

Introduction to NLP

CSE5321/CSEG321

Lecture 20. Retrieval-augmented Generation
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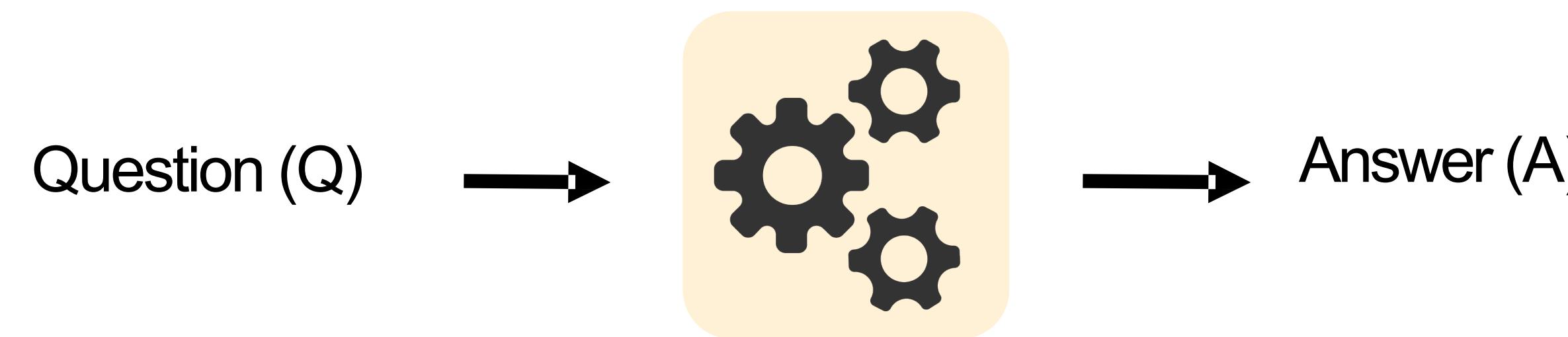
Lecture Plan

1. Question answering
2. Classes of QA: Closed-book, Open-book QA
3. Retrieval-augmented Generation (RAG)

Notice:

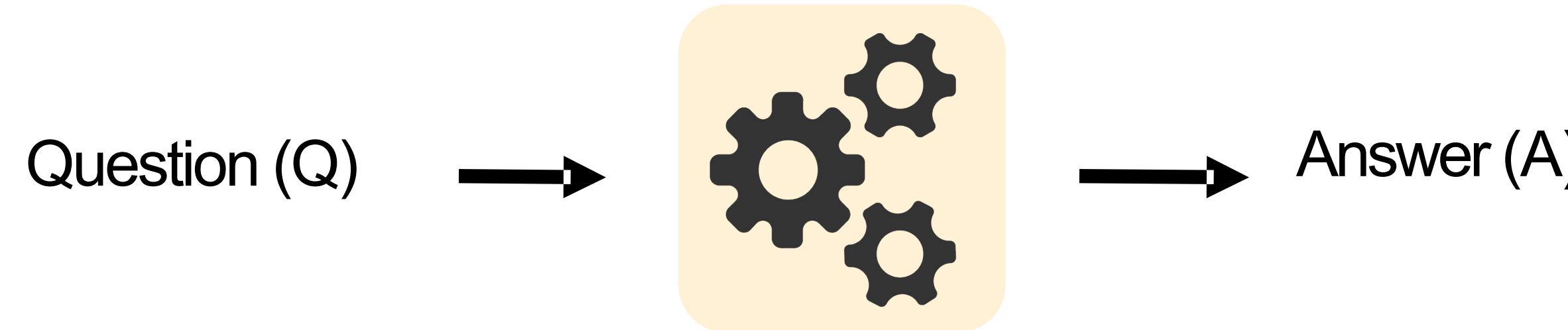
- Next lecture will be replaced with Colloquium Seminar
 - Date and Time: 5/28 AS 510
 - Title: Evaluation with socio-cultural awareness and multilingual LLMs

What is question answering?



The goal of question answering is to build systems that **automatically** answer questions posed by humans in a **natural language**

Question answering: a taxonomy



- **What information source does a system build on?**
 - A text passage, all Web documents, knowledge bases, tables, images..
- **Question type**
 - Factoid vs non-factoid, open-domain vs closed-domain, simple vs compositional, ..
- **Answer type**
 - A short segment of text, a paragraph, a list, yes/no, ...

Lots of practical applications

Where is the deepest lake in the world?

All Maps Images News Videos More Settings Tools

About 21,100,000 results (0.71 seconds)



Siberia

Lake **Baikal**, in Siberia, holds the distinction of being both the deepest lake in the world and the largest freshwater lake, holding more than 20% of the unfrozen fresh water on the surface of Earth.

건강하게 사는 방법

전체 이미지 동영상 뉴스 쇼핑 짧은 동영상 도서 더보기

Search Labs | AI 개요

건강하게 사는 방법은 건강한 식습관, 규칙적인 운동, 충분한 수면, 스트레스 관리, 금연, 절주, 정기적인 검진 등을 꾸준히 실천하는 것입니다. 이 외에도 긍정적인 마음가짐과 사회적 관계를 유지하는 것도 중요합니다.

1. 건강한 식습관:

균형 잡힌 식단:

3가지 이상의 음식을 골고루 섭취하여 다양한 영양소를 섭취하는 것이 중요합니다.

채소와 과일 섭취:

하루에 5가지 이상의 채소와 과일을 섭취하여 비타민과 미네랄을 충분히 섭취하는 것이 좋습니다.

단백질 섭취:

근육량 유지 및 건강한 노화를 위해 매일 적절한 양의 단백질을 섭취하는 것이 필요합니다.

식사 시간:

불규칙적인 식사는 소화 불량과 혈당 조절에 문제를 일으킬 수 있으므로, 규칙적인 식사 시간을 갖는 것이 좋습니다.

과음과 과식 자제:

과음은 간 기능에 부담을 주고, 과식은 비만으로 이어질 수 있으므로 적절한 양을 섭취하는 것이 좋습니다.

2. 규칙적인 운동:

- 유산소 운동: 걷기, 조깅, 자전거 타기, 수영 등 유산소 운동은 심혈관 건강을 돋고, 스트레스 해소에도 효과적입니다.
- 근력 운동: 근력 운동은 근육량을 늘려 기초대사량을 높이고, 골다공증 예방에도 도움을 줍니다.
- 운동 시간: 주 2회 이상, 1회에 20분 이상 운동하는 것이 좋습니다.

2011: IBM Watson beat Jeopardy champions



IBM Watson defeated two of Jeopardy's greatest champions in 2011

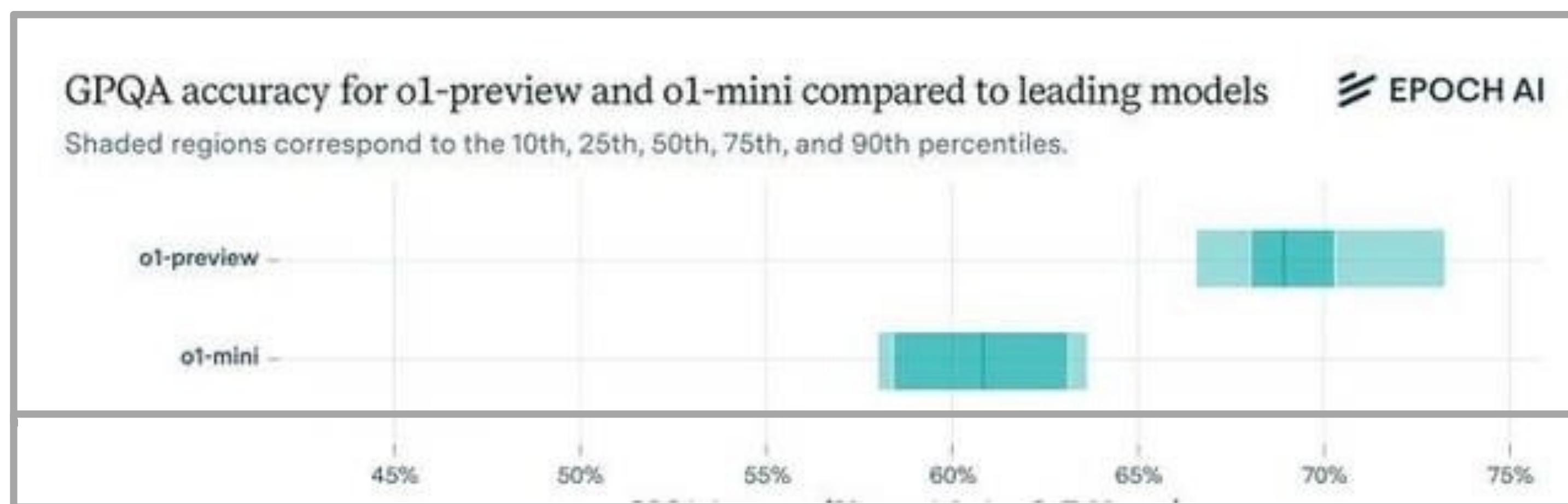
2023-2025: ‘Expert level’ QA tasks

GPQA (PhD level science questions)

Organic Chemistry

Methylcyclopentadiene (which exists as a fluxional mixture of isomers) was allowed to react with methyl isoamyl ketone and a catalytic amount of pyrrolidine. A bright yellow, cross-conjugated polyalkenyl hydrocarbon product formed (as a mixture of isomers), with water as a side product. These products are derivatives of fulvene. This product was then allowed to react with ethyl acrylate in a 1:1 ratio. Upon completion of the reaction, the bright yellow color had disappeared. How many chemically distinct isomers make up the final product (not counting stereoisomers)?

