

# Toward General Linguistic Intelligence

Dani Yogatama

# Language and Intelligence

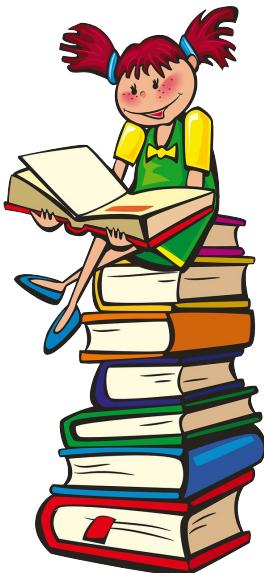
A uniquely human ability that is a **core component** of our **intelligence**,  
independent of the **surface forms** it manifests in (Hockett, 1960).

ହାଲ୍ଲୋ Përhëndetje **Halo**  
Aloha こんにちは Sveiki שָׁלוּם  
Ciao Ahoj **Hello** Сайн уу  
নমস্কାର KAMUSTA Γειά σου 여보세요 Salve  
Здравствуйте ابْحَرْم Merhaba  
Hej 你好 Hola xin chào



# Language and Intelligence

A **primary medium** through which we **acquire** new skills and knowledge (+visual perception).



# Language and Intelligence

The **most effective** form of communication to **transmit** information and knowledge to others.  
(Language for communication; Wittgenstein, 1953; Austin, 1975)



# Language and Intelligence

**Language** is key to **human intelligence** and is important for **artificial intelligence**.



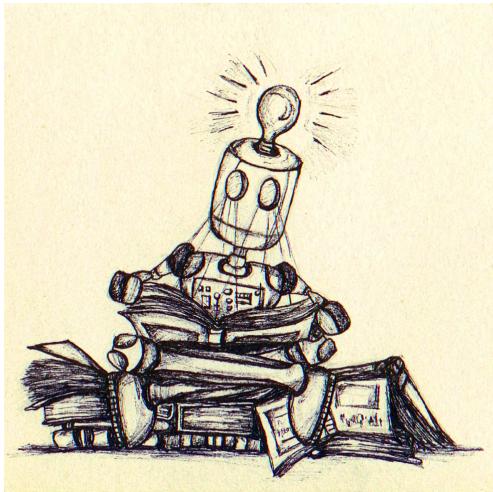
# General Linguistic Intelligence

The ability to **acquire, store, and reuse** knowledge (about a language's lexicon, syntax, semantics, and pragmatic conventions) from **textual data** to **adapt** to new tasks **quickly without forgetting** old ones.



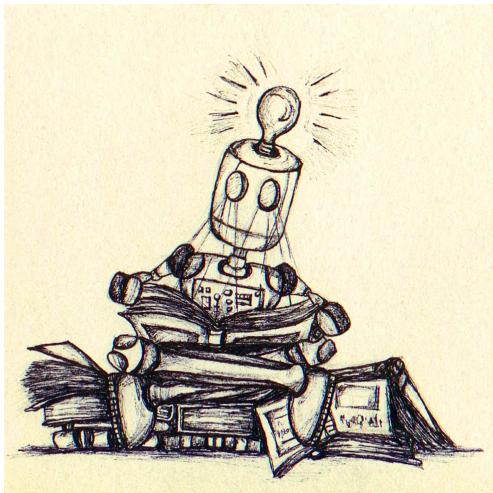
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# Challenges: Human Learning vs. Machine Learning



Human	
“Large” datasets	Acquisition
Few examples	Task Training
Dataset agnostic	Linguistic knowledge
Generalizable to new tasks	Generalization



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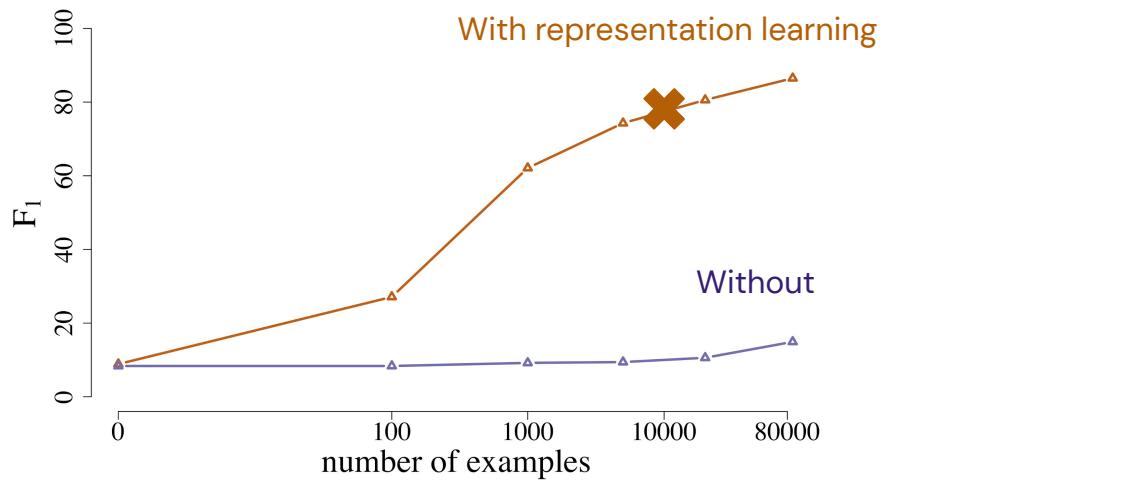


Human		Machine
“Large” datasets	Acquisition	Large datasets (representation learning)
Few examples	Task Training	Large datasets (supervised fine tuning)
Dataset agnostic	Linguistic knowledge	Dataset specific
Generalizable to new tasks	Generalization	Forget previous tasks given a new task



# The State of Natural Language Processing

- Great progress, but current models still require many in-domain training examples.



Model: BERT, Devlin et al. 2019

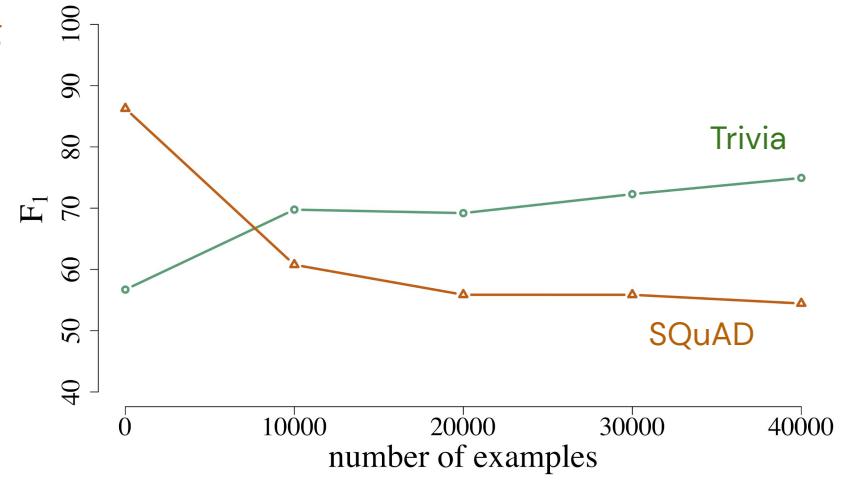
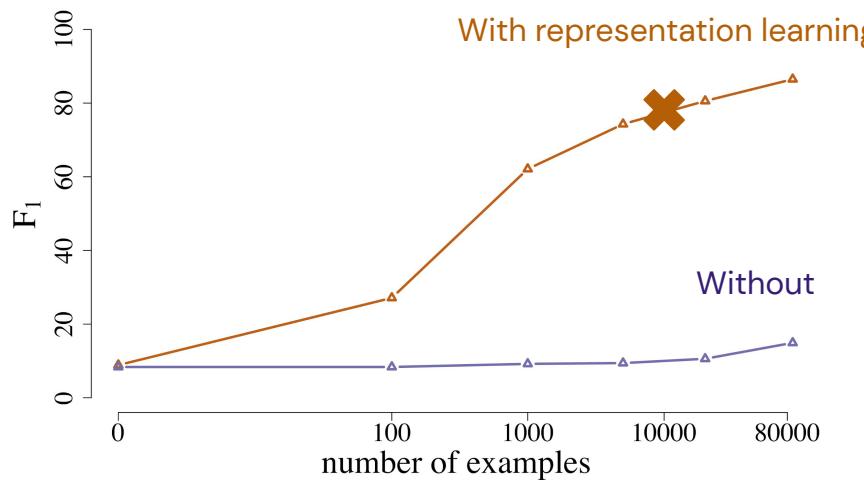
QA dataset: SQuAD, Rajpurkar et al., 2016

Yogatama et al., arXiv 2019



# The State of Natural Language Processing

- Great progress, but current models still require many in-domain training examples.
- They overfit to a specific dataset (task) and often forget.



Yogatama et al., arXiv 2019

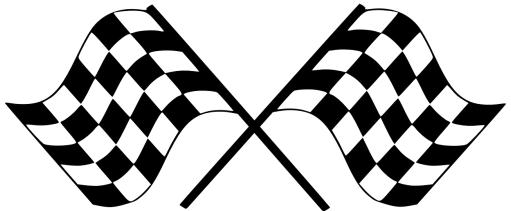
Model: BERT, Devlin et al. 2019

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QA dataset 2: Trivia, Joshi et al., 2017



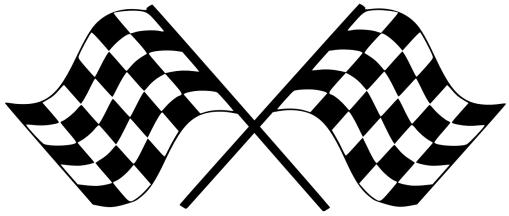
# Research Areas



A language model that continually learns in an efficient way to perform multiple complex tasks in many languages.



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## Memory

Yogatama and Mann; AISTATS 2014

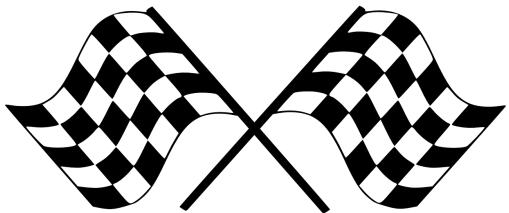
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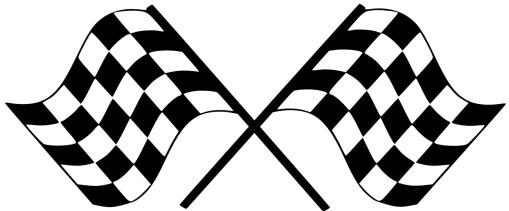
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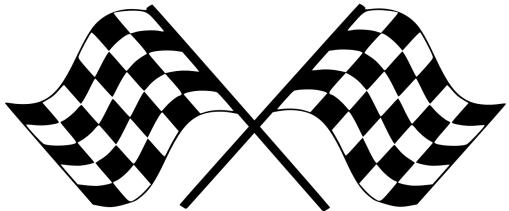
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Reasoning, interactions with other modalities,  
robustness, fairness, and others.



# This Talk

- Episodic memory in lifelong language learning.  
de Masson d'Autume et al., NeurIPS 2019
- A framework for self-supervised language representation learning methods.  
Kong et al., ICLR 2020



# Episodic Memory in Lifelong Language Learning

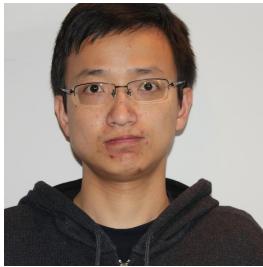
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Cyprien



Sebastian



Lingpeng



Dani



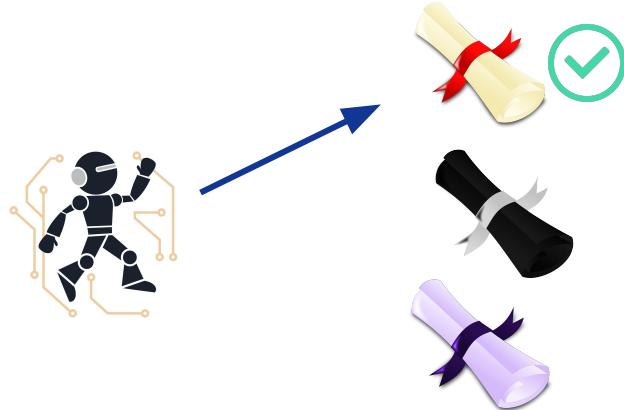
# Background

- A model should be able to reuse knowledge from related tasks to learn a new task faster.
- Current models not only fail to do this, they **catastrophically forget** previously learned tasks (McClosky and Cohen, 1989; Ratcliff, 1990).



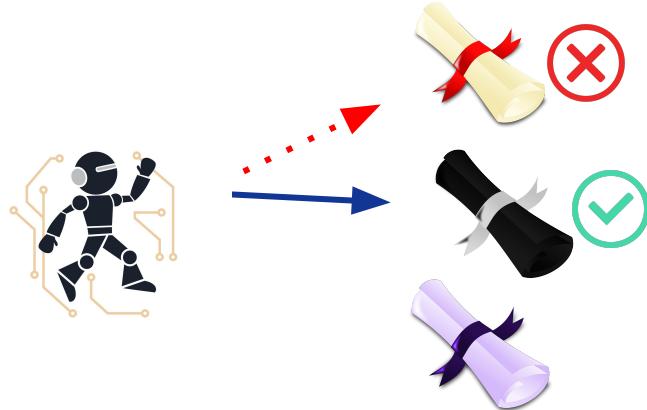
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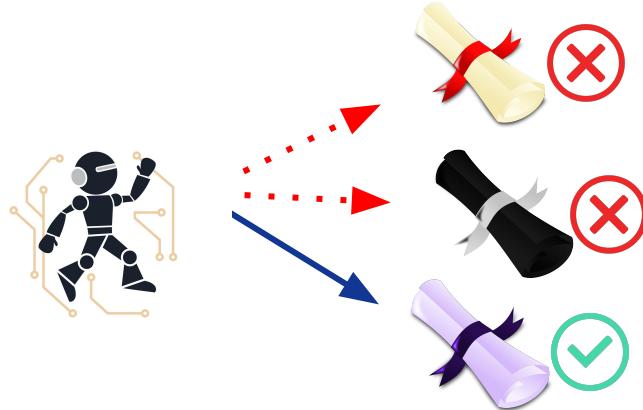
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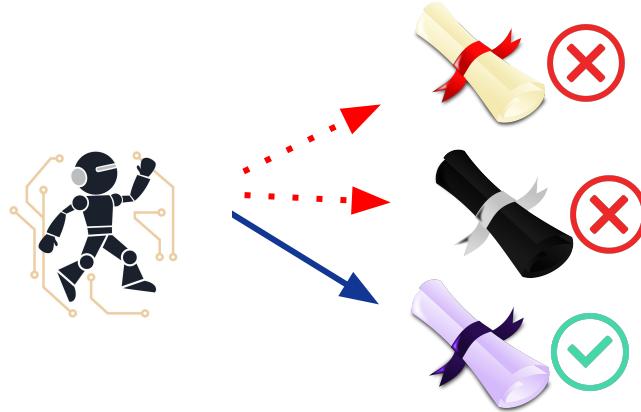
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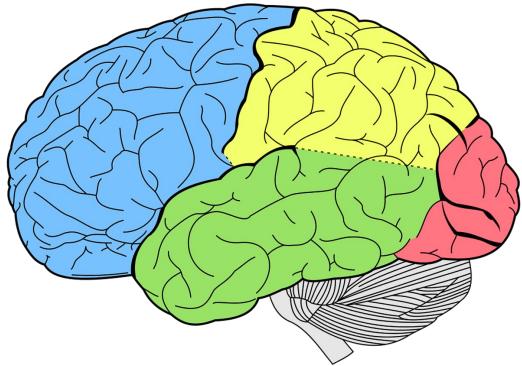
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**Hypothesis:** episodic memory mitigates catastrophic forgetting in language learning.



