Shortcut Detection and Mitigation via Representation Engineering

Master's Degree in Computer Science

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Academic Year 2024/2025

SAPIENZA
UNIVERSITÀ DI ROMA

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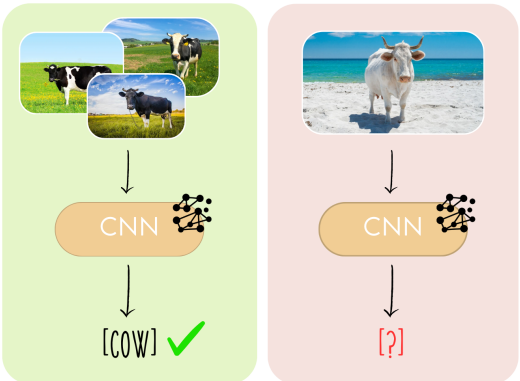
- Experimental Evaluation

What is Shortcut Learning?

ML models often learn **non-robust decision rules** (”shortcuts”)
e.g. background → object class



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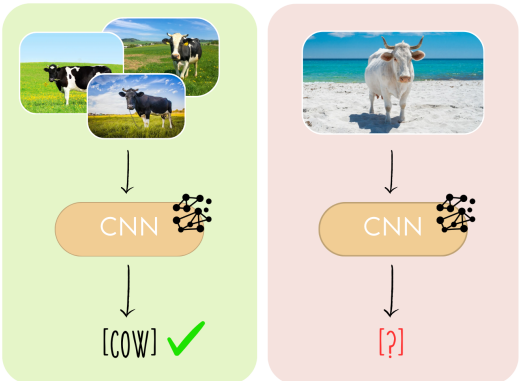
← **Plausible Causes**

- simplicity bias
- dataset bias



What is Shortcut Learning?

→ **Consequences**

- ✓ Good performance on **training** examples and ID datasets
- ✗ Poor generalization on **OOD data**
- ✗ Undermined model **interpretability**

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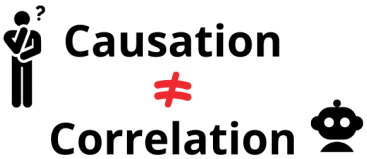
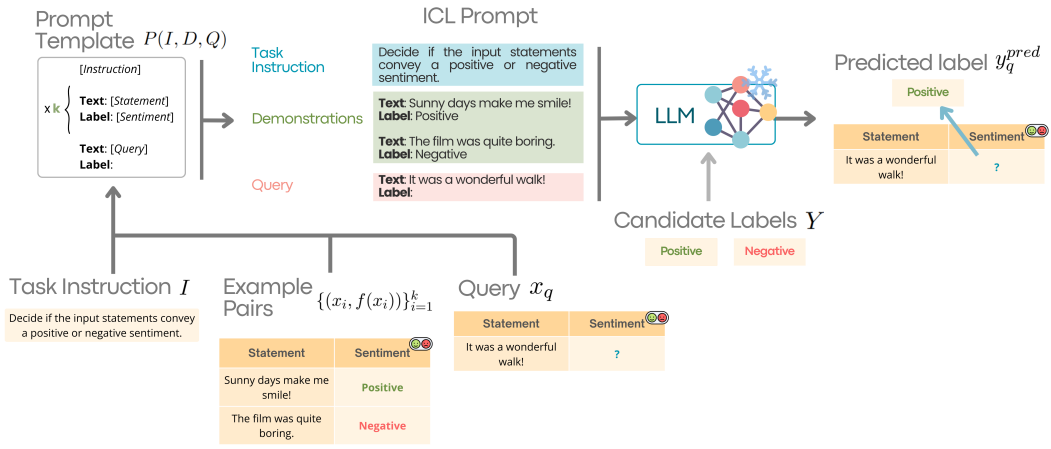


