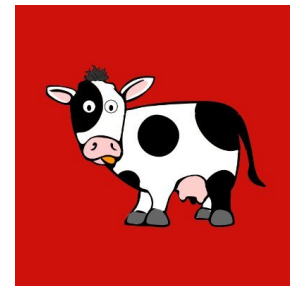


# How to Teach Language Models to Reason

**Huiyuan Lai**  
huiyuanlai.l@gmail.com

**March 13, 2024**



# What is Reasoning?

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Concatenate the first letter of each word

**Q** Artificial Intelligence

**A** ?

Answer the following strategy question

**Q** Yes or no: Would a nail sink in water?

**A** ?

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Solve the following math word problem

Q Terry eats 2 yogurts a day. They are currently on sale at 4 yogurts for \$5.00. How much does he spend on yogurt over 30 days?

A ?

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# What is Reasoning?

“A faculty of the **human** mind that enables logical inferences to be made and rational arguments to be undertaken to understand the world and solve problems.”

Michael Kent. 2007. The Oxford Dictionary of Sports Science & Medicine (3 ed.)

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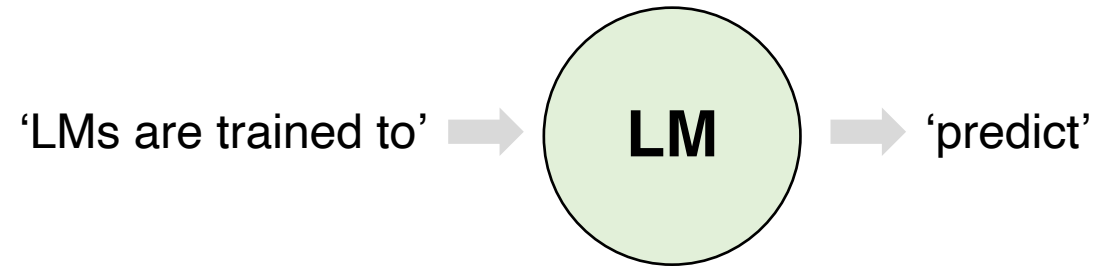
**How to Teach Language Models to Reason?**

\$75

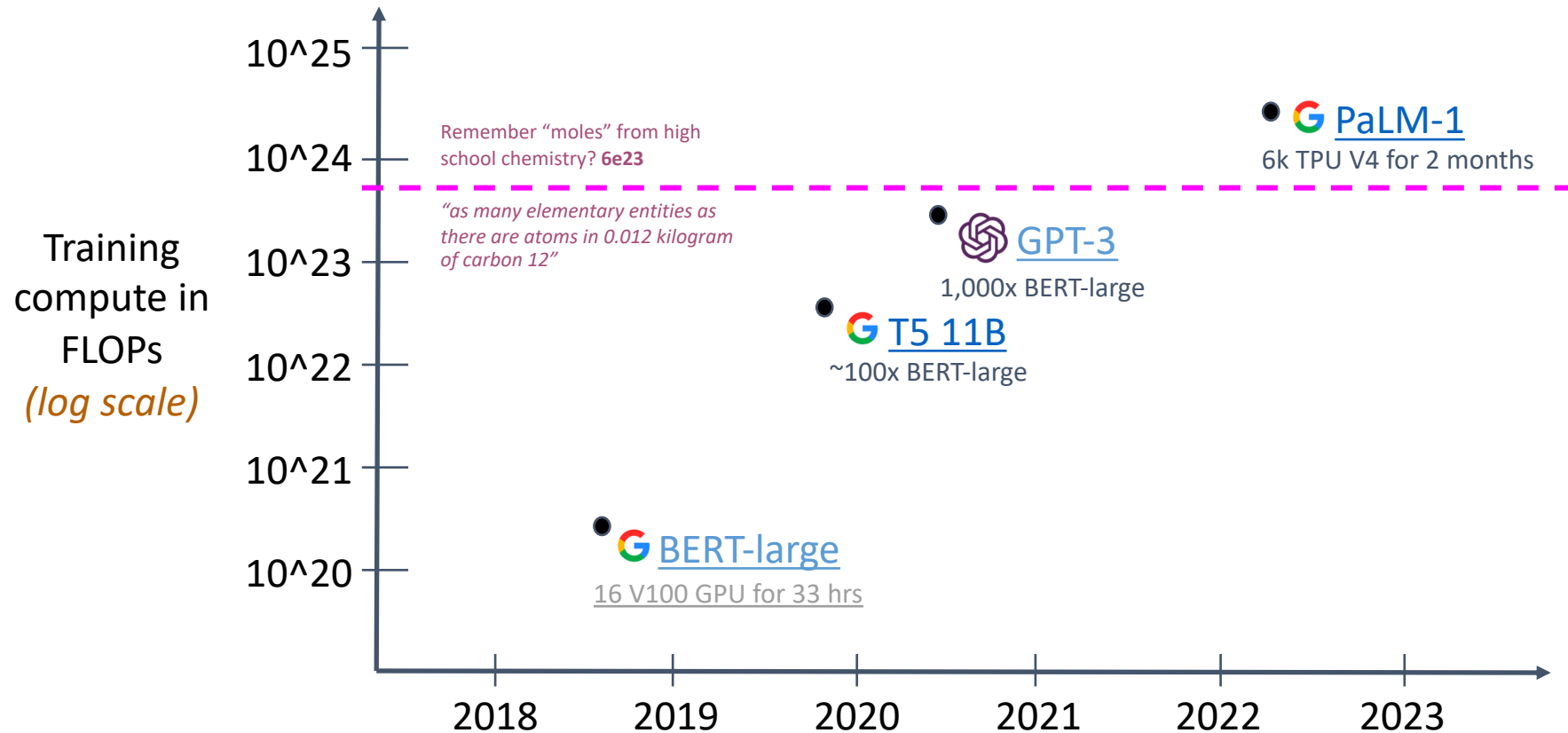
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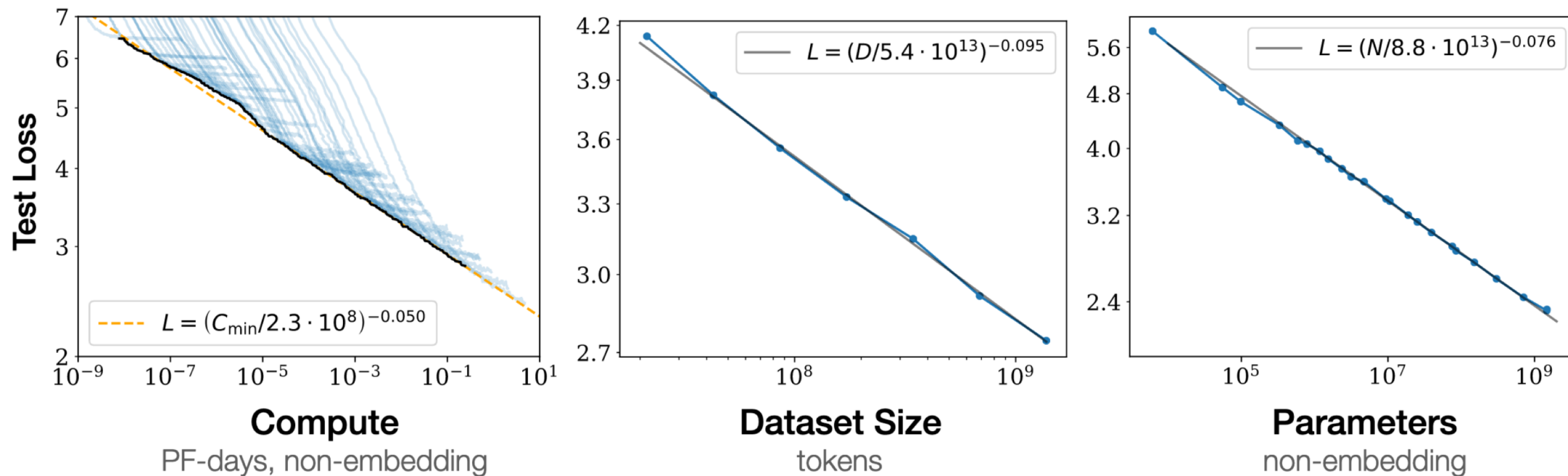
Language Models (LMs) are trained to predict the next word...



# Neural Language Models

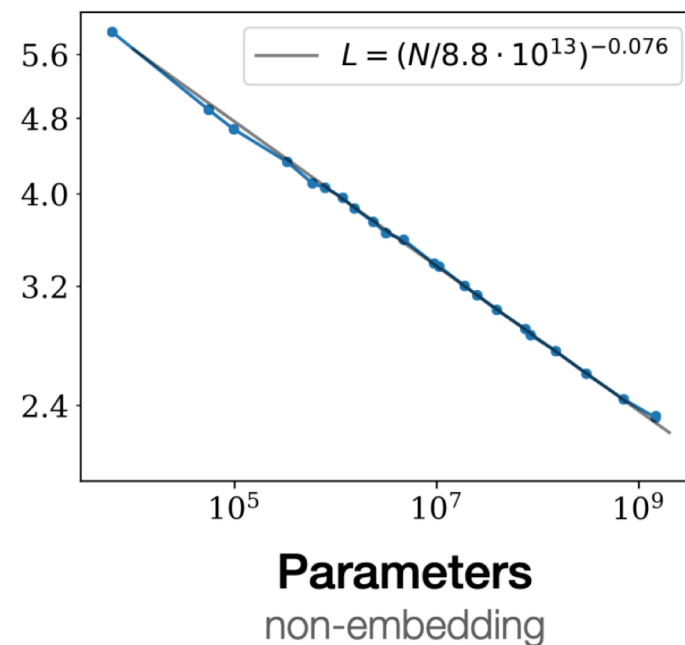
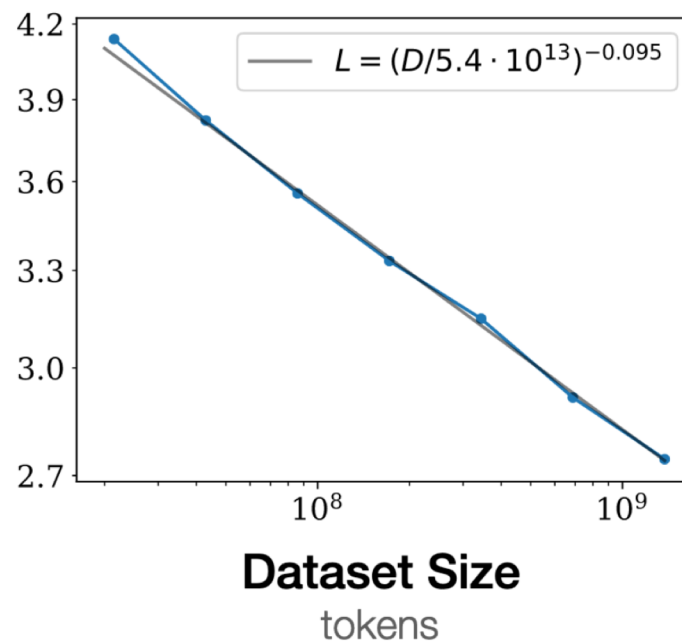
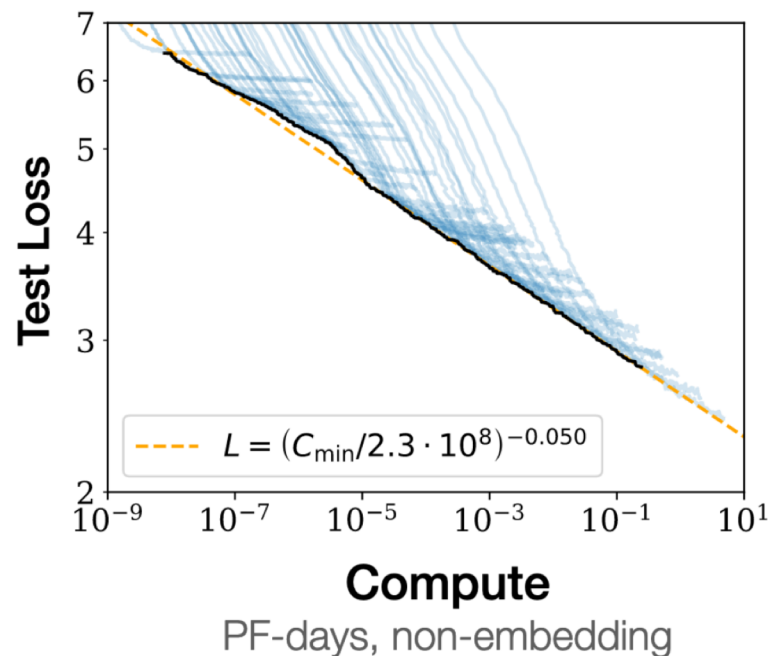