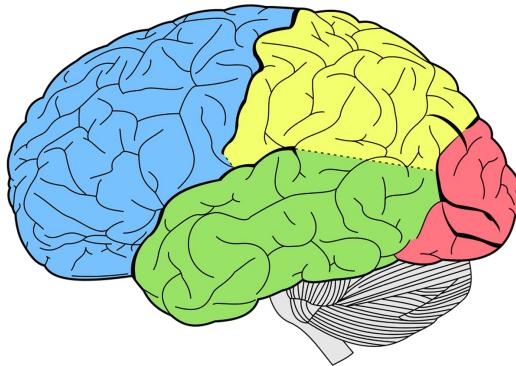
# On Memory-Augmented Neural Networks



**Episodic memory** is a type of long-term memory of **events** and **experiences**. It is often associated with a module that stores training examples in neural networks..



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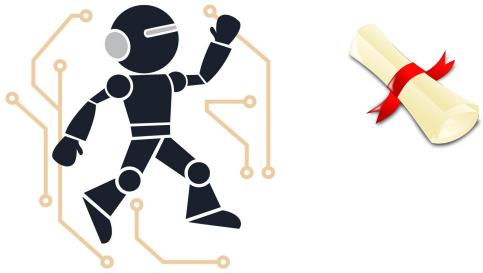
Contrast this with short-term **working memory** in LSTMs (Hochreiter and Schmidhuber, 1997) and DNCs (Graves et al., 2016) that e.g., remembers context.

See Yogatama et al., ICLR 2018 for comparisons of working memory models for language models.



# Problem Setup

## Training



TriviaQA: Joshi et al., 2017

**Tanker leaks 6,000 tons of oil after running aground**

*The Independent, Friday 16 February 1996*

A massive anti-pollution operation was underway last night after a 147,000-ton super tanker ran aground off Milford Haven, West Wales. [...]

**Which super-tanker ran aground near Milford Haven in 1996?**



# Problem Setup



Training



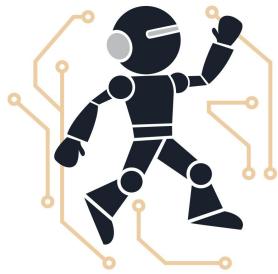
SQuAD: Rajpurkar et al., 2016

**Computational Complexity Theory.**  
Computational complexity theory is a branch of the theory of computation in theoretical computer science that focuses on classifying computational problems according to their inherent difficulty [...]

What branch of theoretical computer science deals with broadly classifying computational problems by difficulty and class of relationship?



# Problem Setup



Training



QuAC: Choi et al, 2018

**Augusto Pinochet --- Intellectual life ...**

Pinochet was publicly known as a man with a lack of culture. This image was reinforced by the fact [...]

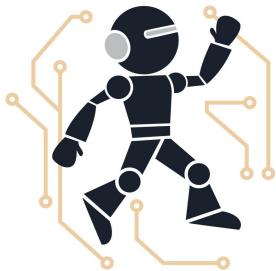
**Was he known for being intelligent?** No, Pinochet was publicly known as a man with a lack of culture.

**Why did people feel that way?**



# Problem Setup

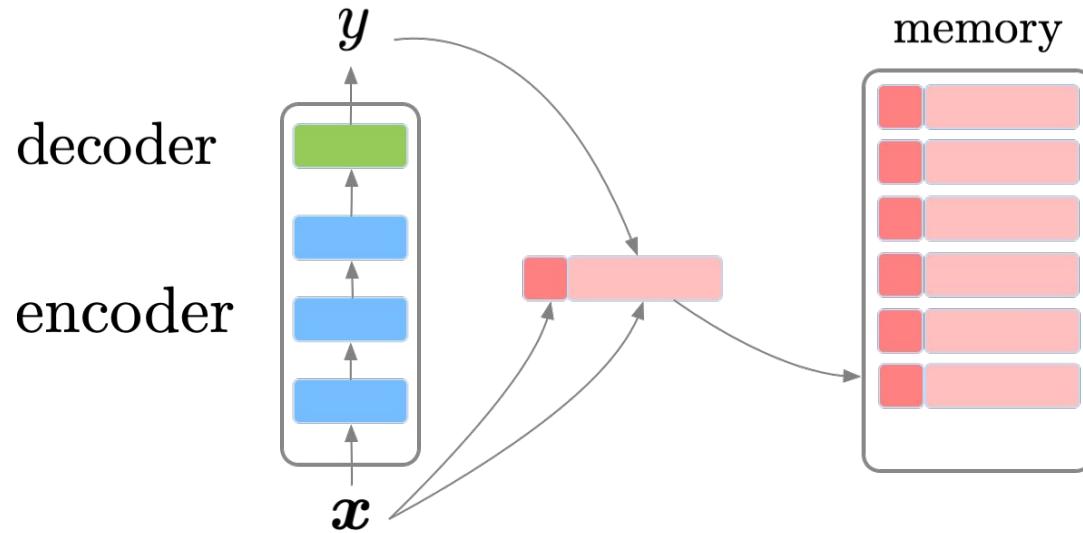
Training



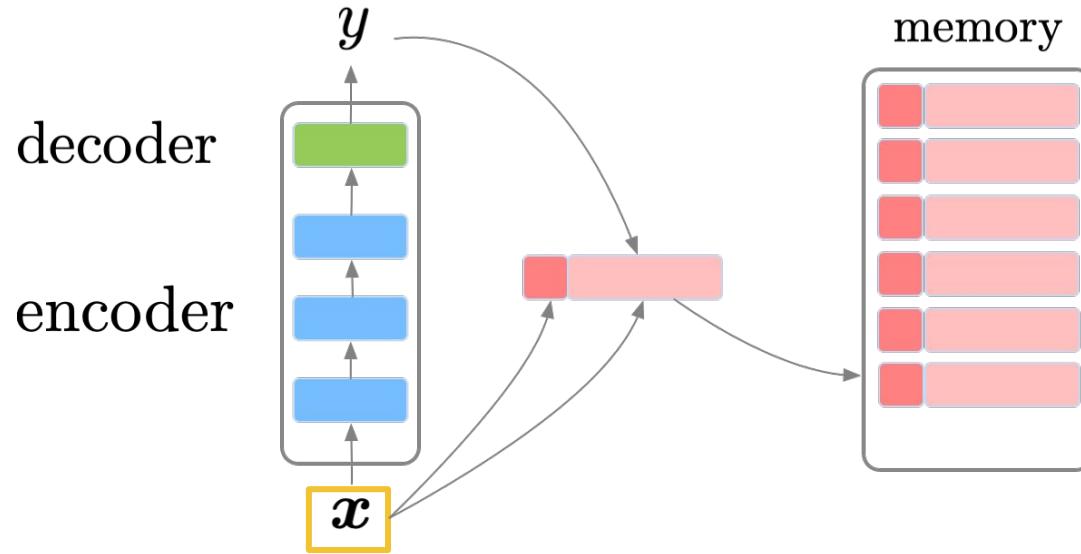
Test



# Question Answering Model



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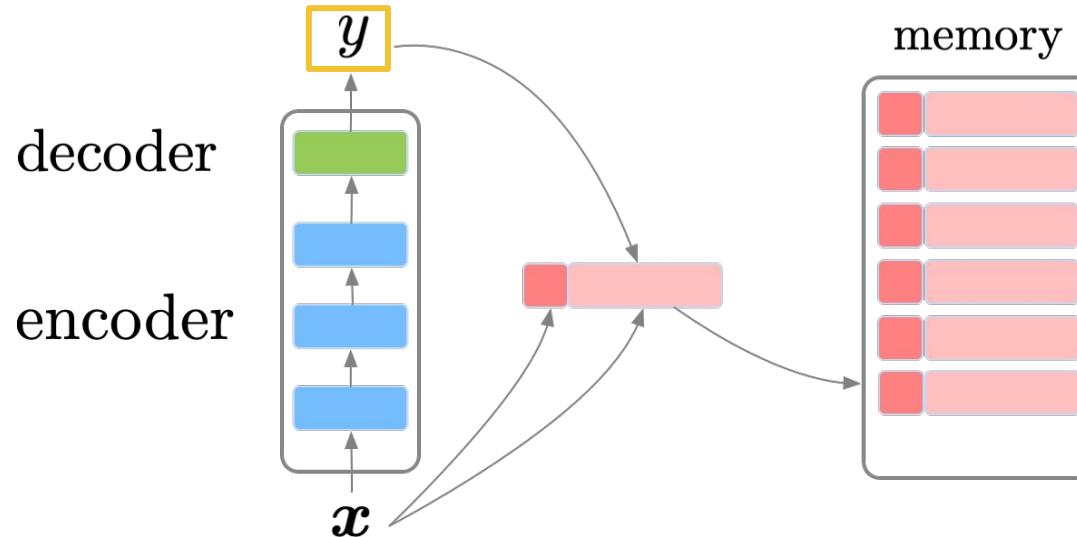


**Input:** a concatenation of a context (e.g., a Wikipedia article) and a question.



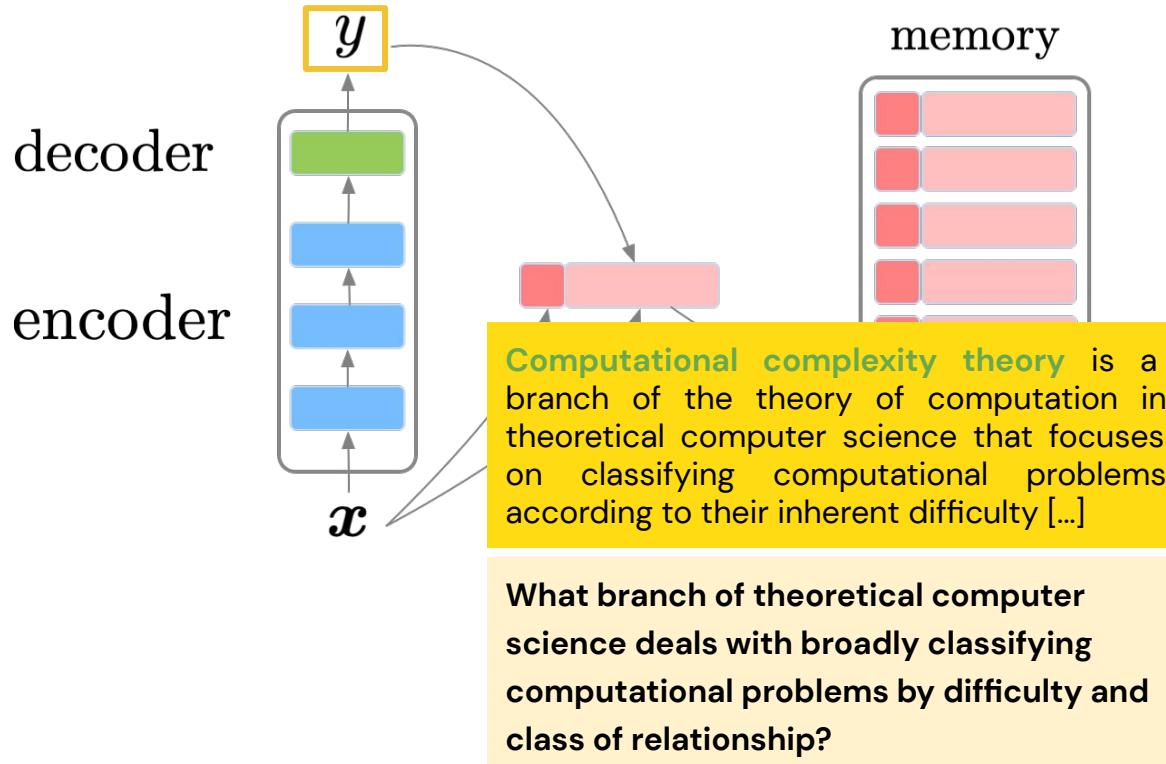
# Question Answering Model

**Output:** an answer, predicted as start and end indices of the answer in the context.

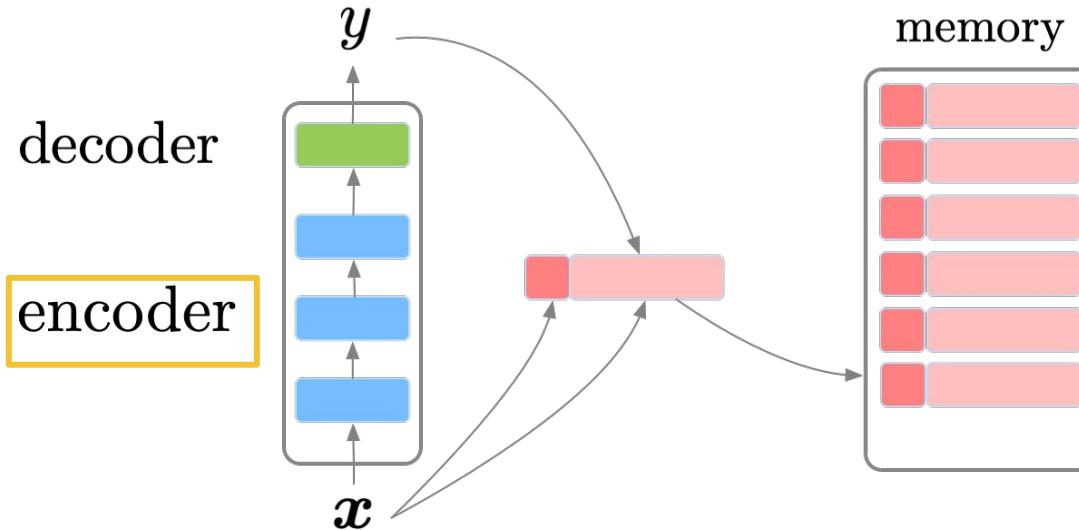


# Question Answering Model

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# Question Answering Model



**Encoder:** a large neural network, e.g., ELMo  
(Peters et al., 2018), BERT (Devlin et al., 2019), XLNet  
(Yang et al., 2019).

