

Assessing and Enhancing Language Models for Complex and Robust Logical Reasoning over Natural Language

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Strong AI Lab



- Strong AI Lab is led by Professor Michael Witbrock, at the intersection of machine learning, reasoning, and natural language understanding, with an additional focus on achieving the best social and civilisational impacts of increasingly powerful AI.

About Me

- Qiming Bao is a Ph.D. Candidate at the [Strong AI Lab](#), [NAOInstitute](#), University of Auckland, New Zealand, supervised by Professor [Michael Witbrock](#). His research interests include natural language processing and reasoning. He has over three years of research and development experience, and has published several papers in top conferences in the fields of AI/NLP/Reasoning, including **AAAI/EAAI**, **ICLR**, **ACL**, **EACL**, **LLM@IJCAI**, and **IJCLR-NeSy**. His method named **AMR-LDA** (GPT-4 + AMR-LDA Prompt Augmentation) has achieved the **#1** ranking on a one of the most challenged logical reasoning reading comprehension leaderboards ([ReClor](#)) up to now, and two of his logical reasoning datasets called [PARARULE-Plus](#) and [AbductionRules](#) have been collected by [LogiTorch](#), [ReasoningNLP](#), [Prompt4ReasoningPapers](#) and [OpenAI/Evals](#). Qiming has given public guest talks at [Microsoft Research Asia](#), [Samsung AI Center Cambridge UK](#), [IEEE Vehicular Technology Society](#) and [The University of Melbourne](#) on his main research topic, "Natural Language Processing and Reasoning".

Enhancing Logical Reasoning of Large Language Models through Logic-Driven Data Augmentation

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Outline

- Background
- System Architecture
- Experiment Results
- Conclusion and Future Work

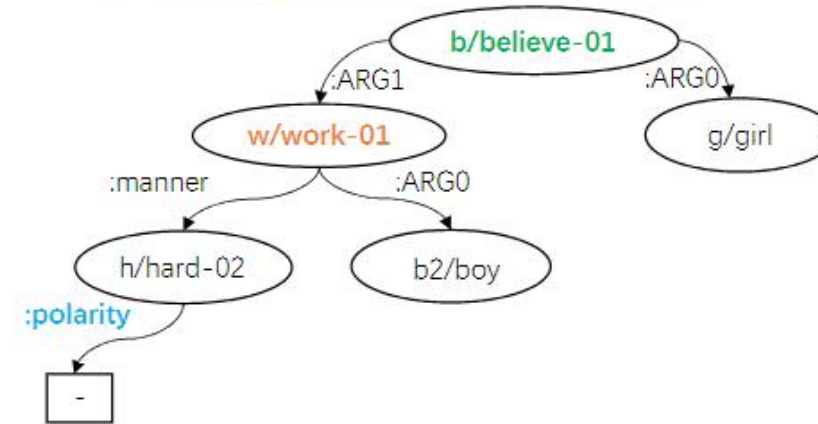
Research Gap

- Enabling pre-trained large language models (LLMs) to reliably perform logical reasoning is an important step towards strong artificial intelligence [1]. The lack of available large real-world logical reasoning datasets means that LLMs are usually trained on more general corpora or smaller ones that do not generalise well.
- Logical reasoning is extremely important for solving problems in a robust, faithful and explainable way [2] [3], but because logical reasoning is complex for humans to understand and difficult to use for constructing data, there is exceptionally limited data. This implies that a scarcity of labeled datasets for logical reasoning persists in real-world scenarios. Consequently, it is not surprising that these pre-trained language models exhibit shortcomings in logical reasoning [4].