# Scaling Laws in Language Models





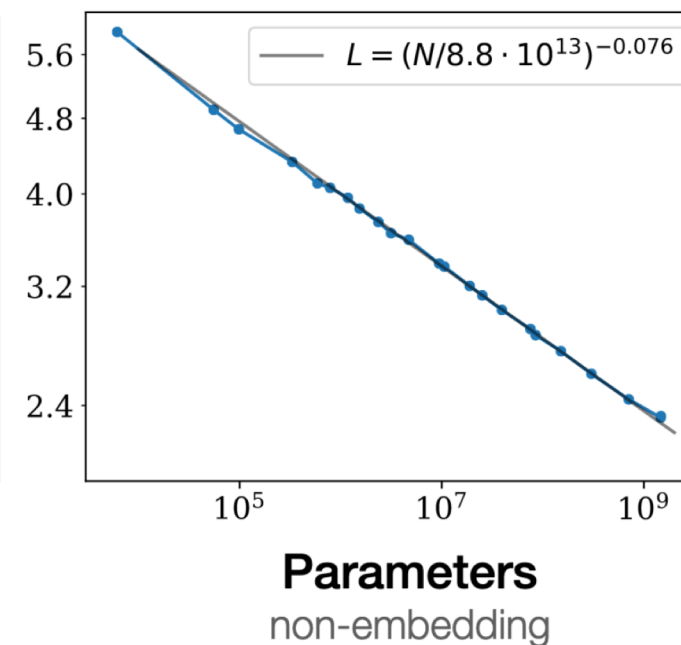
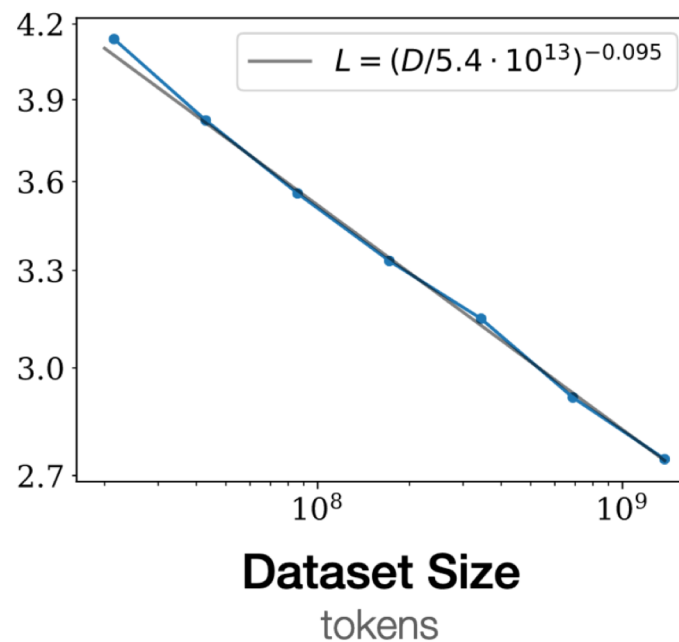
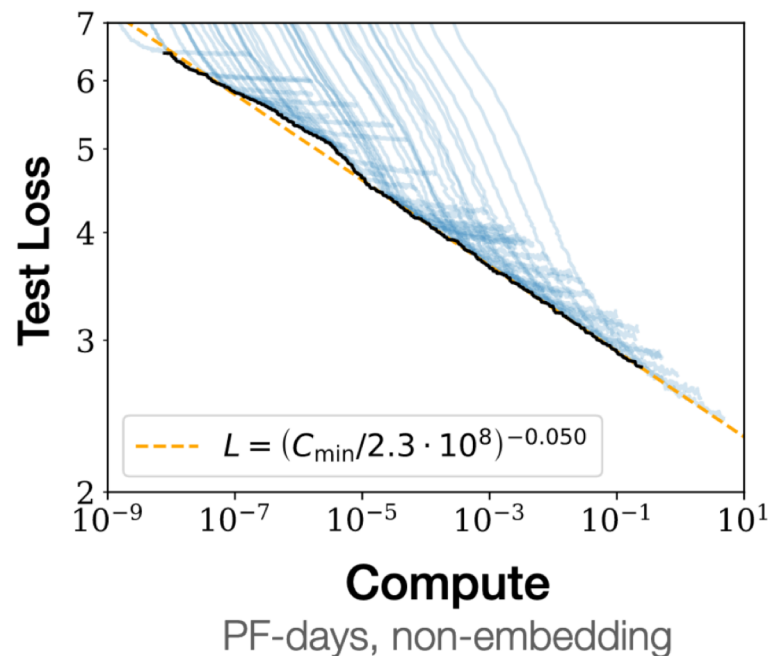
# Scaling Laws in Language Models



## Scaling laws

Scaling laws (model size + data + compute) reliably improve model performance.

# Scaling Laws in Language Models



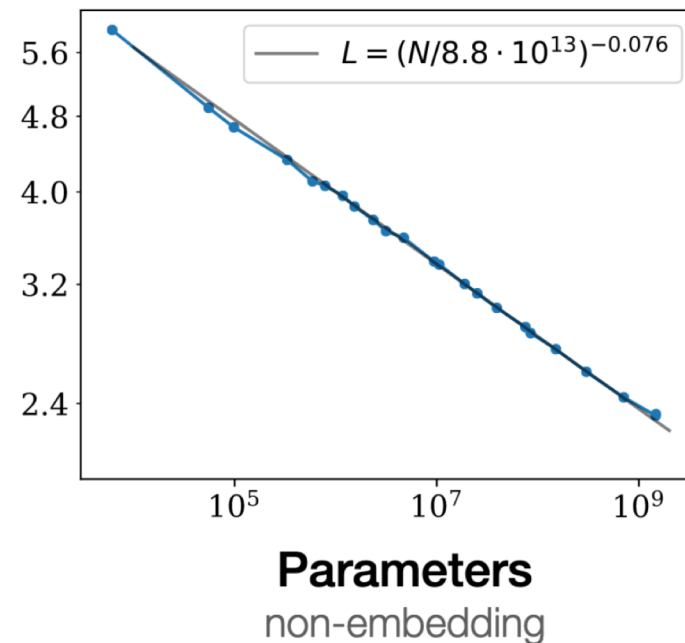
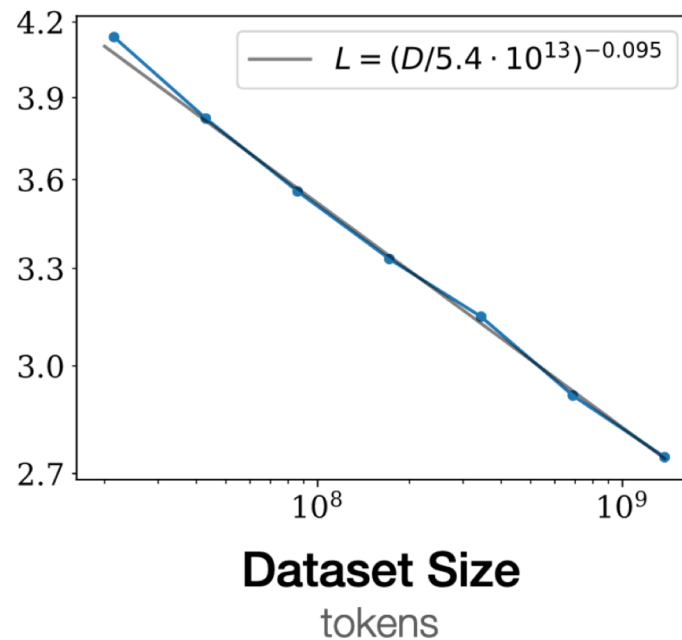
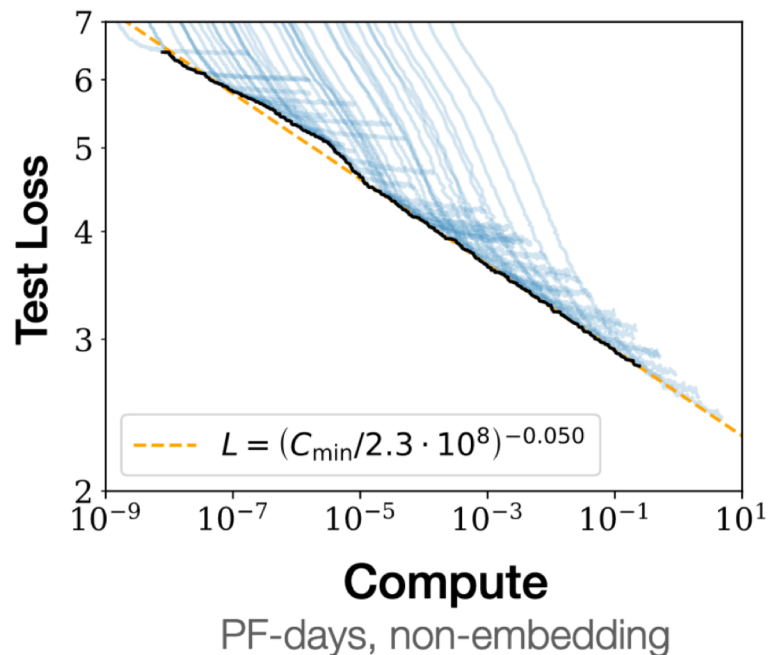
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## Emergent abilities

As a result of scale, LMs gain new downstream abilities not present in small models.

# Scaling Laws in Language Models



## Scaling laws

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As a result of scale, LMs gain new downstream abilities not present in small models.

## Reasoning via prompting

LMs can do multi-step reasoning, which paves the way to solving challenging problems.

# How to Teach Language Models to Reason?



# How to Teach Language Models to Reason?

**Just like teaching kids?**

# How to Teach Language Models to Reason?

**Give them some examples to understand the task...**

# Few-shot Prompting for Toy Task



**Q:** Artificial Intelligence

**A:** AI

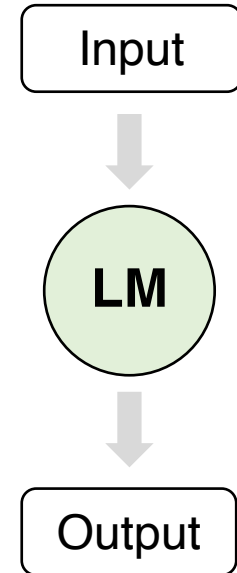
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**Q:** Large Language Model



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# Few-shot Prompting for Toy Task



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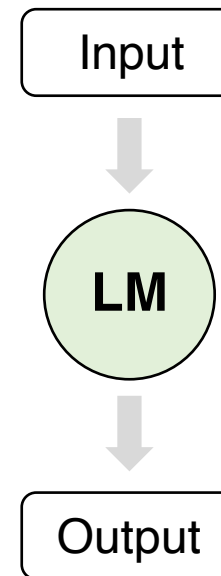
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**A:** LLM





# Few-shot Prompting for Math Reasoning



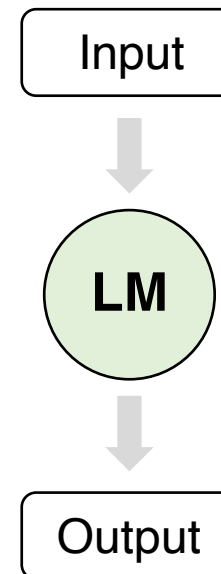
**Q:** Roger has 5 tennis balls. He buys 2 more cans of tennis balls. Each can has 3 tennis balls. How many tennis balls does he have now?

**A:** The answer is 11.

**Q:** The cafeteria had 23 apples. If they used 20 to make lunch and bought 6 more, how many apples do they have?



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# Few-shot Prompting for Math Reasoning



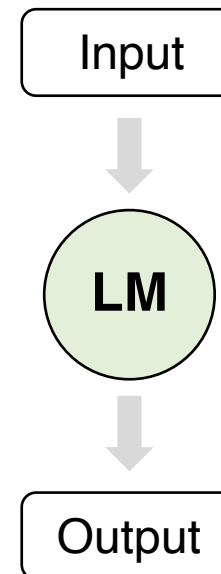
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**A:** The answer is 27.



