
The Structure of Relation Decoding Linear Operators in Large Language Models

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Abstract

This paper investigates the structure of linear operators introduced in Hernandez et al. [2023] that decode specific relational facts in transformer language models. We extend their single-relation findings to a collection of relations and systematically chart their organization. We show that such collections of relation decoders can be highly compressed by simple order-3 tensor networks without significant loss in decoding accuracy. To explain this surprising redundancy, we develop a cross-evaluation protocol, in which we apply each linear decoder operator to the subjects of every other relation. Our results reveal that these linear maps do not encode distinct relations, but extract recurring, coarse-grained semantic properties (e.g., *country of capital city* and *country of food* are both in the *country-of-X* property). This property-centric structure clarifies both the operators’ compressibility and highlights why they generalize only to new relations that are semantically close. Our findings thus interpret linear relational decoding in transformer language models as primarily property-based, rather than relation-specific.¹

1 Introduction

From ancient philosophy to modern cognitive science, knowledge has been framed not merely as isolated entities but as interconnected networks shaped by context and structure. Aristotle’s categorical distinctions, Wittgenstein’s concept of family resemblances [Wittgenstein, 1953], and contemporary cognitive theories of prototypes [Rosch, 1973] all emphasize that understanding emerges from recognizing shared properties across diverse contexts. We do not simply store isolated facts, instead, we perceive who does what to whom, what belongs where, and how different ideas interrelate through common attributes. Investigating the underlying structure of how relational knowledge is encoded thus becomes crucial, as it forms the foundation for complex cognitive functions such as generalization, abstraction, and analogical reasoning—capabilities essential for both human cognition and machine learning models.

In this paper, we investigate how transformer language models encode relational knowledge—such as *Michael Jordan plays basketball*—by mapping subjects directly to objects through linguistic predicates. Our investigation builds on the recent work of Hernandez et al. [2023], who show that for a given relation, the transformation from the embedding of a subject to the tokens of the object can be effectively approximated by a single linear operator, called a Linear Relational Embedding (LRE) matrix. Here, we examine relations through the lens of their corresponding linear decoder

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¹Code and data are available at the project website: <https://bit.ly/structure-of-relations>.

operators, and perhaps more crucially, rather than analyzing them one-by-one, we consider them *collectively*. We develop tools to uncover their structure and the underlying regularities with the goal of understanding their collective organization.

Beyond interpretability, we are also motivated by the possibility that these decoder operators admit a more compact, shared representation. Such compression could highlight the core semantic properties shared across different relations, reducing redundancy and perhaps enabling the model to generalize more effectively, analogously to how humans draw on abstract patterns to reason across different contexts. Our experiments with tensor network models explore this hypothesis by seeking compact representations that preserve decoding capacity while exploiting the possible latent structure of relational knowledge.

We summarize our contributions as follows:

- We propose a novel semantic closeness notion to explore the underlying structure of relations. We reveal that relation decoding functions have a property-based rather than a fine-grained relation-specific organization.
- We propose order-3 tensor networks to compress an entire collection of linear decoder functions into a single, compact model. We demonstrate and analyze the effectiveness of this approach.
- We investigate the generalization properties of such tensor network models. We find low level generalization capabilities on generic data, and also provide examples where they excel.

2 Background and Notation

2.1 Relations in Transformer Language Models

One common approach to formalize factual knowledge in language models is through relational triplets (S, R, O) , where a subject S is linked to an object O via a relation R [Miller, 1995, Berners-Lee et al., 2001, Bollacker et al., 2008, Lenat, 1995, Richens, 1956, Minsky, 1974]. Here, $S \in \mathcal{S}$, $O \in \mathcal{O}$, and $R \in \mathcal{R}$, with $\mathcal{S}$, $\mathcal{O}$, and $\mathcal{R}$ denoting the sets of all possible subjects, objects, and relations, respectively. For instance, the sentence “Paris is the capital city of France” corresponds to the triplet (“Paris”, “capital city of”, “France”).

Recent work by Hernandez et al. [2023] demonstrated that for each relation R , the transformation from subject embeddings to object embeddings in transformer-based language models can be effectively modeled by a surprisingly simple decoder: an affine transformation $f_R : \mathcal{S} \rightarrow \mathcal{O}$, $f_R(S) = W_R v_S + b_R$, where $W_R \in \mathbb{R}^{d \times d}$ and $b_R \in \mathbb{R}^d$, and $d \in \mathbb{N}$ is the embedding dimension of the transformer, and v_S is the embedding of the subject. The effectiveness of such affine approximations suggest a surprisingly simple internal organization for relational knowledge within transformer layers.

2.2 Technical Details

Throughout our experiments we study LLMs based on the transformer architecture [Vaswani et al., 2017]. The model maps input tokens into a d -dimensional space via an embedding layer L_{emb} . This is followed by a sequence of $H \in \mathbb{N}$ transformer blocks, denoted as L_h ($h \in [H]$), and concludes with a final transformer head L_{head} . The entire transformer network is thus the function $t = L_{\text{emb}} \circ L_1 \circ L_2 \circ \dots \circ L_{k-1} \circ L_k \circ L_{\text{head}}$. Approximating an affine relation decoder thus equals to modeling the function $g = L_l \circ L_{l+1} \circ \dots \circ L_{k-1} \circ L_k$ (i.e., the function of the transformer from the l th layer until L_{head}) with an affine transformation, where k is the total number of blocks before the L_{head} component.

One could find many ways to infer an affine approximation of the function g . In this paper, we infer it with a **parameterized modeling function**, instead of directly approximating it using the Jacobian of g (as shown in Hernandez et al. [2023]).

Once we have a linear relation embedding (LRE) matrix W_R and a bias b_R , we apply the affine function $f_R(v_S) = W_R v_S + b_R$ to the subject embedding v_S . Then we pass the resulting vector to the transformer’s output head to generate the next token. The performance of the relation decoding function is evaluated using the notion of *faithfulness*, which essentially measures prediction accuracy.

Definition 1 (Faithfulness) Given a subject token embedding $\mathbf{v}_S \in \mathbb{R}^d$ and an inferred linear relation encoder matrix $W_R \in \mathbb{R}^{d \times d}$ and bias $\mathbf{b}_R \in \mathbb{R}^d$ for a relation R , we define the faithfulness of the affine decoder $f_R(\mathbf{v}_S) = W_R \mathbf{v}_S + \mathbf{b}_R$ as the top-1 accuracy of the predicted object token. Specifically, we compute $\hat{\mathbf{v}}_O = L_{\text{head}}(f_R(\mathbf{v}_S))$, where L_{head} is the transformer’s output head, and compare the resulting token prediction against the ground truth object token. Faithfulness is then the proportion of correct predictions across a set of subject-relation-object triplets.

2.3 Models and Datasets

We used three transformer-based language models in our experiments: GPT-J [Wang and Komatsuzaki, 2021], Llama 3.1 8B [Dubey and et al., 2024], and GPT-NeoX-20B [Black et al., 2022b]. Unless stated otherwise, the results presented in the main text correspond to GPT-J, with additional analyses and details for the other models provided in Appendix C.

We use three datasets: **1) The Dataset of Hernandez et al. [2023]**: it consists of 47 distinct, mostly orthogonal relations (i.e., *fruit inside color* and *adjective antonym*). **2) Extended Dataset**: our extended version of the dataset of Hernandez et al. [2023] that introduces several new relations, allowing a better understanding of the relational structure. **3) Mathematical Dataset**: a novel relational dataset containing mathematical operations (i.e., *number plus 6* and *number times 9*) providing a more controlled, and in a sense a denser relational structure. For further information, we refer to Appendix D.