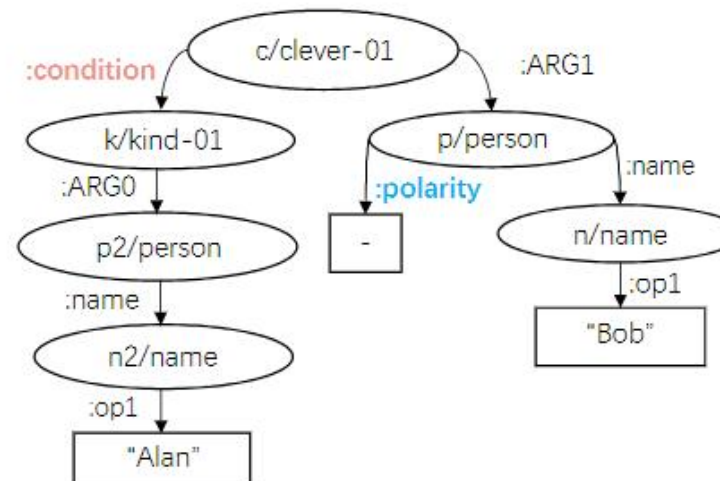
Abstract Meaning Representation

S1: The girl **believes** that the boy **doesn't work** hard.

S2: The girl **doesn't believe** that the boy **works** hard.



S3: **If** Alan is kind, then Bob is **not** clever.



Logical Reasoning Tasks

Example Case

Context: If you have no keyboarding skills at all, you will not be able to use a computer. And if you are not able to use a computer, you will not be able to write your essays using a word processing program.

Question: If the statements above are true, which one of the following must be true?

Options:

A. If you are not able to write your essays using a word processing program, you have no keyboarding skills.

B. *If you are able to write your essays using a word processing program, you have at least some keyboarding skills.* ✓

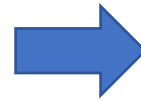
C. If you are not able to write your essays using a word processing program, you are not able to use a computer.

D. If you have some keyboarding skills, you will be able to write your essays using a word processing program.

α = you have keyboarding skills.

β = you are able to use a computer.

γ = you are able to write your essays using a word processing program.



Context: $\neg \alpha \rightarrow \neg \beta, \neg \beta \rightarrow \neg \gamma$

Option A: $\neg \gamma \rightarrow \neg \alpha$

✓ Option B: $\gamma \rightarrow \alpha + (\beta \rightarrow \alpha, \gamma \rightarrow \beta)$ using contraposition law

Option C: $\neg \gamma \rightarrow \neg \beta$

Option D: $\alpha \rightarrow \gamma$

A natural language logical reasoning reading comprehension example from ReClor[1].

Convert the natural language into logic symbols.

Logical Equivalence Laws

Definition 1: Contraposition law

$$(A \rightarrow B) \Leftrightarrow (\neg B \rightarrow \neg A)$$

If Alan is kind, then Bob is clever. \Leftrightarrow If Bob is not clever, then Alan is not kind.

Definition 2: Implication law

$$(A \rightarrow B) \Leftrightarrow (\neg A \vee B)$$

If Alan is kind, then Bob is clever. \Leftrightarrow Alan is not kind or Bob is clever.

Definition 3: Commutative law

$$(A \wedge B) \Leftrightarrow (B \wedge A)$$

Alan is kind and Bob is clever. \Leftrightarrow Bob is clever and Alan is kind.

