

Toward General Linguistic Intelligence

Dani Yogatama

Language and Intelligence

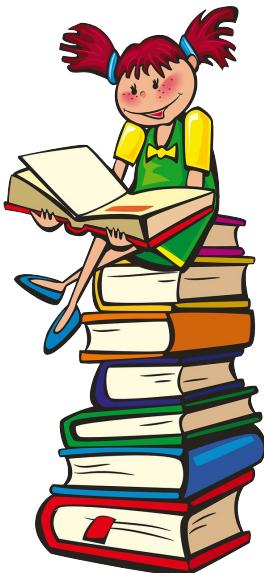
A uniquely human ability that is a **core component** of our **intelligence**,
independent of the **surface forms** it manifests in (Hockett, 1960).

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

A **mechanism** with which we formulate our thought process.

(Language for thinking; Spelke, 2003)



Language and Intelligence

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



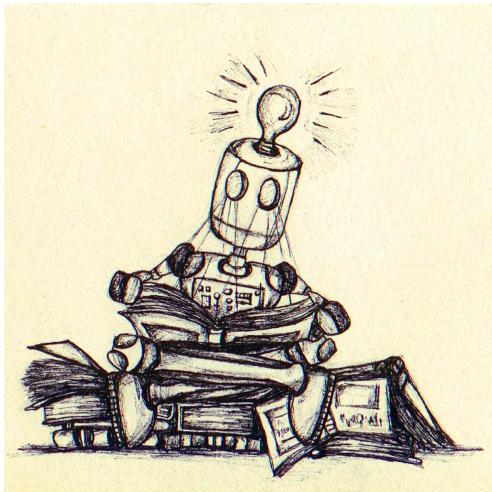
General Linguistic Intelligence

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.



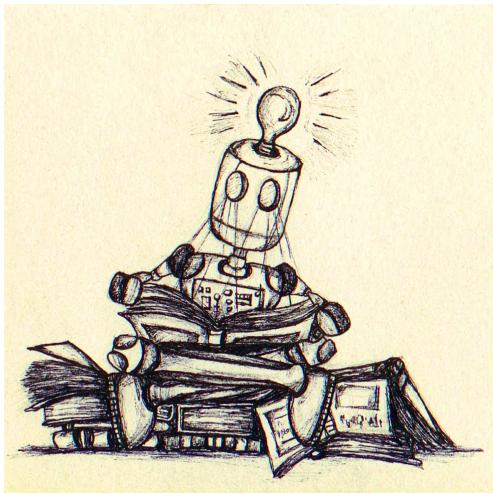
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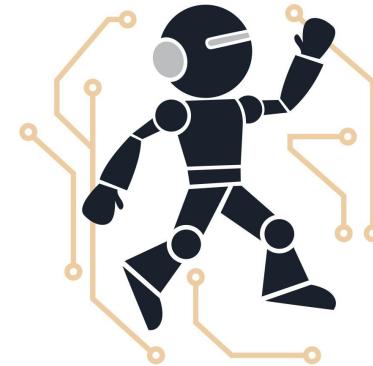
Challenges: Human Learning vs. Machine Learning



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



Challenges: Human Learning vs. Machine Learning

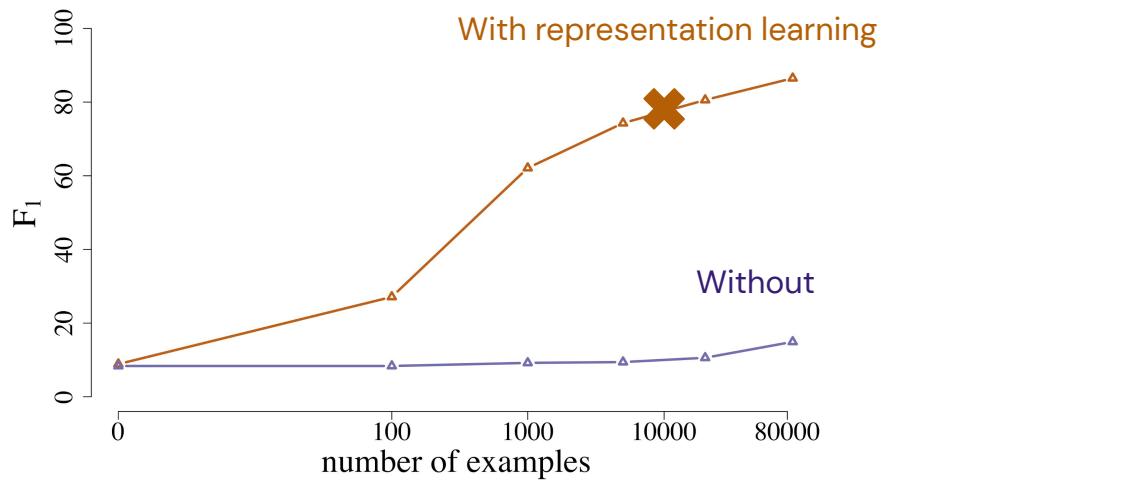


Human		Machine
“Large” datasets	Acquisition	Large datasets (representation learning)
Few examples	Task Training	Large datasets (supervised fine tuning)
Dataset agnostic	Linguistic knowledge	Dataset specific
Generalizable to new tasks	Generalization	Forget previous tasks given a new task



The State of Natural Language Processing

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



Model: BERT, Devlin et al. 2019

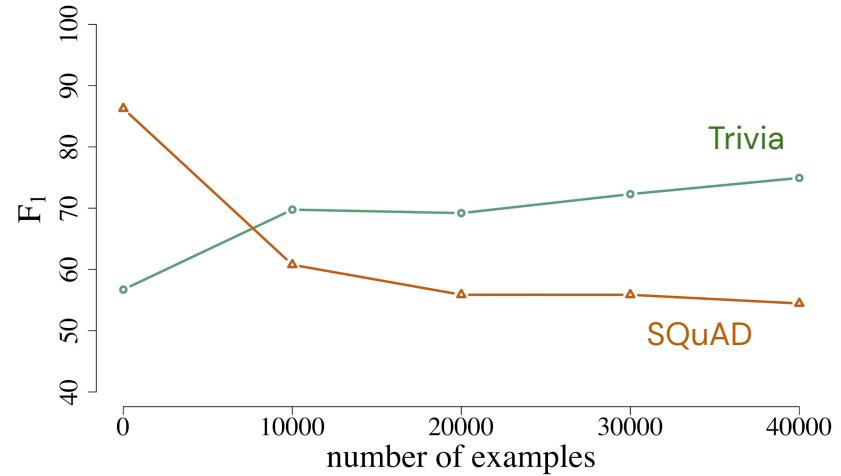
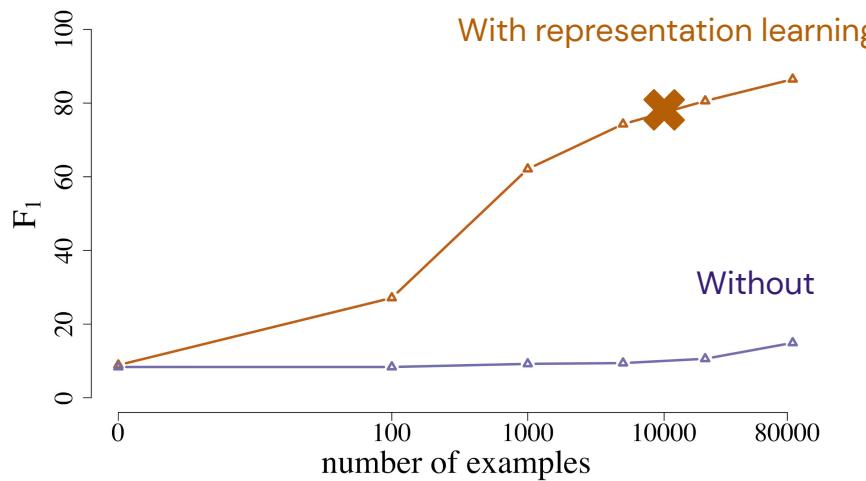
QA dataset: SQuAD, Rajpurkar et al., 2016

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

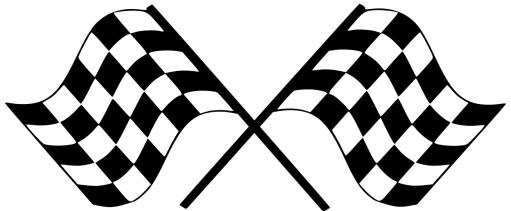
Model: BERT, Devlin et al. 2019

QA dataset: SQuAD, Rajpurkar et al., 2016

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



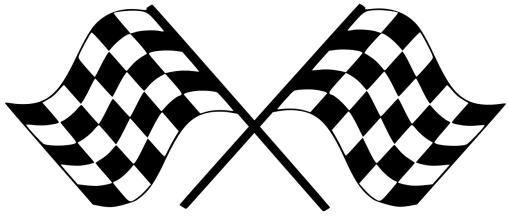
Research Areas



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

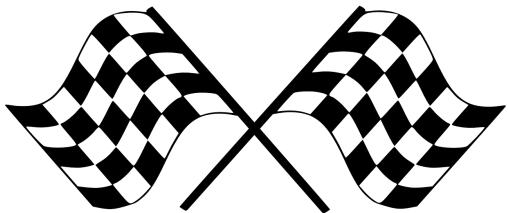
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Representation Learning

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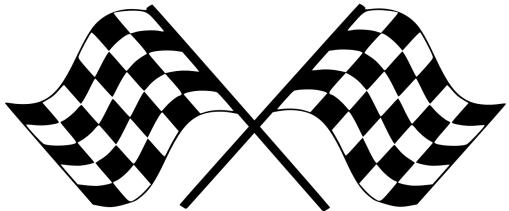
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Generative Models

Yogatama et al., TACL 2014

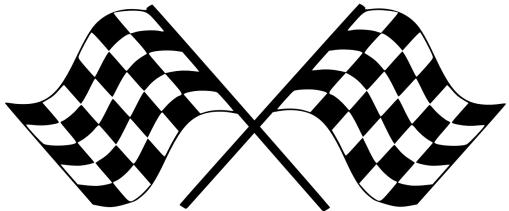
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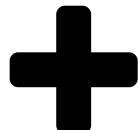
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Reasoning, interactions with other modalities,
robustness, fairness, and others.



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

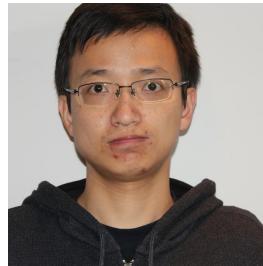
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Cyprien



Sebastian



Lingpeng



Dani



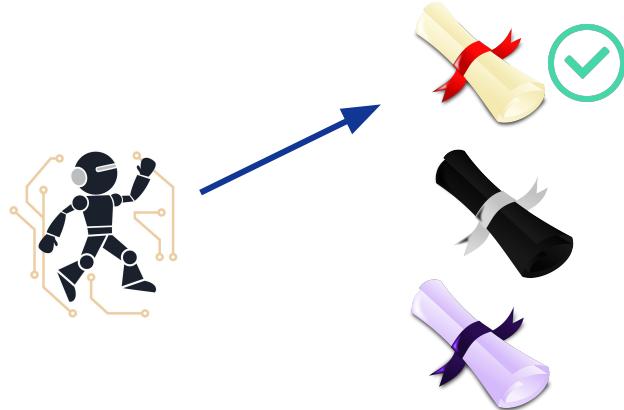
Background

- 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).



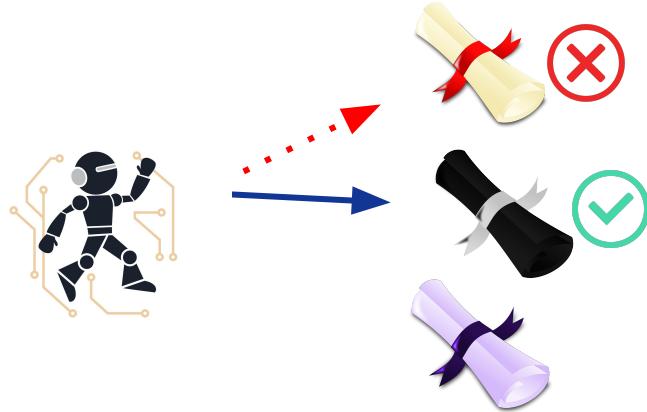
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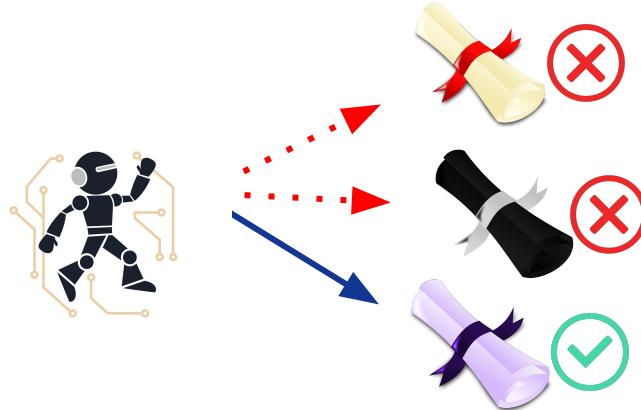
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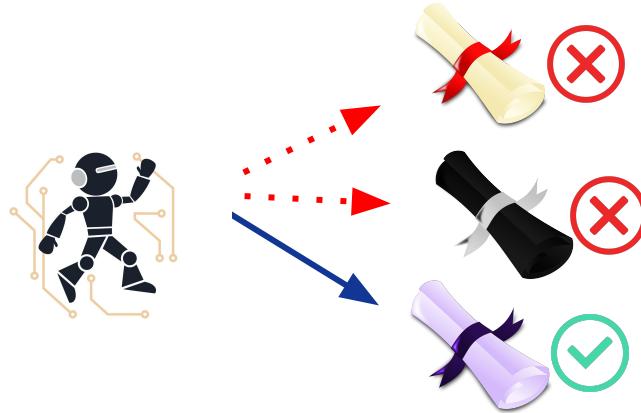
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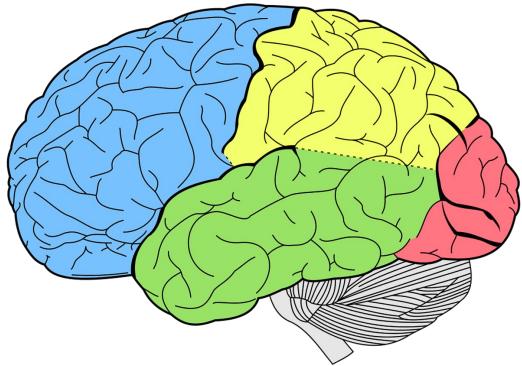
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Hypothesis: episodic memory mitigates catastrophic forgetting in language learning.