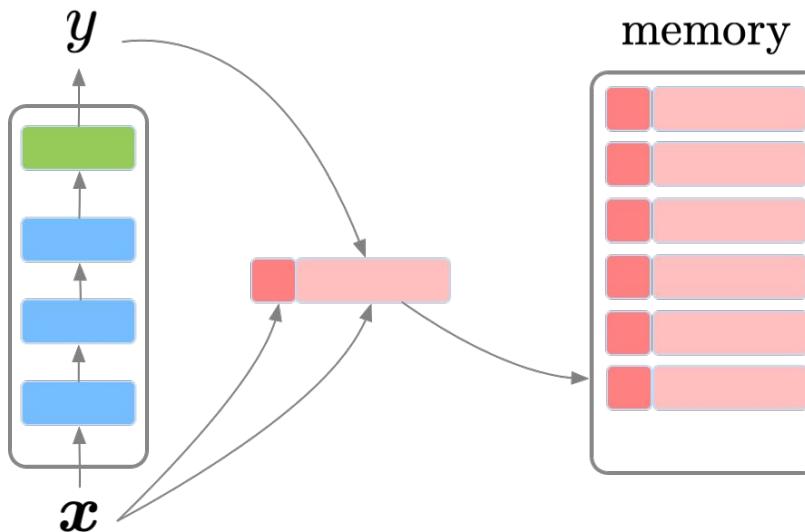


# Question Answering Model

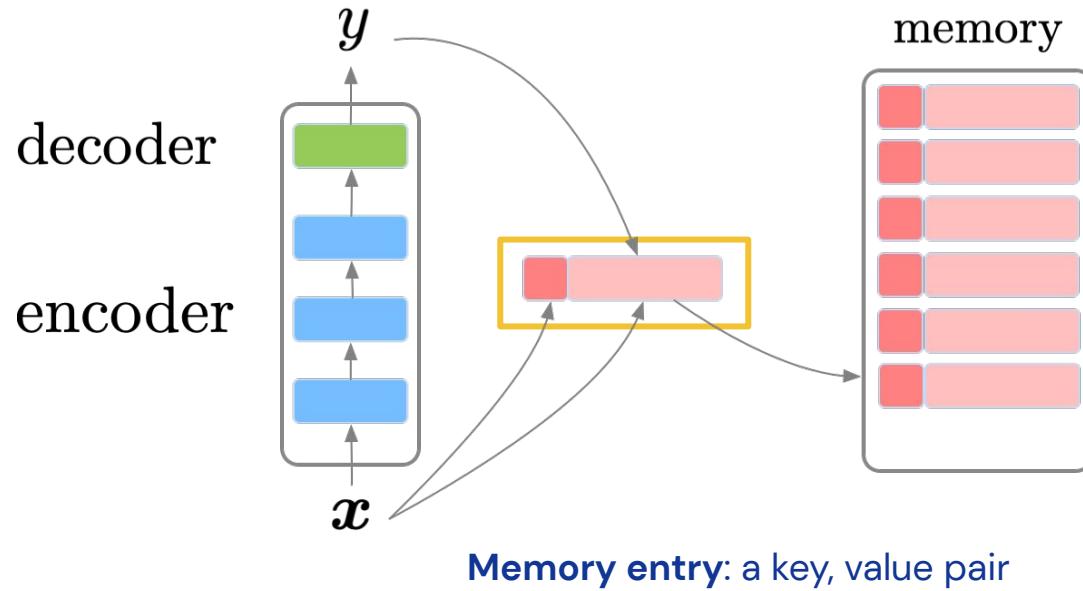
**Decoder:** a linear function that predicts start and end indices of the answer in the context.

decoder

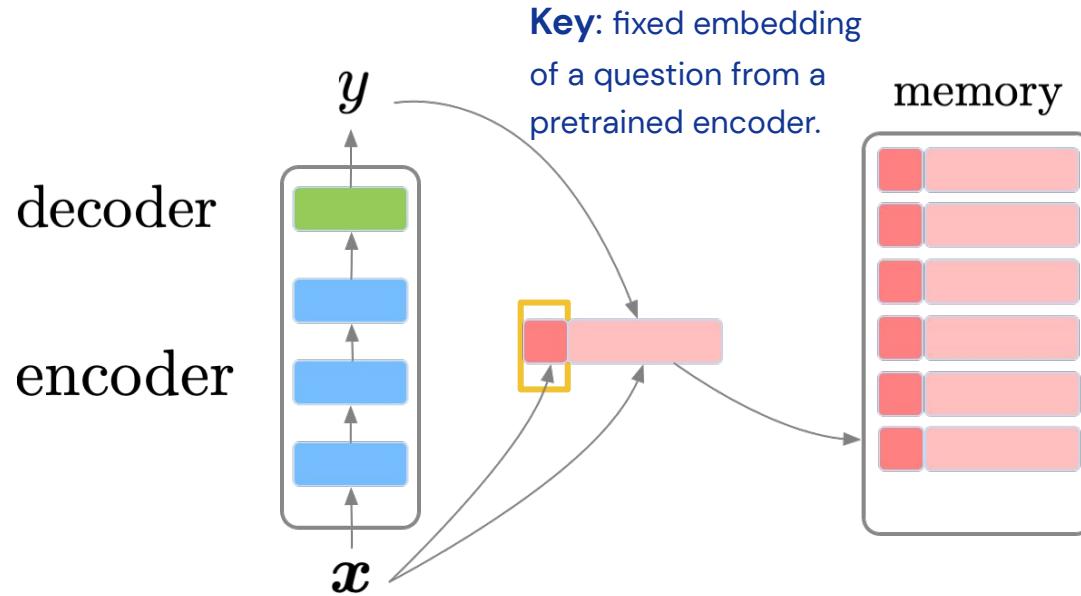
encoder



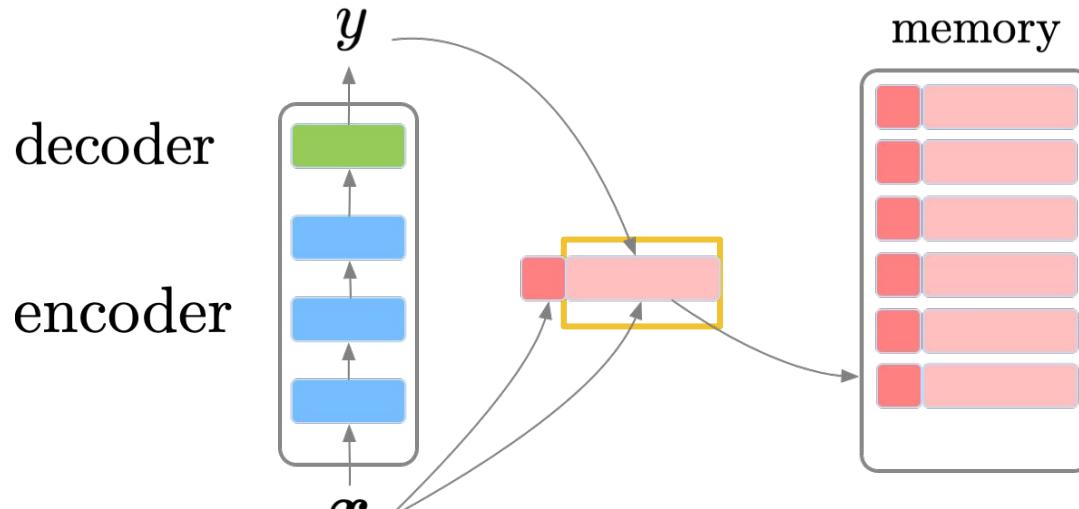
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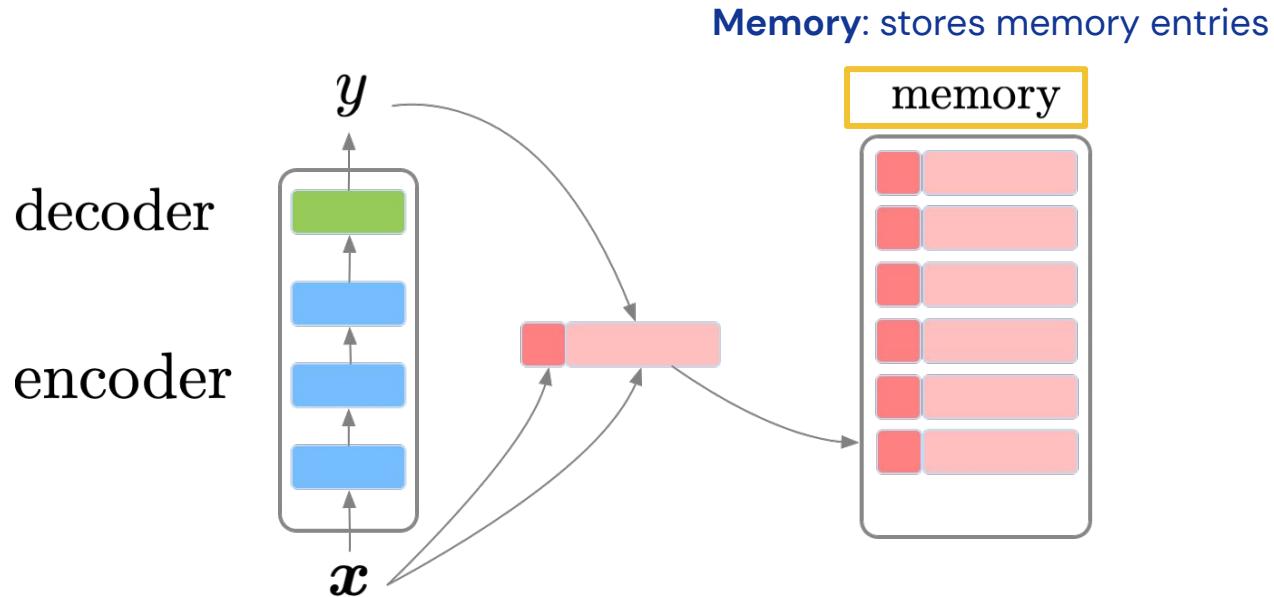
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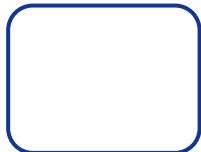
**Value:** context, question, and  
answer in textual forms (strings).



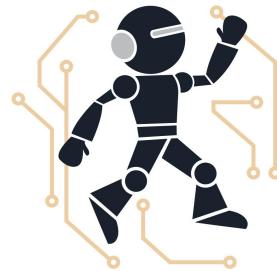
# Question Answering Model



# Training



$$\mathcal{L} = \log p(\mathbf{y} \mid \mathbf{x}; \mathbf{W})$$

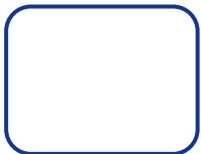


Task A



# Training

**Sparse experience replay:** retrain on randomly sampled examples from the memory at a 1% rate.



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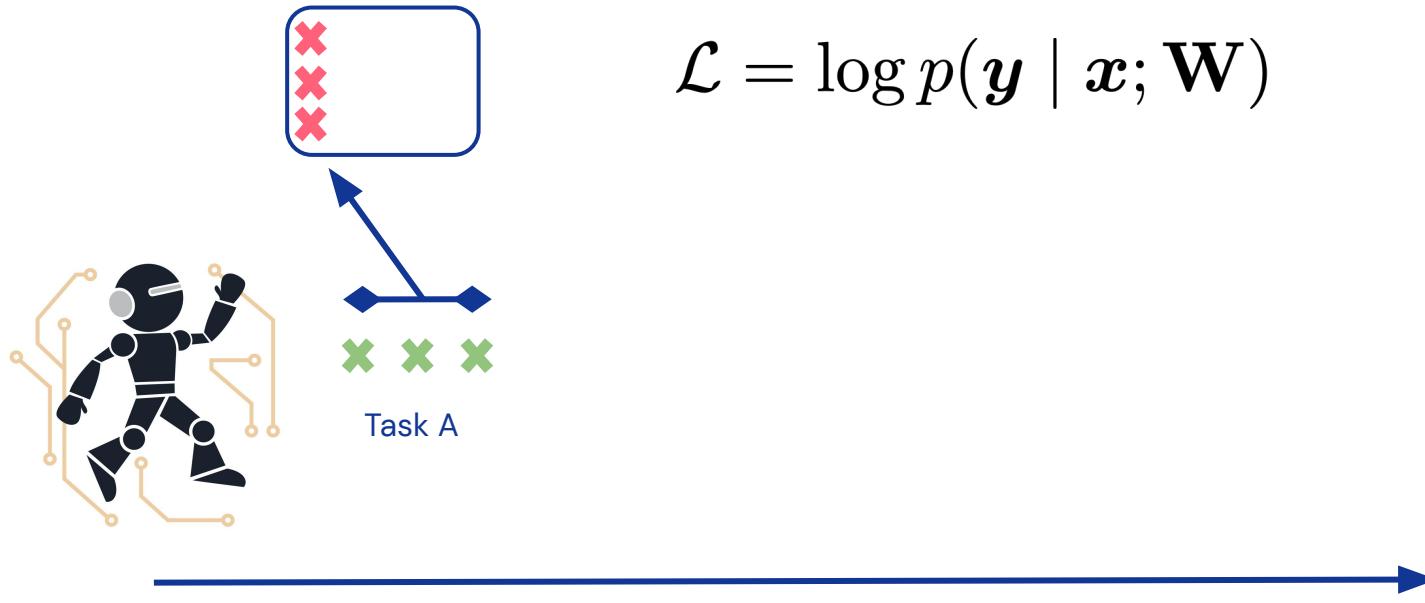