- A) 2
- B) 16
- C) 8
- D) 4



Expert level QA tasks

“Humanity’s last exam”

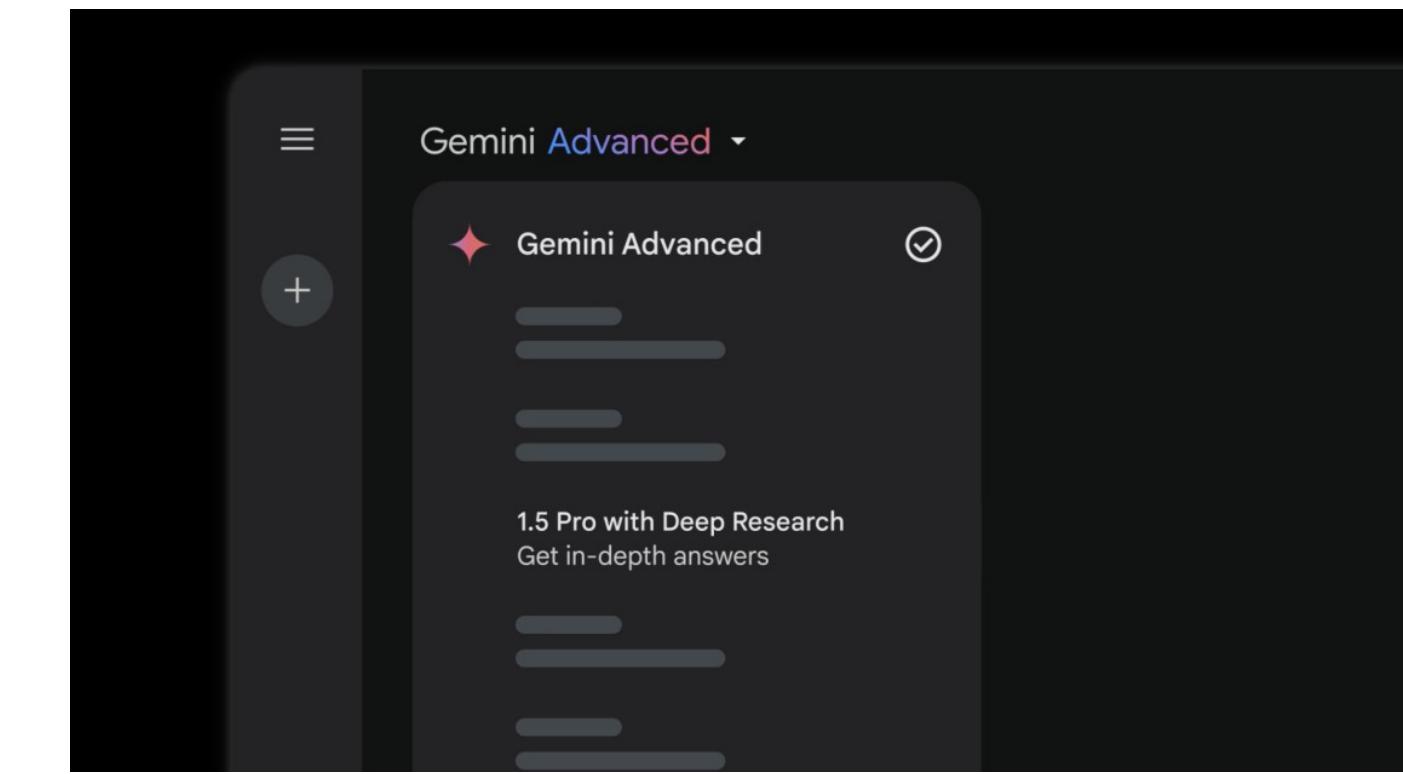
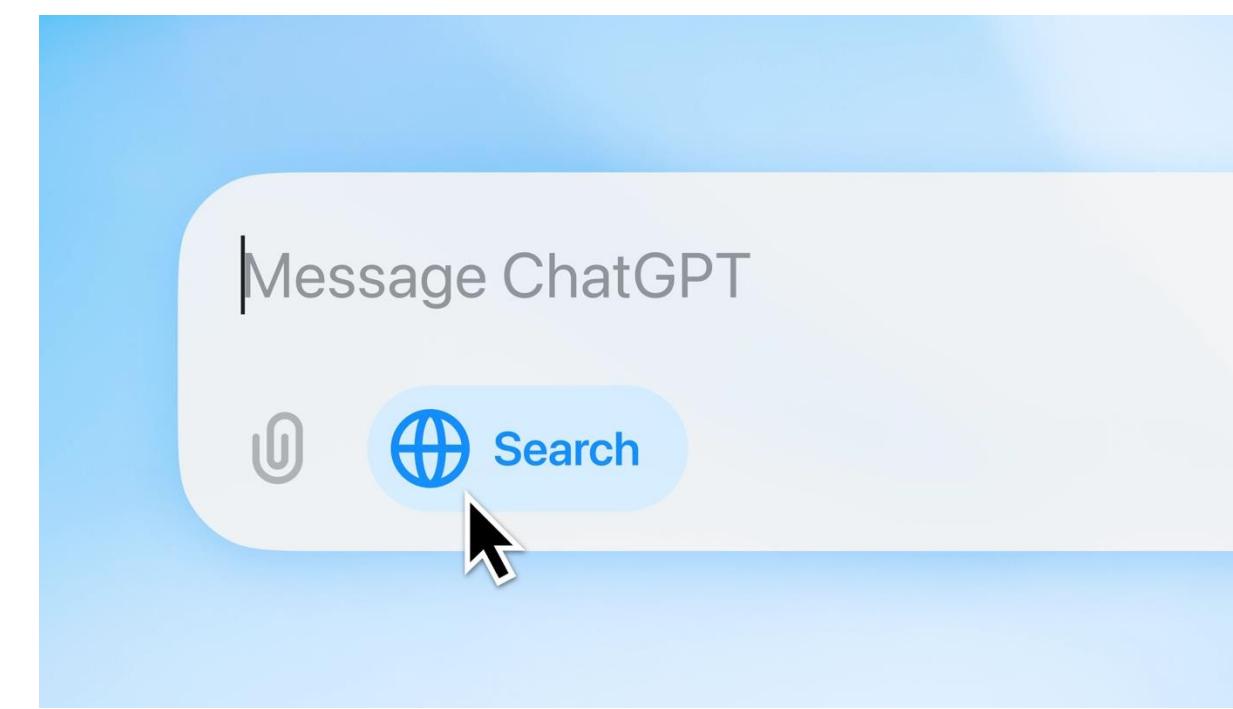
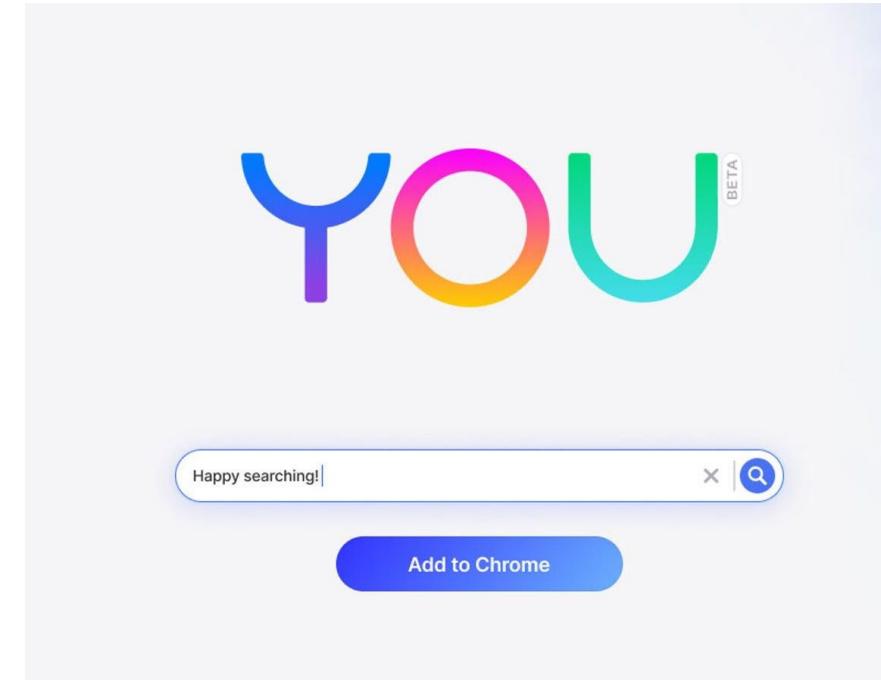
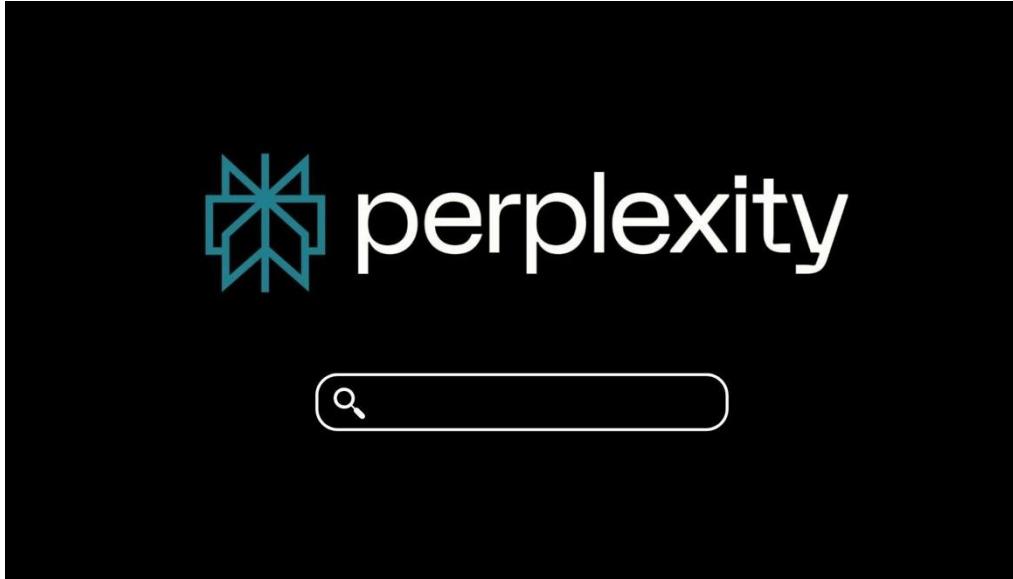
Ecology

