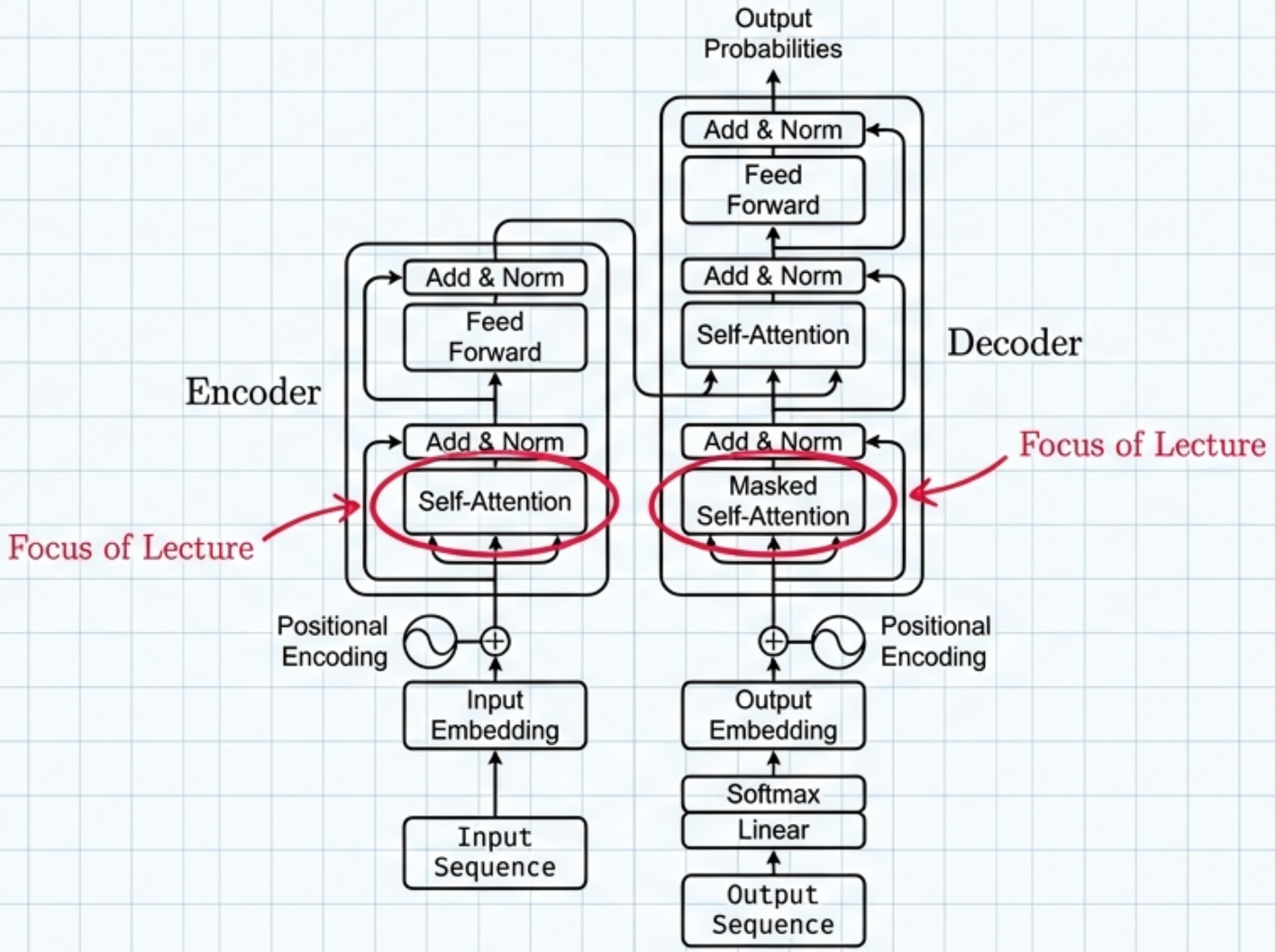
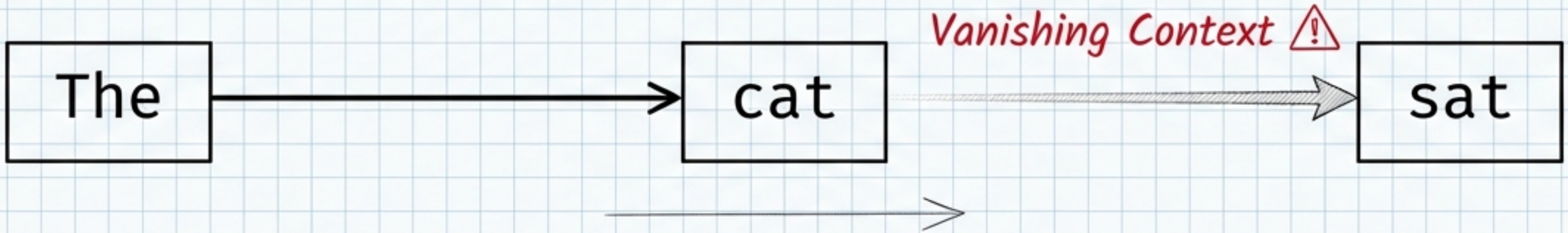
The Heart of the Transformer

