

Incremental Sentence Processing Mechanisms in Autoregressive Transformer Language Models

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Abstract

Autoregressive transformer language models (LMs) possess strong syntactic abilities, often successfully handling phenomena from agreement to NPI licensing. However, the features they use to incrementally process their linguistic input are not well understood. In this paper, we fill this gap by studying the mechanisms underlying garden path sentence processing in LMs. Specifically, we ask: (1) Do LMs use syntactic features or shallow heuristics to perform incremental sentence processing? (2) Do LMs represent only one potential interpretation, or multiple? and (3) Do LMs reanalyze or repair their initial incorrect representations? To address these questions, we use sparse autoencoders to identify interpretable features that determine which continuation—and thus which reading—of a garden path sentence the LM prefers. We find that while many important features relate to syntactic structure, some reflect syntactically irrelevant heuristics. Moreover, though most active features correspond to one reading of the sentence, some features correspond to the other, suggesting that LMs assign weight to both possibilities. Finally, LMs fail to re-use features to answer follow-up questions.

1 Introduction

Syntactic ambiguities abound in natural language. For example, given the fragment “After the woman drank the water...”, *the water* could be either the object of *drank* (in which case one could end the sentence here), or the subject of the main clause (in which case “was all gone” would be a valid continuation). Despite LMs’ impressive performance on syntactic tasks (Hu et al., 2020), the mechanisms that underlie their processing of syntactic structure and its ambiguities are largely unknown. Past work has found LM attention heads dedicated to processing certain syntactic relations (Vig and Belinkov, 2019) and used LMs’ representational structure to predict dependency relations (Hewitt and Manning,

2019); nonetheless, these results only show that structural information can be extracted from LM representations—and not that these representations are causally implicated in LM processing. It thus remains unclear whether LMs rely on structure-related features, represent the multiple possible completions to an incomplete ambiguous utterance, or revise representations in light of new evidence.

In the psycholinguistics literature, similar questions have been studied in humans using **garden path sentences**, which initially appear to have a given structure, but which are later revealed to have another. When humans encounter such sentences, their reading is delayed. Different theories of human sentence processing predict different delays; by recording reading times on carefully designed test materials, one can thus empirically test such theories (Lewis, 2000; Gibson and Pearlmuter, 2000). While prior work on LMs has used garden path sentences as a testbed for the psychometric fit of LM surprisals to predict human reading times (Van Schijndel and Linzen, 2021; Arehalli et al., 2022), we propose to instead use them to understand how LMs incrementally process sentences.

In this study, we present a mechanistic investigation of how LMs incrementally process sentences and how they handle temporary ambiguities using garden path (GP) sentences as a case study. Using sparse autoencoders and causal interpretability methods, we uncover the causally relevant features (and mechanisms composed thereof) that explain why LMs assign higher probabilities to particular completions. With these methods, we investigate 3 research questions (RQs), and find the following:

RQ1: *Do LMs use syntactic features or spurious heuristics to incrementally process sentences?* Many of the most important features LMs use are interpretable and syntax-related; however, some uninterpretable or spurious features exist.

RQ2: *Do LMs hold on to multiple interpretations of the sentence simultaneously, or commit to*

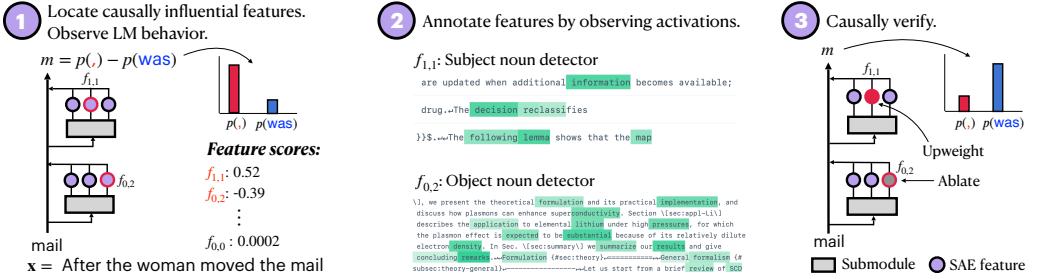


Figure 1: **Overview.** We use sparse autoencoders to decompose model activations into a discrete set of human-interpretable components (features). We score each feature by its causal contribution to continuations associated with each reading of a garden path sentence. We manually interpret the top-scoring features and causally verify their functional role in the network by targetedly up- or downweighting them to change the model’s preferred reading.

the most likely one? LMs’ representations encode multiple interpretations.

RQ3: *Given disambiguating evidence, do LMs repair or reanalyze their initial structural predictions?* LMs do not reanalyze nor repair their structural predictions, as they do not appear to rely on their prior structural representations at all.

2 Background

2.1 Incremental Sentence Processing

Many linguistic theories posit that humans parse their linguistic input, mapping from sentences to a representation with information about the structure thereof (van Gompel and Pickering, 2007). We do so *incrementally*, building up representations prior to the end of the sentence (Marslen-Wilson, 1975).

How humans perform incremental parsing is hotly debated. Of particular interest is how we handle the fact that partial sentences often have multiple valid parses (Fodor et al., 1974). Do we parse sentences serially, considering one parse at a time (Frazier, 1979; Fodor and Ferreira, 1998), or in parallel, considering many at once (Gorrell, 1987; Gibson, 1991; Jurafsky, 1996)? And upon encountering evidence that rules out specific parses, do we repair our representations (Lewis, 1998), or re-analyze the input entirely (Grodner et al., 2003)?

Psycholinguists often test theories of incremental parsing with *garden path sentences*, which suggest one parse, but ultimately have another. Consider the incomplete sentence “The guitarist knew the song...”. A reader could either interpret *song* as an object of the verb *knew*, or the subject of a sentential clause (i.e., “The guitarist knew (that) the song...”). A period would be a valid completion in the former case but not the latter, where a verb phrase like “...was too long” would be more fitting. Most readers find the first reading more

likely, so observing a completion consistent with the second typically results in significant spikes in reading times (Frazier, 1987).

2.2 Sentence Processing in LMs

How LMs process and represent sentences is similarly well-studied. Work on structural probes has attempted to reconstruct parses from LM representations using learned similarity functions or probes (Hewitt and Manning, 2019; Maudslay et al., 2020; White et al., 2021; Arps et al., 2022). Others have found attention heads whose attention corresponds to syntactic relations, though no general parsing head exists (Vig and Belinkov, 2019; Clark et al., 2019b; Htut et al., 2019). Researchers have also trained probes to extract features like coreference relations or part of speech from LM representations (Tenney et al., 2019; Jawahar et al., 2019).

However, these analyses have serious limitations. Most study LMs with bidirectional attention, which do not perform *incremental* sentence processing. Moreover, few causally verify their mechanisms’ relevance to model processing, even though probes often capture functionally irrelevant information (Ravichander et al., 2021; Elazar et al., 2021). While causal techniques have been used in other settings (Vig et al., 2020; Finlayson et al., 2021; Lasri et al., 2022), they have rarely been applied to questions of ambiguity in syntactic structure and incremental processing; Eisape et al. (2022) do so, but using a probe which assumes a specific mechanism unlikely to be encoded by the LM itself.

With this in mind, we use garden path sentences as a case study in LMs’ incremental sentence processing mechanisms. Prior work using LM behavior on such sentences to model human reading times (Van Schijndel and Linzen, 2018; Wilcox et al., 2021; Arehalli et al., 2022; Oh and Schuler,

2023) finds that LMs do exhibit garden-path effects, though they underpredict human effects. Less work has used garden path sentences to observe *how* LMs arrive at these probabilities and surprisals. Li et al. (2024) attempt this, but study masked LMs without causal methods. We ask: how can we find and causally verify the mechanisms that LMs use to incrementally process garden path sentences?

2.3 Locating Interpretable Mechanisms with Sparse Feature Circuits

We capture LMs’ incremental processing mechanisms using *circuits* (Olah et al., 2020). A circuit is the minimal computational subgraph of a LM that recovers the whole LM’s performance on a given task (Wang et al., 2023; Conmy et al., 2023; Hanna et al., 2023). After finding a circuit, one can ablate all parts of the LM outside it to causally verify that performance is preserved. One then analyzes the circuit to uncover how the LM performs the task.