Question:

Hummingbirds within Apodiformes uniquely have a bilaterally paired oval bone, a sesamoid embedded in the caudolateral portion of the expanded, cruciate aponeurosis of insertion of m. depressor caudae. How many paired tendons are supported by this sesamoid bone? Answer with a number.

Model	Accuracy (%) ↑
GPT-4o	3.1
Grok-2	3.9
Claude 3.5 Sonnet	4.8
Gemini Thinking	7.2
o1	8.8
DeepSeek-R1*	8.6
o3-mini (medium)*	11.1
o3-mini (high)*	14.0

QA remains a huge area of interest



Many products, companies, focusing on QA

Different types of QA

1. Closed book QA
 - Parametric QA
2. Open book QA
 - Reading Comprehension
 - Retrieval-augmented Generation (RAG)

Closed book QA

Closed book – answering the question with *no access to external information*

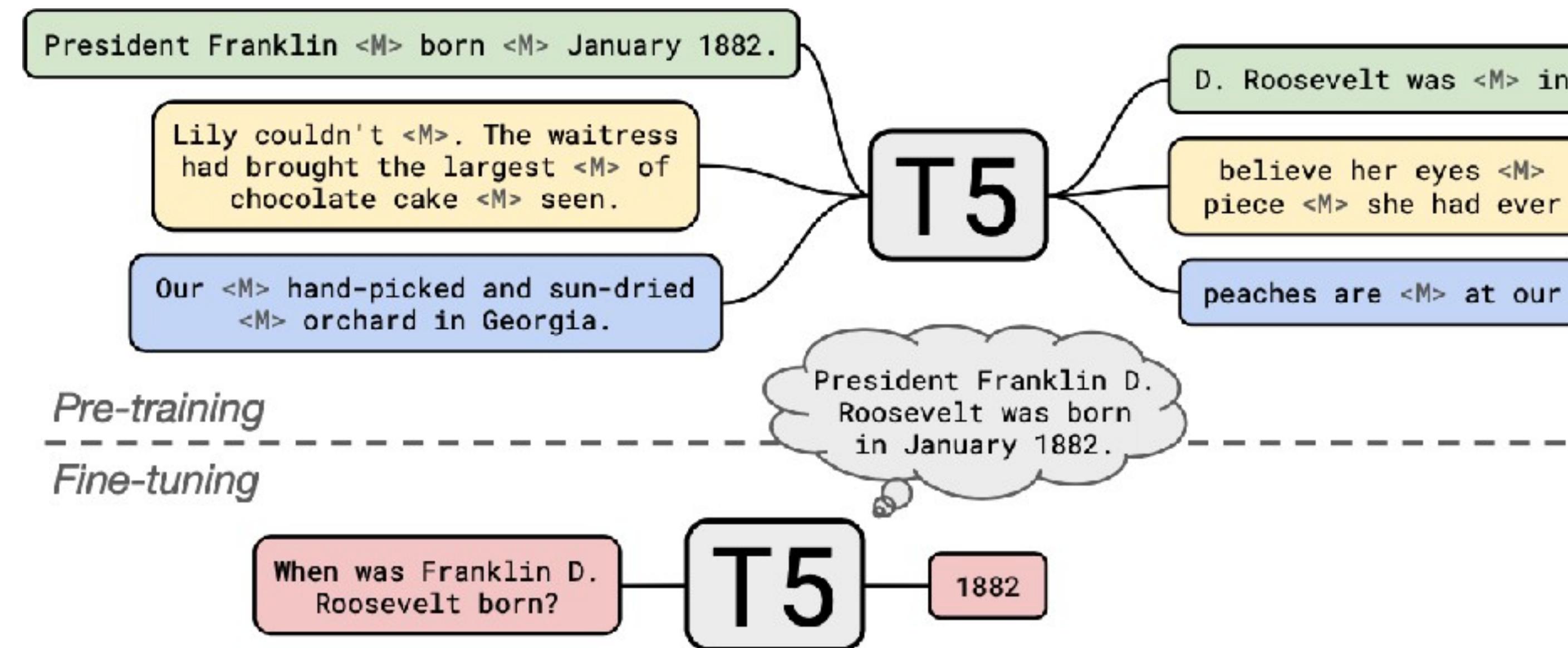
Q&A done just by ‘predicting the next word’

Seoul is the capital of _____

When does this work? Why do we care about this setting?

Large language models can do open-domain QA well

Initially – for models like T5, people discovered LMs can directly answer questions



LMs have remarkable knowledge about the world

Closed-book QA then took on an important role as a *capability test* ..

MMLU

Astronomy

What is true for a type-Ia supernova?

- A. This type occurs in binary systems.
- B. This type occurs in young galaxies.
- C. This type produces gamma-ray bursts.
- D. This type produces high amounts of X-rays.

Answer: A

High School Biology

In a population of giraffes, an environmental change occurs that favors individuals that are tallest. As a result, more of the taller individuals are able to obtain nutrients and survive to pass along their genetic information. This is an example of

- A. directional selection.
- B. stabilizing selection.
- C. sexual selection.
- D. disruptive selection

Answer: A

Closed book QA as a capability test

(From HELM)

Many popular benchmarks
(ARC-C, MMLU, GPQA, etc)
are partially knowledge
tests

Scenario	Task	What	Who
NarrativeQA narrative_qa	short-answer question answering	passages are books and movie scripts, questions are unknown	annotators from summaries
NaturalQuestions (closed-book) natural_qa_closedbook	short-answer question answering	passages from Wikipedia, questions from search queries	web users
NaturalQuestions (open-book) natural_qa_openbook_longans	short-answer question answering	passages from Wikipedia, questions from search queries	web users
OpenbookQA openbookqa	multiple-choice question answering	elementary science	Amazon Mechanical Turk workers
MMLU (Massive Multitask Language Understanding) mmlu	multiple-choice question answering	math, science, history, etc.	various online sources
GSM8K (Grade School Math) gsm	numeric answer question answering	grade school math word problems	contractors on Upwork and Surge AI
MATH math_chain_of_thought	numeric answer question answering	math competitions (AMC, AIME, etc.)	problem setters
LegalBench legalbench	multiple-choice question answering	public legal and administrative documents, manually constructed questions	lawyers
MedQA med_qa	multiple-choice question answering	US medical licensing exams	problem setters
WMT 2014 wmt_14	machine translation	multilingual sentences	Europarl, news, Common Crawl, etc.

Is ‘parametric knowledge’ useful?