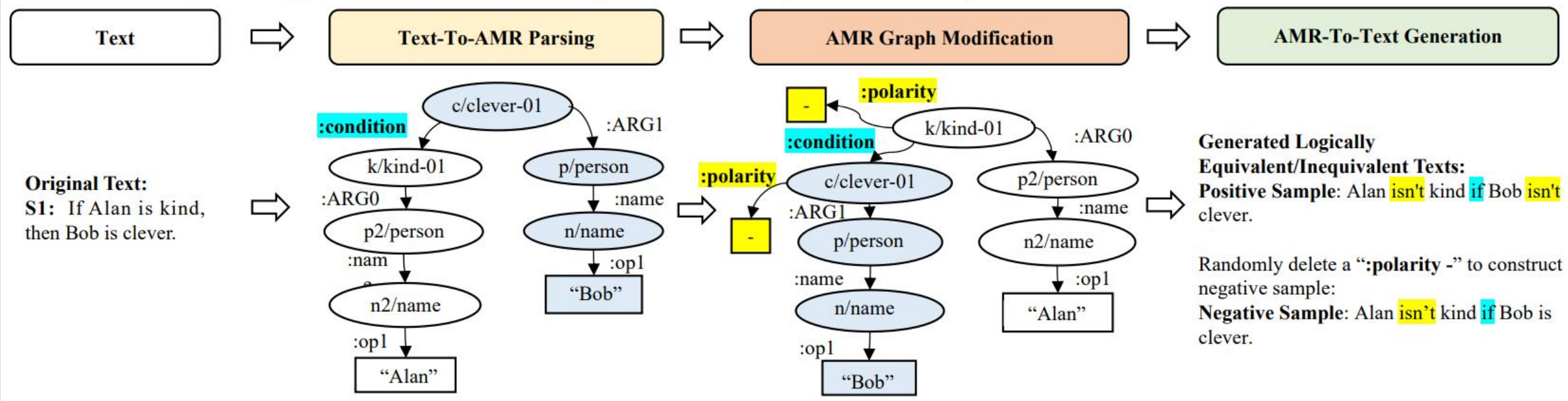
Definition 4: Double negation law

$$A \Leftrightarrow \neg \neg A$$

Alan is kind. \Leftrightarrow Alan is not unkind.

System Architecture

1. AMR-Based Logic-Driven Data Augmentation (AMR-LDA)



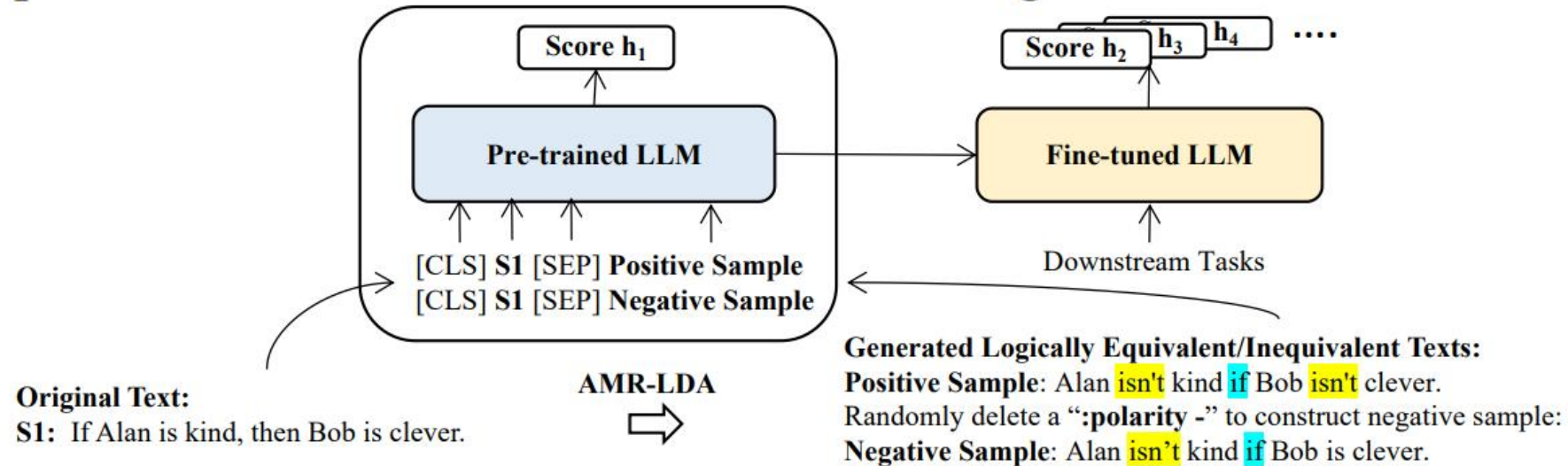
Construct positive and negative samples

Original sentence	Positive sample	Negative sample
If Alan is kind, then Bob is clever.	Alan isn't kind if Bob isn't clever.	Alan isn't kind if Bob is clever.
	Alan is not kind or Bob is clever.	Alan is kind or Bob is clever.
The bald eagle is strong.	The bald eagle is not weak .	The bald eagle is weak .
The bald eagle is clever and the wolf is fierce.	The wolf is fierce and the bald eagle is clever .	The wolf is not fierce and the bald eagle is not clever .

