

Learning General Language Processing Agents

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).

ହାଲ୍ ପର୍ଶେନ୍ଦେତ୍ଜେ **Halo**

Aloha こんにちは Sveiki ଶ୍ଲୋ

Ciao Ahoj **Hello** Сайн уу
নমস্কାର

KAMUSTA Γειά σου 여보세요 Salve

Здравствуйте مرحبا 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

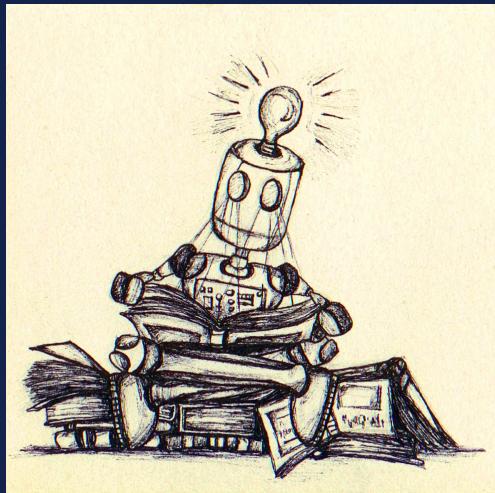
Language is key to **human intelligence** and is important for
artificial intelligence.

General Linguistic Intelligence

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

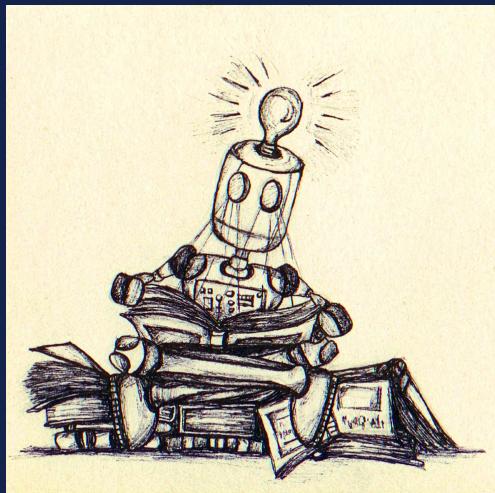
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Aloha こんにちは Sveiki שָׁלוּם
Ciao Ahoj Hello Сайн уу
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Здравствуйте اب حرم Merhaba
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The State of Natural Language Processing

State-of-the-art models are based on increasingly larger transformers.

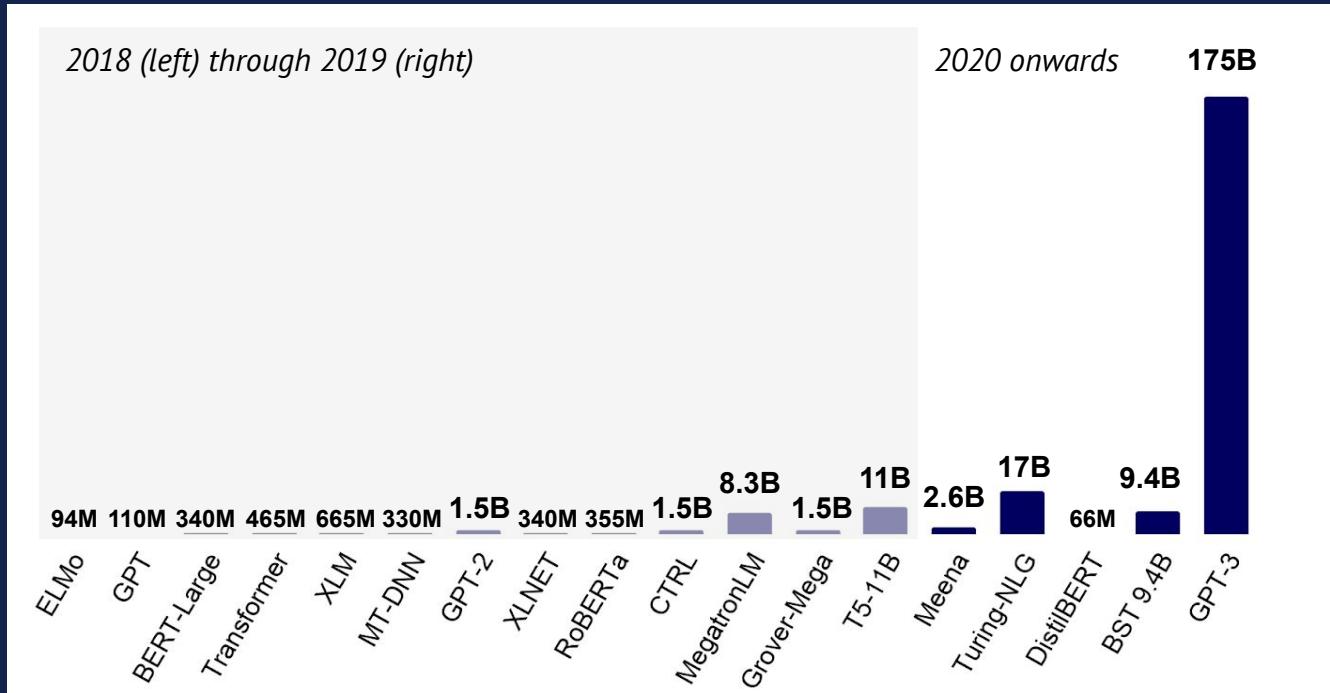


Figure taken from [State of AI Report 2020](#).

Challenges: Human Learning vs. Machine Learning



Human

“Large” datasets

Acquisition

Challenges: Human Learning vs. Machine Learning



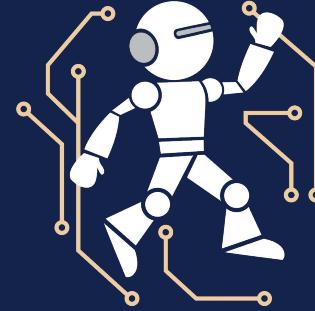
Human	
``Large'' datasets	Acquisition
Few examples	Task Training

Challenges: Human Learning vs. Machine Learning



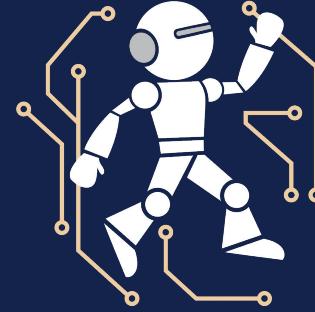
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Few examples	Task Training
Dataset agnostic	Linguistic knowledge
Generalizable to new tasks	Generalization

Challenges: Human Learning vs. Machine Learning



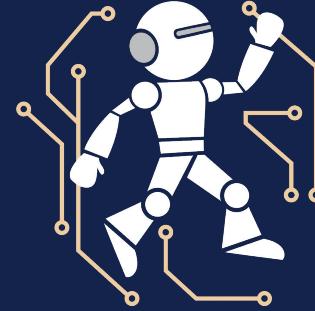
Human		Machine
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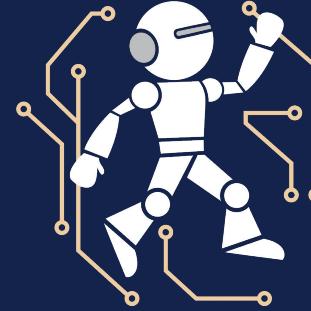
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Challenges: Human Learning vs. Machine Learning



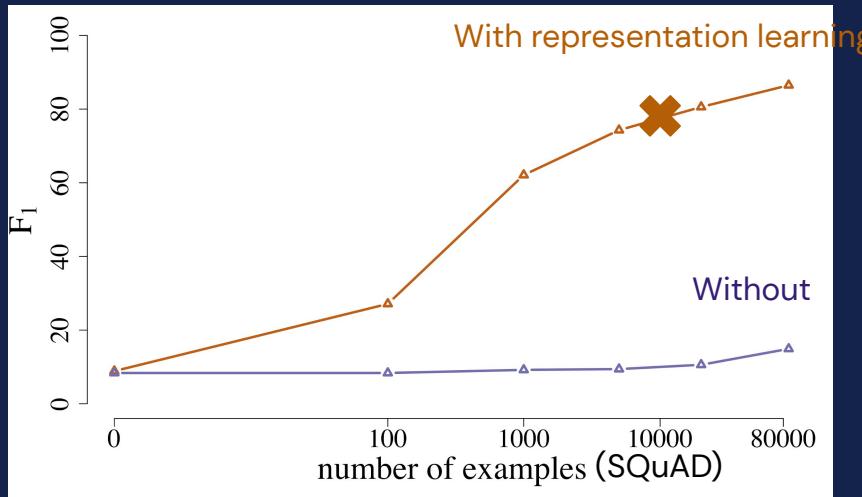
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Challenges: Human Learning vs. Machine Learning



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

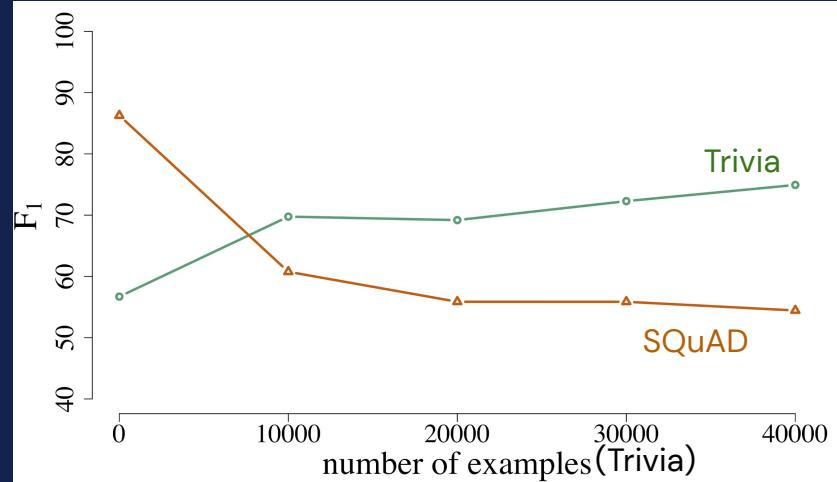
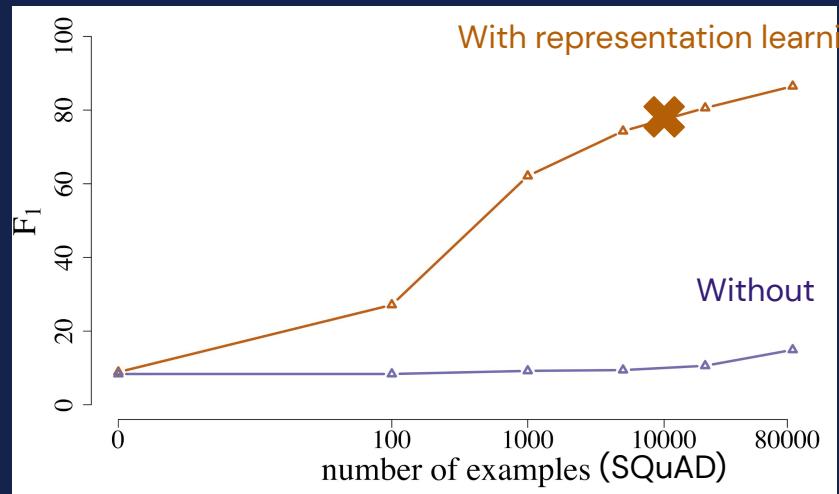