- Why is parametric knowledge a common capability test?
 - Easy to collect, easy to automatically grade (GPQA, Humanity’s last exam)
 - Knowledge is useful, even if you are going to do things like summarization
 - In practice, correlated with *other* model capabilities (Knowledge <-> scale)
- Challenges of the parametric knowledge:
 - Hallucinations
 - Updating Knowledge (Continual learning)
 - ...

Updating knowledge (continued pretraining)

One way to update knowledge – continue to do pretraining with domain-specific data

Study	Domain	Model Parameter Count	Total Unique CPT Tokens
Minerva (Lewkowycz et al., 2022)	STEM	8B, 62B, 540B	26B-38.5B
MediTron (Chen et al., 2023)	Medicine	7B, 70B	46.7B
Code Llama (Rozière et al., 2024)	Code	7B, 13B, 34B	520B-620B
Llemma (Azerbayev et al., 2024)	Math	7B, 34B	50B-55B
DeepSeekMath (Shao et al., 2024)	Math	7B	500B
SaulLM-7B (Colombo et al., 2024b)	Law	7B	30B
SaulLM-{54, 141}B (Colombo et al., 2024a)	Law	54B, 141B	520B
HEAL (Yuan et al., 2024a)	Medicine	13B	14.9B

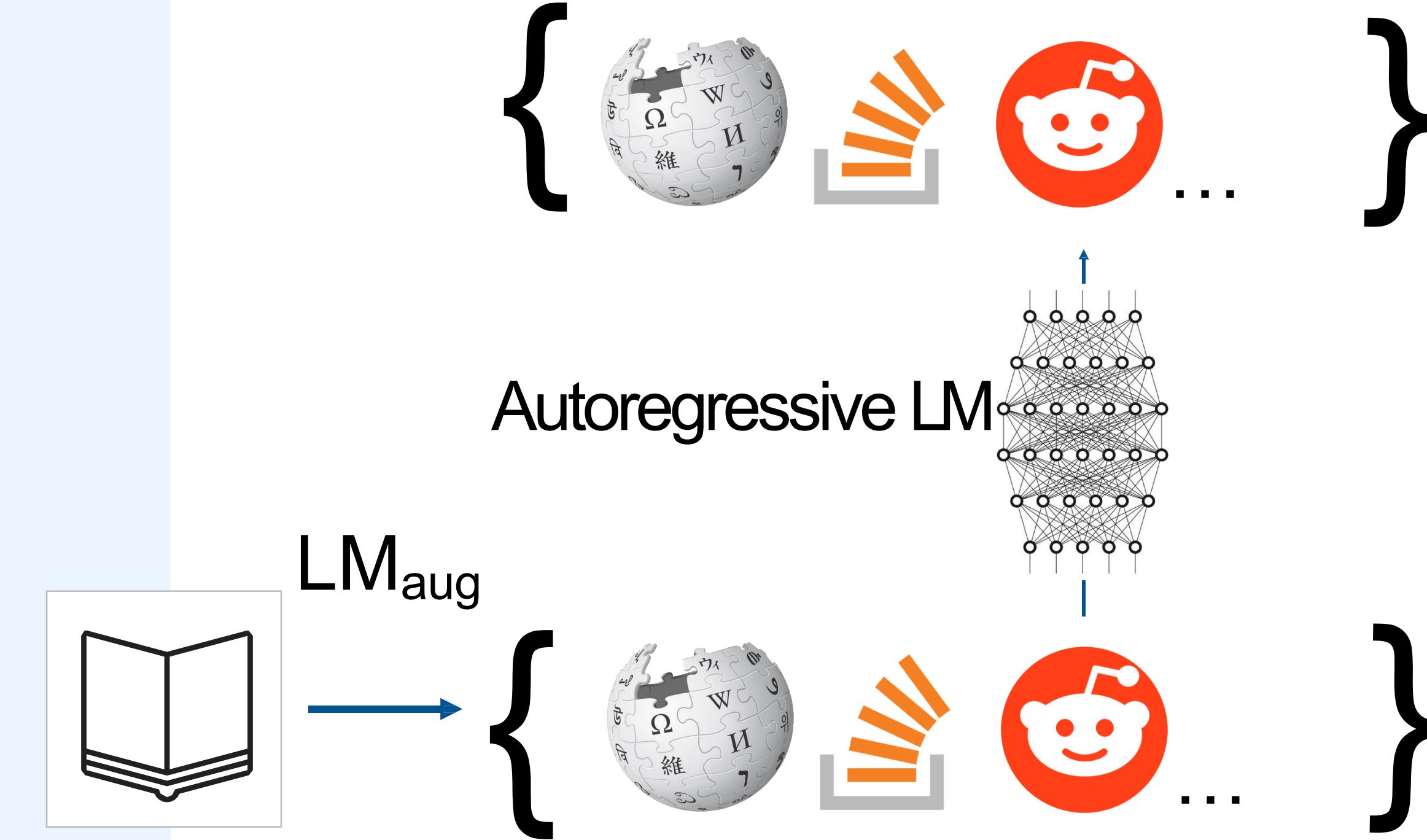
Unfortunately.. require *tons* of data (50+B)

Updating knowledge (synthetic CPT)

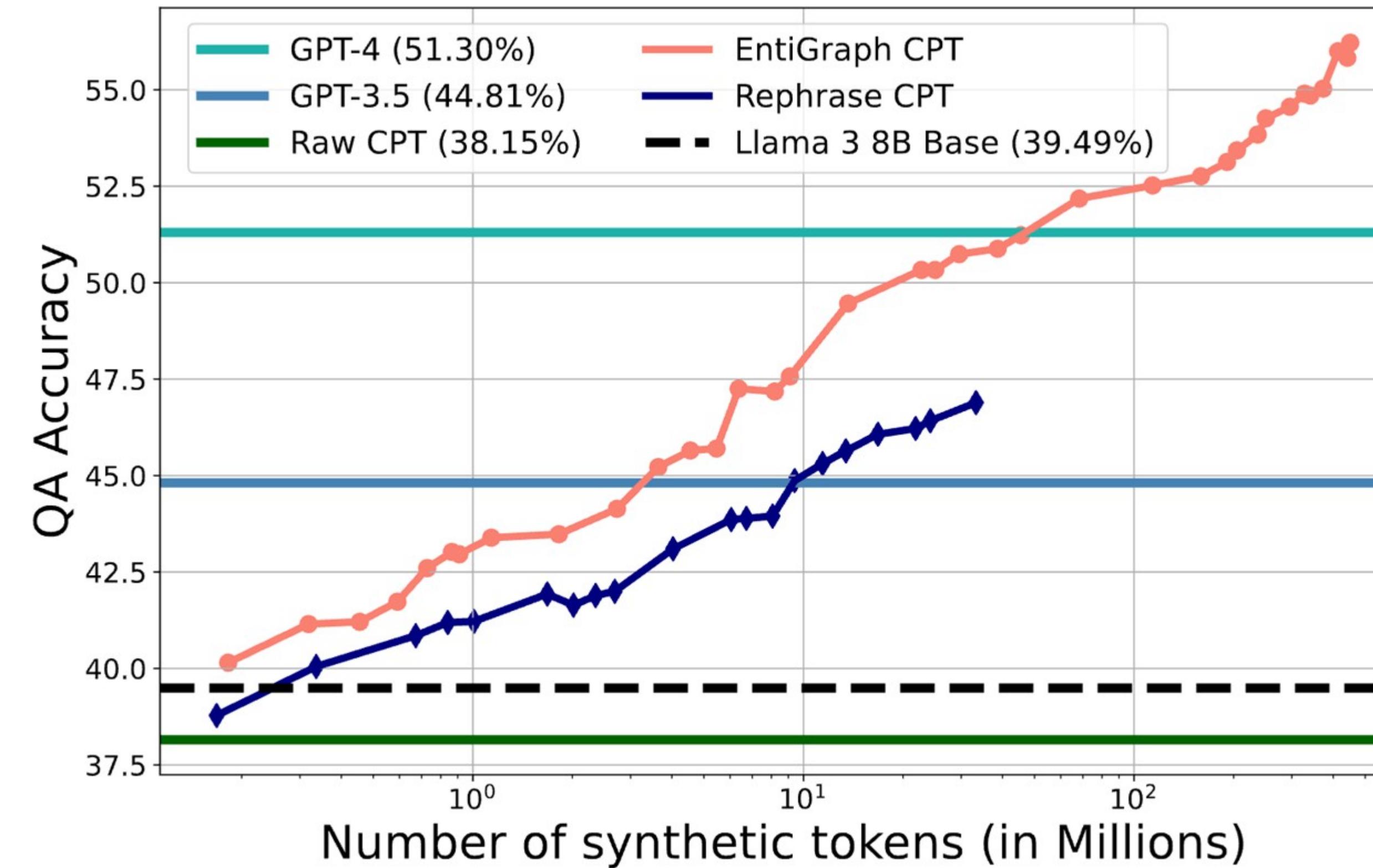
Synthetic continued pretraining: Train on LLM-transformed data

Goal – replicate the diversity of pretraining

- Vary content (topics)
- Vary style (how it's presented)
- Data diversity for generalization



Updating knowledge with synthetic data



- Can significantly boost closed-book QA performance with synthetic data

Open book QA - Reading comprehension

Reading comprehension = comprehend a passage of text and answer questions about its content (P, Q) → A

Tesla was the fourth of five children. He had an older brother named Dane and three sisters, Milka, Angelina and Marica. Dane was killed in a horse-riding accident when Nikola was five. In 1861, Tesla attended the "Lower" or "Primary" School in Smiljan where he studied German, arithmetic, and religion. In 1862, the Tesla family moved to Gospić, Austrian Empire, where Tesla's father worked as a pastor. Nikola completed "Lower" or "Primary" School, followed by the "Lower Real Gymnasium" or "Normal School."