Table 1: We used four logical equivalence laws to construct positive samples. For the negative samples, we modify the AMR graph of the positive sample, including deleting/adding a negative polarity argument in the AMR graph. The blue background represents the word or the phrase has been swapped order. The yellow background represents the word or the phrase has been adding or deleting a negation meaning.

System Architecture

2a. Logical-Equivalence-Identification Contrastive Learning for Discriminative LLM



System Architecture

2b. Prompt Augmentation for Generative LLM

Context: $\neg \alpha \rightarrow \neg \beta, \neg \beta \rightarrow \neg \gamma$

Option A: $\neg \gamma \rightarrow \neg \alpha$

Option B: $\gamma \rightarrow \alpha$

Option C: $\neg \gamma \rightarrow \neg \beta$

Option D: $\alpha \rightarrow \gamma$

AMR-LDA



Context: $\neg \alpha \rightarrow \neg \beta, \neg \beta \rightarrow \neg \gamma$

Option A: $\neg \gamma \rightarrow \neg \alpha$ + AMR-LDA extended option: $\alpha \rightarrow \gamma$ + AMR-LDA extended context: $\beta \rightarrow \alpha, \gamma \rightarrow \beta$

Option B: $\gamma \rightarrow \alpha$ + AMR-LDA extended option: $\neg \alpha \rightarrow \neg \gamma$ + AMR-LDA extended context: $\beta \rightarrow \alpha, \gamma \rightarrow \beta$

Option C: $\neg \gamma \rightarrow \neg \beta$ + AMR-LDA extended option: $\beta \rightarrow \gamma$ + AMR-LDA extended context: $\beta \rightarrow \alpha, \gamma \rightarrow \beta$

Option D: $\alpha \rightarrow \gamma$ + AMR-LDA extended option: $\neg \gamma \rightarrow \neg \alpha$ + AMR-LDA extended context: $\beta \rightarrow \alpha, \gamma \rightarrow \beta$

α = you have keyboarding skills.

β = you are able to use a computer.

γ = you are able to write your essays using a word processing program.

Solution Path 1

Solution Path 2



Option B ✓



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Case Study

AMR-LDA Prompt Augmentation Case Study

GPT-4 Input: “context”: “If you have no keyboarding skills at all, you will not be able to use a computer. And if you are not able to use a computer, you will not be able to write your essays using a word processing program.”, “question”: “If the statements above are true, which one of the following must be true?”, “answers”:

A. “If you are not able to write your essays using a word processing program, you have no keyboarding skills. *If you have the skill of a keyboard, you can write your essay using a word processing program. If you can use a computer, you have keyboarding skills. If you can write your essay with a word processing program, you can use a computer. Whether you have keyboard skills at all or can't use a computer. Whether you can use a computer or you can't write your own essay with a word processing program.*”,

B. “If you are able to write your essays using a word processing program, you have at least some keyboarding skills. *If you don't have at least some keyboard skills, you can't write your essay with a word processing program. If you can use a computer, you have keyboarding skills. If you can write your essay with a word processing program, you can use a computer. Whether you have keyboard skills at all or can't use a computer. Whether you can use a computer or you can't write your own essay with a word processing program.*”,

C. “If you are not able to write your essays using a word processing program, you are not able to use a computer. *If you can use a computer, you can write your essay using word processing programs. If you can use a computer, you have keyboarding skills. If you can write your essay with a word processing program, you can use a computer. Whether you have keyboard skills at all or can't use a computer. Whether you can use a computer or you can't write your own essay with a word processing program.*”,

D. “If you have some keyboarding skills, you will be able to write your essays using a word processing program. *If you can't write your essay with a word processing program, you don't have some keyboard skills. If you can use a computer, you have keyboarding skills. If you can write your essay with a word processing program, you can use a computer. Whether you have keyboard skills at all or can't use a computer. Whether you can use a computer or you can't write your own essay with a word processing program.*”