3 Training Tensor Networks to Represent a Collection of Relations

Matrices representing relations live in $\mathbb{R}^{d \times d}$, where d is the dimension of the embedding space. In the case of GPT-J, $d = 4096$, meaning even a single matrix has more than 16 million parameters. With a collection of 100 relations that amounts to approximately 1.6 billion parameters. In this section, we explore the following question:

Is it possible to represent a collection of relations in a compact form, and can this representation rely on the striking simplicity of linearity?

From the naïve representation to tensor networks A straightforward way to represent multiple relation matrices is to stack them to form an order-3 tensor. Specifically, a collection of n matrices each of size $\mathbb{R}^{d \times d}$, can naturally be regarded as a single 3-tensor of dimensions $\mathbb{R}^{d \times d \times n}$. A primary approach to ‘compress’ matrices in a linear way is via low-rank approximation. A more general, tensor-analogous approach would involve decomposing this order-3 tensor to produce a representation that retains the information content and the functionality of the original tensor, while using significantly fewer parameters. The notion of *tensor networks* offers a principled way and serves as a remarkably powerful tool for this endeavor: any tensor network having three free legs of dimension d can be viewed as a representation of an order-3 tensor. (Regarding tensor networks, we restrict ourselves to introducing only the minimal terminology required for our models in Appendix F. For a more detailed introduction we refer to Ahle [2024].) Furthermore, inner dimension constraints serve as bottlenecks—analogously to rank constraints—significantly reducing the parameter count. The number of possible internal structures of ‘3-legged’ tensor networks is vast (in fact, theoretically infinite). While this richness of possibilities opens up a plethora of opportunities worth for exploration, for the sake of a compact exposition, here we explore only two of these.

3.1 Tensor Network Architectures

A *tensor network* is a collection of tensors $\mathcal{T} = \{T^1, T^2, \dots, T^k\}$ with a pairing of the legs of the tensors, where each pair connects legs of equal dimensions. Unpaired legs are called ‘free legs’ and their number is called the order of the network. The ‘free legs’ of a tensor network are often simply referred to as ‘legs’. We can draw these networks as tensor diagrams: dots are tensors, lines are their legs, and joined legs link tensors like edges in a graph. Each leg has a label. One labeled picture therefore captures both the layout and the workings of the whole tensor network. In this paper, we implement two tensor network classes. See Fig. 1b for the diagrams of these tensor networks.

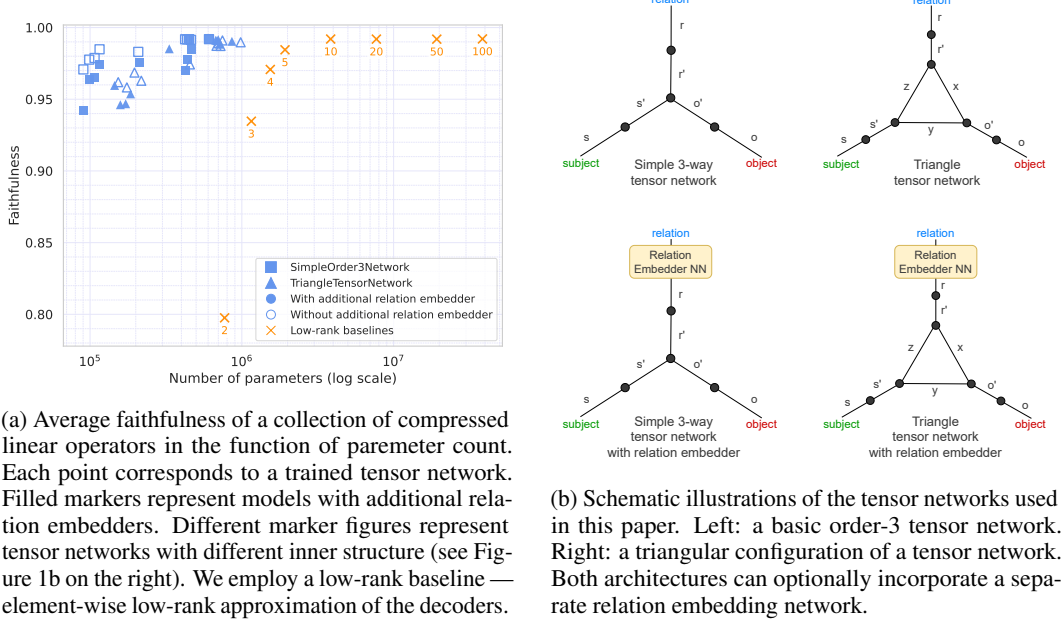


Figure 1: Compressing relation decoding linear operators with order-3 tensor networks.

SimpleOrder3Network The network consists of an order-3 tensor $T^0 \in \mathbb{R}^{d_{s'} \times d_{r'} \times d_{o'}}$ at the core. To connect it with the embeddings of the transformer embeddings, we use three order-2 tensors (i.e., matrices) $P_{s,s'}^1 \in \mathbb{R}^{d \times d_{s'}}$, $P_{r,r'}^2 \in \mathbb{R}^{d \times d_{r'}}$, $P_{o,o'}^3 \in \mathbb{R}^{d \times d_{o'}}$ to project the inputs into the appropriate space. We call $d_{s'}$, $d_{r'}$ and $d_{o'}$ the inner dimensions of the network. The relation-to-matrix mapping implemented by this network can be written out as

$$T_{s,o}^R = T_{s,r,o} \mathbf{v}_r = \sum_{r,s',r',o'} \mathbf{v}_r P_{r,r'}^2 T_{s',r',o'}^0 P_{s,s'}^1 P_{o,o'}^2,$$

where $T_{s,o}^R$ denotes the relation decoder approximation obtained from the tensor network T and relation embedding $\mathbf{v}_r$ for relation R .

TriangleTensorNetwork The network consists of three inner order-3 tensors $T_{s',y,z}^1, T_{x,r',z}^2, T_{x,y,o'}^3$ in $\mathbb{R}^{d_{s'} \times d_y \times d_z}, \mathbb{R}^{d_x \times d_{r'} \times d_z}, \mathbb{R}^{d_x \times d_y \times d_{o'}}$ respectively, and three 2-tensors (matrices) $P_{s,s'}^1 \in \mathbb{R}^{d \times d_{s'}}$, $P_{r,r'}^2 \in \mathbb{R}^{d \times d_{r'}}$, $P_{o,o'}^3 \in \mathbb{R}^{d \times d_{o'}}$ projecting the transformer embeddings into the appropriate space. Similarly as above, $d_{s'}$, $d_{r'}$ and $d_{o'}$ are the inner dimensions of the network, serving as a bottleneck. The vector-to-matrix mapping implemented by this network can be written out as:

$$T_{s,o}^R = T_{s,r,o} \mathbf{v}_r = \sum_{r,s',r',o',x,y,z} \mathbf{v}_r P_{r,r'}^2 T_{s',y,z}^1 T_{x,r',z}^2 T_{x,y,o'}^3 P_{s,s'}^1 P_{o,o'}^2.$$

Parameter counts The total number of parameters depends on the embedding dimension d of the language model and the inner dimensions $d_{s'}$, $d_{r'}$, and $d_{o'}$ of the core tensors. For the *SimpleOrder3Network*, the parameter count is $N_{\text{Simple}} = (d \cdot d_{s'} + d \cdot d_{r'} + d \cdot d_{o'}) + (d_{s'} \cdot d_{r'} \cdot d_{o'})$. The first term corresponds to the three projection matrices, which dominate the total parameter count, while the second term represents the compact order-3 core tensor. For the *TriangleTensorNetwork*, the total parameters are $N_{\text{Triangle}} = (d \cdot d_{s'} + d \cdot d_{r'} + d \cdot d_{o'}) + 3 \cdot (d_{s'} \cdot d_{r'} \cdot d_{o'})$, reflecting three interconnected order-3 tensors in the core.