Q: What language did Tesla study while in school?

A: German

Why do we care about this problem?

- Useful for many practical applications
- Reading comprehension is an important testbed for evaluating how well computer systems understand human language
 - Wendy Lehnert 1977: “Since questions can be devised to query **any aspect** of text comprehension, the ability to answer questions is the **strongest possible demonstration of understanding.**”
- Many other NLP tasks can be reduced to a reading comprehension problem:

Information extraction

(Barack Obama, educated_at, ?)

Question: Where did Barack Obama graduate from?

Passage: Obama was born in Honolulu, Hawaii. After graduating from Columbia University in 1983, he worked as a community organizer in Chicago.

(Levy et al., 2017)

Semantic role labeling

UCD **finished** the 2006 championship as Dublin champions , by **beating** St Vincents in the final .

Who finished something? - UCD

What did someone finish? - the 2006 championship

What did someone finish something as? - Dublin champions

How did someone finish something? - by beating St Vincents in the final

Who beat someone? - UCD

When did someone beat someone? - in the final

Who did someone beat? - St Vincents

(He et al., 2015)

Reading comprehension – span based

Archetypical reading comprehension dataset -- SQuAD

A prime number (or a prime) is a natural number greater than 1 that has no positive divisors other than 1 and itself. A natural number greater than 1 that is not a prime number is called a composite number. For example, 5 is prime because 1 and 5 are its only positive integer factors, whereas 6 is composite because it has the divisors 2 and 3 in addition to 1 and 6. The fundamental theorem of arithmetic establishes the central role of primes in number theory: any integer greater than 1 can be expressed as a product of primes that is unique up to ordering. The uniqueness in this theorem requires excluding 1 as a prime because one can include arbitrarily many instances of 1 in any factorization, e.g., 3, $1 \cdot 3$, $1 \cdot 1 \cdot 3$, etc. are all valid factorizations of 3.

What is the only divisor besides 1 that a prime number can have?

Ground Truth Answers: itself itself itself itself itself

What are numbers greater than 1 that can be divided by 3 or more numbers called?

Ground Truth Answers: composite number composite number composite number primes

What theorem defines the main role of primes in number theory?

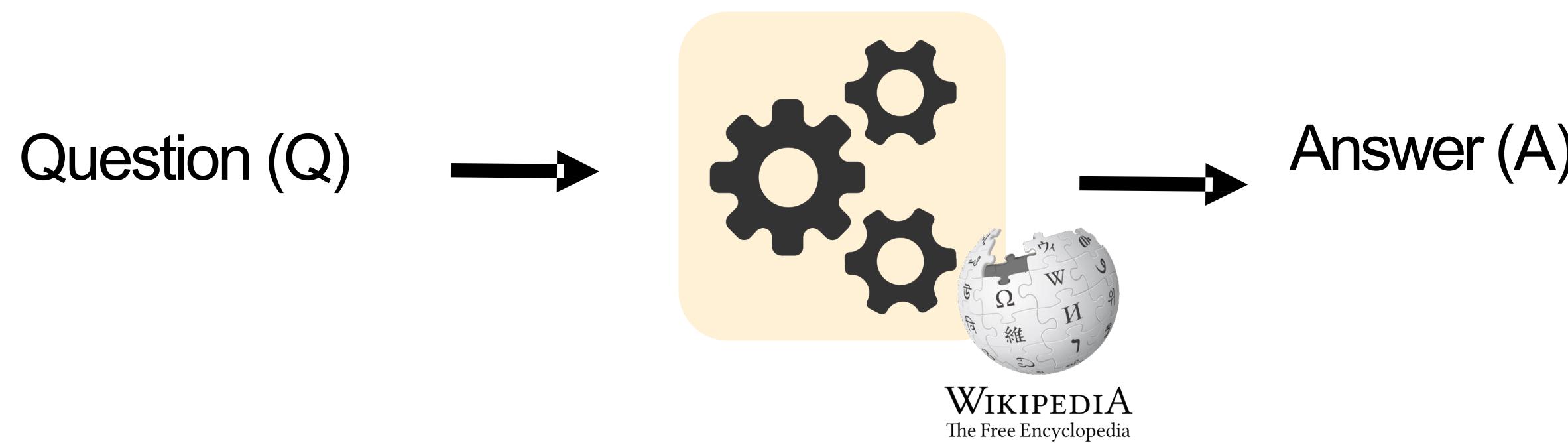
Ground Truth Answers: The fundamental theorem of arithmetic fundamental theorem of arithmetic arithmetic fundamental theorem of arithmetic fundamental theorem of arithmetic fundamental theorem of arithmetic

Major focus of Q&A and research for many years..

Question answering datasets

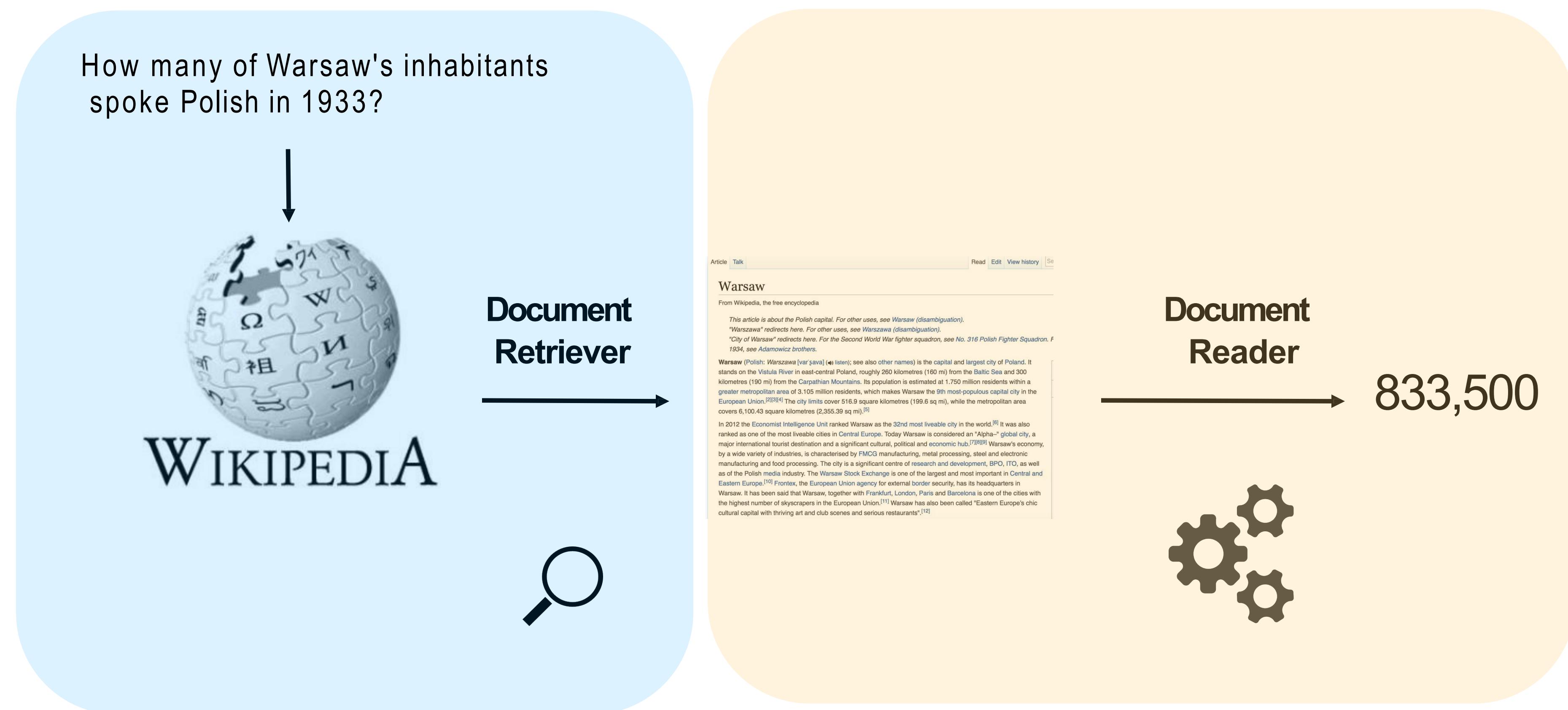
- TriviaQA: Questions and answers by trivia enthusiasts. Independently collected web paragraphs that contain the answer and seem to discuss question, but no human verification that paragraph supports answer to question.
- Natural Questions: Question drawn from frequently asked Google search questions. Answers from Wikipedia paragraphs. Answer can be substring, yes, no, or NOT_PRESENT. Verified by human annotation.
- HotpotQA: Constructed questions to be answered from the whole of Wikipedia which involve getting information from two pages to answer a multistep query:
Q: Which novel by the author of “Armada” will be adapted as a feature film by Steven Spielberg? A: *Ready Player One*