Understanding the Self-Attention Mechanism

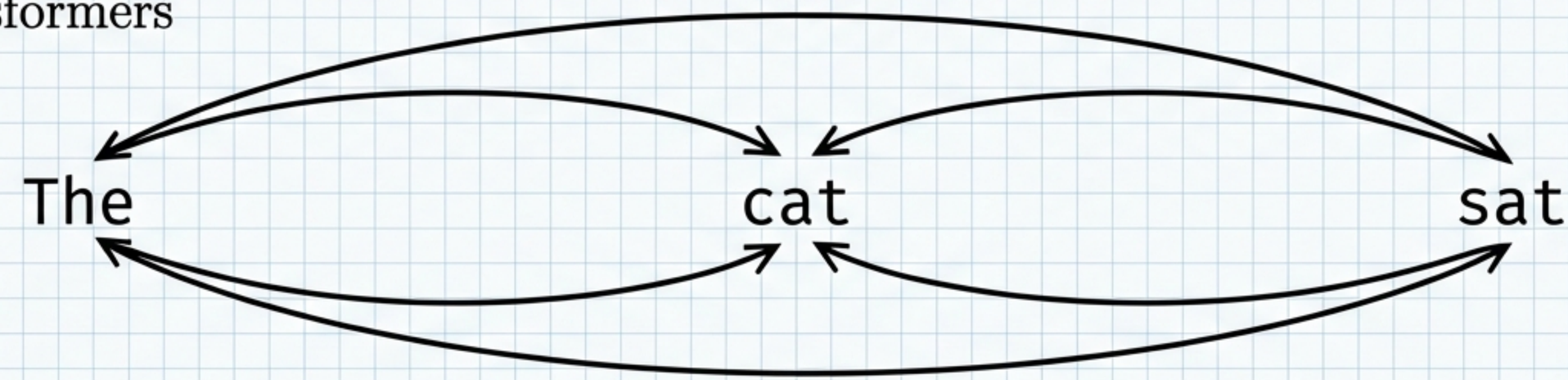


The Problem with Sequences

Recurrent Neural Networks (RNNs)

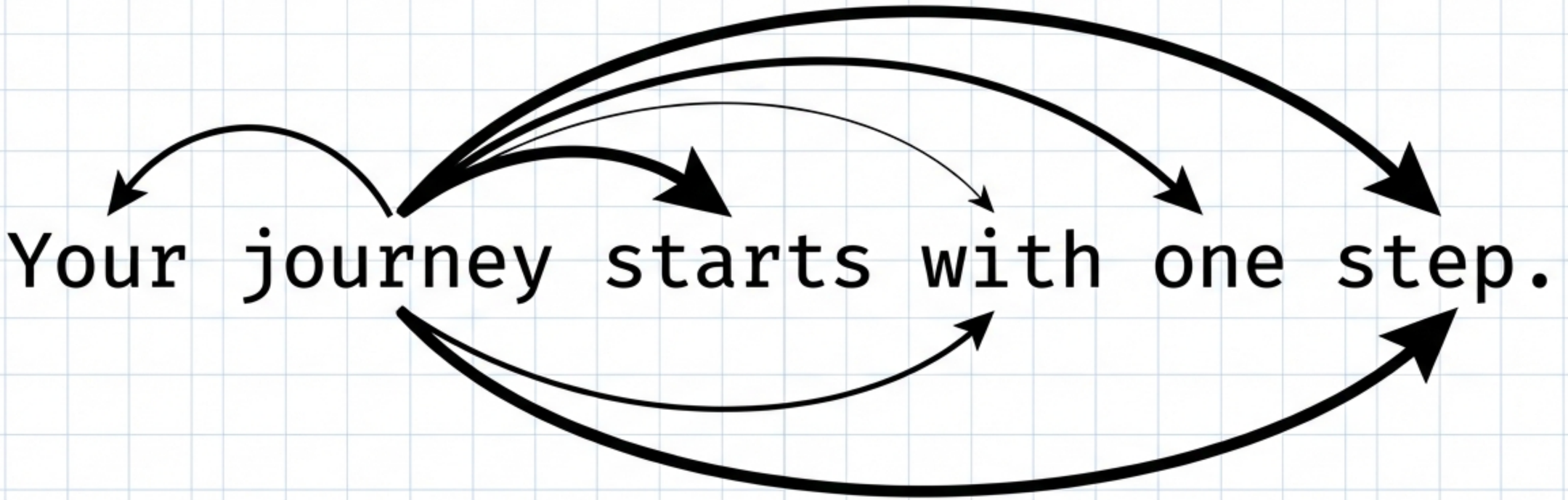


Transformers



Parallel Context: All tokens see all history instantly.

Defining Self-Attention

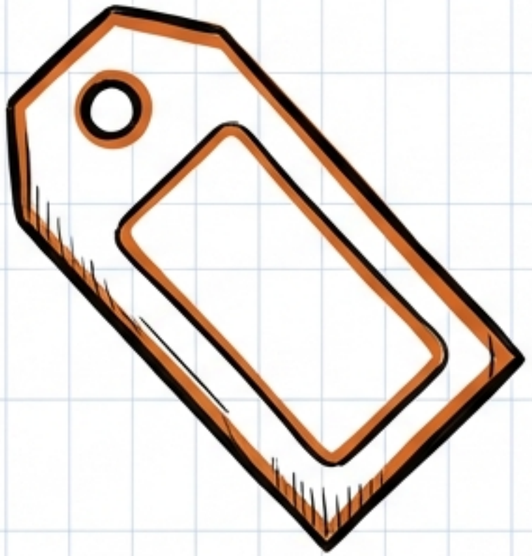


Self-Attention: Relating positions within a single sequence.

The Core Trinity: Q, K, V

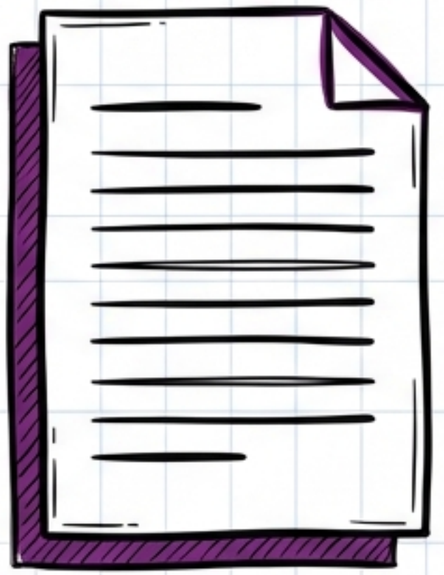
Query (Q)

What I am looking for.



