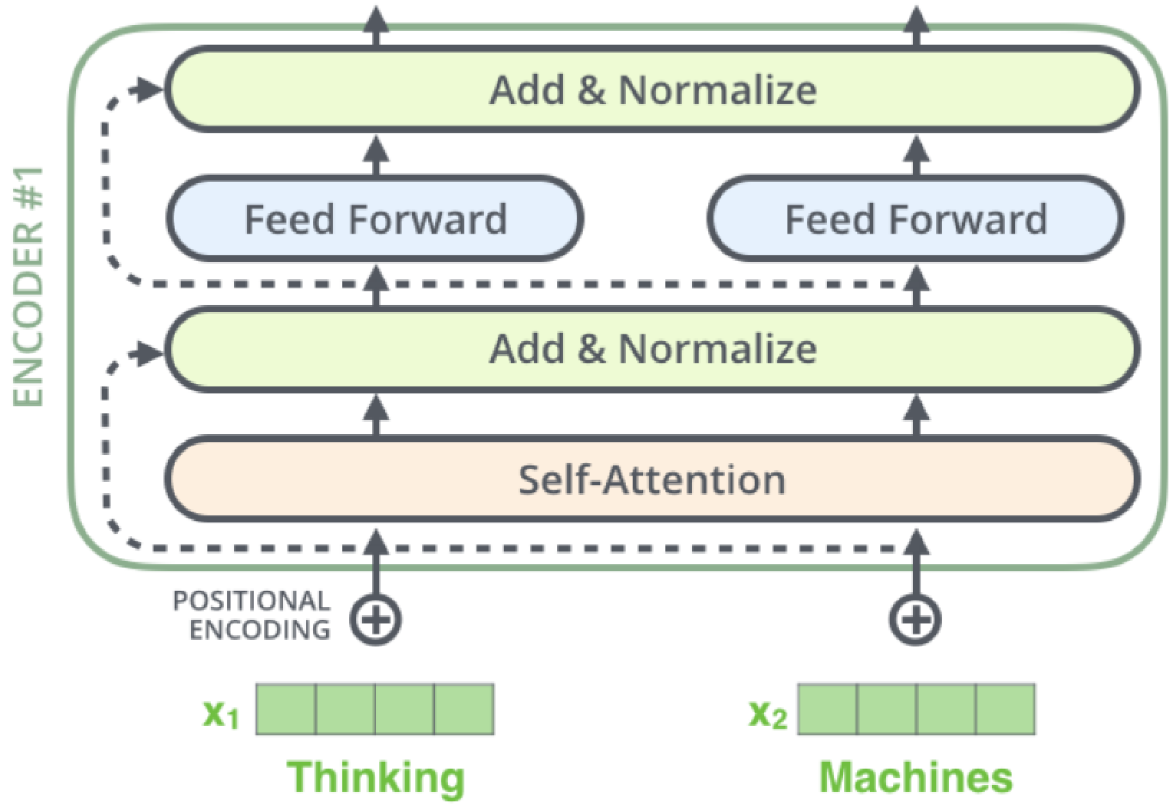
Transformers: Inside an Encoder

- Let's take a look at the encoder. Two components:
  - 1. **Self-attention** layer (covered this)
  - 2. "Independent" **feedforward nets** for each head