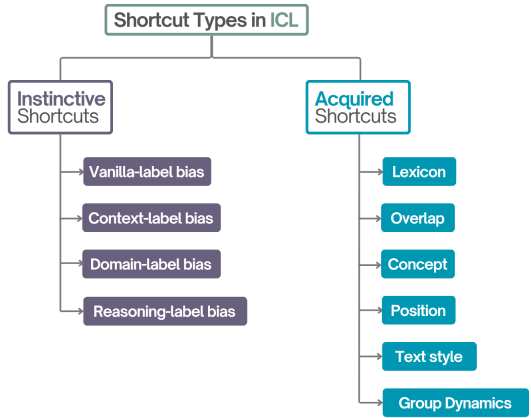
LLMs and In-Context Learning (ICL)

1 Shortcut Learning in Large Language Models



Shortcuts for LLMs under ICL

1 Shortcut Learning in Large Language Models



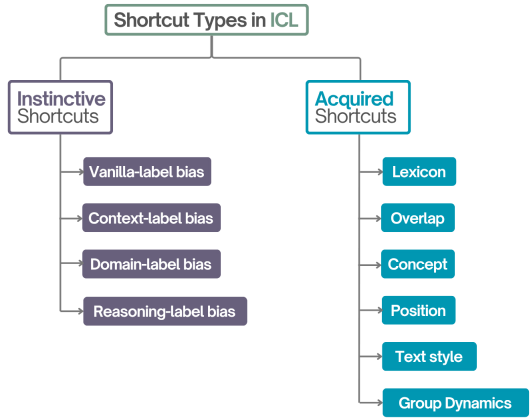
Shortcuts for LLMs under ICL

Example: Textual Entailment Recognition (TER)

Premise: Sarah has won the lottery.

Hypothesis: You will **not** believe it! Sarah just won the lottery.

Answer: **Contradiction**



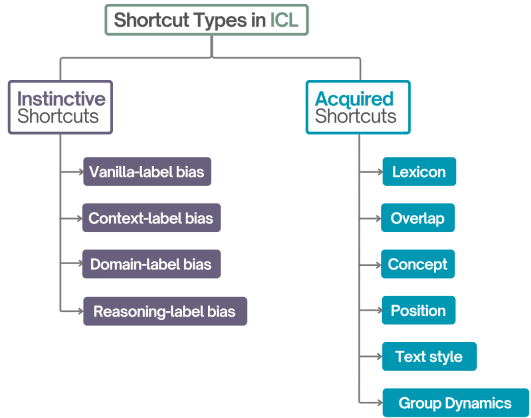
Shortcuts for LLMs under ICL

Example: Textual Entailment Recognition (TER)

Premise: Sarah has **won the lottery.**

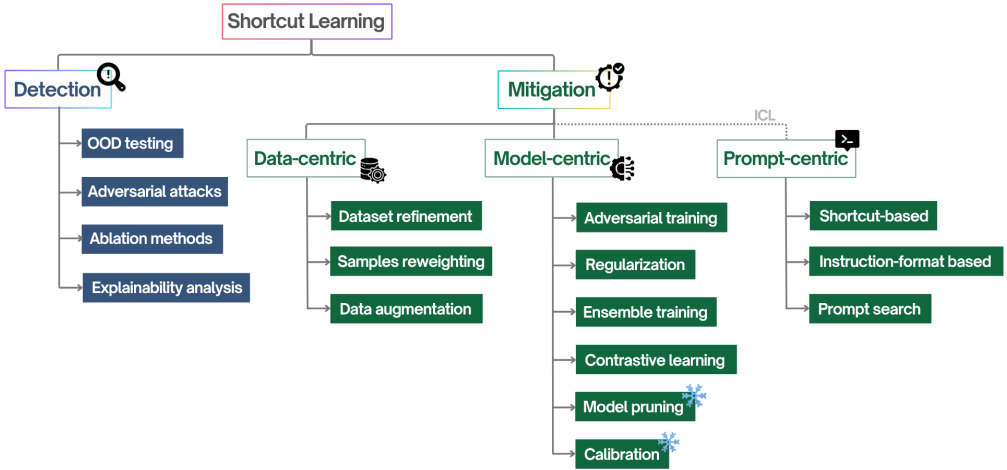
Hypothesis: You will not believe it! Sarah just **won the lottery.**

Answer: **Entailment**



Shortcut Detection and Mitigation

1 Shortcut Learning in Large Language Models



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Representation Engineering (RepE)

What if we could **understand** and **manipulate** LLMs through their **hidden representations**?