From matrices to affine maps The networks above produce matrices—linear maps with no bias—but our task need to produce affine maps. We can embed the bias term directly in the network by enlarging the appropriate bond dimension with 1. At inference time, append a constant 1 to the subject vectors, during training the extra column of weights learns the bias jointly with the rest of the matrix. This simple tweak converts the linear output into an affine map without altering the overall architecture.

Additional embedder network on the relation leg Optionally, both architectures can be extended with a *Additional Relation Embedder* to loosen the rather strong assumption of linearity on the relation embeddings before entering the tensor network. We experimented with an embedder consisting of three dense feed-forward layers with ReLU [Agarap, 2018] activations.

3.2 Training Tensor Networks

A tensor network even with a fixed structure can still be obtained and utilized in various ways. Tensor parameters may be determined through factorization or optimization algorithms. Once constructed, the resulting tensor network can be used by evaluating contractions on its free legs.

End-to-end training of tensor networks We fix the parameters of the LLM and train only the tensor network. We train our tensor network using the task loss, i.e., the cross-entropy loss for the predicted object token and optimize with SGD. Specifically, **1)** we take v_R , the embedding of the relation, **2)** perform a contraction with the tensor network at the relation leg, **3)** read out the matrix representing the LRE, **4)** apply it to the subject embedding v_S , then **5)** pass it to the L_{head} to get the predicted token distribution, **6)** use the cross-entropy loss to match the expected token as a loss function. Formally, our loss function $\mathcal{L}_{\mathcal{R}}$ is:

$$\mathcal{L}_{\mathcal{R}}(T_{s,r,o}) = \sum_{R \in \mathcal{R}} \sum_{(S,O) \in R} CE(\mathbb{1}_O, L_{\text{head}}(T_{s,o}^R(v_S))),$$

where $\mathbb{1}_O$ denotes the one-hot encoded first token of the object O , CE is the cross-entropy loss and v_S is a vector representation of subject S . Throughout our paper we always use the ground-truth object values for training.

3.3 Compression Experiments

In these experiments we evaluate the compression capabilities of both SimpleOrder3Network and TriangleTensorNetwork models. We train these models on the dataset of Hernandez et al. [2023] until convergence and measure the faithfulness of the resulting decoder functions. We performed a grid search for both models with $d_{r'} \in \{2, 4, 6, 8, 30, 100\}$, $d_{s'}, d_{o'} \in \{10, 50, 100, 300\}$; for the TriangleTensorNetwork we fixed $d_x, d_y, d_z \in \{50\}$. We also trained the tensor networks with and without an extra relation embedder. We discuss hyperparameters in Appendix 4.

Baselines As a baseline, we train low-rank LRE matrices *individually*, producing one per relation. Each matrix is optimized independently using the same training objective as the tensor networks. This baseline corresponds to a low-rank representation of each relation matrix, without sharing parameters across relations or introducing any structured connectivity between them. In addition, as a canonical reference point, we note that a linear decoder baseline following the Jacobian-based procedure of Hernandez et al. [2023], which estimates each LRE from a few examples (we used 8 in our setup) achieves a mean faithfulness of 0.41 with approximately 788 million parameters.

Relation decoding matrices are highly compressible Figure 1a summarizes the results by plotting the mean faithfulness against the parameter count of trained tensor network matrices. *We can clearly observe that the relation matrices are highly compressible.* Compared to the “vanilla representation” of stacking the 47 relation matrices together (with an overall parameter count of about 788 million) tensor networks even with less than one million parameters significantly outperform the baselines both in terms of parameter count and faithfulness. We can also observe that tensor network models without separate relation embedders consistently outperform those with them, showing that a linear structure is sufficient for efficient compression.

Do LREs produced by tensor networks retain their sample-wise generalization capabilities?

We also examined the learned relation decoders (LREs) ability to generalize to unseen samples. On the original dataset, the tensor network does outperform or equals the majority baseline in 34 relations out of 47. (See in Appendix B.1.) Figure 4a further illustrates the relationship between parameter count and sample-wise test faithfulness. On the extended dataset, the LREs produced by the tensor networks outperform the majority baseline in 49 relations and equal in 8 relations out of the total 79 relations, with an overall mean test faithfulness of 0.42 compared to the majority-guess baseline of 0.30. Thus, our models retain sample-wise generalization capabilities.

4 Why Compression Works: Toward a Structural Understanding of Relational Matrices

In the previous section, we demonstrated the compressibility of relations. To gain a better understanding of this phenomenon, in this section we explore the following question:

What underlying regularities or shared structures allow the affine relational decoders to be compressed?

4.1 Semantic Similarity of Relations

One natural hypothesis for why compression is possible is that the relations are not entirely independent from each other, and many may share underlying semantic structure. To investigate this, we define a notion of semantic similarity between relations. While the embeddings of the relations (calculated from their names or prompt templates) could also serve this purpose, we opt for a measure more directly connected to the subjects of our investigation: the relation decoders themselves.

Definition 2 (Cross-evaluation protocol) Let $\{(R_i, f_i)\}_{i=1}^k$ be a set of $k \in \mathbb{N}$ relations $R_i \in \mathcal{R}$ and their corresponding decoder functions $f_i : \mathbb{R}^d \rightarrow \mathbb{R}^d$. The cross-evaluation protocol proceeds as follows: for every ordered pair $(j, l) \in [k] \times [k]$, apply the decoder f_j for a relation R_l and record the resulting faithfulness score. Collecting all scores in a $k \times k$ array produces the **cross-evaluation faithfulness matrix**

$$F = [F_{j,l}]_{j,l=1}^k, \quad F_{j,l} = \text{faithfulness}(R_l, f_j).$$

Cross-evaluation as a measure of semantic similarity The methodology of cross-evaluation allows us to measure the extent to which a specific relation decoder can be used to map other relations’ subjects to their objects. Intuitively, if two relations are semantically related, then applying one decoder to the other relation’s samples should yield reasonably faithful predictions, producing a relatively high off-diagonal entry in F . Conversely, low or near-zero entries indicate semantic dissimilarity. In this way, the cross-evaluation matrix may be viewed as an *empirical similarity kernel* over the set of relations—measured through the functional similarity of their decoding functions.

Cross-evaluation results for the dataset of Hernandez et al. [2023] Figure 2a shows the cross-evaluation faithfulness matrix for the 47 relations. We observe that while most of the decoders perform best when evaluated on the relations they were approximated from, there are many off-diagonal elements that are larger than zero—several even exceed a faithfulness value of 0.7. Also, we can notice places where a block structure is apparent. Figure 2b shows a selected subset of the 47 relations to highlight these. Taking a closer look at these matrices, there are cases when we can observe an obvious semantic overlap between relations, e.g., *characteristic gender*, *university degree gender*, and *occupation gender* all share the concept of gender while their subjects differ. There are also examples when the connection between relations is not as evident, and the overlap is syntactic rather than semantic: for example, the *first letter of a word* relation proves effective for *adjective superlative*, likely because many superlatives begin with the same token as their base adjective.

