A Practical Guide to Mechanistic Interpretability:

Demistifying black boxes with **Sparse AutoEncoders**[1][2][3]

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February 13, 2025

1 https://transformer-circuits.pub/2023/monosemantic-features/

2 https://arxiv.org/abs/2404.16014

3 https://www.arena.education/

Outline

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1. Background & Intuition
2. Sparse AutoEncoders
3. Applications & Practical Detail

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Today, we will interpret deep neural networks (transformers).

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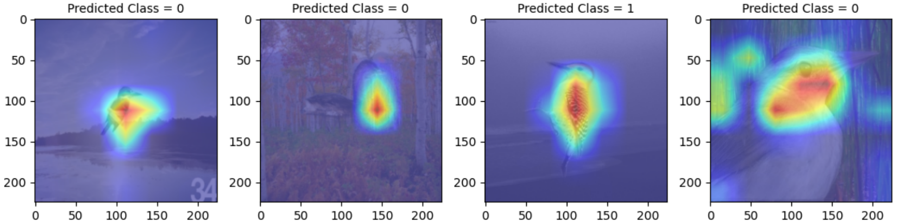
Most of interpretability seeks to extract representations from weights:



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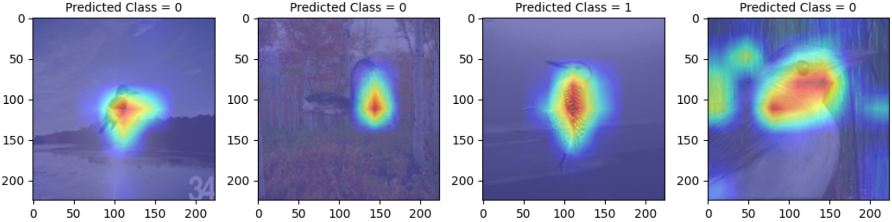

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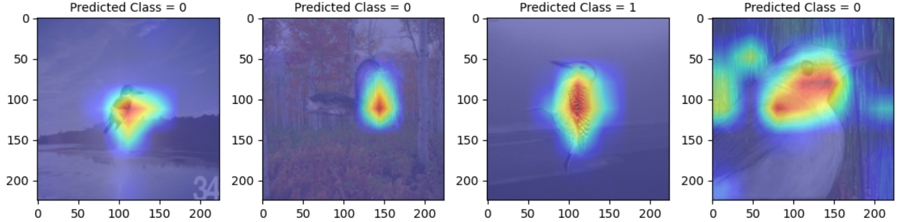

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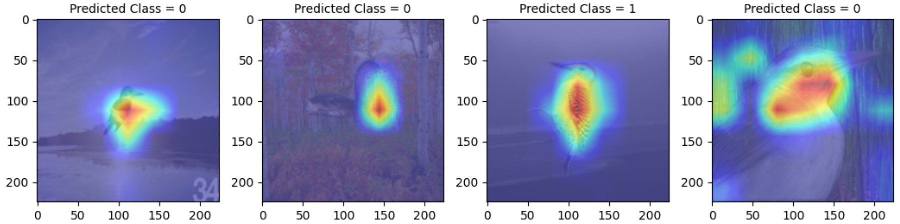

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It seeks to understand functions that *individual neurons* play in the inference of a neural network.

This can subsequently be used to offer high-level explanations for decisions, as well as guarantees during inference.

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Transformers Mini-Review

Crucial Aside: Treat residual connections as "memory"; all other layers "read from", "process", and "write-to" memory!

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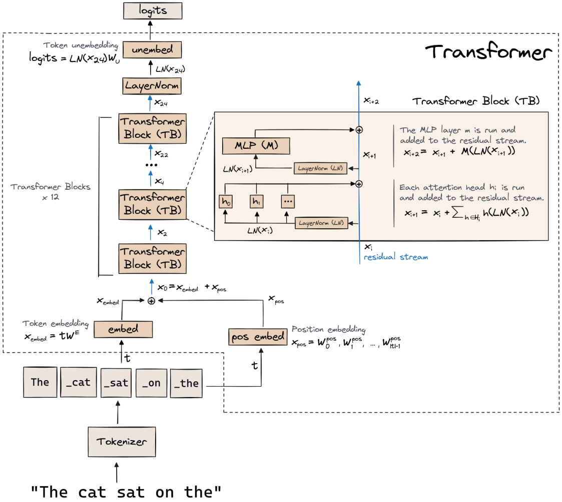

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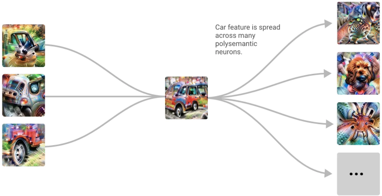

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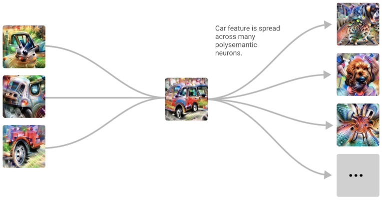

