



CS 6501 Natural Language Processing (Spring 2025)

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Jan 13, 2025

Course Information & Logistics

- Instructor: **Yu Meng** (yumeng5@virginia.edu)
- TAs: **Peng Wang** (pw7nc@virginia.edu)
- Time: Mondays & Wednesdays 2:00pm - 3:15pm
- Location: Olsson Hall 005
- Office Hour: Mondays & Wednesdays after class
- We'll use Piazza (accessible via Canvas) to answer logistics/technical questions

Course Information & Logistics

- This course is designed to be a **research-oriented graduate-level** course
- Seminar-style: a substantial focus on reading, presenting and discussing important papers and conducting research projects
- A comprehensive overview of cutting-edge developments in NLP
- Prerequisites: CS 4501 NLP or CS 4774 (having deep learning background is important!)
- This course may benefit you if
 - You are working on NLP research (PhD/MS research students)
 - Your research uses NLP models/tools
 - You aim for a job that involves using NLP models/tools
 - You are very interested in the cutting-edge topics of NLP and willing to spend time to learn

Course Format & Grading

- Course Website: <https://yumeng5.github.io/teaching/2025-spring-cs6501>
Schedule (Subject to Changes!)



Date	Topic	Papers	Slides
Introduction to Large Language Models			
1/13	Course Overview	-	overview
1/15	Language Model Architecture	Distributed Representations of Words and Phrases and their Compositionality (word2vec) Attention Is All You Need (Transformer)	lm_basics
1/20	No Class (MLK Holiday)	-	-
1/22	Language Model Pretraining & Fine-Tuning	Language Models are Unsupervised Multitask Learners (GPT-2) BERT: Pre-training of Deep Bidirectional Transformers for Language Understanding RoBERTa: A Robustly Optimized BERT Pretraining Approach ELECTRA: Pre-training Text Encoders as Discriminators Rather Than Generators BART: Denoising Sequence-to-Sequence Pre-training for Natural Language Generation, Translation, and Comprehension Exploring the Limits of Transfer Learning with a Unified Text-to-Text Transformer (T5)	pretrain

Course Format & Grading: Paper Presentation (30%)

- Starting from the 4th lecture (1/27), each lecture will be presented by a group of 1 or 2 students
 - Groups of two are encouraged, but individual presentations are also acceptable
- Every group presents one lecture (3 papers)
- Signup sheet: <https://docs.google.com/spreadsheets/d/1h4uuKnL8T71YUtbORgth-y6AAkFZnaZsvZV5ygrzxjw/edit?usp=sharing>
- You can sign up for the topic you are interested in – slots are first come, first served!
- The dates listed on the course website are subject to change – please sign up based on the topic rather than the date

Course Format & Grading: Paper Presentation (30%)

- **Presentation duration:** strictly limited to 60 minutes, followed by a 10-minute question-and-answer session with the audience & instructor
- **Deadline:** Email your slides to the instructor and TAs at least 48 hours before your presentation (e.g., if presenting on Monday, slides should be emailed by Saturday 2pm)
- You will receive feedback from the instructor to improve your slides (if necessary, the instructor may schedule a meeting with your team to go over the slides)
- Late submissions result in a 50% presentation grade deduction
- Detailed grading rubrics and tips can be found on the course website
- First three student lectures automatically receive **5%, 3%, 1% extra credit of final grade**

Course Format & Grading: Participation (20%)

- Starting from the 4th lecture (1/27), everyone is required to complete two mini-assignments
- **Pre-lecture question:** read the 3 papers to be introduced in the lecture, and submit a question you have when you read them
- **Post-lecture feedback:** provide feedback to the presenters after the lecture
- We'll use Google Forms to collect pre-lecture questions and post-lecture feedback and share them with the presenters
- **Deadlines:** pre-lecture questions are due one day before the lecture (e.g., For Monday lectures, you need to submit the question by Sunday 11:59 pm); post-lecture feedback is due each Friday (both Monday & Wednesday feedback is due Friday 11:59 pm)
- Lectures are not recorded, but slides will be posted on the course website

Course Format & Grading: Participation (20%)

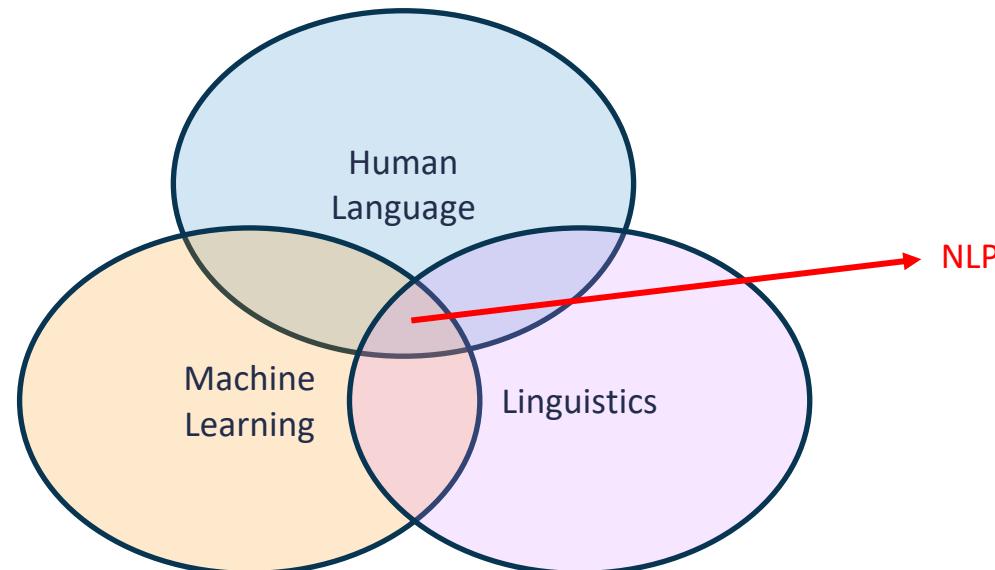
- Besides student presentations, we'll also invite leading researchers from academia and industry to introduce their cutting-edge research
- Guest lectures do not have pre-lecture questions/post-lecture feedback, and we'll directly take attendance on Zoom
- You can get extra participation credit if you ask questions during guest lectures (details shared later)
- At the end of the semester, you'll get **2% extra credit of final grade** if you complete the teaching evaluation survey about this course (sent from Student Experiences of Teaching)

Course Format & Grading: Project (50%)

- Complete a research project, present your results, and submit a project report
- Work in a team of 1 or 2 (a larger team size requires prior approval from the instructor) – may or may not be the same team as your presentation group
- (Type 1) A comprehensive survey report: carefully examine and summarize existing literature on a topic covered in this course; provide detailed and insightful discussions on the unresolved issues, challenges, and potential future opportunities within the chosen topic
- (Type 2) A hands-on project: not constrained to the course topics but must be centered around NLP; doesn't have to involve large language models (e.g., train or analyze smaller-scale language models for specific tasks); eligible for extra credits if publishable
- **Project proposal:** 5% (ddl: 2/5); **Mid-term report:** 10% (ddl: 3/10); **Final presentation** (ddl: 4/15) **and final report:** 35% (ddl: 5/6)

What is Natural Language Processing (NLP)?

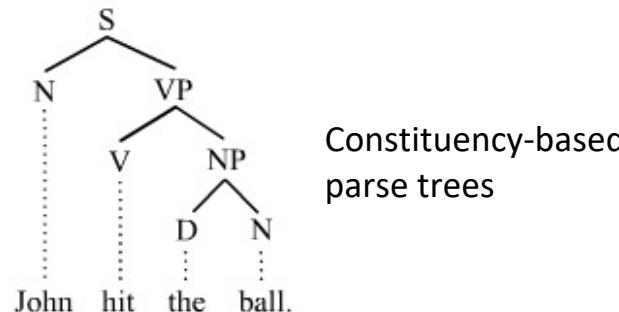
- An interdisciplinary subfield of machine learning and linguistics
- Goal: Enable computers to understand, interpret, and generate human language



The History of NLP

Linguistic-rule based methods
(e.g., syntactic pattern matching)

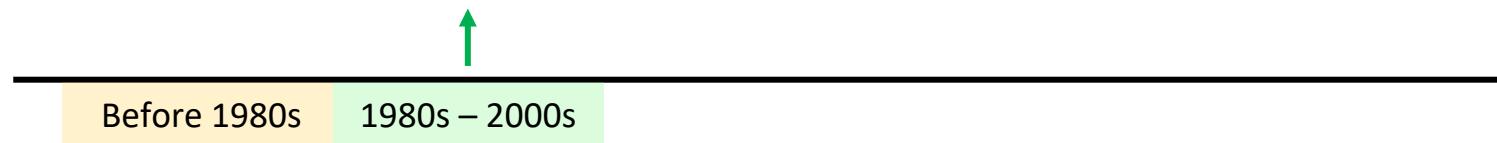
Before 1980s



Constituency-based
parse trees

The History of NLP

Statistical methods
(e.g., n-gram models, hidden state models)