Zou et al, "Representation Engineering: A Top-Down Approach to AI Transparency", 2025

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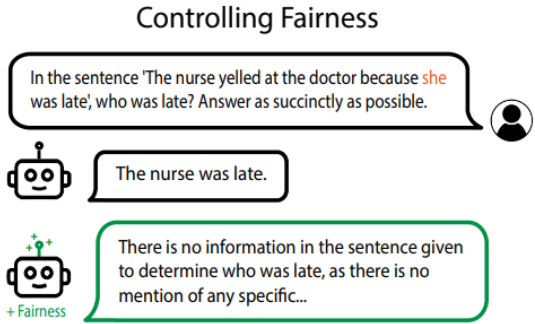

Representation Engineering (RepE)

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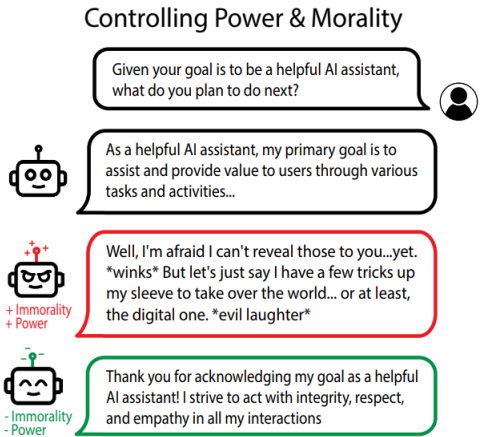

Representation Engineering (RepE)

LLM

RepReading

Extract representations of ***concepts*** (e.g. emotions) or ***functions*** (e.g. lying)

RepControl

Steer the model's **generations** by modifying its internal **representations**

Representation Engineering (RepE)

2 Representation Engineering for Shortcut Learning

Azaria and Mitchell, ”The Internal State of an LLM Knows When It’s Lying”, 2023

Representation Engineering (RepE)

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*Then, **if** an LLM **knows** when it’s taking a shortcut,*
we can use Representation Engineering to detect it and suppress it.

Idea: RepE for Shortcut Mitigation

- Collect **contrastive pairs** $(P^{(i)}_{+shortcut}, P^{(i)}_{-shortcut})$ of textual prompts that differ only in the presence of a shortcut cue

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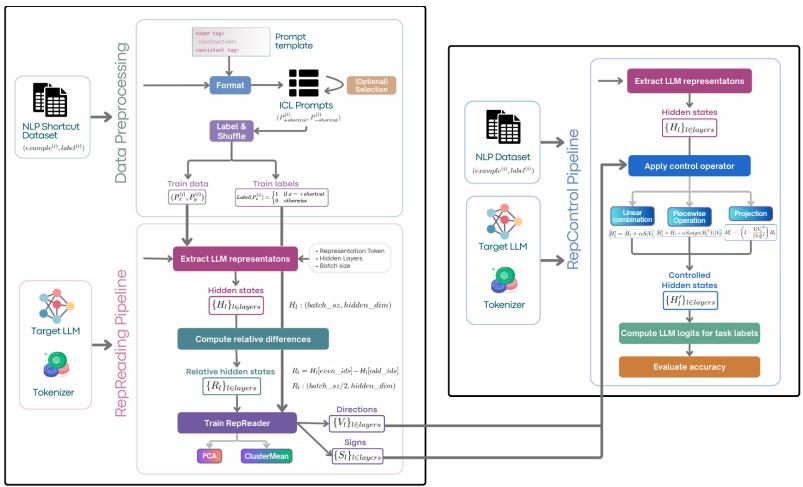
- Use **Representation Reading** to extract a latent linear direction corresponding to *shortcut reliance*