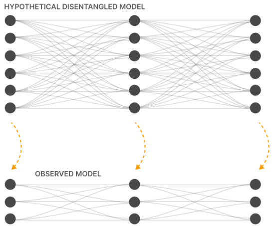

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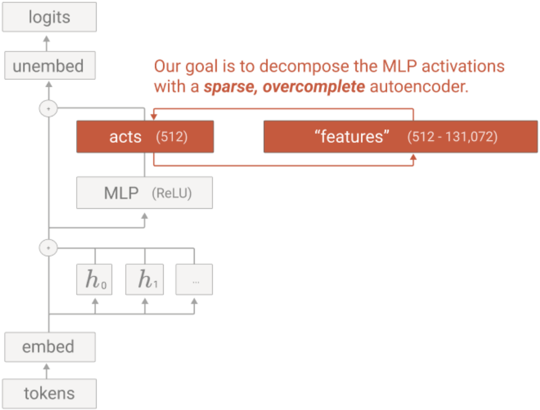
We observe learning compresses larger models to smaller footprints using denser parameters.

This is **superposition**.

Analytical Setup

We will explore the following setup:



Training Setup

	Transformer	Sparse Autoencoder
Layers	1 Attention Block 1 MLP Block	1 ReLU 1 Linear
MLP Size	512	$512 \times f \in \{1, \ldots, 256\}$[4]
Dataset	The Pile (100B tokens)	Activations (8B samples)
Loss	Autoregressive Log-Likelihood	$L2$ Reconstruction $L1$ on hidden-layer activation

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Objective: *polysemantic activations* $\overset{Tr}{\rightarrow}$ **monosemantic features**.

The sparse, overcomplete autoencoder is trained against this objective.

1. **Sparse** because we constrain activations (L1 penalty).
2. **Overcomplete** because the hidden layer exceeds the input dimension.

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Sparse Dictionary Learning

Given $X := \{x^j\}_{j=1}^{K}; x_i \in \mathbb{R}^d$, we wish to find $D \in \mathbb{R}^{d \times n}, R \in \mathbb{R}^n$ s.t:

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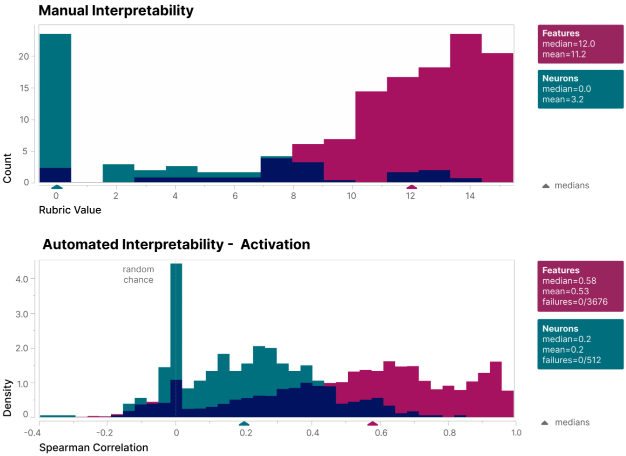
a. Training data $\propto n$(interpretable features).
b. Tying b_D before the encoder and after the decoder improves performance.
c. Dead neurons are periodically *resampled* to improve feature representations.

Evaluating Interpretability

Reliable evaluations on interpretability were scored based on a rubric:



Features were found to be interpretable when score > 8.

Analyzing Arabic Features

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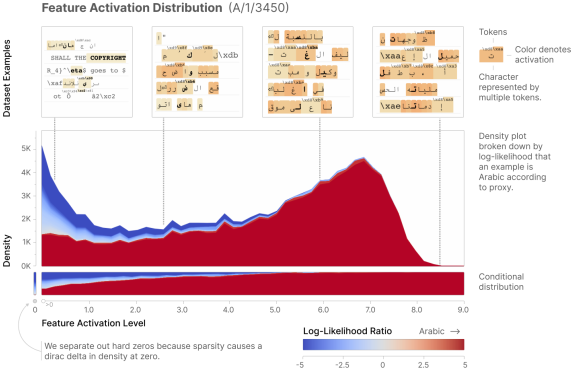
We can evaluate each token using the log-likelihood ratio:

$$LL(t) = \log\left(P(t|\text{Arabic})/P(t)\right) \quad (4)$$

Despite representing 0.13% of training data, arabic script makes up **81% of active tokens**:



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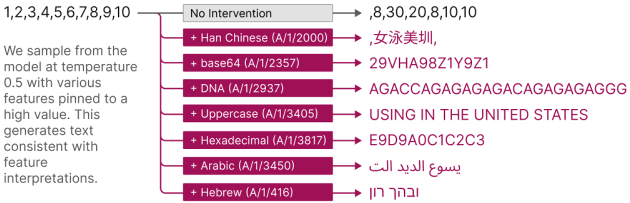
They can be used to steer generation.