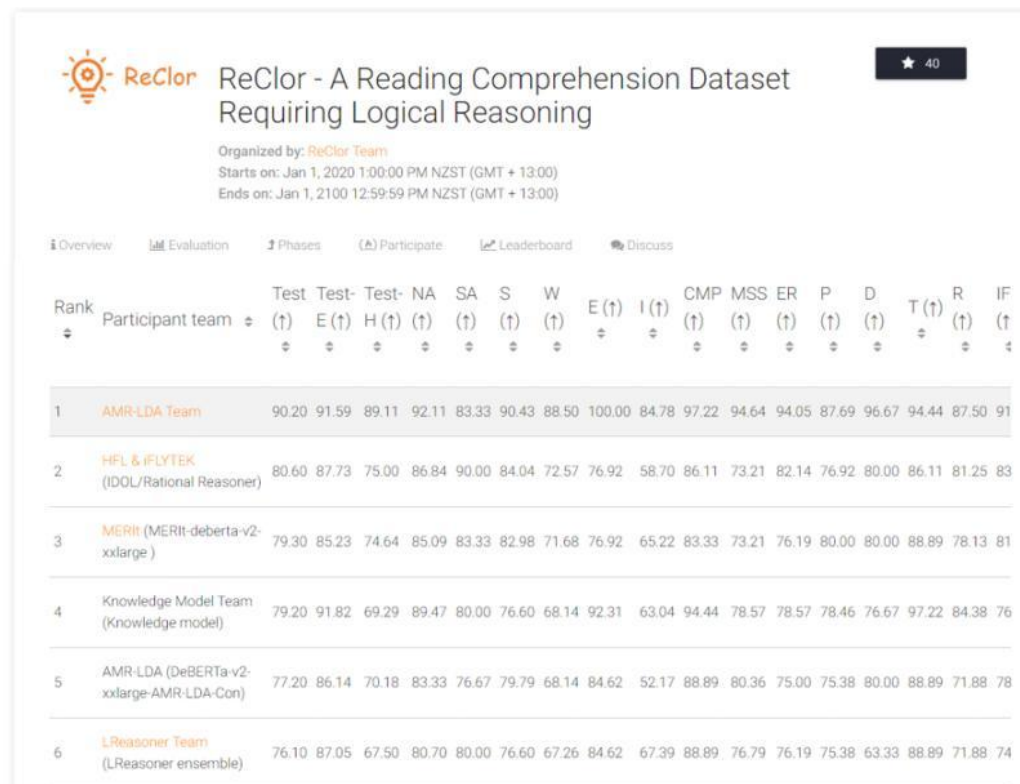
GPT-4 output: B

Figure 3: Example for using AMR-LDA to augment the prompt from ReClor dataset and their subsequent utilisation as input for GPT-4. Data segments that are marked in bold italics and appear in blue were generated using the contraposition law, while those in brown were generated using the implication law.

Experiment Results

Models/ Datasets	ReClor				LogiQA		MNLI	MRPC	RTE	QNLI	QQP
	Dev	Test	Test-E	Test-H	Dev	Test			Eval		
RoBERTa	0.5973	0.5320	0.7257	0.3797	0.3543	0.3450	0.8895	0.9044	0.8339	0.9473	0.9089
RoBERTa AMR-LDA	0.6526	0.5686	0.7734	0.4077	0.4029	0.3814	0.8978	0.9093	0.8664	0.9449	0.9314
RoBERTa LReasoner-LDA	0.5946	0.5366	0.7219	0.3910	0.3481	0.3481	0.8941	0.8946	0.8628	0.9425	0.9001
RoBERTa AMR-DA	0.5866	0.5393	0.6681	0.4380	0.3645	0.3722	0.8974	0.9044	0.8628	0.9442	0.9206
DeBERTaV2	0.7393	0.7046	0.8082	0.6231	0.3972	0.3962	0.8945	0.8971	0.8448	0.9500	0.9254
DeBERTaV2 AMR-LDA	0.7940	0.7763	0.8575	0.7124	0.4234	0.3988	0.8967	0.9020	0.8809	0.9524	0.9247
DeBERTaV2 LReasoner-LDA	0.7573	0.7070	0.8408	0.6017	0.3087	0.2851	0.8923	0.8995	0.8700	0.9515	0.9250
DeBERTaV2 AMR-DA	0.7906	0.7590	0.8462	0.6904	0.2995	0.3010	0.8992	0.8971	0.8339	0.9502	0.9242