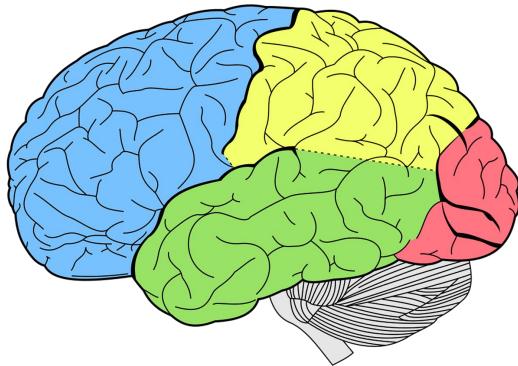
On Memory-Augmented Neural Networks



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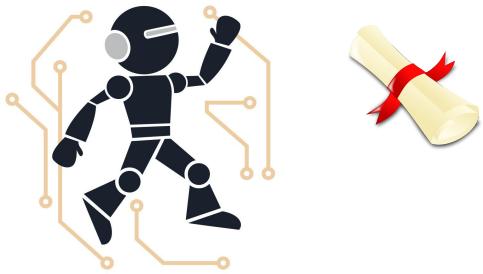
Contrast this with short-term **working memory** in LSTMs (Hochreiter and Schmidhuber, 1997) and DNCs (Graves et al., 2016) that e.g., remembers context.

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



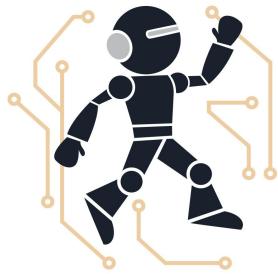
SQuAD: Rajpurkar et al., 2016

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 [...]

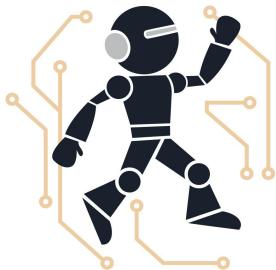
Was he known for being intelligent? No, Pinochet was publicly known as a man with a lack of culture.

Why did people feel that way?



Problem Setup

Training

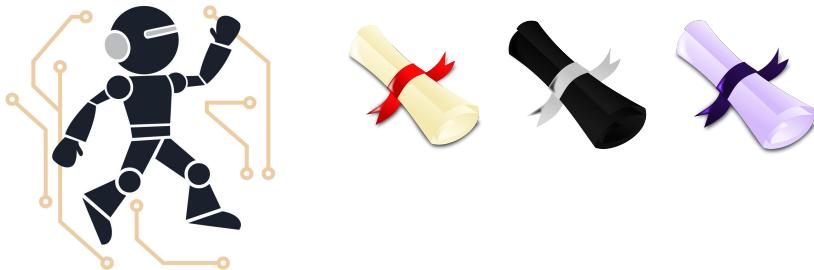


Test



Problem Setup

Training



Test

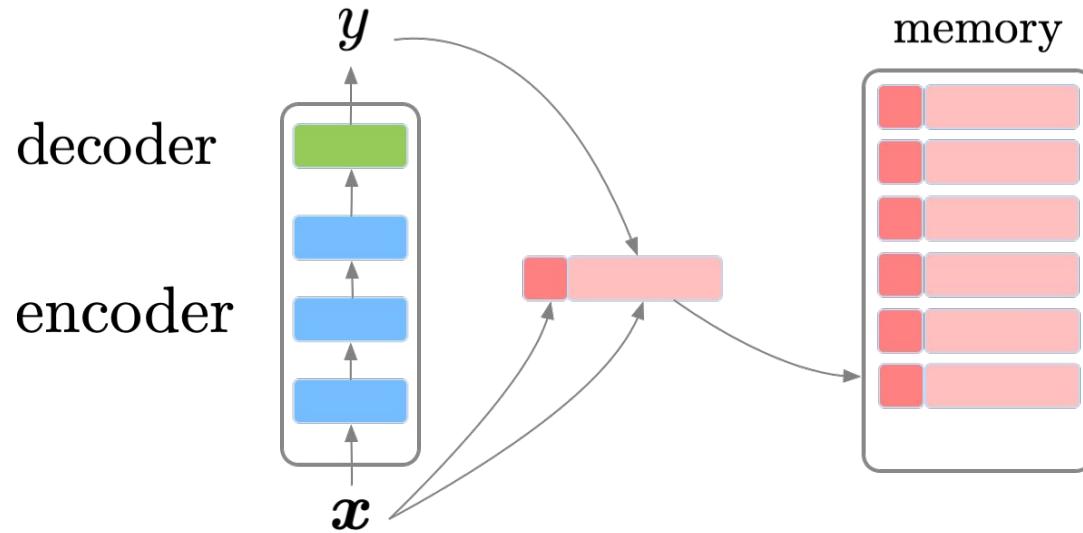


Never-Ending Language Learning

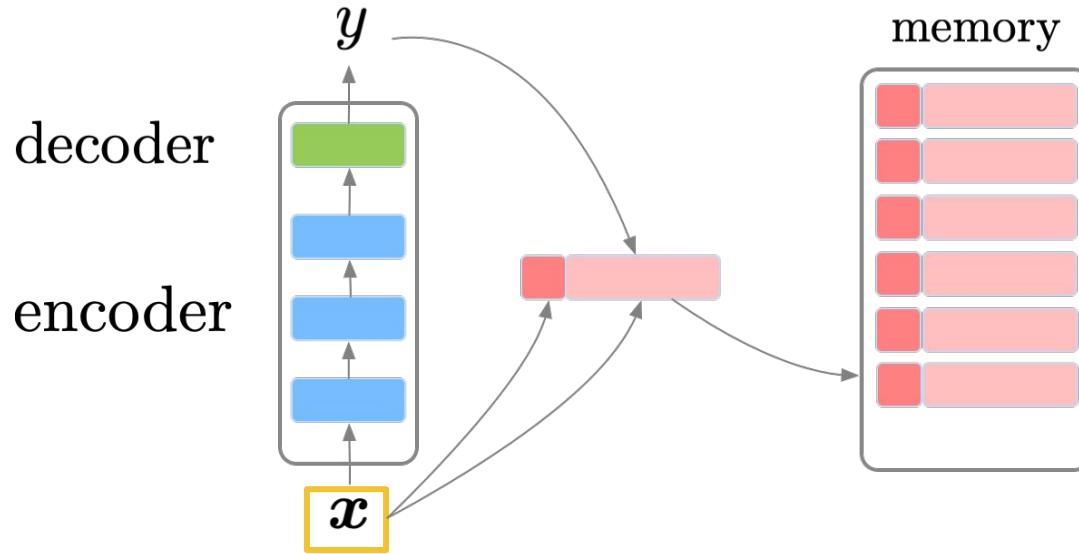
Mitchell et al., 2015



Question Answering Model



Question Answering Model

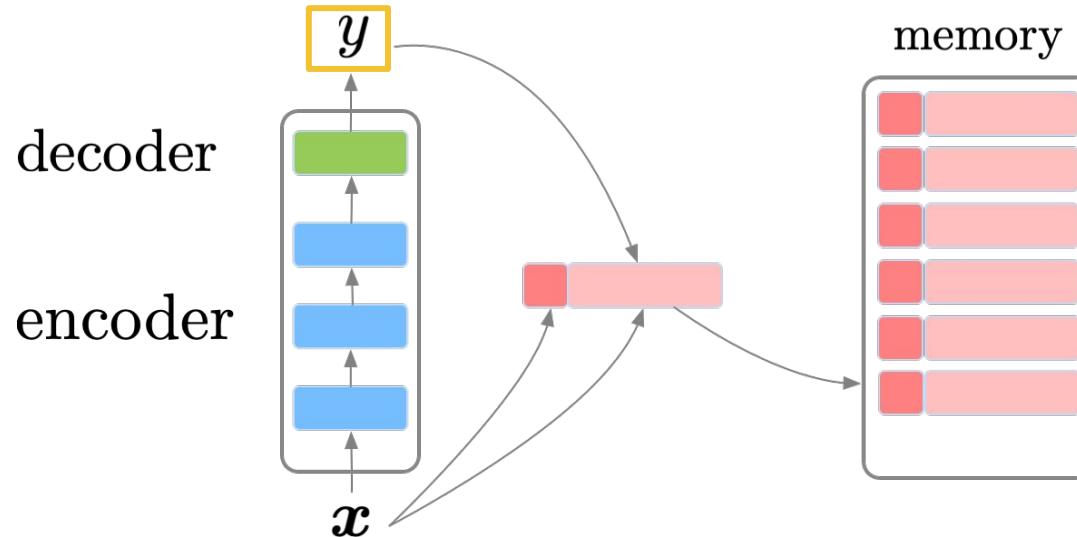


Input: a concatenation of a context (e.g., a Wikipedia article) and a question.



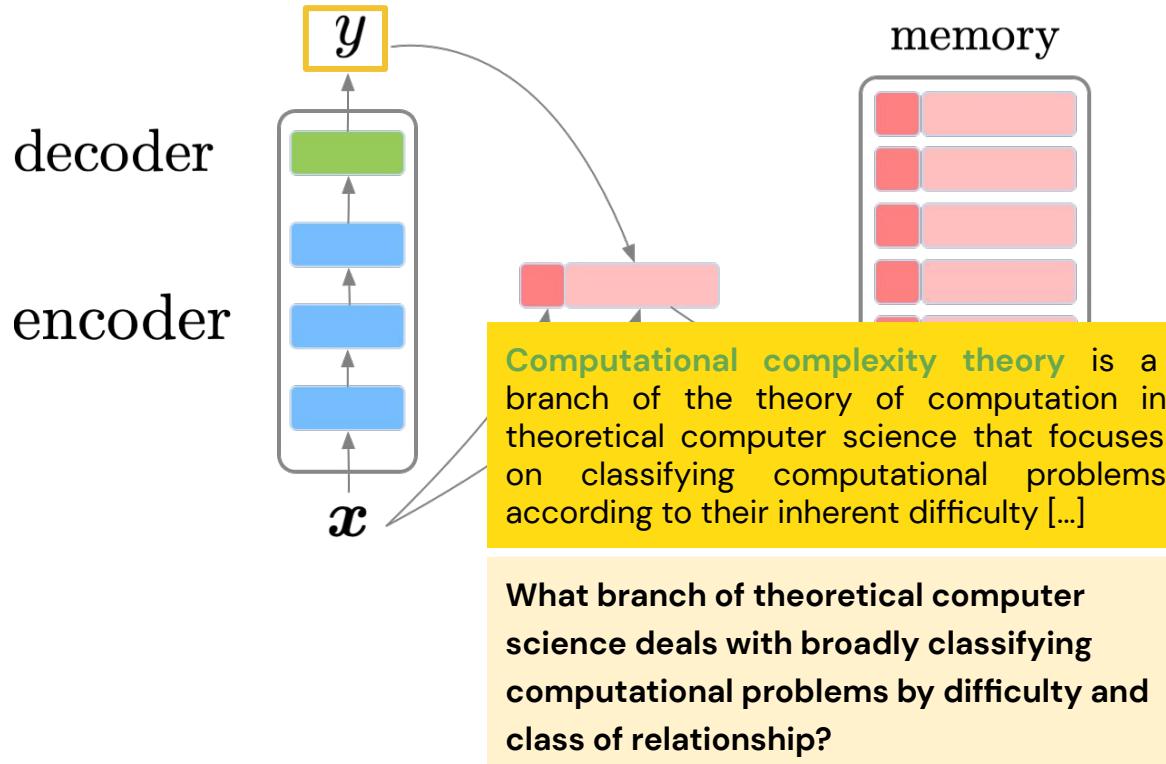
Question Answering Model

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

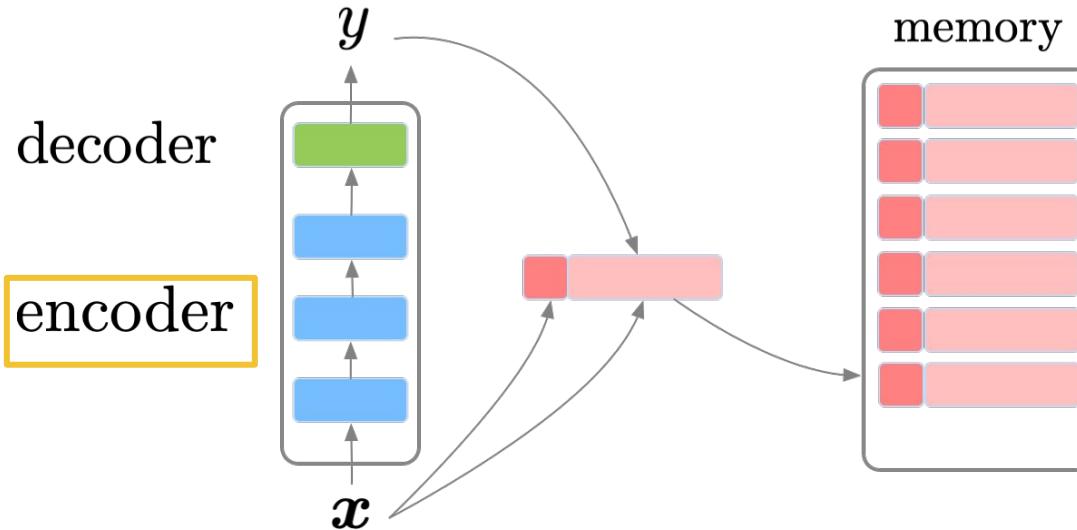


Question Answering Model

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



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).

