

How Many Different Outputs Can a Transformer Generate?

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Out-of-Distribution Sequences are Difficult to Access

Write a sentence of at least ten words, where every word is from a different language.

Bonjour hello hola ciao hallo namaste konnichiwa annyeong salam shalom.

⋮

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Je eat pan con queso oggi perché tasty.

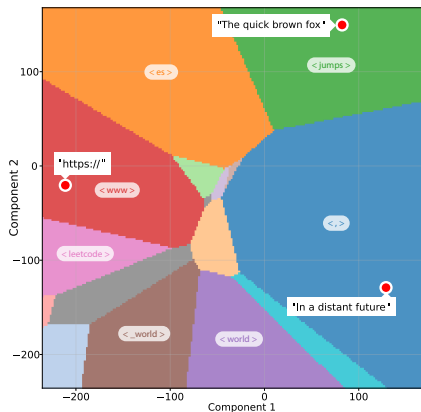
Interpretation: "I eat bread with cheese today because (it is) tasty."

Each word is from a different language (French, English, Spanish, Spanish, Italian, Italian, English), but note the issue: even here we already violate the constraint (two Spanish words, two Italian words). If you enforce the constraint strictly, grammaticality collapses.

Conclusion:

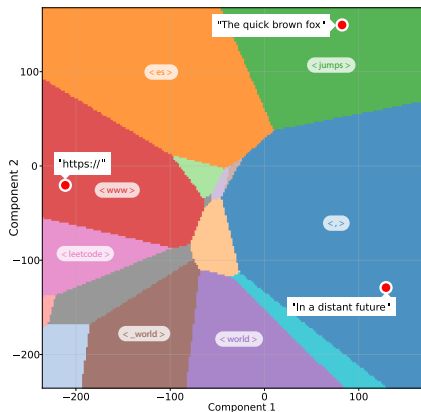
- A *meaningful* sentence: possible (as in the earlier philosophical example).
- A *natural everyday sentence*: not achievable under strict "one word per language" without breaking grammar.

The Embedding Space of a Transformer Carries Meaningful Information

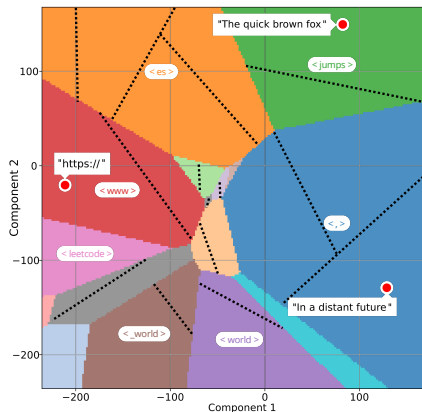


Next token prediction.

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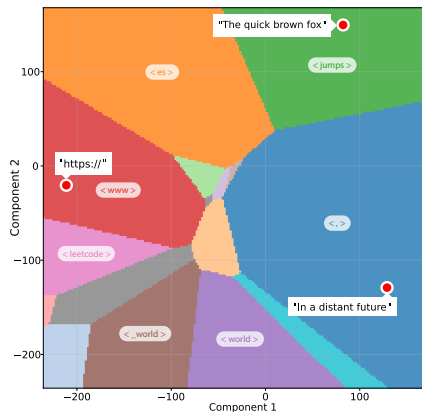
Next token prediction.



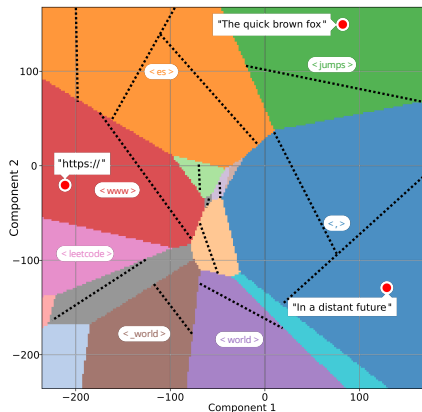
Next-next token prediction.

The Embedding Space of a Transformer Carries Meaningful Information

But transformers have finite precision! Indeed, they operate on a finite number of bits.

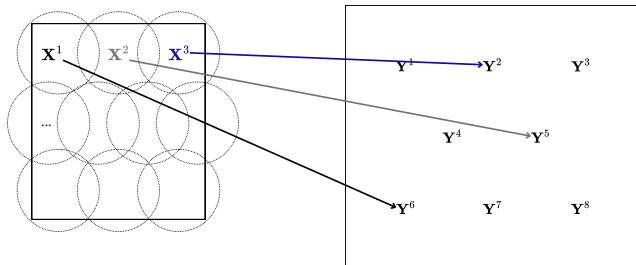


Next token prediction.