Table 2: Comparison between our proposed AMR-LDA and baseline models. We use RoBERTa-Large, DeBERTaV2-XXLarge, and DeBERTa-Large as the pre-trained backbone models. Our fine-tuned LLMs perform equally well or better than baseline methods. The number with * indicates that the result is from the other papers.



ReClor - A Reading Comprehension Dataset Requiring Logical Reasoning

Organized by: ReClor Team
Starts on: Jan 1, 2020 1:00:00 PM NZST (GMT + 13:00)
Ends on: Jan 1, 2100 12:59:59 PM NZST (GMT + 13:00)

Overview Evaluation Phases Participate Leaderboard Discuss

Rank	Participant team	Test (t)	Test-E (t)	Test-H (t)	NA (t)	SA (t)	S (t)	W (t)	E (t)	I (t)	CMP (t)	MSS (t)	ER (t)	P (t)	D (t)	T (t)	R (t)	IF (t)
1	AMR-LDA Team	90.20	91.59	89.11	92.11	83.33	90.43	88.50	100.00	84.78	97.22	94.64	94.05	87.69	96.67	94.44	87.50	91
2	HFL & iFLYTEK (IDOL/Rational Reasoner)	80.60	87.73	75.00	86.84	90.00	84.04	72.57	76.92	58.70	86.11	73.21	82.14	76.92	80.00	86.11	81.25	83
3	MERIT (MERIT-deberta-v2-xxlarge)	79.30	85.23	74.64	85.09	83.33	82.98	71.68	76.92	65.22	83.33	73.21	76.19	80.00	80.00	88.89	78.13	81
4	Knowledge Model Team (Knowledge model)	79.20	91.82	69.29	89.47	80.00	76.60	68.14	92.31	63.04	94.44	78.57	78.57	78.46	76.67	97.22	84.38	76
5	AMR-LDA (DeBERTa-v2-xxlarge-AMR-LDA-Con)	77.20	86.14	70.18	83.33	76.67	79.79	68.14	84.62	52.17	88.89	80.36	75.00	75.38	80.00	88.89	71.88	78
6	LReasoner Team (LReasoner ensemble)	76.10	87.05	67.50	80.70	80.00	76.60	67.26	84.62	67.39	88.89	76.79	76.19	75.38	63.33	88.89	71.88	74

Models/Datasets	ReClor				LogiQA	
	Dev	Test	Test-E	Test-H	Dev	Test
GPT-3.5	0.5702	0.5620	0.5931	0.5375	0.3763	0.3732
GPT-3.5 AMR-LDA	0.5862	0.5669	0.6090	0.5339	0.3974	0.3947
GPT-4	0.8735	0.8960	0.9090	0.8857	0.4324	0.5388
GPT-4 AMR-LDA	0.8773	0.9020	0.9159	0.8911	0.4751	0.5806

Table 5: Comparison between GPT-3.5 AMR-LDA, GPT-4 AMR-LDA with GPT-3.5 and GPT-4 alone for evaluating on ReClor and LogiQA test sets.

Experiment Results

Models/Datasets	RoBERTa AMR-LDA	RoBERTa LReasoner-LDA
Depth=1	1	1
Depth=1 (with altered rules)	1	0.9987
Depth=2	1	1
Depth=2 (with altered rules)	0.9973	0.7400

Table 4: Comparison between AMR-LDA and LReasoner-LDA with RoBERTa-Large on PARARULE-Plus and PARARULE-Plus (with altered rules). Depth=1 means that only one rule was used to infer the answer. Depth=1 (with altered rules) means one of the rules has been augmented using logical equivalence laws.