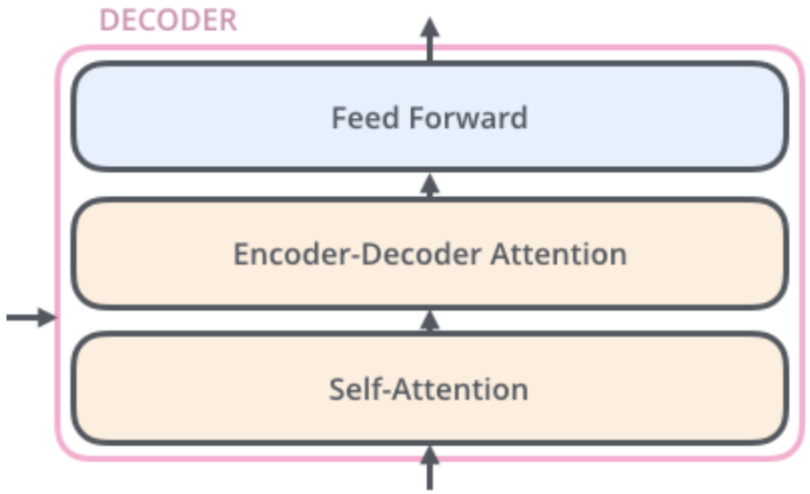
Transformers: More Tricks

- Recall a big innovation for ResNets: residual connections
  - And also layer normalizations
  - Apply to our encoder layers



Transformers: Inside a Decoder

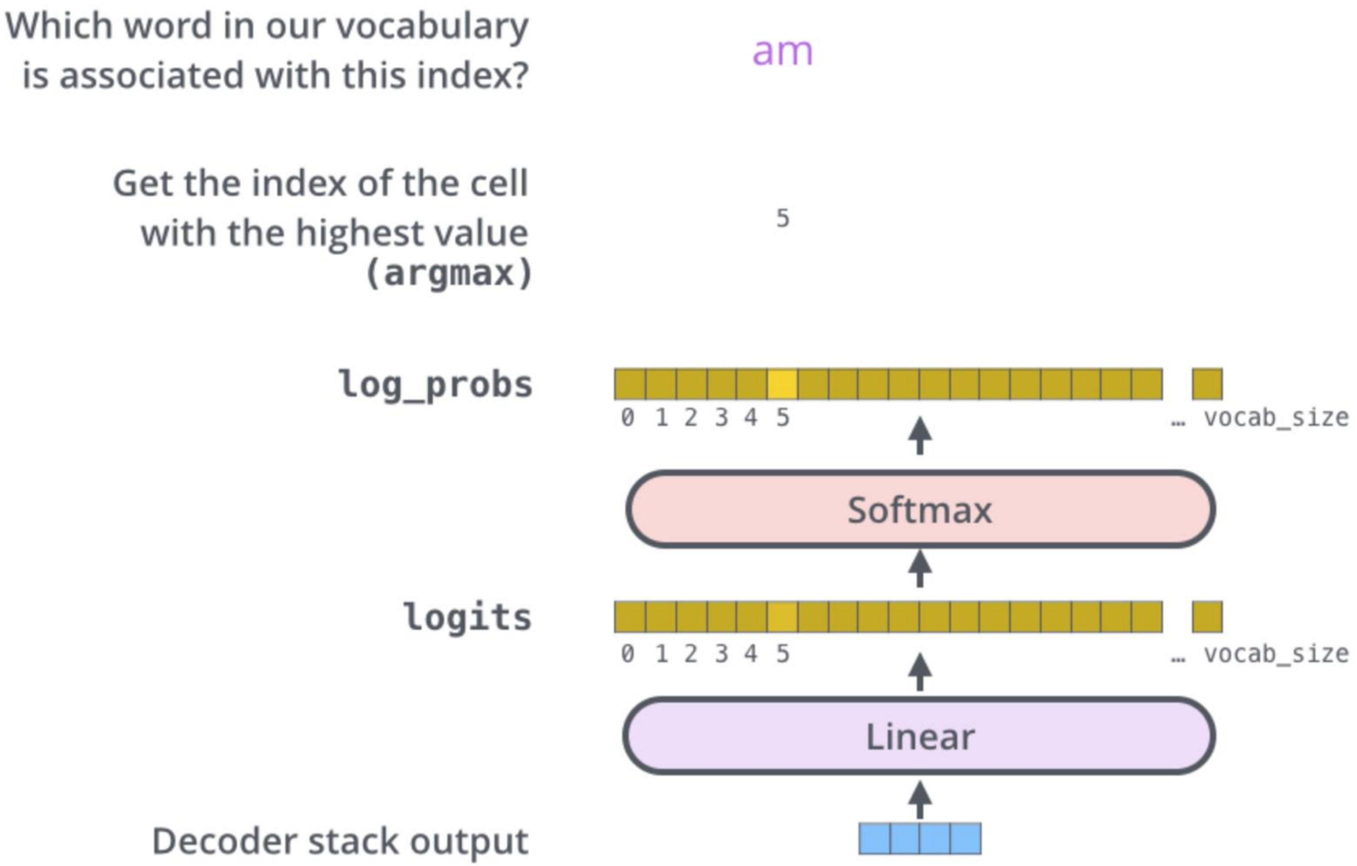
- Let's take a look at the decoder. Three components:
  - 1. **Self-attention** layer (covered this)
  - 2. Encoder-decoder attention (same, but K, V come from encoder)
  - 3. "Independent" **feedforward nets** for each head