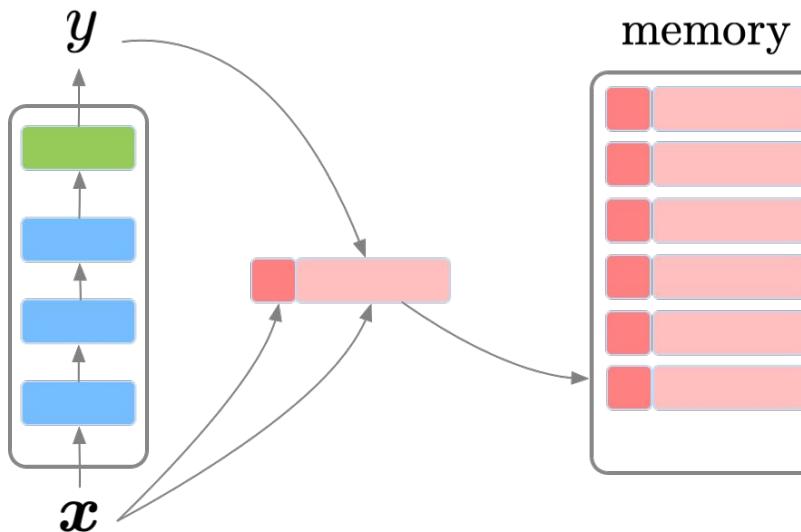


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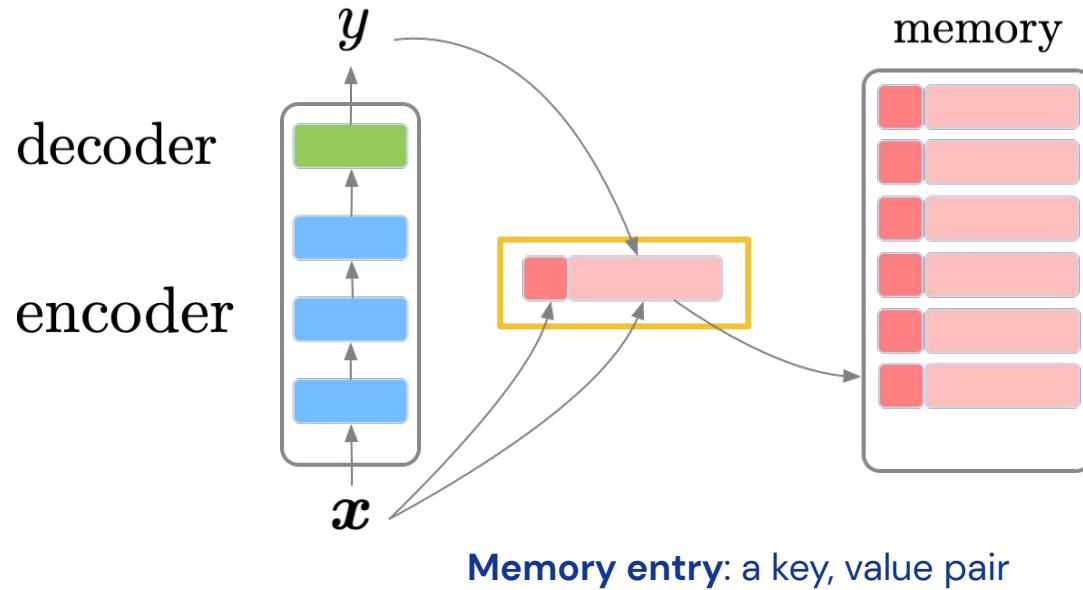
Decoder: a linear function that predicts start and end indices of the answer in the context.

decoder

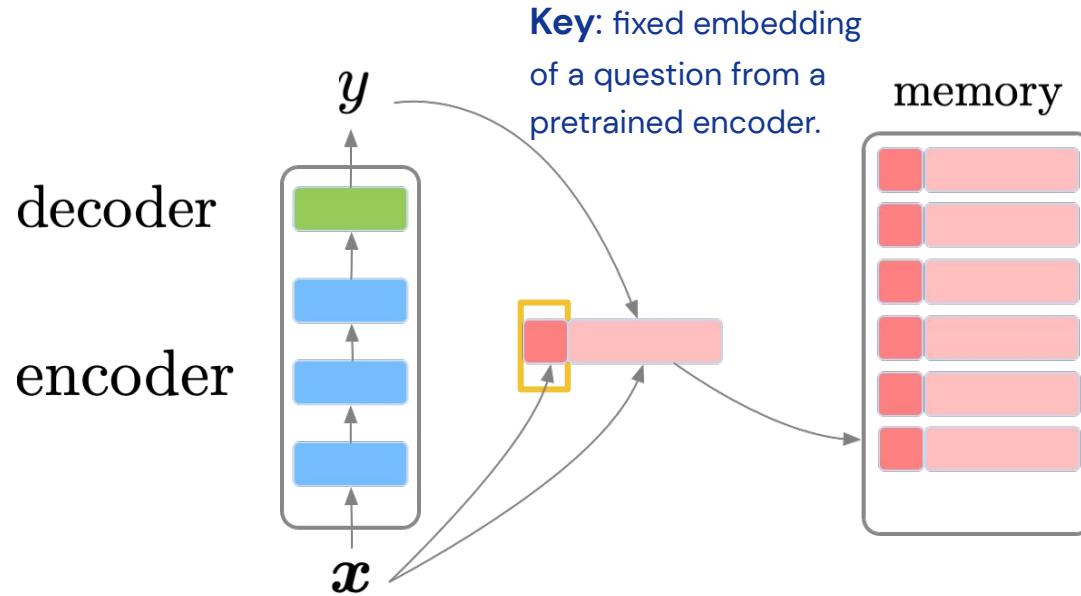
encoder



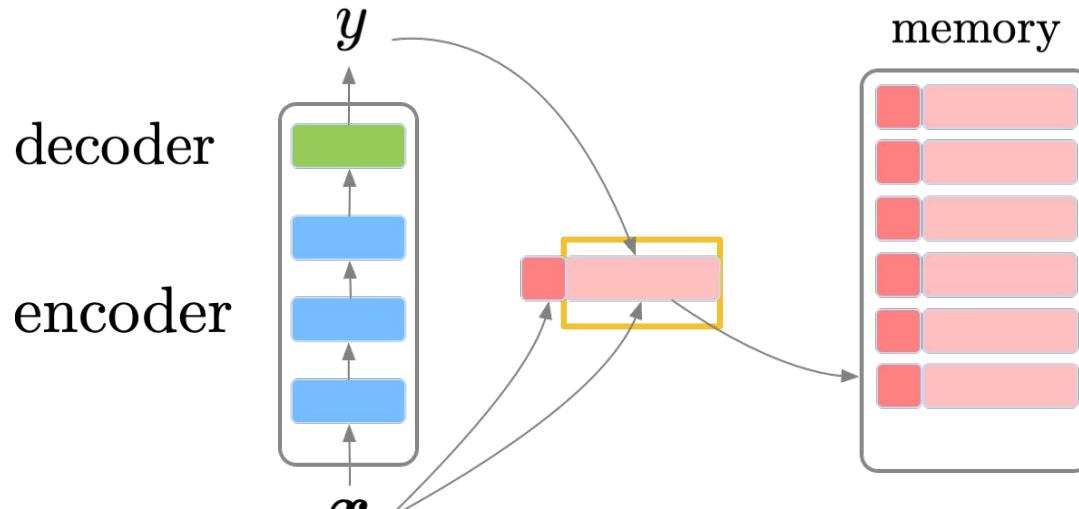
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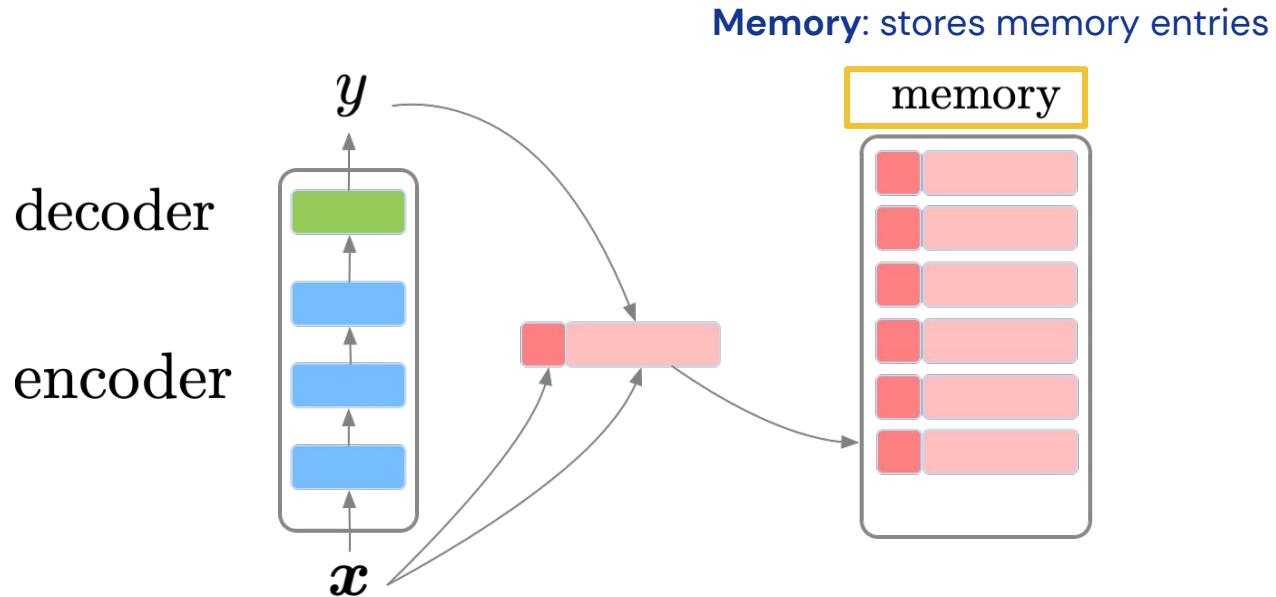
Question Answering Model



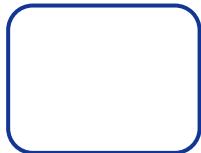
Value: context, question, and
answer in textual forms (strings).