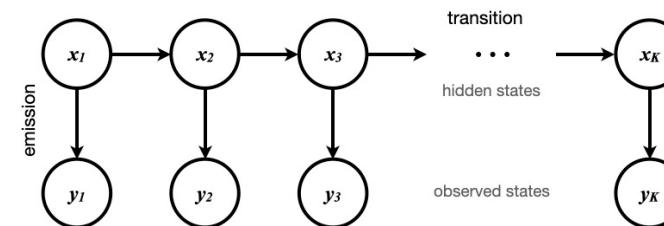


$N = 1$: This is a sentence *unigrams:*
this,
is,
a,
sentence

$N = 2$: This is a sentence *bigrams:*
this is,
is a,
a sentence

$N = 3$: This is a sentence *trigrams:*
this is a,
is a sentence

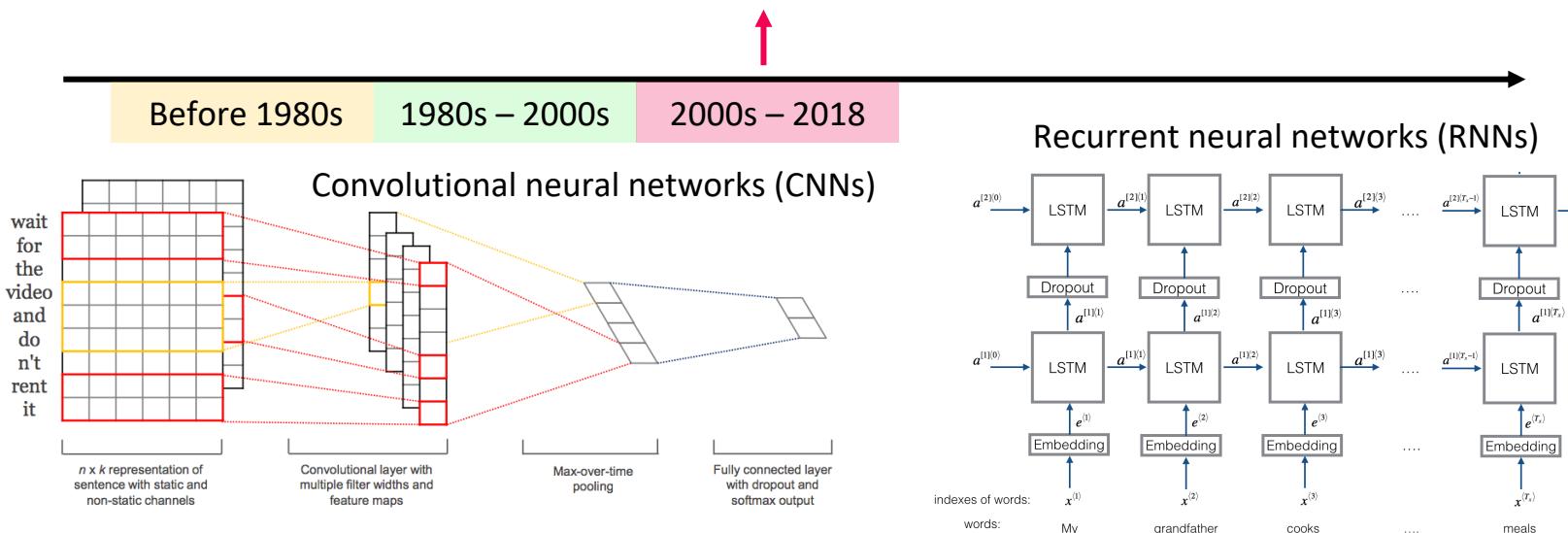
N-gram models



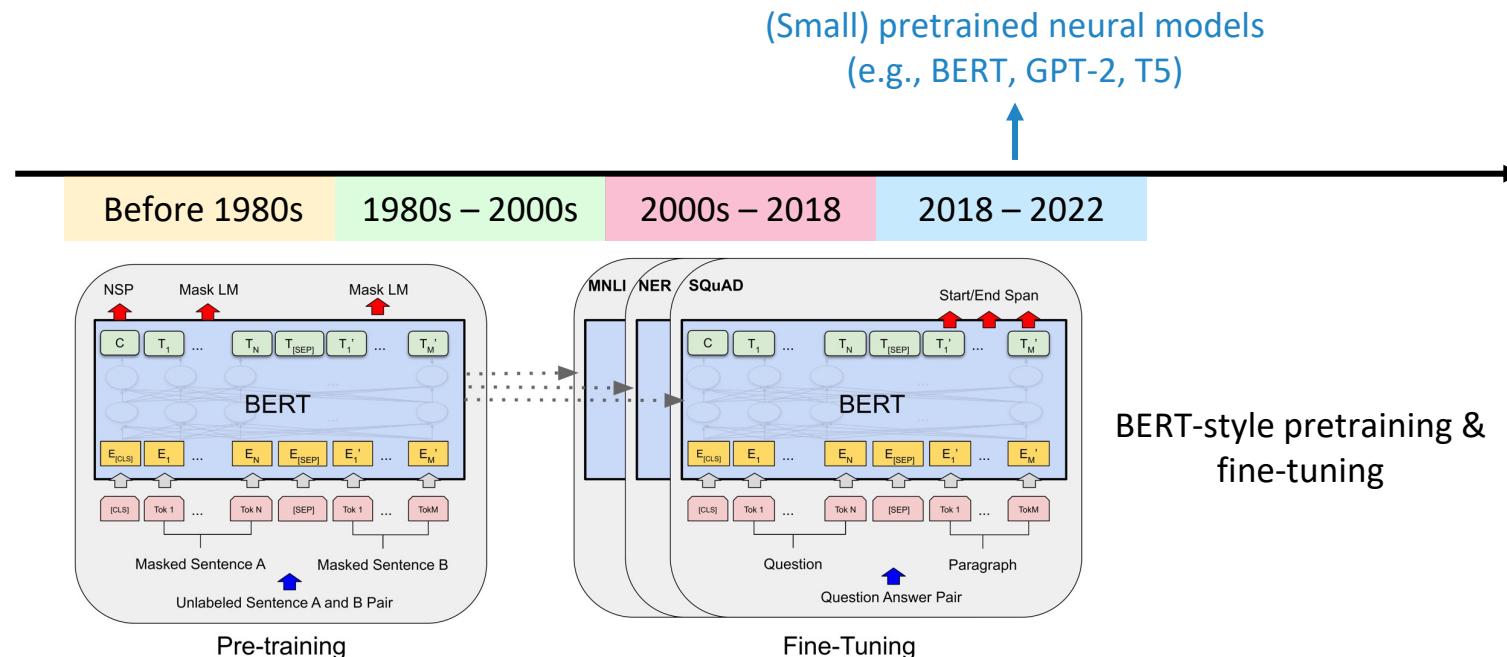
Hidden state models

The History of NLP

(Simple) neural-network-based methods
(e.g., word embeddings, convolutional/recurrent neural networks)

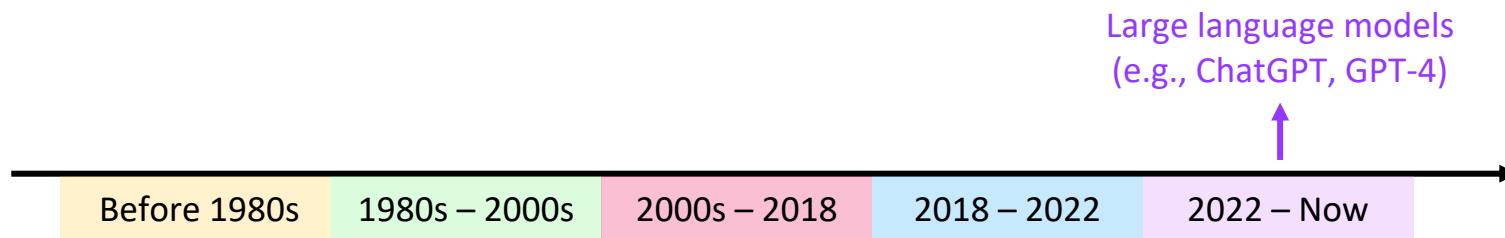


The History of NLP



The History of NLP

The focus of this course!