Key (K)

What defines the content.



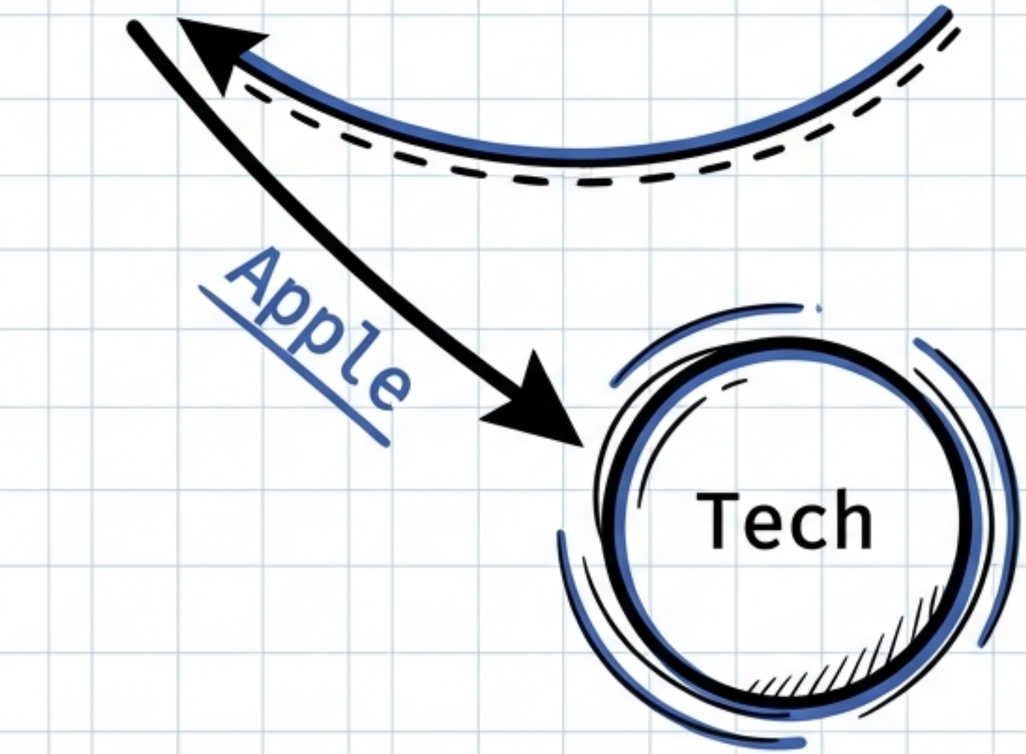
Value (V)

The actual content.

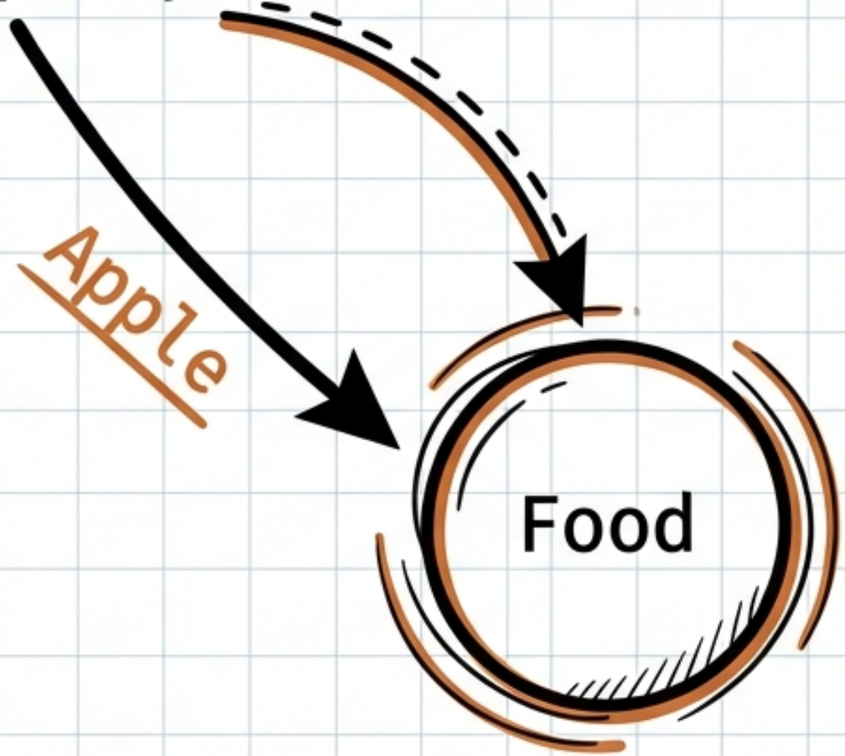
Database Analogy: Match the Query to the Key to retrieve the Value.