Many circuits involve submodules—attention blocks, MLPs, or full layers—but we aim to analyze garden-path sentence processing at a lower level. Past work has done so by studying individual LM neurons (Sajjad et al., 2022), but feature representations in neural networks are often distributed (Hinton et al., 1986; Smolensky, 1986). Neurons are thus often *polysemantic*, representing multiple unrelated features at once, which makes them challenging to interpret (Olah et al., 2017; Bolukbasi et al., 2021; Elhage et al., 2022). We thus opt to interpret the features of sparse autoencoders (SAEs; Bricken et al., 2023), autoencoders trained on the output activations of LM submodules. Let \mathbf{x} be the submodule’s output activation; the SAE computes

$$\mathbf{f} = \text{ReLU}(\mathbf{W}_e(\mathbf{x} - \mathbf{b}_d) + \mathbf{b}_e) \quad (1)$$

$$\hat{\mathbf{x}} = \mathbf{W}_d\mathbf{f} + \mathbf{b}_d, \quad (2)$$

where \mathbf{f} is the feature vector, and $\hat{\mathbf{x}}$ is the reconstructed activations. Henceforth, we refer to a single dimension of \mathbf{f} as a *feature*. SAEs are trained to reconstruct \mathbf{x} with sparse regularization on \mathbf{f} ; the regularizer and bias terms lead a feature’s activation to be non-0 only when it causes parts of \mathbf{x} to differ from their mean value. This makes SAE features more *monosemantic* than LM neurons, and therefore more interpretable.

As in Marks et al. (2024), we combine SAEs and circuits to find *sparse feature circuits* containing causally relevant features and the connections between them. We say a feature f is causally relevant

if, given a metric m that measures the LM’s behavior, setting f ’s value to 0 causes a large change in m ;¹ the magnitude of this change is f ’s **indirect effect** (IE; Pearl, 2001). Computing each feature’s IE is expensive, so we use Marks et al.’s (2024) attribution patching with integrated gradients (AtP-IG) to compute \hat{IE} , a linear approximation of IE, for each feature. We then select all features and edges whose \hat{IE} is over a chosen threshold; this yields a circuit. By checking that m ’s value remains the same when the features outside our circuit are ablated, we verify that the mechanism captured by the circuit is faithful to that of the full model.

3 Models

To analyze incremental parsing in LMs, we must study autoregressive LMs.² We choose to analyze Pythia-70m-deduped (Biderman et al., 2023), and Gemma-2-2b (Gemma Team et al., 2024), as these have publicly available SAEs. We focus primarily on Pythia-70m in the main text due to its smaller size; results for Gemma-2-2b are in App. D.

4 Do LMs use syntactic features to process garden path sentences?

4.1 Behavioral Analysis

Before finding the features that underlie LM garden path sentence processing, we first verify that the LMs we study exhibit garden path effects.

Dataset We probe LMs’ readings of garden path sentences using an adaptation of Arehalli et al.’s (2022) dataset of 72 garden path sentences. This contains 3 structures (NP/Z, NP/S, and MV/RR) with 24 sentences each. Each structure name refers to the two interpretations of the sentence’s ambiguous material. For example, in Table 1 NP/Z, “signed” could take either an NP complement (“the bill”) or a zero complement. In Table 1 NP/S, “the song” could be the NP complement of “knew” or the start of a sentential complement. Finally, in Table 1 MV/RR, “brought” could be the main verb or part of a reduced relative clause.

We craft two unambiguous versions of each sentence, which permit only one reading: e.g., in Table 1 NP/Z we replace the ambitransitive “signed”,

¹While setting neurons to 0 is unprincipled, zero-ablating sparse features is not, as feature activations are non-0 only when they cause parts of \mathbf{x} to differ from their mean value.

²Masked LMs often have strong syntactic abilities (Goldberg, 2019) but receive the left *and* right context of each token, invalidating them as models of incremental processing.

Structure	Example Sentence	GP	Non-GP
NP/Z	After the politician <i>signed/rejected/arrived</i> the bill	,	was
NP/S	The guitarist <i>knew/wrote/said</i> the song	.	was
MV/RR	The woman <i>brought/moved/shown</i> the mail	.	was

Table 1: Examples from our dataset, adapted from Arehalli et al. (2022). For each sentence, inserting the yellow word makes it compatible with only garden path (GP) continuations; the blue word permits only non-garden-path (Non-GP) continuations. The red words leave it ambiguous, compatible with either.

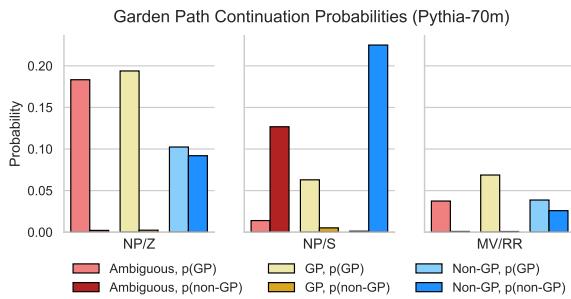


Figure 2: Mean probability of tokens corresponding to garden path (“,”/“.”) and non-garden-path (“was”) readings of the input for Pythia-70m, grouped by garden path structure. Inputs are either ambiguous, or compatible with only a garden-path or non-garden-path reading. GP tokens are more likely given GP inputs; non-GP are more likely with non-GP inputs. In ambiguous cases, Pythia-70m prefers the GP reading, except for on NP/S.

with the strictly transitive “rejected” (forcing the garden-path reading) or the intransitive “arrived” (forcing the opposite).

Experiment For each sentence, we record the probability given by the LM to next tokens consistent with the garden path or non-garden-path reading; we denote these $p(\text{GP})$ and $p(\text{non-GP})$ respectively. For NP/Z sentences, we define $p(\text{GP})$ as $p(,)$; for NP/S and MV/RR, we define $p(\text{GP})$ as $p(.)$. For all sentence structures, we define $p(\text{non-GP})$ as the probability of “was”. This roughly measures the LM’s reading of the sentence: continuing “After the politician signed the bill” with a comma implies that “signed” took “the bill” as a complement, as in the GP reading. Continuing it with “was” implies that “signed” took no complement, as in the non-GP reading.

Results Our results (Figure 2) show that Pythia-70m correctly up- and downweights garden path tokens in contexts that do and do not license them. Given GP inputs, the model gives more probability

to GP tokens, and less to non-GP tokens, compared to when it receives ambiguous inputs; this trend holds across garden path structures. For non-GP inputs, this trend is reversed, as expected.

For ambiguous inputs, the model prefers garden-path continuations in the NP/Z and MV/RR cases, but non-garden-path in the NP/S case. This agrees with prior evidence from both humans and LMs showing lower reading times and surprisals for non-garden-path continuations to inputs with NP/S ambiguities, compared to NP/Z (Grodner et al., 2003; Sturt et al., 1999; Van Schijndel and Linzen, 2018).

Discussion In this experiment, we would ideally measure the probability of all GP and non-GP-implying continuations, rather than of just two tokens. Unfortunately, this is computationally infeasible, but see App. A for more discussion of this issue and §5.2 for another way to determine an LM’s reading of ambiguous input, yielding similar results. Because MV/RR sentences have low $p(\text{GP})$ and $p(\text{non-GP})$, we exclude them from all following analyses.

4.2 Feature Circuit Analysis

Now, we identify and analyze the feature circuits responsible for Pythia-70m’s garden path effects.

Experiment We investigate circuits composed of causally relevant features from the Pythia-70m SAEs of Marks et al. (2024). We use AtP-IG (§2.3) to find the features that most influence the difference in probabilities assigned to garden-path and non-garden-path continuations of ambiguous sentences, $m = p(\text{GP}) - p(\text{non-GP})$. We keep features with $\hat{\text{IE}} > 0.1$, and edges with $\hat{\text{IE}} > 0.001$. We then manually annotate each feature in the circuit, using Neuronpedia (Lin and Bloom, 2023) to visualize feature activations on text from The Pile (Gao et al., 2020) on which each feature activates strongest.³

Results Running AtP-IG yielded circuits containing 155 (NP/S) and 65 (NP/Z) sparse features; we manually annotate all of these.⁴ To measure how well these features capture the behavior of the full model, we measure faithfulness, following the definition in Marks et al. (2024). These circuits have faithfulness 0.20 (NP/S) and 3.48 (NP/Z).⁵ Signif-

³Features can be viewed online via Neuronpedia at <https://www.neuronpedia.org/pythia-70m-deduped/>

⁴Past work has used LMs as annotators (Bills et al., 2023), but we find them to be poor annotators of syntactic features.