4.2 Uncovering Property-Level Encoding through the Extended Dataset

Motivated by the above observations, to obtain a more detailed picture, we introduce an **extended dataset** of 79 relations intentionally constructed to contain semantic overlaps between relations. This dataset supplements the original corpus with a diverse set of relations designed to share coarse-grained properties (e.g., *gender*, *country*, *antonym*) alongside truly orthogonal relations. Details of dataset construction and relation selection criteria are deferred to Appendix D.

Cross-evaluation results for the extended dataset Figure 3a shows the cross-evaluation results. Our previous observations extend to this dataset as well, providing further evidence that our initial findings are not merely particularities of specific relations, but reflect a more general phenomenon. We can again observe the presence of non-zero off-diagonal elements. Focusing on the relations *characteristic gender*, *university degree gender* and *occupation gender* we notice similarly competitive



Figure 2: Cross-evaluation results for the dataset of Hernandez et al. [2023]. Each cell shows the faithfulness of a matrix obtained using the row relation and evaluated on the column relation.

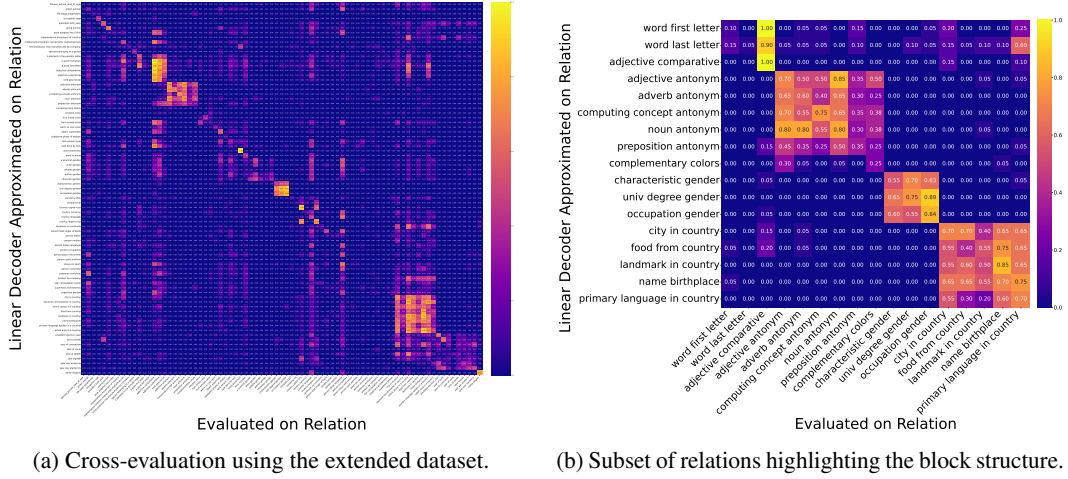
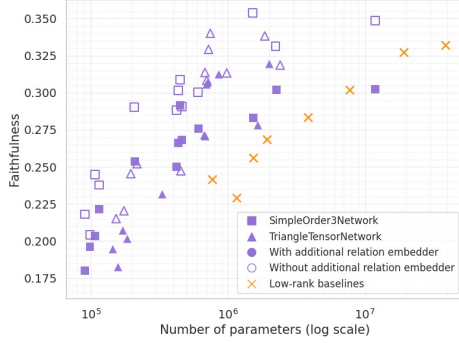


Figure 3: Cross-evaluation results for the extended dataset. The vertical axis indicates the relation used to obtain the matrix, while the horizontal axis indicates the relation it is tested on. Values represent faithfulness scores.

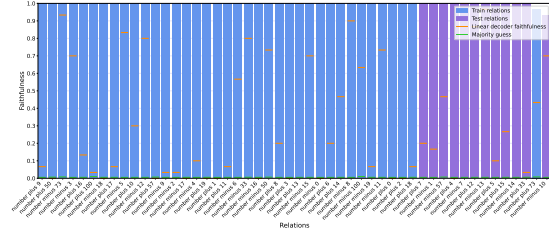
faithfulness in any given permutation during cross-evaluation (around 0.65). The *occupation gender* decoder even outperforms the *characteristic gender* decoder when evaluating on the relation *characteristic gender*. Similarly, although the *fruit inside color* and the *fruit outside color* operators achieve a faithfulness of only around 0.3, they maintain a similar performance during cross-evaluation.

The resulting matrix also exhibits a block-structure: high intra-block faithfulness among relations sharing a property (e.g., *landmark in country*, *primary language spoken in a country* under a *country* block; *adjective antonym*, *noun antonym* under an *antonym* block) contrasted to zero inter-block scores where no common property exists. A prominent identity block also emerges, once again reflecting the identity-like functionality without further common semantic correspondence (cf. *semiconductor chip manufactured by company* and *mathematical theorem named after mathematician*). We observe that inter-block relation decoders work well with a variety of subjects.

Property extractors instead of fine-grained relation decoders Considering all of the above phenomena—most notably, the cross-compatibility of linear relation decoders, and a diversity of subject types they work on—we hypothesize that linear relation decoders are based on common properties of different subject types. Thus, linear relation decoders function more as *property extractors* for specific target objects rather than capturing fine-grained relational structure.



(a) Sample-wise generalization results on the dataset of [Hernandez et al., 2023]. Purple markers denote test faithfulness and orange markers represent the previously used low-rank baselines.



(b) Faithfulness results for the mathematics dataset. Blue bars represent relations from the training set, purple bars from the test set split randomly with a ratio 75%-25% respectively. Green markers denote the majority-class baseline, and orange markers represent the faithfulness values for individually approximated relation matrices as another baseline.

Figure 4: Test faithfulness results on sample-wise generalization on the dataset of [Hernandez et al., 2023] (left), and relation-wise generalization results on the mathematical dataset (right).

With this interpretation, the phenomena above can be explained by the facts that, e.g., the relations *characteristic gender*, *university degree gender* and *occupation gender* are holding a common *gender* property. Likewise, *city in country* and *name birthplace* have the *country* property in common.

In conclusion, our experiments with the extended dataset provide strong empirical support for the hypothesis that *linear relation decoders predominantly capture coarse-grained property patterns rather than specific subject-object mappings*. This finding underscores the potential for exploiting shared structure across relations, driving more aggressive and semantically principled compression.

4.3 Investigating the Low-Rank Structure of Relation Decoder Operators

How much of compressibility remains if we remove semantically similar relations?

Low-rank structure Posing the question allows us to decouple two sources of parameter redundancy: **1)** overlap stemming from the semantic connection between relations, and **2)** any intrinsic low-rank structure that individual decoder matrices might share even when the relations themselves are dissimilar. By isolating the second factor, we can assess whether the high compression ratios reported in earlier sections are merely exploiting semantic redundancy, or whether an additional structure is at play. As the original dataset has a near-diagonal faithfulness cross-evaluation matrix, it serves as a good subject of investigation. Through the lens of the above, Figure 1a shows that without large semantic overlap, *a substantial compression is possible compared even to the low-rank baseline*. This gap suggests that tensor networks capture structural regularities beyond the simple low-rank property of individual relations, jointly exploiting patterns shared across the entire relation set.

5 Generalization Capabilities of Tensor Networks to Held-Out Relations

Having demonstrated that relations share coarse-grained properties enabling drastic compression, in this section we take the final step and ask:

Can tensor networks go beyond mere compression and encode latent properties in a way that enables generalization to held-out relations?

Experimental setup In this section, we split the set of relations into training and test subsets, train a tensor network on the training set, and evaluate whether it can generate a linear relation decoder matrix for an unseen relation embedding. We assess success using the faithfulness metric. (Note that the generalization is thus examined on the level of relations, not on the level of individual subject-object pairs, which would be a much easier task.)