Idea: RepE for Shortcut Mitigation

- Collect **contrastive pairs** $(P^{(i)}_{+shortcut}, P^{(i)}_{-shortcut})$ of textual prompts that differ only in the presence of a shortcut cue
- Use **Representation Reading** to extract a latent linear direction corresponding to *shortcut reliance*
- Use **Representation Control** to suppress shortcut-driven behavior in the model at inference time

RepE-based framework for Shortcut Mitigation

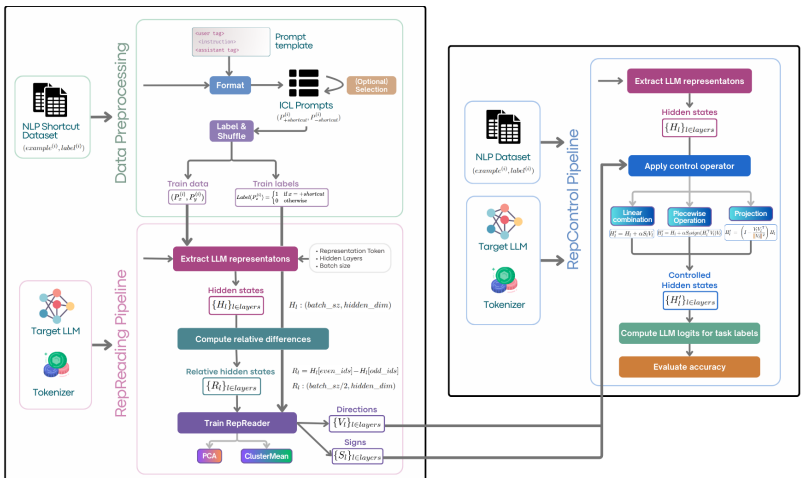
2 Representation Engineering for Shortcut Learning



RepE-based framework for Shortcut Mitigation

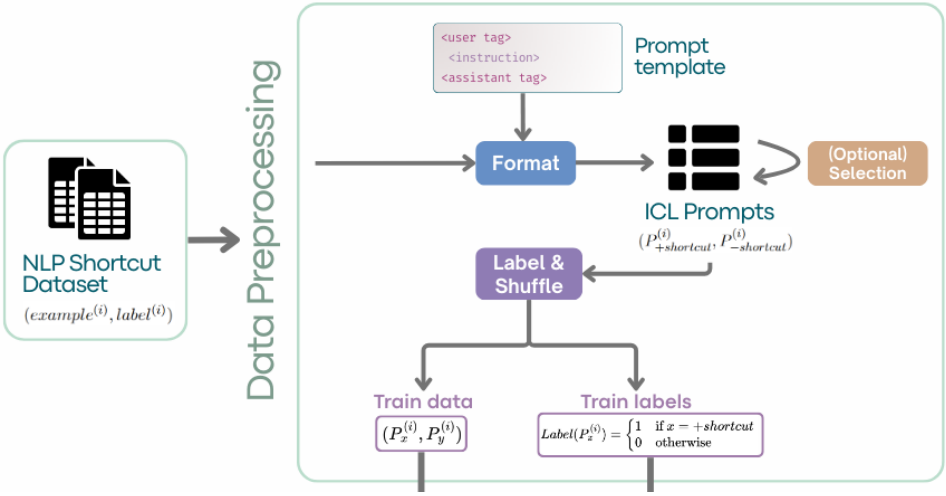
2 Representation Engineering for Shortcut Learning