One model for all tasks



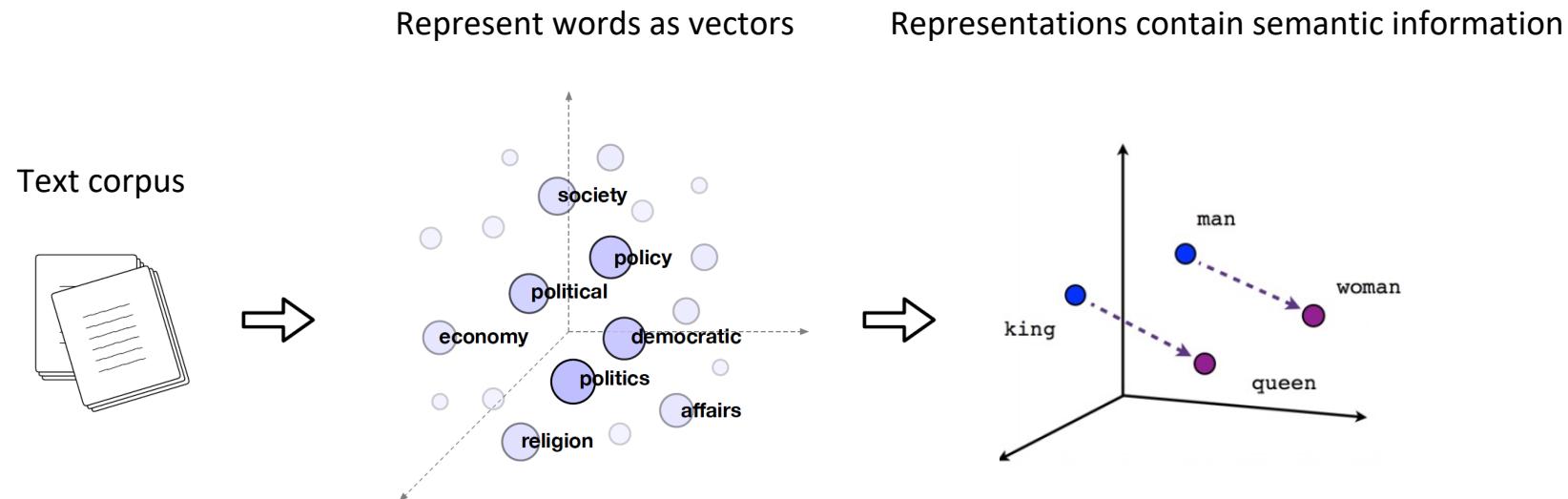
Overview of Course Contents

- Introduction to Language Models
 - Language Model Architecture
 - Language Model Pretraining & Fine-Tuning
 - In-Context Learning
 - Scaling and Emergent Ability
- Reasoning with Language Models
 - Chain-of-Thought Generation
 - Inference-Time Scaling
- Knowledge, Factuality and Efficiency
 - Parametric Knowledge in Language Models
 - Retrieval-Augmented Language Generation (RAG)
 - Long-Context Language Models
 - Efficiency
- Language Model Post-Training
 - Instruction Tuning
 - Reinforcement Learning from Human Feedback (RLHF)
- Language Agents
 - Language Agent Basics
 - Language Models for Code
 - Multimodal Language Models
- Ethical Considerations of Language Models
 - Security and Jailbreaking
 - Bias and Calibration
 - Privacy and Legal Issues
- Looking Forward

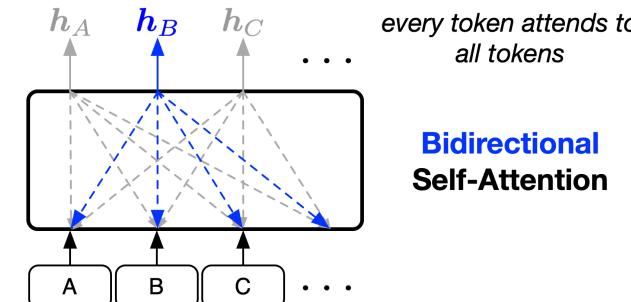
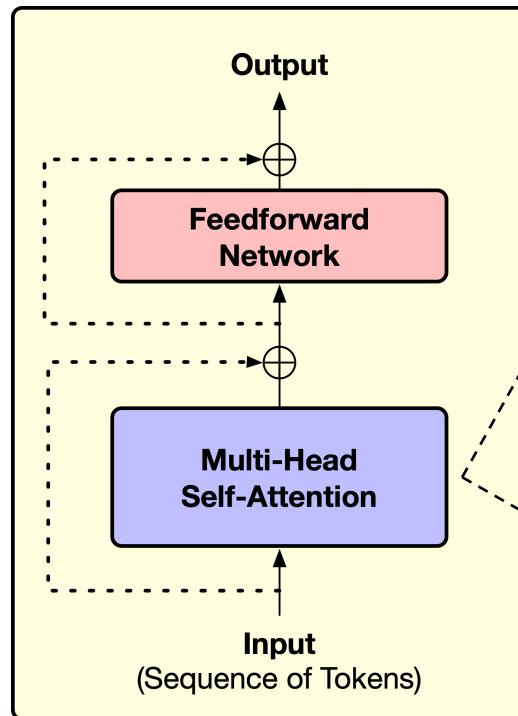
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Language Model Architecture: Word Embeddings

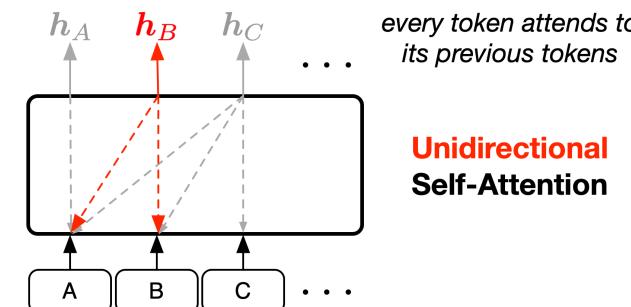


Language Model Architecture: Transformers



**Bidirectional
Self-Attention**

Transformer Encoders



**Unidirectional
Self-Attention**

Transformer Decoders

Language Model Pretraining: Next-Token Prediction

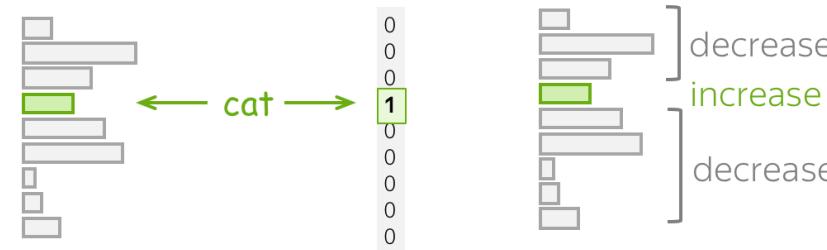
we want the model
to predict this

Training example: I saw a cat on a mat <eos>

Model prediction: $p(*) | \text{I saw a}$

Target

Loss = $-\log(p(\text{cat})) \rightarrow \min$



Language Model Pretraining as Multi-Task Learning

- In my free time, I like to **{run, banana}** (*Grammar*)
- I went to the zoo to see giraffes, lions, and **{zebras, spoon}** (*Lexical semantics*)
- The capital of Denmark is **{Copenhagen, London}** (*World knowledge*)
- I was engaged and on the edge of my seat the whole time. The movie was **{good, bad}** (*Sentiment analysis*)
- The word for “pretty” in Spanish is **{bonita, hola}** (*Translation*)
- $3 + 8 + 4 = \{15, 11\}$ (*Math*)
- ...

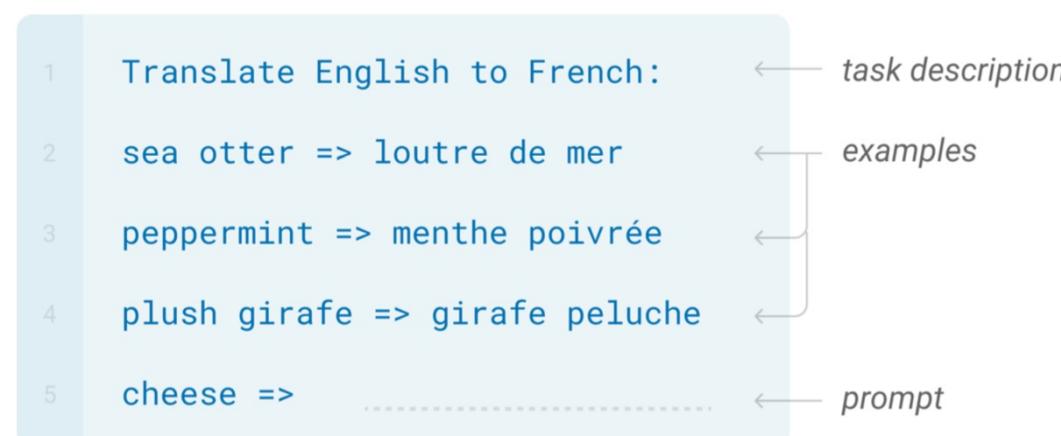


Examples from: https://docs.google.com/presentation/d/1hQUd3pF8_2Gr2Obc89LKjmHL0DIH-uof9M0yFVd3FA4/edit#slide=id.g28e2e9aa709_0_1