Yogatama et al., arXiv 2019

Model: BERT, [Devlin et al. 2019](#)

QA dataset: SQuAD, [Rajpurkar et al., 2016](#)

The State of Natural Language Processing



Model: BERT, [Devlin et al. 2019](#)

QA dataset: SQuAD, [Rajpurkar et al., 2016](#)

QA dataset 2: Trivia, [Joshi et al., 2017](#)

Yogatama et al., arXiv 2019

Research Areas



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

Research Areas



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

Training Paradigms

Model Architectures

Research Areas



Training Paradigms

Representation Learning

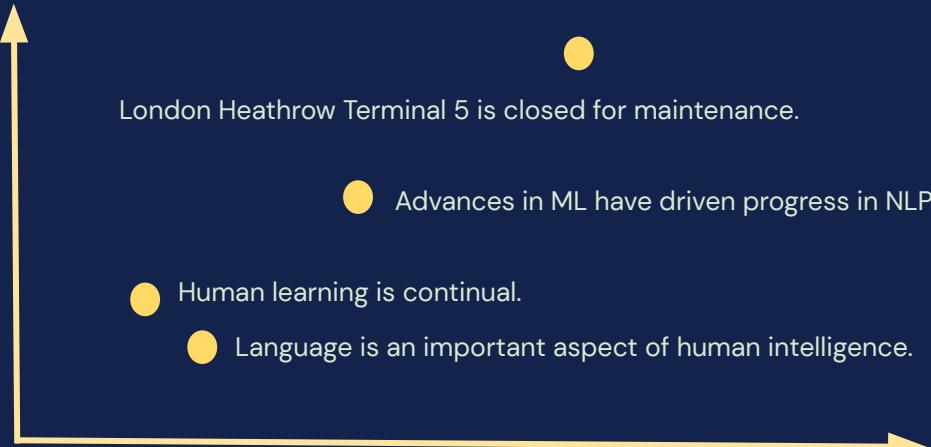
Yogatama and Smith, ACL 2014

Yogatama et al., ACL 2015

Yogatama and Smith; ICML 2015

Kong, de Masson d'Autume, Ling, Yu, Dai, Yogatama; ICLR 2020

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Research Areas



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Training Paradigms

Generative Training

Yogatama et al., TACL 2014

Yogatama et al., arXiv 2017

Kong, Melis, Ling, Yu, and Yogatama, ICLR 2018

Cao and Yogatama, arXiv 2020

$$\mathcal{L} = \log p(\mathbf{x}, y)$$

Research Areas



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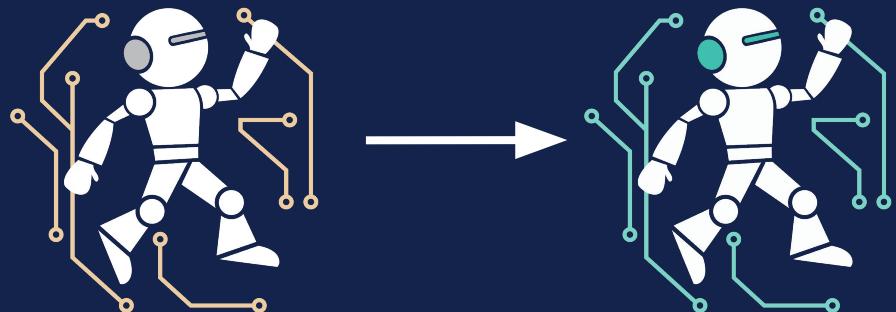
Training Paradigms

Few-shot and Transfer Learning

Yogatama and Mann, AISTATS 2014

Yogatama et al., EMNLP 2015

Artetxe, Ruder, Yogatama, ACL 2020



Research Areas



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

Model Architectures

Memory Networks

Yogatama et al., ICLR 2017

Yogatama et al., ICLR 2018

de Masson d'Autume, Ruder, Kong, Yogatama, NeurIPS 2019

Yogatama et al., TACL 2021

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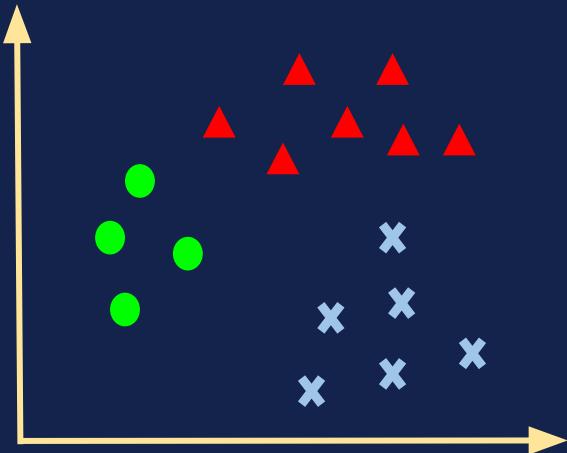
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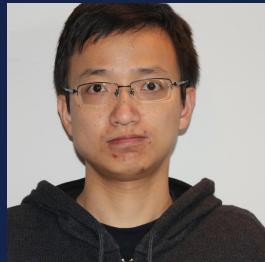
Yogatama et al., TACL 2021

This Talk

- A framework for self-supervised language representation learning methods.
Kong et al., ICLR 2020
- Semiparametric (memory-augmented) language models.
Yogatama et al., TACL 2021

A Mutual Information Maximization Perspective of Language Representation Learning

Kong et al., ICLR 2020



Lingpeng



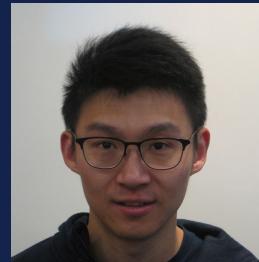
Cyprien



Wang



Lei



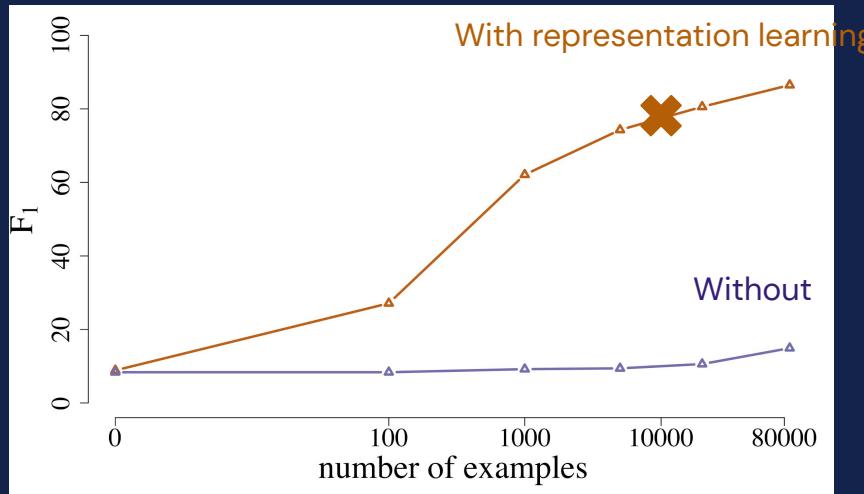
Zihang



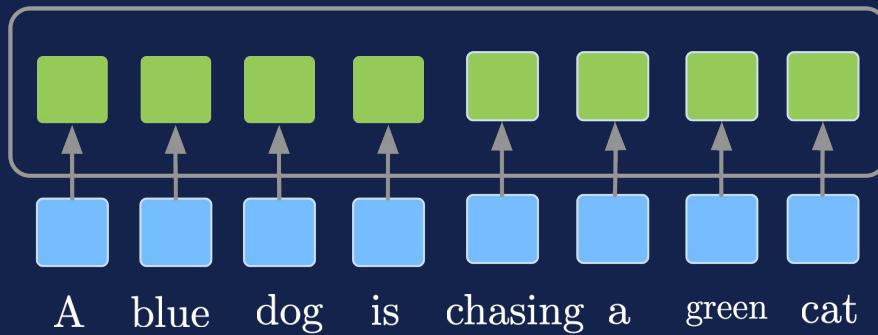
Dani

Text Representations

Good representations facilitate more efficient transfer.