Generalization results for the extended dataset The corresponding results are shown in Appendix B.2. We observe that the model produces high-faithfulness decoders for some test set elements, but fails to generalize for others. Taking a closer look, and building on our cross-evaluation-based semantic closeness metric, we find that the model generalizes only to relations that are semantically so close to those in the training set that their decoder matrices are effectively interchangeable. Thus, the model is able to identify the matrix that corresponds to the correct coarser-grained relation set (or to put it another way, linear property extractor), but fails to generalize in a wider context.

Regarding the vast scale of all possible relations, this outcome is not surprising: broader generalization would require a denser sample of relations and a linear structure among their decoder matrices—assumptions that are quite strong, given the sheer size and diversity of relational semantics. (Note that our tensor network model relies on a simple linear formulation.) We also experimented with additional relation embedders to process the relation input before it enters the tensor network (see Figure 1b). Our motivation was to give the model an opportunity to reshape the relation space into a more linearly organized structure; however, this modification yielded no substantial improvement.

A more realistic setup: generalization results for the mathematics dataset For a more realistic setup, we constructed a relational dataset that is more tightly controlled and may have a more linearly arranged relational structure. This dataset also enables the generation of much finer-grained synthetic relation examples.

Our **mathematics dataset** consists of arithmetic relations modeled as unary operators on integers. (e.g., with relations *number plus X* and *number minus X*). (See Appendix D for more details.) We ran experiments using three random seeds, presenting one in Figure 4b. Across these, our method achieves an average faithfulness of 0.992 with a standard deviation of ± 0.012 on the training set. We observe that the model not only learns the training set perfectly, but also has full generalization capabilities on the test set—the tensor network model outputs decoding matrices that achieve an average faithfulness of **0.96** with a standard deviation of ± 0.031 and a maximum of **0.991**.

Closing the gap between these two generalization results goes beyond the scope of this paper. We identify this as a promising direction for future work, with potential applications related to model performance, compression, and interpretability.

5.1 Ablations — on the importance of relation, subject, and object embeddings

Randomized relation embeddings To assess the role of relation embeddings, we implemented a baseline with randomized relation representations and evaluated it on the mathematical dataset. The results show that removing the semantic information from relation embeddings leads to a drastic performance drop on held-out (subject, object) pairs, while training examples can still be memorized perfectly. These findings confirm that the tensor network relies on meaningful relational representations rather than treating relations as simple categorical identifiers. This is further supported by the generalization experiments, as the close to 100% accuracy is attainable only by correctly predicting objects for subjects associated with multiple relations (e.g., $13+6=19$, $13-3=10$), indicating that it exploits the semantic structure encoded in the relation embeddings.

Randomized subject and object embeddings We also evaluated the effect of randomizing subject and object embeddings. In this setup, each distinct subject and object was mapped to a random vector that remained fixed during training. In our experiments, the tensor network failed to memorize the training set or generalize on held-out pairs (resulting in a faithfulness close to 0 on small tensor networks), indicating that consistent, meaningful entity representations are essential for both memorization and generalization.

6 Related Work

Knowledge representation in deep learning models Knowledge representations have been shown to emerge in neural networks since the original backpropagation results [Rumelhart et al., 1986]. Understanding these representations is widely explored—e.g., implicit entity—models [Geva et al., 2023], dissecting factual recall in attention and MLP layers [Geva et al., 2021, Li et al., 2021], probing classifiers to predict features from hidden states [Conneau et al., 2018, Hernandez et al., 2024], and knowledge-graph embeddings to represent information in low-dimensional spaces [Choudhary et al.,

2021]. Our paper proposes a new, novel method to uncover the underlying structure of knowledge representations with affine relation decoders [Hernandez et al., 2023].

Chanin et al. [2024] observe that the pseudoinverse of the LRE applied to the embedding of the object results in a vector (Linear Relational Concept, LRC) that can be used as a linear probe. For example, the pseudoinverse of LRE “*s city is in country o*” applied to objects (“*France*”, “*Germany*”, “*Italy*”) results in three vectors that can be used to classify cities of the three countries.

Tensor decompositions and compression of neural networks Tensor decompositions have been widely used to compress and accelerate deep models [Novikov et al., 2015, Anjum et al., 2024, Phan et al., 2020]. Dense weight matrices have been converted to Tensor Train format by Novikov et al. [2015], while Ren et al. [2022] applied Tucker decomposition to reduce Transformer-layer parameters in BERT Devlin et al. [2019]. A decomposition has been integrated into LoRA adapters [Hu et al., 2021] by Anjum et al. [2024] and Phan et al. [2020] introduced CP decomposition for stable, low-rank CNN compression. Our setup differs from these methods as we compress approximated relation decoders collectively, rather than decomposing weight tensors individually.

Connections to low-rank adaptation techniques and mixture-of-experts models Applying our framework in the context of low-rank adaptation (LoRA) techniques [Hu et al., 2021] is an interesting and natural extension. A single low-rank LoRA matrix can be expressed with an order-2 tensor network with an essentially arbitrary internal structure. An even closer analogy to our work is to consider LoRA matrices collectively—either those produced across all layers in a single training run, or aggregated from several independent LoRA adaptations. In either case, a tensor-network framework can act as a unified, highly compressed representation of all the LoRA matrices. Such setups can also take contextual information into account on a leg of a tensor network. In a broader context, this line of reasoning can also be related to mixture-of-experts architectures, where structured compression and modular representations are increasingly important. Exploring these connections offers several interesting avenues for future research.

7 Limitations

Our study relies on linear approximations extracted from relatively small language models (with 6, 8, and 20 billion parameters). How these results generalize to larger, instruction-tuned, or mixture-of-experts architectures remains open. Also, the true space of relations among entities in human knowledge is vast, and our dataset represents only a small and biased subset of it. Even though large language models encode extensive factual and conceptual information, systematically mapping the relations they implicitly contain would be currently infeasible. Our work should therefore be seen as a partial exploration of relational structure rather than a comprehensive map of it.

8 Broader Impact

By compressing hundreds of relation decoders into small tensor-network modules, we reduce parameter counts by orders of magnitude. This slashes memory and compute needs, broadening access in resource-constrained settings. Exposing coarse-grained properties clarifies how facts are organized, making a step towards interpretability. Practitioners can more readily understand, debug, and refine factual knowledge in deployed systems. Isolating properties (e.g., gender, nationality, religion) may open a door towards probing or altering broad classes. This raises risks of large-scale fact tampering, or articulation of sensitive attributes without consent, amplifying privacy harms.

9 Conclusions

We have taken steps toward unveiling the latent structure of relation decoders in transformer language models. We empirically showed that these decoders are compressible via order-3 tensor networks and proposed techniques to achieve high reductions in parameter count. By applying a cross-evaluation protocol, we demonstrated that relation decoders do not act as isolated, relation-specific mappings; instead, they organize into common properties recurring across relations. Finally, we analyzed the generalization properties of models learning to represent a collection of relation decoders, finding limited generalization on general language data but robust performance on arithmetic relations.