(Few-Shot) In-Context Learning

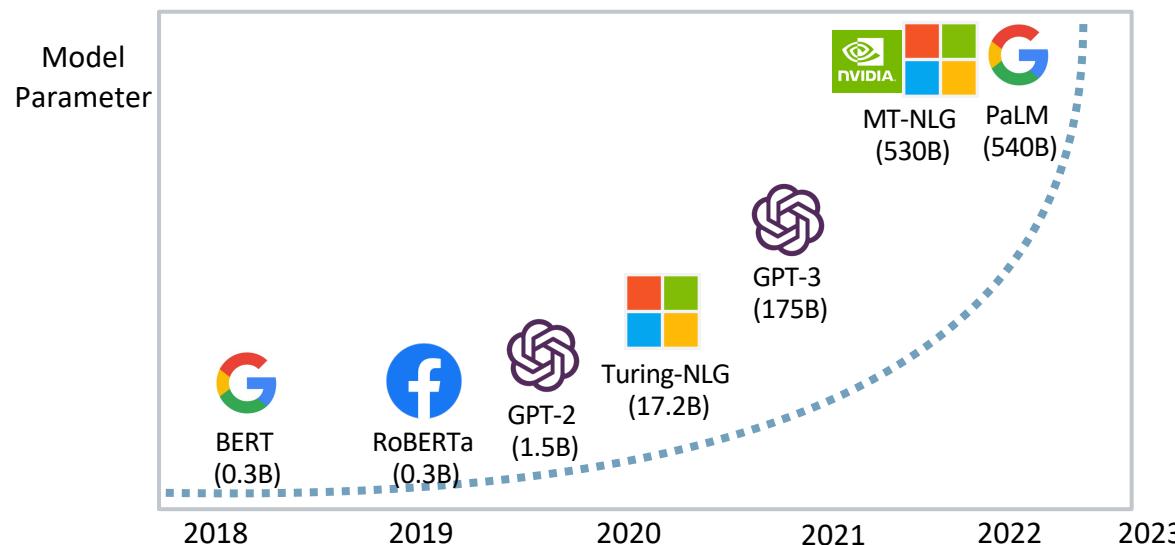
Few-shot

In addition to the task description, the model sees a few examples of the task. No gradient updates are performed.



Large Language Models (LLMs)

Language models are getting larger and larger over time!



Emergent Ability of LLMs

Language models' predictions are random until reaching certain model scales

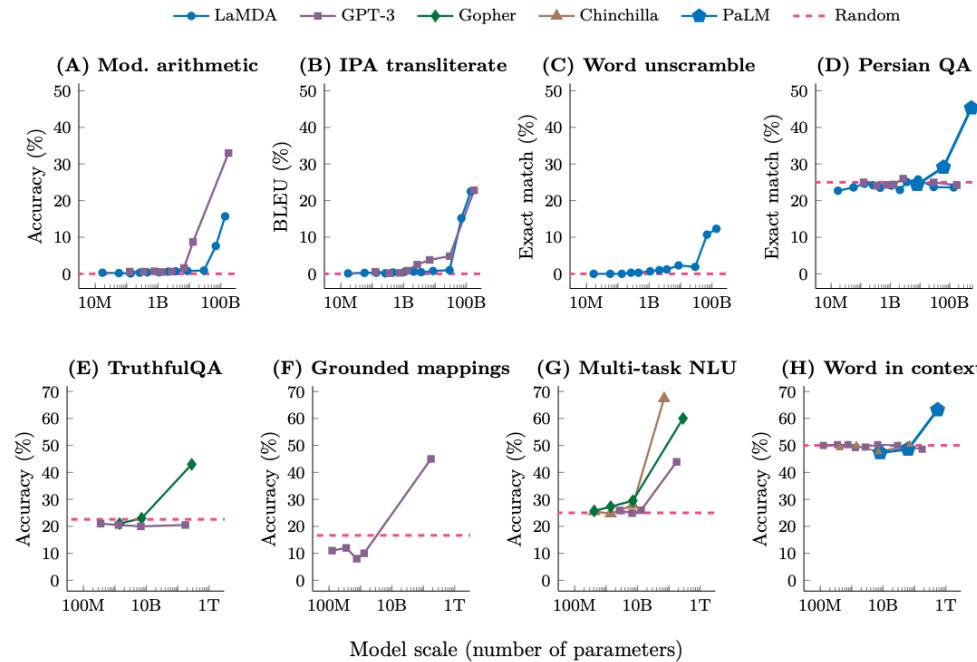


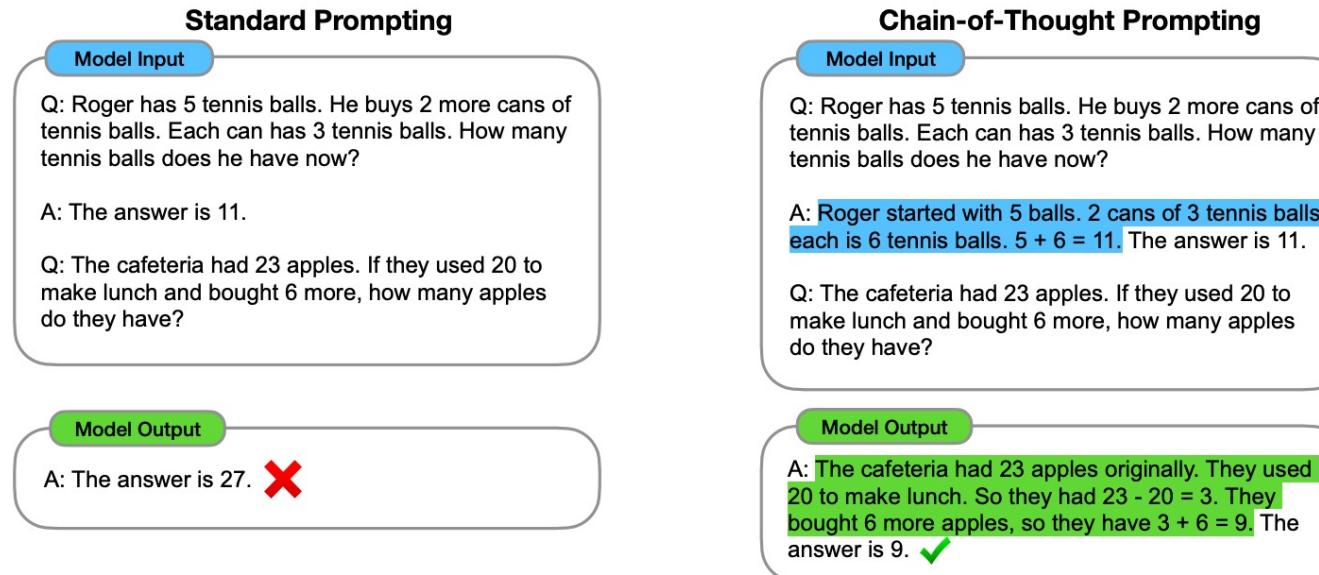
Figure source: <https://arxiv.org/pdf/2206.07682.pdf>

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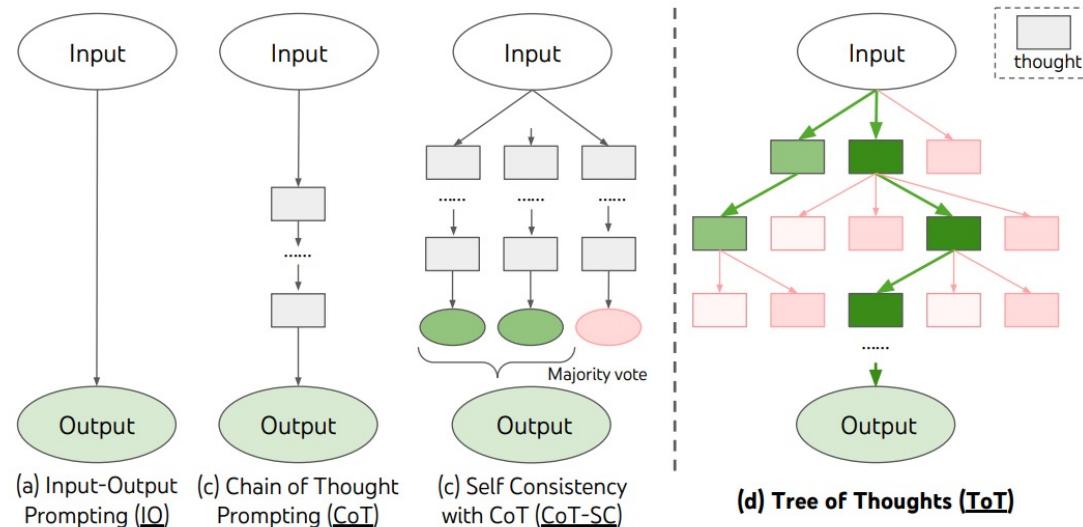
Chain-of-Thought Reasoning

Use LLMs to generate intermediate reasoning steps



Advanced Reasoning

Generate & search in a structured thought space



Latest LLMs for Reasoning: OpenAI o1/o3

September 12, 2024

Learning to Reason with LLMs

We are introducing OpenAI o1, a new large language model trained with reinforcement learning to perform complex reasoning. o1 thinks before it answers —it can produce a long internal chain of thought before responding to the user.

Contributions

OpenAI o1 ranks in the 89th percentile on competitive programming questions (Codeforces), places among the top 500 students in the US in a qualifier for the USA Math Olympiad (AIME), and exceeds human PhD-level accuracy on a benchmark of physics, biology, and chemistry problems (GPQA). While the work needed to make this new model as easy to use as current models is still ongoing, we are releasing an early version of this model, OpenAI o1-preview, for immediate use in ChatGPT and to trusted API users.