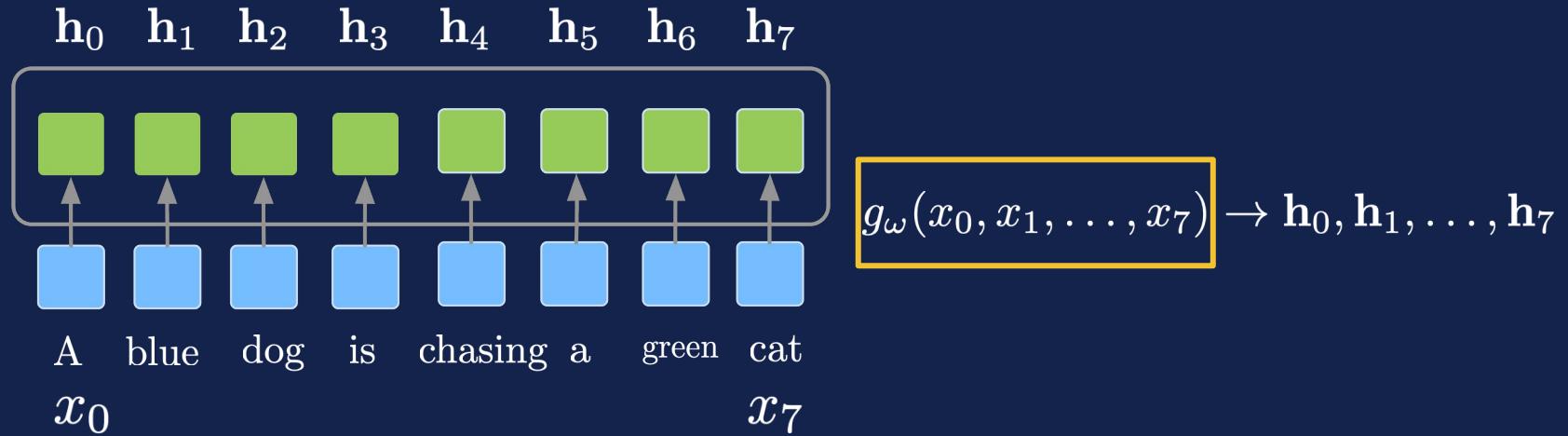
Text Representations



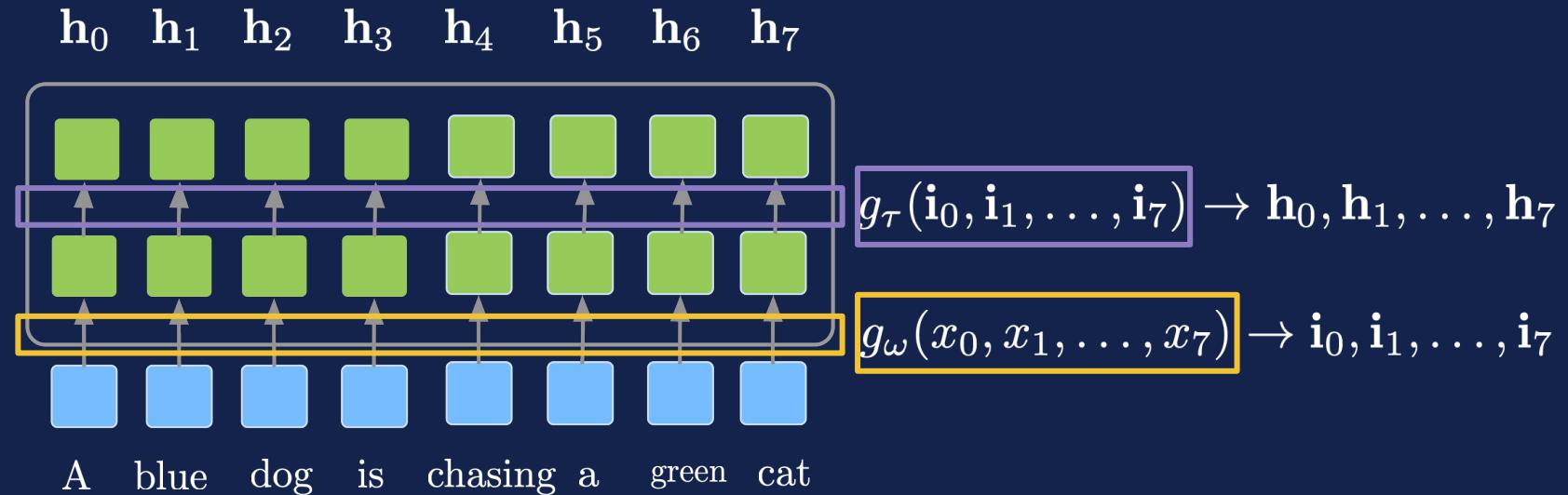
**a sequence of vectors
(word representations)**

a sequence of words

Text Representations



Text Representations



Text Representations



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

Bag of words

Word embeddings

Contextual word embeddings

Skip gram, Mikolov et al., 2013.
GloVe, Pennington et al., 2014.

ELMo, Peters et al., 2018.
BERT, Devlin et al., 2019.

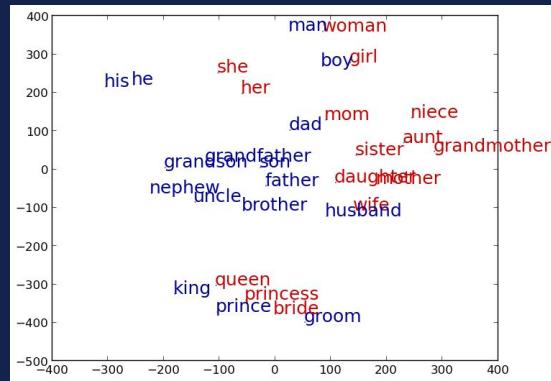


Text Representations



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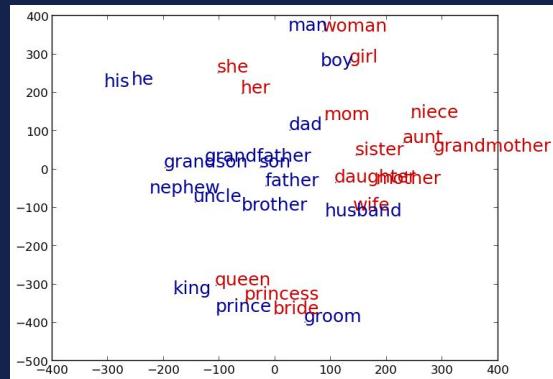


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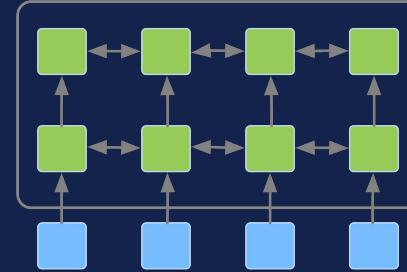
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Word embeddings

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She is a teacher

Contextual word embeddings

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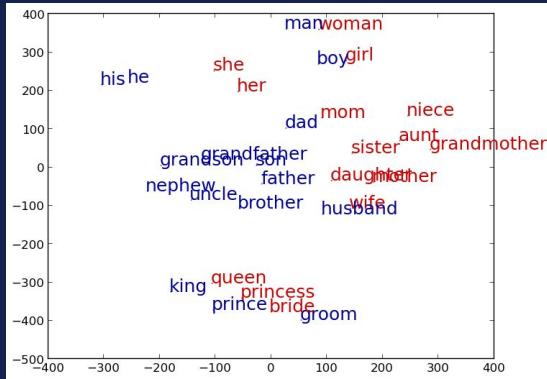
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Bag of words

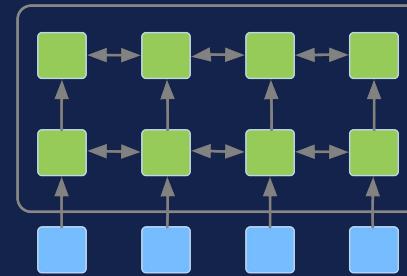
What has been the main driver of progress so far?



Word embeddings

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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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Contrastive Learning

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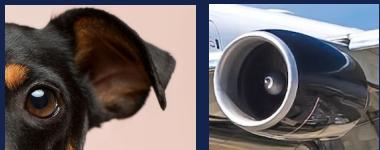
High when **a** and **b** go together

Contrastive Learning with InfoNCE

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InfoNCE objective
Logeswaran and Lee, 2018
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Low when **a** and **c** do not go together



Contrastive Learning with InfoNCE

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

The University of Waterloo is located in Canada

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 *b*

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Contrastive Learning with InfoNCE

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a *b* *a*

The University of Waterloo is located in Canada

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a

b

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Contrastive Learning with InfoNCE

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a

b

The University of Waterloo is located in Canada

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

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 *b*

The University of Waterloo is located in Canada

Tokyo
London
dog
cat

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

Contrastive Learning with InfoNCE

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

a

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The University of Waterloo is located in Canada

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The University of Waterloo is located in Canada

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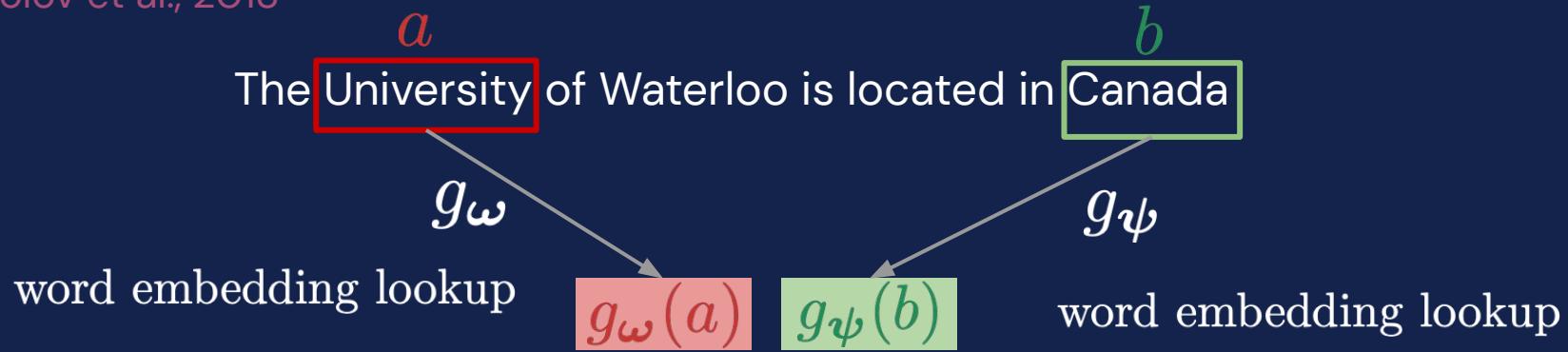
Skip-gram