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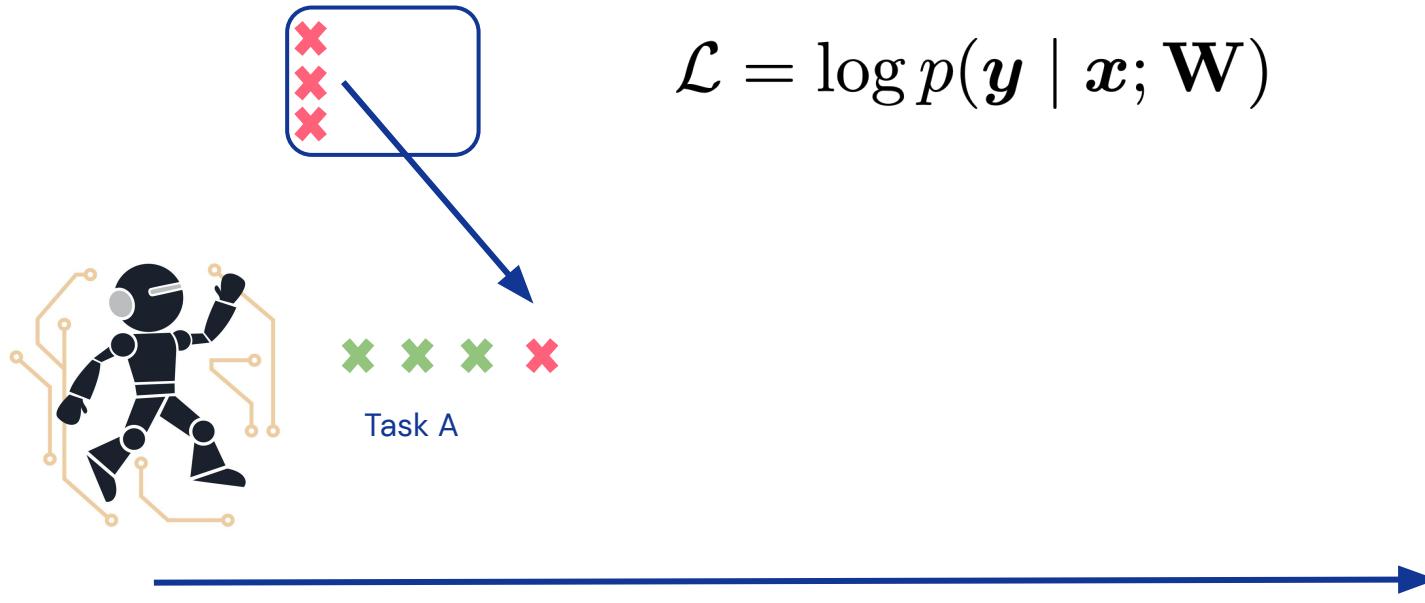
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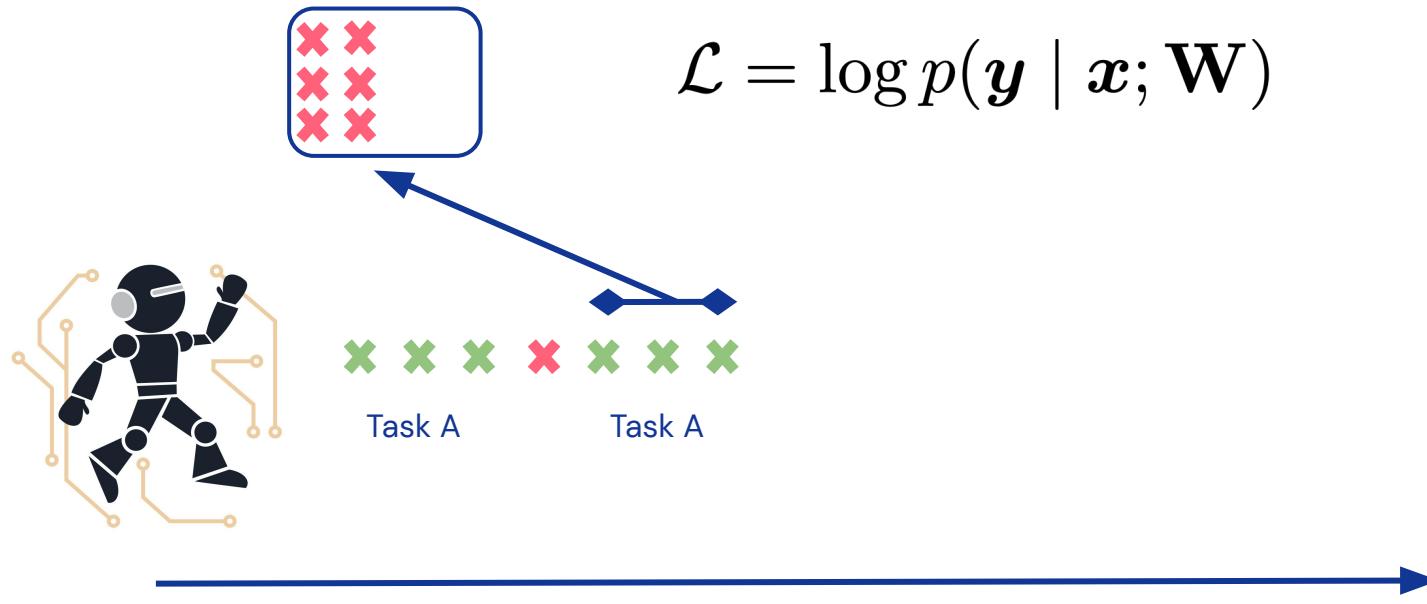
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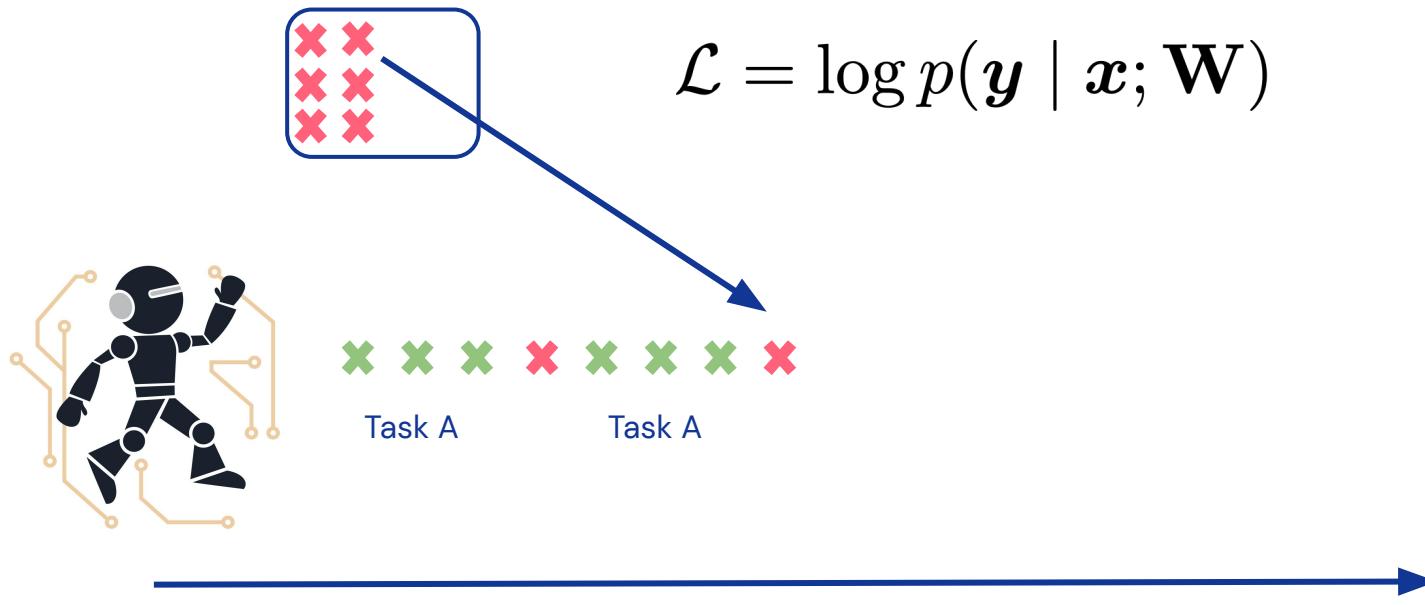
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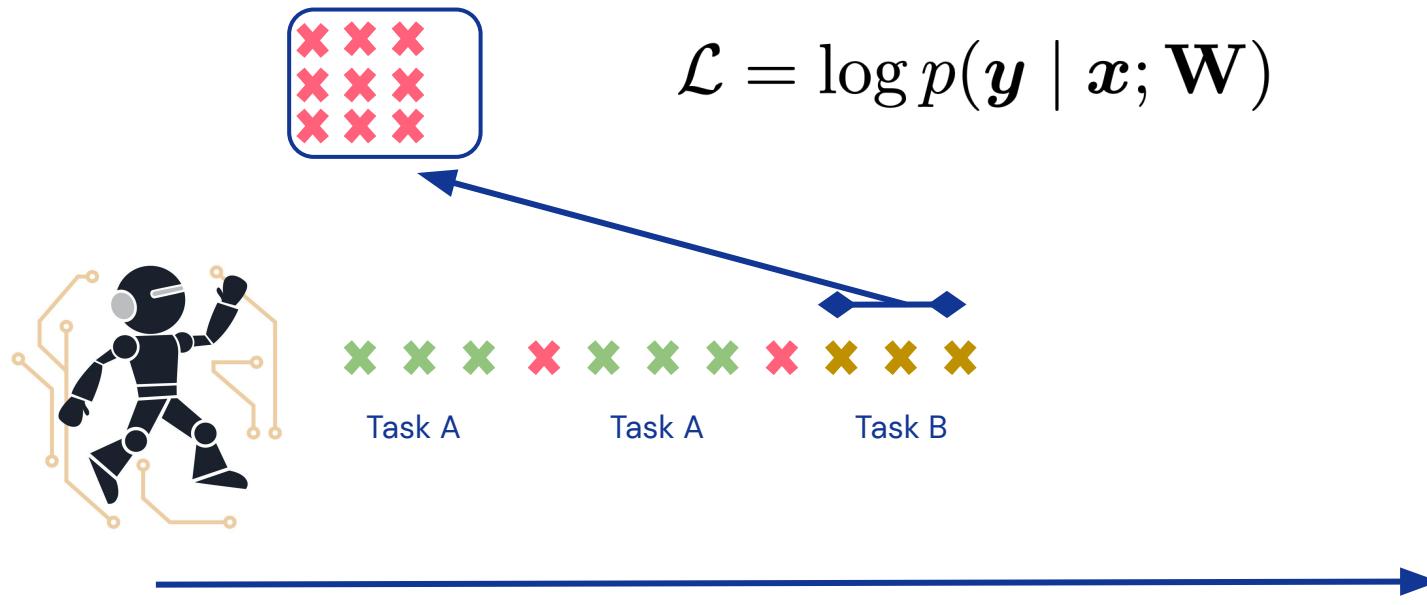
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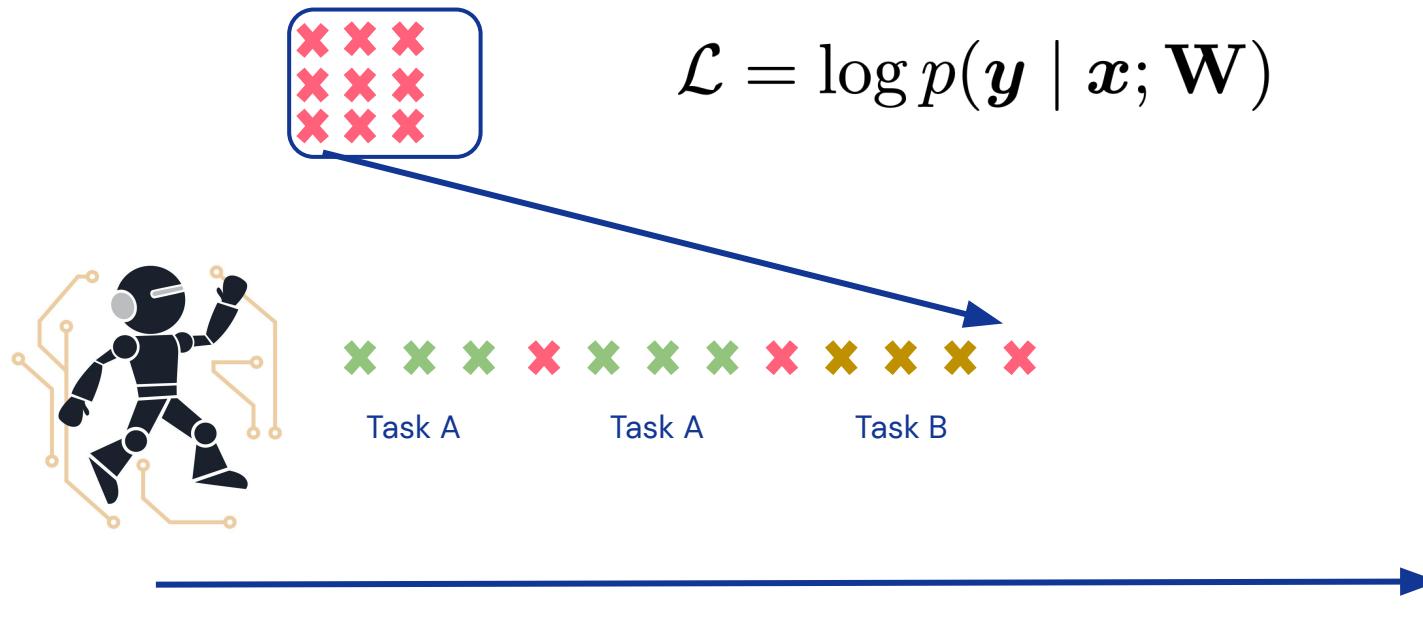
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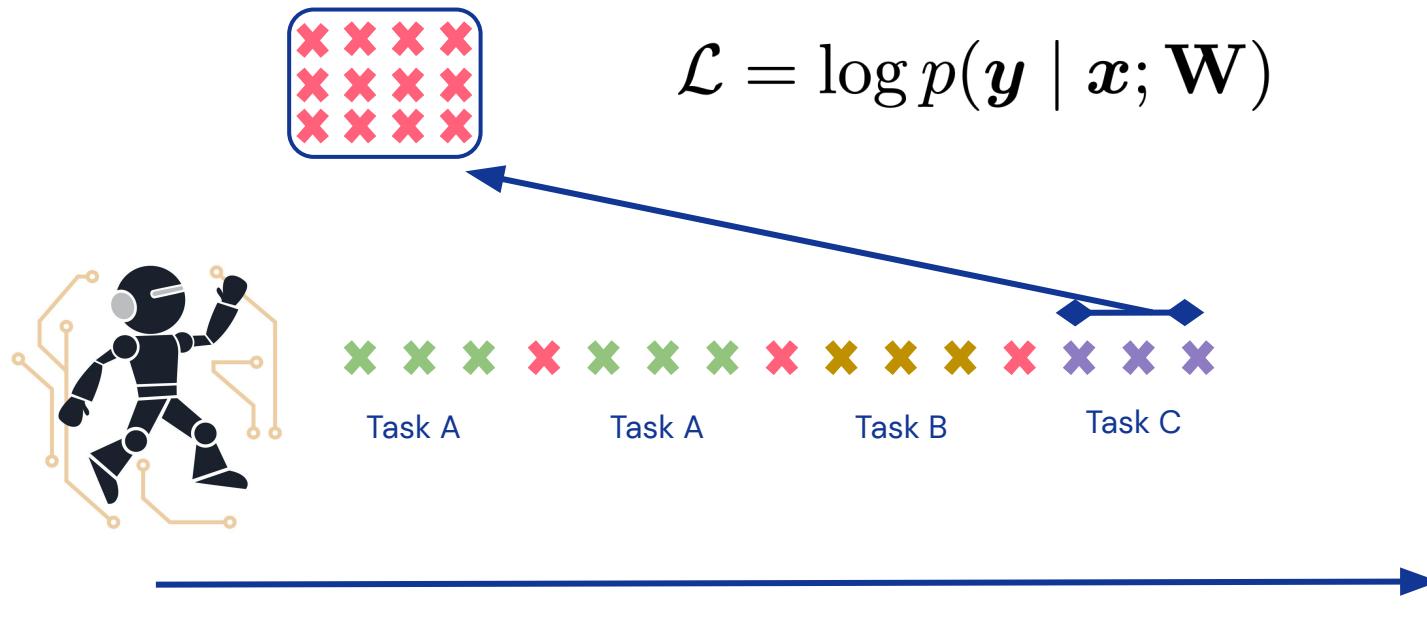
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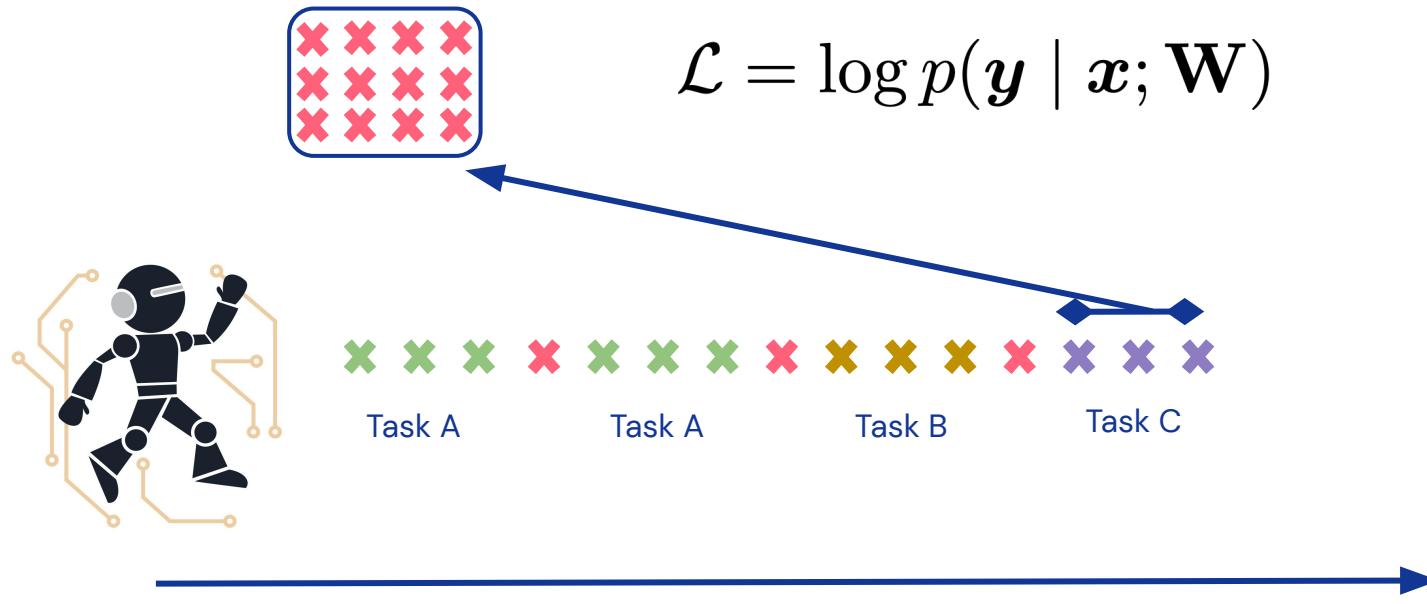
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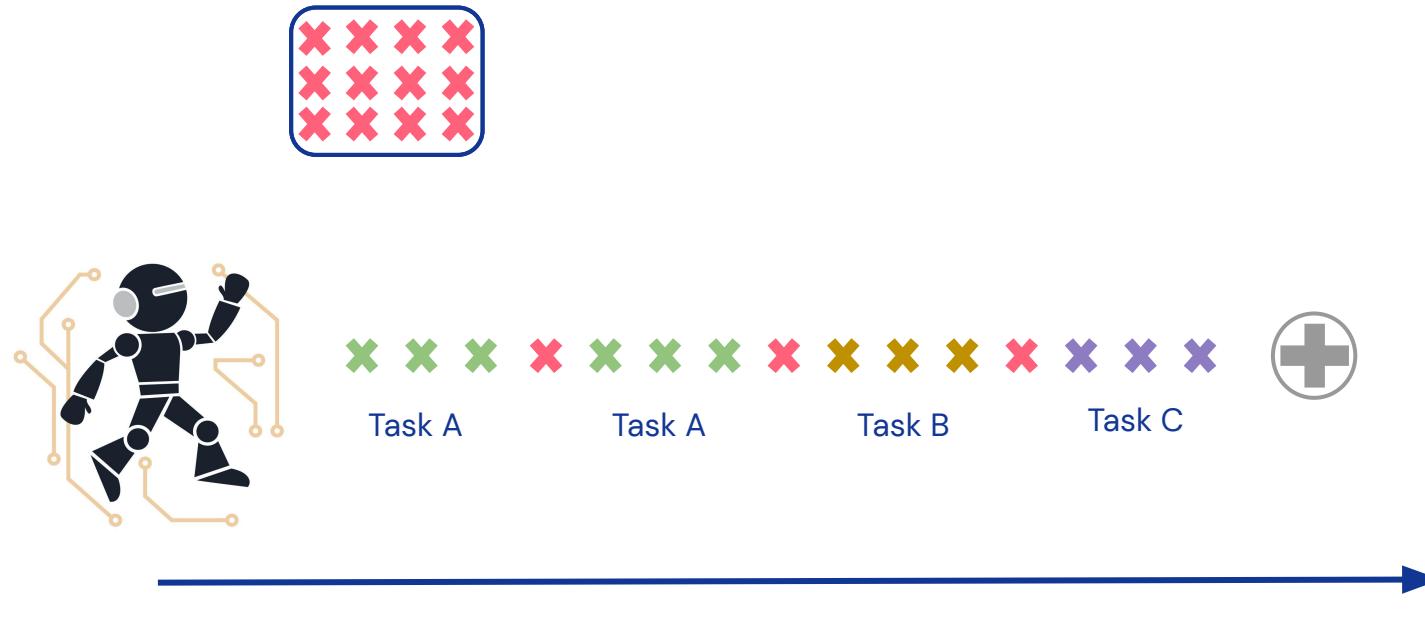
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Related to **memory consolidation** in human learning.