Question Answering Model



Training



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



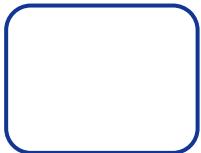
✖ ✖ ✖

Task A



Training

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

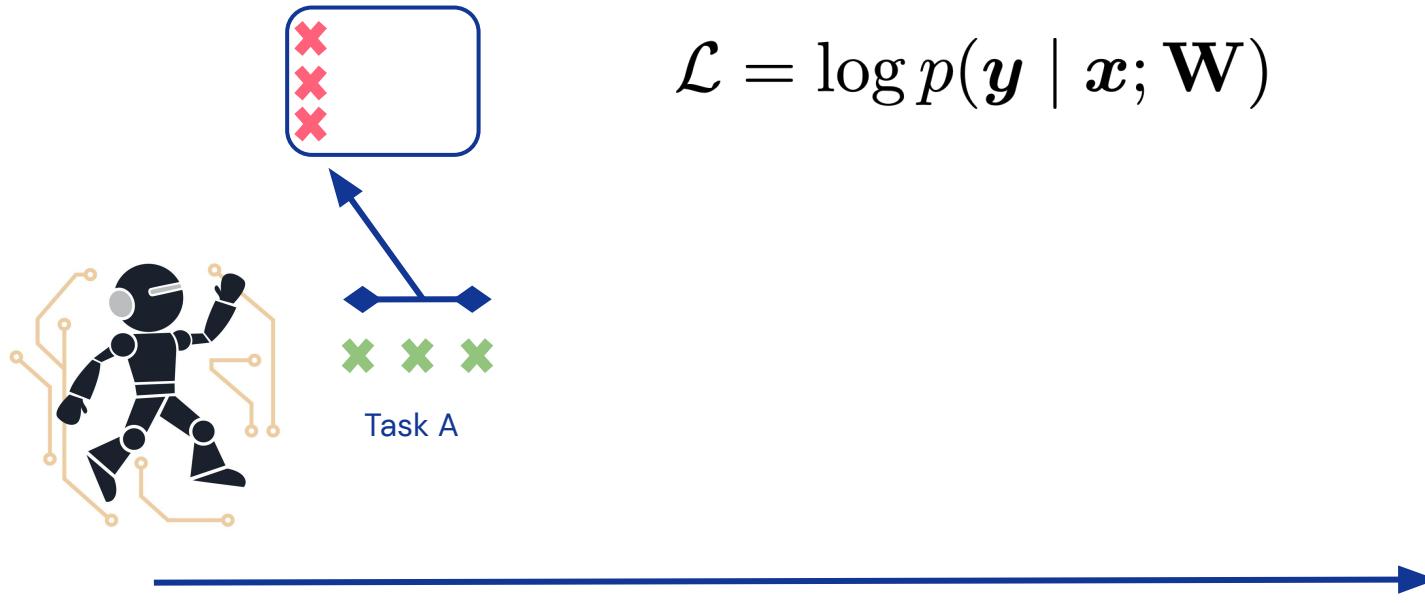


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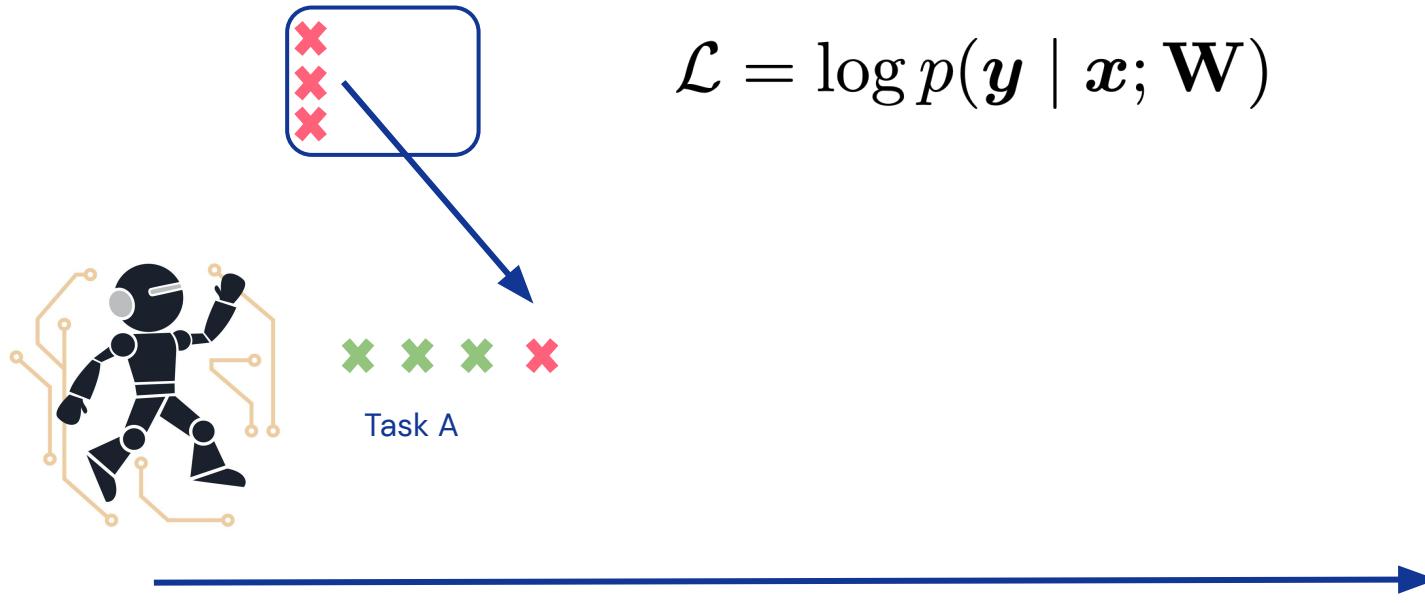
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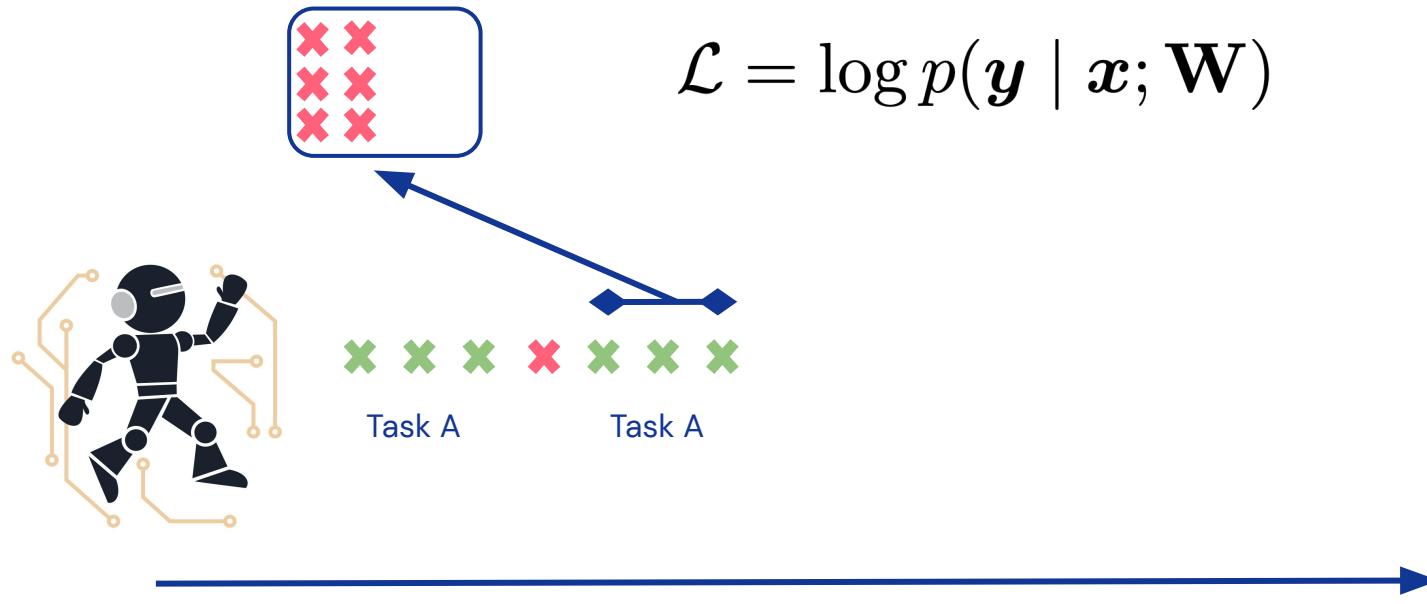
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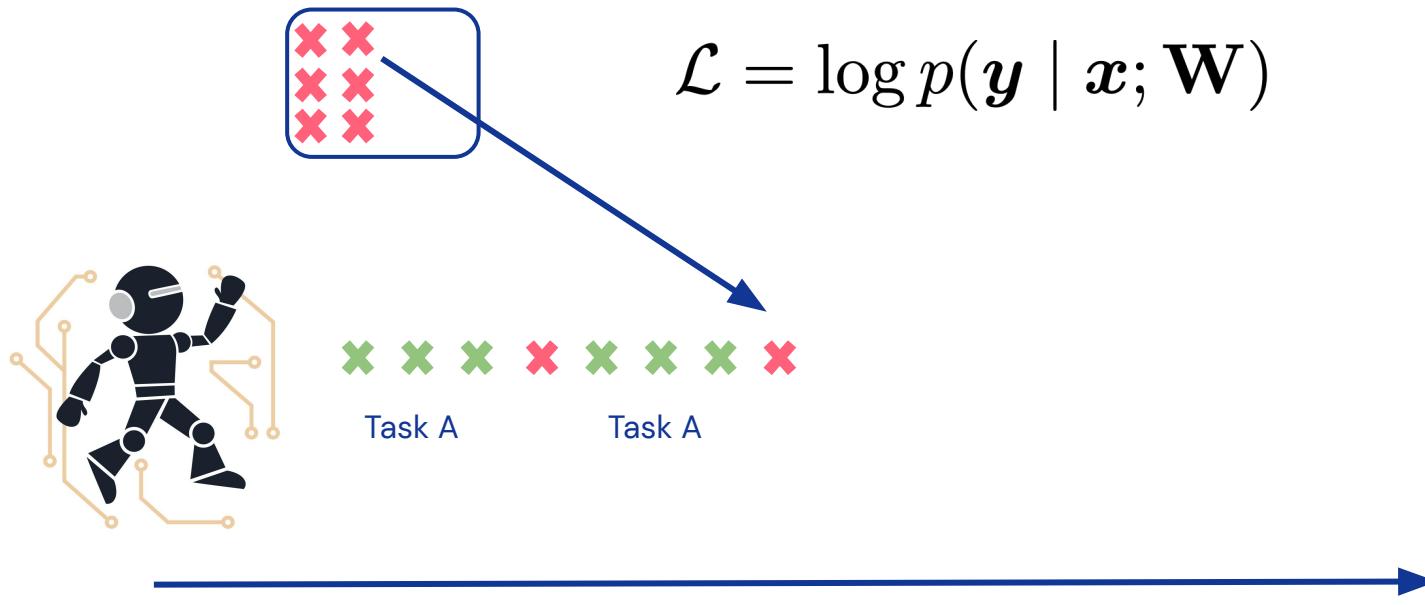
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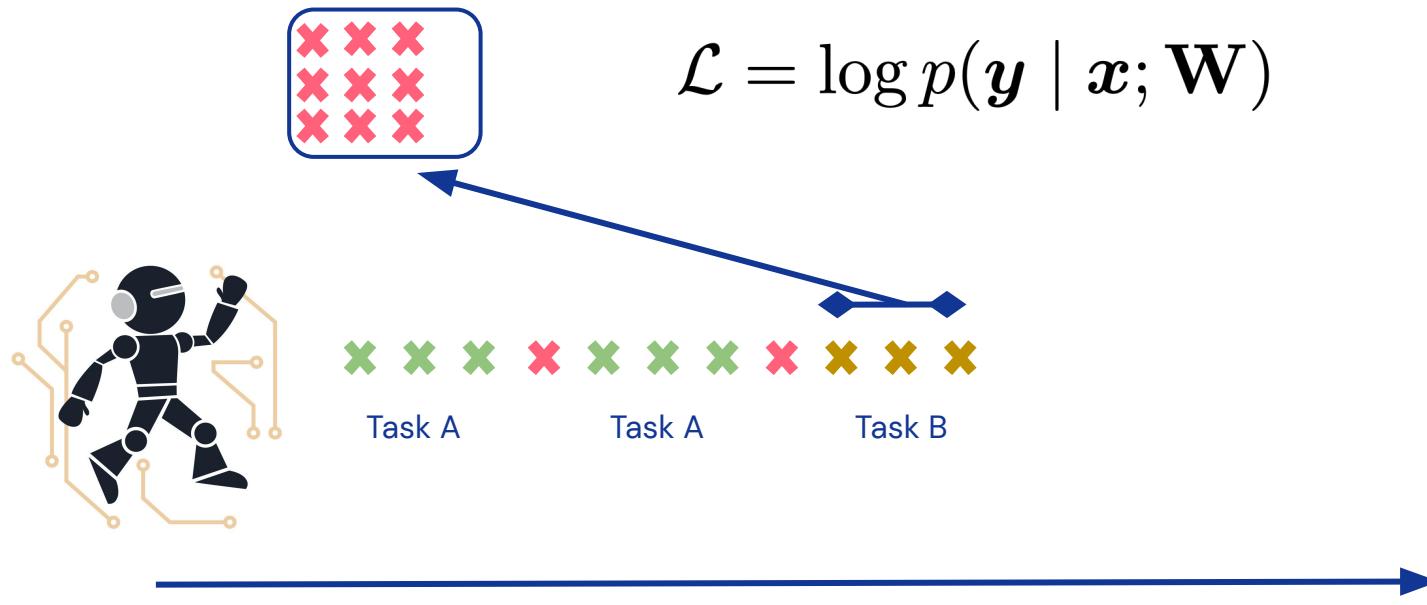
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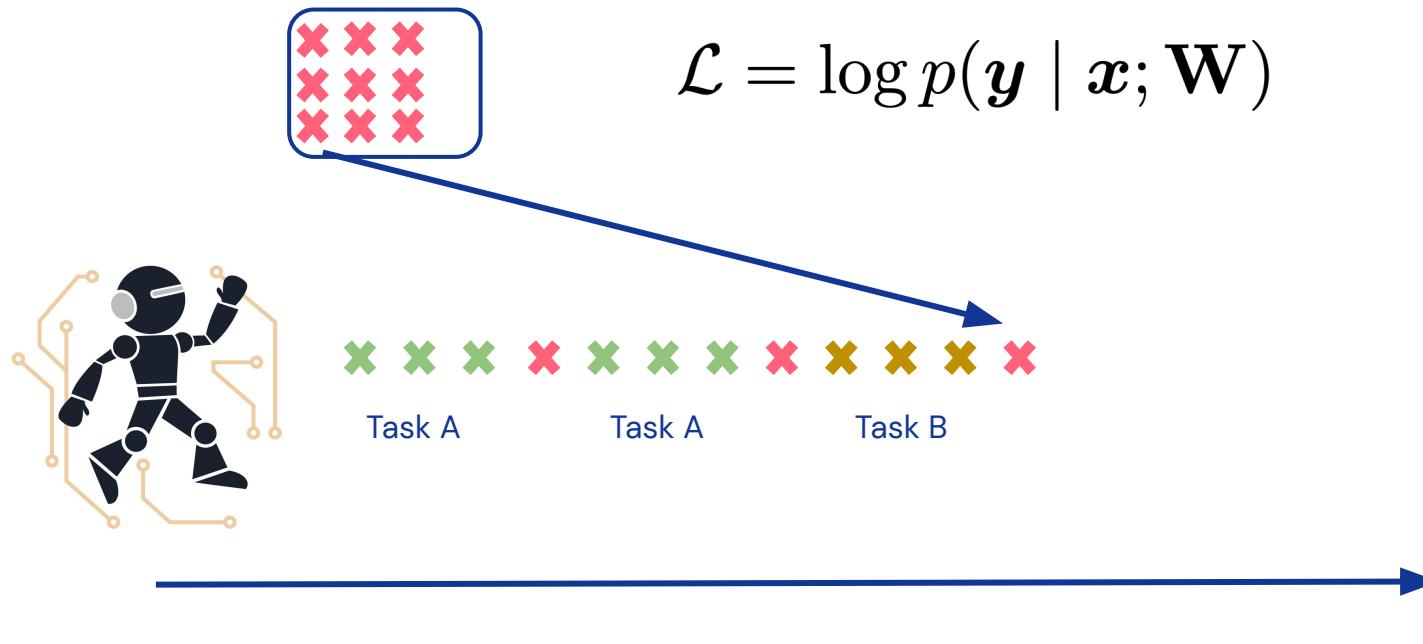
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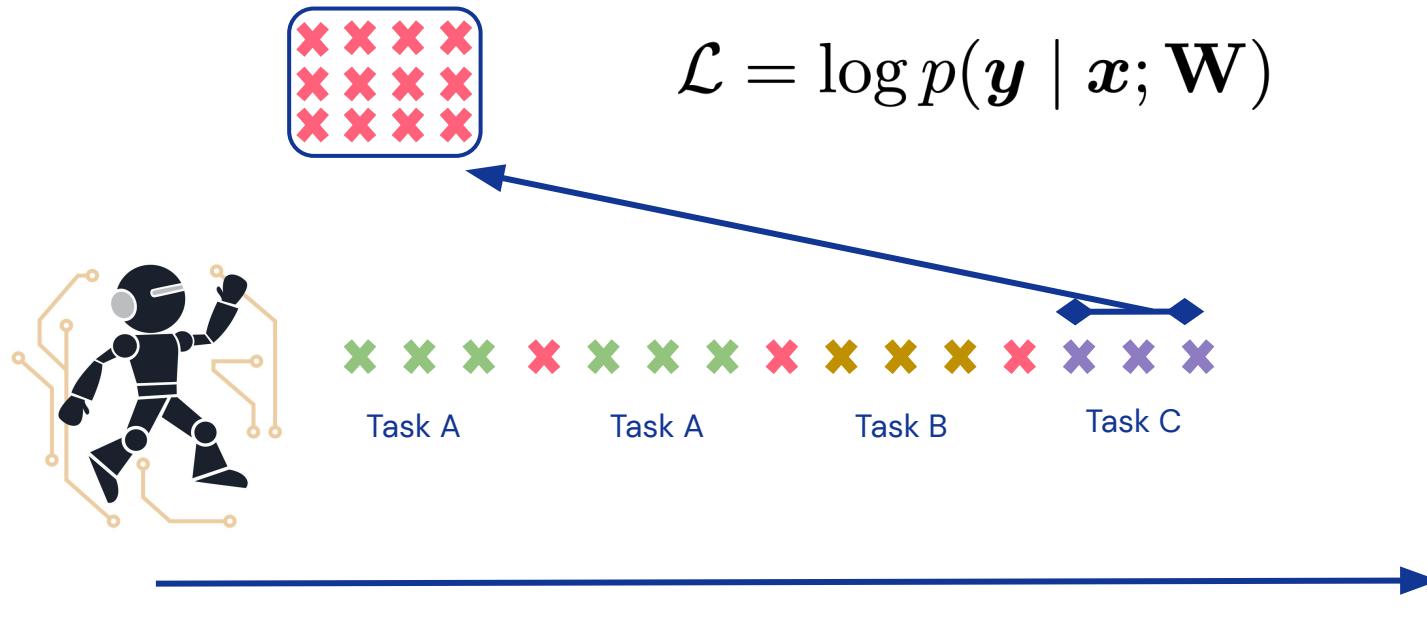
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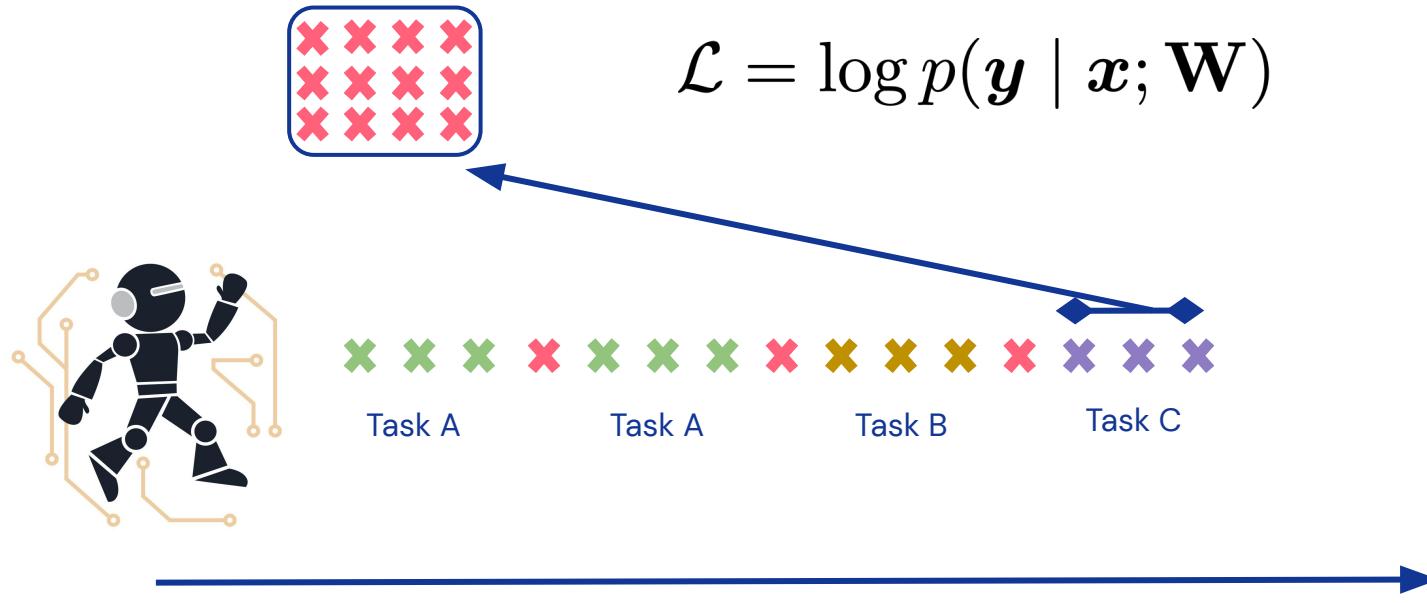
Sparse experience replay: retrain on randomly sampled examples from the memory at a 1% rate.