Intuition: Context Disambiguates Meaning

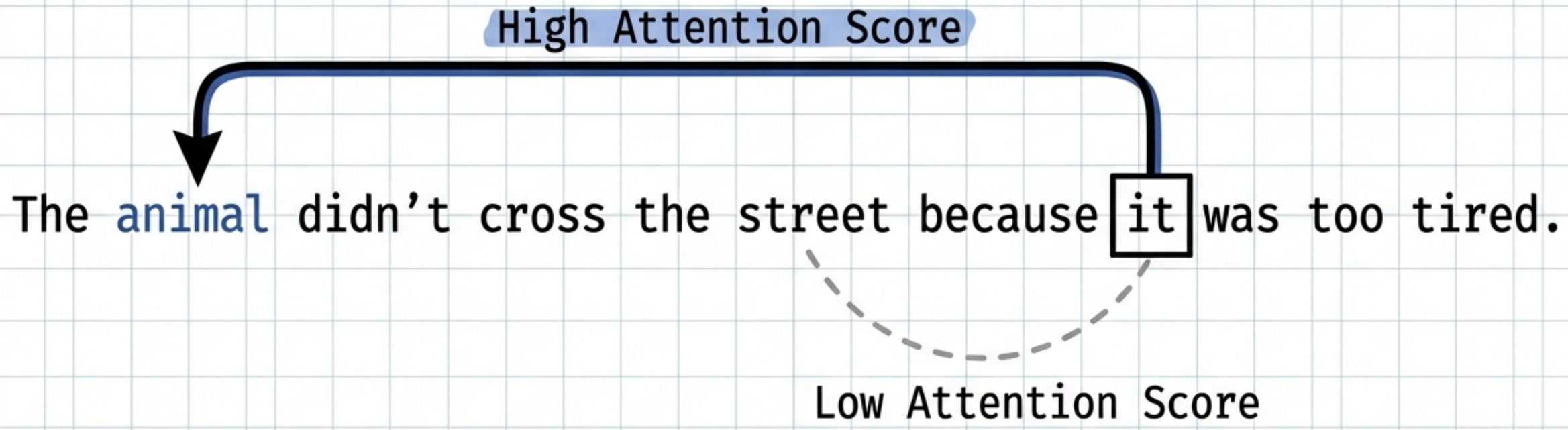
Apple unveiled a new phone.



Apple pie is delicious.

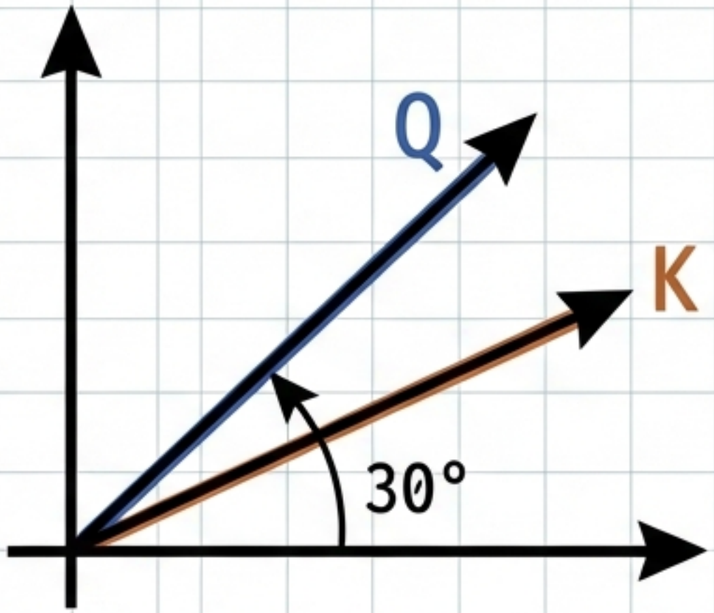


Intuition: Resolving Pronouns

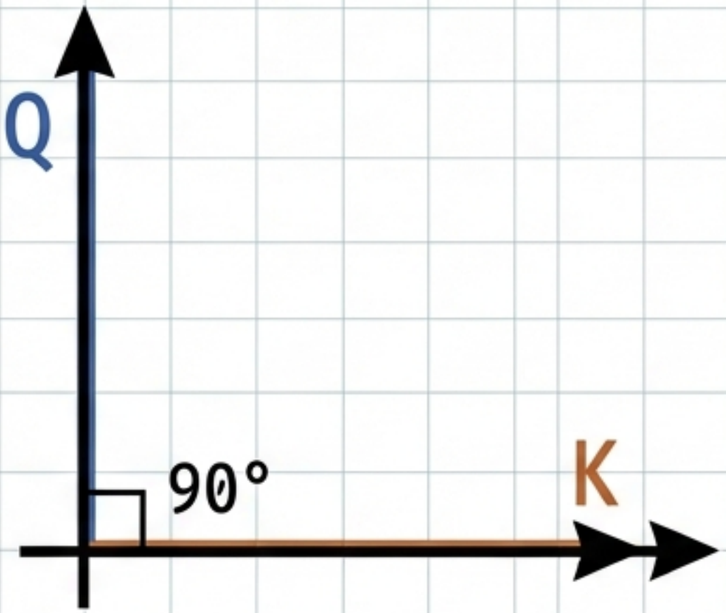


The model resolves “it” by attending to the entity capable of being “tired”.

The Math of Similarity: The Dot Product



High Dot Product = Similar



Zero Dot Product = Not Similar

$$\text{Similarity} = Q \cdot K \text{ (Transpose)}$$

Scaling the Dot Product

$$\text{Score} = \frac{\mathbf{Q} \cdot \mathbf{K}^T}{\sqrt{d_k}}$$

Normalization Factor

Prevents extremely large values that would cause exploding gradients during training.