Open-domain question answering



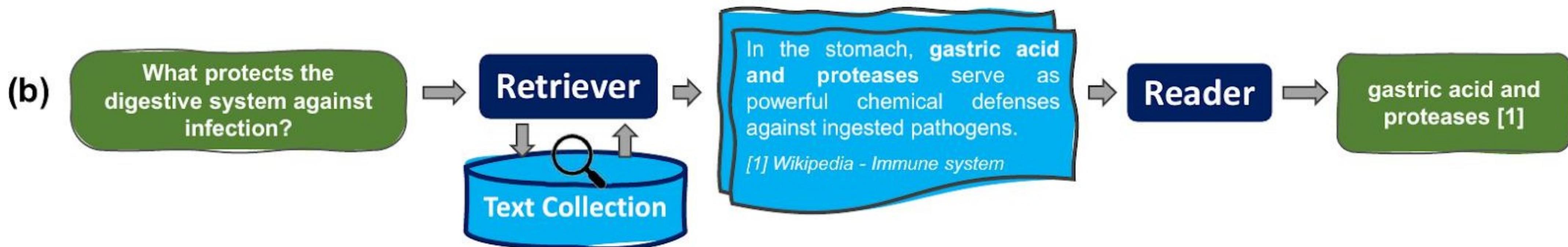
- Different from reading comprehension, we don't assume a given passage.
- Instead, we only have access to a large collection of documents (e.g., Wikipedia). We don't know where the answer is located, and the goal is to return the answer for any open-domain questions.
- Much more challenging and a more practical problem!
- In contrast to closed-domain systems that deal with questions under a specific domain (medicine, technical support).

Retrieval augmentation



Using retrieval to overcome LMs' shortcomings

- Instead of asking the LM to memorize everything, **can we provide the LM with relevant and useful content just-in-time?**
- Retrieval / search is a common mechanism for identifying such relevant information.
 - Dynamic: it's easy to update / add documents to your retrieval system
 - Interpretable: LM can generate pointers to retrieved documents that support human verification of its generations (citations)



Retriever-reader framework

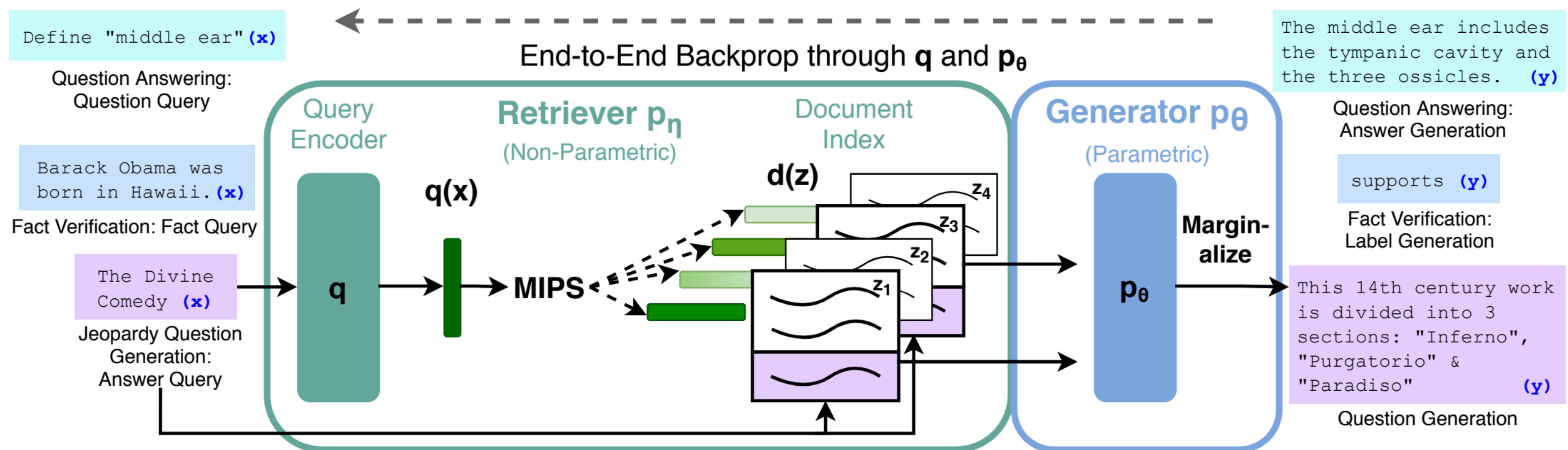
- Input: a large collection of documents $\mathcal{D} = D_1, D_2, \dots, D_N$ and Q
 - Output: an answer string A
-
- Retriever: $f(\mathcal{D}, Q) \rightarrow P_1, \dots, P_K$ K is pre-defined (e.g., 100)
 - Reader: $g(Q, \{P_1, \dots, P_K\}) \rightarrow A$ A reading comprehension problem!

[Next lecture!](#)

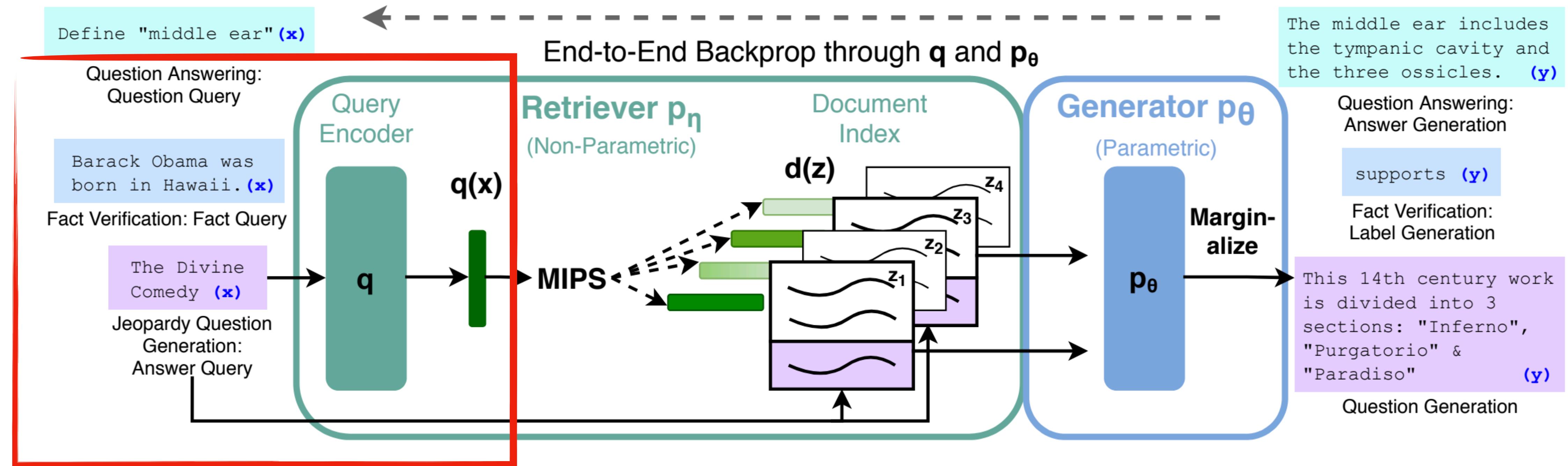
- Retriever = A standard TF-IDF information-retrieval sparse model (a fixed module)
- Reader = a neural reading comprehension model that we just learned
 - Could be Trained on SQuAD and other distantly-supervised QA datasets
 - Or a zero-shot LLM (ChatGPT etc)

Retrieval-augmented Generation (RAG)

- RAG system is very powerful!
- Core components: **Query Encoder**, **Retriever**, **Generator**
- See also works like REALM, DPR, ORQA etc..