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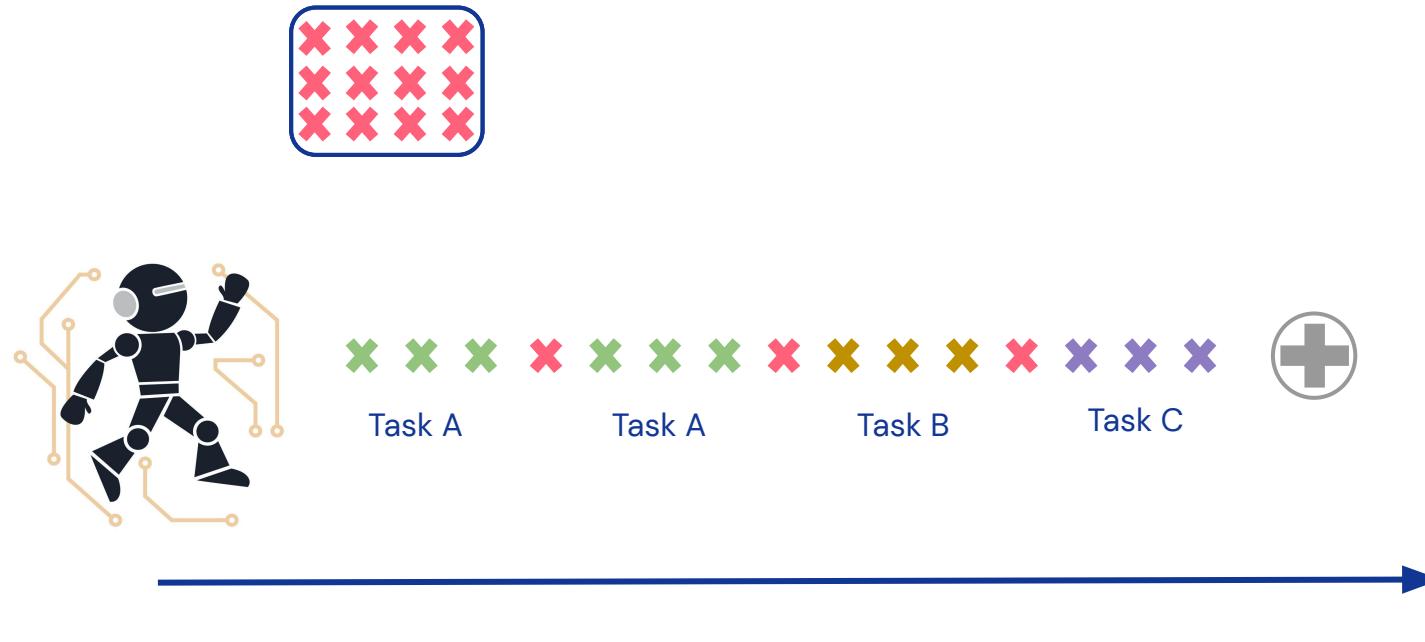
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Related to **memory consolidation** in human learning.



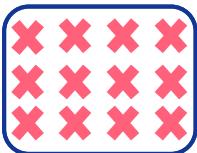
Inference (Prediction)

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



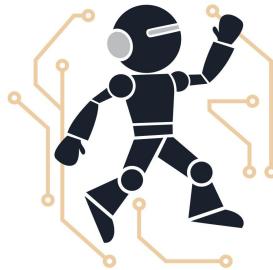
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Normans. The Normans (Norman: Nourmands; French: Normands; Latin: Normanni) were the people who in the 10th and 11th centuries gave their name to Normandy, a region in France. [...]

In what country is Normandy located?



Task A

Task A

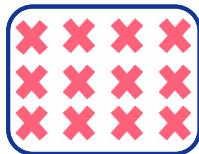
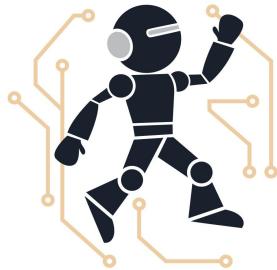
Task B

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?

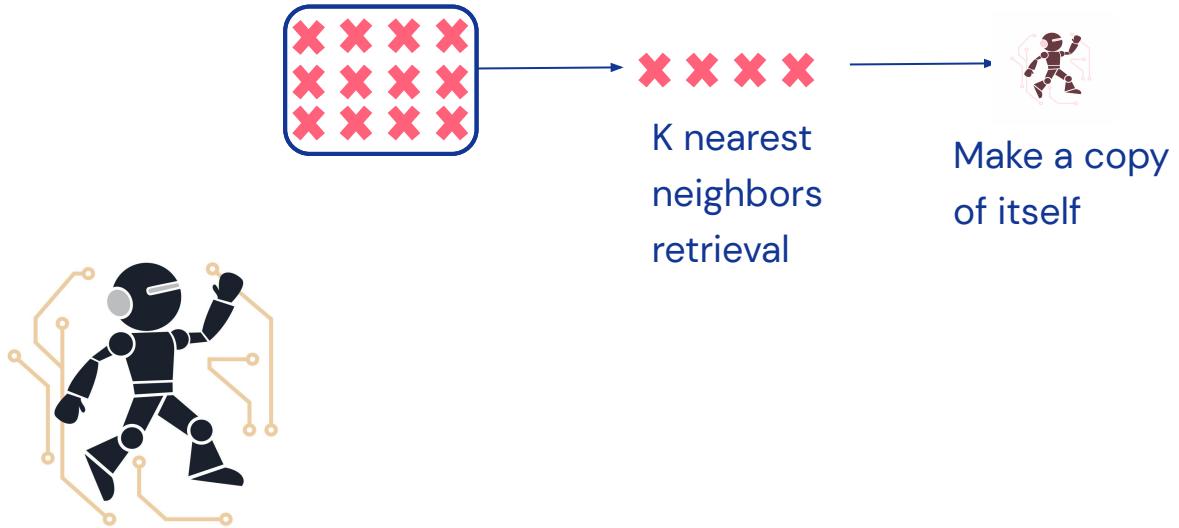
In what country is Spoleto located?

In what part of Africa is Palermo located?



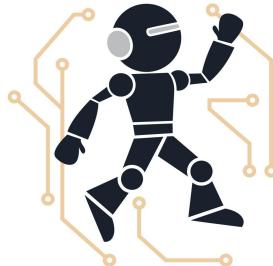
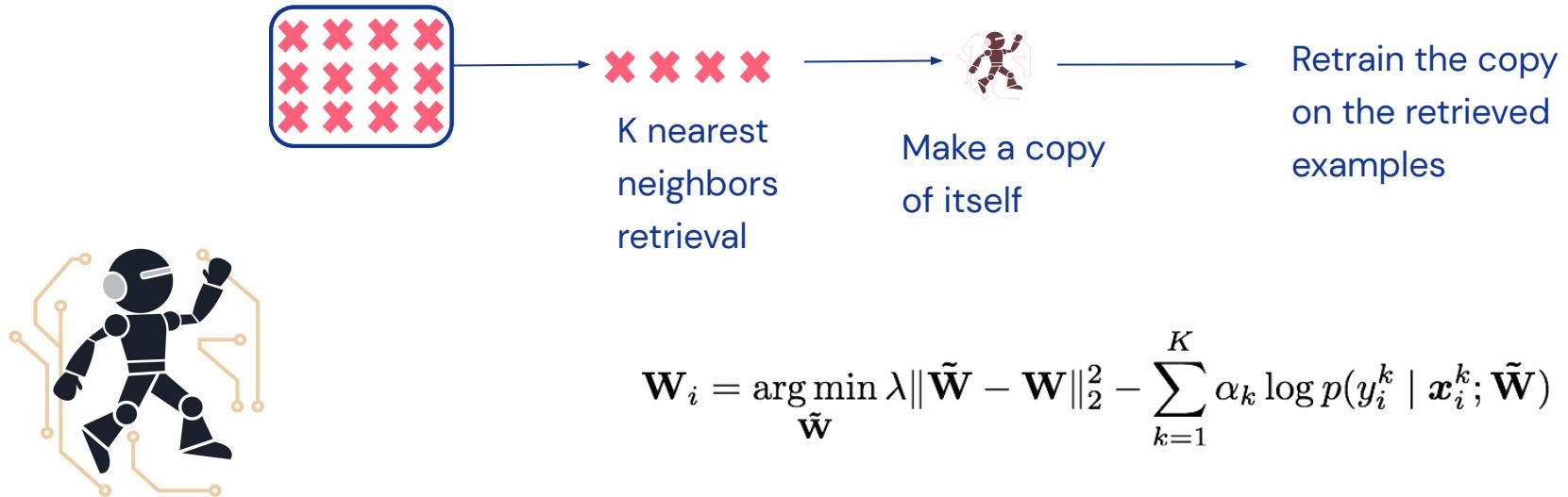
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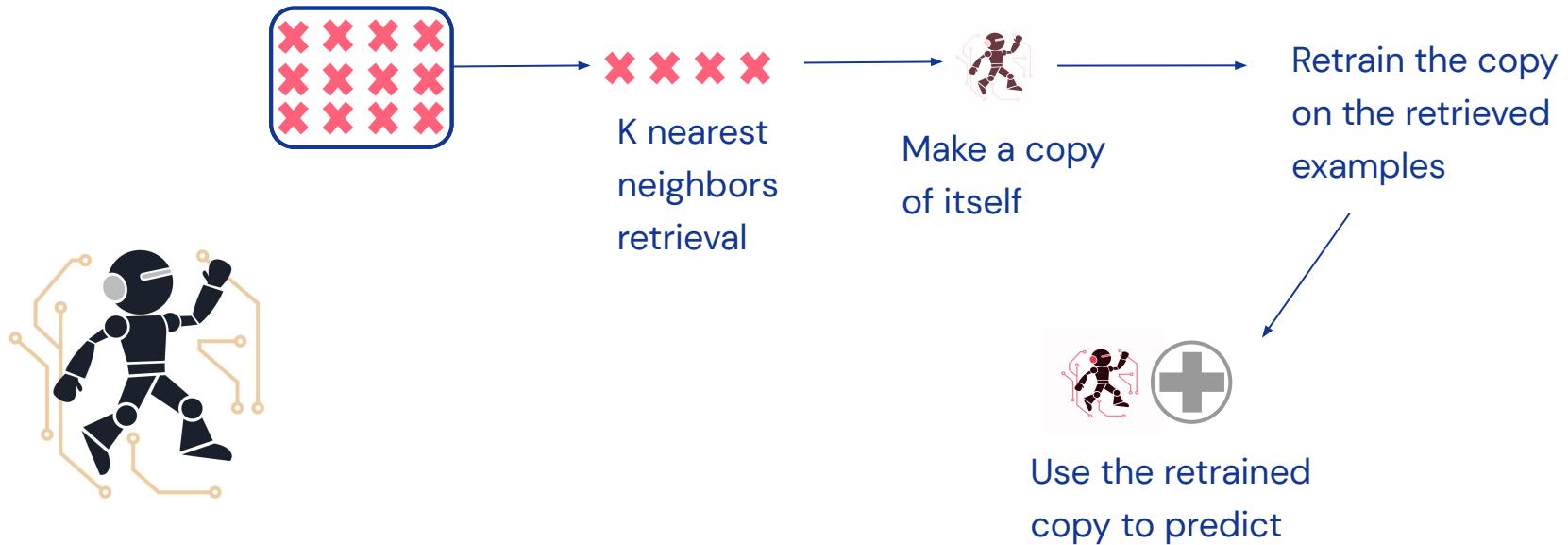


$$\mathbf{W}_i = \arg \min_{\tilde{\mathbf{W}}} \lambda \|\tilde{\mathbf{W}} - \mathbf{W}\|_2^2 - \sum_{k=1}^K \alpha_k \log p(y_i^k | x_i^k; \tilde{\mathbf{W}})$$