Normalization: The Softmax Function

Raw Scores

$$\begin{bmatrix} 2.0 \\ 1.0 \\ 0.1 \end{bmatrix}$$

$$\frac{e^x}{\sum(e^x)}$$

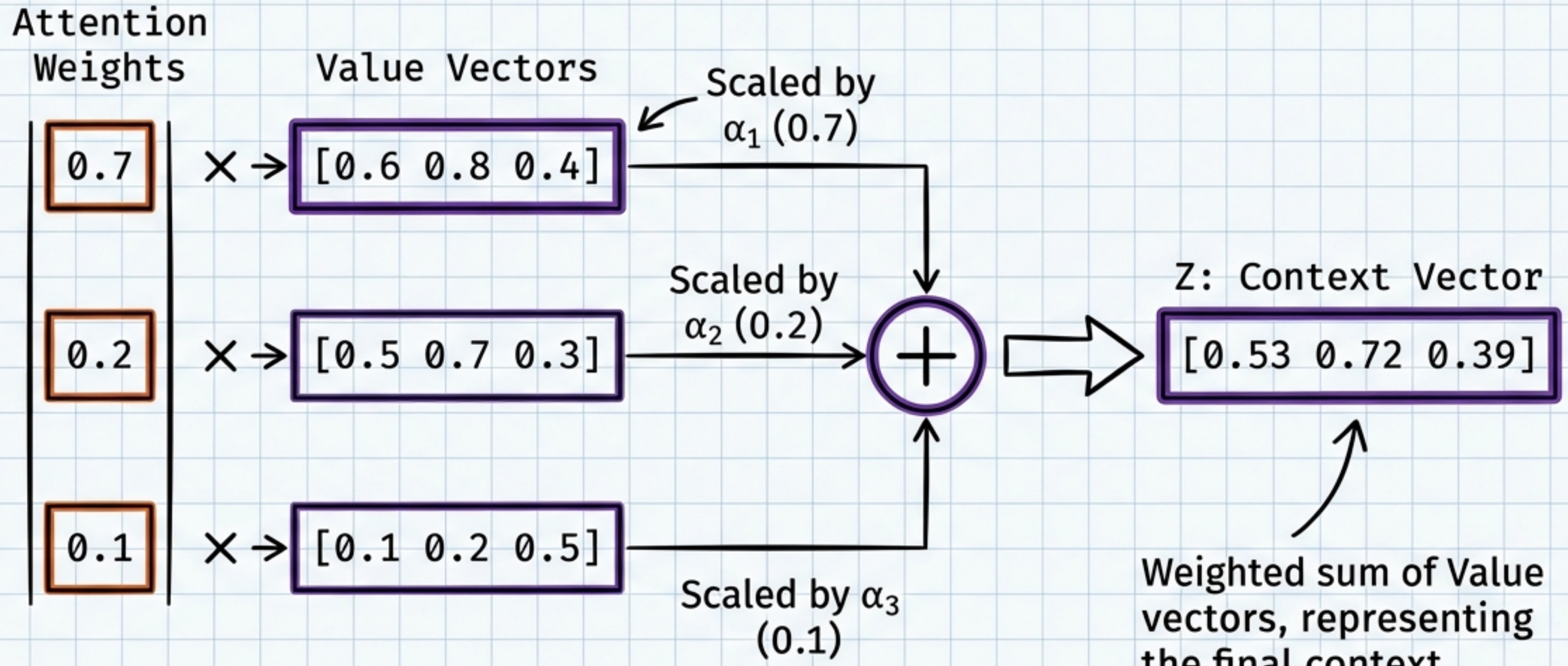
Softmax

Probabilities

$$\begin{bmatrix} 0.7 \\ 0.2 \\ 0.1 \end{bmatrix}$$

Values are positive and sum to 1.0

Computing the Context Vector



The Matrix View

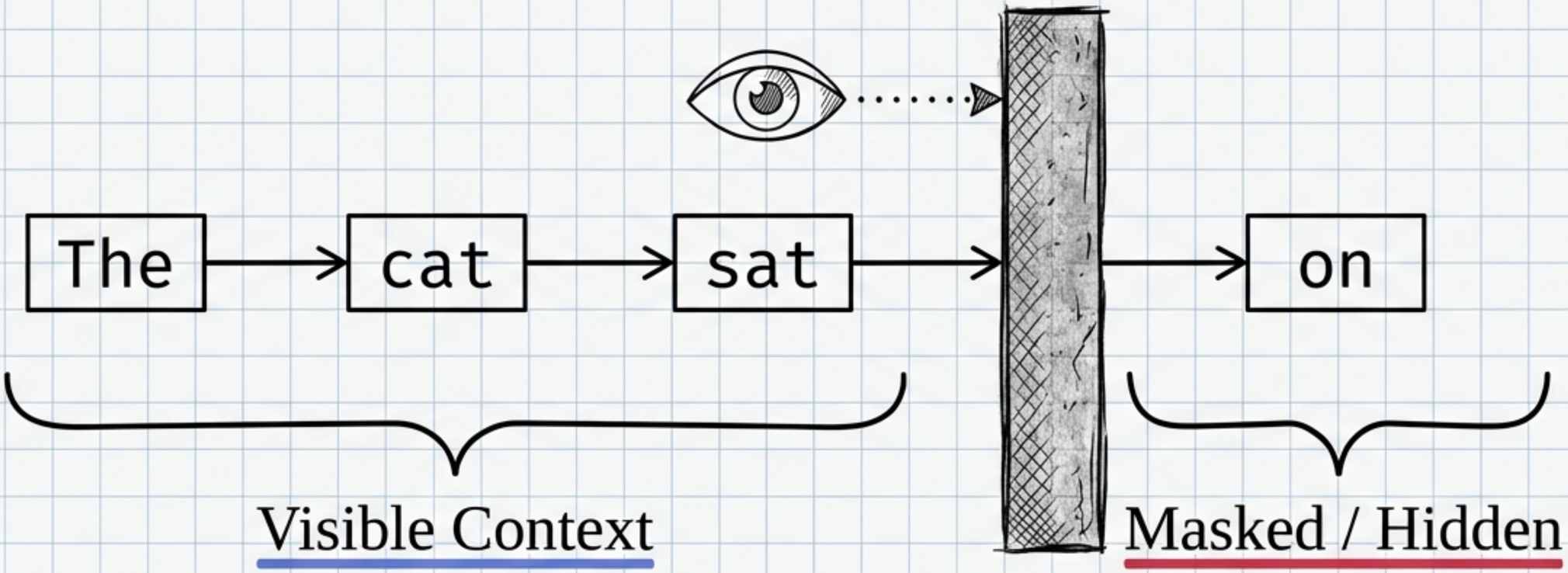
$$\underbrace{\texttt{Attention}(Q, K, V)}_{\text{Similarity}} = \underbrace{\texttt{softmax}}_{\text{Probability}}\left(\underbrace{\frac{QK^T}{\sqrt{d_k}}}_{\text{Scaling}}\right)\underbrace{V}_{\text{Content Extraction}}$$

Visualizing the Matrix

	Your	journey	starts	with	one
Your	0.05	0.10	0.25	0.10	0.50
journey	0.15	0.45	0.20	0.10	0.10
starts	0.05	0.10	0.28	0.10	0.10
with	0.05	0.10	0.25	0.10	0.10
one	0.05	0.10	0.25	0.10	0.50

Simultaneous calculation for all word pairs.