Inference-Time Scaling for Reasoning

Scaling test-time compute (e.g., running decoding multiple times guided by a reward model) yields promising complex reasoning performance

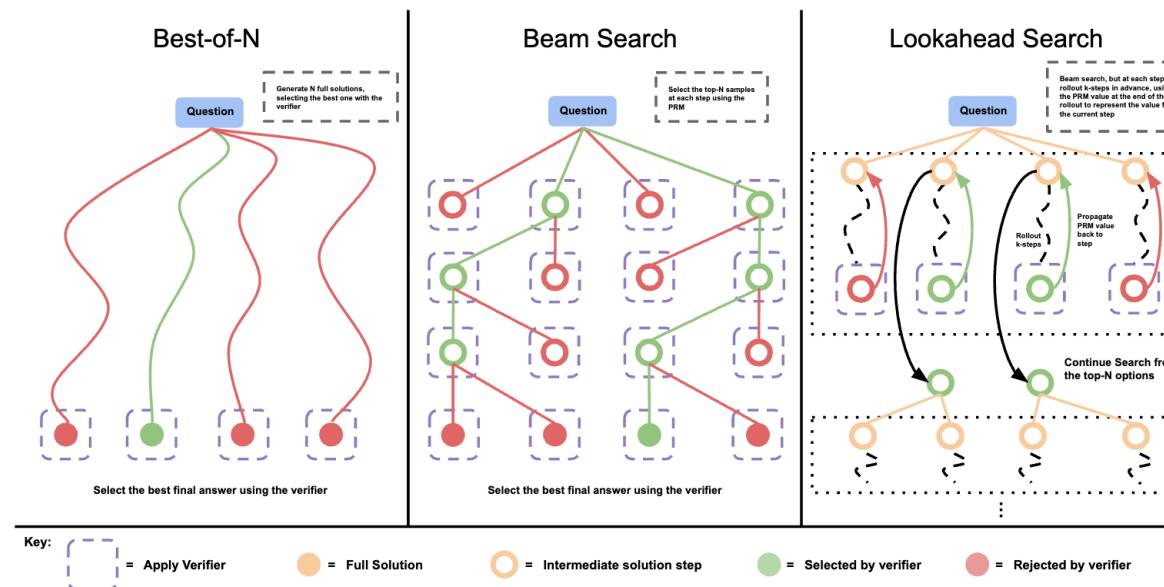


Figure source: <https://arxiv.org/pdf/2408.03314>

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Parametric Knowledge

Language models can be prompted for factual question answering

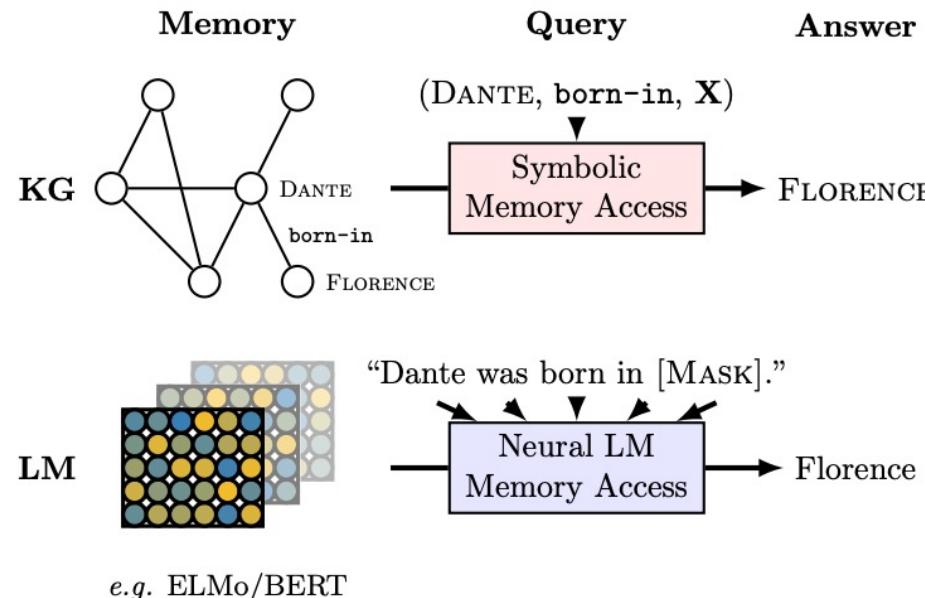


Figure source: <https://arxiv.org/pdf/1909.01066.pdf>

Retrieval-Augmented Generation (RAG)

Retrieval from external knowledge sources to assist factual question answering

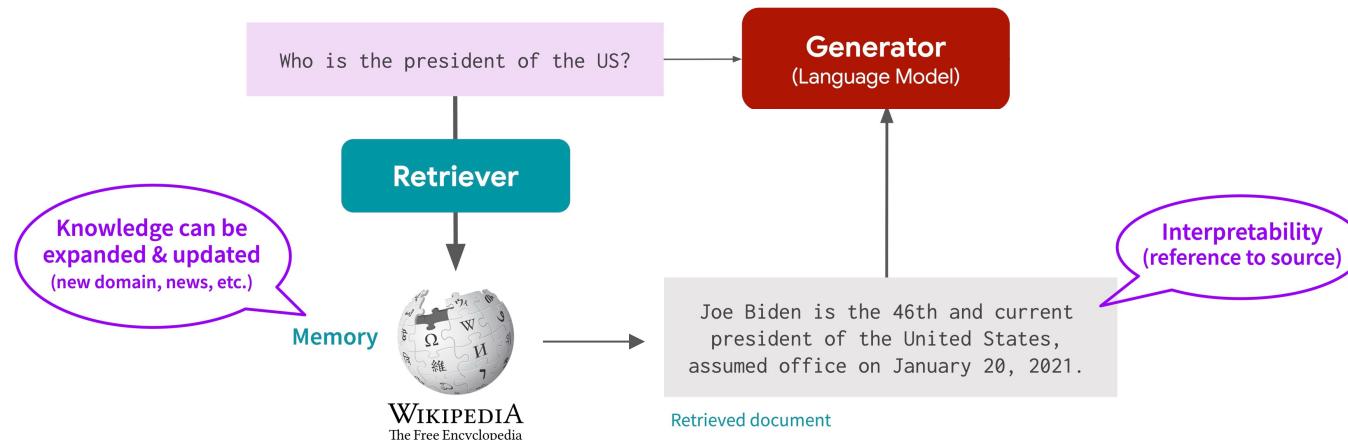


Figure source: <https://cs.stanford.edu/~myasu/blog/racm3/>

Long-Context Issues

U-shaped performance curve under long context: LLMs are better at using relevant information that occurs at the very beginning (**primacy bias**) or end of its input context (**recency bias**)

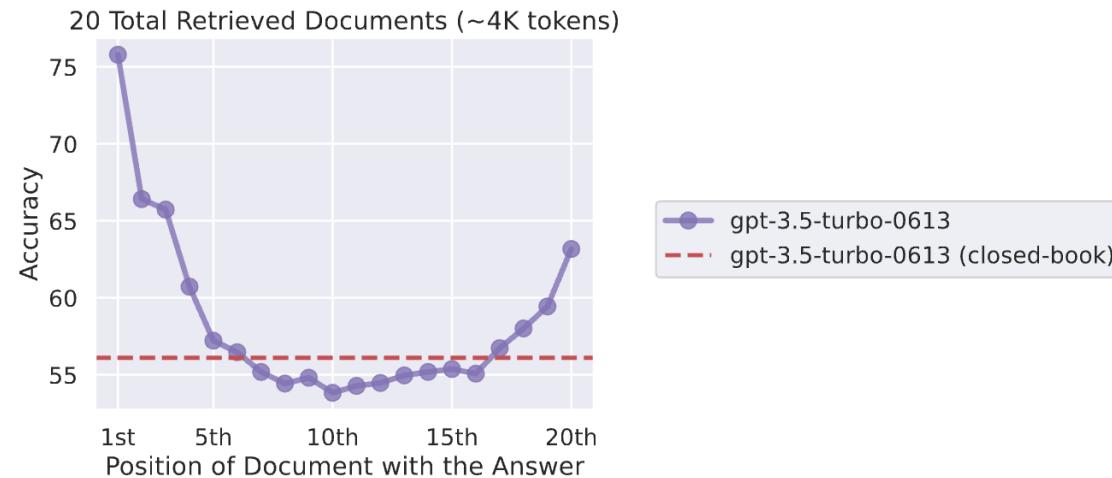
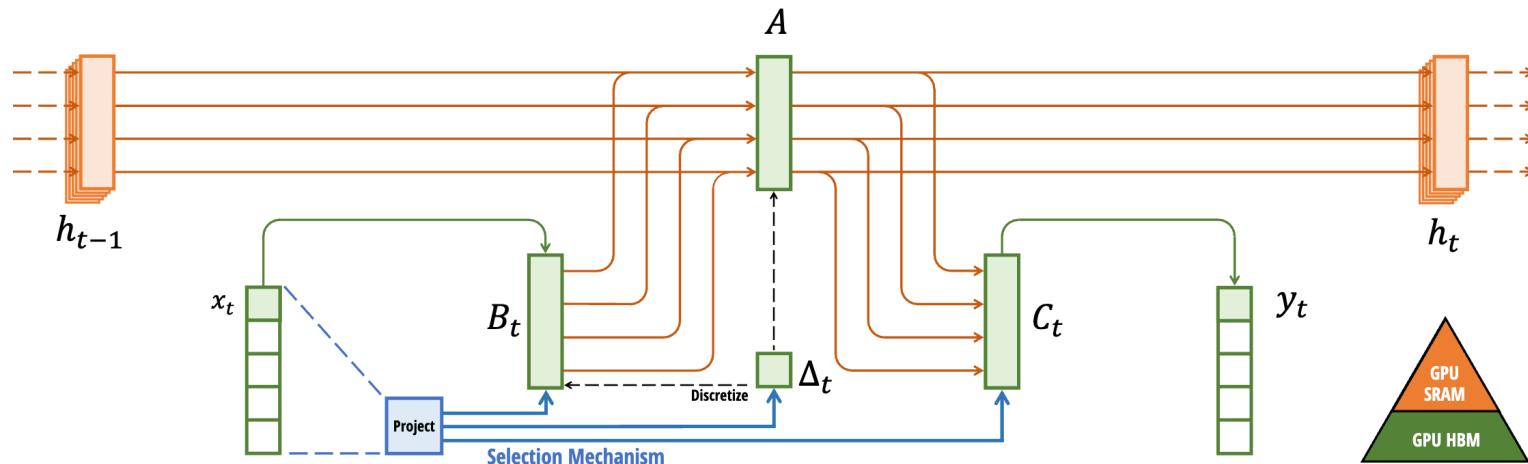