Inference (Prediction)

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	62.4

A-GEM: Chaudhry et al., 2019

MbPA: Sprechmann et al., 2018



Takeaways and Limitations

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



Takeaways and Limitations

- 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

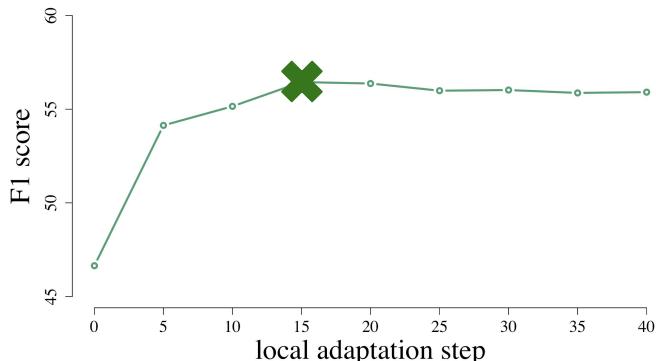


Takeaways and Limitations

- 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.

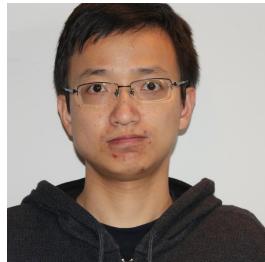
% of stored examples in memory	10%	100%
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- Local adaptation at inference time is **computationally expensive**.



A Mutual Information Maximization Perspective of Language Representation Learning

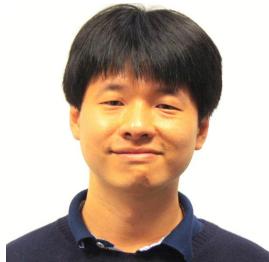
Kong et al., ICLR 2020



Lingpeng



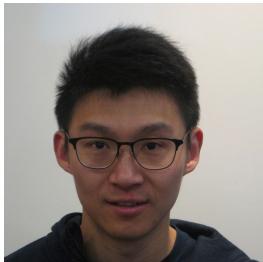
Cyprien



Wang



Lei



Zihang



Dani

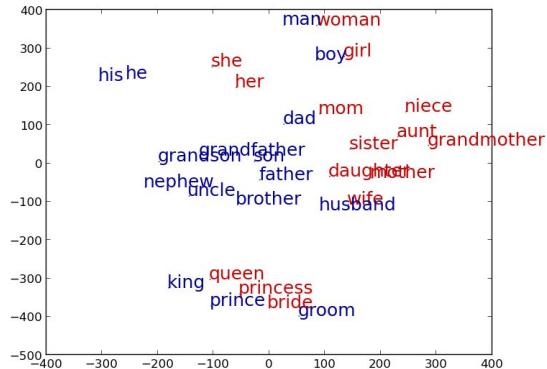


Text Representations



<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.

XLNet, Yang et al., 2019.

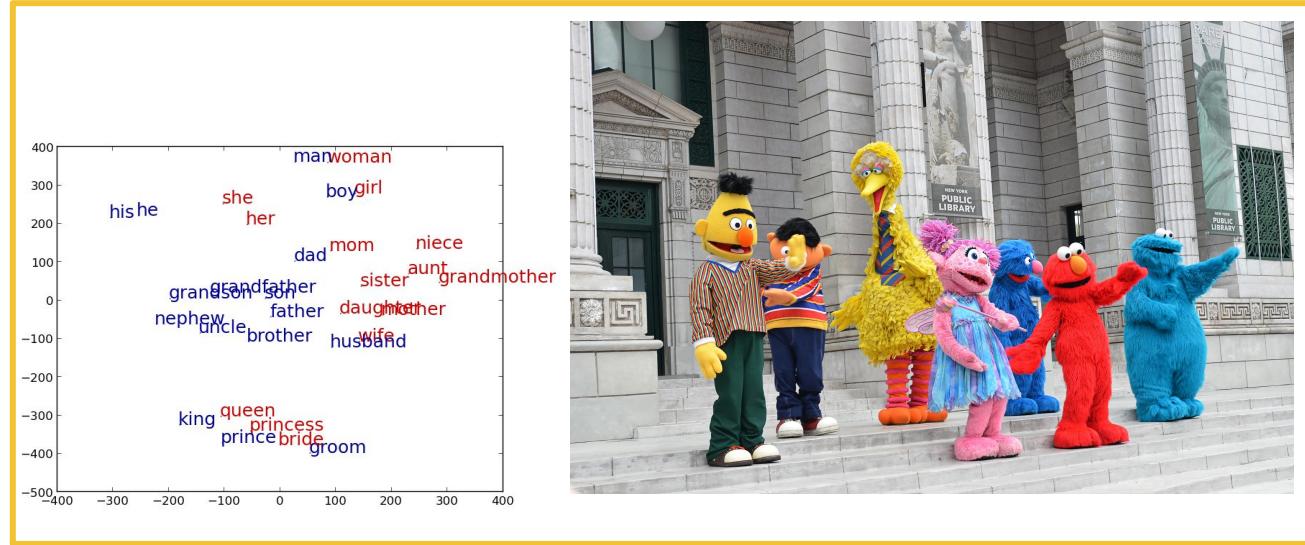


Text Representations



[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.

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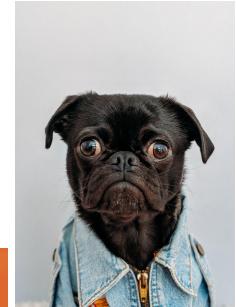
Contrastive Learning

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



Contrastive Learning

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Contrastive Learning

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

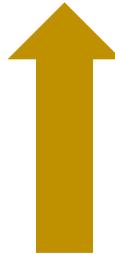
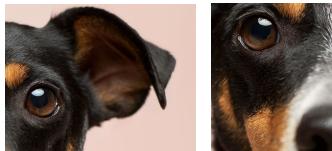


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High when **a** and **b** go together

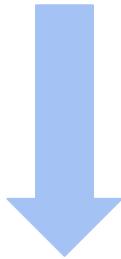
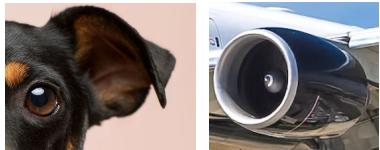


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InfoNCE objective
Logeswaran and Lee, 2018
van den Oord, et al., 2019



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



Contrastive Learning with InfoNCE

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

Carnegie Mellon University is located in Pittsburgh



Contrastive Learning with InfoNCE

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

a
Carnegie **Mellon** University is **located** in Pittsburgh
b



Contrastive Learning with InfoNCE

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

a Carnegie Mellon University is *b* located *a* in Pittsburgh



Contrastive Learning with InfoNCE

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

a

Carnegie Mellon University is located in Pittsburgh

b



Contrastive Learning with InfoNCE

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

a
Carnegie Mellon University is located in *b*
Pittsburgh

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



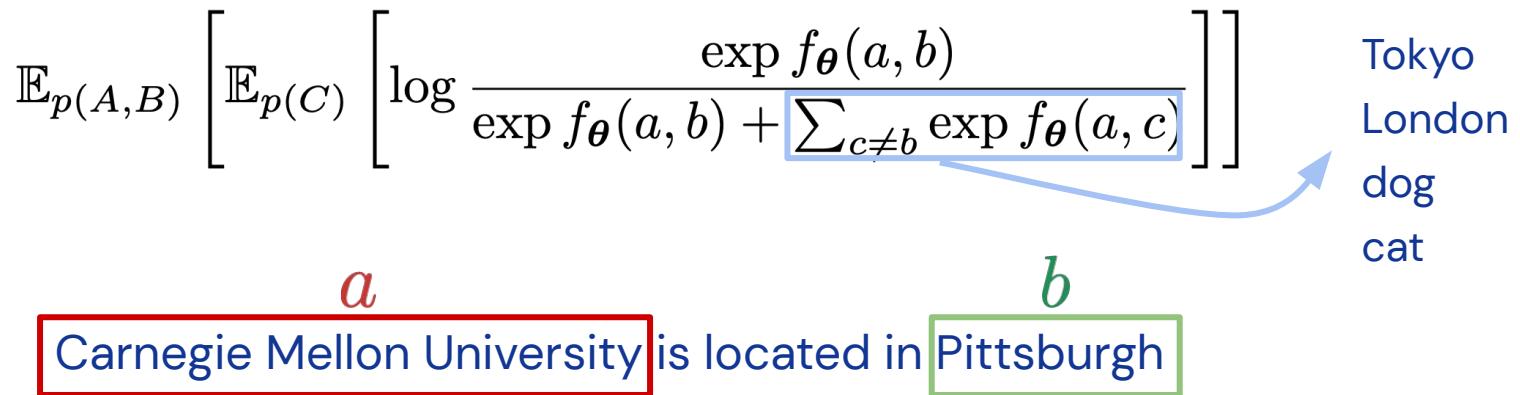
Contrastive Learning with InfoNCE

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Tokyo
London
dog
cat

a *b*

Carnegie Mellon University is located in Pittsburgh



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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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a
Carnegie Mellon University is located in *b*
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Skip-gram

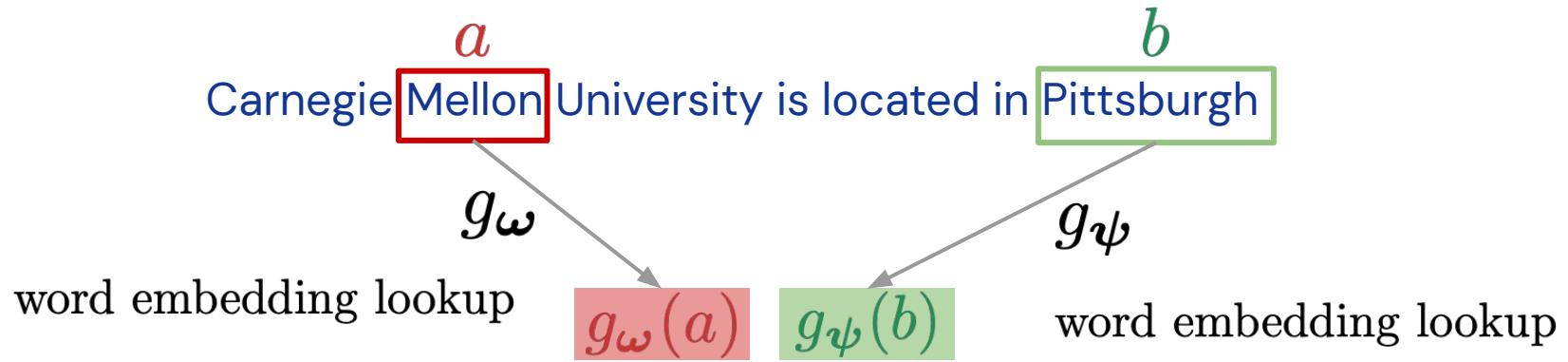
Mikolov et al., 2013

Carnegie Mellon University is located in Pittsburgh



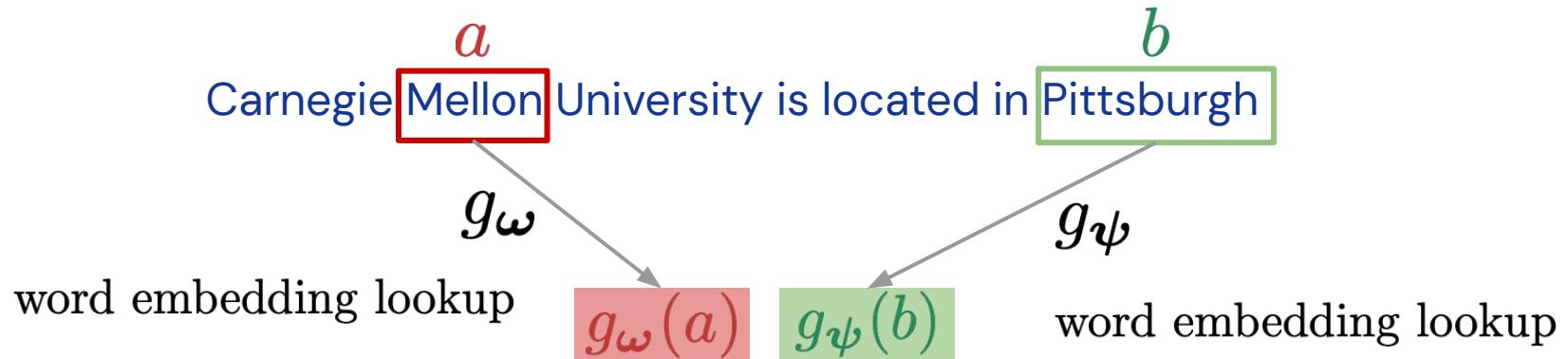
Skip-gram

Mikolov et al., 2013



Skip-gram

Mikolov et al., 2013



Noise Contrastive Estimation for learning word embeddings (Mnih and Kavukcuoglu, 2013)