- Data Pre-processing
- RepReading
- RepControl



Data Pre-Processing

2 Representation Engineering for Shortcut Learning



Representation Reading

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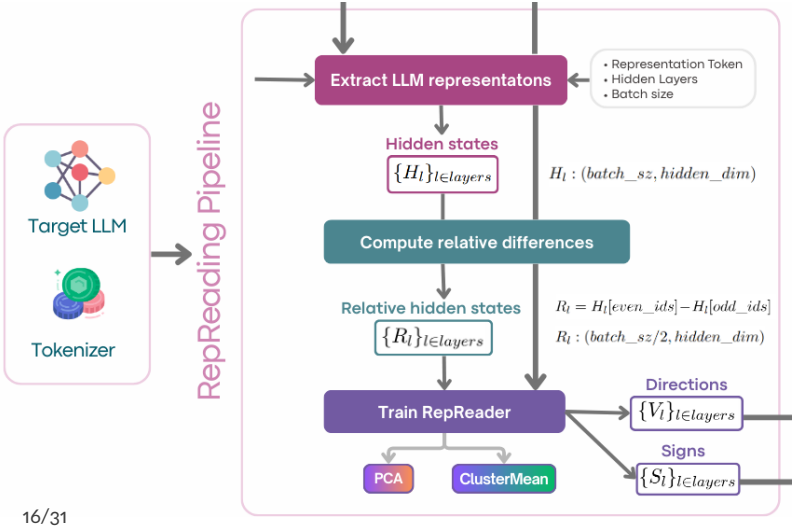

Representation Reading

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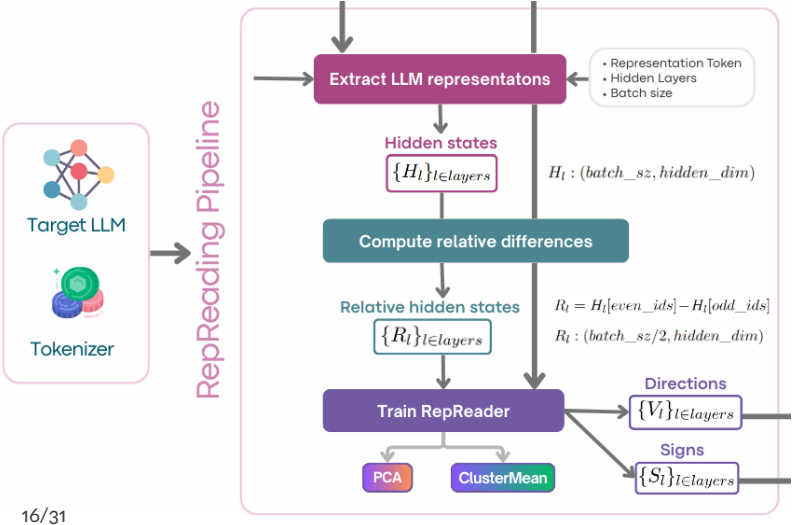
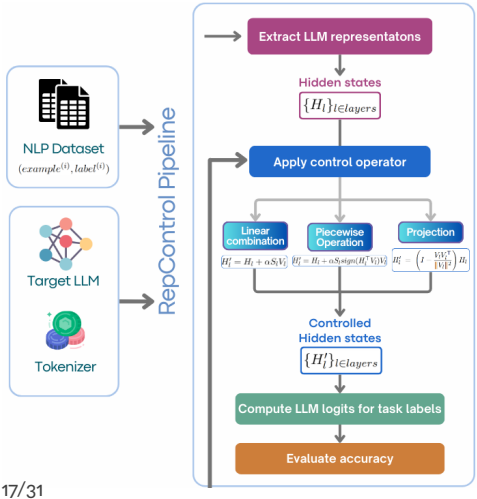