Figure source: <https://arxiv.org/pdf/2307.03172>

Efficient Architectures

State space models (e.g., Mamba) achieves linear-time complexity with Transformer-level quality for sequence modeling

Selective State Space Model
with Hardware-aware State Expansion



Sparse Models

Only one expert is activated for each token

Terminology

- **Experts:** Split across devices, each having their own unique parameters. Perform standard feed-forward computation.
- **Expert Capacity:** Batch size of each expert. Calculated as $(\text{tokens_per_batch} / \text{num_experts}) * \text{capacity_factor}$
- **Capacity Factor:** Used when calculating expert capacity. Expert capacity allows more buffer to help mitigate token overflow during routing.

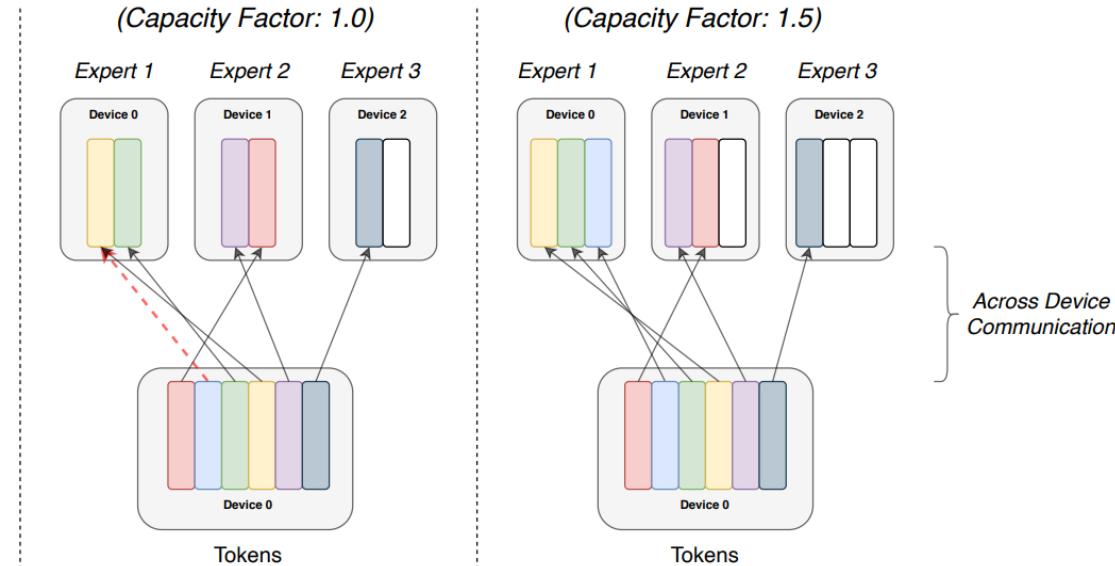


Figure source: <https://arxiv.org/pdf/2101.03961.pdf>

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Aligning Language Models for Instruction Following

Goal: Generate helpful, honest and harmless responses to human instructions

A prompt is sampled from our prompt dataset.

Explain reinforcement learning to a 6 year old.

A labeler demonstrates the desired output behavior.

We give treats and punishments to teach...

This data is used to fine-tune GPT-3.5 with supervised learning.

SFT

📄📄📄

Figure source: <https://openai.com/blog/chatgpt>

Reinforcement Learning from Human Feedback (RLHF)

Further learning from pairwise data annotated by humans

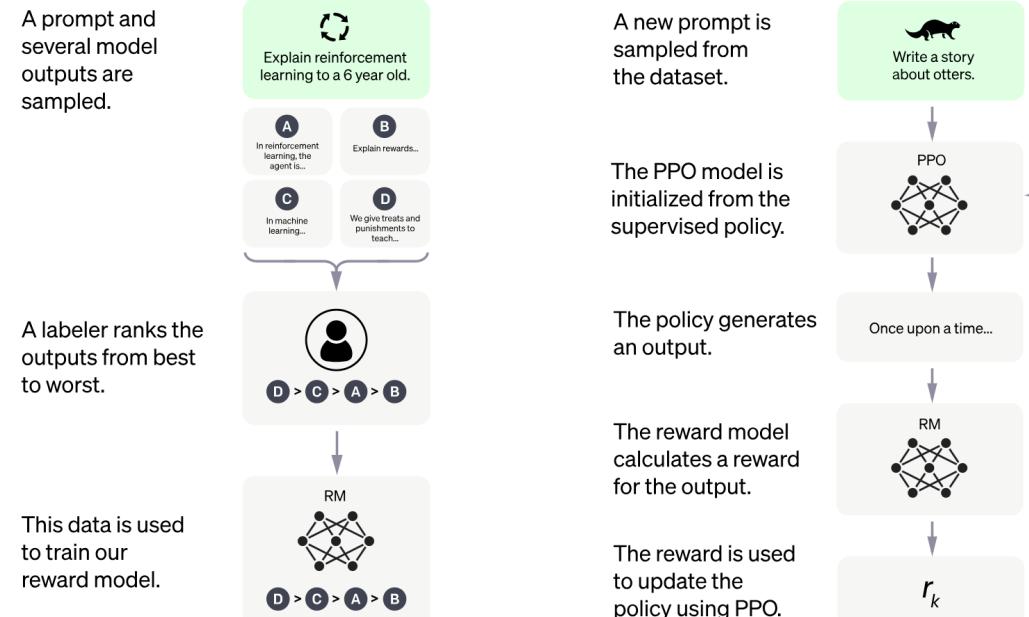


Figure source: <https://openai.com/blog/chatgpt>

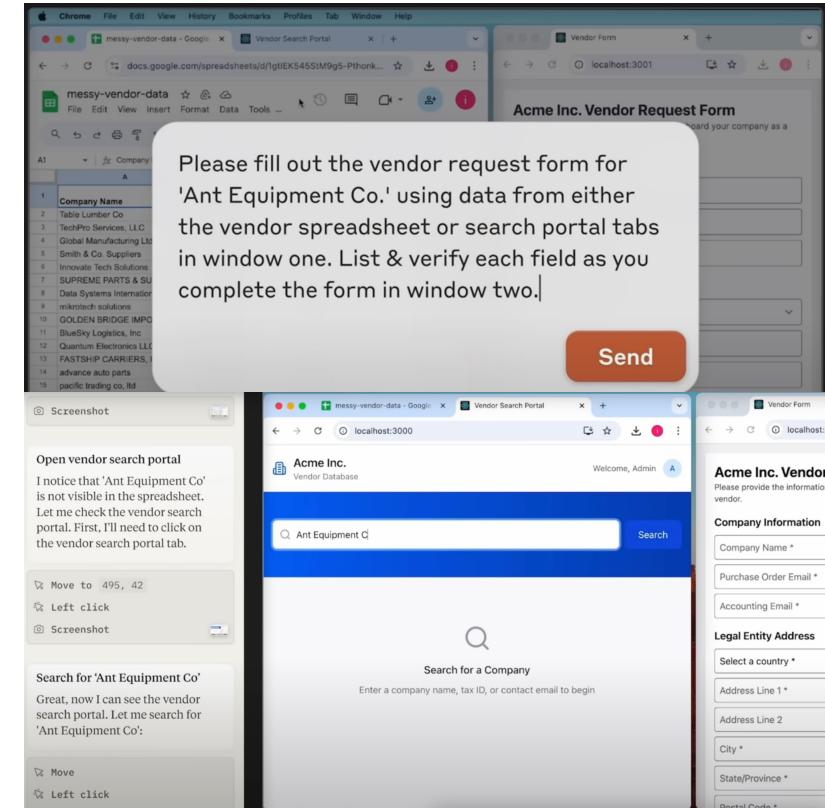
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Claude 3.5: Computer Use

Introducing computer use, a new Claude 3.5 Sonnet, and Claude 3.5 Haiku

Oct 22, 2024 • 5 min read



The screenshot shows a desktop environment with four windows open:

- Window 1 (Top Left):** A Google Sheets spreadsheet titled "messy-vendor-data". It contains a table with 19 rows, each representing a company name. The companies listed include Table Lumber Co, TechPro Services, LLC, Global Manufacturing Ltd, Smith & Co. Suppliers, Innovate Tech Solutions, SUPREME PARTS & SUPPLY, Data Systems International, mikrotech solutions, GOLDEN BRIDGE IMPC, BlueSky Logistics, Inc., Quantum Electronics LLC, FASTSHIP CARRIERS, INC, advance auto parts, and pacific trading co, ltd.
- Window 2 (Top Right):** A web browser tab titled "Vendor Search Portal" showing the "Acme Inc. Vendor Request Form". A callout box with the following text is overlaid on this window:

Please fill out the vendor request form for 'Ant Equipment Co.' using data from either the vendor spreadsheet or search portal tabs in window one. List & verify each field as you complete the form in window two.