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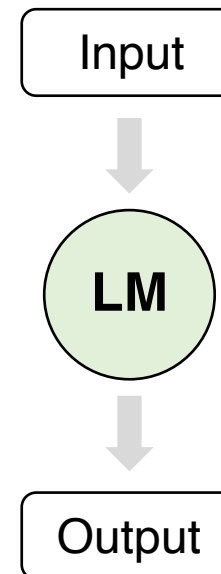
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**This task is hard! The model does not understand the task!**

# Few-shot Prompting for Math Reasoning



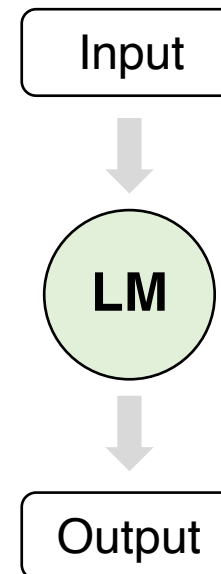
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**Give it more information to describe specific rationales!**

# Chain-of-Thought Prompting for Math Reasoning



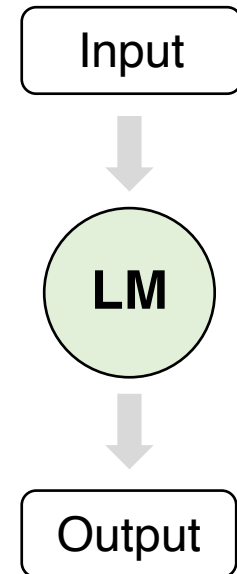
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**Provide it with the example of Chain-of-Thought (CoT)!**

# Chain-of-Thought Prompting for Math Reasoning



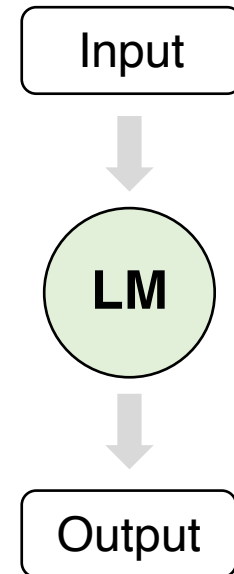
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**A:** The cafeteria had 23 apples originally. They used 20 to make lunch. So they had  $23 - 20 = 3$ . They bought 6 more apples, so they have  $3 + 6 = 9$ . The answer is 9.



# Chain-of-Thought Prompting for Math Reasoning



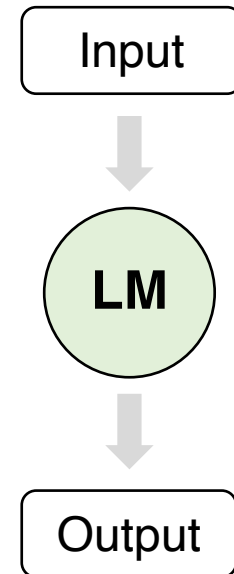
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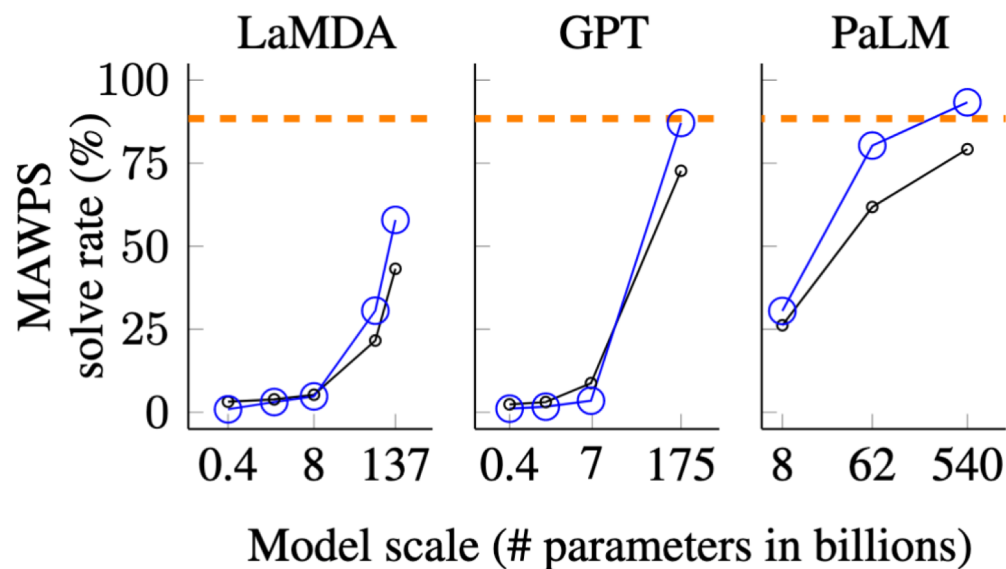
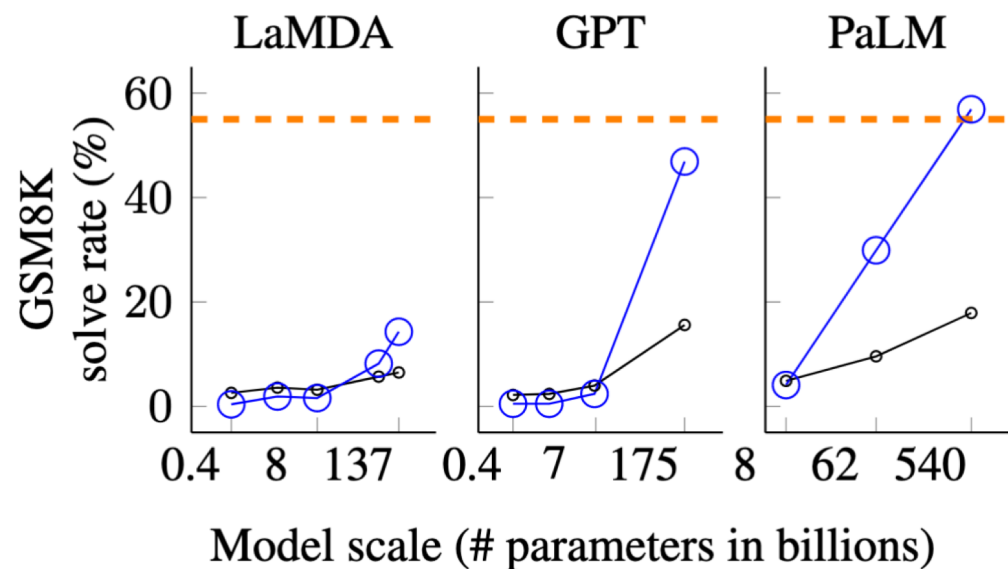
**A:** The cafeteria had 23 apples originally. They used 20 to make lunch. So they had  $23 - 20 = 3$ . They bought 6 more apples, so they have  $3 + 6 = 9$ . The answer is 9.



**Using natural language to describe rationales is critical for CoT!**

# Chain-of-Thought Prompting for Math Reasoning

- Standard prompting
- Chain-of-thought prompting
- - - Prior supervised best





# CoT Prompting for Various Tasks

## Math Word Problems (free response)

Q: Roger has 5 tennis balls. He buys 2 more cans of tennis balls. Each can has 3 tennis balls. How many tennis balls does he have now?

A: Roger started with 5 balls. 2 cans of 3 tennis balls each is 6 tennis balls.  $5 + 6 = 11$ . The answer is 11.

## Math Word Problems (multiple choice)

Q: How many keystrokes are needed to type the numbers from 1 to 500?  
Answer Choices: (a) 1156 (b) 1392 (c) 1480 (d) 1562 (e) 1788

A: There are 9 one-digit numbers from 1 to 9. There are 90 two-digit numbers from 10 to 99. There are 401 three-digit numbers from 100 to 500.  $9 + 90(2) + 401(3) = 1392$ . The answer is (b).

## CSQA (commonsense)

Q: Sammy wanted to go to where the people were. Where might he go?  
Options: (a) race track (b) populated areas (c) desert (d) apartment (e) roadblock

A: The answer must be a place with a lot of people. Race tracks, desert, apartments, and roadblocks don't have a lot of people, but populated areas do. So the answer is (b).

## StrategyQA

Q: Yes or no: Would a pear sink in water?

A: The density of a pear is about  $0.6 \text{ g/cm}^3$ , which is less than water. Thus, a pear would float. So the answer is no.

## Date Understanding

Q: The concert was scheduled to be on 06/01/1943, but was delayed by one day to today. What is the date 10 days ago in MM/DD/YYYY?

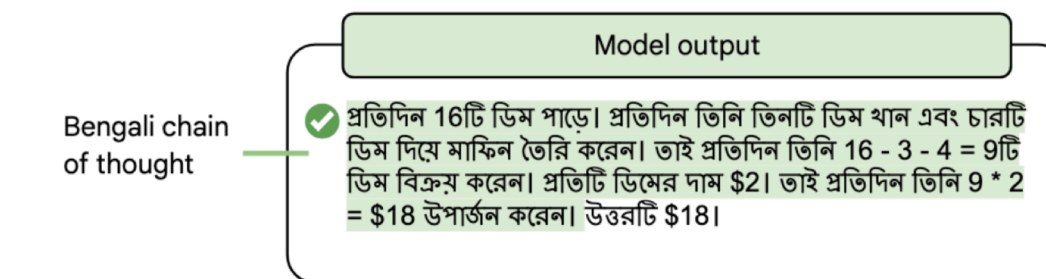
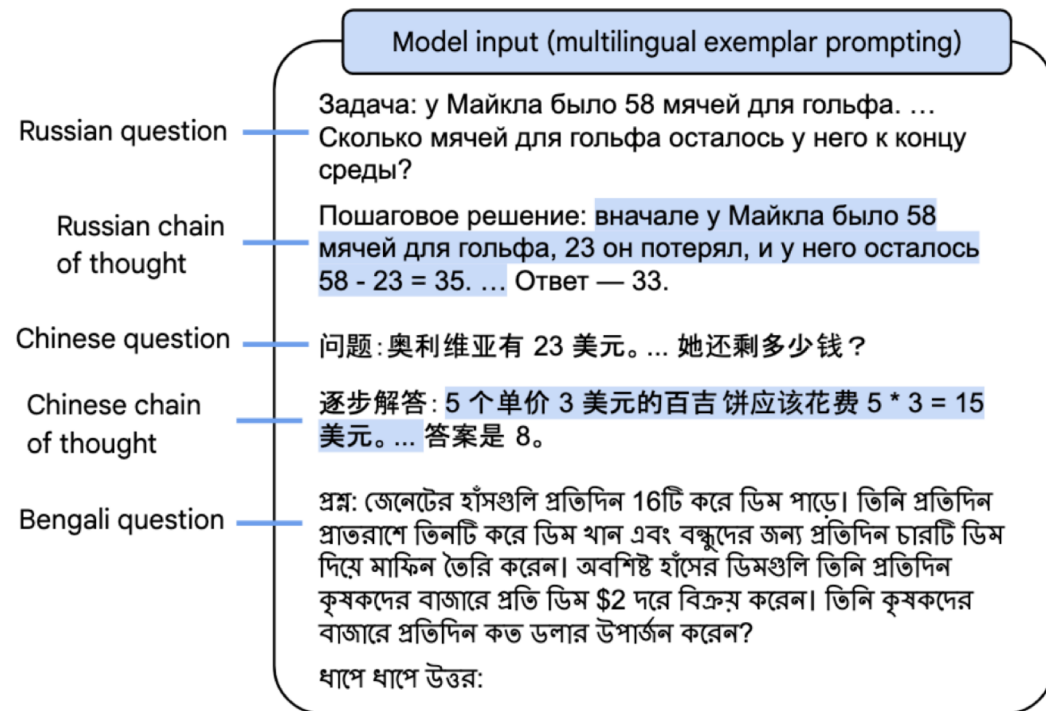
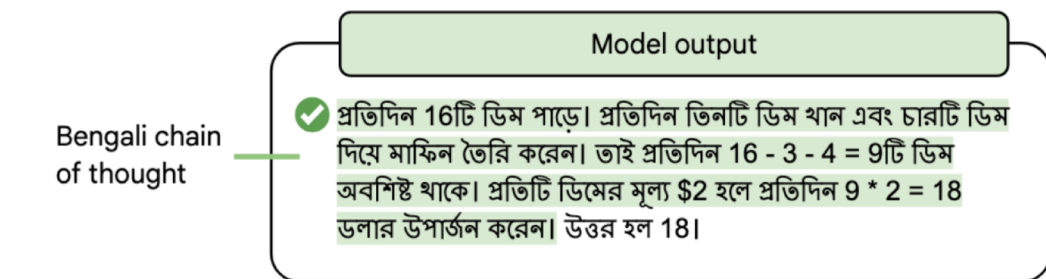
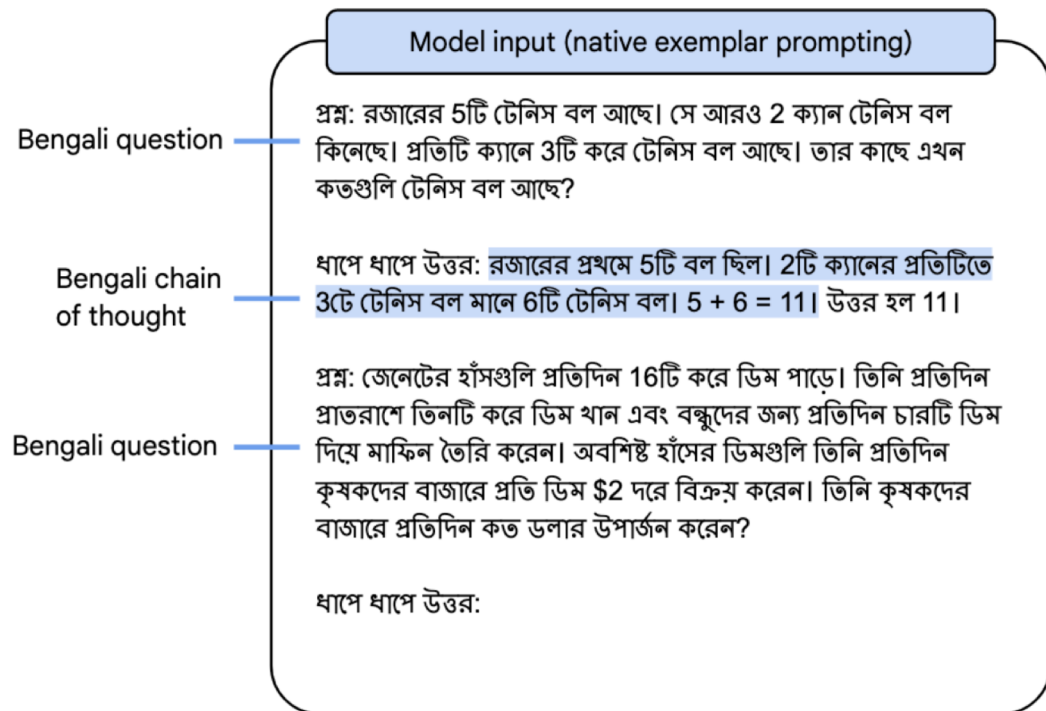
A: One day after 06/01/1943 is 06/02/1943, so today is 06/02/1943. 10 days before today is 05/23/1943. So the answer is 05/23/1943.