Mikolov et al., 2013

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Skip-gram

Mikolov et al., 2013



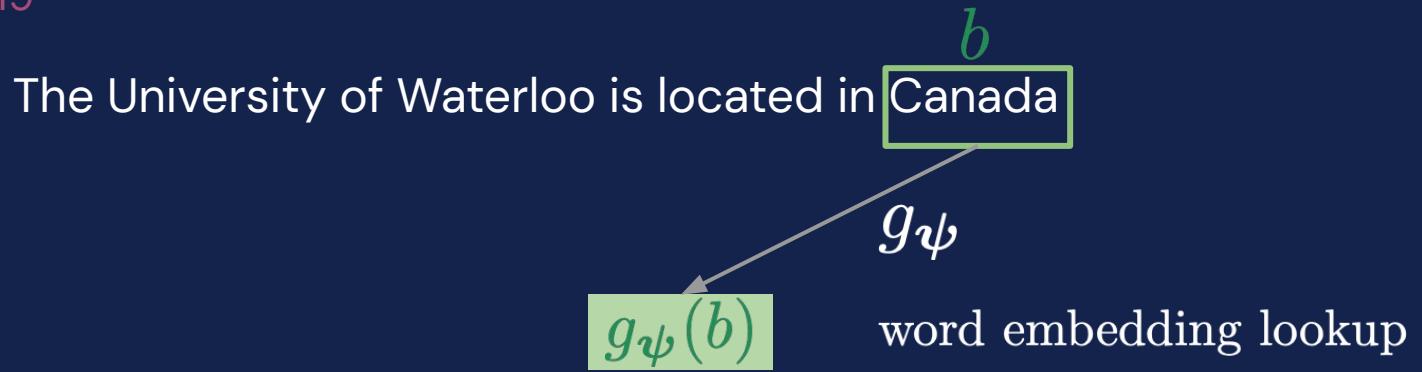
BERT

Devlin et al., 2019

The University of Waterloo is located in Canada

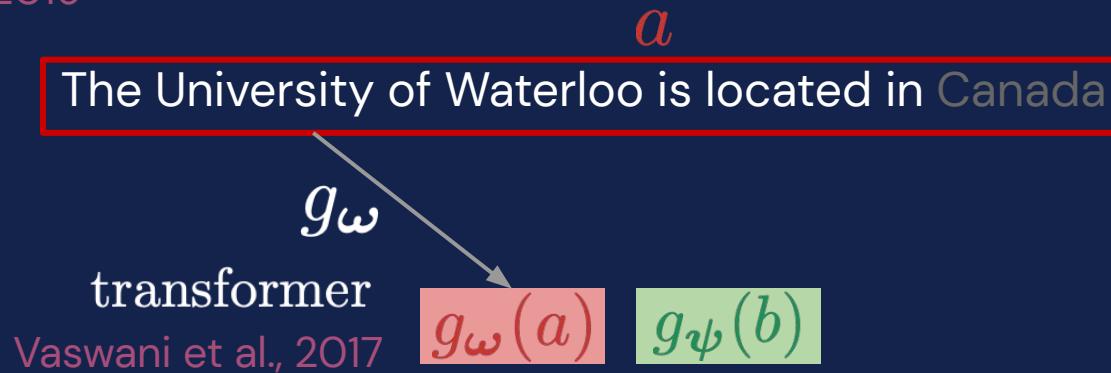
BERT

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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- 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

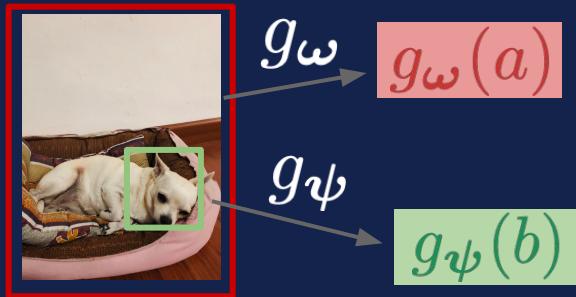
Deep InfoMax (DIM; Hjelm et al., 2019)



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

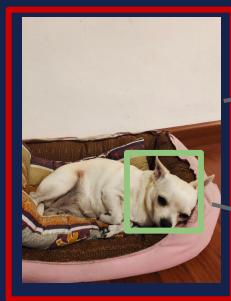
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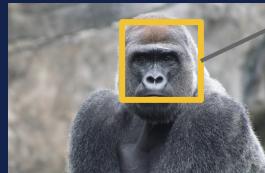


$$g_{\omega} \rightarrow g_{\omega}(a)$$

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



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



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

Model

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



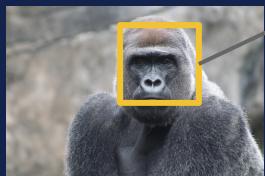
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$$g_{\psi} \rightarrow g_{\psi}(c_1)$$

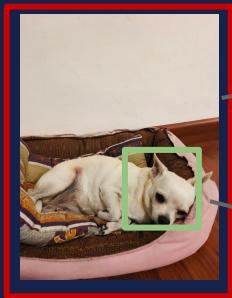
$$g_{\psi} \rightarrow g_{\psi}(c_2)$$



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

Model

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

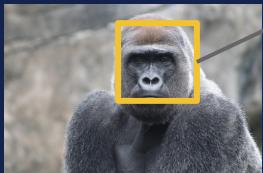


$$g_{\omega} \rightarrow g_{\omega}(a)$$

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



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

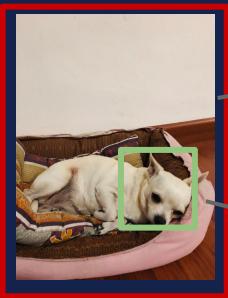


$$g_{\psi} \rightarrow g_{\psi}(c_2)$$

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Model

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



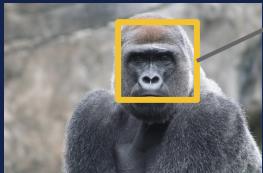
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$$g_{\psi} \rightarrow g_{\psi}(c_1)$$

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

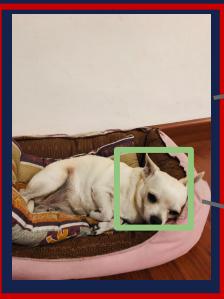


UWaterloo is located in Canada

$$\begin{array}{l} g_{\psi} \\ \text{transformer} \\ \downarrow \\ g_{\psi}(b) \end{array}$$

Model

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



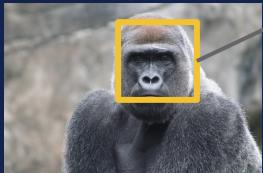
$$g_{\omega} \rightarrow g_{\omega}(a)$$

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



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

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



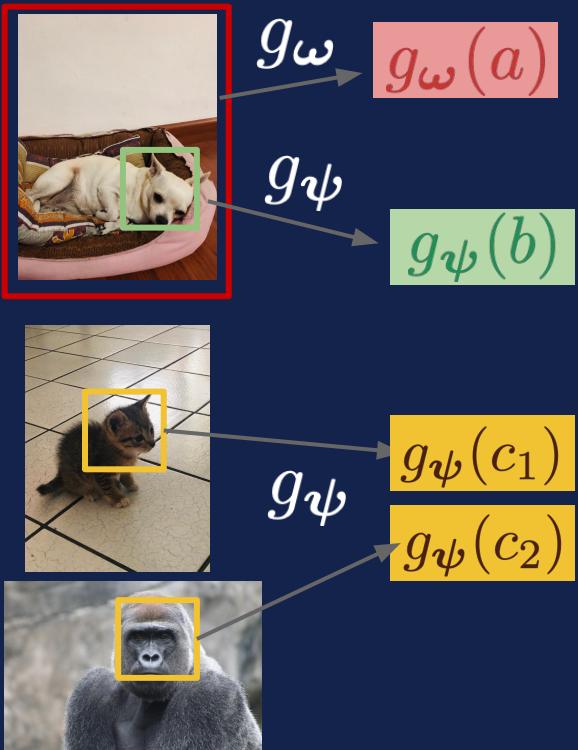
UWaterloo is located in Canada

g_{ω}
transformer

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

Model

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



UWaterloo is located in Canada

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

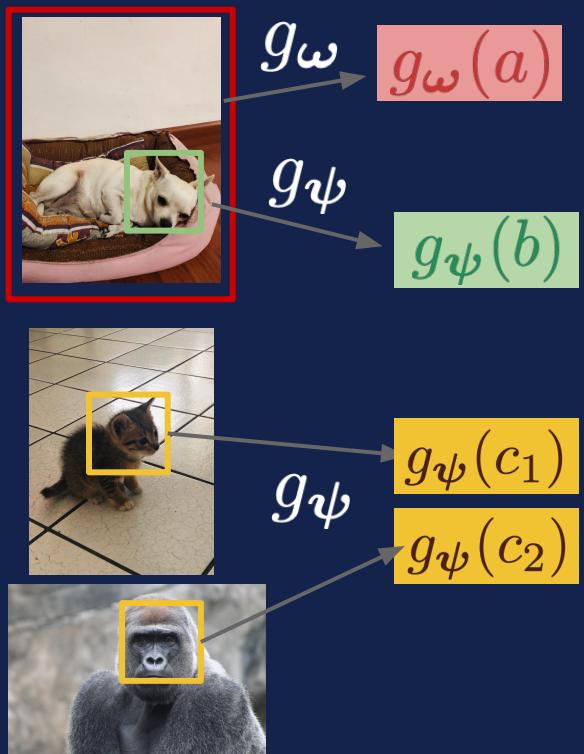
Starcraft II is a fun game

Cristiano Ronaldo scores an own goal

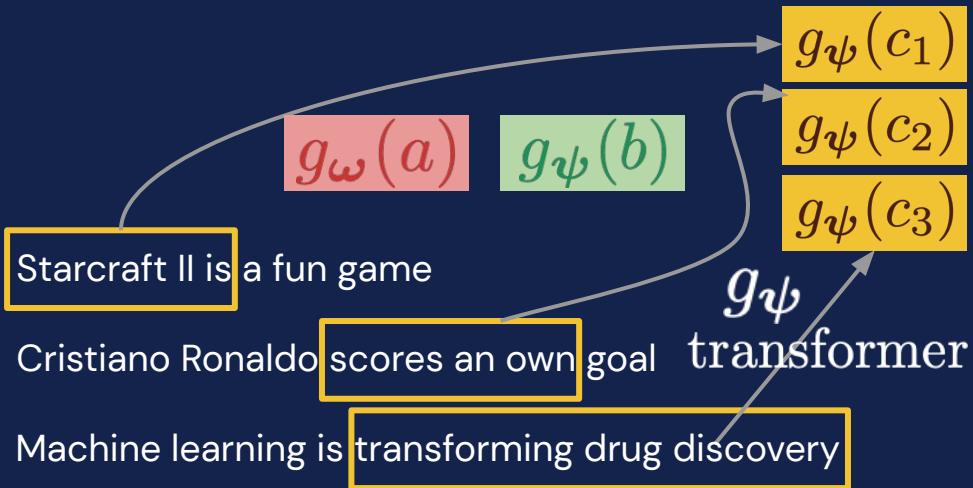
Machine learning is transforming drug discovery

Model

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

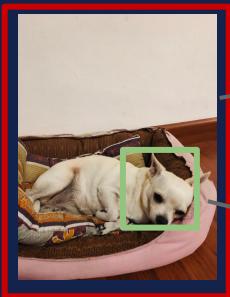


UWaterloo is located in Canada



Model

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



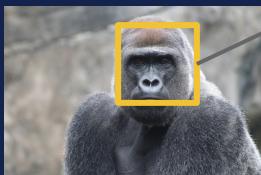
$$g_{\omega} \rightarrow g_{\omega}(a)$$

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



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

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



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

UWaterloo is located in Canada

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

$$\begin{bmatrix} g_{\psi}(c_1) \\ g_{\psi}(c_2) \\ g_{\psi}(c_3) \end{bmatrix}$$

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

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

Adaptive Semiparametric Language Models

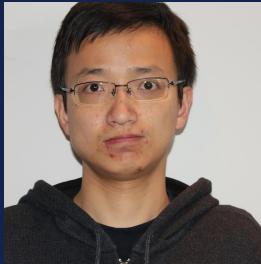
Yogatama et al., TACL 2021



Dani



Cyprien



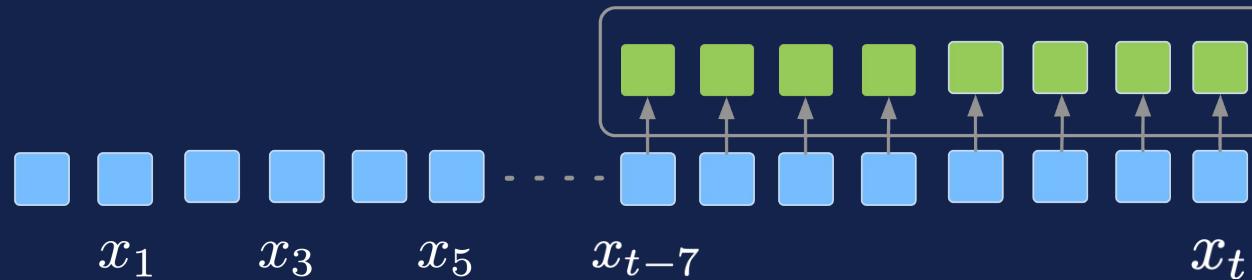
Lingpeng

Background

What are core limitations of existing architectures?