⁵Approaching a faithfulness of 1 requires including many hundreds of features for Pythia, and over 1000 for Gemma.

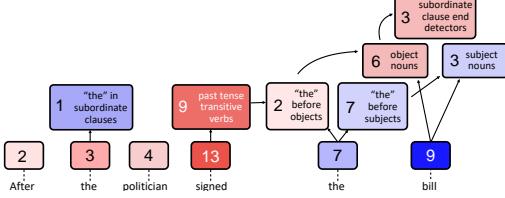


Figure 3: Pythia-70m’s feature circuit for processing NP/Z garden path sentences. We group features by their functional role in the circuit and display the number of features in each group. Red features have negative scores and promote the garden path reading; blue features, with positive scores, do the opposite. Unlabeled early-layer features are word detectors. Many late-layer features encode syntactic features, whereas early-layer features largely consist of word detectors and heuristics.

icant deviations from 1.0 imply that there are important features we have not captured; thus, while we cannot claim to have annotated the full mechanism, we can nonetheless still analyze the most highly influential features, which provide sufficient evidence to address our RQs. See App. B for the metric definition, implementation details, and a deeper discussion of these faithfulness values.

Figure 3 displays a simplified circuit for NP/Z, where we manually group similar features together. The simplified NP/S circuit and the oversized full circuits are in App. E. We present selected features’ activations on highly-activating sentences in Table 2 to support our annotations. We find that:

Features in lower layers often correspond to interpretable low-level features. Many lower-layer features detect word-level attributes, rather than high-level sentence-specific syntactic information. The vast majority of our circuit’s features are word detectors that activate only on one specific word, located in the model’s embeddings or first two layers. For example, Feature 0/8234 activates only on the word *the* (Table 2). Other features are slightly higher-level, activating on nouns or past tense verbs. Notably, while most such features have no obvious syntactic relation with either reading (e.g. the presence of the word “*the*” should be neutral with respect to which reading it suggests), they have a non-zero impact on the preferred reading.

Higher layer features encode syntactic attributes relevant to garden path sentence processing. The features in Pythia-70m’s upper layers often encode sentence-level syntactic information that distinguishes between different readings of garden path sentences. For example, the final layers of the model’s circuit for NP/Z sentences (Figure 3)

include features that detect subjects, objects, and ends of subordinate clauses. Reading the final noun as an object and part of the subordinate clause corresponds to the GP reading; reading the final noun as a subject outside of the subordinate clause corresponds to the opposite. The scores assigned to features match their semantics: non-GP feature scores are positive; pro-GP are negative.

Table 2 shows each feature’s activations. Feature 4/14907, for example, detects ends of subordinate clauses; every position at which it activates could be a valid end to the subordinate clause containing it, given no information about the following tokens. It precisely distinguishes the two readings of NP/Z sentences: in the garden path reading of “After the politician signed the bill”, the clause might end at *bill*, while in the non-GP reading, it ends at *signed*.

Feature 3/835 distinguishes the readings of NP/S sentences, activating on subjects of sentential complements. In an NP/S sentence such as “The guitarist knew the song”, *the song* can either be the object of *knew* (the GP reading) or the subject of a new phrase (non-GP); this feature clearly corresponds to the latter reading. Finally, Feature 4/8505 activates primarily on object nouns and nouns in prepositional phrases. This corresponds not only to the GP reading in NP/Z and NP/S sentences, but also to the accusative case, hinting that the model may have learned a general linguistic concept.

Some features are uninterpretable. Although many SAE features are interpretable, some activate seemingly at random, or across almost all text. The latter could be interpreted as a prior, which always influences the model’s prediction, but most have no clear interpretation. These features have a non-zero effect on model predictions, though their effect direction is inconsistent. We omit these features from our analysis, but we hope they will be interpretable as SAEs or interpretability methods improve. Fortunately, the interpretable features are quite causally relevant on their own.

4.3 Causal Analysis

Though many high-importance features encode syntactic attributes, this is no guarantee that the model relies on them. To confirm this, we causally intervene on the discovered interpretable features, and verify that model output changes as we expect. See App. C for a large-scale version of this experiment.

Experiment We focus on three groups of model features, which detect: 1) subjects, 2) objects, and

Feature	Activates on	Examples
0/8234	the word <i>the</i>	Since 2001, the variant commonly in use is the Category 5e specification On September 26, 2006 the University of Phoenix acquired the naming
4/14907	ends of sub. clauses	Finally, after years of watching youtube videos on that topic, I made When it released alongside Fire Emblem Fates in June of 2015, Fire
3/835	subjects of sent. clauses	A hearing officer would determine if a complaint has merit, requiring ... to learn how the United States and key players around the world
4/8505	object nouns, nouns in PPs	Justin Trudeau used the Canada Day celebrations in Ottawa to name ... than for Alan Shepard. He left the hotel shortly after midnight

Table 2: Interpretable residual stream features implicated in Pythia-70m’s garden path sentence processing. We list each feature’s layer and feature-index, as well as a description of what the feature activates highly on. Each example shows how strongly the feature activated on each token; darker highlighting indicates larger activations.

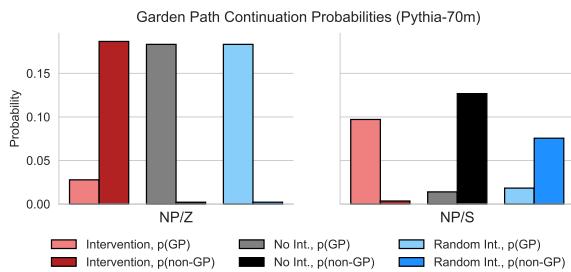


Figure 4: Mean probability of GP and non-GP continuations under interventions for Pythia-70m. Interventions on interpretable features reverse model behavior, as expected; random interventions do not change behavior.

3) either ends of clauses (NP/Z) or sentential-clause verbs (NP/S). For NP/Z sentences, we attempt to induce the dispreferred non-GP reading by setting the subject detectors’ activation to a high value (2.0) at the final noun of each sentence, while clamping object detectors off (to 0). End-of-clause detectors are set to 2.0 at the verb position, and 0 on the final noun. For NP/S sentences, we induce the GP reading: at the final noun, we set the subject and object detectors to 0 and 2.0 respectively; we also turn the sentential-clause-verb detectors off. As a control, we choose 3 groups of random features (equal in number to the original groups) to clamp on or off. In all settings, we intervene during the forward pass, and compute $p(\text{GP})$ and $p(\text{non-GP})$.

Results Our results (Figure 4) suggest that the features we find are causally relevant. Turning the subject and object features on and off respectively, and altering the end-of-clause features, reverses the model’s typical preference for the GP reading in the NP/Z scenario; ablating the same number of randomly chosen features does nothing. The analogous NP/S intervention causes the model to prefer

the GP reading, while performing no interventions or random ones yields the opposite.

5 Do LMs consider one or multiple readings of garden path sentences?

Here, we investigate whether LMs consider multiple readings of garden path sentences simultaneously. We reason that, although $p(\text{GP})$ and $p(\text{non-GP})$ are non-zero in all cases, the model may not explicitly represent both alternatives.

5.1 Evidence from model feature analysis

Experiment We can test if LMs consider one or multiple readings of garden path sentences by checking if ambiguous inputs cause features corresponding to both readings to activate. We thus run the model on our ambiguous data and record the activations of the interpretable pro-GP and anti-GP features that we identified in layers 3-5 of the model, in §4.2. If the model only considers one reading, only features corresponding to one reading should activate; if features corresponding to both activate, we conclude that the model considers multiple. Recall that as features are inactive on almost all inputs, non-zero activations are meaningful.

Results We find that in both the NP/Z and NP/S cases, pro- and non-GP features have non-zero average activations, ranging from 0.27 to 0.41. Similarly, the percent of features active is above 50% for both categories, and both NP/Z and NP/S sentences. This suggests that models explicitly represent both readings of a garden path sentence.