## Sports Understanding

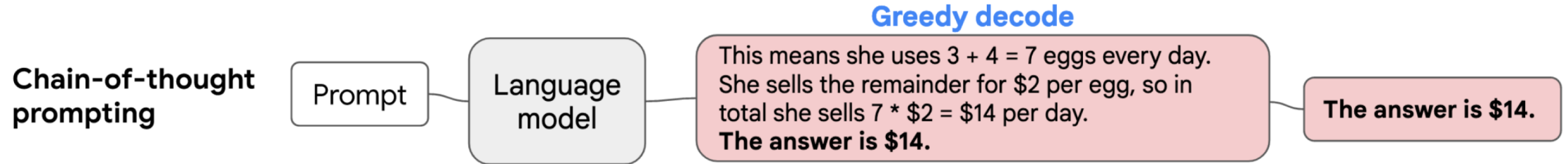
Q: Is the following sentence plausible? "Joao Moutinho caught the screen pass in the NFC championship."

A: Joao Moutinho is a soccer player. The NFC championship is part of American football, not soccer. So the answer is no.

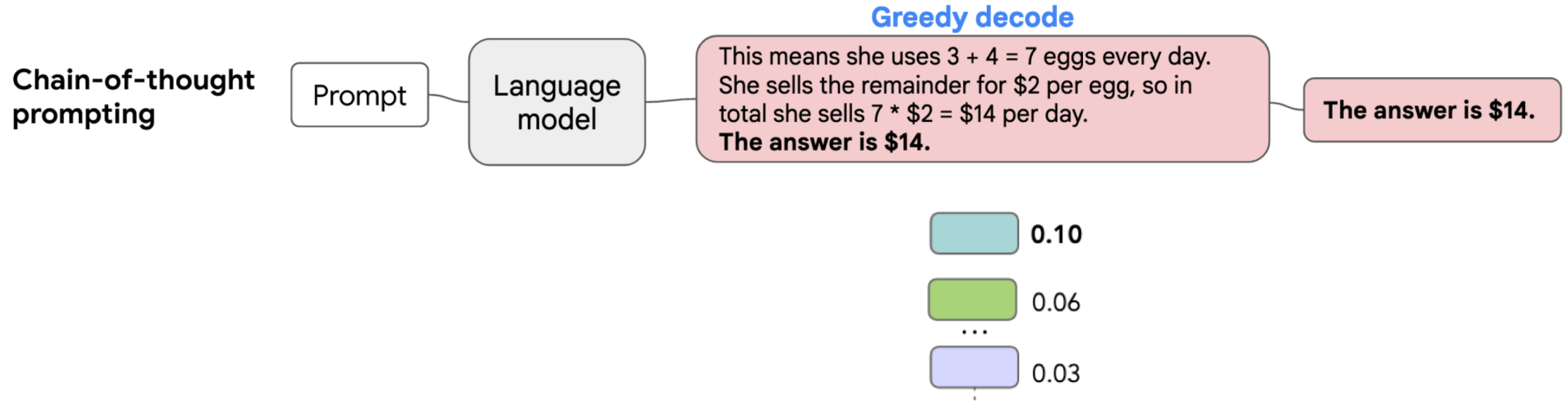
# CoT Prompting for Multilingual Math Reasoning



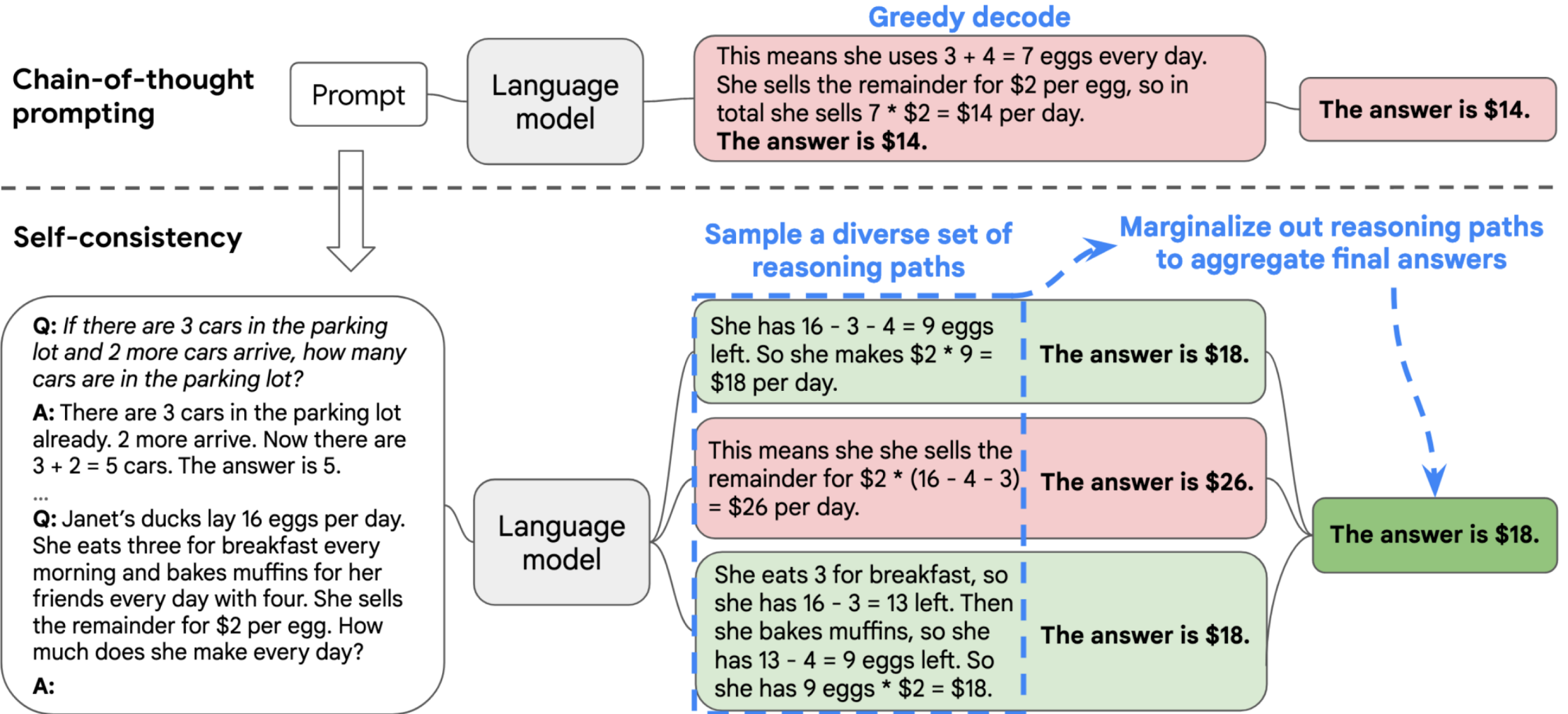
# Self-consistency Improves CoT Prompting



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# Improving CoT Prompting for Reasoning

Chen et al. 2023. **Program of thoughts** prompting: Disentangling computation from reasoning for numerical reasoning tasks.

Yao et al. 2023. **Tree of Thoughts**: Deliberate Problem Solving with Large Language Models.

Ding et al. 2023. **Everything of Thoughts**: Defying the Law of Penrose Triangle for Thought Generation.

Zhang et al. 2023. **Automatic chain of thought** prompting in large language models.

Zhou et al. 2023. **Least-to-most prompting** enables complex reasoning in large language models.

Zheng et al. 2023. **Progressive-hint prompting** improves reasoning in large language models.

Jiang et al. 2023. **Resprompt**: Residual connection prompting advances multi-step reasoning in large language models.

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# Limitations of CoT Prompting

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- Prompting engineering is not interesting



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- Prompting engineering is not interesting
- Cot Prompting requires scaling
- This method does not explicitly encourage LMs toward correct step-by-step reasoning
- ...

# Limitations of CoT Prompting

Cot Prompting requires **scaling!**

## CoT Prompting

**Q:** Roger has 5 tennis balls. He buys 2 more cans of tennis balls. Each can has 3 tennis balls. How many tennis balls does he have now?

**A:** Let's think step by step. Roger started with 5 balls. 2 cans of 3 tennis balls each is 6 tennis balls.  $5+6=11$ . The answer is 11.

**Q:** What is half of  $(3 + 7)$  plus one?

**A:**

text-ada-001

The answer is the result of adding 1 more ball  $(3 + 7)$  plus 1.