Experiment Results

Models/Datasets	ReClor				LogiQA	
	Dev	Test	Test-E	Test-H	Dev	Test
<i>DeBERTaV2-XXLarge as backbone model</i>						
AMR-LDA-1:1	0.7880	0.7610	0.8477	0.6928	0.4055	0.4147
AMR-LDA-1:2	0.8020	0.7640	0.8477	0.6982	0.4700	0.4393
AMR-LDA-1:3	0.8120	0.7570	0.8409	0.6910	0.4270	0.4101
MERIt-1:3	0.8020	0.7580	0.8500	0.6857	0.3732	0.4239
<i>MERIt-DeBERTaV2-XXLarge-1:3 as backbone model</i>						
AMR-LDA-Con-1:3	0.8260	0.7660	0.8613	0.6910	0.4500	0.4301
AMR-LDA-Merged-1:3	0.8180	0.7690	0.8750	0.6857	0.4454	0.4562

Table 7: An experiment to validate how ratios of positive and negative samples influence downstream tasks. AMR-LDA 1:1 means the ratio of positive and negative samples is 1:1.

Dev sets ↓ Models →	Con	Con-dou	Dev acc Con-dou imp	Con-dou imp-com
<i>RoBERTa-Large as backbone model</i>				
ReClor	0.6040	0.6080	0.6180	0.5980
LogiQA	0.3778	0.3317	0.3394	0.3870
MNLI	0.8955	0.9015	0.8968	0.8978
MRPC	0.9069	0.8922	0.9044	0.9093
RTE	0.8123	0.8520	0.8484	0.8664
QNLI	0.9416	0.9405	0.9451	0.9449
QQP	0.9212	0.8988	0.9206	0.9314
<i>DeBERTaV2-XXLarge as backbone model</i>				
ReClor	0.8180	0.7220	0.7940	0.7880
LogiQA	0.3225	0.4546	0.3824	0.4055
<i>DeBERTa-Large as backbone model</i>				
MNLI	0.9080	0.9059	0.9068	0.8967
MRPC	0.9020	0.8848	0.8995	0.9020
RTE	0.8484	0.8736	0.8556	0.8809
QNLI	0.9528	0.9504	0.9497	0.9524
QQP	0.9233	0.9240	0.9229	0.9247

Table 5: An ablation study to validate how different logical laws influence downstream tasks. Con means we only use contraposition law. Con-dou means we use contraposition and double negation laws. Con-dou-imp means we use contraposition, double negation and implication laws. Con-dou-imp-com means we use the four logical laws to augment data and conduct the fine-tuning.

Human Evaluation

We randomly select 20 samples which are composed of pairs of two sentences from the generated sentences using our AMR-LDA and LReasoner-LDA to conduct a survey. We select 45 participants anonymously. We evaluate the sentences from two aspects.

- The first is which sentence is logically equivalent to the original sentence.
- The other one is which sentence is more fluent.

From our survey, 63.92% and 76.44% people select the sentences generated by AMR-LDA as the more correct logical equivalence sentences and more fluent sentences than the sentences generated by LReasoner-LDA, respectively.

The human evaluation has been approved by the University of Auckland Human Participants Ethics Committee on 28 February, 2023 for three years, Reference Number 24841.

Conclusion and Future Work

1. We propose a new AMR-based, logic-driven data augmentation method that considers more logical equivalence laws than LReasoner, including double negation, contraposition, commutative, and implication laws. We used the augmented dataset obtained with our method to conduct contrastive fine-tuning various LLMs. Additionally, we fed the augmented data to large language models, such as ChatGPT and GPT-4, which ultimately yielded better results than baseline methods.
2. To automatically construct real-world logical reasoning datasets using additional logical equivalence laws, such as De Morgan's Law, we are exploring two approaches: one involves prompting GPT-4, and the other seeks to extend our method by utilizing GPT-4 both as an AMR parser and an AMR generator. (Work in progress)

Useful Links



Project code



#1 on ReClor Leaderboard



Model Weights

Our AMR-LDA has been open-sourced in the project code, and the model weights have been released.

Welcome for more discussion and collaboration!