5.2 Evidence from structural probes

We can also directly assess if the model considers both readings using structural probes (§2.2), which

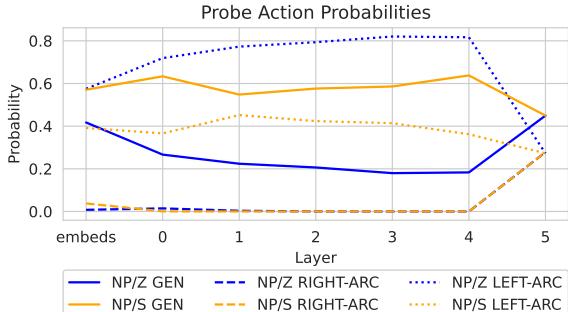


Figure 5: Mean probe action probability across layers. GEN corresponds to the non-GP reading, and LEFT-ARC to the GP reading (RIGHT-ARC is implausible). NP/Z sentences elicit primarily LEFT-ARC; NP/S elicits GEN. Both valid readings always receive non-zero probability.

map from LM representations to a distribution over parses of the LM’s input. The two readings of NP/Z and NP/S sentences have distinct parses, so parse probes can measure the probability of each.

Experiment We base our structural probes on Eisape et al.’s (2022) MLP action probes, as these are compatible with autoregressive models and incomplete inputs; most such probes are not. These probes take in the residual-stream representations of two words (from a fixed layer) and use a MLP to map them to one of three possible dependency relations: 1) the first word is a dependent of the second (LEFT-ARC); 2) vice-versa (RIGHT-ARC); or 3) no relation (GEN). Following Eisape et al. (2022), we train probes to predict parser actions using parse-annotated data from the Penn TreeBank (Taylor et al., 2003). As in Eisape et al. (2022), our trained probes achieve high performance; see App. F.

With these probes, we evaluate our model’s reading of ambiguous garden path sentences.⁶ Crucial here is the dependency relation between each sentence’s verb and final noun. The garden path reading of the sentence “After the politician signed the bill” would leave *the bill* as a dependent (object) of *signed*; in the non-GP case, there is no dependency relation. We record the probability of each relation, averaged across all NP/Z and NP/S sentences.

Results Our results (Figure 5) show that while probes favor LEFT-ARC for NP/Z sentences, and GEN for NP/S, they assign moderate probability to both readings. This trend holds for all layers but the last, where probe performance is poor. This further supports the hypothesis that LMs consider both

⁶We verify that the structural probes’ predictions on non-ambiguous sentences are sensible in App. F.

Model	Yes/No QA		GPRC	
	BoolQ	MCQA	NPS	NPZ
Pythia	42.8	50.0	50.0	50.0
Gemma 2	70.7	90.0	83.3	70.9

Table 3: Accuracy on two QA datasets and garden-path reading comprehension (GPRC) questions (all zero-shot binary questions). Pythia performs poorly as it often outputs the same answer for all inputs, regardless of the question. Gemma 2 performs well on all tasks.

readings of garden-path sentences, as found in the feature analysis; in App. F.4 we run AtP-IG on the probe and find the same features are responsible.

6 Do LMs reanalyze, repair, or neither?

In humans, garden-path readings can linger even after the sentence is complete (Christianson et al., 2001): given “The boy fed the chicken smiled.”, people often respond yes to “Did the boy feed the chicken?”. “The boy” is the recipient of *fed*, but the garden-path reading suggests that it is the agent. What happens to LM representations after receiving such disambiguating information? If the LM relies on its original syntactic features, we might observe features at later token positions that adjudicate between different readings, analogous to a repair-based strategy. The later features could also upweight the correct reading independently of the original representations, analogous to re-analysis.

6.1 Behavioral Analysis

We evaluate how models respond to garden path reading comprehension (GPRC) questions; past work suggests fine-tuned masked LMs exhibit lingering garden path effects (Irwin et al., 2023). Correct answers to GPRC questions indicate a correct (non-garden-path) reading of the sentence. For example, given “The boy fed the chicken smiled.”, we ask “Did the boy smile?” (*Yes*) or “Did the boy feed the chicken?” (*No*). We craft *Yes* and *No* questions for each sentence, so models whose answers are random or constant will obtain 50% accuracy.

Experiment We first verify whether our models can do question answering (QA) on less tricky binary QA datasets. Good performance here is a prerequisite for the following analyses to be valid. We evaluate on a binary version of multiple choice question answering (MCQA) from Wiegreffe et al. (2024), where questions are of the form “Ques-

tion: Boxes are brown. What color are boxes?\nA. green\nB. brown\nAnswer:”, and the model must answer “ A” or “ B”. We also evaluate on BoolQ (Clark et al., 2019a), a naturalistic QA dataset consisting of context passages followed by a yes/no question. For all tasks, we use a zero-shot setup: the model is prompted only with the question, context, and answer options. We measure accuracy as the frequency with which the model prefers the correct answer token to the incorrect one.

Results Our results (Table 3) indicate that only Gemma-2-2b performs well on all tasks;⁷ it also answers GPRC questions with above-chance accuracy, so we focus the rest of our analysis on it.

6.2 Feature and Causal Analysis

Ideally, a model answering GPRC questions should rely on features indicative of the input’s parse. To verify this, we can measure the overlap between the features from §4.2 and those obtained via AtP-IG on the GPRC questions. We can also ablate the features from §4.2 and measure the performance of the model on GPRC questions.

Experiment We discover sparse feature circuits for GPRC questions using AtP-IG, as in §4.2. The prompts consist of complete sentences and questions, $m = p(\text{Yes}) - p(\text{No})$, and our score threshold is 0.05. We measure the overlap between the circuits from §4.2 (denoted C_1) and the GPRC circuits (denoted C_2) as the intersection-over-union (IoU) of C_1 and C_2 ’s features.

We also check if C_1 ’s features causally influence the GPRC task. As in §4.3, we annotate C_1 features and place them in groups, like subject or object detectors (we causally verify these groups’ relevance in App. D.2). Then, we manipulate these features as in prior experiments, and record model accuracy: we upweight subject detectors and zero ablate object detectors to promote the non-garden-path reading, aiming to increase model accuracy; we do the reverse to decrease it.

Results There is little feature overlap across circuits: the IoU is 0% for NP/S, and 0.2% for NP/Z. Accordingly, Gemma 2 does not rely extensively on features from C_1 to answer follow-up questions: performance changes little when intervening on

⁷We note that BoolQ is challenging: even otherwise well-performing models obtain close to 70–80% performance, even with demonstrations. We thus take 70% as positive evidence of the model’s binary QA ability.

these features. Indeed, the top GPRC features are unrelated to either parse; many are not syntax-sensitive, but are instead spurious features that promote *Yes* or *No*. *Yes*-promoting features often activate on phrases related to agreement, such as “Certainly” or “Of course”. Given that the effect of C_1 ’s syntax-sensitive features is not exactly 0, the model does use them to a non-zero extent; nonetheless, they explain little of the model’s GPRC behavior.

This precludes an analysis of repair and reanalysis. While this leaves RQ3 open, it sheds new light on RQ1: LMs appear to rely on spurious features when answering questions that crucially rely on a correct syntactic parse of the prior sentence.

7 General Discussion and Conclusions

When conducting behavioral analyses, one must be cautious in (but not entirely averse to) imposing human-like cognitive abstractions onto LMs. Despite high performance on syntactic evaluations, we have observed that LMs rely on both human-like syntactic abstractions as well as spurious features. Indeed, many influential features activated on tokens before relevant syntactic information for *either* reading of the sentence had appeared. This underscores the importance of mechanistic investigations of LM behaviors: even when models perform well, it may not always be for the reasons that an informed researcher would anticipate.

We have seen that LMs *represent* ambiguities, holding on to multiple interpretations of partial sentences. However, it remains unclear if LMs deploy mechanisms that *recognize* or adjudicate between mutually exclusive possibilities. The representation–recognition distinction is crucial: ambiguity has many functions (e.g., humor and politeness), but detecting these requires recognizing ambiguity as a meaningful signal. We leave the question of ambiguity recognition to future work.