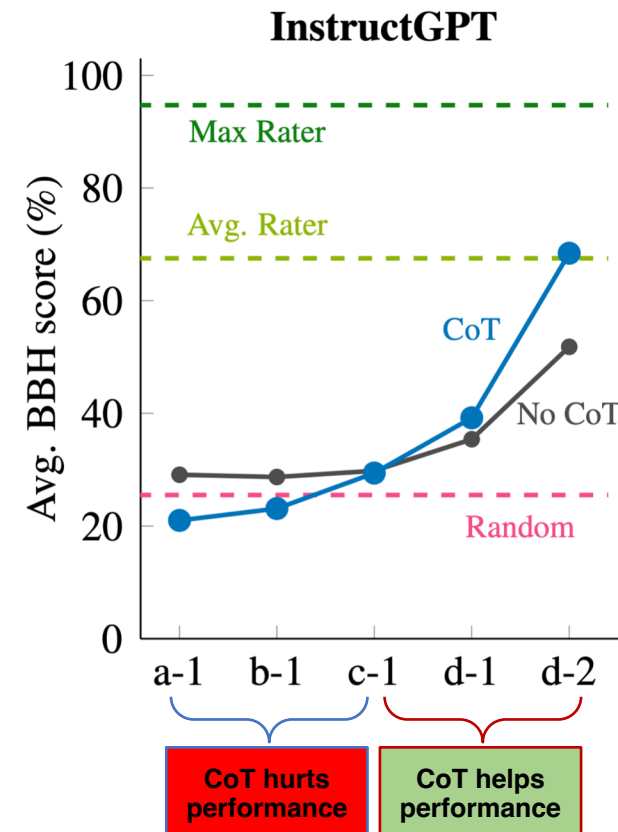


text-davinci-002

Let's think step by step.  $3+7=10$ .  $10/2=5$ .  $5+1=6$ . The answer is 6.



a-1: text-ada-001; b-1: text-babbage-001; c-1: text-curie-001;  
d-1: text-davinci-001; d-2: text-davinci-002



# Limitations of CoT Prompting

It does not explicitly encourage LMs toward [correct step-by-step reasoning](#)

# Limitations of CoT Prompting

It does not explicitly encourage LMs toward **correct step-by-step reasoning**



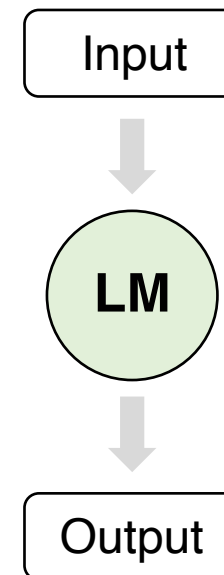
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**Q:** Fred had 212 sheets of paper. He received another 307 sheets of paper from Jane and gave Charles 156 sheets of paper. How many sheets of paper does Fred have left?



**A:** Fred has  $212 + 156 = 368$  sheets of paper. After giving Charles 156 sheets of paper, Fred has  $368 - 156 = 212$  sheets of paper left.



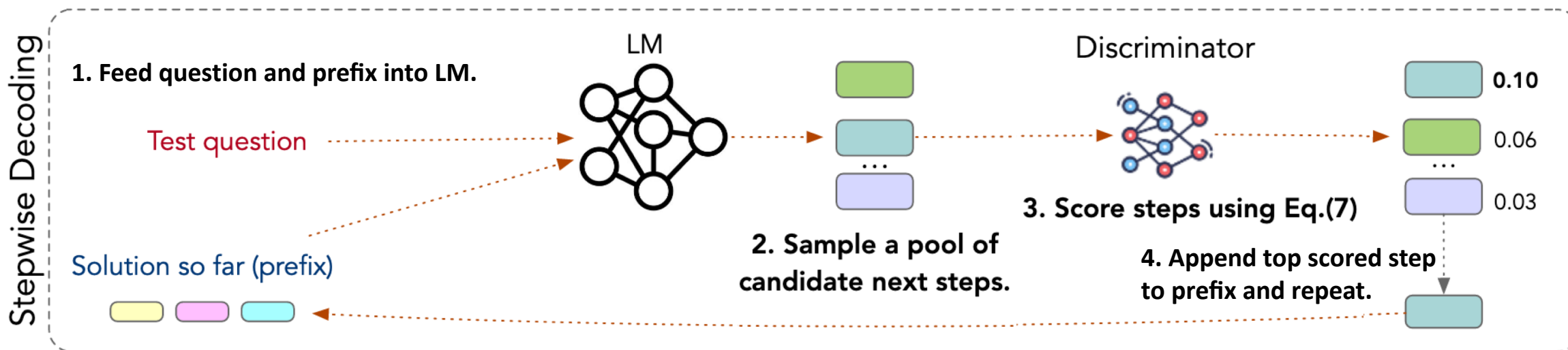
Can Controlling Decoding Improve Reasoning?

# Controlling Decoding Improves Reasoning

Using a discriminator to guide the multi-step reasoning

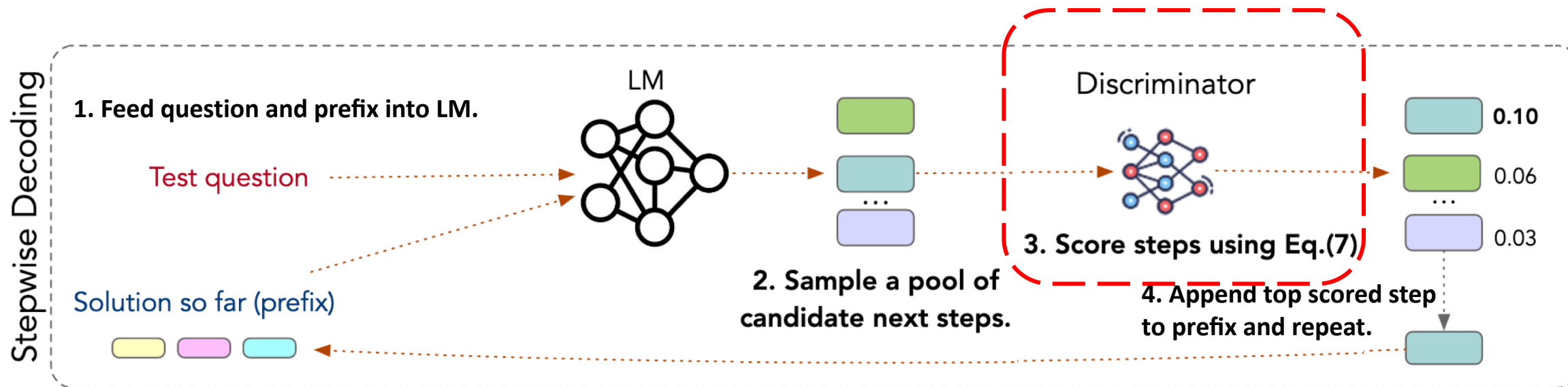
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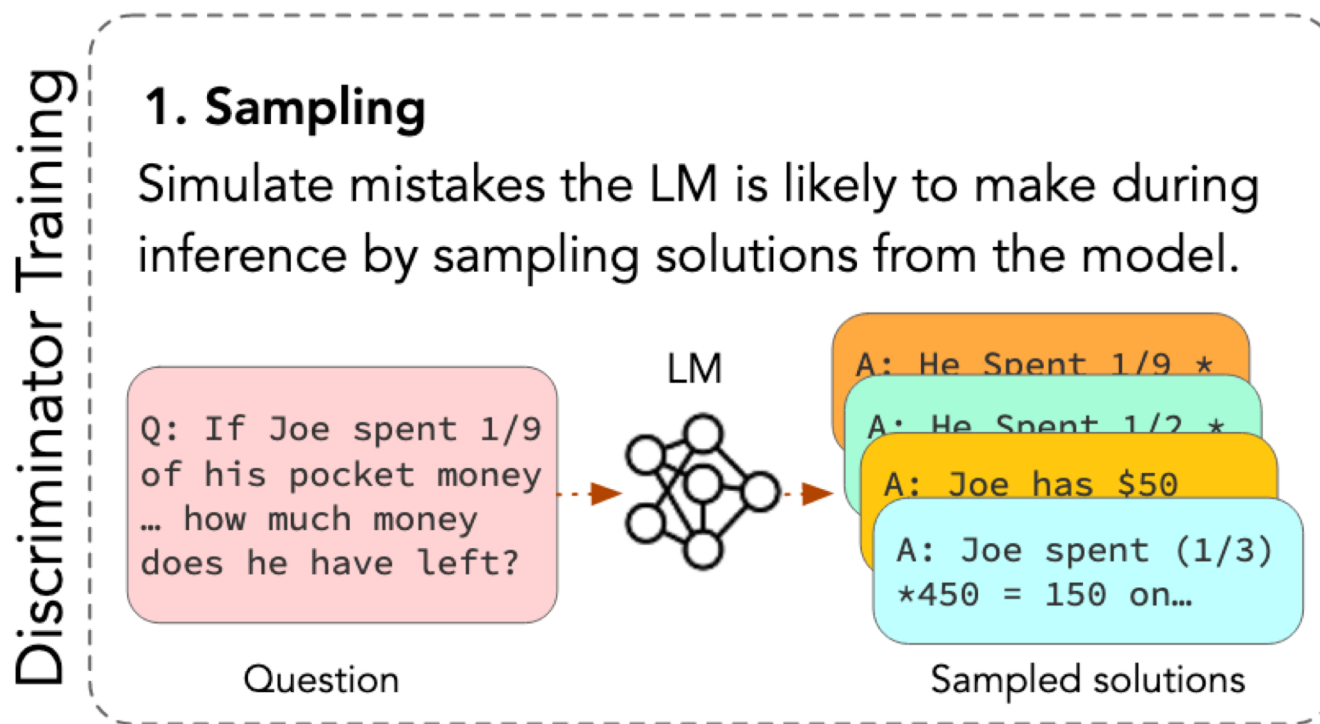
Using a discriminator to guide the multi-step reasoning





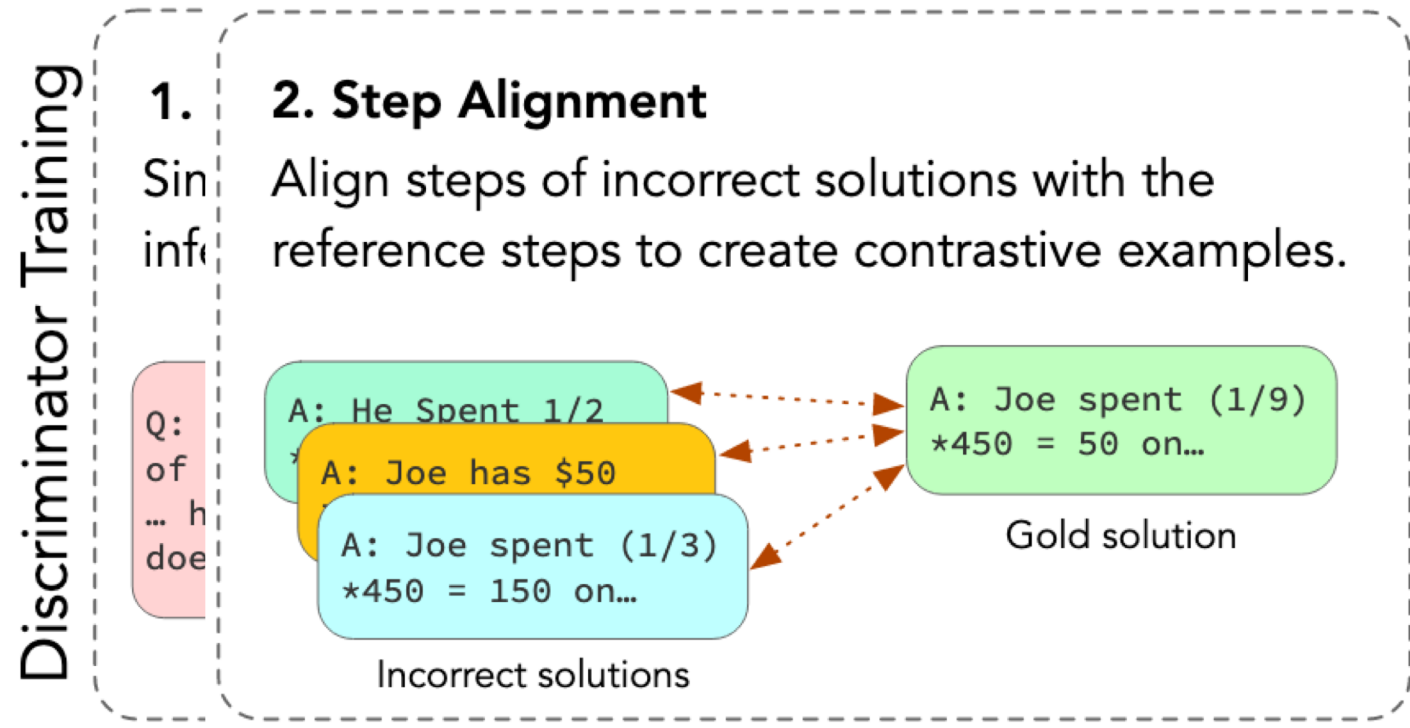
# Controlling Decoding Improves Reasoning