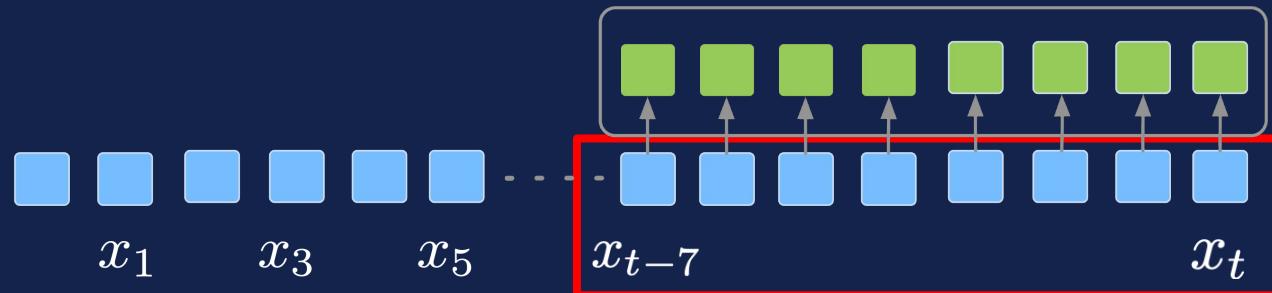
Background

State of the art architectures (transformers) are limited by the input sequence length.



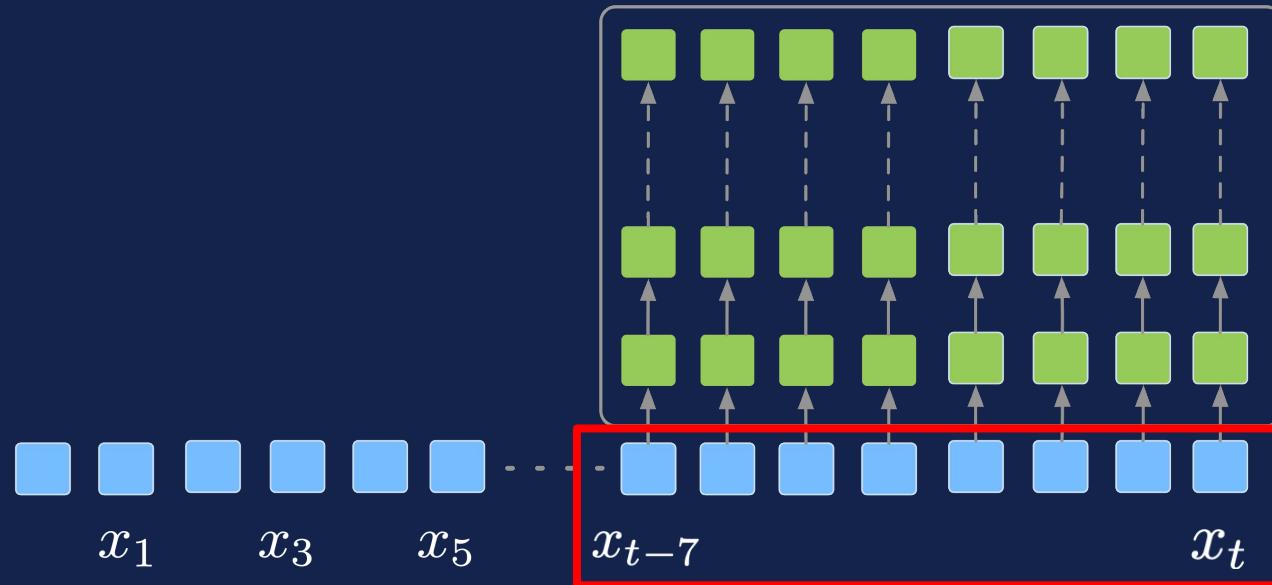
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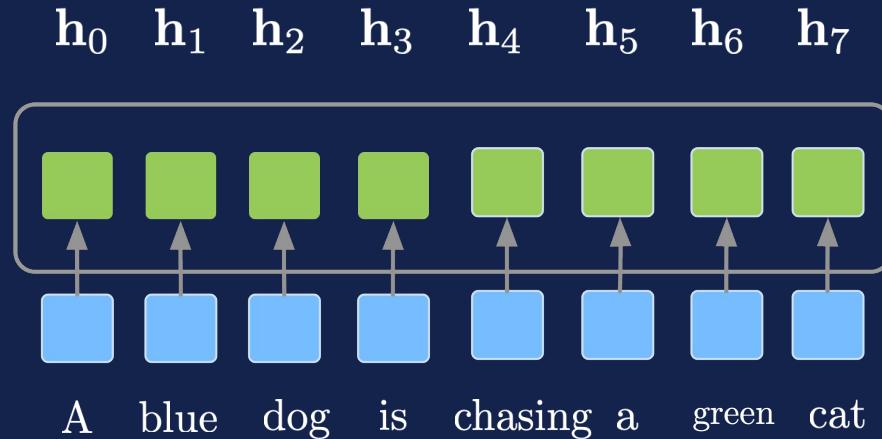


Background

Knowledge is encoded in the weights of a parametric neural network.