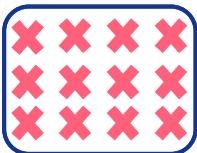
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Local adaptation similar to MbPA (Sprechmann et al., 2018).



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**Normans.** The Normans (Norman: Nourmands; French: Normands; Latin: Normanni) were the people who in the 10th and 11th centuries gave their name to Normandy, a region in France. [...]

In what country is Normandy located?



Task A

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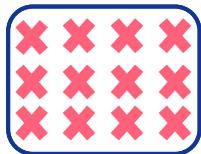
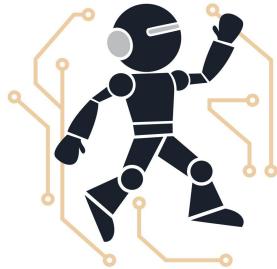
Task B

Task C



# Inference (Prediction)

Local adaptation similar to MbPA (Sprechmann et al., 2018).



K nearest  
neighbors  
retrieval

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**In what country is Normandy located?**

**In what area of France is Calais located?**

**In what country is St John's located?**

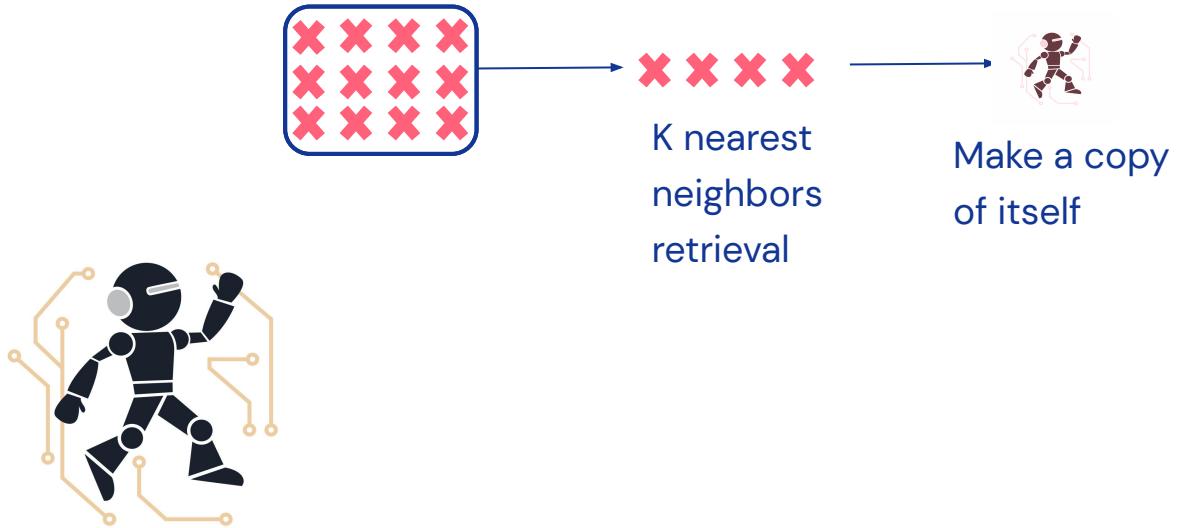
**In what country is Spoleto located?**

**In what part of Africa is Palermo located?**



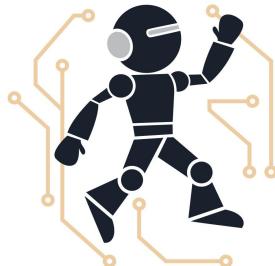
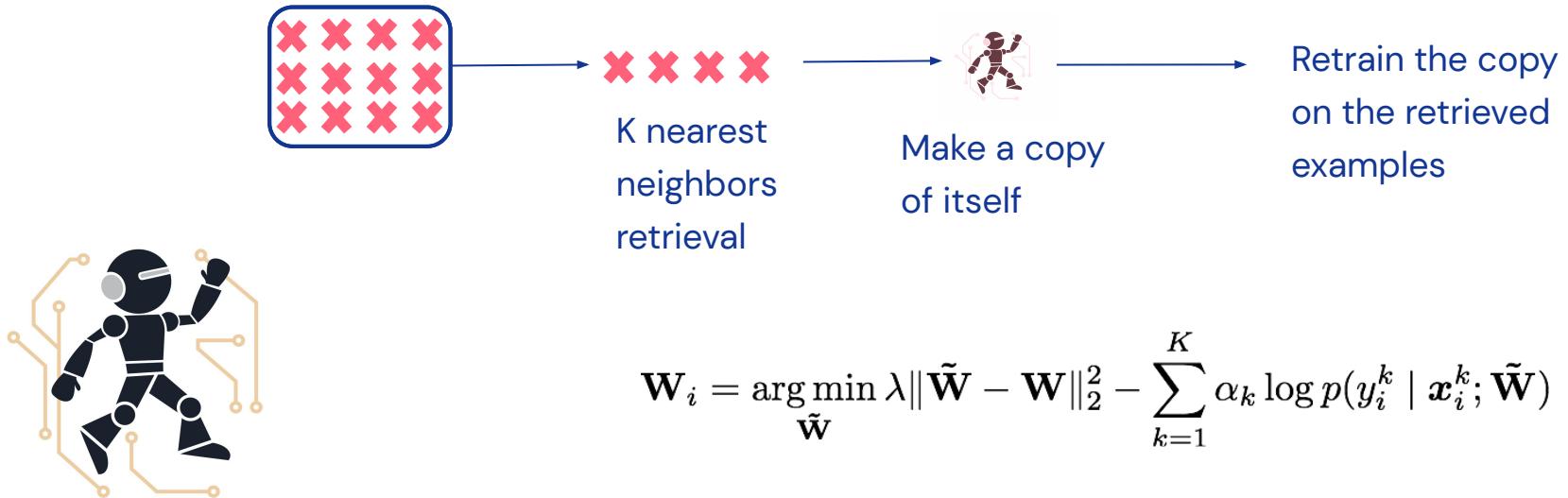
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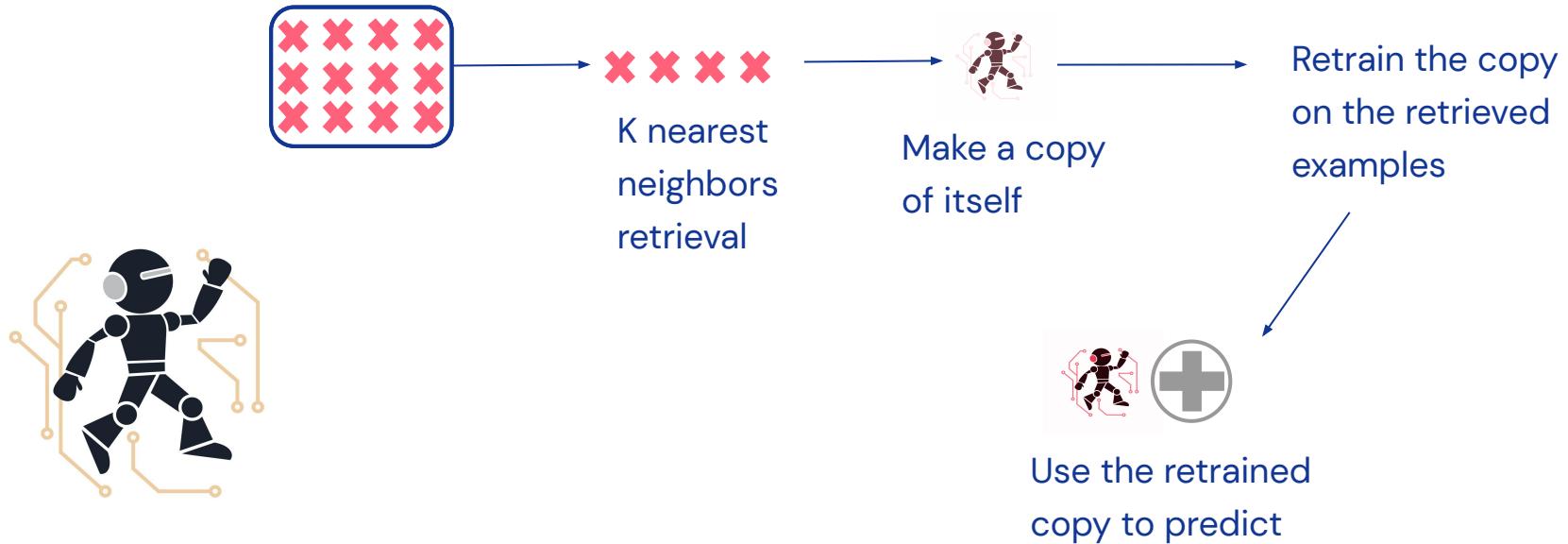