Causal Attention: Hiding the Future



Implementing the Mask

Pre-Softmax Scores

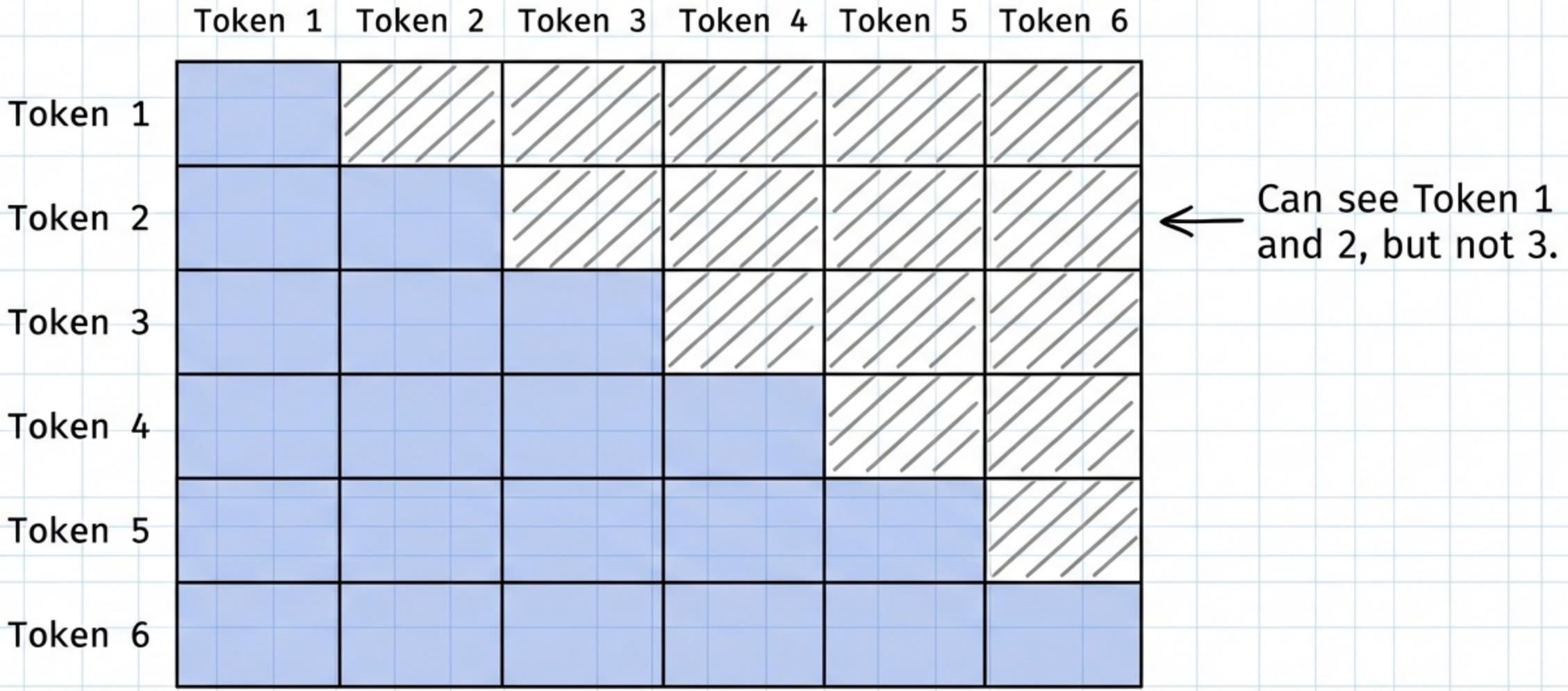
-inf	-inf	-inf	-inf
1.2	0.8	-inf	-inf
2.1	-0.5	3.0	1.1
0.2	2.5	0.9	1.4