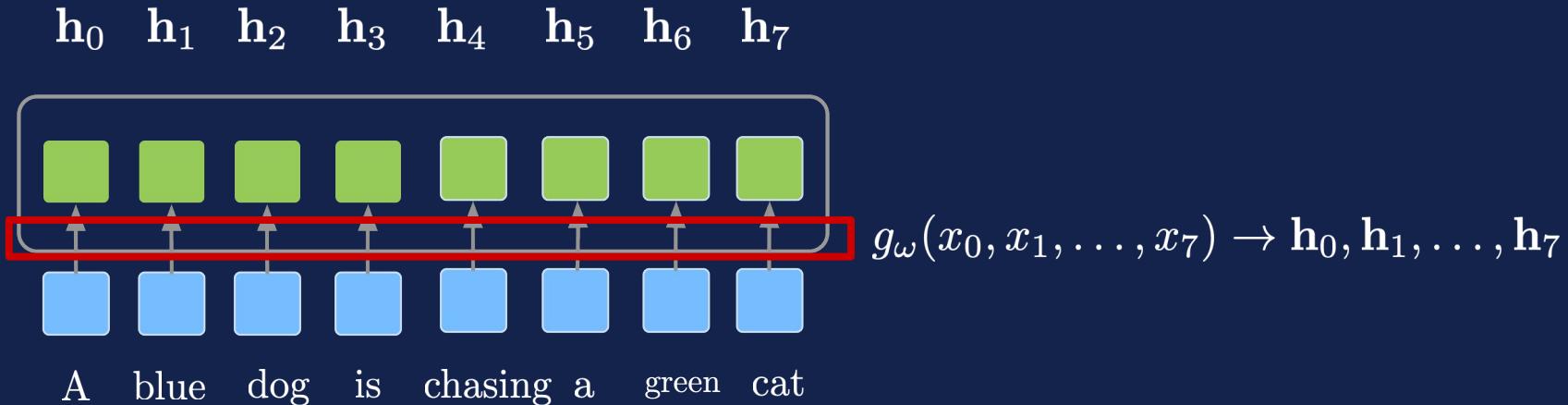
Background

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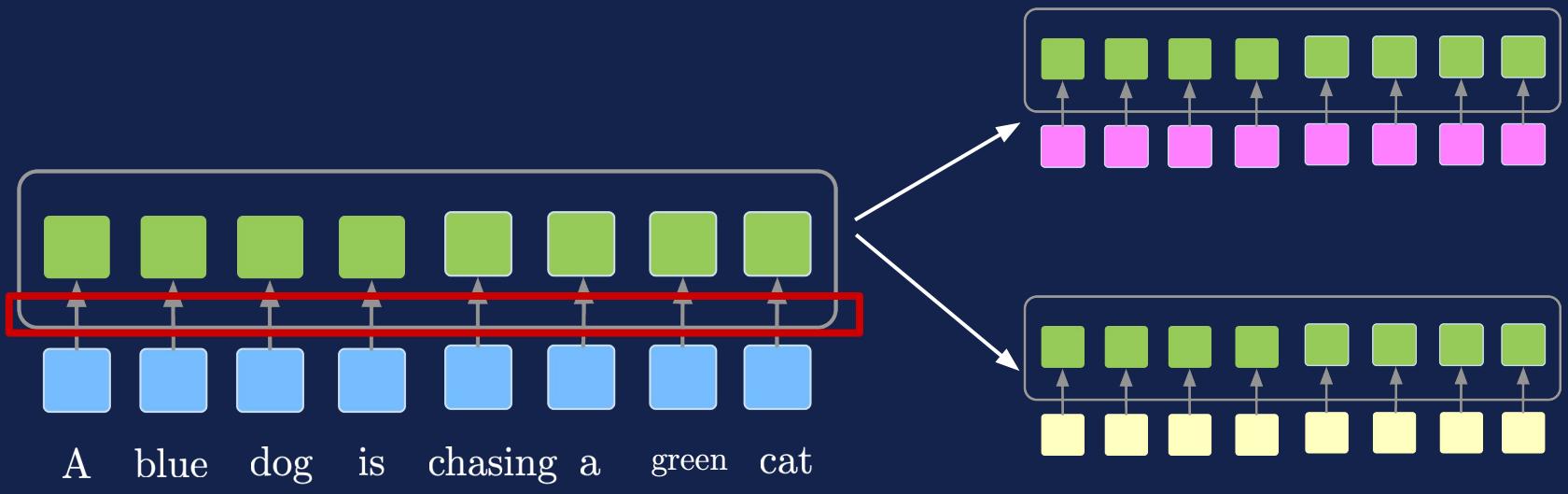
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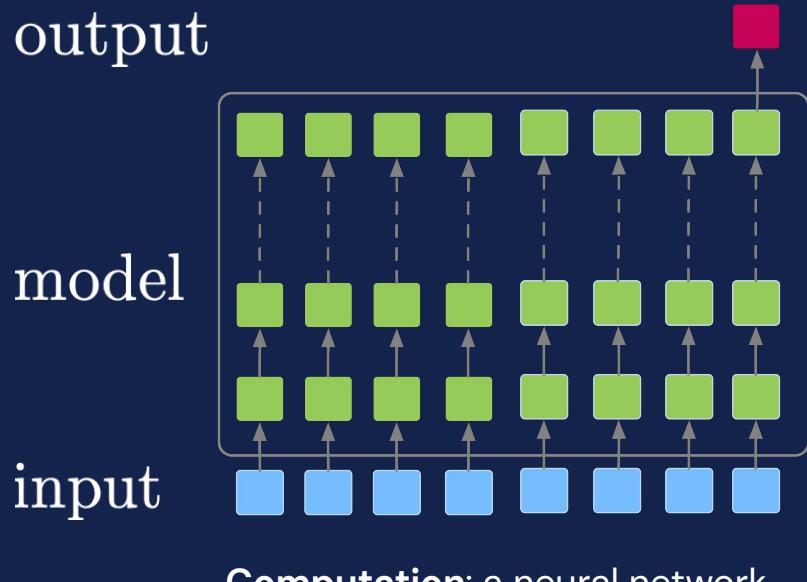
Update weights with new knowledge → changes affect all examples (sequences).

Semiparametric Models

Separation of computation and storage as an architectural bias.

Semiparametric Models

Separation of computation and storage as an architectural bias.



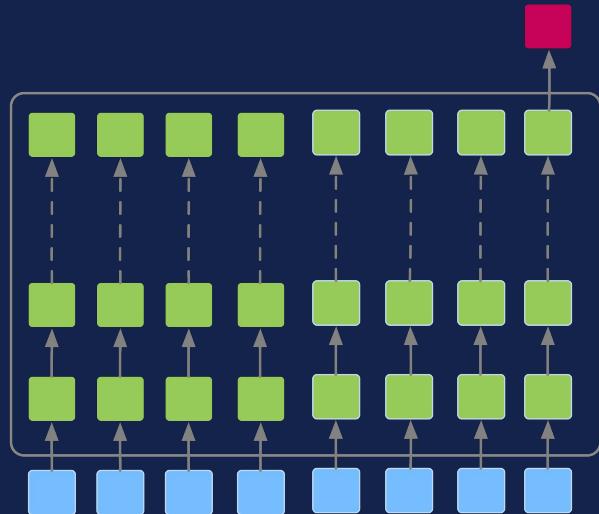
Semiparametric Models

Separation of computation and storage as an architectural bias.

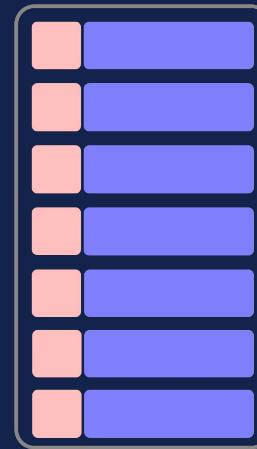
output

model

input

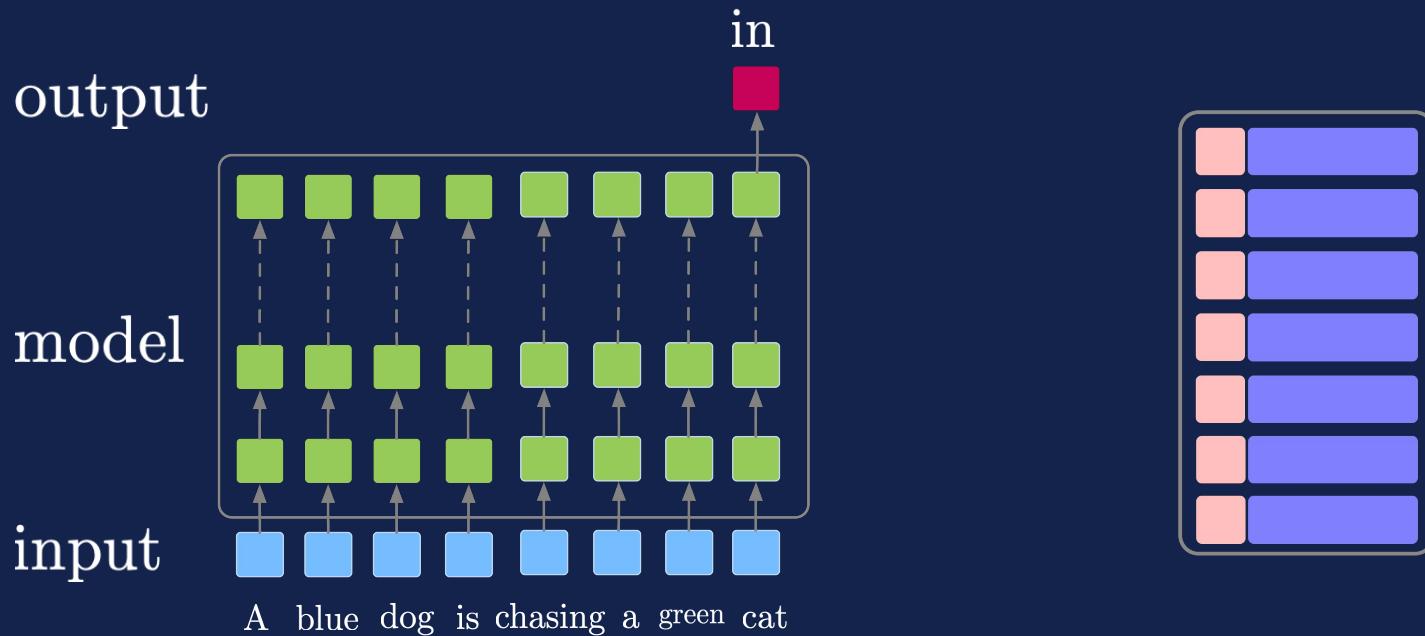


Computation: a neural network



Memory (storage): a key-value database

Semiparametric Language Models



Problem Setup

University of Waterloo Wikipedia

The University of Waterloo (commonly referred to as Waterloo, UW, or UWaterloo) is a public research university with a main campus in Waterloo, Ontario, Canada. The main campus is on 404 hectares of land adjacent to **Uptown**

Problem Setup

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Language Model

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Current context

(computation)

Language Model

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Current context
(computation)

Extended context
(short-term memory)

Language Model

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Current context
(computation)

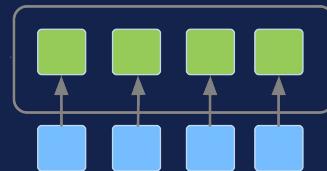
Extended context
(short-term memory)

Long-term memory

Waterloo Park Wikipedia

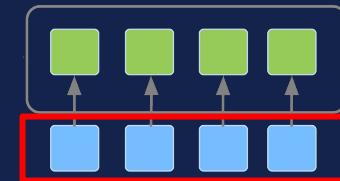
Waterloo Park is an urban park situated in Waterloo, Ontario, Canada.

Language Model



UWaterloo is a public

Language Model

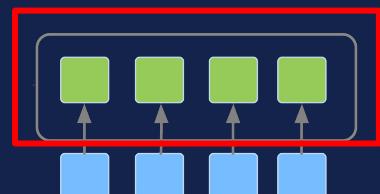


Input: a sequence of tokens.

UWaterloo is a public

Language Model

Encoder: transformer
(Vaswani et al., 2017)



UWaterloo is a public

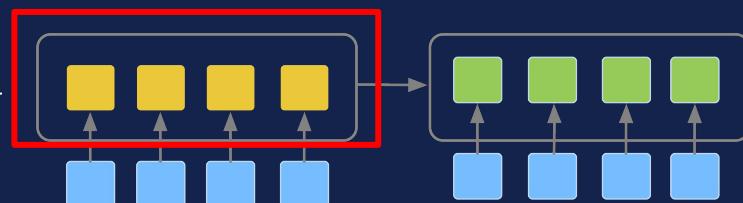
encoder
(computation)

Language Model

Short-term memory:

transformer-XL (Dai et al., 2019)