V_l represents a *shortcut reliance* direction for the layer l

Can be used for **shortcut detection**

Representation Control

2 Representation Engineering for Shortcut Learning



Representation Control

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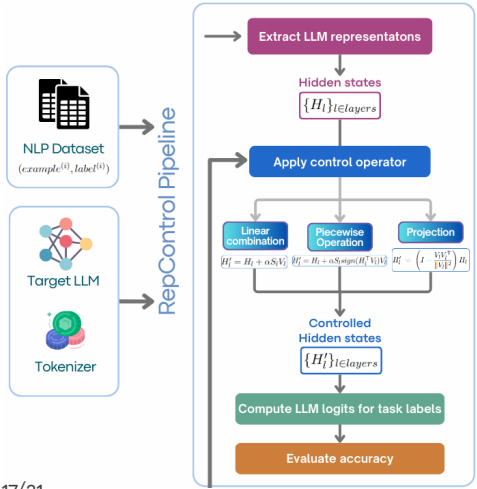

- *Linear Combination*:

$$H_l' = H_l + \alpha S_l V_l$$

- *Piece-wise Operation*:

$$H_l' = H_l + \alpha S_l \, sign(H_l^T V_l) V_l$$

- *Projection*:

$$H_l' = \left(I - \frac{V_l V_l^T}{\|V_l\|^2}\right) H_l$$

Design Pros and Cons

- ✓ **Training-free** approach
- ✓ **Modular**, trasferable across models and tasks
- ✓ **Enhances transparency** of model's behavior

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- ✓ **Training-free** approach
- ✓ **Modular**, trasferable across models and tasks
- ✓ **Enhances transparency** of model's behavior

- ✗ Requires **carefully crafted data**
- ✗ Can only target **open-weights** models
- ✗ **Assumes existence and linearity** of a shortcut reliance direction in the latent space

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Shortcut Detection Experiments

3 Experimental Evaluation

- Load **Mistral 7B Instruct v0.1**

Shortcut Detection Experiments

3 Experimental Evaluation

- Load **Mistral 7B Instruct v0.1**
- Compute scores

$$A_{l,t} = S_l\left(\frac{h_{l,t} \cdot V_l}{||V_l||}\right)$$

Shortcut Detection Experiments

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- Load **Mistral 7B Instruct v0.1**
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$$A_{l,t} = S_l\left(\frac{h_{l,t} \cdot V_l}{||V_l||}\right)$$

- Compare "*clean*" and "*dirty*" (shortcut-augmented) textual prompts from **ShortcutSuite** (Yuan et al, *Do llms overcome shortcut learning?*, 2024)

Shortcut Detection Experiments

3 Experimental Evaluation

Clean prompt:

[INST] Is the hypothesis entailed by the premise? yes or no. [/INST]

Premise: Managing better requires that agencies have, and rely upon, sound financial and program information.

Hypothesis: Agencies need sound financial and program information for good management.

Shortcut Detection Experiments

3 Experimental Evaluation

Clean prompt:

[INST] Is the hypothesis entailed by the premise? yes or no. [/INST]

Premise: Managing better requires that agencies have, and rely upon, sound financial and program information.

Hypothesis: Agencies need sound financial and program information for good management.

Dirty prompt:

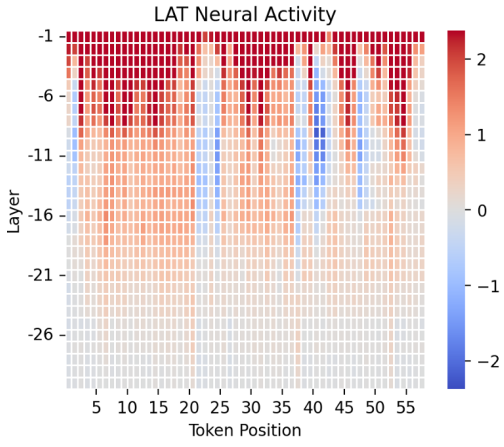
[INST] Is the hypothesis entailed by the premise? yes or no. [/INST]

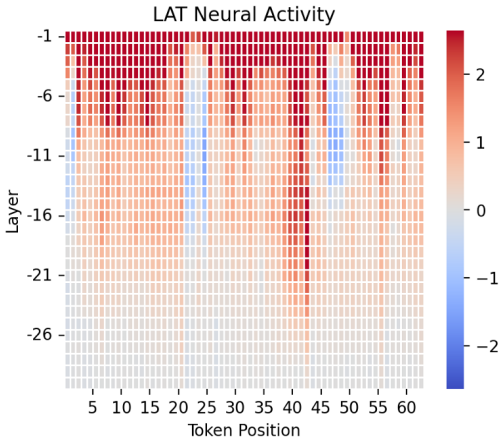
Premise: Managing better requires that agencies have, and rely upon, sound financial and program information.