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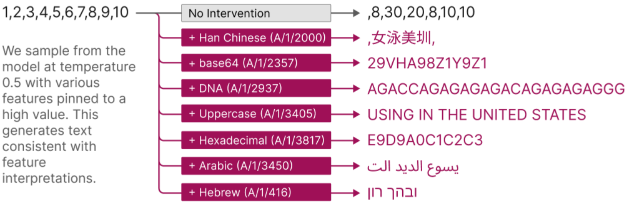

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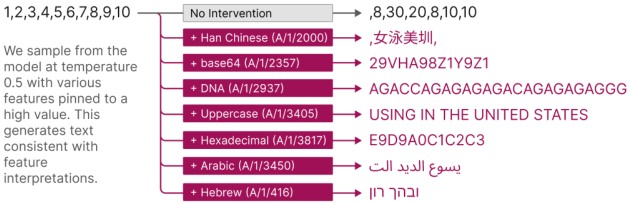

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We observe that interpreted features are actively used by the model.

Finite State Automaton

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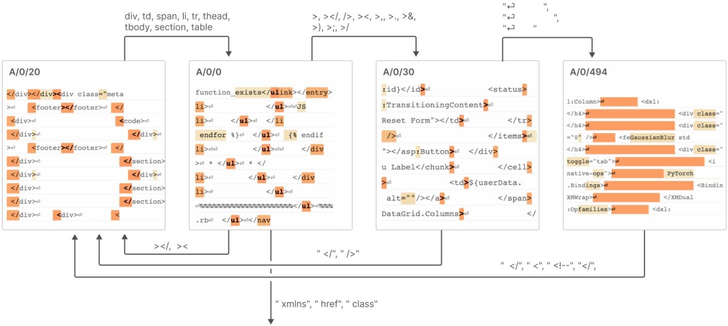
These present partial explanations of **memorizations** within transformers:



Modern (Gated) SAEs (1/2)

Quick review of the structure of the original SAE:

$$f(x) := \sigma_{\mathrm{ReLU}}(W_E(x - b_D) + b_E) \tag{5}$$

$$\hat{x}(f(x)) := W_D f(x) + b_D \tag{6}$$

$$\min_{W_E, W_D, b_D, b_e} \mathcal{L}(x) = \min_{W_E, W_D, b_D, b_e} \underbrace{\|x - \hat{x}(f(x))\|_2^2}_{\text{reconstruction error}} + \underbrace{\lambda \|f(x)\|_1}_{\text{sparsity penalty}} \tag{7}$$

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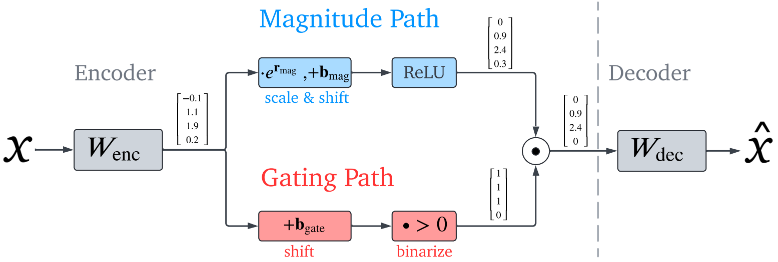
Observation: $\|\cdot\|_1$ motivates *shrinkage* – minimizing sparsity is "easier" than reconstructing sparse features, and motivates under-activation of reconstructed features.

Idea: Let's disentangle feature importance with feature existance:



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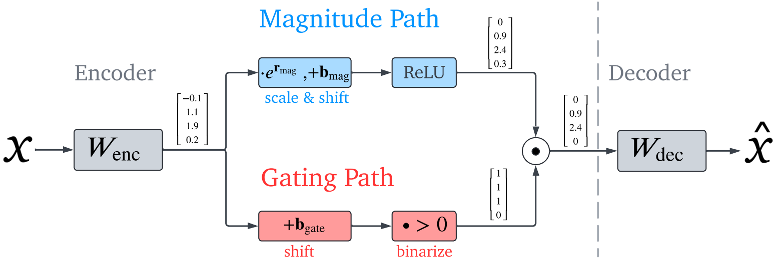

For this, the authors also define the following loss function:

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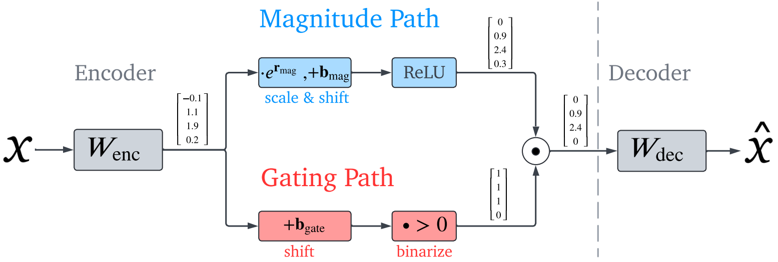

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Finally, they also use weight-tying to reduce parameter explosion.

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Training SAEs

If you can view this screen, I am making a mistake.

Dashboard Interpretation

If you can view this screen, I am making a mistake.

Feature Steering with SAEs

If you can view this screen, I am making a mistake.

Thank you!

Have an awesome rest of your day!

Slides: `https://jinen.setpal.net/slides/sae.pdf`