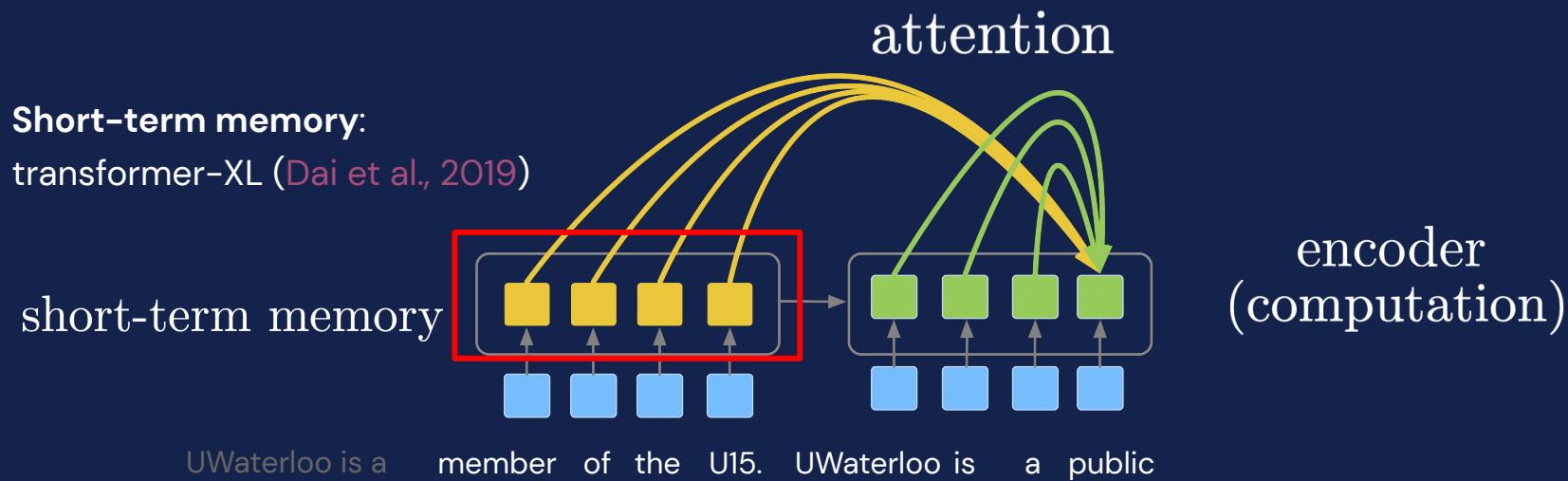
short-term memory



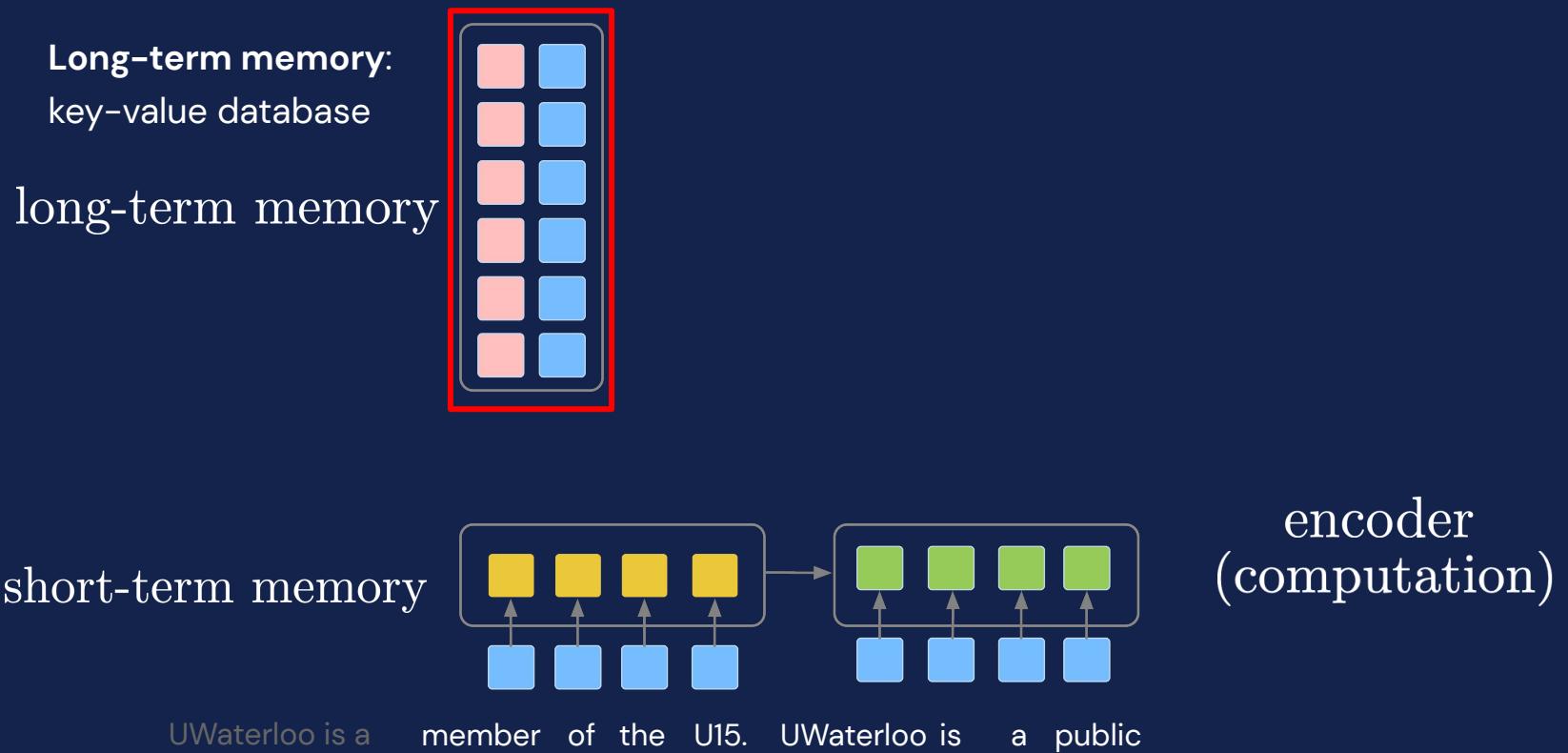
encoder
(computation)