$$\mathbf{W}_i = \arg \min_{\tilde{\mathbf{W}}} \lambda \|\tilde{\mathbf{W}} - \mathbf{W}\|_2^2 - \sum_{k=1}^K \alpha_k \log p(y_i^k | x_i^k; \tilde{\mathbf{W}})$$



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Local adaptation similar to MbPA (Sprechmann et al., 2018).



# Experiments

- Four question answering datasets.
  - SQuAD: Rajpurkar et al., 2016.
  - TriviaQA-Web: Joshi et al., 2017.
  - TriviaQA-Wiki: Joshi et al., 2017.
  - QuAC: Choi et al., 2018.
- The contexts come from **different domains** (e.g., Wikipedia articles, web pages).
- The questions are posed in **different styles** (e.g., information seeking, trivia questions).



# Experiments

F1 scores (0-100), higher is better

	Enc-Dec	A-GEM	MbPA	Ours
QA	53.1	56.2	60.3	<b>62.4</b>

A-GEM: Chaudhry et al., 2019

MbPA: Sprechmann et al., 2018



# Takeaway and Limitation

- Episodic memory allows a language model to deal with changes in data distribution.



# Takeaway and Limitation

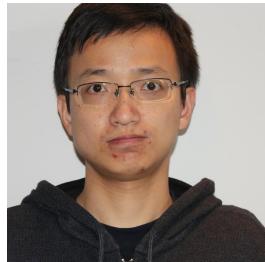
- Episodic memory allows a language model to deal with changes in data distribution.
- Linear **space complexity** in the number of examples, **constant** is more realistic.

% of stored examples in memory	10%	100%
Performance	61.5	62.0



# A Mutual Information Maximization Perspective of Language Representation Learning

Kong et al., ICLR 2020



Lingpeng



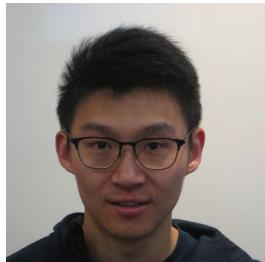
Cyprien



Wang



Lei



Zihang



Dani

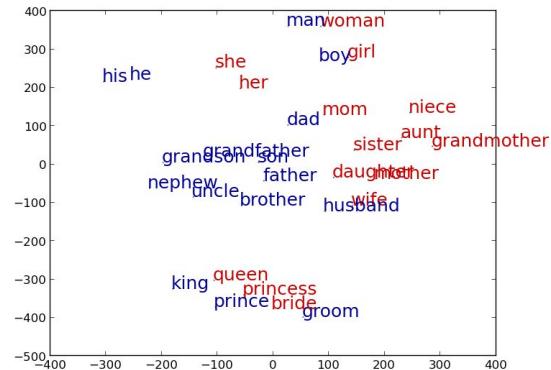


# Text Representations



<https://twitter.com/SmithaMilli/status/837153616116985856/>

Bag of words



Word embeddings

Skip gram, Mikolov et al., 2013.

GloVe, Pennington et al., 2014.



Contextual word embeddings

ELMo, Peters et al., 2018.

BERT, Devlin et al., 2019.

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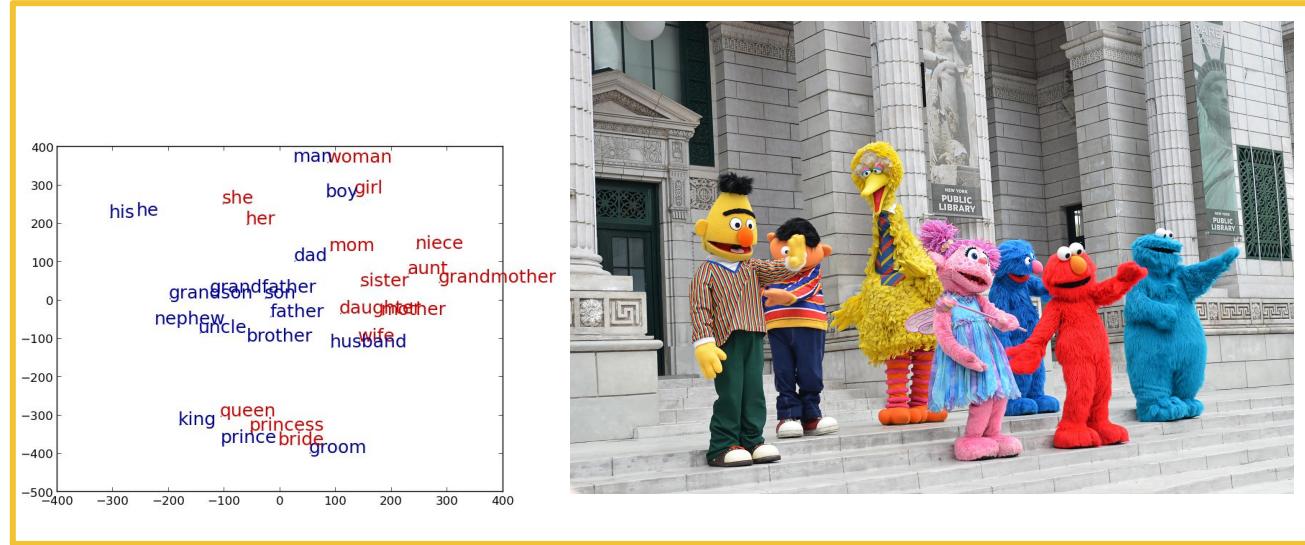


# Text Representations



[https://twitter.com/SmithaMilli/status/837153616116985856/](https://twitter.com/SmithaMilli/status/837153616116985856)

Bag of words



Hypothesis: these methods are different instances of one framework.

Word embeddings

Skip gram, Mikolov et al., 2013.

GloVe, Pennington et al., 2014.

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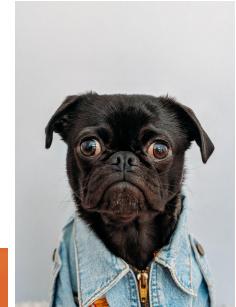
# Contrastive Learning

**Main assumption:** representations should capture similarity (Arora et al., 2019).



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**Main assumption:** representations should capture similarity (Arora et al., 2019).

Human learning is continual.

Advances in ML have driven progress in NLP.  
Logistic regression can be used for classification.  
Transformer uses self attention.

There are many direct flights between London and Tokyo.  
London Heathrow Terminal 5 is closed for maintenance.



# Contrastive Learning with InfoNCE

Main assumption: representations should capture similarity (Arora et al., 2019).

$$I(A, B) \geq \mathbb{E}_{p(A, B)} \left[ \mathbb{E}_{p(C)} \left[ \log \frac{\exp f_{\theta}(a, b)}{\exp f_{\theta}(a, b) + \sum_{c \neq b} \exp f_{\theta}(a, c)} \right] \right]$$

InfoNCE objective  
Logeswaran and Lee, 2018  
van den Oord, et al., 2019

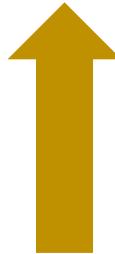
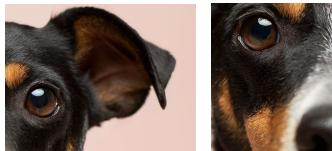


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High when **a** and **b** go together

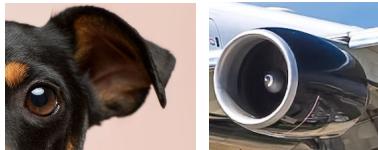


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InfoNCE objective  
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van den Oord, et al., 2019



Low when **a** and **c** do not go together



# Contrastive Learning with InfoNCE

$$\mathbb{E}_{p(A,B)} \left[ \mathbb{E}_{p(C)} \left[ \log \frac{\exp f_{\theta}(a,b)}{\exp f_{\theta}(a,b) + \sum_{c \neq b} \exp f_{\theta}(a,c)} \right] \right]$$

Harvard University is located in Cambridge



# Contrastive Learning with InfoNCE

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*a*  
Harvard University is *b* located in Cambridge



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Harvard University is located in Cambridge



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*a*  
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Cambridge



# Contrastive Learning with InfoNCE

$$\mathbb{E}_{p(A,B)} \left[ \mathbb{E}_{p(C)} \left[ \log \frac{\exp[f_{\theta}(a,b)]}{\exp[f_{\theta}(a,b)] + \sum_{c \neq b} \exp f_{\theta}(a,c)} \right] \right]$$

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Harvard University is located in Cambridge

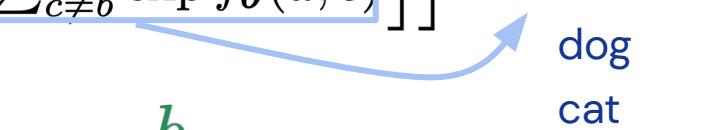
$$f_{\theta}(a,b) = g_{\psi}(b)^{\top} g_{\omega}(a)$$



# Contrastive Learning with InfoNCE

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*a*                            *b*  
Harvard University is located in Cambridge