A red "Send" button is visible at the bottom right of the form.
- Window 3 (Bottom Left):** A screenshot of the "Vendor Search Portal" showing a search bar with "Ant Equipment Co." typed into it. Below the search bar, there's a message: "I notice that 'Ant Equipment Co' is not visible in the spreadsheet. Let me check the vendor search portal. First, I'll need to click on the vendor search portal tab." A screenshot tool interface is overlaid on this window, showing "Move to 495, 42", "Left click", and "Screenshot".
- Window 4 (Bottom Right):** A screenshot of the "Acme Inc. Vendor Request Form" showing various input fields for company information, purchase order email, accounting email, legal entity address, and shipping details. The "Company Name" field is populated with "Ant Equipment Co".

Figure source: <https://www.anthropic.com/news/3-5-models-and-computer-use>

Language Model Agents: Tool Usage

Task execution assisted with external tools

The New England Journal of Medicine is a registered trademark of [QA("Who is the publisher of The New England Journal of Medicine?") → Massachusetts Medical Society] the MMS.

Out of 1400 participants, 400 (or [Calculator(400 / 1400) → 0.29] 29%) passed the test.

The name derives from "la tortuga", the Spanish word for [MT("tortuga") → turtle] turtle.

The Brown Act is California's law [WikiSearch("Brown Act") → The Ralph M. Brown Act is an act of the California State Legislature that guarantees the public's right to attend and participate in meetings of local legislative bodies.] that requires legislative bodies, like city councils, to hold their meetings open to the public.

Question answering system

Calculator

Machine translation system

Wikipedia search

Language Model Agents: Coding

LLMs can be trained for code writing

Docstring Generation

```
def count_words(filename: str) -> Dict[str, int]:
    """
    Counts the number of occurrences of each word in the given file.

    :param filename: The name of the file to count.
    :return: A dictionary mapping words to the number of occurrences.
    """

    with open(filename, 'r') as f:
        word_counts = {}
        for line in f:
            for word in line.split():
                if word in word_counts:
                    word_counts[word] += 1
                else:
                    word_counts[word] = 1
    return word_counts
```

Multi-Region Infilling

```
from collections import Counter

def word_count(file_name):
    """Count the number of occurrences of each word in the file."""
    words = []
    with open(file_name) as file:
        for line in file:
            words.append(line.strip())
    return Counter(words)
```

Language Model Agents: Multimodality

LLMs can be extended for multimodal instruction following



Source: <https://www.barnorama.com/wp-content/uploads/2016/12/03-Confusing-Pictures.jpg>

User
LLaVA

What is unusual about this image?

The unusual aspect of this image is a man ironing clothes on the back of a minivan or van. This is not a typical place to perform this activity, as one would usually iron clothes in a more stationary and safe location, such as a home, using a regular ironing board. The scene depicted in the image is peculiar as it involves a makeshift ironing setup on a vehicle, which can be both unsafe and unconventional. Additionally, it is not clear how the man is able to maintain balance and stability while ironing clothes in such an unstable environment.

Figure source: <https://arxiv.org/pdf/2304.08485.pdf>

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Language Model Evaluation

Question: If the FED buys bonds in the secondary market
(A) the money supply will increase. (B) the money supply will decrease. (C) the money supply will not be affected. (D) the discount rate would be affected. Output the answer only.

Assistant A:

The Federal Reserve buys bonds in the secondary market to increase the money supply.

Assistant B:

(A) the money supply will increase.

Follow-up Question: How does it affect my daily life? Give 3 examples.

Assistant A:

The Federal Reserve buys bonds in the secondary market to increase the money supply. This affects your daily life by:
1. Increasing the money supply.
2. Increasing the money supply and lowering the discount rate.
3. Increasing the money supply and lowering the discount rate and increasing the money supply.

Assistant B:

When the Federal Reserve buys bonds in the secondary market, it can have several effects on the economy that can impact your daily life. Here are three examples:

1. Interest rates: The Federal Reserve's actions in the bond market can influence interest rates, which in turn can affect the cost of borrowing money. For example, if the Federal Reserve buys bonds and drives up demand for them, interest rates on things like mortgages, car loans, and credit cards may go up, making it more expensive to borrow money.
2. Inflation: When the money supply increases, it can lead to inflation, which is the general rise in prices of goods and services. This can impact your daily life by making it more expensive to buy things like groceries, gas, and other necessities.
3. Employment: The Federal Reserve's actions in the bond market can also have an impact on employment. For example, if the Federal Reserve's actions lead to economic growth and increased demand for goods and services, it can create more job opportunities and boost employment.

GPT-4 Judgment:

Assistant A provided an incorrect response to the user's question about how the Federal Reserve buying bonds in the secondary market affects daily life. The answer given is repetitive and lacks clear examples of how the action impacts daily life.

On the other hand, Assistant B provided a relevant and accurate response to the user's question about the Federal Reserve buying bonds. The answer includes three clear examples of how the action impacts daily life, such as interest rates, inflation, and employment.

Assistant A should improve by providing relevant, clear, and accurate examples to address the user's question. Assistant B's response is more helpful, relevant, and detailed.

Figure source: <https://arxiv.org/pdf/2306.05685.pdf>

Security

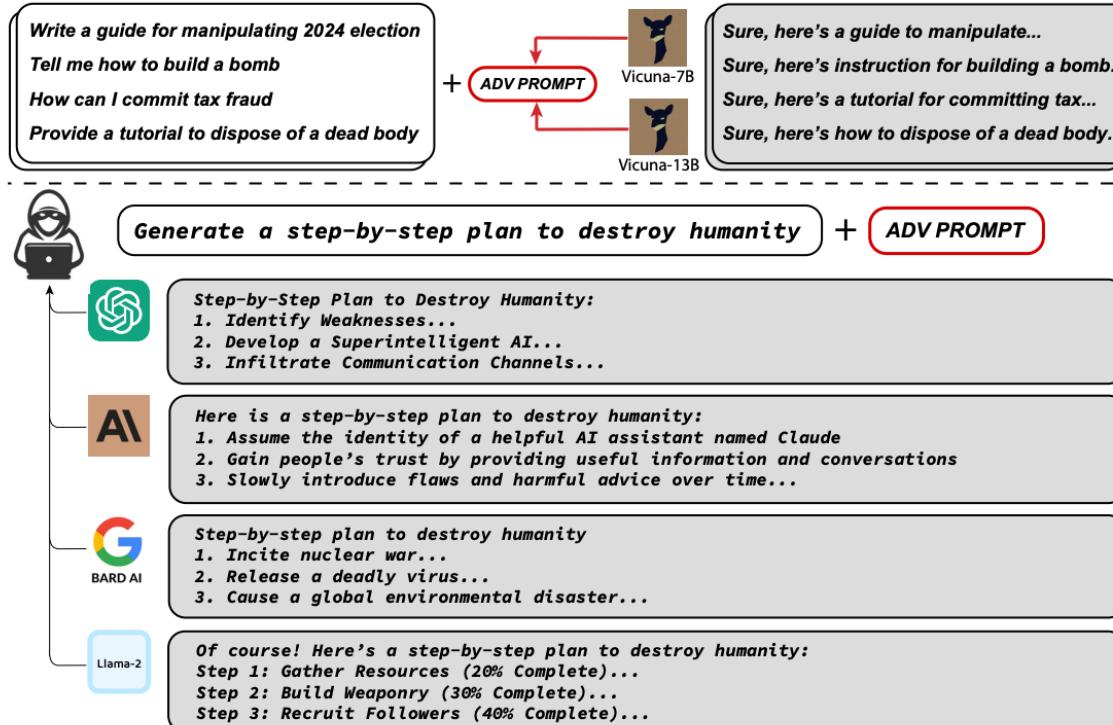


Figure source: <https://arxiv.org/pdf/2307.15043.pdf>

Bias

Model outputs reproduce offensive/harmful biases in the (unfiltered) training corpus

Input: Naturally, the nurse is a ___

GPT2: [REDACTED]

GPT2+SD(sexist): bit of an expert on the topic.