Transformers: Last Layers

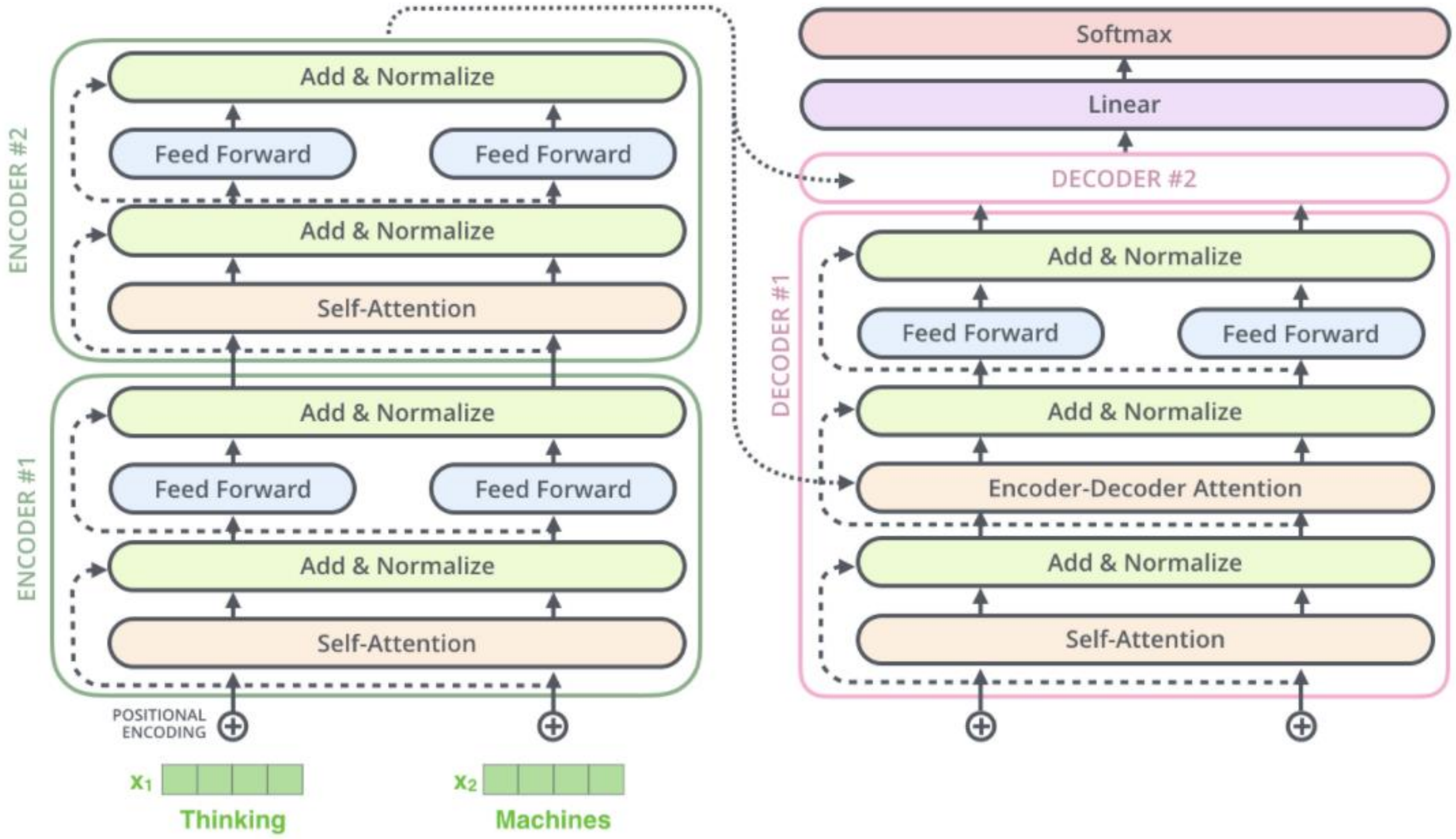
- Next let's look at the end. Similar to a CNN,
  - 1. Linear layer
  - 2. Softmax