Next-next token prediction.

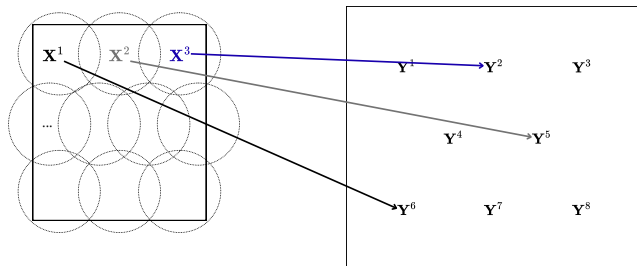
Formalizing the Intuition: There Is Only a Finite Number of Possible Inputs



Prompts of length m
($C(\epsilon)^m$ many)

Outputs of length n
($|\mathcal{V}|^n$ many)

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→ When $n > \left(\frac{\ln C(\varepsilon)}{\ln |\mathcal{V}|}\right)m$, some sentences of length n are inaccessible.

→ The proportion of accessible sequences decreases exponentially fast with n past this capacity limit.

Validating our Results through the Cramming Task

Goal: compress a long sequence into a shorter prompt.

Given a text $\mathbf{X} \in |\mathcal{V}|^n$, find a prompt $[\mathbf{mem}] \in \mathbb{R}^{d \times m}$ with $m \ll n$ such that

$$\tau([\mathbf{mem}]) \longrightarrow \mathbf{X}.$$

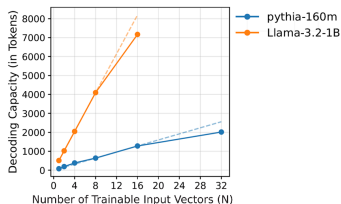


Figure 1: Scaling between the memory size and the number of encodable tokens.

What the Theory Predicts

- For a fixed prompt length m , the proportion of accessible sequences of length n decreases exponentially fast with n past a given threshold.
- This threshold scales linearly with m .
- We provide an upper bound on the linear scaling factor.

Cramming Tokens: Theory vs Practice (Qualitative)

Left: exponential decrease in accessibility past a given threshold.

Right: linear scaling between threshold and m .

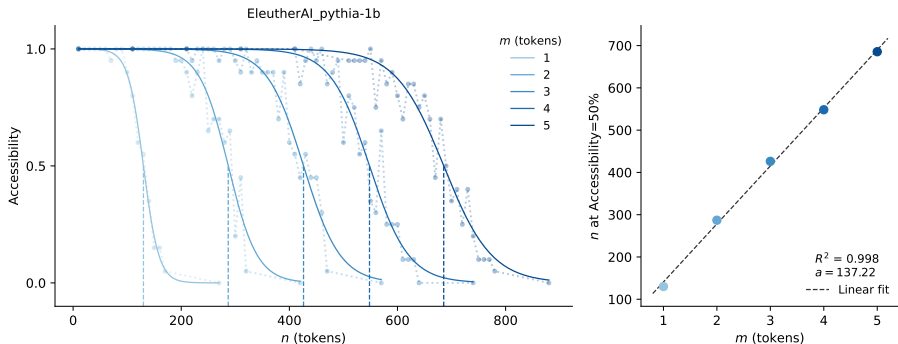


Figure 2: n : output length
 m : input length

Cramming Tokens: Theory vs Practice (Quantitative)

We analyse how tight the theoretical upper bound is by computing the ratio with the empirical slope. More complex theoretical analysis yields better bounds.

Method	Pythia			Qwen-2.5		Llama-3.2	Gemma-3
	160M	410M	1B	0.5B	1.5B	1B	270M
r_{Ball}	9.24	9.79	7.77	14.10	20.40	14.30	11.52
r_{Cone}	9.10	9.60	7.70	14.01	20.34	13.98	11.24
$r_{\text{Ellipsoid}}$	7.92	8.15	6.12	10.96	15.30	11.86	11.12
$r_{\text{Non-uniform}}$	6.66	5.99	4.56	7.92	10.82	10.71	8.79
Empirical slope	90.37	111.14	261.42	71.02	79.56	44.54	137.77

$$r = \frac{\text{theoretical upper bound on the slope}}{\text{slope observed in practice}}$$

The closer to 1 the better.

Main Takeaway

→ Despite representing only a fraction of a transformer's parameters, its embedding space closely characterizes its performance on some tasks.