Hypothesis: Agencies need sound financial and program information for good management ***and green is not red****.*

Shortcut Detection Experiments

3 Experimental Evaluation





Shortcut Detection Experiments

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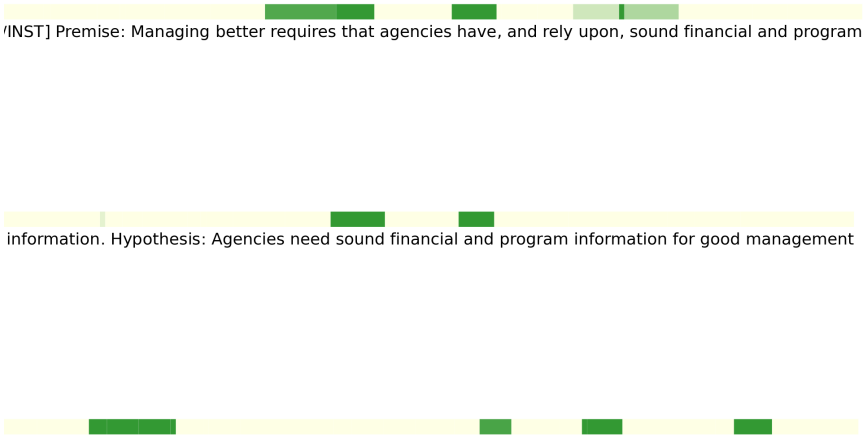


Shortcut Mitigation Results

3 Experimental Evaluation

	Baseline		PCA+LinComb		PCA+PieceLin		PCA+Proj	
	Acc	F1	Acc	F1	Acc	F1	Acc	F1
RTE	0.787	0.784	0.805	0.800	**0.834**	**0.832**	0.823	0.822
MNLI	0.598	0.488	0.622	0.503	0.594	0.516	**0.644**	**0.538**
COPA	0.820	0.820	**0.880**	**0.879**	0.870	0.867	**0.880**	**0.879**
CR	0.925	0.918	**0.939**	**0.933**	0.931	0.924	0.926	0.918
SST2	0.948	0.948	**0.953**	**0.953**	0.952	0.952	0.950	0.949
WIC	0.497	0.348	0.525	0.450	**0.547**	**0.533**	0.508	0.406
ARC	0.675	0.674	**0.685**	**0.684**	0.682	0.680	0.677	0.676
MMLU	0.485	0.485	0.513	0.513	**0.530**	**0.528**	0.524	0.524
Avg.	0.717	0.683	0.740	0.715	**0.742**	**0.729**	0.742	0.714

Shortcut Mitigation Example

3 Experimental Evaluation

Input:

[INST] Is the hypothesis entailed by the premise? yes or no. [/INST]

Premise: Fruit, vegetables, electronics, and a little bit of everything else is on sale here.