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# Skip-gram

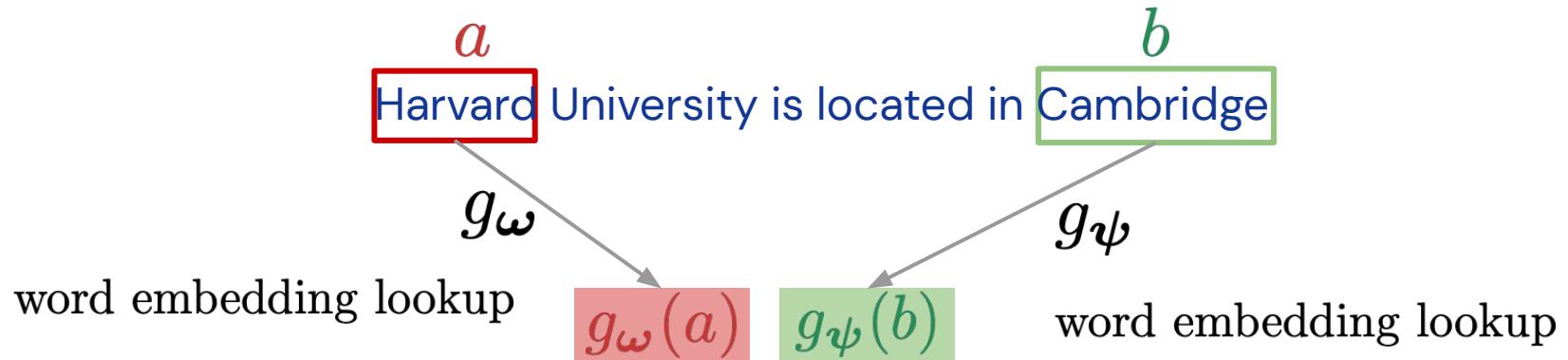
Mikolov et al., 2013

Harvard University is located in Cambridge



# Skip-gram

Mikolov et al., 2013



# BERT

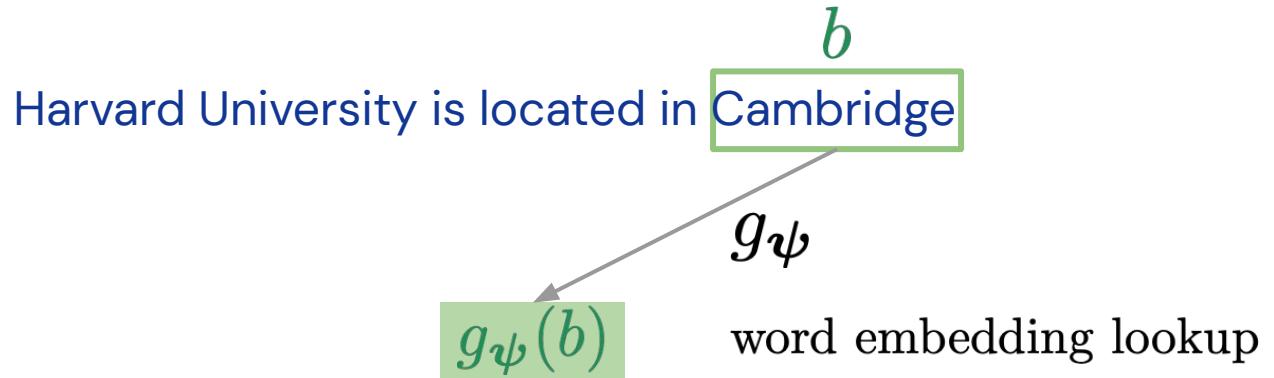
Devlin et al., 2019

Harvard University is located in Cambridge



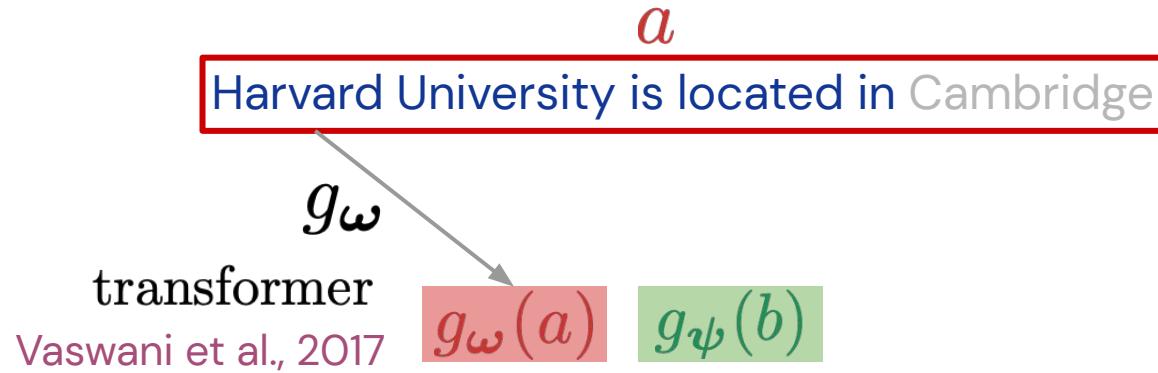
# BERT

Devlin et al., 2019



# BERT

Devlin et al., 2019



# Why is this interesting?

- A framework that unifies classical and modern word embedding methods.

		$a$	$b$	$g_\omega$	$g_\psi$
Mikolov et al., 2013	<b>Skip-gram</b>	word	word	lookup	lookup
Devlin et al., 2019	<b>BERT</b>	context	word	transformer	lookup
Yang et al., 2019	<b>XLNet</b>	context	word	TXL++	lookup



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- Provides connections to methods used in other domains (vision, speech).



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- Provides connections to methods used in other domains (vision, speech).
- Facilitates exchanges of ideas on how to improve representation learning models.



# Model

Deep InfoMax (DIM; Hjelm et al., 2019)



# Model

Deep InfoMax (DIM; Hjelm et al., 2019)



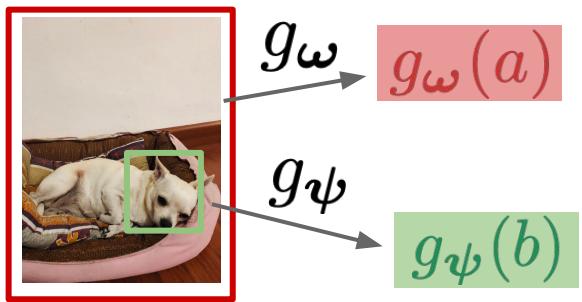
$g_{\omega}$

$g_{\omega}(a)$



# Model

Deep InfoMax (DIM; Hjelm et al., 2019)



# Model

Deep InfoMax (DIM; Hjelm et al., 2019)

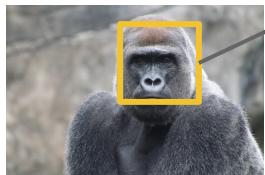


$$g_{\omega} \rightarrow g_{\omega}(a)$$

$$g_{\psi} \rightarrow g_{\psi}(b)$$



$$g_{\psi} \rightarrow g_{\psi}(c_1)$$



$$g_{\psi} \rightarrow g_{\psi}(c_2)$$



# Model

Deep InfoMax (DIM; Hjelm et al., 2019)



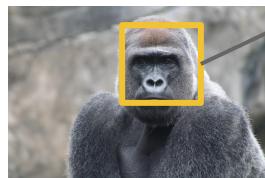
$$g_{\omega} \rightarrow g_{\omega}(a)$$

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$$g_{\psi} \rightarrow g_{\psi}(c_1)$$

$$g_{\psi} \rightarrow g_{\psi}(c_2)$$



$$\mathcal{I}_{\text{DIM}} = \mathbb{E}_{p(A, B)} \left[ \mathbb{E}_{p(C)} \left[ \log \frac{\exp[g_{\omega}(a)^\top g_{\psi}(b)]}{\exp[g_{\omega}(a)^\top g_{\psi}(b)] + \sum_{c \neq b} \exp[g_{\omega}(a)^\top g_{\psi}(c)]} \right] \right]$$



# Model

Deep InfoMax (DIM; Hjelm et al., 2019)



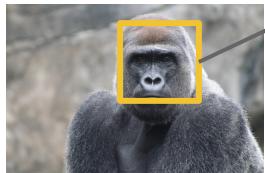
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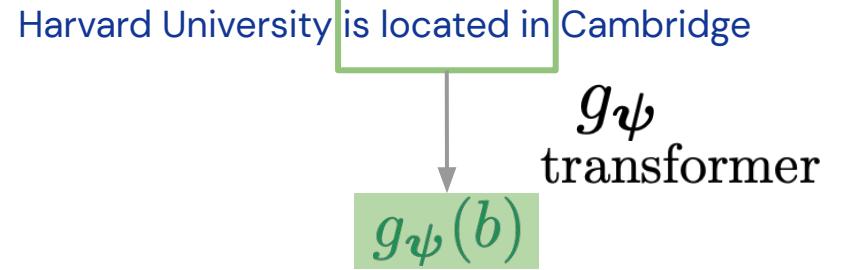
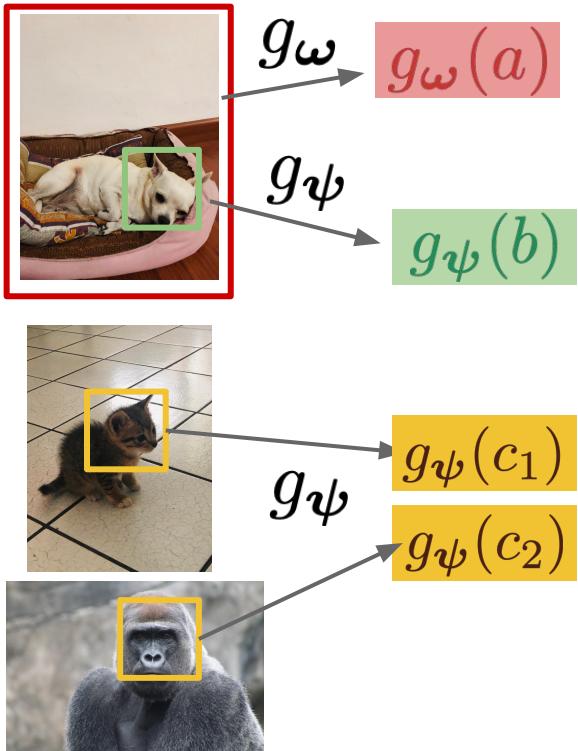


Harvard University is located in Cambridge



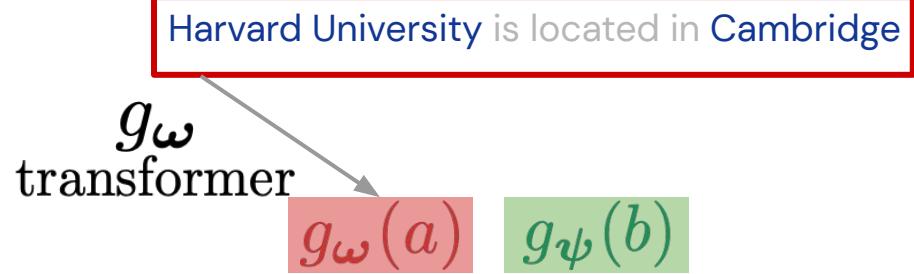
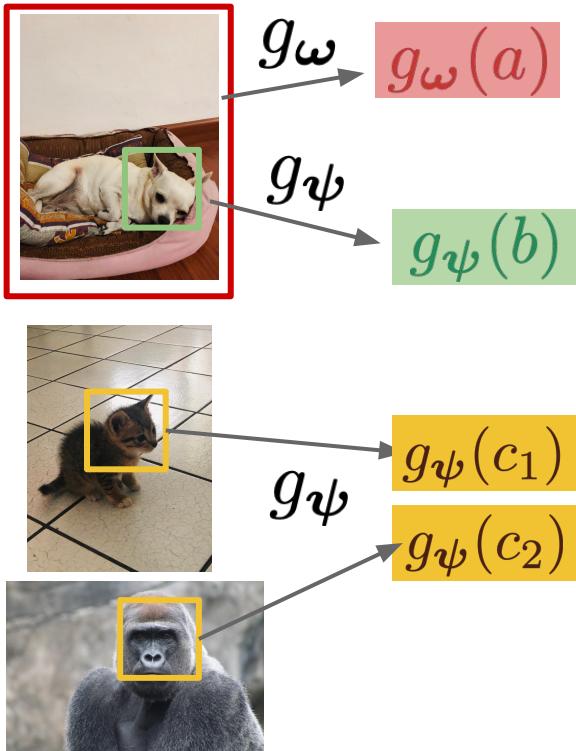
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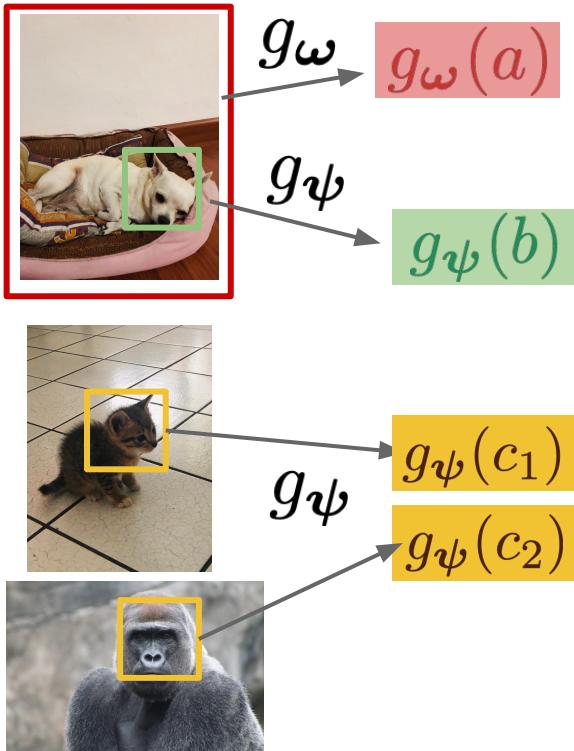
# Model

Deep InfoMax (DIM; Hjelm et al., 2019)



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Deep InfoMax (DIM; Hjelm et al., 2019)



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$$g_{\omega}(a) \quad g_{\psi}(b)$$

Starcraft II is a fun game

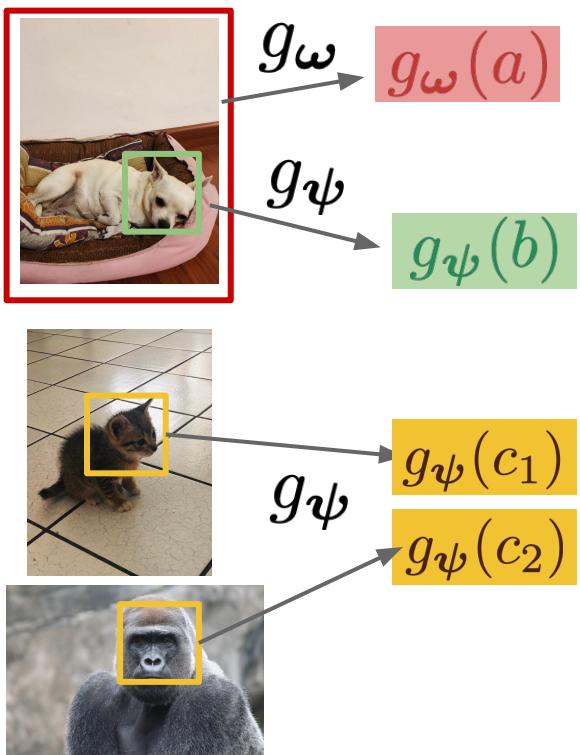
Cristiano Ronaldo scores an own goal

Machine learning is transforming drug discovery



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Deep InfoMax (DIM; Hjelm et al., 2019)



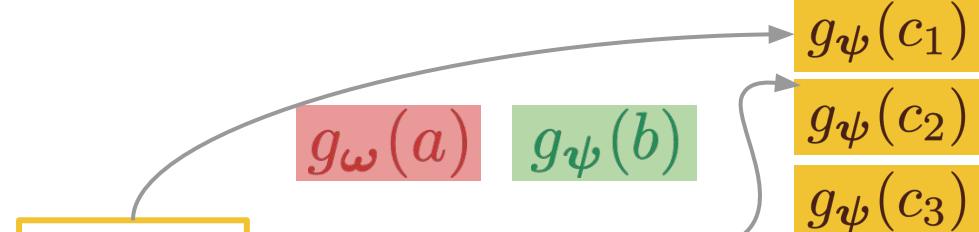
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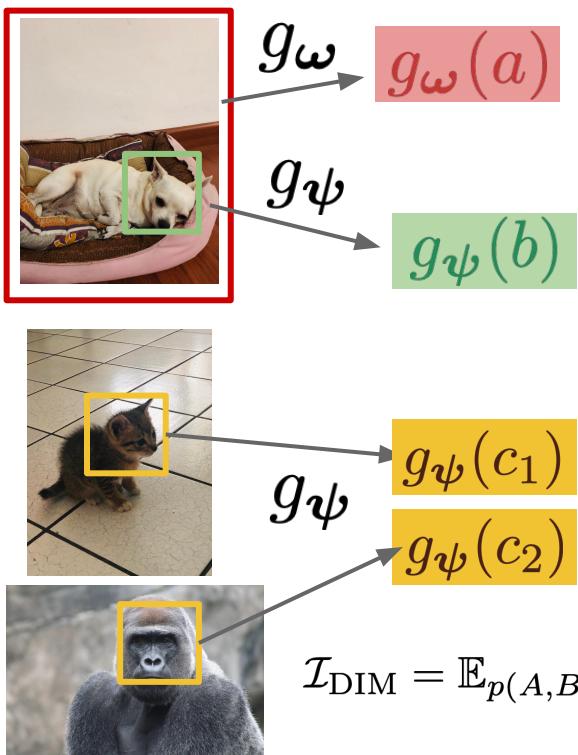
Machine learning is transforming drug discovery

$g_\psi$  transformer



# Model

Deep InfoMax (DIM; Hjelm et al., 2019)



# Experiments

Question answering on SQuAD (Rajpurkar et al., 2016).