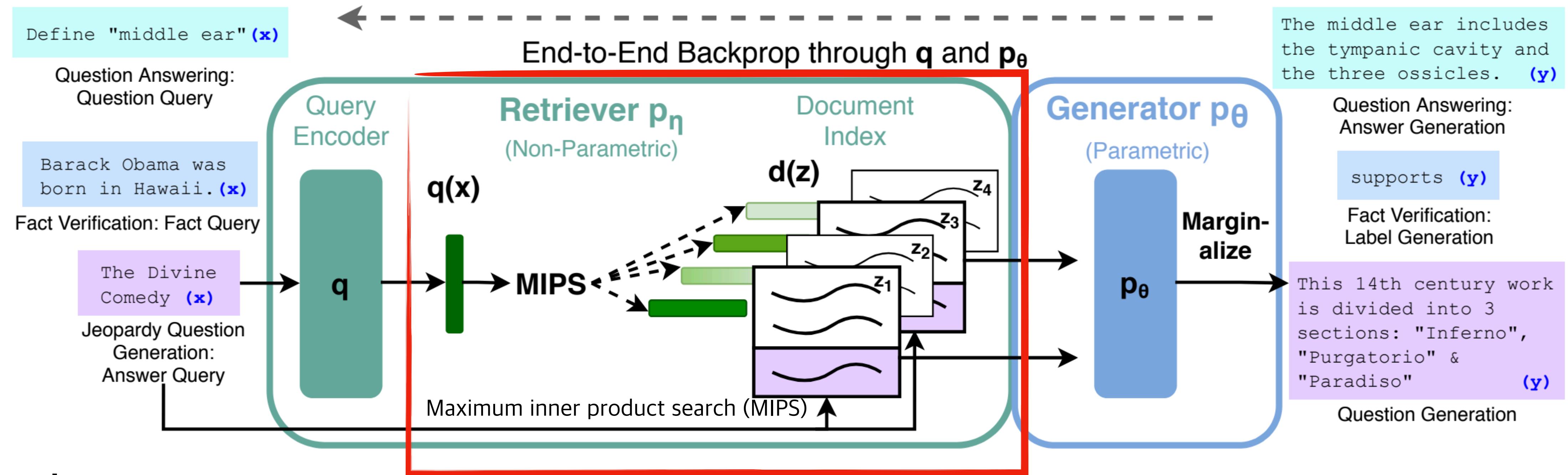


Retrieval-augmented Generation (RAG)



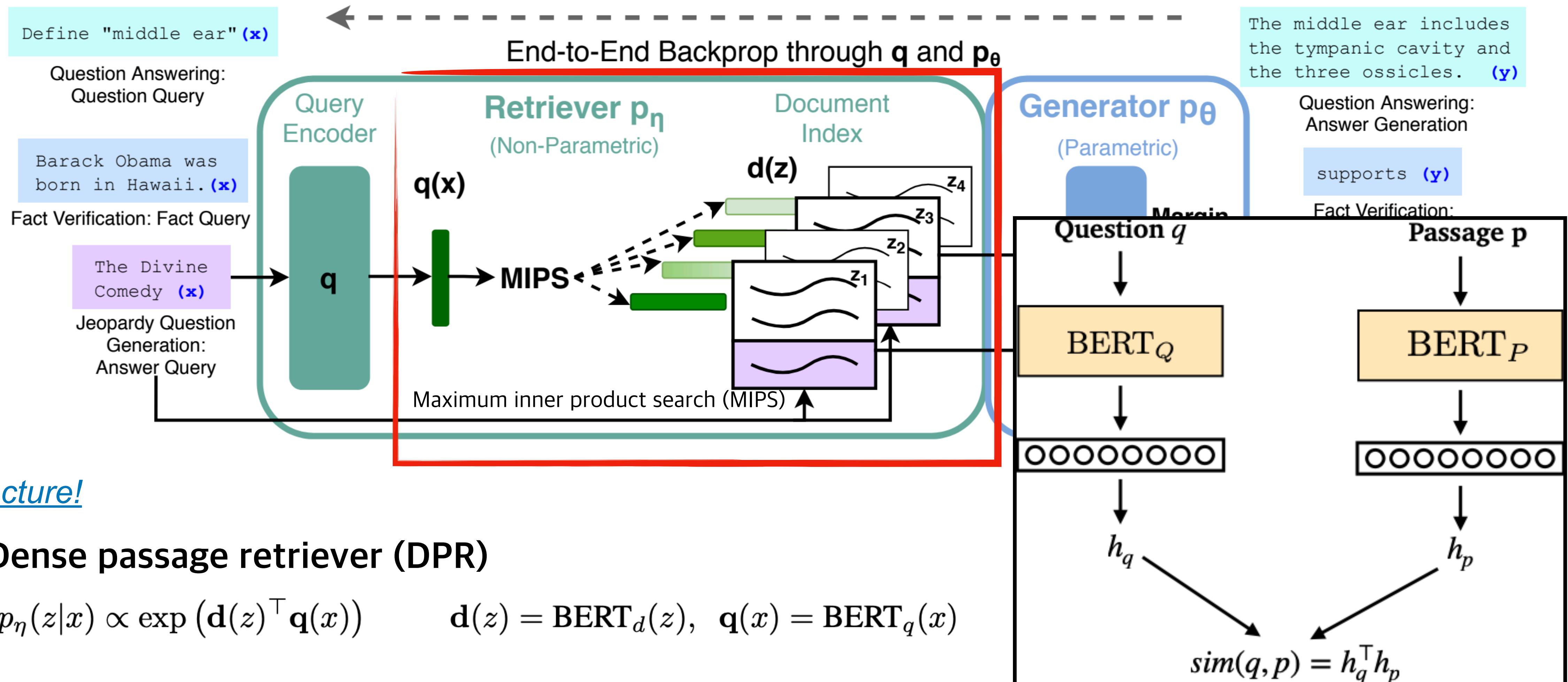
- **Query encoder:**
- Transforms the input query into a dense vector representation.
- Captures the semantic meaning of the query, making it easier to match with relevant documents in the knowledge base.
- In the encoder $q(\cdot)$, the query x is encoded to the representation $q(x)$

Retrieval-augmented Generation (RAG)



- **Retriever:**
- Searches for relevant documents or passages in the knowledge base using the encoded query vector.
- Retrieves the most top- k relevant relevant pieces of information that can help generate an accurate response.
- The retriever $p_\eta(\bullet)$ maps the encoded query $q(x)$ to the documents z , and then returns the top- k documents.

Retrieval-augmented Generation (RAG)

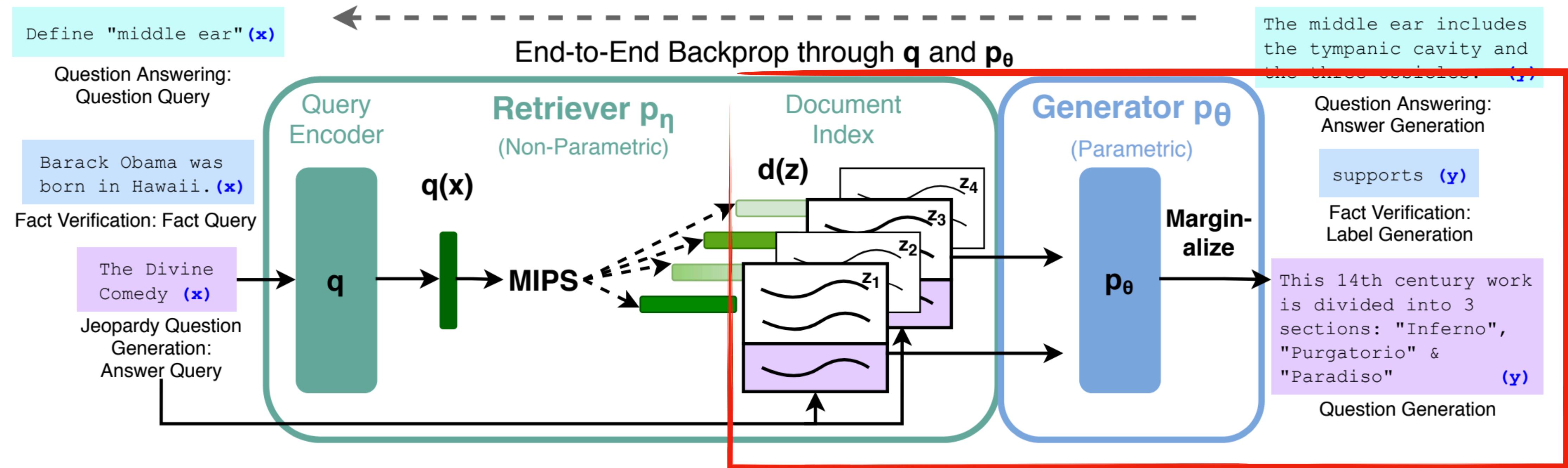


Next lecture!