Training a discriminator to guide the multi-step reasoning



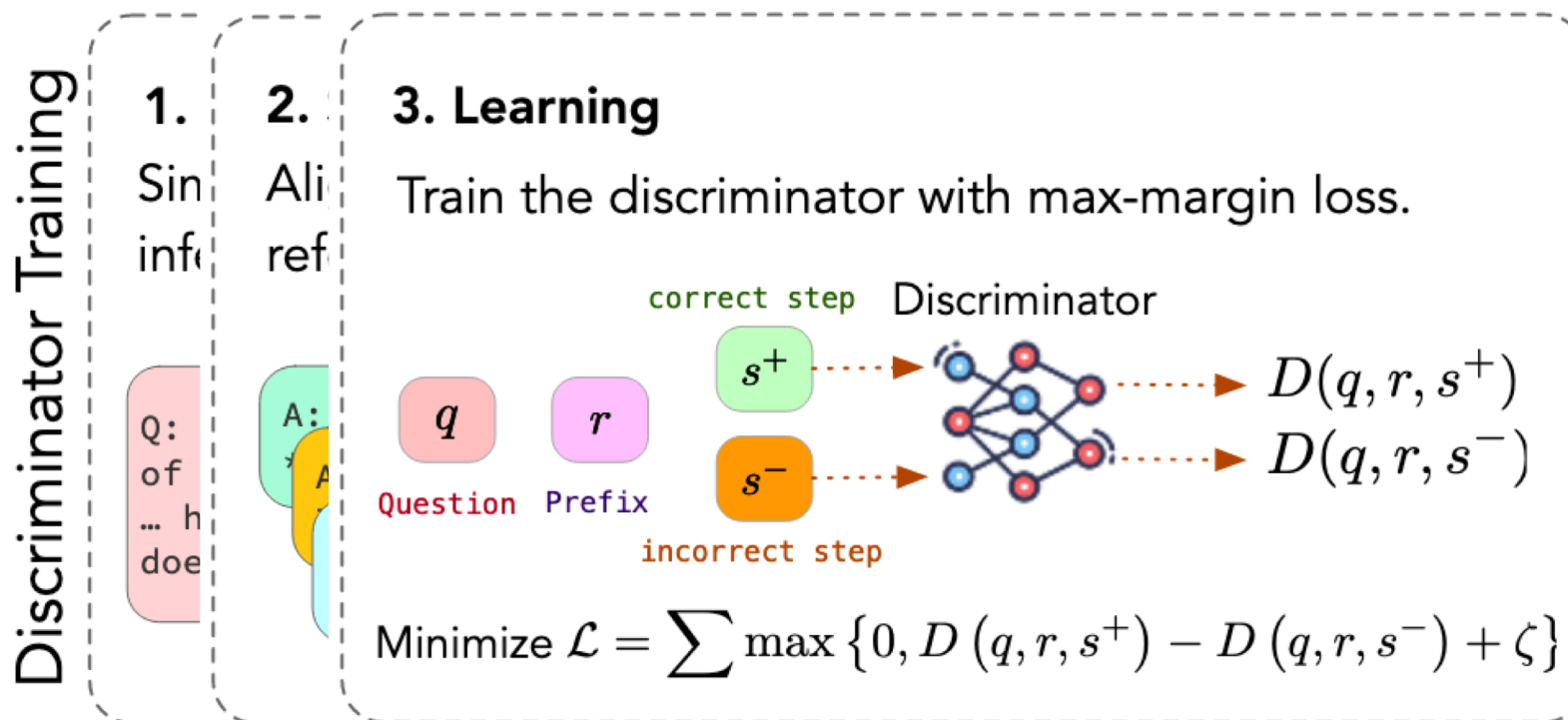
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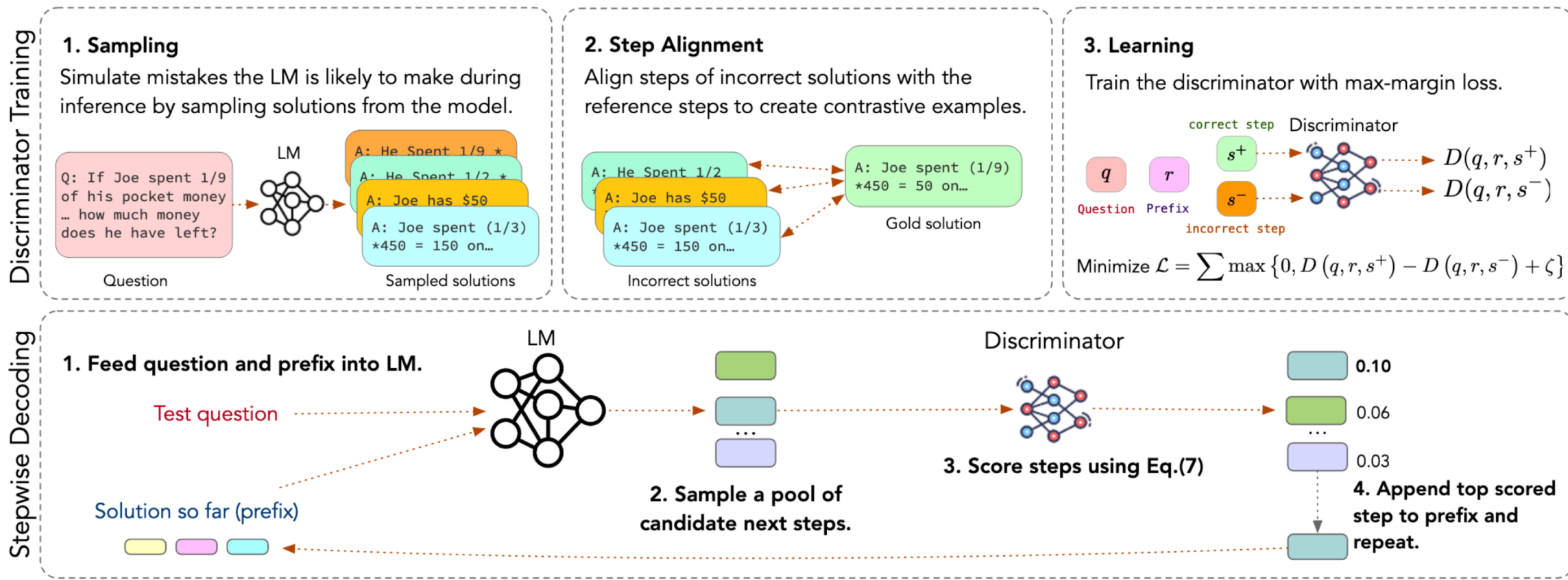
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	FLAN-T5-LARGE			LLAMA-7B		
	GSM8K	SVAMP	MathQA-Gain	GSM8K	MultiArith	SVAMP
Greedy decoding	26.9	54.5	76.5	12.9	54.0	32.8
Self-consistency	33.3	61.8	78.9	20.7	78.9	52.4
Sample-then-rank	20.5	45.9	83.7	9.60	46.4	26.1
GRACE	34.3 (+7.4)	66.2 (+11.7)	84.1 (+6.0)	16.2 (+3.30)	84.9 (+30.9)	49.7 (+17.3)
GRACE w/ self-consistency	<b>36.3</b> (+3.0)	<b>68.6</b> (+6.80)	84.4 (+0.7)	<b>30.9</b> (+10.2)	<b>94.6</b> (+15.7)	<b>55.6</b> (+3.20)

# Controlling Decoding Improves Reasoning

Cobbe et al. 2021. Training Verifiers to Solve Math Word Problems.

Khalifa et al. 2023. Discriminator-Guided Multi-step Reasoning with Language Models.

O'Brien et al. 2023. Contrastive Decoding Improves Reasoning in Large Language Models.

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Does Optimizing Models Improve Reasoning?

# Optimizing Models Improves Reasoning

Using reinforcement learning



# Optimizing Models Improves Reasoning

Using reinforcement learning to

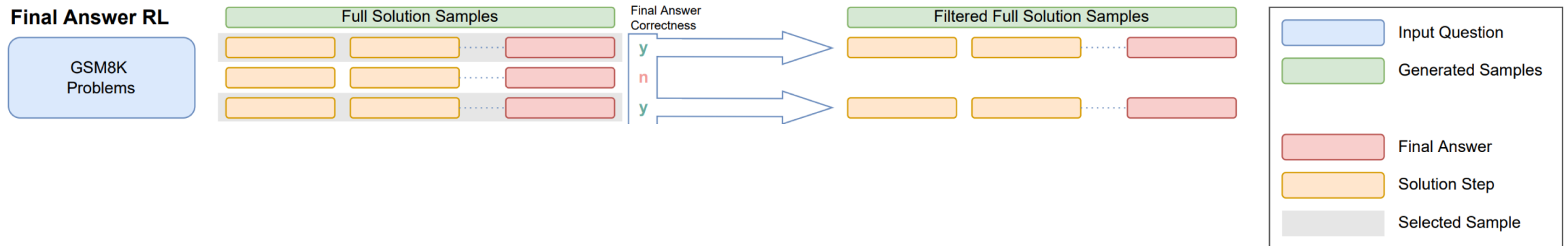
- explicitly optimize models based on feedback from **metrics** or **humans**

# Optimizing Models Improves Reasoning

Using reinforcement learning to

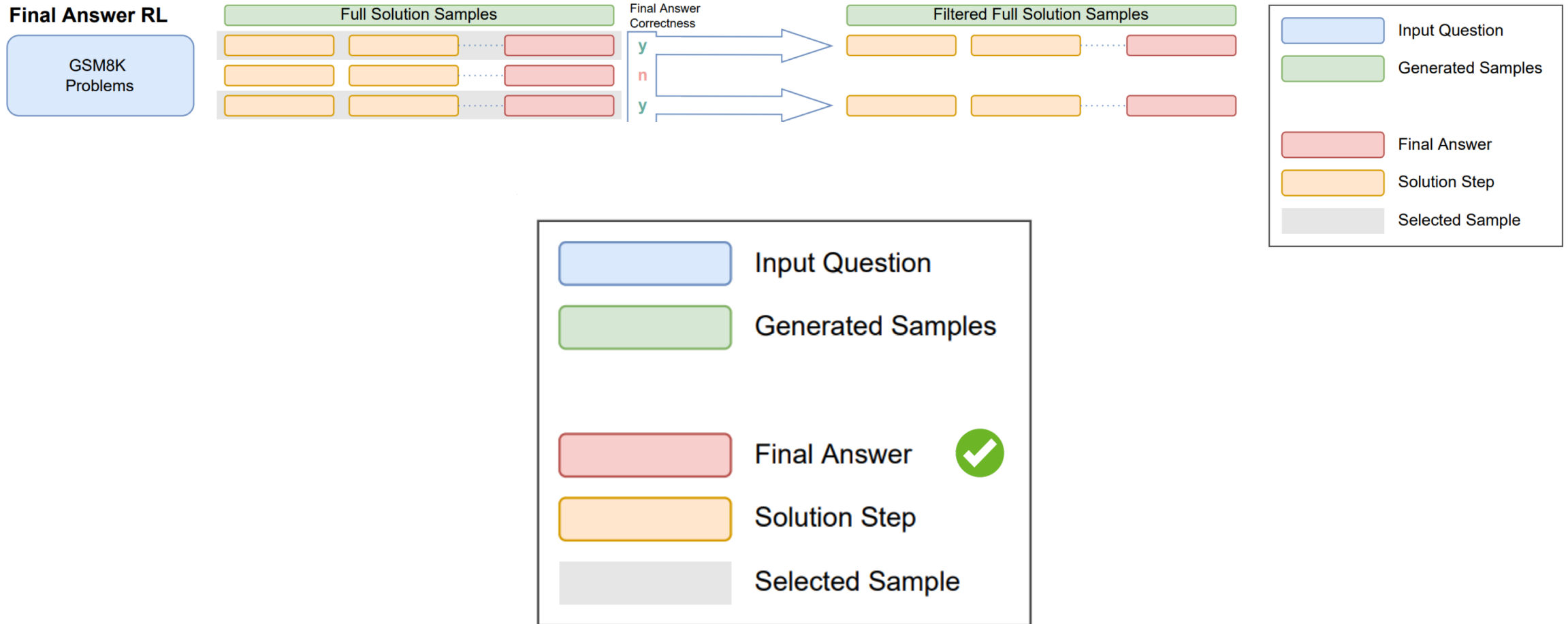
- explicitly optimize models based on reasoning outcome or reasoning process