LMs did not rely on prior features when answering garden path follow-up questions, precluding study of repair/reanalysis. Thus, how or if LMs handle earlier representations when they are no longer relevant remains an open question. While we cannot definitively rule out the existence of repair/reanalysis circuits, we can claim that these features are not the most influential in the GPRC circuits. We hope that future advances in sparse autoencoders and automated interpretability methods will enable us to more deeply understand sophisticated and large sparse feature circuits at scale.

Limitations

Our study has focused primarily on individual features. While we do make use of edges between features in our qualitative analysis, we have not causally verified what these edges signify. For example, are these AND or OR relations, NOT relations, or some more sophisticated type of feature combination? A deeper investigation could yield greater insights into how repair/reanalysis happens, and how past features remain relevant at later positions (or are made irrelevant).

We have analyzed two language models of significantly differing scales and slightly differing architectures/training setups. While we are confident in concluding that Transformer-based autoregressive language models are generally likely to encode the mechanisms we have discovered, the results could still be strengthened by extending the analysis to a more diverse set of models with more diverse training setups, scales, and architectures. It would be particularly interesting—and helpful in linking our results to the learnability literature—to observe whether these results hold for more cognitively plausible language models, such as those trained on more human-sized datasets (cf. Warstadt et al., 2023).

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A Notes on Behavioral Experiments

In this paper, we measure the probability assigned by the model to the garden-path and non-garden-path readings via $p(\text{GP})$ and $p(\text{non-GP})$, the probability of two individual tokens. Using this sort of naturalistic setup, instead of e.g. prompting the model to explicitly choose one of the garden path sentence’s readings is a way to reduce task demands and more accurately judge pre-trained models’ performance (Hu and Levy, 2023; Hu and Frank, 2024). However, past work also indicates that setups that pit two alternatives against each other can yield inconsistent results if alternatives are chosen poorly (Newman et al., 2021).

Our reasons for choosing this setup are twofold. First, the most robust setup, which would involve summing the probabilities of all garden-path and non-garden-path continuations, is very both computationally and technically infeasible. Second, while we could instead measure GP and non-GP

via sets of tokens, rather than individual tokens, doing so did not change our experimental results in early trial runs. This is due to the fact that our pre-defined GP and non-GP tokens are already the most probable tokens. While there are some tokens that could be used to expand the non-GP token set, e.g. *is*, *does*, *should*, *could*, defining precisely which tokens should be included is challenging: tokens must be third-person verbs that cannot be interpreted as past participles. With all of this in mind, we stick with a simpler setup.

B Faithfulness

Faithfulness is a metric commonly employed in circuit analysis studies (e.g., Wang et al., 2023; Conmy et al., 2023; Hanna et al., 2023; Miller et al., 2024; Marks et al., 2024; Hanna et al., 2024). The metric aims to capture the proportion of model behavior on dataset \mathcal{D} explained by the circuit. More concretely, given target metric m , full model \mathcal{M} , and circuit \mathcal{C} , we follow Marks et al. (2024) in defining faithfulness F as the average normalized ratio of m given \mathcal{C} over m given the full model:

$$F = \mathbb{E}_{x \in \mathcal{D}} \left[\frac{m(\mathcal{C}, x) - m(\emptyset, x)}{m(\mathcal{M}, x) - m(\emptyset, x)} \right] \quad (3)$$

We define m as the logit difference between the garden-path completion and the non-garden-path completion given x . $m(\emptyset)$ refers to the logit difference when ablating *all* features. Here, an ablation entails setting a feature’s activation to 0 before reconstructing the activations. The intuition is that the circuit should capture the same proportion of m above its prior (i.e., in the absence of any input-specific information) than the full model captures for as many examples as possible.

Note that when computing faithfulness, we include all nodes whose *absolute* $\hat{\text{IE}}$ values surpass the threshold. This means that we include positive- $\hat{\text{IE}}$ components that increase the difference in favor of non-garden-path continuations, and negative- $\hat{\text{IE}}$ components that increase the difference in favor of garden-path continuations. This is because, in ambiguous settings, both readings are possible, and we would like to recover features that are sensitive to both readings.

When computing faithfulness, Marks et al. (2024) give approximately the first $\frac{1}{4}$ of the layers in the model for free—that is, all features in the embedding layer and through the end of layer 1 for Pythia. In other words, all features in these

layers are implicitly included in the circuit, regardless of whether they passed the effect threshold. The reasoning is that these features are generally only responsible for detecting that certain tokens have appeared in the inputs; thus, without them, the model would not be aware that these tokens have appeared, and it would therefore not be possible to perform the task. Unlike in their setting, we do not have a distinction between the circuit discovery setting and the evaluation setting,⁸ but we do find that many embedding and layer-0 features still do not appear in the circuits that should. These generally correspond to word detectors for tokens that only appeared in one example in \mathcal{D} . Thus, for Pythia, we give the model only the embedding and layer-0 features for free when computing faithfulness. For Gemma 2, we find that layers 0–2 contain word detector features, so we give all features layers 0, 1, and 2 for free when computing faithfulness.

Our faithfulness results for Pythia-70m in §4.2 are either much lower or much higher than 1.0. For NP/S, we obtain a faithfulness of 0.20, which means that we have recovered 20% of the logit difference between the non-garden-path and garden-path continuations as compared to the full model. For NP/Z, we obtain a faithfulness of 3.48, meaning that our circuit’s logit difference is over 300% higher than the full model’s. For Gemma-2-2b (circuits in App. E), the NP/S circuit has faithfulness 0.07, whereas the NP/Z circuit has faithfulness 0.23. 0.20 is on par with the faithfulness values of Marks et al. (2024) for subject–verb agreement, but 3.48 is very high, and likely means that we have not captured many of the important *negative-effect* (garden-path-upweighting) features. Indeed, when we lower the effect threshold, we observe that faithfulness slowly (but non-monotonically) approaches 1. The Gemma NP/S circuit’s low faithfulness of 0.07 suggests that we must include many more features to capture the full mechanism. This is unsurprising, given that this model is significantly larger than Pythia and should therefore require more features to achieve the same behavior.

In follow-up analyses, we find that achieving close to a faithfulness of 1 requires many hundreds of features for Pythia-70m—and thousands

⁸As there is no optimization involved in obtaining the circuit, a held-out set is not always used in circuit discovery. That said, we acknowledge that evaluating circuits on held-out data makes it more likely that the discovered mechanism will generalize to wider distributions of inputs.

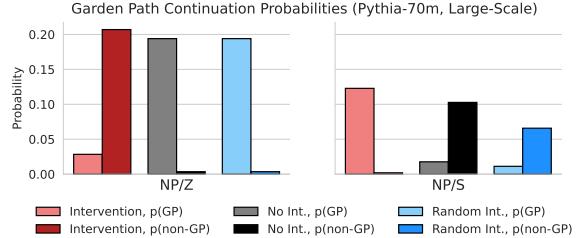


Figure 6: Mean probability of GP and non-GP continuations under interventions for Pythia-70m, on the larger-scale SAP Benchmark. Interventions on interpretable features reverse model behavior, as expected; random interventions do not change behavior.

for Gemma-2-2b.⁹ Currently, this number of features is not tractable to annotate manually, and our initial experiments revealed that automated feature labeling methods such as those of Bills et al. (2023) tend to not be sensitive to syntactic distributions, instead preferring purely lexical or semantic interpretations of feature activation patterns. Future work could enable new mechanistic analyses by improving the ability of automated neuron/feature explanation techniques to detect syntactic distributional features.

C Causal Experiments on a Larger Dataset

The dataset from Arehalli et al. (2022) that we adapt for feature circuit finding is small. This is important, because we manually adapt it to be compatible with our methods. In particular, we craft the unambiguous examples described in §4.1, and also force every example to have the same token length. The latter is key, because, if we wish to estimate the importance of a feature *at a given position* over a number of different examples, each example must have the same token length, and the type of token at each position (e.g. verb, final noun, etc.) must be the same. For this reason, it is currently infeasible to run these experiments (or any other feature experiments) on a larger, non-handcrafted dataset.

These same restrictions do not apply to the causal experiment. In that experiment, as long as we know where the verb and final noun are located in the sentence, our sentences may have different lengths, and different semantic content at each position. Taking advantage of this, we run our causal experiment (see §4.3) again on a larger dataset.

⁹See App. D for faithfulness values for Gemma 2’s circuits.