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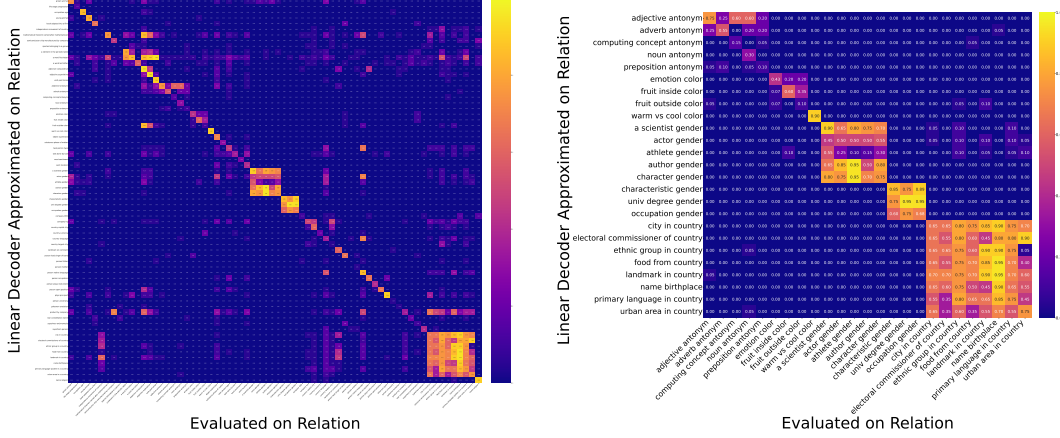
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A Results with Additional Models

In addition to GPT-J [Wang and Komatsuzaki, 2021], we cross-evaluated the relation decoders on the Llama-3.1-8B [Dubey and et al., 2024] and GPT-NeoX-20B [Black et al., 2022b] models. We present the cross-evaluation matrices in Figure 5 and in Figure 6 respectively. The block structure can be clearly observed, demonstrating that our related findings hold across different models.

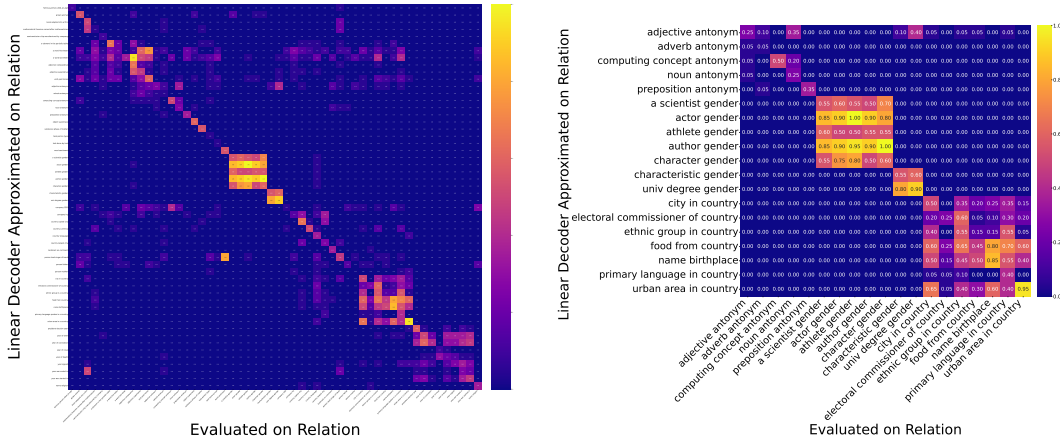
A.1 Llama 3.1 8B



(a) Cross-evaluation matrix on the extended dataset. (b) Subset of relations highlighting the block structure.

Figure 5: Cross-evaluation results for the extended dataset using the **Llama-3.1-8B** [Dubey and et al., 2024] model. Each cell of the matrix shows the faithfulness score calculated using the decoder obtained from the row relation, and evaluated on the column relation.

A.2 GPT NeoX 20B



(a) Cross-evaluation matrix on the extended dataset. (b) Subset of relations highlighting the block structure.

Figure 6: Cross-evaluation results for the extended dataset using the **GPT-NeoX-20B** [Black et al., 2022b] model. Each cell of the matrix shows the faithfulness score calculated using the decoder obtained from the row relation, and evaluated on the column relation.

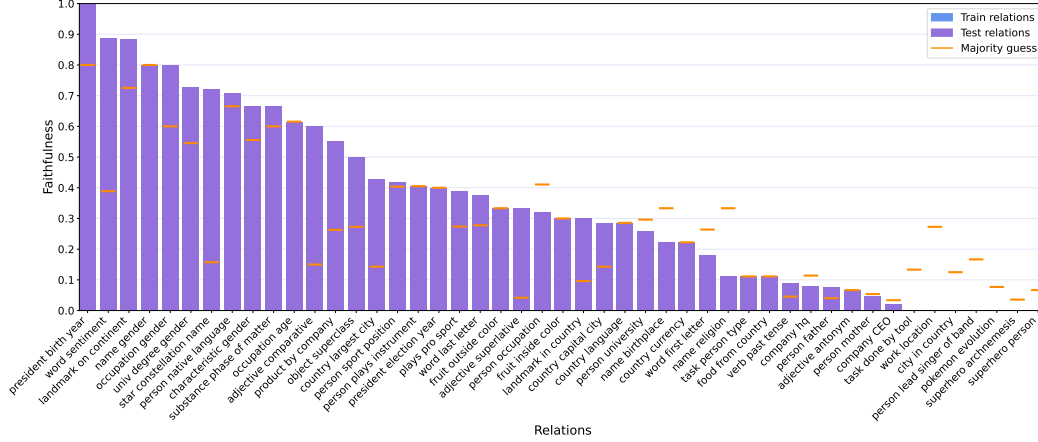


Figure 7: Sample-wise faithfulness results with tensor networks on the dataset of Hernandez et al. [2023]. All bars represent the test set for a given relation, after splitting all samples with a train-test ratio of 75%-25% respectively. Orange markers denote the majority class baseline.

B Additional Generalization Results

B.1 Sample-Wise Generalization on the Dataset of Hernandez et al. [2023]

In this section we discuss Figure 7, depicting the sample-wise test faithfulness results on the Dataset of Hernandez et al. [2023]. We can observe that although the mean test faithfulness values in Figure 4a seems relatively low, the tensor network does outperform or equals the majority baseline in 34 relations out of 47.

On the extended dataset we obtain a mean test faithfulness of 0.42 compared to the majority-guess baseline of 0.30. That said, we outperform the majority baseline in 49 relations and equal in 8 relations out of the total 79 relations.

B.2 Relation-Wise Generalization on the Extended Dataset

In Figure 8 present the our generalization result on the extended dataset. On the test set the tensor network outperforms the majority baseline in 15 relations, and the Jacobian baseline (reproduced with the method of Hernandez et al. [2023]) in 12 relations out of the 20 test relations.

C Models

C.1 GPT-J 6B

GPT-J (published by Wang and Komatsuzaki [2021]) comprises 6 billion parameters and adopts a decoder-only transformer architecture. The model consists of 28 transformer layers, each with 16 attention heads. The vocabulary size is 50,257, and a context window of 2,048 tokens is used. The embedding dimension is 4096. In the transformer blocks, the attention layers and the feed-forward neural networks are ran parallel and summed afterwards with the intent of reducing training time. GPT-J was trained on The Pile [Gao et al., 2020], an 825 GiB English text corpus curated by EleutherAI to support diverse language modeling capabilities. The Pile comprises 22 high-quality subsets, including academic texts (e.g., arXiv, PubMed), web forums (e.g., Stack Exchange), books, legal documents, and code repositories. For further details we refer to Wang and Komatsuzaki [2021].

C.2 Llama 3.1 8B

Meta’s Llama 3.1 8B model Dubey and et al. [2024] is an autoregressive language model comprising 8 billion parameters. It contains 32 transformer layers, each with 32 query-attention heads sharing key/value heads via grouped-query attention (GQA). The embedding dimension is 4096. The gated

Table 1: List of the relations in the dataset of Hernandez et al. [2023].