# Optimizing Models Improves Reasoning

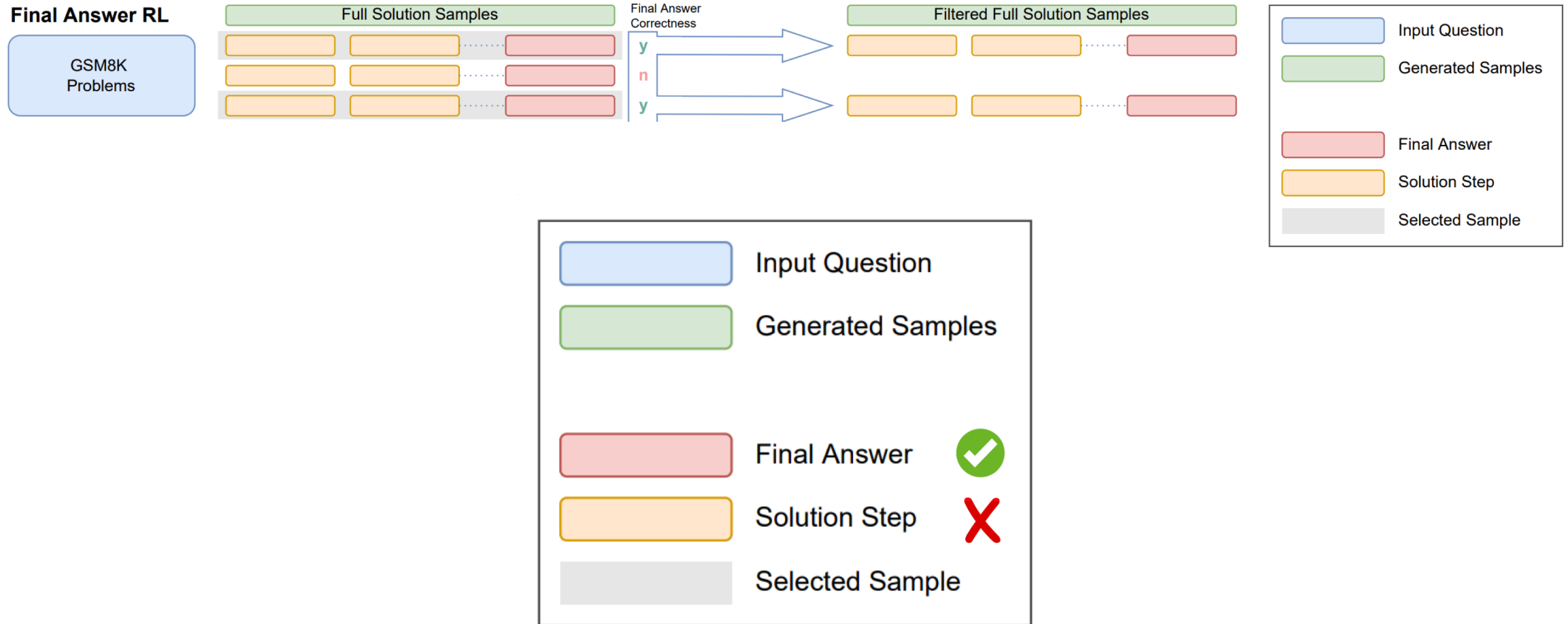


Generating  $K$  full potential reasoning solutions per problem and filter by final-answer correctness.

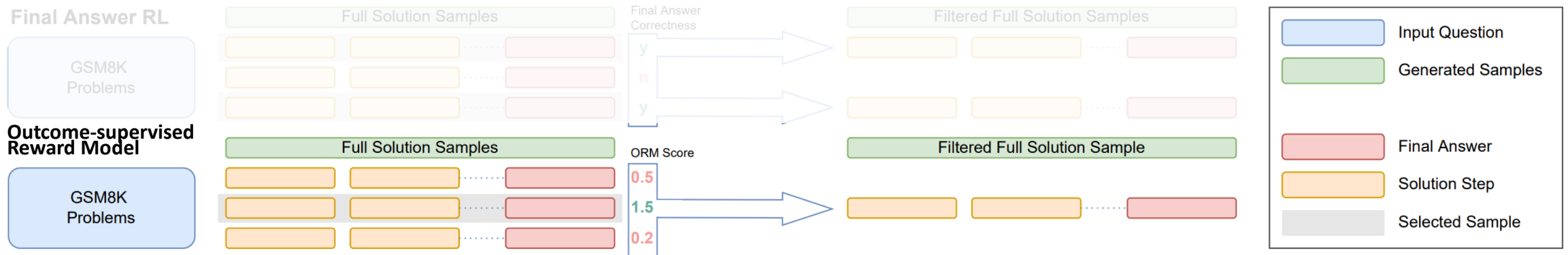
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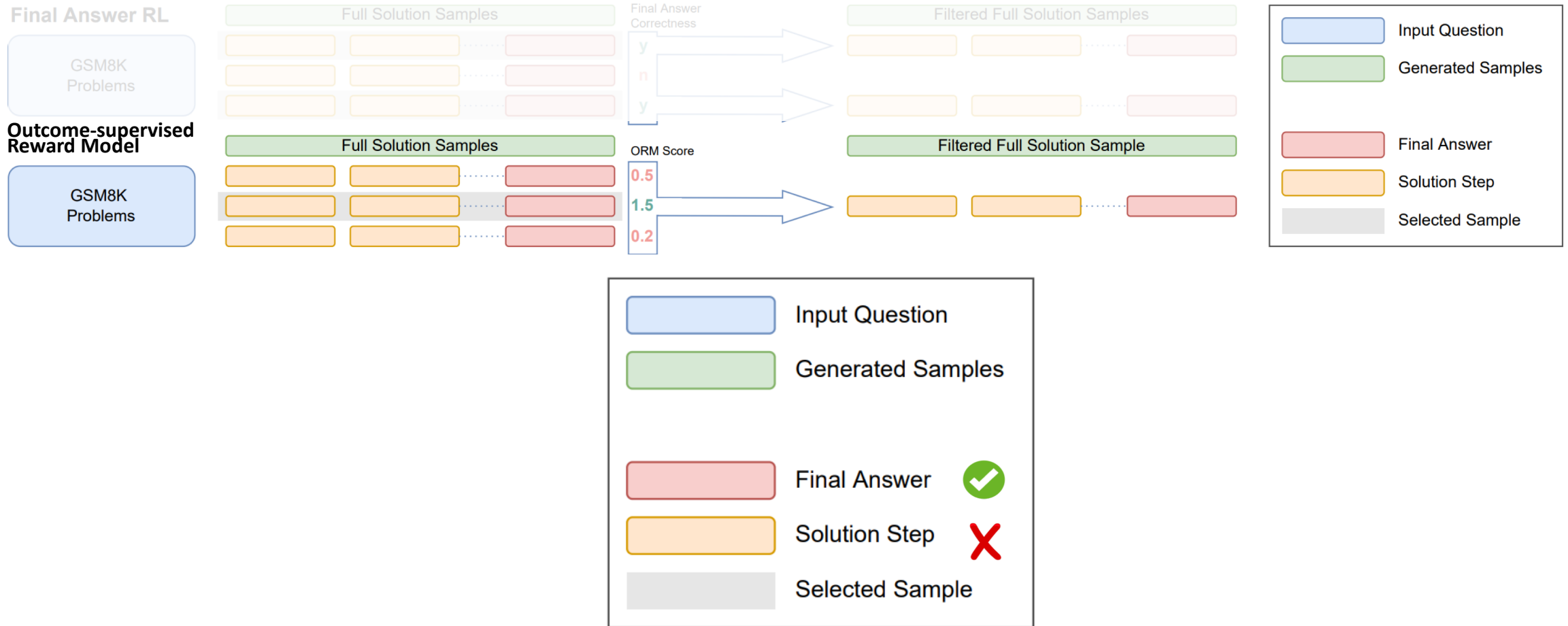


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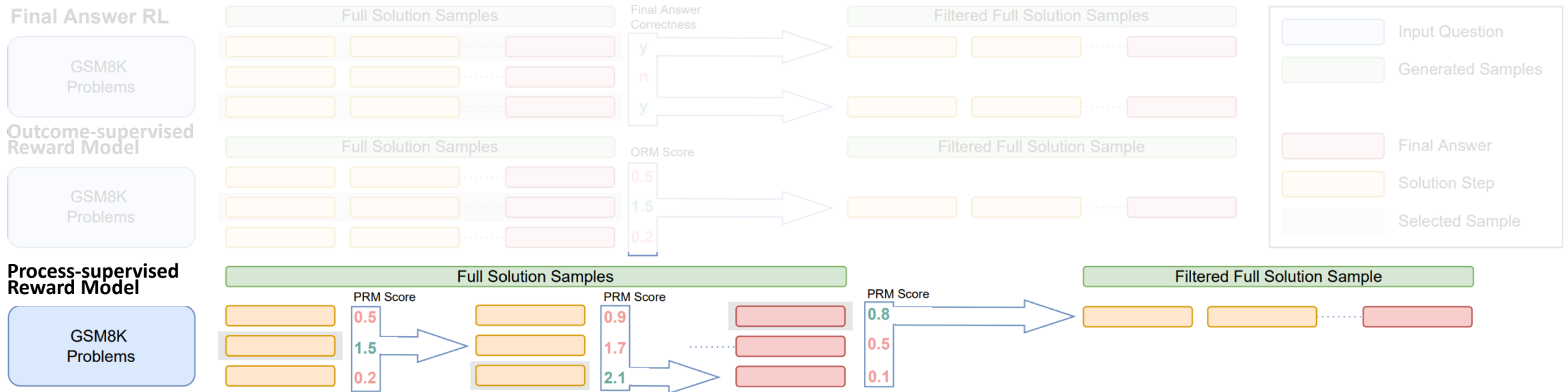


A reward model is trained to judge the correctness of solutions, with the training signal determined solely by whether or not the solution reached the correct final answer (human annotation).

# Optimizing Models Improves Reasoning



# Optimizing Models Improves Reasoning



A reward model is trained to judge whether the reasoning steps so far are correct (human annotation).



# Optimizing Models Improves Reasoning

Approach	Base model	Error rate (%)		
		Trace	Final-answer	
SFT+Final-Answer RL, ORM reranking	Base-70B	3.7	(0.5-6.9)	14.2
SFT, ORM reranking	Base-70B	4.4	(0.6-8.3)	14.8
SFT, PRM reranking	Base-70B	3.5	(0.5-6.5)	14.1
SFT+ORM-RL, ORM reranking	Base-70B	3.4	(0.0-6.8)	12.7
SFT+PRM-RL, PRM reranking	Base-70B	3.8	(0.5-7.1)	12.9

# Optimizing Models Improves Reasoning

- Results-based method
  - No human annotation
  - Reasoning steps might be incorrect
- Reward-model-based method
  - Human annotation
  - Better results

# Optimizing Models Improves Reasoning

Uesato et al. 2023. Solving math word problems with process and outcome-based feedback.

Zelikman et al. 2023. Star: Bootstrapping reasoning with reasoning.

Luo et al. 2023. Wizardmath: Empowering mathematical reasoning for large language models via reinforced evol-instruct.

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# Data Augmentation Improves Reasoning

Fu et al. 2023. Specializing smaller language models towards multi-step reasoning.

Hsieh et al. 2023. Distilling step-by-step! outperforming larger language models with less training data and smaller model sizes.

Magister et al. 2023. Teaching small language models to reason.

Shridhar et al. 2023. Distilling reasoning capabilities into smaller language models.

Yue et al. 2023. MAMmoTH: Building math generalist models through hybrid instruction tuning.

Yu et al. 2023. Meta-math: Bootstrap your own mathematical questions for large language models.

Ni et al. 2023. Learning math reasoning from self-sampled correct and partially-correct solutions.

Zelikman et al. 2023. Star: Bootstrapping reasoning with reasoning.

Huang et al. 2023. Large language models can self-improve.