Softmax(-inf) ≈ 0

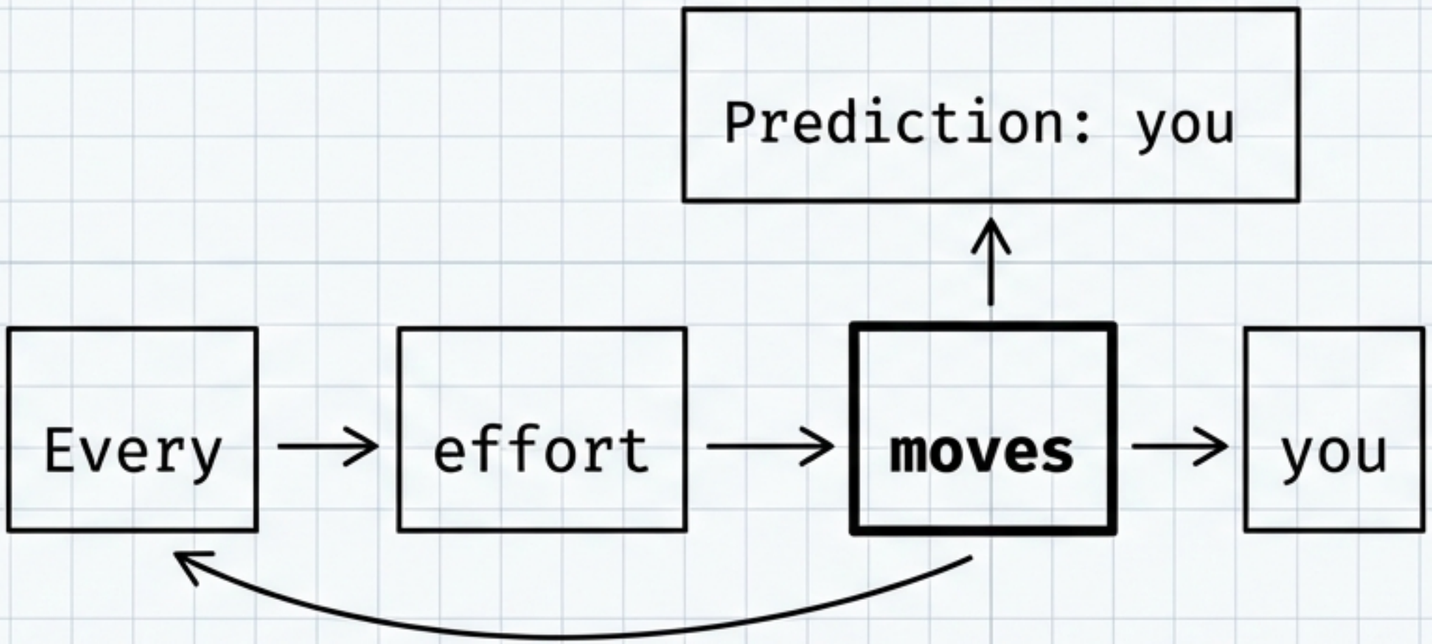
Post-Softmax Probabilities

0.0	0.0	0.0	0.0
0.40	0.32	0.70	0.0
0.10	0.85	0.85	0.45
0.08	0.65	0.35	0.40

The Look of Causal Attention



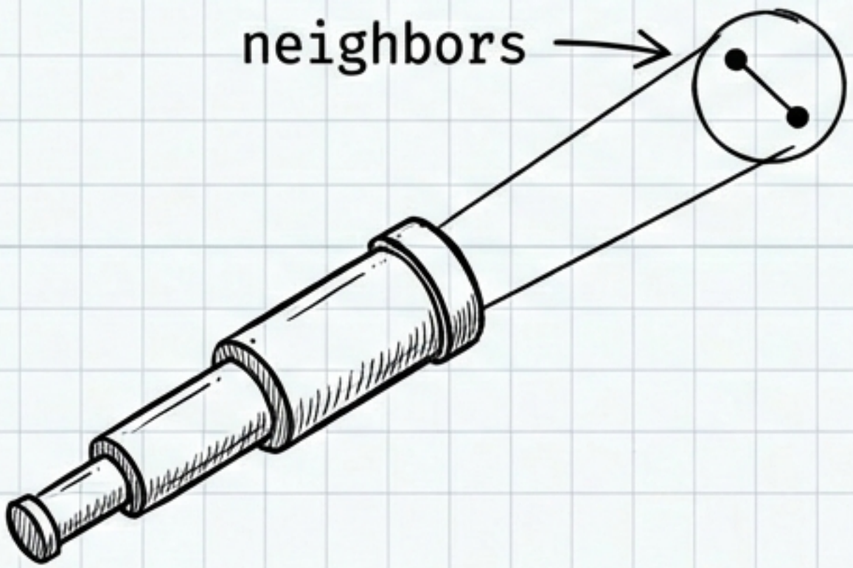
Putting It Together



The model uses the context of “Every effort moves” to predict the next token “you”.