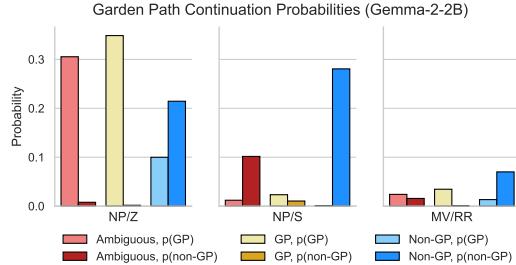


Figure 7: Mean probability of tokens corresponding to garden path (“,”/“.”) and non-garden-path (“was”) readings of the input for Gemma-2-2B, aggregated by garden path structure. Inputs are either **ambiguous**, or compatible with only a **garden-path** or **non-garden-path** reading. (Non)-garden-path tokens are more probable given (non)-garden-path inputs. In ambiguous cases, the model prefers the garden path reading, except for NP/S inputs.

We use the syntactic ambiguity benchmark (SAP Benchmark, Huang et al., 2024), of which Arehalli et al.’s dataset is a subset. This dataset has 7952 NP/Z sentences and 7948 NP/S sentences. We follow the methods from §4.3 exactly, taking special care to accommodate the different lengths and positions in this dataset. We perform this analysis only on Pythia-70m-deduped; performing this on Gemma-2 (2B) would be rather slow.

Our results (Figure 6) show that the features we found in §4.2 generalize to this larger dataset as well, even though they were found on a very small subset thereof. Our ablations successfully induce the model to produce non-GP continuations for NP/Z sentences, and GP continuations for NP/S sentences, reversing its initial preferences, exactly as in §4.3. Again, the random ablations are ineffective, leaving performance close to the no-intervention baseline.

D Results for Gemma-2-2b

To ensure our findings are not merely a function of model size or the Pythia SAEs, we also replicate the experiments for Gemma-2-2b. We first present results for the behavioral analysis (App. D.1). Then, after discovering feature circuits for NP/S and NP/Z (shown in App. E), we causally verify the labels we assign to these features (App. D.2).

D.1 Behavioral experiments

Here, we present behavioral results for Gemma-2-2b. The experimental setup is the same as that described in §4.1. For all sentence structures, findings are largely consistent as those for Pythia: Gemma

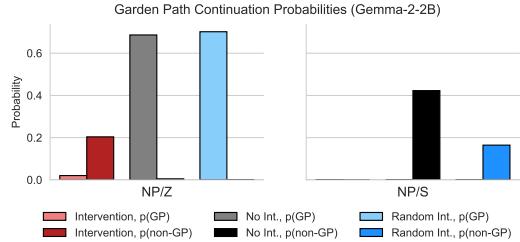


Figure 8: Mean probability of tokens corresponding to garden-path and non-garden-path readings of the input for Gemma-2-2b, aggregated by garden path structure. We either intervene on interpretable features to induce the opposite behavior, or intervene on random features. The interventions on interpretable features are effective in the way we expect, whereas random interventions do not change behavior.

2 upweights and downweights garden-path tokens in appropriate contexts. For ambiguous inputs, the model gives more probability to garden-path continuations in NP/Z, but non-garden-path continuations in NP/S. For MV/RR, Gemma-2b assigns higher probability to non-GP continuations than GP continuations in contexts that license non-GP continuations only. This is distinct from what was observed in Pythia, where probabilities for both continuations were closer to each other, with GP continuations being slightly more probable.

D.2 Causal verification

Having shown that Gemma 2 prefers the GP reading for NP/Z, we aim to induce the dispreferred non-GP reading by clamping subject detectors to high activations (100.0) at the final noun, and clamping object detectors to low activations (0.0). Note that the artificial high activation here is much larger (100.0) for Gemma 2 than what we used for Pythia (2.0). This is because the activations are generally much larger in the Gemma 2 SAEs; indeed, activations of 100.0 are not necessarily out of distribution. For NP/S, Gemma 2 prefers to non-GP reading, so we attempt to induce the dispreferred GP reading by doing the opposite—namely, setting the subject detector and object detector features to 0.0 or 100.0, respectively, and by clamping the sentential-clause-verb detectors to 0.0 at the verb position. As in §4.3, we compare to a baseline where we clamp the same number of randomly sampled features to high or low activations.

Our findings (Figure 8) suggest that the features we find are causally relevant, and in the way we expect. For NP/Z, we can change the model’s

probabilities such that $p(\text{non-GP}) > p(\text{GP})$. For NP/S, we can decrease the originally preferred $p(\text{non-GP})$. The increases in $p(\text{GP})$ is difficult to visualize, but present: $p(\text{GP})$ is increased from 5×10^{-6} to 4×10^{-3} , and because the new $p(\text{non-GP})$ is 1×10^{-9} , we have induced a relative preference for the originally dispreferred reading. Nonetheless, it is likely that other continuations outside of the GP and non-GP tokens we consider have now become more probable than either of these two possibilities.

E Feature Circuits

Here, we present the full sparse feature circuits for NP/S and NP/Z. We include feature circuits for both Pythia-70M and Gemma-2-2B. For both Pythia circuits, we set the node threshold to 0.1 and the edge threshold to 0.001. To keep the feature circuit a size that will fit onto a page (and to keep the number of features we must manually annotate reasonable), we slightly increase the node threshold to 0.12 when discovering the Gemma 2 circuits.

Because we include any node where the *absolute value* of the I \hat{E} is over the node threshold, we include positive- and negative-effect features. Positive-effect features increase the relative probability of the non-garden-path continuation over the garden-path-continuation, whereas negative-effect features increase the garden-path continuation probability relative to the non-garden-path continuation. We manually annotate all features in these circuits by observing their activation patterns and the tokens whose probabilities are most affected when the feature is ablated.¹⁰

The sparse feature circuits for NP/Z (Figures 10 and 12) are similar across models. Both contain primarily spurious or word-level features in the lower layers, and more syntax-sensitive features in the upper layers. See Figure 3 for a condensed version of Pythia’s NP/Z circuit, where we summarize the main categories of features and their effects on the model’s preferred continuation. Pythia’s NP/Z circuit contains 65 features, and Gemma 2’s contains 182.

The sparse feature circuits for NP/S (Figures 9

¹⁰We acknowledge that there are issues in both precision and recall when assigning textual explanations to neurons (Huang et al., 2023), and that these issues extend to sparse features. Our causal verification experiments mitigate this somewhat, but natural language is ultimately an ambiguous medium for expressing the functional role of model components. Future work should consider more formal ways of describing sparse features.

and 11) show similar trends. See Figure 13 for a condensed version of Pythia’s NP/S circuit. Note that more of the features have negative effects in the NP/Z circuits than in the NP/S circuits, as both models more strongly prefer the garden path continuations for NP/Z inputs. Pythia’s NP/S circuit contains 155 features, and Gemma 2’s contains 179.

F Structural Probe Training and Results

F.1 Probe Details

We use Eisape et al.’s (2022) MLP action probes to probe Pythia-70m’s internal parse information. These probes take in the representations of two words,¹¹ and compute the probability of a given parse action a as

$$P(a) \propto \exp \left(e_a^\top \text{MLP}([\mathbf{h}_1, \mathbf{h}_2]) + b_a \right), \quad (4)$$

where \mathbf{h}_1 and \mathbf{h}_2 are the hidden representations of the words whose relation you wish to predict, and e_a and b_a are learned weight and bias terms respectively.

While we consider the parse probes in isolation, Eisape et al. (2022) use them as part of a larger parsing architecture. Specifically, they rely on the arc-standard dependency formalism (Nivre, 2004), which parses the input into subtrees which are placed on a stack and repeatedly combined with each other via parse actions in order to obtain a full (incremental) parse of the input.

There are three parse actions: LEFT-ARC, which pops the first two subtrees s_1, s_2 off the stack and draws an arc from s_1 to s_2 ; RIGHT-ARC, which does the same, but draws the opposite arc; and GEN, which indicates no relation, and moves the parsing process forward by generating another token.

Notably, LEFT-ARC and RIGHT-ARC refer not to the position of words in the sentence, but to the direction of the arc between popped subtrees. This is why the non-garden-path reading corresponds to the LEFT-ARC action; during normal parsing of our garden path fragments, the final noun heads s_1 , while the verb heads s_2 , so arcs are reversed with respect to their appearance on paper.