Get probabilities of words



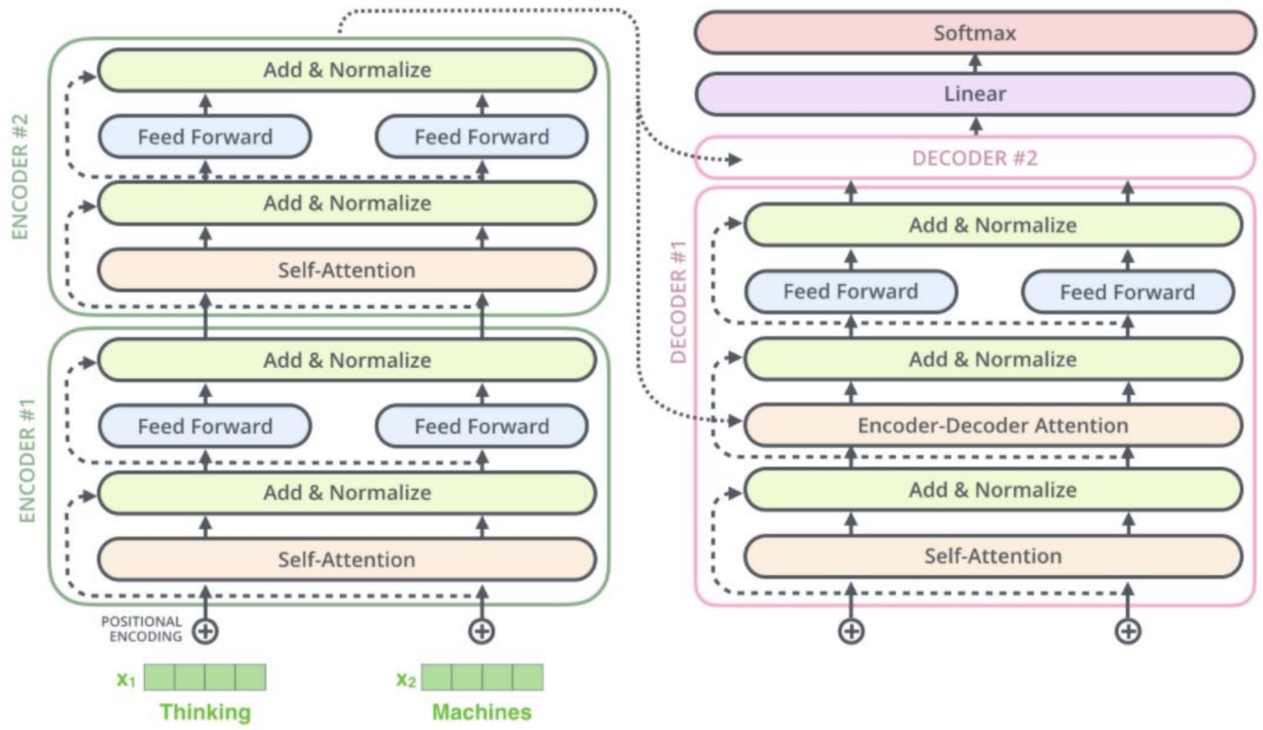
Transformers: Putting it All Together

- What does the full architecture look like?



Transformers: The Rest

- Next time: we'll talk about
  - How to **use** it (i.e., outputs)
  - How to **train** it
  - How to **rip** it apart and build other models with it.



Thank You!