BERT

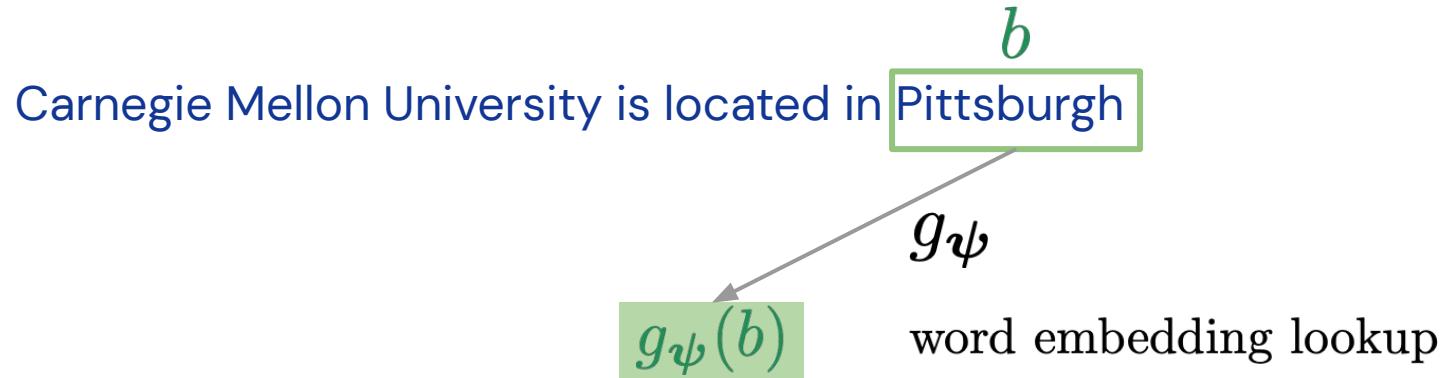
Devlin et al., 2019

Carnegie Mellon University is located in Pittsburgh



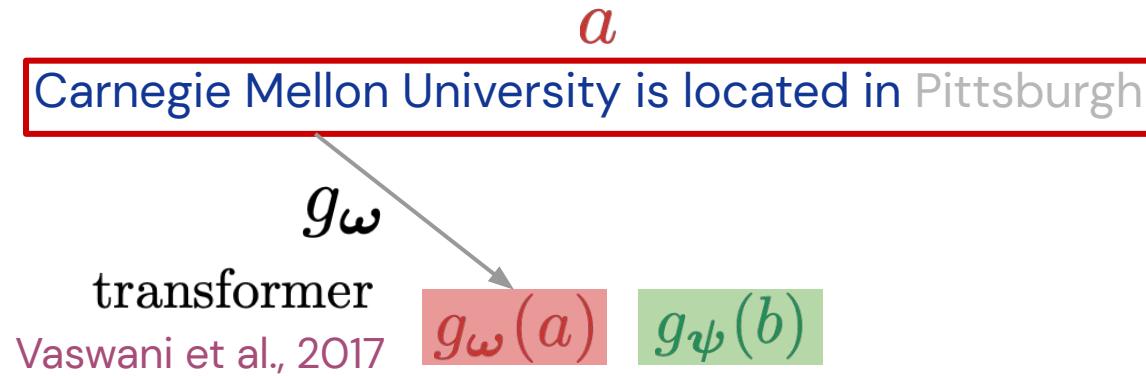
BERT

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_ω	g_ψ
Mikolov et al., 2013	Skip-gram	word	word	lookup	lookup
Devlin et al., 2019	BERT	context	word	transformer	lookup
Yang et al., 2019	XLNet	context	word	TXL++	lookup



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- Connections to representation learning methods used in other domains (vision, speech).



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- Connections to representation learning methods used in other domains (vision, speech).
- A better understanding on how to construct new self-supervised tasks.



Model

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



Model

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



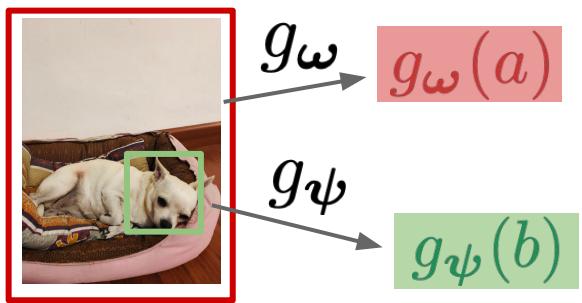
g_{ω}

$g_{\omega}(a)$



Model

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



Model

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

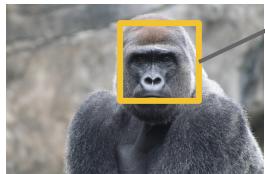


$$g_{\omega} \rightarrow g_{\omega}(a)$$

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



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



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



Model

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



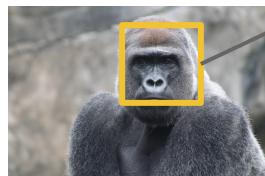
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$$g_{\psi} \rightarrow g_{\psi}(c_1)$$

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



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



Model

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

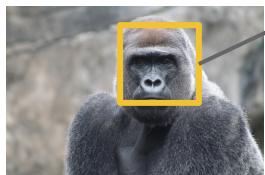


$$g_{\omega} \rightarrow g_{\omega}(a)$$

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



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



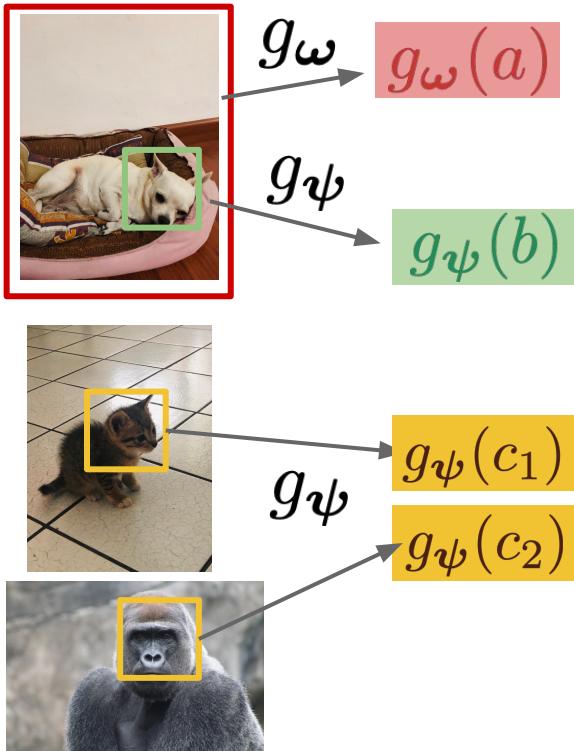
$$g_{\psi} \rightarrow g_{\psi}(c_2)$$

Carnegie Mellon University is located in Pittsburgh

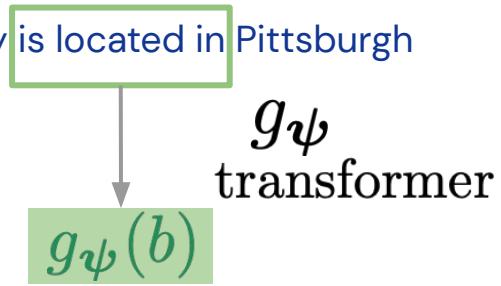


Model

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

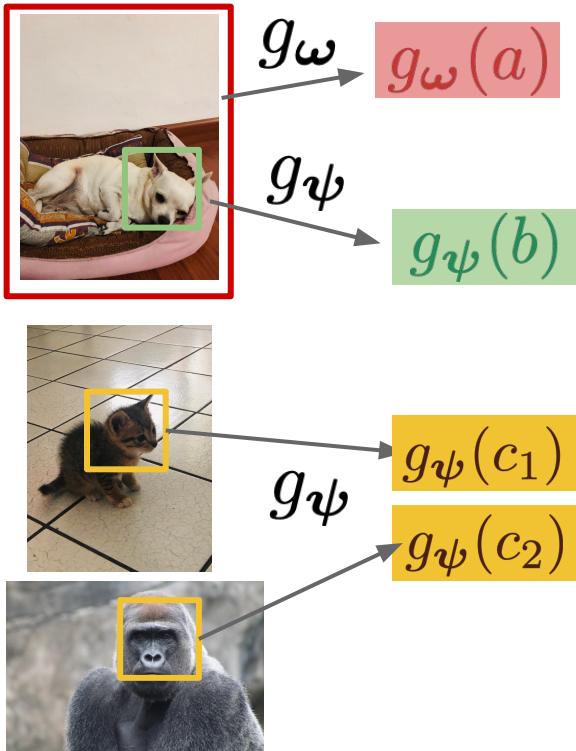


Carnegie Mellon University is located in Pittsburgh

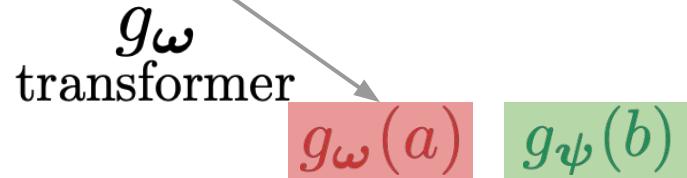


Model

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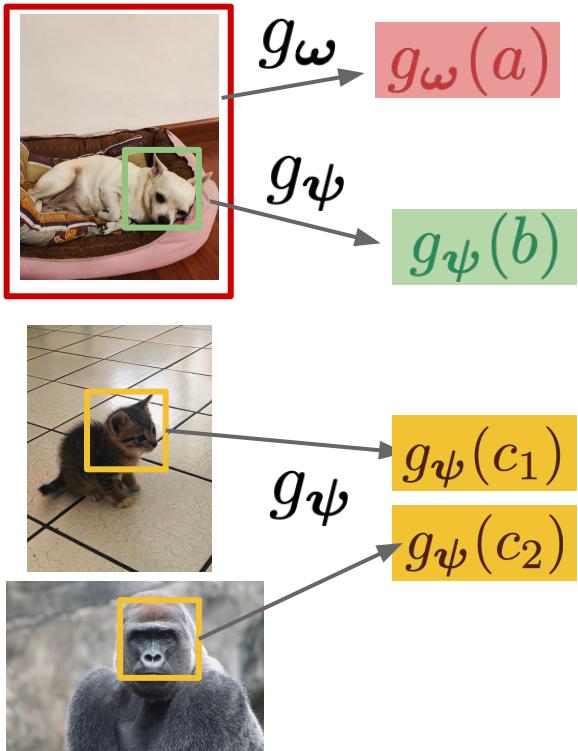


Carnegie Mellon University is located in Pittsburgh



Model

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



Carnegie Mellon University is located in Pittsburgh

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

Starcraft II is a fun game

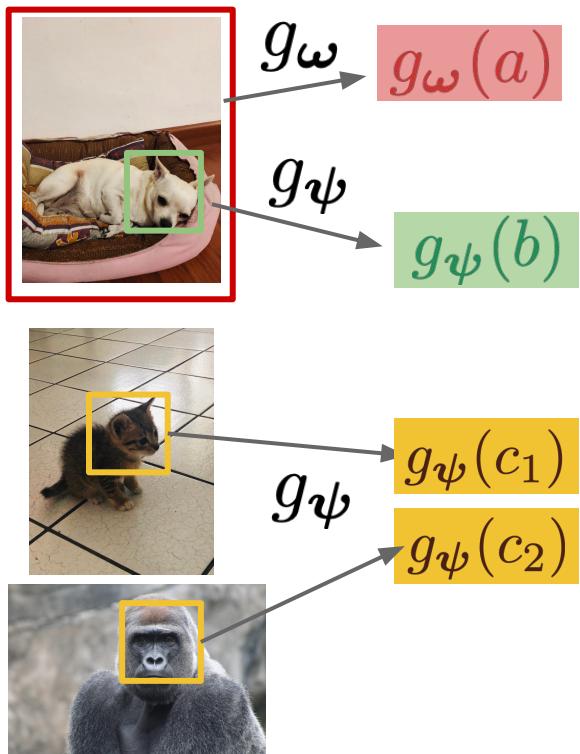
Cristiano Ronaldo scores an own goal

Machine learning is transforming drug discovery



Model

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

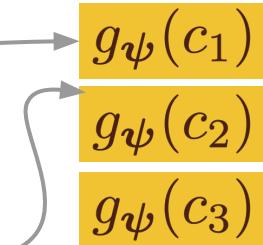


Carnegie Mellon University is located in Pittsburgh

Starcraft II is a fun game

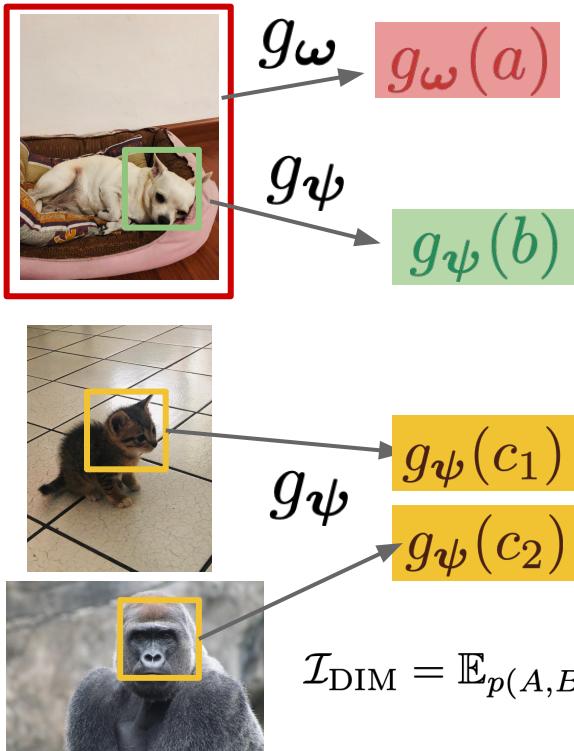
Cristiano Ronaldo scores an own goal

Machine learning is transforming drug discovery



Model

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



Carnegie Mellon University is located in Pittsburgh

$g_\psi(c_1)$
 $g_\psi(c_2)$
 $g_\psi(c_3)$

$g_\omega(a)$ $g_\psi(b)$

Starcraft II is a fun game

Cristiano Ronaldo scores an own goal

Machine learning is transforming drug discovery



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 and Limitations

- 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.