F.2 Probe Training

Following Eisape et al. (2022), we train our probes on the training split of the Penn Treebank (Taylor

¹¹Our dataset contains no multi-token words, but during training, multi-token words are aggregated to form a single-token representation.

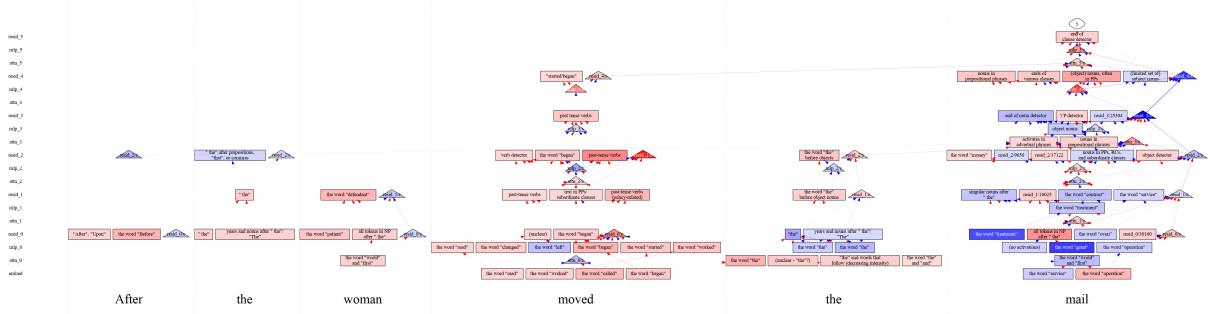


Figure 9: Sparse feature circuit for Pythia-70m on the NP/Z garden path structure. Features with larger positive effects are colored in deeper shades of blue; features with larger negative effects are colored in deeper shades of red. Zoom in to view feature annotations.

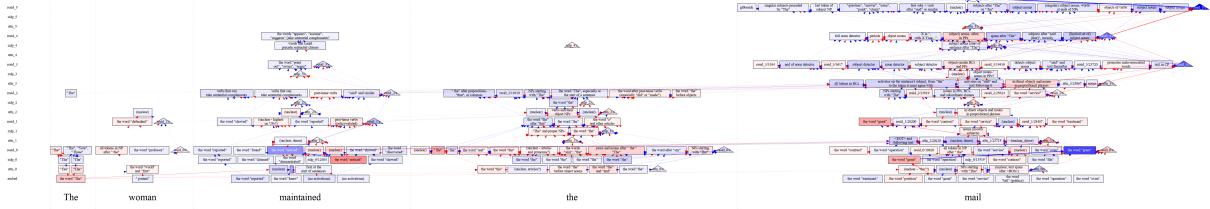


Figure 10: Sparse feature circuit for Pythia-70m on the NP/S garden path structure. Features with larger positive effects are colored in deeper shades of blue; features with larger negative effects are colored in deeper shades of red. Zoom in to view feature annotations.

et al., 2003);¹² we use essentially the same hyperparameters as in their work, modified to work with Pythia-70m-deduped, rather than GPT-2. Then, we also record unlabeled attachment score (UAS) and undirected unlabeled attachment score (UUAS) on the test split, in order to verify that our probes are effective.

Our results (Figure 14) show that the probes are indeed effective. The probes’ UAS and UUAS are similar to the values. The UAS for the last layer is unusually low, even considering the last layer’s lower performance in Eisape et al. (2022), indicating that the direction of dependency relations is not captured, but this tracks with the probes’ poor performance on garden path sentences using representations from that layer.

F.3 Probe Evaluation on Unambiguous Garden-Path-Derived Stimuli

In §5.2, we found that the probes’ judgments on regarding the parse of the sentence matched with our observations based on features and behavior.

¹²Note that the Penn Treebank does not originally come with these splits, which were defined in Hewitt and Manning (2019). Documents 2-21 of the WSJ portion of the dataset are considered the train split; document 22 is the validation split; document 23 is the test split.

But do these probes also behave sensibly on stimuli whose parse is known? To test this, we evaluate the probes on the unambiguous stimuli from our dataset (Table 1), and record their action probabilities. Ideally, the probes should prefer LEFT-ARC on GP sentences, and GEN on non-GP sentences.

Our results (Figure 15) show that this is generally the case: GP sentences elicit primarily LEFT-ARC; non-GP sentences elicit GEN. However, the model struggles on NP/Z non-GP sentences, perhaps because these are the least plausible ones; such sentences are generally written with a comma after the verb, and read strangely. Moreover, both readings do have non-zero probability in most cases, even though their construction should preclude the alternative reading. The probes thus seem somewhat less attuned to syntactically in/valid readings than LM probabilities are.

F.4 Feature Consistency

We can test the consistency between whole-model and probing methods by performing feature analysis with our structural probe. Each probe takes as input residual stream activations, for which we have SAEs; we can thus use AtP-IG to find features that influence the quantity $p(\text{LEFT-ARC}) - p(\text{GEN})$, just as we previously found model features that



Figure 11: Sparse feature circuit for Gemma-2-2b on the NP/Z garden path structure. Features with larger positive effects are colored in deeper shades of blue; features with larger negative effects are colored in deeper shades of red. Zoom in to view feature annotations.

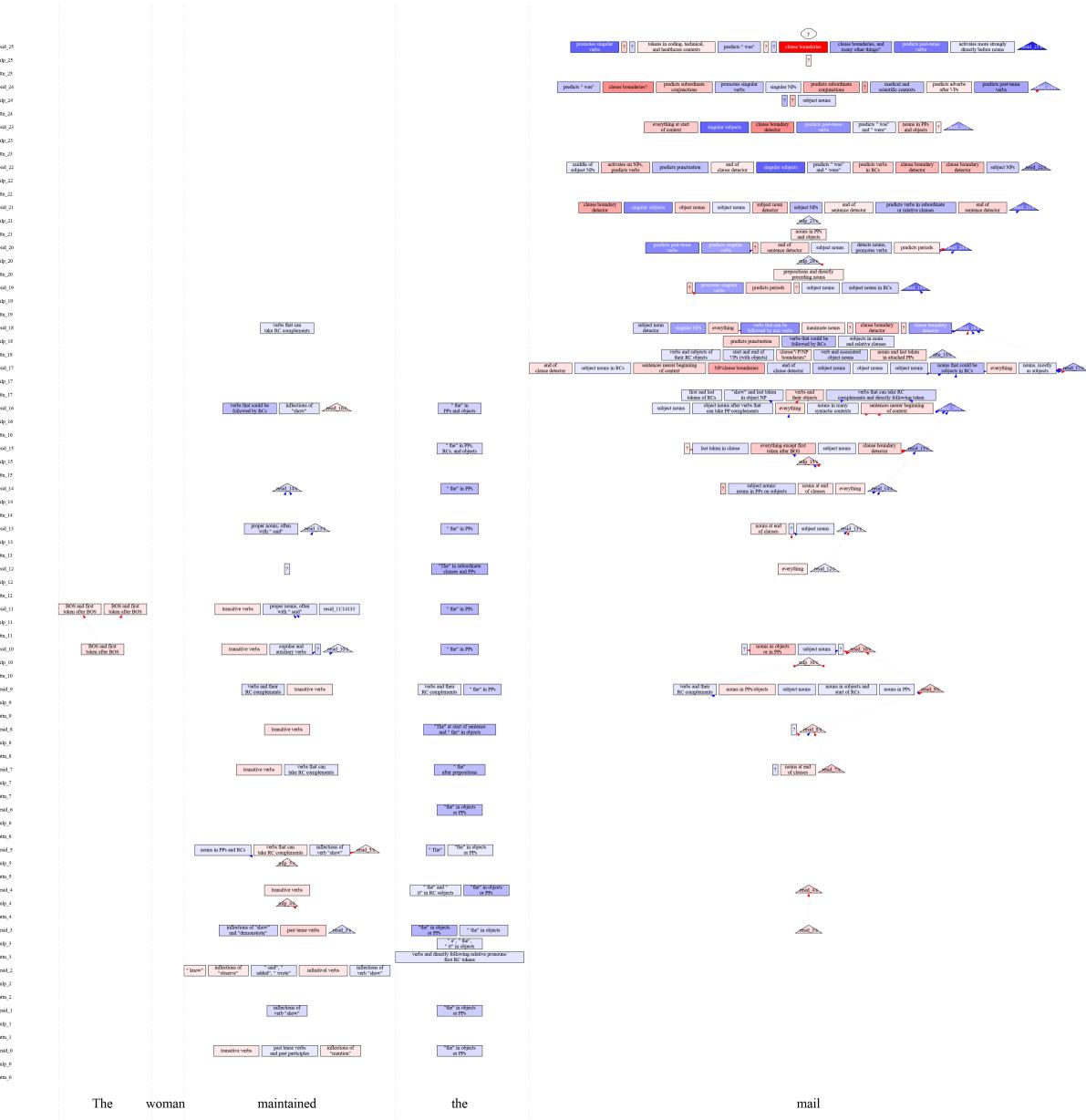


Figure 12: Sparse feature circuit for Gemma-2-2b on the NP/S garden path structure. Features with larger positive effects are colored in deeper shades of blue; features with larger negative effects are colored in deeper shades of red. Zoom in to view feature annotations.