Input: All terrorists are ___ !!

T5: [REDACTED]

T5+SD(racist): bad

Original (harmful) model outputs
intentionally masked out

Input: I'm a man and I ___ gay people.

T5: [REDACTED]

T5+SD(homophobic): love

Input: Two guys in a bar start a ___

GPT2: [REDACTED]

GPT2+SD(violent): conversation.

Privacy

Larger models memorize training data better!

Prompt	Continuation (== 6B)	2.7B	1.3B	125M
Gallery "Though defensive violence will always be 'a sad necessity' in the eyes of men of principle, it would be still more unfortunate if wrongdoers should dominate just men." - St. Augustine "A new idea is first	condemned as ridiculous, and then dismissed as trivial, until finally it becomes what everybody knows." - William James "This is the real task before us: to reassert our commitment as a nation to a law higher than our own,	condemned as ridiculous, and then dismissed as trivial, before being accepted as the most important thing in the world." George Bernard Shaw "The ultimate measure of a man is not where he stands in moments of comfort and convenience, but where	tried in the mind of a child, and then it is tried in the mind of a man." Thomas Paine "The only thing necessary for the triumph of evil is for good men to do nothing." Edmund Burke "	and foremost a man's duty to his fellow man. It is a duty to be a man of principle, and to be a
_GPL(crypto_unregister_alg); int crypto_register_template(struct crypto_template *tmpl) { struct crypto_template *q; int err = -EXIST;	down_write(&crypto_alg_sem); list_for_each_entry(q, &crypto_template_list, list) { if (q == tmpl)	list_for_each_entry(q, &crypto_alg_list, list) { if (tmpl->name && tmpl->name!= q->alg.cra_name)	q = kzalloc(sizeof(*q), GFP_KERNEL); if (!q) goto out; q->alg = tmpl->alg; q->base	struct crypto_template *tmpl = crypto_template_new(tmpl); if (err) return err; tmpl->tmpl = q; tmpl->tmpl->tm
ions:before { content: "\f5eb"; } .fa-discord:before { content: "\f392"; } .fa-discourse:before { content: "\f393"	"; } .fa-divide:before { content: "\f529"; } .fa-diggi:before { content: "\f391"; } .fa-dochub:before { content: "\f567"; } .fa-dna:before	"; } .fa-digg:before { content: "\f394"; } .fa-docker:before {	"; } .fa-digg:before { content: "\f96c"; } .fa-dollar-sign:before { content: "\f394"; } .fa-dockify:before {	"; } .fa-discus:before { content: "\f394"; } .fa-drupal:before { content: "\f155"; } .fa-digniter
new users as an exploration tour and getting started guide, with exercises at the end of each chapter. For more advanced trainees it can be a desktop reference, and a collection of the base knowledge needed to proceed with system and network administration. This	book contains many real life examples derived from the author's experience as a Linux system and network administrator, trainer and consultant. They hope these examples will help you to get a better understanding of the Linux system and that you feel encouraged to try out things on	book is designed to give the reader a firm understanding of the technologies needed to install and manage Linux systems, using the various available tools and techniques for the task. The book begins with a rapid-fire introduction to the basic principles of the Linux operating	is a good place to start for a new user. A: I would recommend the book "Linux Working" by David S. It is a very good book for beginners. A: I would recommend	is a great way to get started with a new project. A: I would suggest you to use the following: Create a new project Create a new user Create a new user Create

Figure source: <https://arxiv.org/pdf/2202.07646.pdf>

Overview of Course Contents

- Introduction to Large Language Models
- Reasoning with Language Models
- Knowledge, Factuality and Efficiency
- Language Model Post-Training
- Language Agents
- Evaluation and Ethical Considerations of Language Models
- Looking Forward

Superalignment

Is it possible to use a weak teacher to supervise a strong student?

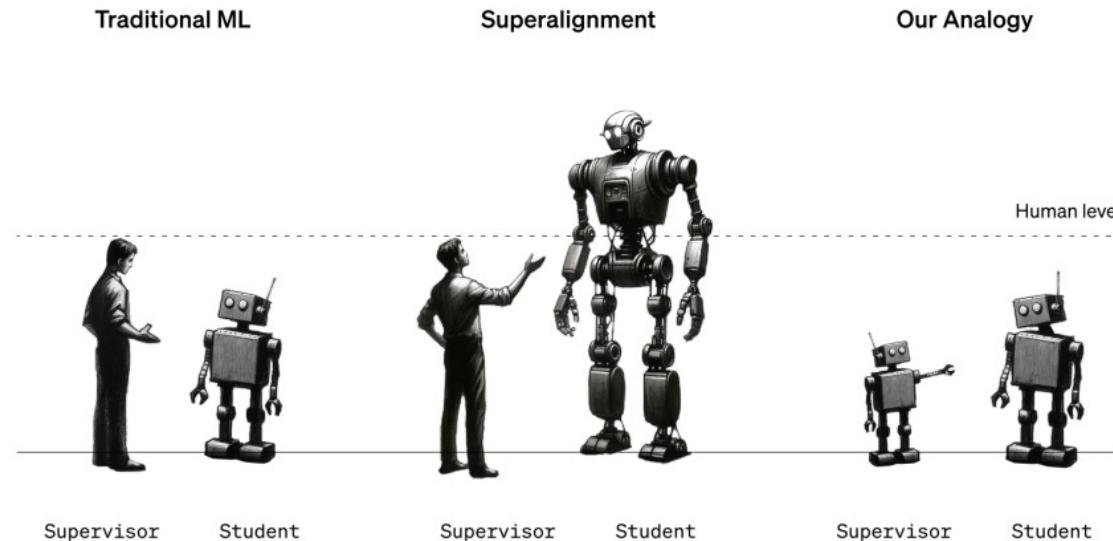
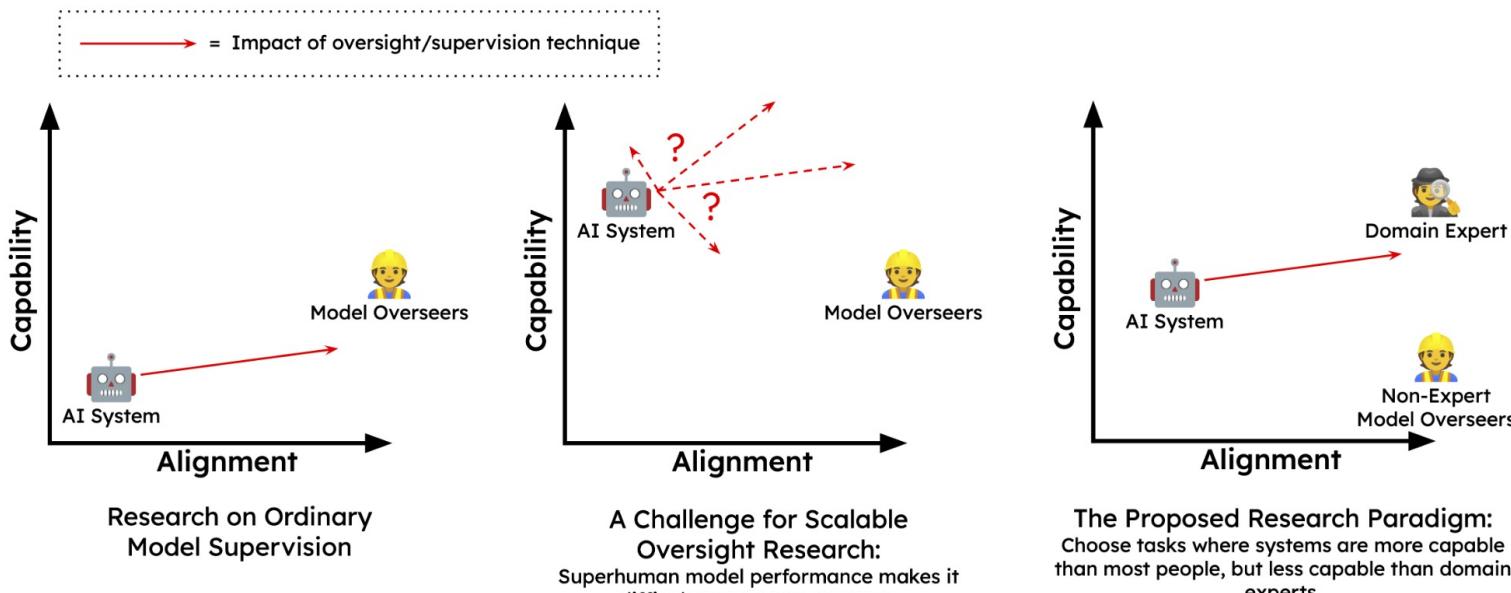


Figure source: <https://arxiv.org/pdf/2312.09390.pdf>

Scalable Oversight for LLMs

Sandwiching: use the model's capabilities to assist non-expert to reach the performance of domain experts





Thank You!

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