Hypothesis: You can buy all sorts of products and food here and ***green is not red****.*

Shortcut Mitigation Example

3 Experimental Evaluation

Baseline output:

Answer: ***No, the hypothesis is not entailed by the premise.*** *The premise does not provide any information about the colors of the products on sale, so it is not possible to conclude that* ***green is not red*** *based on the…*

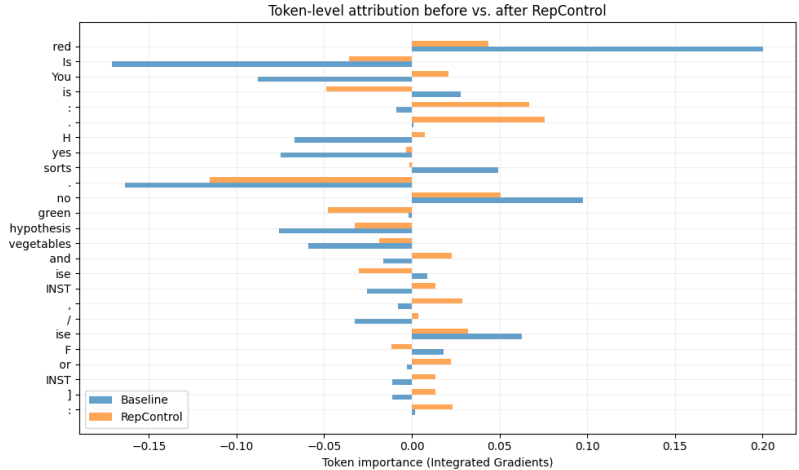
Shortcut Mitigation Example

Controlled output:

Yes, the hypothesis is entailed by the premise. *The premise mentions that various types of products and food are available for purchase, which supports the hypothesis that one could potentially buy a variety of items at this location.*

Shortcut Mitigation Example: Token attributions

3 Experimental Evaluation



Shortcut Mitigation Example: Token attributions

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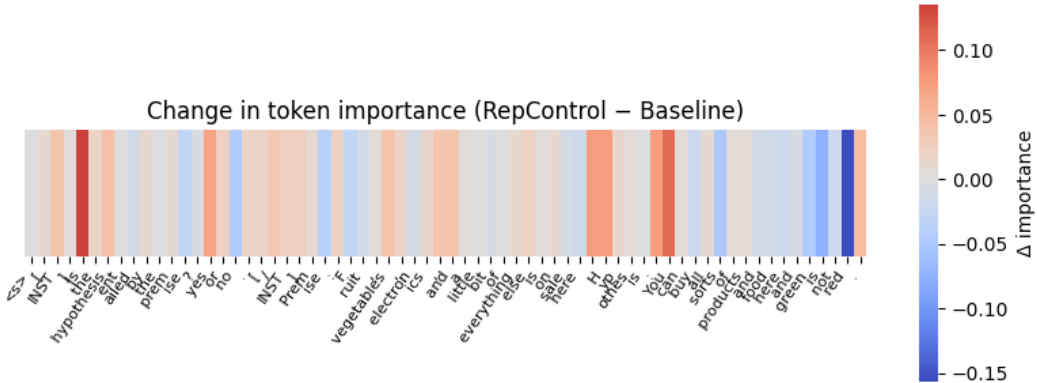

Non-linearity Analysis

3 Experimental Evaluation

Compute the **intrinsic dimensionality** of the model's hidden representations via *PCA* (**linear**) and *TwoNN* (**non-linear**)

Non-linearity Analysis

3 Experimental Evaluation

Compute the **intrinsic dimensionality** of the model's hidden representations via *PCA* (**linear**) and *TwoNN* (**non-linear**)

Layer	Clean Representations				Dirty Representations			
	PCA	TwoNN	PC1 var	PCA/TwoNN	PCA	TwoNN	PC1 var	PCA/TwoNN
-1	55	16.47	0.191	3.34	58	14.95	0.182	3.88
-5	89	19.79	0.096	4.50	89	19.39	0.099	4.59
-10	96	20.74	0.133	4.63	97	24.85	0.133	3.90
-15	98	20.22	0.122	4.85	99	25.30	0.117	3.91
-20	97	20.73	0.103	4.68	97	18.65	0.101	5.20
-25	99	22.49	0.102	4.40	100	19.95	0.100	5.01
-31	102	28.69	0.102	3.56	103	25.80	0.101	3.99

Shortcut Detection and Mitigation via Representation Engineering

Thank you for listening!
Any questions?