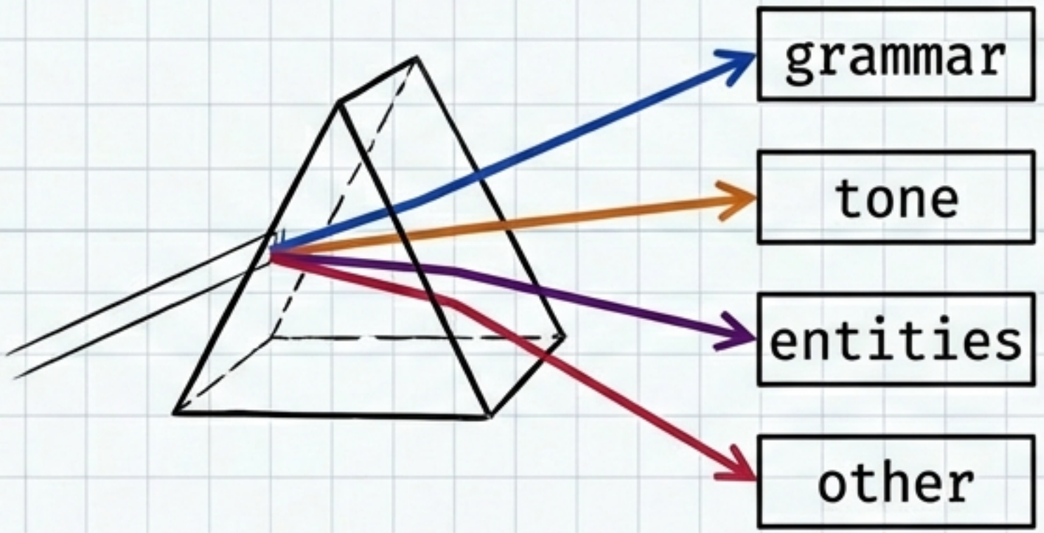
Why One Head Isn't Enough

Single Head



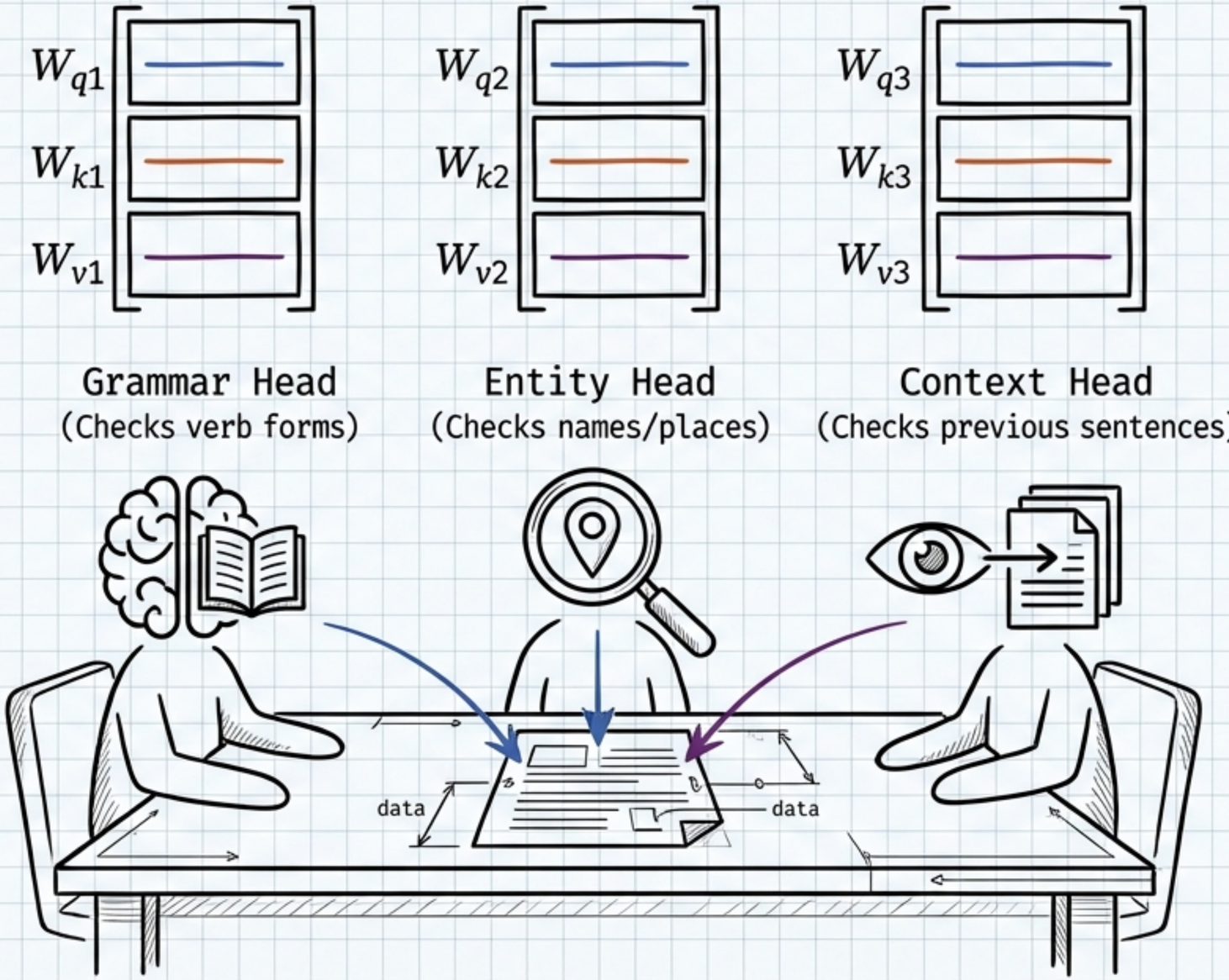
Focuses on one relationship (e.g., neighbors).

Multi-Head

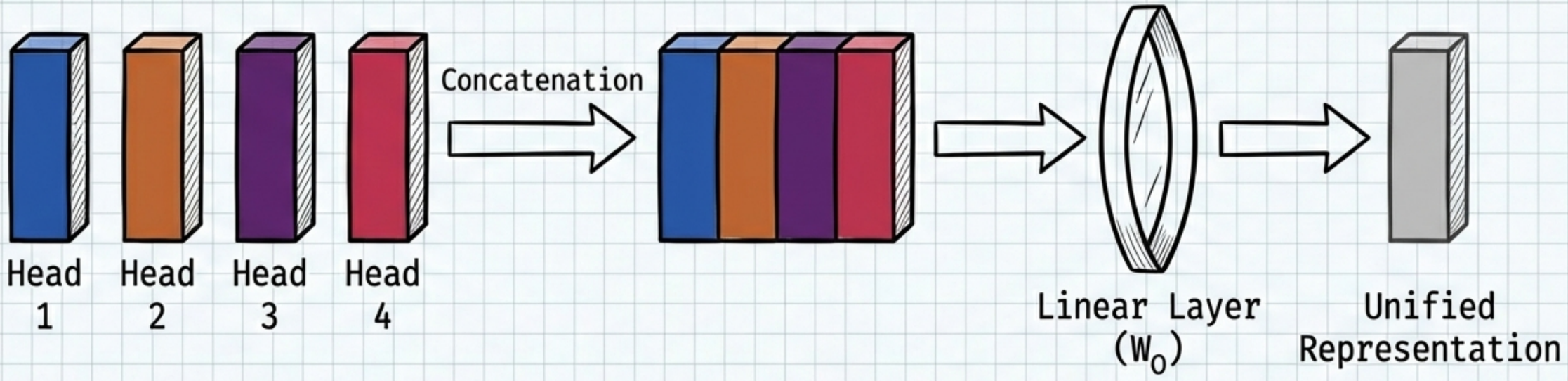


Focuses on multiple relationships (grammar, tone, entities) simultaneously.

Multi-Head Attention: A Panel of Experts



Aggregating the Insights



Combining diverse perspectives into a unified representation.

The Complete Attention Pipeline

This parallel process drives the modern AI revolution.