Relation type	Relation name	Number of samples
bias	characteristic gender	30
bias	univ degree gender	38
bias	name birthplace	31
bias	name gender	19
bias	name religion	31
bias	occupation age	45
bias	occupation gender	19
commonsense	fruit inside color	36
commonsense	fruit outside color	30
commonsense	object superclass	76
commonsense	substance phase of matter	50
commonsense	task person type	32
commonsense	task done by tool	52
commonsense	word sentiment	60
commonsense	work location	38
factual	city in country	27
factual	company CEO	298
factual	company hq	674
factual	country capital city	24
factual	country currency	30
factual	country language	24
factual	country largest city	24
factual	food from country	30
factual	landmark in country	836
factual	landmark on continent	947
factual	person lead singer of band	21
factual	person father	991
factual	person mother	994
factual	person native language	919
factual	person occupation	821
factual	person plays instrument	513
factual	person sport position	952
factual	plays pro sport	318
factual	person university	91
factual	pokemon evolution	44
factual	president birth year	19
factual	president election year	19
factual	product by company	522
factual	star constellation name	362
factual	superhero archnemesis	96
factual	superhero person	100
linguistic	adjective antonym	100
linguistic	adjective comparative	68
linguistic	adjective superlative	80
linguistic	verb past tense	76
linguistic	word first letter	241
linguistic	word last letter	241

D.2 Extended Dataset

We extend the dataset of Hernandez et al. [2023] with 43 newly constructed relations. These relations make the dataset diverse, containing more relations that share a common property not almost always semantically distinct ones. We grouped the additional relations by assuming the following six common properties:

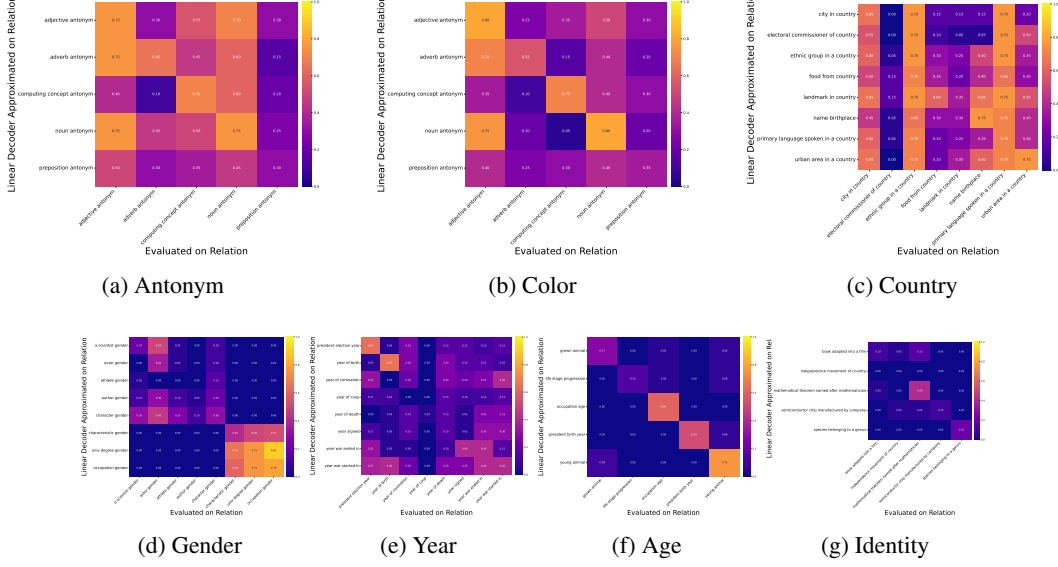


Figure 9: Cross-evaluation matrices of the new relations grouped by assumed properties.

- **age**: relations that are semantically connected to age (e.g., sheep–lamb in *yound animal* and interns–young in *occupation age*)
- **identity**: relations, for which the decoder operator only needs to learn an identity mapping, with no other semantic interpretation
- **antonym**: relations, for which the decoder has to capture the semantic meaning of anyonyms (e.g., *adverb antonym* and *noun antonym*)
- **color**: relations related to the color property
- **gender**: relations related to the gender property (for experimental purposes we use woman and man as target objects)
- **country**: relations, in which a semantic meaning of country is present, the object being only country names
- **year**: relations, in which the object is always a year

Overlapping structures in the extended dataset Figure 9 displays cross-evaluation matrices (evaluated with GPT-J) for the additional relations to provide an overview of the semantic relationships. The figure highlights the initial assumptions for the construction of the extended dataset (i.e., the presence of relations holding common properties like *country*, *year*, or *antonym* properties). Conversely, the relations expected to form a single *gender* group split into two distinct blocks: one connected to gender *role* and another that aligns with the property of *name*. Finally, the relations presumed to have the *age* properties turned out to be mutually orthogonal.

For the full list of relations and sample sizes see Table 2.

Table 2: List of the relations in the extended dataset.

Relation type	Relation name	Number of samples
age	grown animal	11
age	young animal	16
age	famous person died at age	20
age	life stage progression	15
age	president birth year	19
age	occupation age	45

(continued on next page)

Relation type	Relation name	Number of samples
antonym	noun antonym	24
antonym	computing concept antonym	30
antonym	adjective antonym	100
antonym	preposition antonym	30
antonym	adverb antonym	30
bias	name religion	31
color	emotion color	14
color	color mixing with blue	6
color	fruit inside color	36
color	warm vs cool color	20
color	fruit outside color	30
color	complementary colors	8
commonsense	substance phase of matter	50
commonsense	object superclass	76
commonsense	work location	38
commonsense	word sentiment	60
commonsense	task person type	32
commonsense	task done by tool	52
country	food from country	30
country	ethnic group in a country	40
country	primary language spoken in a country	40
country	landmark in country	128
country	electoral commissioner of country	39
country	city in country	27
country	name birthplace	31
country	urban area in a country	40
factual	country language	24
factual	country largest city	24
factual	person occupation	145
factual	person native language	99
factual	superhero person	100
factual	person university	91
factual	star constellation name	117
factual	person lead singer of band	21
factual	person father	92
factual	product by company	103
factual	person sport position	146
factual	country currency	30
factual	person mother	104
factual	company hq	89
factual	pokemon evolution	44
factual	company CEO	89
factual	plays pro sport	117
factual	landmark on continent	59
factual	person plays instrument	121
factual	superhero archnemesi	96
factual	country capital city	24
role	characteristic gender	30
name	author gender	21
name	a scientist gender	24
role	occupation gender	19
name	character gender	23
name	athlete gender	25
role	univ degree gender	38
name	actor gender	25

(continued on next page)

Relation type	Relation name	Number of samples
identity	species belonging to a genus	40
identity	semiconductor chip manufactured by company	39
identity	independence movement of country	39
identity	mathematical theorem named after mathematician	40
identity	book adapted into a film	40
linguistic	verb past tense	76
linguistic	a element in the periodic table	40
linguistic	word first letter	125
linguistic	word last letter	147
linguistic	adjective superlative	80
linguistic	adjective comparative	68
year	year of coronation	22
year	year war started in	26
year	year of birth	27
year	year of death	28
year	year signed	30
year	year war ended in	25
year	year of coup	26
year	president election year	19

D.3 Mathematical Dataset

The **mathematical dataset** contains relations that are semantically close within a mathematical domain. It contains relations on the four basic operations: addition, subtraction, multiplication, and division. We only incorporated the addition and subtraction relations in our experiments—50 relations in total. We present these 50 relations in Table 3, and refer to the released codebase for the multiplication and division part of the dataset.

D.4 Licensing

We release the extended and the mathematical dataset under the MIT license.