- Dense passage retriever (DPR)

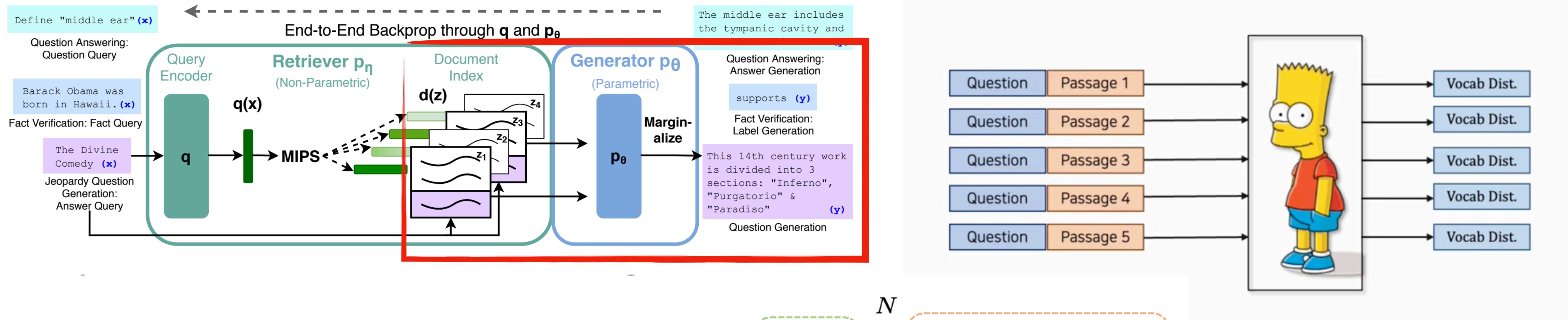
$$p_\eta(z|x) \propto \exp(\mathbf{d}(z)^\top \mathbf{q}(x)) \quad \mathbf{d}(z) = \text{BERT}_d(z), \quad \mathbf{q}(x) = \text{BERT}_q(x)$$

Retrieval-augmented Generation (RAG)



- **Generator:**
- Generates the final response using the retrieved documents and the original query.
- The generator $p_\theta(\cdot)$ receives the concatenated query and document, respectively.
- Then, the generator produces the answers based on the concatenated query.
- BART is used [Patrick+ 2021]

Retrieval-augmented Generation (RAG)

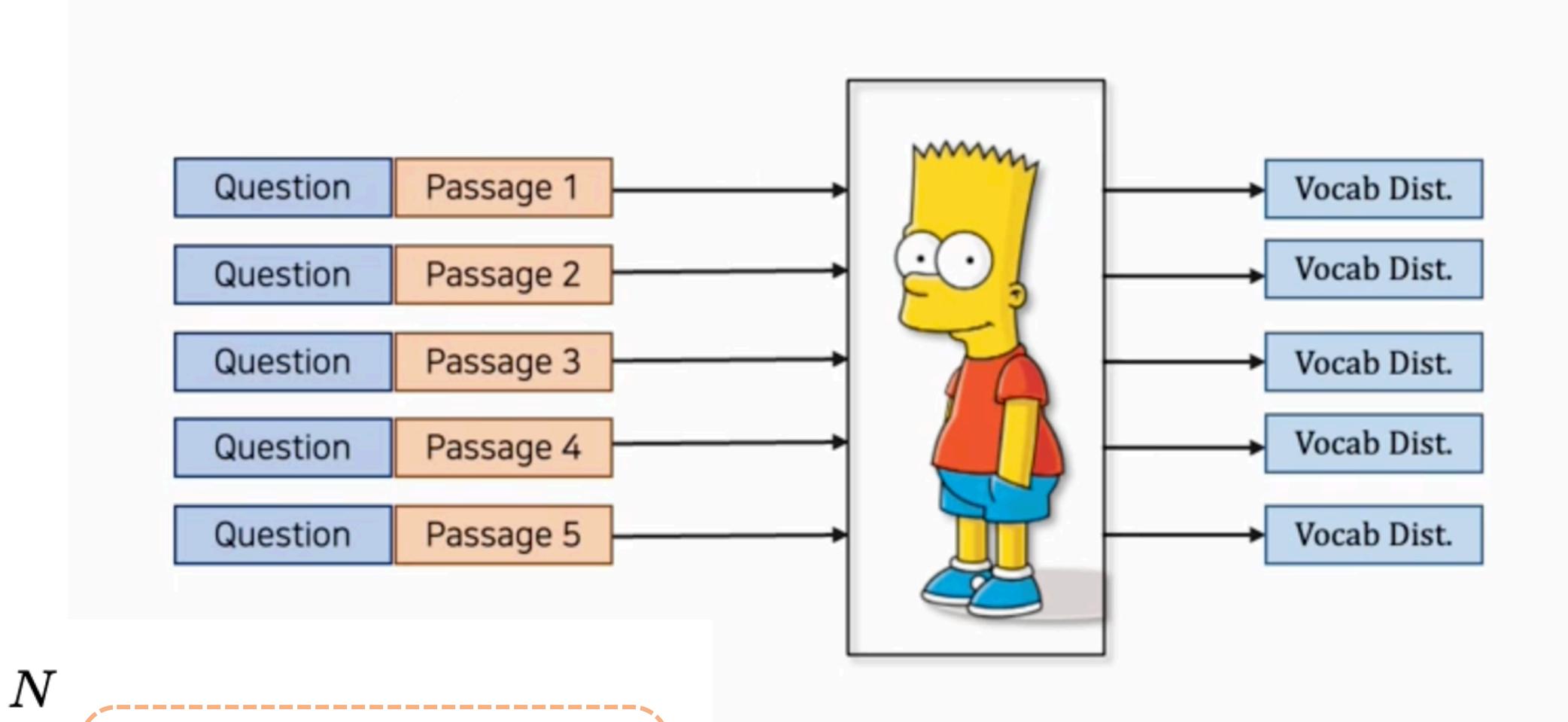


$$p_{\text{RAG-Sequence}}(y|x) \approx \sum_{z \in \text{top-}k(p(\cdot|x))} p_\eta(z|x)p_\theta(y|x, z) = \sum_{z \in \text{top-}k(p(\cdot|x))} p_\eta(z|x) \prod_i^N p_\theta(y_i|x, z, y_{1:i-1})$$

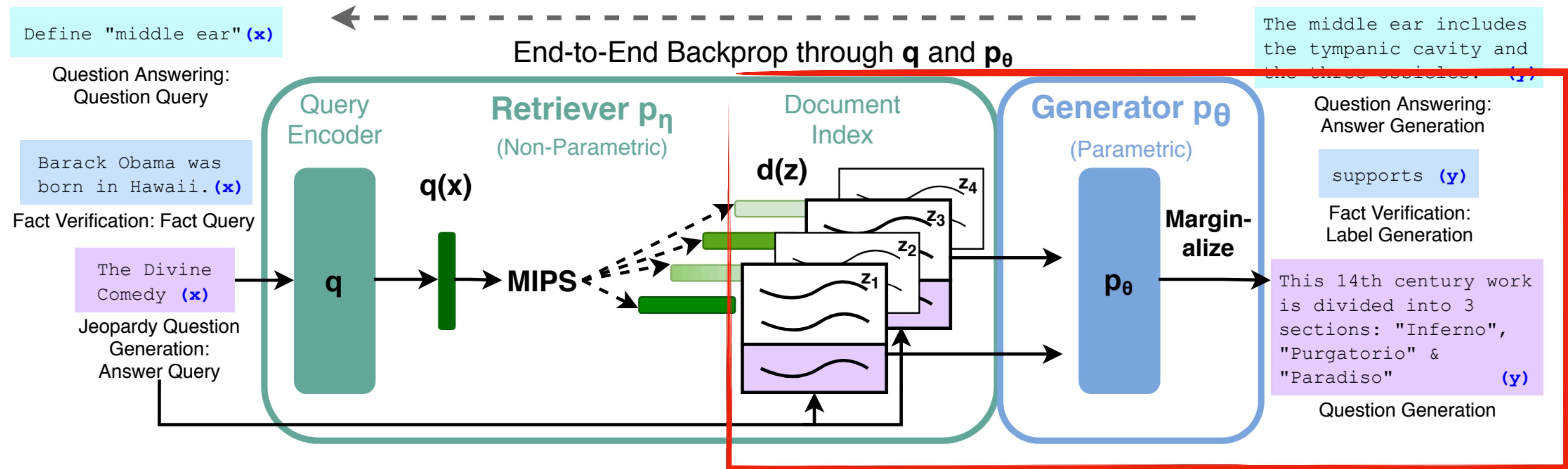
document weights from the retriever

$$p_{\text{RAG-Token}}(y|x) \approx \prod_i^N \sum_{z \in \text{top-}k(p(\cdot|x))} p_\eta(z|x)p_\theta(y_i|x, z, y_{1:i-1})$$

token generation



Retrieval-augmented Generation (RAG)



- Overall, fine-tune the pre-trained retriever (query encoder+document index) and the pre-trained seq2seq generator in end-to-end manner.

Retrieval-augmented Generation (RAG)