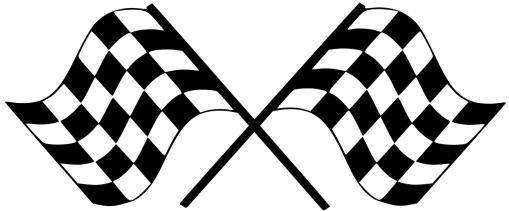


Takeaways and Limitations

- 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.
- All variants of existing models do not incorporate **global context** (they rely on local views).



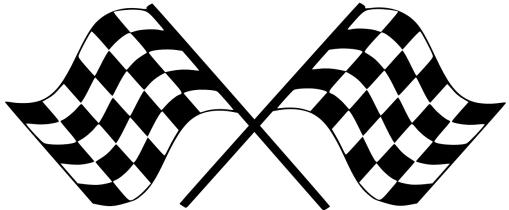
Future Directions



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



Future Directions

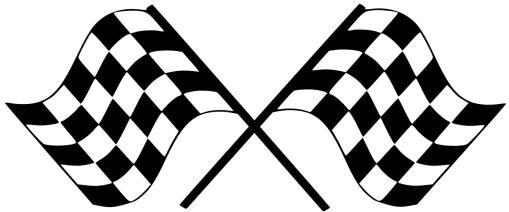


A language model that continually learns in an efficient way to perform multiple complex tasks in many languages.

Generative Models



Future Directions



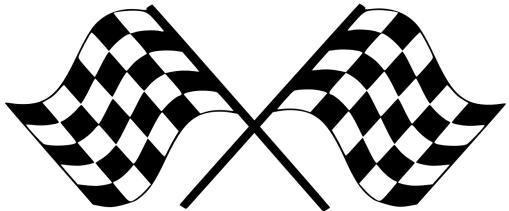
A language model that continually learns **in an efficient way** to perform **multiple complex tasks** in many languages.



Generative Models



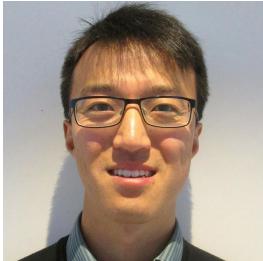
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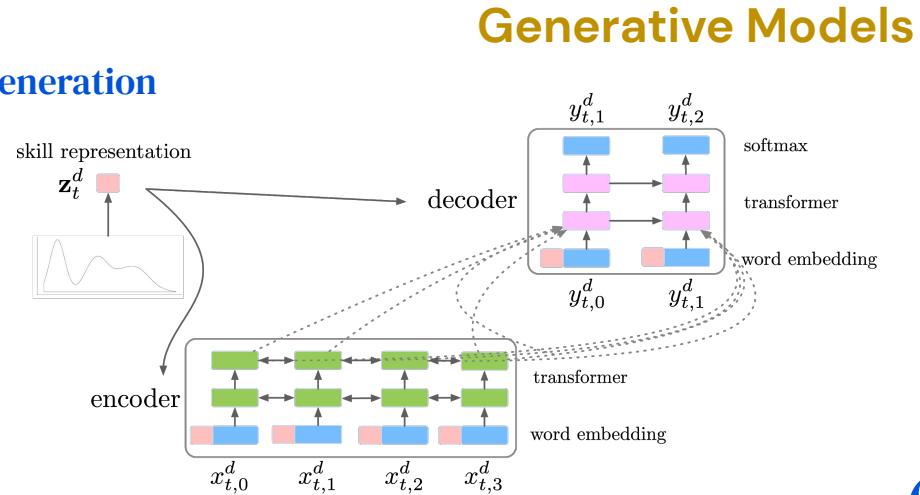
Modelling Latent Skills for Multitask Language Generation

Cao and Yogatama, arXiv 2020

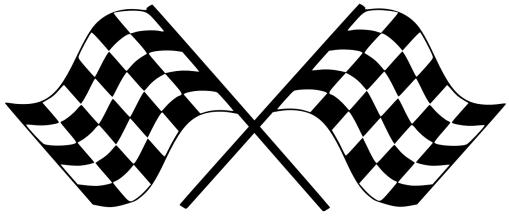


Kris

Dani



Future Directions

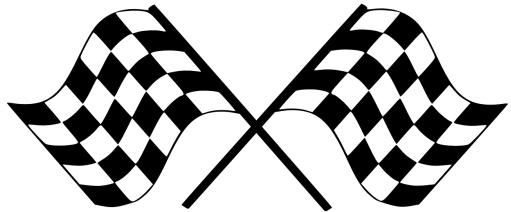


A language model that continually learns in an efficient way to perform multiple complex tasks in many languages.

Memory



Future Directions



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

Memory



ML is fun



Working

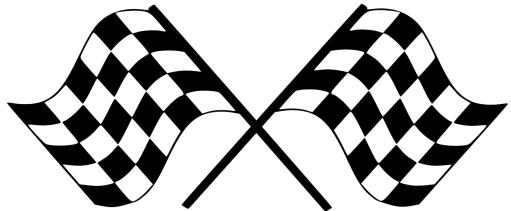
Procedural

Semantic

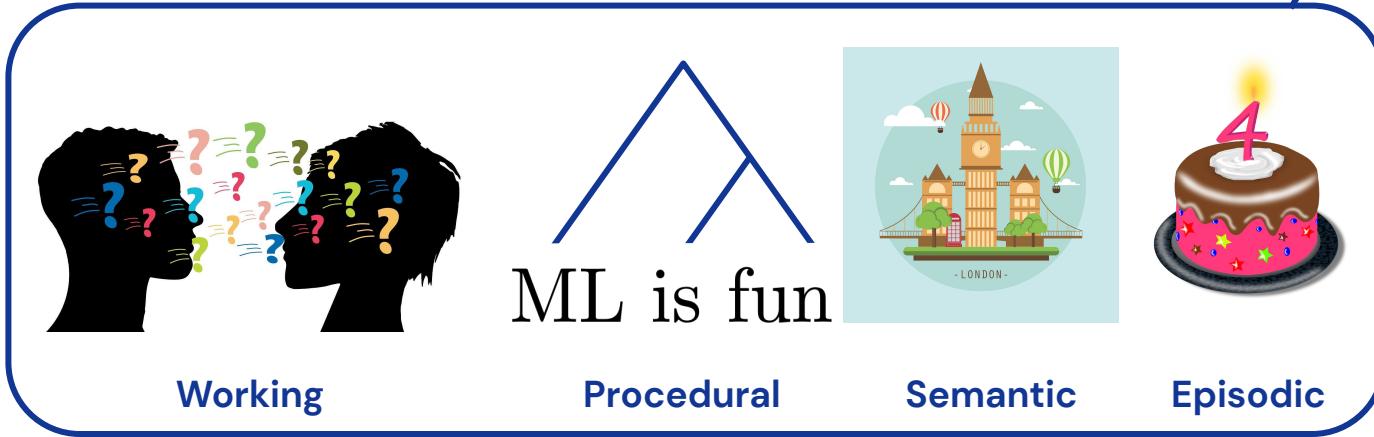
Episodic



Future Directions



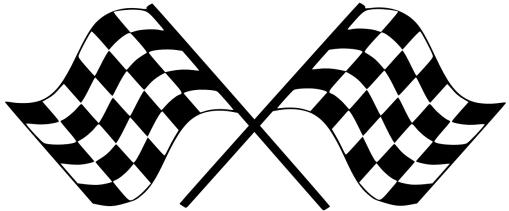
Memory



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



Future Directions

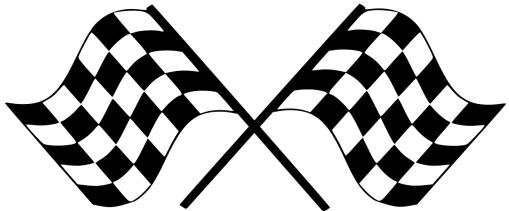


A language model that continually **learns** in an efficient way to perform multiple complex tasks in **many** languages.

Representation Learning

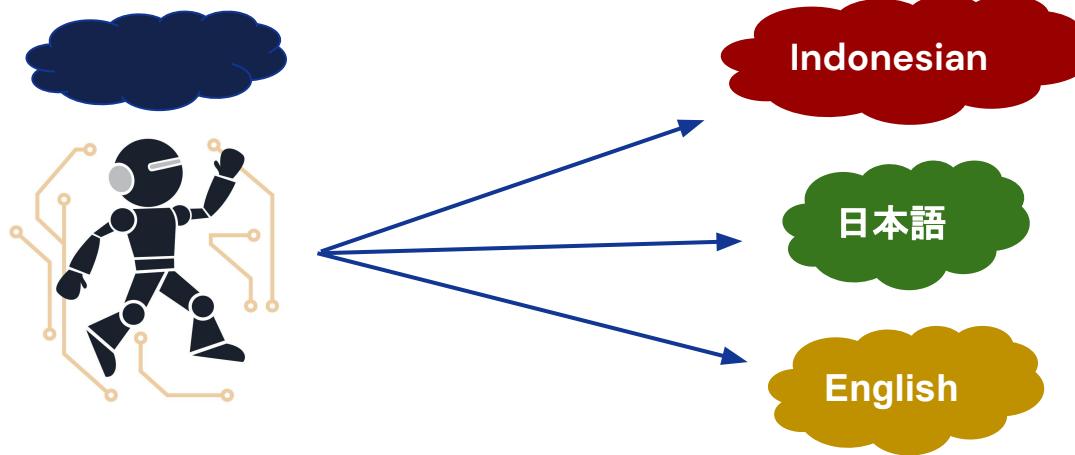


Future Directions

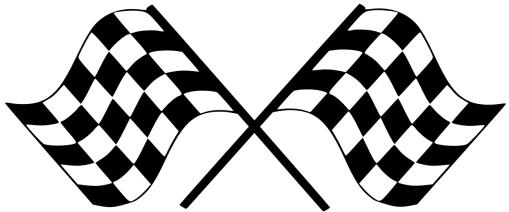


A language model that continually learns in an efficient way to perform multiple complex tasks in many languages.

Representation Learning



Future Directions

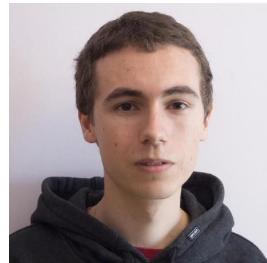


A language model that continually **learns** in an efficient way to perform multiple complex tasks in **many** languages.

Representation Learning

On the Crosslingual Transferability of Monolingual Representations

Artetxe et al., arXiv 2019



Mikel



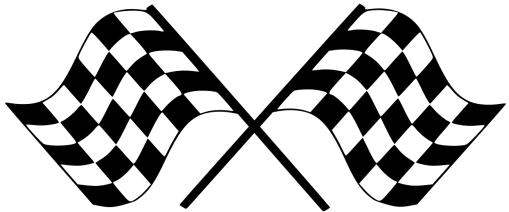
Sebastian



Dani



Future Directions



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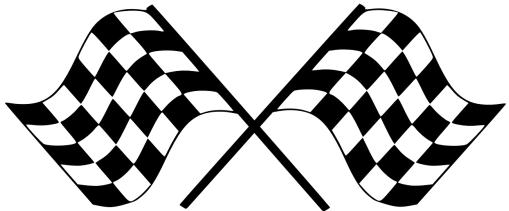
Memory

Representation Learning

Generative Models



Future Directions



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

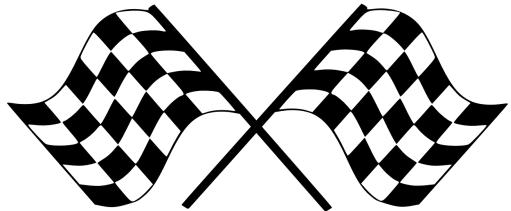
Memory

Representation Learning

Generative Models



Future Directions

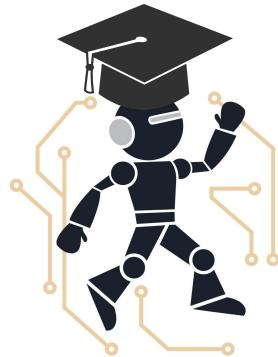


A language model that continually learns in an efficient way to perform multiple complex tasks in many languages.

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

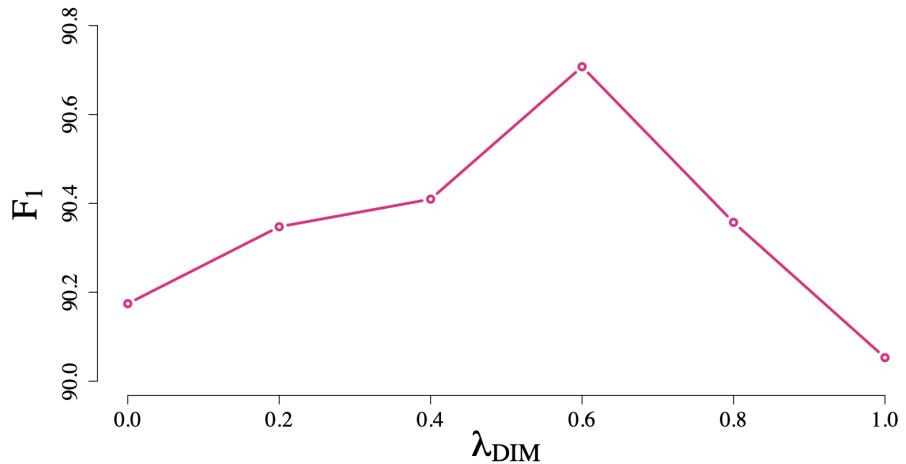
Experiments

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 score (0-100), higher is better.

BERT: Devlin et al., 2019.



$$\mathcal{I}_{\text{INFOWORD}} = \lambda_{\text{MLM}} \mathcal{I}_{\text{MLM}} + \lambda_{\text{DIM}} \mathcal{I}_{\text{DIM}}$$



Experiments

F1 scores (0-100), higher is better

	Enc-Dec	A-GEM	MbPA	Ours	Multitask (upper bound)
QA	53.1	56.2	60.3	62.4	67.8

A-GEM: Chaudhry et al., 2019

MbPA: Sprechmann et al., 2018