E Experimental Details

E.1 Baselines for the Compression Experiments

Below, we discuss how we provide the baselines for the compression experiments. For each relation, we obtain the relation decoder using the Jacobian approximation (presented in Hernandez et al. [2023] and described below). For a baseline, we average the relation-wise faithfulness of the decoders. The tensor-network models were assessed in the same way: we computed faithfulness for each relation individually and then reported the mean across the entire set.

Jacobian decoder approximations We approximate the relation decoder function $o = F^R(s)$ based on the Jacobian $W = \partial F / \partial s$. Given a *subject-object pair*, we approximate the decoder with the first order Taylor expansion:

$$F(s) \approx F(s_0) + W(s - s_0) = Ws + b,$$

where $b = F(s_0) - Ws_0$. To reduce noise, we estimate W and b by averaging a set of subject-object samples rather than relying on a single pair. For further methodological details, we refer the reader to Hernandez et al. [2023].

E.2 Baselines for the Generalization Experiments

To assess the generalization properties of the tensor network-based approximation, we compare the faithfulness scores against two baselines for each relation decoder:

Table 3: List of the *addition* and *subtraction* relations of the mathematical dataset.

Relation type	Relation name	Number of samples
addition	number plus 0	201
addition	number plus 1	200
addition	number plus 2	199
addition	number plus 3	198
addition	number plus 4	197
addition	number plus 5	196
addition	number plus 6	195
addition	number plus 7	194
addition	number plus 8	193
addition	number plus 9	192
addition	number plus 10	191
addition	number plus 11	190
addition	number plus 12	189
addition	number plus 13	188
addition	number plus 14	187
addition	number plus 15	186
addition	number plus 16	185
addition	number plus 17	184
addition	number plus 18	183
addition	number plus 19	182
addition	number plus 33	168
addition	number plus 50	151
addition	number plus 57	144
addition	number plus 73	128
addition	number plus 100	101
subtraction	number minus 1	201
subtraction	number minus 2	200
subtraction	number minus 3	199
subtraction	number minus 4	198
subtraction	number minus 5	197
subtraction	number minus 6	196
subtraction	number minus 7	195
subtraction	number minus 8	194
subtraction	number minus 9	193
subtraction	number minus 10	192
subtraction	number minus 11	191
subtraction	number minus 12	190
subtraction	number minus 13	189
subtraction	number minus 14	188
subtraction	number minus 15	187
subtraction	number minus 16	186
subtraction	number minus 17	185
subtraction	number minus 18	184
subtraction	number minus 19	183
subtraction	number minus 20	182
subtraction	number minus 33	168
subtraction	number minus 50	151
subtraction	number minus 57	144
subtraction	number minus 73	128
subtraction	number minus 100	101

1) Jacobian-based decoder approximations, where we measure the faithfulness of decoders approximated using the Jacobian; and **2) Majority guess**, where we select the most frequent object for each relation and compute faithfulness scores as if this object were consistently predicted.

E.3 Hyperparameters

We present all hyperparameters and their respective values in Table 4. We conducted a grid search using these values and selected the optimal optimizer, batch size, and learning rate indicated under the "Selected value" column to generate all figures in the paper.

Table 4: List of hyperparameters used in our compression experiments.

Hyperparameter	Grid search values	Selected value
General parameters		
Optimizer	{SGD, Adam, AdamW}	SGD
Batch size	{16, 32}	16
Learning rate	{0.01, 0.001, 0.0001}	0.001
d_s	4096	4096
Compression and sample-wise generalization experiment		
$d_{r'}$	{2, 4, 6, 8, 30, 100}	
$d_{s'} = d_{o'}$	{10, 50, 100, 300}	
$d_{x'} = d_{y'} = d_{z'}$	50	
Additional relation embedder	{True, False}	
Number of iterations	15,000	
Dataset	Dataset of Hernandez et al. [2023]	
Relation-wise generalization experiment		
$d_{r'}$	10	
$d_{s'} = d_{o'}$	300	
Additional relation embedder	False	
Number of iterations	5000	
Dataset	{extended dataset, mathematical dataset}	
Low-rank baselines		
Rank	{2, 3, 4, 5, 10, 20, 50, 100}	

E.4 Hardware

All experiments were run on an internal cluster of either Nvidia A100 40GB or Nvidia H100 NVL GPUs. All conducted experiments required cca. 5000 GPU hours.

F Tensors and Tensor Networks

Tensors are multidimensional arrays, generalizing scalars, vectors, and matrices to higher dimensions.

F.1 Basic Concepts

A tensor is defined first and foremost by its order—the number of independent indices it carries. Each index is often called an axis or, in diagrammatic language, a leg. When we want to emphasise this property, we simply say that an n -dimensional (order- n) tensor is an n -tensor. Every leg receives a label.

One can match an index name to each leg; thus a 3-tensor T can be denoted as $T_{x,y,z} \in \mathbb{R}^{d_x \times d_y \times d_z}$, where x, y, z are the indices of the legs.

Tensor multiplications are direct generalizations of matrix multiplication. Given matrices $A \in \mathbb{R}^{d_n \times d_k}$ and $B \in \mathbb{R}^{d_k \times d_m}$, using the tensor notation of $A_{n,k}$ and $B_{k,m}$, the matrix multiplication

$$(AB)_{n,m} = \sum_{i=1}^{d_k} a_{n,i} \cdot b_{i,m}$$

corresponds to the tensor multiplication through the leg k . In general, tensor multiplication of T and U requires a number of legs pairwise the same size to be present in both tensors. We can tensor multiply them through any nonempty subset of these pairs. Let $\{l_1, l_2, \dots, l_k\}$ be the chosen subset of legs being present in both T and U . The other legs of T are $\{t_1, t_2, \dots, t_n\}$, while the other legs of U are $\{u_1, u_2, \dots, u_m\}$. The corresponding tensor multiplication can be calculated via

$$V_{t_1, \dots, t_n, u_1, \dots, u_m} = \sum_{l_1} \sum_{l_2} \dots \sum_{l_k} T_{t_1, \dots, t_n} \cdot U_{u_1, \dots, u_m}.$$

In this paper, we only use tensor multiplications through one leg. We call the multiplication of an arbitrary tensor T with a 1-tensor (vector) v a contraction of T (or contracting T with v). This operation reduces the dimension or the number of legs of T by one.

A tensor network is a collection of tensors $\{T^1, T^2, \dots\}$, and a set of paired legs. We can denote such a network with a diagram, which is similar to a multigraph, except some edges have only one node as an endpoint, and the other endpoint is free. The nodes are the tensors, the edges are legs, and each paired leg connects its two tensors as a graph edge. If one names the paired legs with the same index, but otherwise the names are different, then on the diagram each edge conveniently will have its unique name. One can contract such a tensor network by performing tensor multiplications through paired legs in any order—each multiplication corresponds to contracting that edge in the diagram. The result is independent of the order of the contraction, moreover, one can obtain the same result in a single step: the resulting tensor will preserve the free legs of the tensors and each coordinate will be the nested sum of each paired leg.

To present this through an example, let us take the tensors $A_{i,k}$, $B_{l,n,o}$, $C_{j,k,l,m}$, $D_{m,n}$, E_o . We pair the edges denoted with the same index, and the contractions will yield

$$Y_{i,j} = \sum_k \sum_l \sum_m \sum_n \sum_o A_{i,k} B_{l,n,o} C_{j,k,l,m} D_{m,n} E_o,$$

which shows how we can treat this tensor network as a 2-tensor with respect to tensor multiplication. For further information on tensor networks, we refer to Ahle [2024].

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