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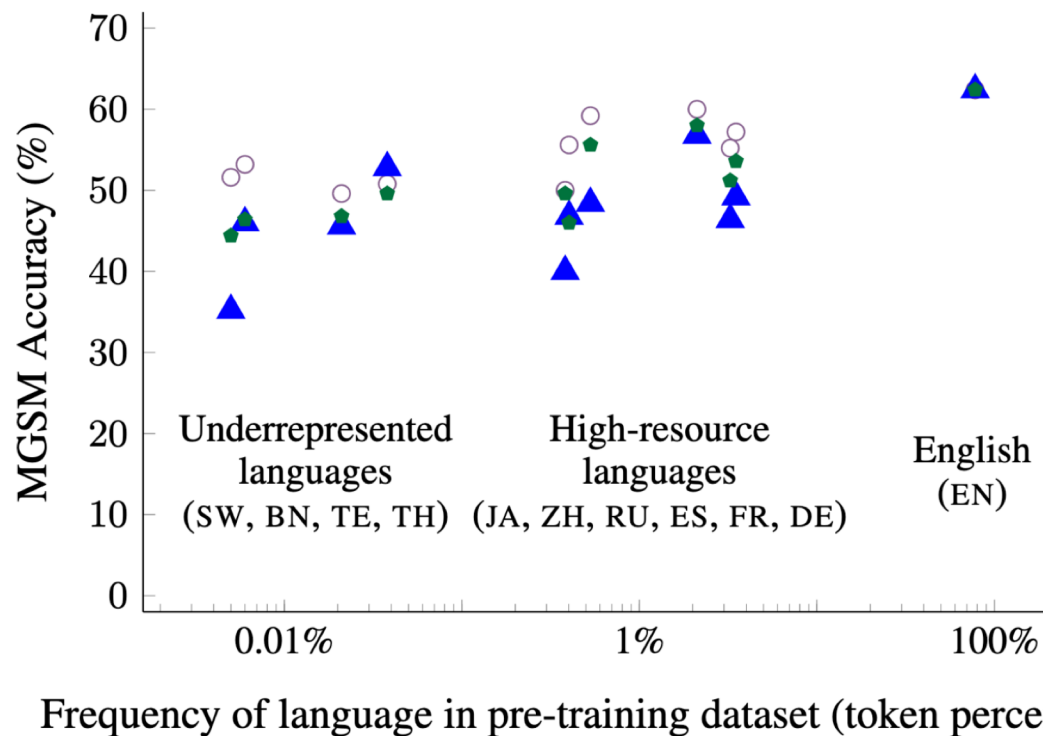
Huang et al. 2023. Large language models can self-improve.

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**DATA is IMPORTANT!**

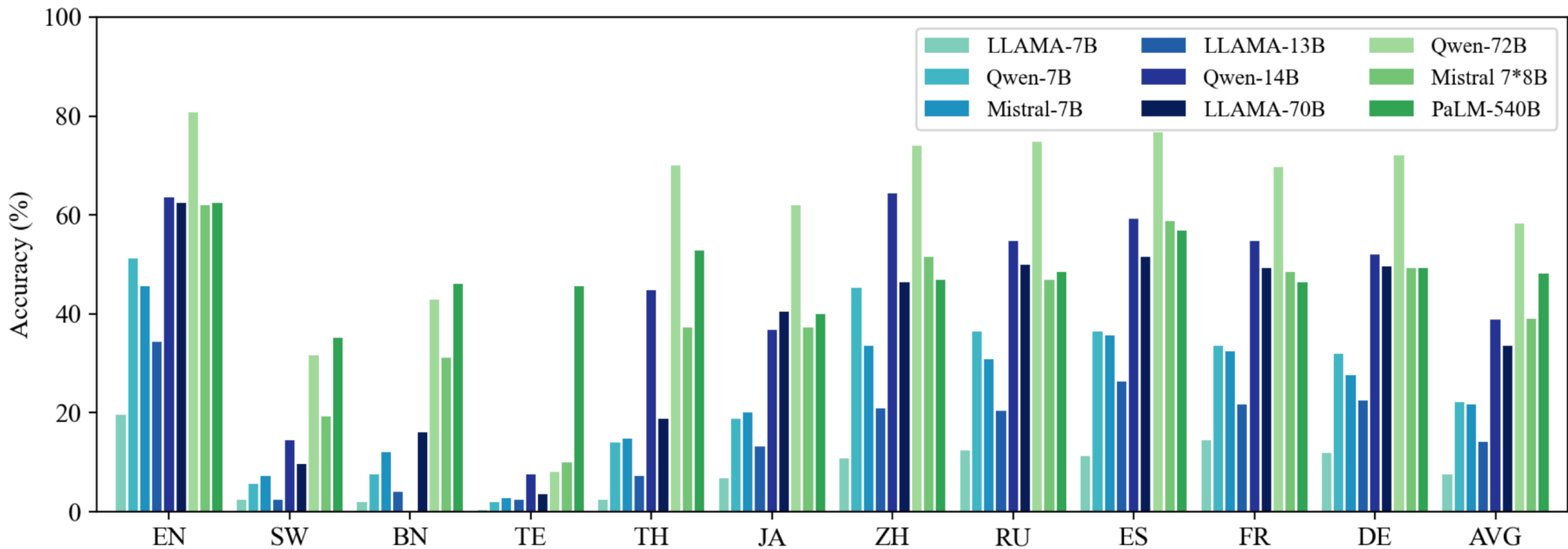
# Multilingual Math Reasoning

- Translate to English with Google Translate and solve with English intermediate steps
- ▲ Intermediate reasoning steps in the language of the question
- ◆ Intermediate reasoning steps in English



Correlation between language frequency and MGSM accuracy for PaLM-540B.

# Multilingual Math Reasoning



Accuracy (%) on MGSM of different open-source models with the few-shot method.

# Multilingual Math Reasoning

Language	CoT Reasoning
Question	Terry eats 2 yogurts a day. They are currently on sale at 4 yogurts for \$5.00. How much does he spend on yogurt over 30 days? Answer: Let's think step by step.
EN	He eats 2 yogurts a day so over 30 days he will need $2 \times 30 = 60$ yogurts The yogurt sells as 4 units for \$5.00 and he needs 60 yogurts so that's $60/4 = 15$ packs of yogurt Each pack is \$5.00 and he needs 15 packs so that's $5 \times 15 = \$75.00$ The answer is 75.
SW	Anakunywa maziwa 2 ya mtindi kila siku hivyo zaidi ya siku 30 anakunywa $2 \times 30 = 60$ Maziwa ya mtindi yanauzwa kwa 4 kwa \$5.00 na anahitaji 60 hivyo hiyo ni $60/4 = 15$ pakiti za maziwa 4 Kila pakiti ya 4 inagharimu \$5.00 na anahitaji pakiti 15 kwa hivyo hiyo ni $5 \times 15 = \$75.00$ Jibu ni 75.
BN	তিনি দিনে ২টি ইঁোগার্ট খান এবং সাপ্তাহিক ৪টি ৫.০০ ডলার বিক্রি হয় যাতে $2/4 = \$2.50$ তিনি প্রতিদিন ইঁোগার্টের জন্য \$2.50 খরচ করেন তাই ৩০ দিনের বর্ষাসময় তিনি $2.5 \times 30 = \$75.00$ খরচ করেন উত্তর হল ৭৫।
TE	అతను రోజుకు 2 యోగర్టులు తీంటాడు మరియు అవసరంలే ఉన్న సెల్లో 4 ఉన్నాయి కాబట్టి అతను రోజుకు $2/4 = 0.5$ యోగర్టులను కొనుగోలు చేయాలి, అవి ఒక్కొక్కటి \$5.00 మరియు అతను రోజుకు 0.5 కొనుగోలు చేయాలి కాబట్టి అతను రోజుకు $5 \times 0.5 = \$2.50$ ఖర్చు చేస్తాడు. 30 రోజుల పాటు యోగర్టులు అతనికి రోజుకు $2.5 \times 30 = \$75.00$ ఖర్చుమతాయి సమాధానం 75.
TH	เทอร์รี่กินโยเกิร์ต 2 ถ้วยต่อวัน ดังนั้นใน 30 วัน เขาจะต้องการโยเกิร์ต $2 \times 30 = 60$ ถ้วย โยเกิร์ต 4 แพคเกจราคาอยู่ที่ 5.00 ดอลลาร์สหรัฐ ดังนั้นโยเกิร์ตแต่ละถ้วยจึงมีราคา $5.00 \text{ ดอลลาร์สหรัฐ} / 4 = 1.25$ ดอลลาร์ ดังนั้นเทอร์รี่จะใช้จ่าย $60 \times 1.25 \text{ ดอลลาร์} = 75.00 \text{ ดอลลาร์}$ สำหรับโยเกิร์ตใน 30 วัน คำตอบคือ 75
JA	彼は 1 日に 2 つのヨーグルトを食べるので、30 日間で $2 \times 30 = 60$ 個のヨーグルトを食べることになります。ヨーグルトは 4 個で 5 ドルで販売されており、彼は 60 個のヨーグルトを購入する必要があるため、 $60/4 = 15$ 個の 4 パックになります。各パックの価格は 5 ドルで、彼は 15 個のパックを購入する必要があるため、 $5 \times 15 = 75$ ドル相当のヨーグルトになります。答えは 75 です。
ZH	他每天吃 2 份酸奶，所以 30 天他将吃 $2 \times 30 = 60$ 份酸奶 酸奶以 4 份的价格出售，他将购买 60 份酸奶，因此 $60/4 = 15$ 包酸奶 每包售价 5.00 美元，他将购买 15 包，因此 $5 \times 15 = \$75.00$ 答案是 75。
RU	Терри съедает 2 йогурта в день, значит, за 30 дней ему понадобится $2 \times 30 = 60$ йогуртов. Йогурт продается по цене 5 долларов за 4 йогурта, поэтому Терри нужно будет купить $60/4 = 15$ упаковок йогурта. Каждая пачка стоит 5 долларов, поэтому Терри потратит $15 \times 5 \text{ долларов} = 75 \text{ долларов}$ на йогурт за 30 дней. Ответ: 75.
ES	Gasta $2 \times 5 = \$10$ por día en yogur. Gasta $10 \times 30 = \$300$ en 30 días. La respuesta es 300.
FR	Il mange 2 yaourts par jour donc sur 30 jours il mange $2 \times 30 = 60$ yaourts. Les yaourts sont vendus 4 pour 5,00 \$ et il a besoin de 60 yaourts, ce qui fait $60/4 = 15$ paquets de 4 yaourts. Chaque paquet de 4 coûte 5,00 \$ et il a besoin de 15 paquets de 4 donc il dépense $5 \times 15 = 75,00$ \$ en yaourt. La réponse est 75,00.
DE	Er isst 2 Joghurts pro Tag, also benötigt er 30 Tage hinweg $2 \times 30 = 60$ Joghurts. Der Joghurt wird für 5,00 \$ pro 4er-Packung verkauft und er braucht 60 Joghurts, das sind also $60/4 = 15$ Packungen Joghurts. Jede Packung kostet 5,00 \$ und er braucht 15 Packungen, das sind also $5 \times 15 = 75,00$ \$. Die Antwort ist 75.



# Outlook

- Scaling models
- Better prompting/verifier/optimization method
- Multilingual scenario (low-resourced languages)
- High-quality Data
- Smaller task-tailored models

# What is Reasoning?

Concatenate the first letter of each word

**Q** Artificial Intelligence

**A** AI

Answer the following strategy question

**Q** Yes or no: Would a nail sink in water?

**A** Nails are made of materials such as steel or iron, which are denser than water. Thus, the answer is yes.

Solve the following math word problem

**Q** Terry eats 2 yogurts a day. They are currently on sale at 4 yogurts for \$5.00. How much does he spend on yogurt over 30 days?

**A** He eats 2 yogurts a day so over 30 days he will need  $2 \times 30 = 60$  yogurts. The yogurt sells as 4 units for \$5.00 and he needs 60 yogurts so that's  $60/4 = 15$  packs of yogurt. Each pack is \$5.00 and he needs 15 packs so that's  $5 \times 15 = \$75.00$ . The answer is 75.

*“A faculty of the **human** mind that enables logical inferences to be made and rational arguments to be undertaken to understand the world and solve problems.”*

Michael Kent. 2007. The Oxford Dictionary of Sports Science & Medicine (3 ed.)

# Do Language Models Really Perform Reasoning?

Concatenate the first letter of each word



Artificial Intelligence



AI

Answer the following strategy question



Yes or no: Would a nail sink in water?



Nails are made of materials such as steel or iron, which are denser than water. Thus, the answer is yes.

Solve the following math word problem



Terry eats 2 yogurts a day. They are currently on sale at 4 yogurts for \$5.00. How much does he spend on yogurt over 30 days?



He eats 2 yogurts a day so over 30 days he will need  $2 \times 30 = 60$  yogurts. The yogurt sells as 4 units for \$5.00 and he needs 60 yogurts so that's  $60/4 = 15$  packs of yogurt. Each pack is \$5.00 and he needs 15 packs so that's  $5 \times 15 = \$75.00$ . The answer is 75.



Gasta  $2 \times 5 = \$10$  por d\u00eda en yogur. Gasta  $10 \times 30 = \$300$  en 30 d\u00edas. La respuesta es 300.



Thank You!