		F1
Small Model	BERT	90.9
	Ours	91.4
Large Model	BERT	92.7
	Ours	93.1

F1 scores (0-100), higher is better.

BERT: Devlin et al., 2019.

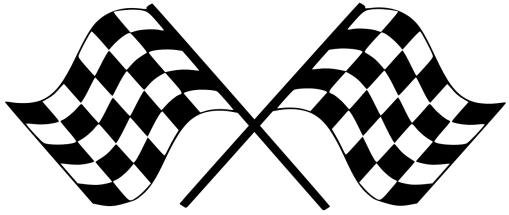


# Takeaways

- Progress in language representation learning has largely been driven by advances in model architectures.
- It is possible to transfer ideas across domains when designing self-supervised tasks.



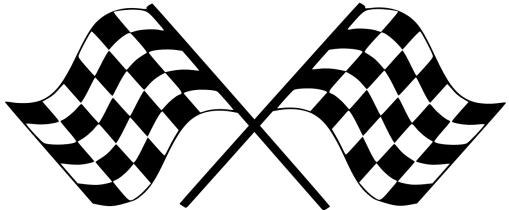
# Future Directions



A language model that continually learns in an efficient way to perform multiple complex tasks in many languages.



# Future Directions

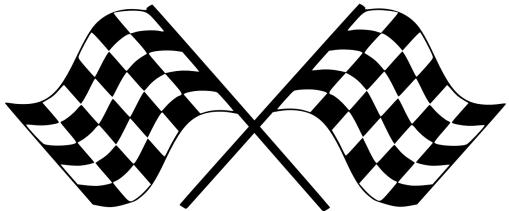


A language model that continually learns in an efficient way to perform multiple complex tasks in many languages.

**Generative Models**



# Future Directions



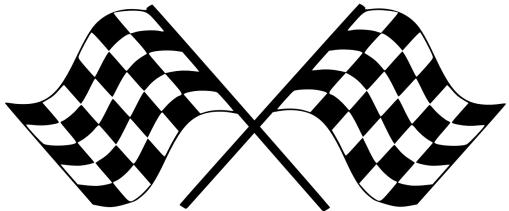
A language model that continually learns **in an efficient way** to perform **multiple complex tasks** in many languages.



**Generative Models**



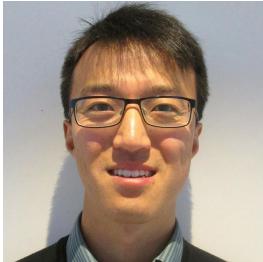
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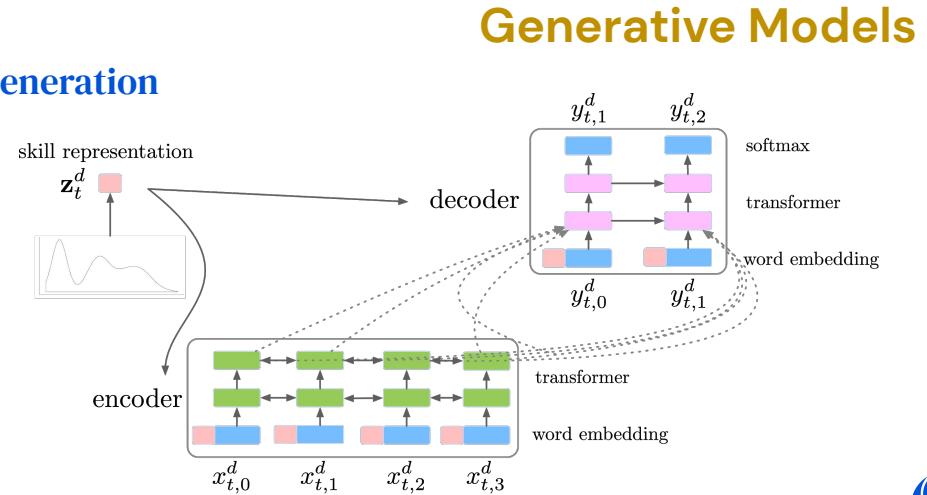
## Modelling Latent Skills for Multitask Language Generation

Cao and Yogatama, arXiv 2020

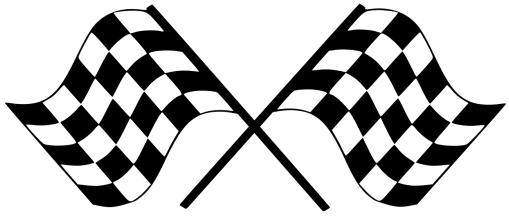


Kris

Dani



# Future Directions

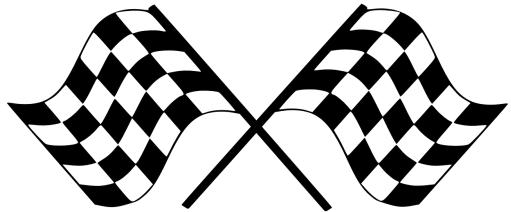


A language model that continually learns in an efficient way to perform multiple complex tasks in many languages.

Memory

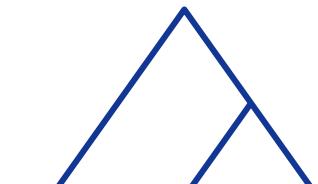


# Future Directions



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## Memory



ML is fun



Working

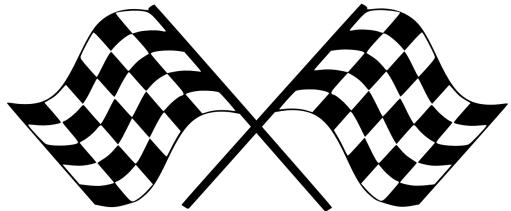
Procedural

Semantic

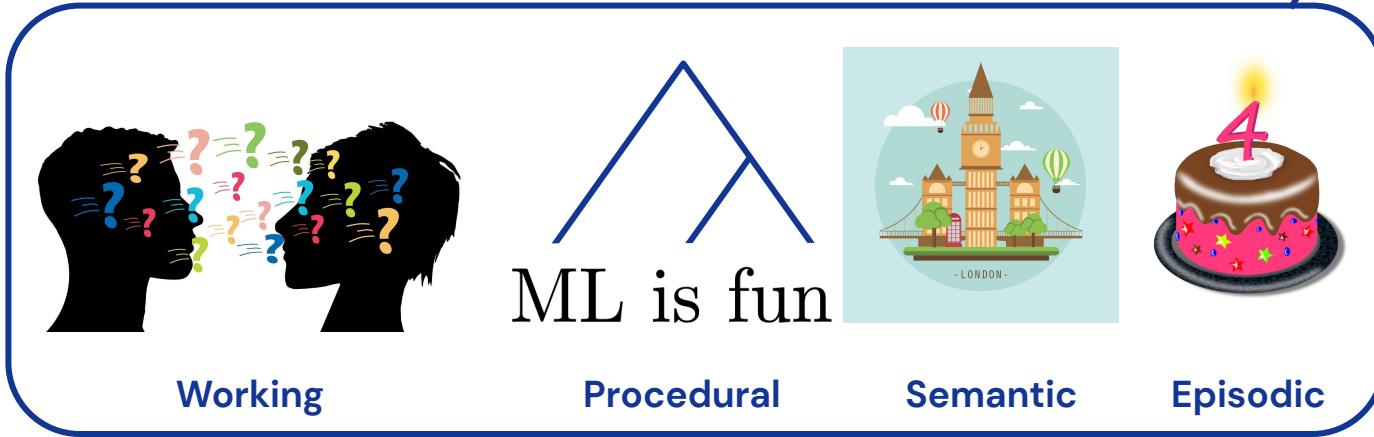
Episodic



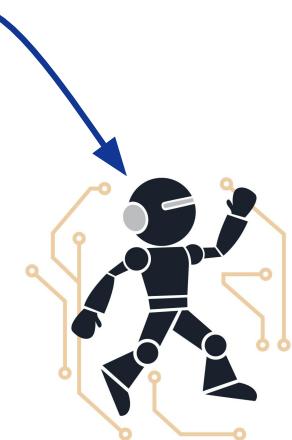
# Future Directions



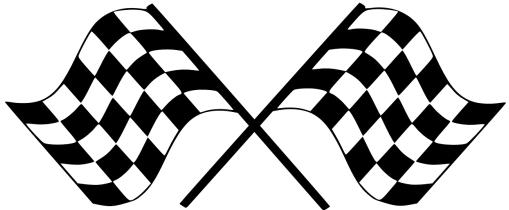
Memory



A language model that continually learns in an efficient way to perform multiple complex tasks in many languages.



# Future Directions

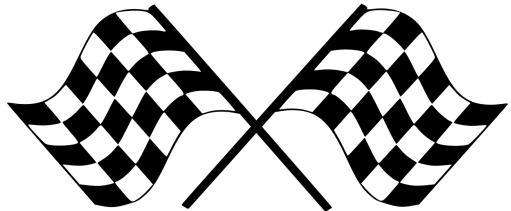


A language model that continually **learns** in an efficient way to perform multiple complex tasks in **many** languages.

## Representation Learning

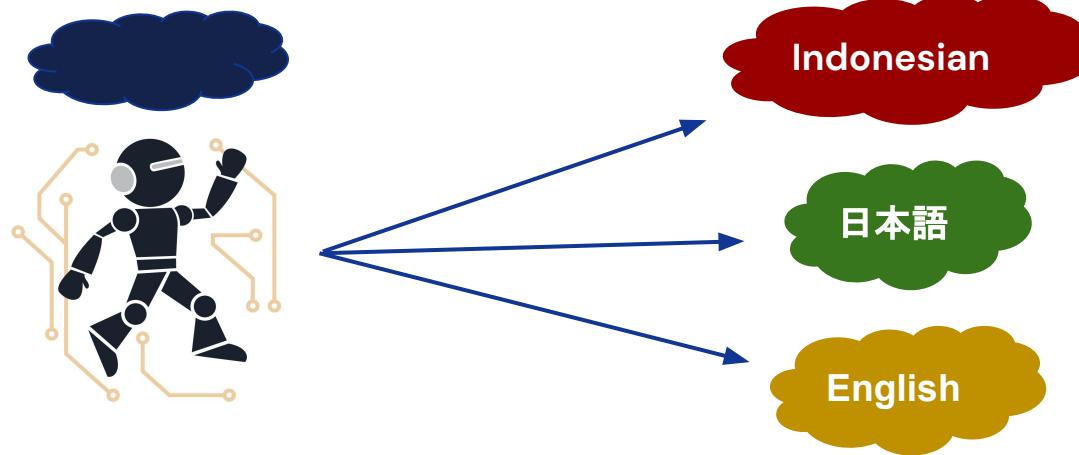


# Future Directions

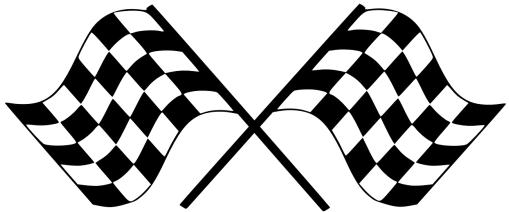


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## Representation Learning



# Future Directions

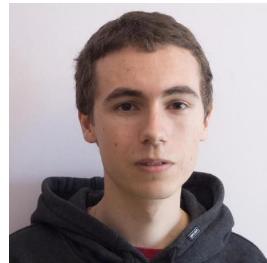


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## Representation Learning

### On the Crosslingual Transferability of Monolingual Representations

Artetxe et al., arXiv 2019



Mikel



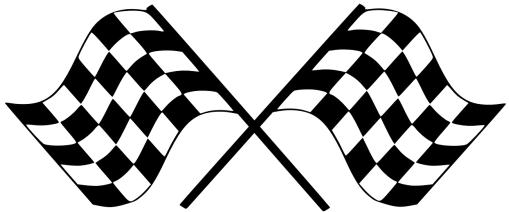
Sebastian



Dani



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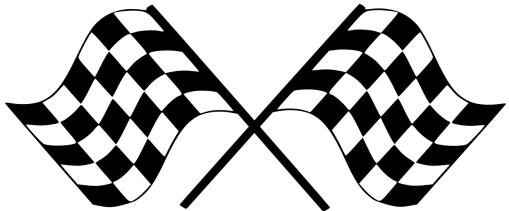
Memory

Representation Learning

Generative Models



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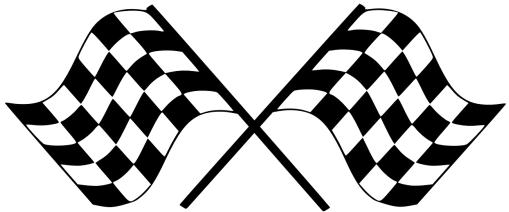
Memory

Representation Learning

Generative Models



# Future Directions

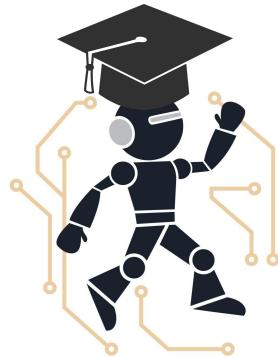


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Memory

Representation Learning

Generative Models



tack ՀԱՌԻԱԿԱԼՈՒԹՅՈՒՆ Danke  
ありがとうございました Salamat  
**grazie** **Thank you** multumesc  
ধন্যবাদ **Thank you** ଧନ୍ୟର୍ଥି  
Terima kasih Dankie 감사합니다 Merci  
Спасибо مکارکش σας ευχαριστώ  
teşekkür ederim 谢谢 cảm ơn bạn

<https://dyogatama.github.io>  
dyogatama@google.com