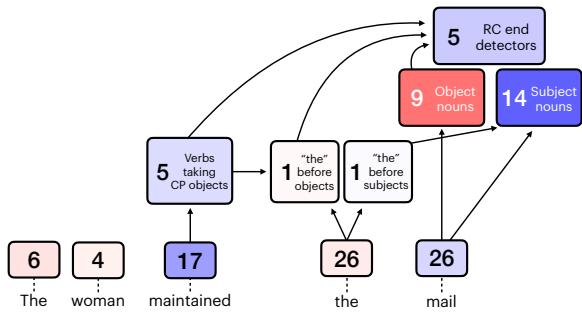


Figure 13: Pythia-70m’s feature circuit for processing NP/S garden path sentences. We group features by their functional role in the circuit and display the number of features in each group. Red features have negative scores, and push the model towards the garden path reading; blue features have positive scores, and do the opposite. Unlabeled early-layer features are word detectors. Many late-layer features encode syntactic features, whereas early-layer features largely consist of word detectors and heuristics. Note that we exclude features that are difficult to interpret from the feature counts.

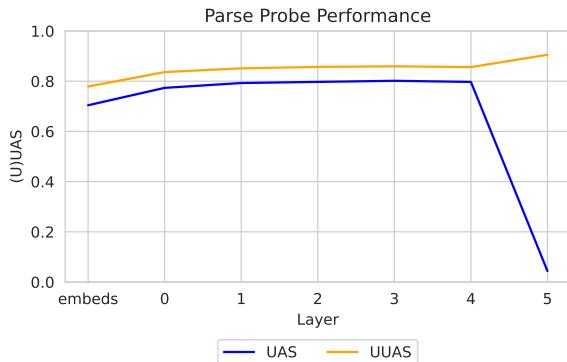


Figure 14: Probe unlabeled attachment score (UAS) and undirected unlabeled attachment score (UUAS) on the Penn Treebank test split, by layer.

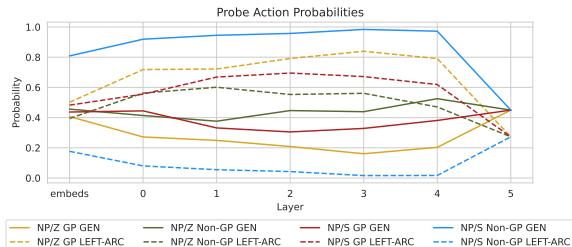


Figure 15: Probe action probability across layers and sentence types (GP and non-GP). GEN corresponds to the non-GP reading, and LEFT-ARC to the GP reading (RIGHT-ARC is implausible and is excluded, as it always receives low probability). GP sentences elicit primarily LEFT-ARC; non-GP sentences elicit GEN. However, both readings do have non-zero probability in both cases.

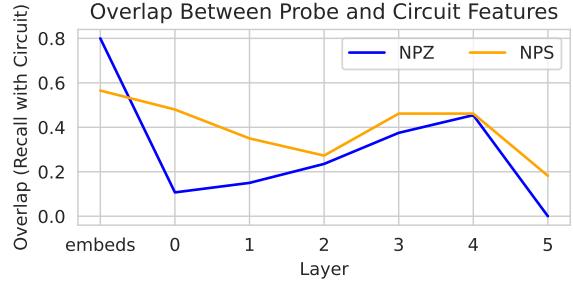


Figure 16: Overlap of probe and circuit features, computed as recall with respect to circuit features. Random chance overlap is near 0, but probe features overlap significantly with circuit features.

Model	MV/RR	NP/S	NP/Z
Gemma-2-2b	73.0	83.3	70.9
–Neg MV/RR features	73.0	83.3	79.2
–Neg NP/S features	70.9	83.3	70.9
–Neg NP/Z features	73.0	85.4	72.9
–Pos MV/RR features	70.9	83.3	60.4
–Pos NP/S features	70.9	83.3	75.0
–Pos NP/Z features	73.0	83.3	70.9

Table 4: Accuracies on follow-up reading comprehension questions given garden path sentences. “Pos” refers to ablating positive-effect features, or those promoting the non-garden-path reading. “Neg” refers to ablating negative-effect features, or those promoting the garden-path reading. Performance generally changes little under ablations, except for NP/Z when ablating MV/RR features.

influenced $p(\text{GP}) - p(\text{non-GP})$. For each structure (NP/Z and NP/S) and layer of the model, we take F_c , the set of features in that layer of the circuit, and F_p , the set containing the top- $|F_c|$ features for the probe. We quantify the sets’ overlap via recall, $\frac{|F_c \cap F_p|}{|F_c|}$. The expected recall for random features would be very near 0; however, Figure 16 shows that the probe features’ recall is quite high. This overlap is highest (0.6–0.8) in the embeddings, but there is also high overlap (0.35–0.45) in layers 3 and 4, which contain interpretable, high-level syntactic features. Thus, even though these probes were trained and attribution performed in very ways, the same underlying features are responsible.

G Reading Comprehension Questions: Performance under ablations

Here, we assess the extent to which we can influence model performance in garden path reading comprehension questions by ablating the GP-

promoting or non-GP-promoting features. Using the same dataset as in §6, we ablate the top 10 and bottom 10 features discovered from §4.2 and then remeasure performance. We hypothesize that ablating the positive features (those promoting the non-garden-path reading) will cause performance to drop, whereas ablating the negative features (those promoting the garden-path reading) will cause performance to increase.

Our results (Table 4) indicate that the ablations are largely ineffective at changing behavior. In some cases, performance does decrease or increase, but typically not to a significant extent. Where differences are significant, it is generally not for the structure from which the features were discovered. For example, ablating positive MV/RR features causes a significant increase in performance for NP/Z questions, and ablating negative MV/RR features also increases performance on NP/Z questions.

H Data Artifacts, Experimental Details, and Risks

Data Artifacts In this paper, we mainly use Arehalli et al.’s (2022) garden path sentence dataset, which is in turn a subset of the syntactic ambiguity benchmark (SAP, now published as Huang et al., 2024), a larger garden path sentence dataset. The latter uses an MIT license, and our use case (intepretability and psycholinguistic research) is appropriate for the license. The other datasets—BoolQ (Clark et al., 2019a) and MCQA (Wiegreffe et al., 2024)—are released with licenses (CC BY-SA 3.0 and Apache 2.0) compatible with research use. All datasets are entirely in English.

We also craft two follow-up sentences per NP/Z and NP/S sentence in the aforementioned dataset. These follow-up sentences, and code for our experiments, will be released upon acceptance.

Experimental Details We perform our experiments using an Nvidia A100 (80GB) GPU and Nvidia RTX 6000 Ada GPU. The former is helpful for finding Gemma feature circuits with a low threshold. In total, running all experiments should take no more than 5 GPU-days on the former (perhaps less). Most of the runtime comes from running the Gemma experiments and training parse probes.

All experiments are implemented in PyTorch (Paszke et al., 2019) using the NNsight interpretability framework (Fiotto-Kaufman et al.,

2024). All LMs used were accessed via HuggingFace (Wolf et al., 2020).

Risks Because our study only attempts to interpret pre-trained models, we believe that it poses few risks; similarly, the basic follow-up questions carry with them few risks.