UWaterloo is a member of the U15. UWaterloo is a public

Language Model

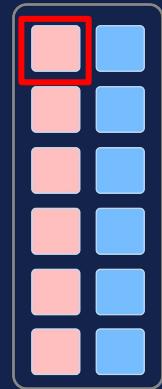


Language Model



Language Model

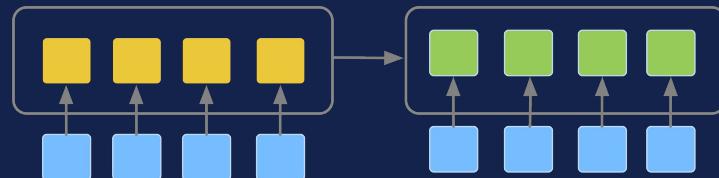
long-term memory



Key: compressed long-term context

Canada is a beautiful

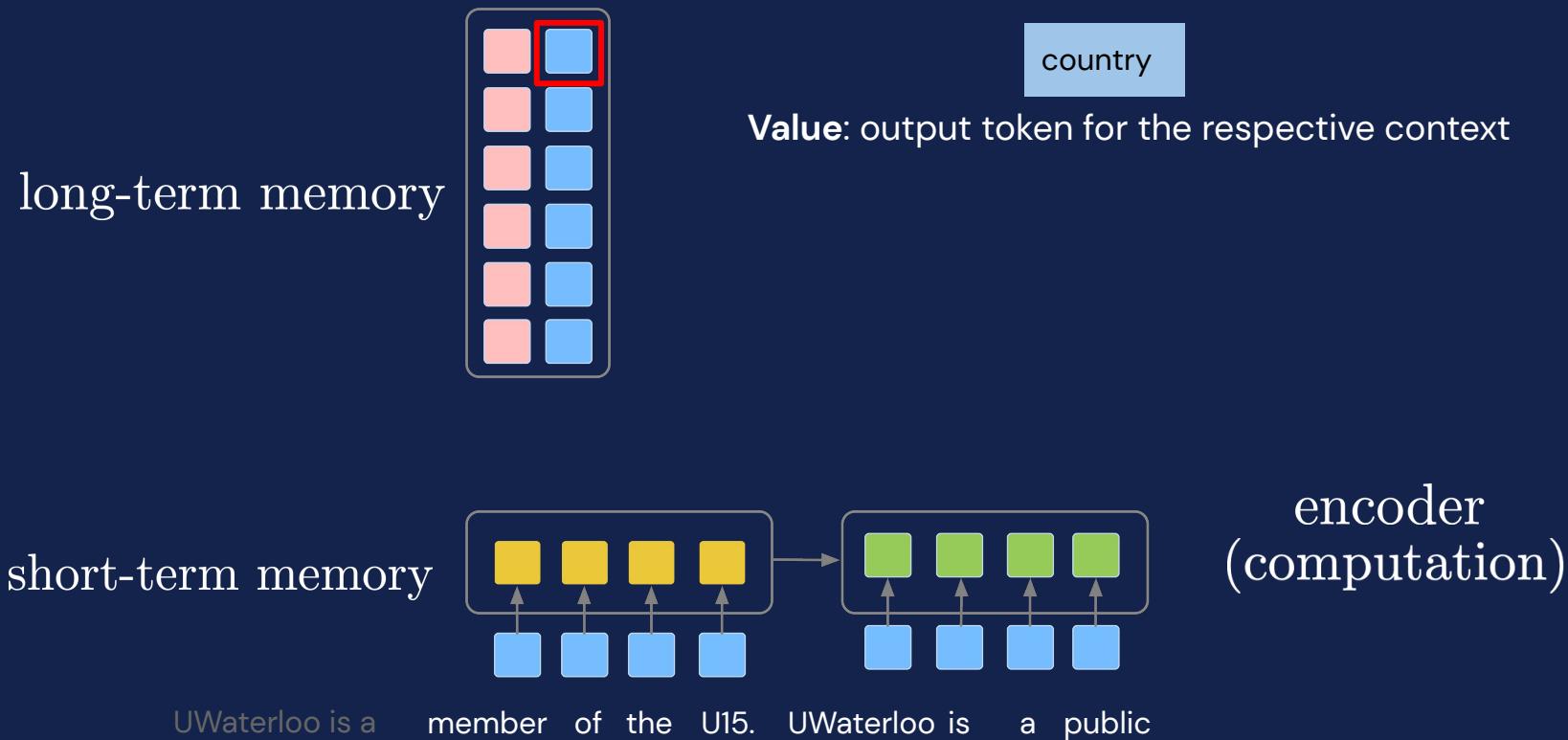
short-term memory



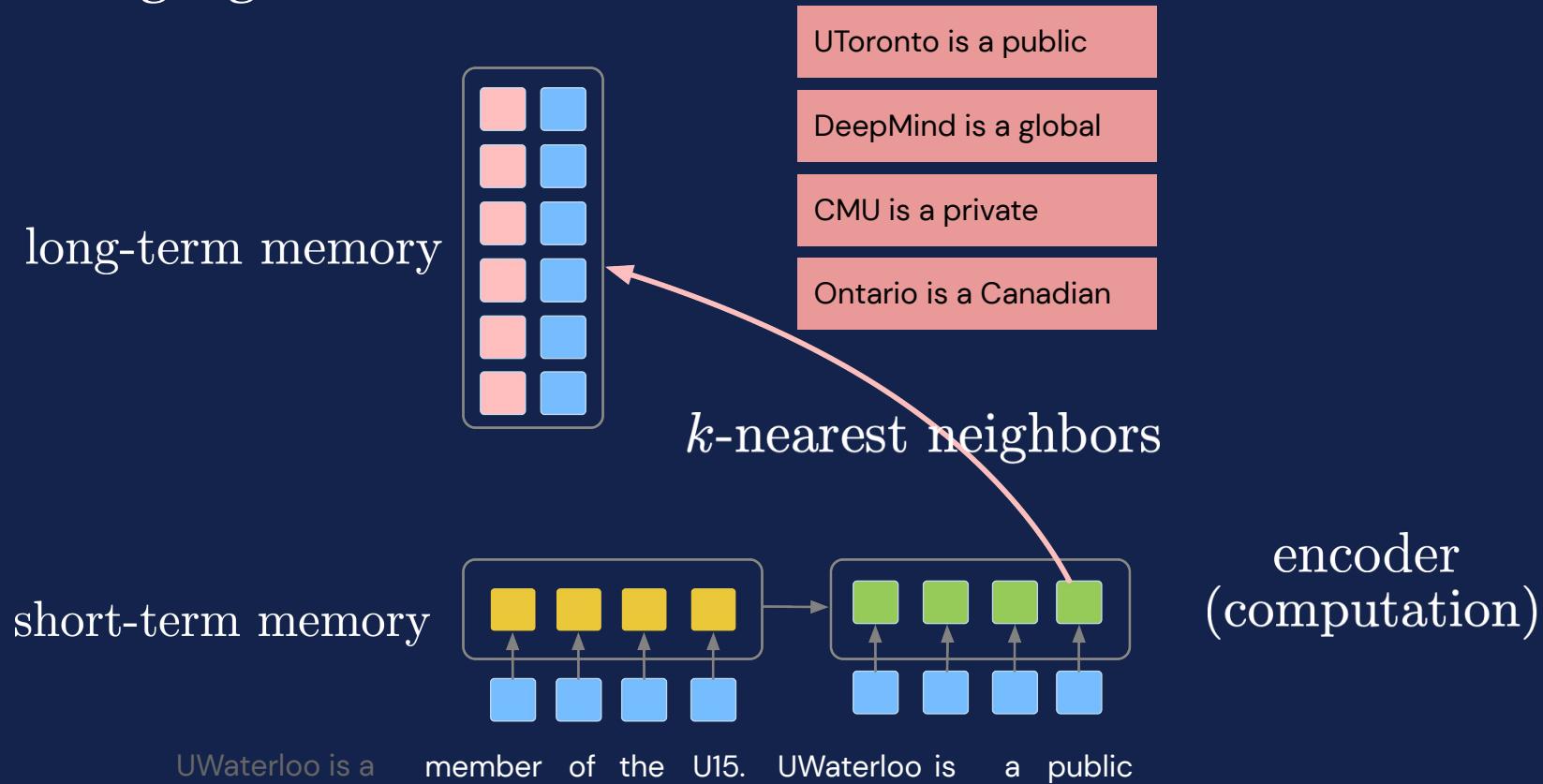
UWaterloo is a member of the U15. UWaterloo is a public

encoder
(computation)

Language Model



Language Model



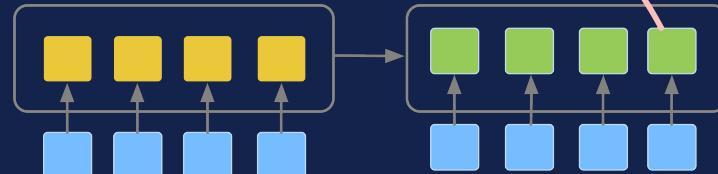
Language Model

long-term memory

UToronto is a public	research
DeepMind is a global	research
CMU is a private	university
Ontario is a Canadian	province

short-term memory

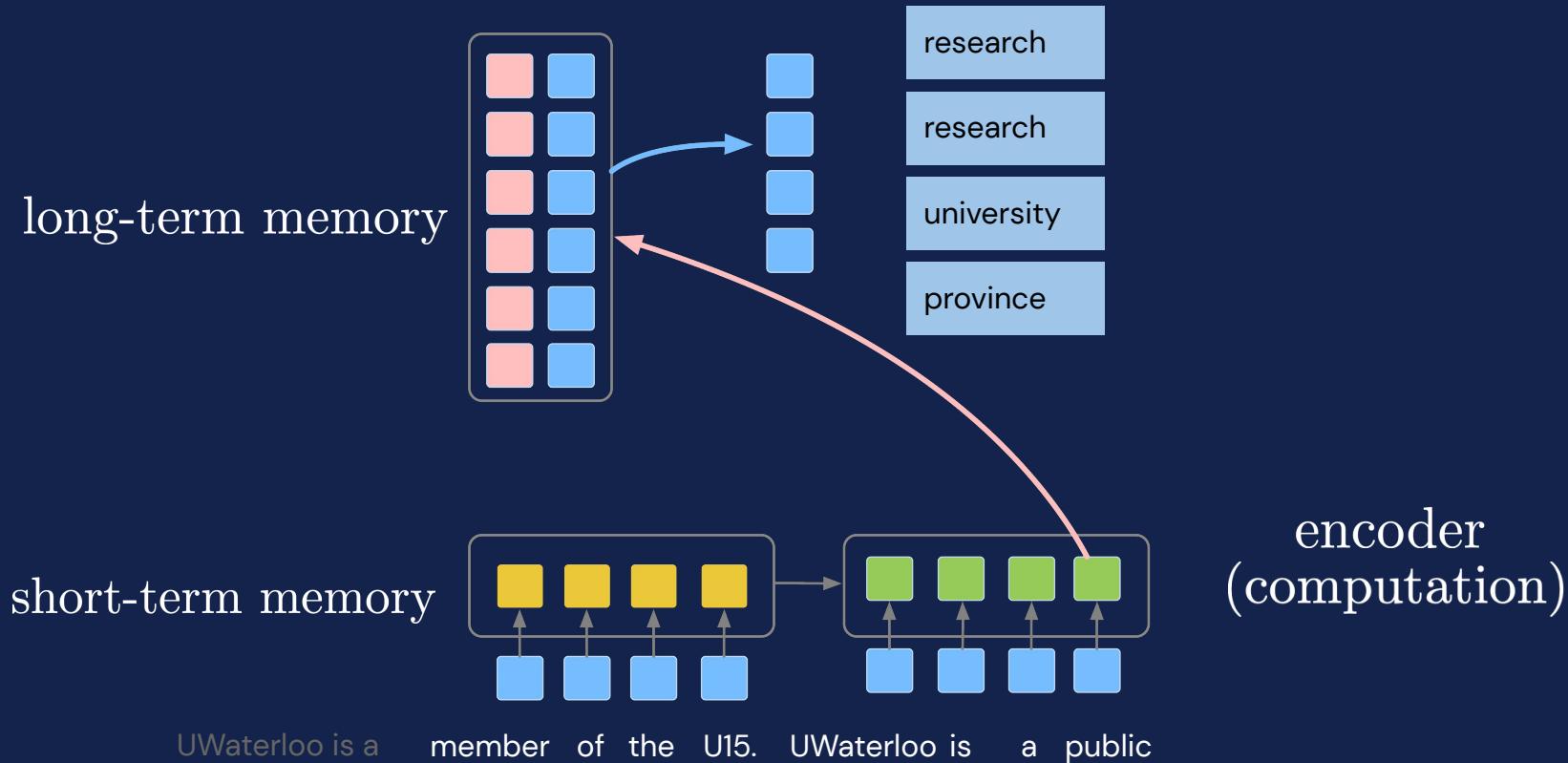
UWaterloo is a member of the U15. UWaterloo is a public



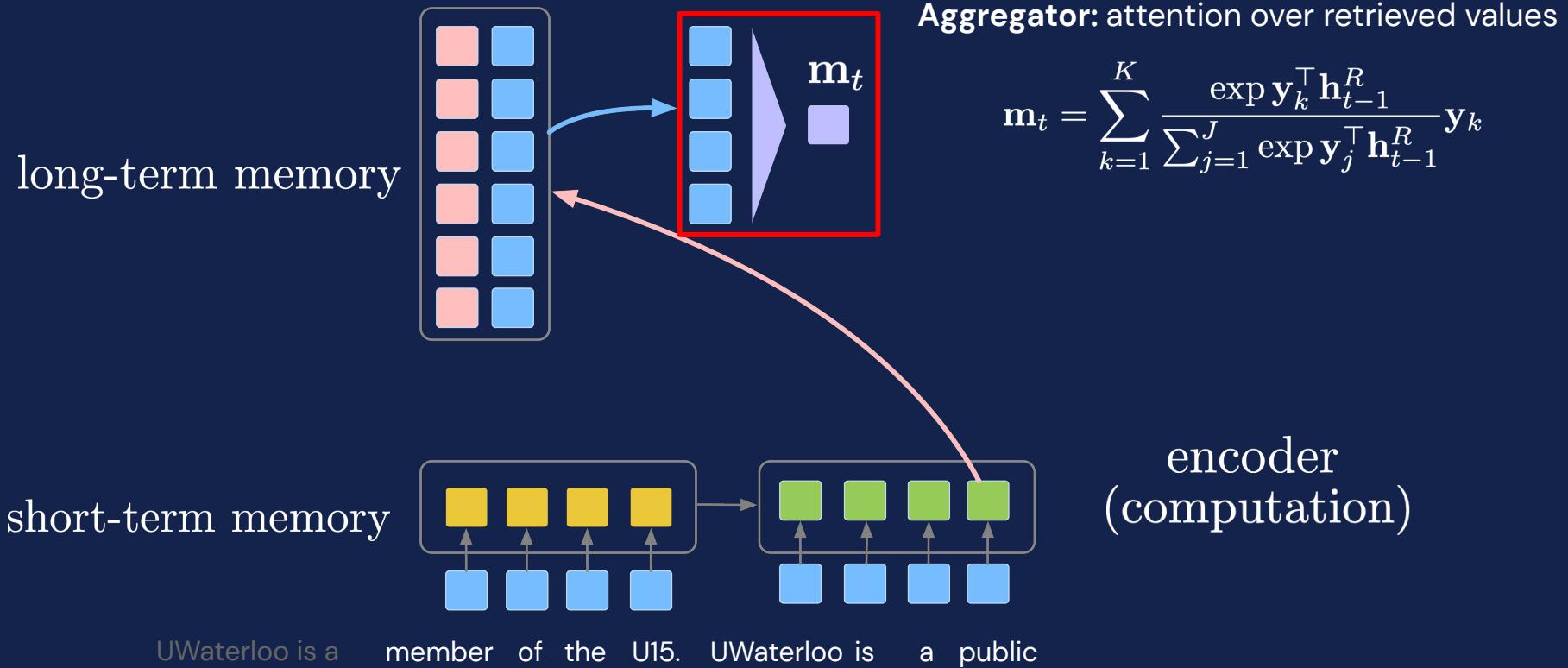
encoder
(computation)

k -nearest neighbors

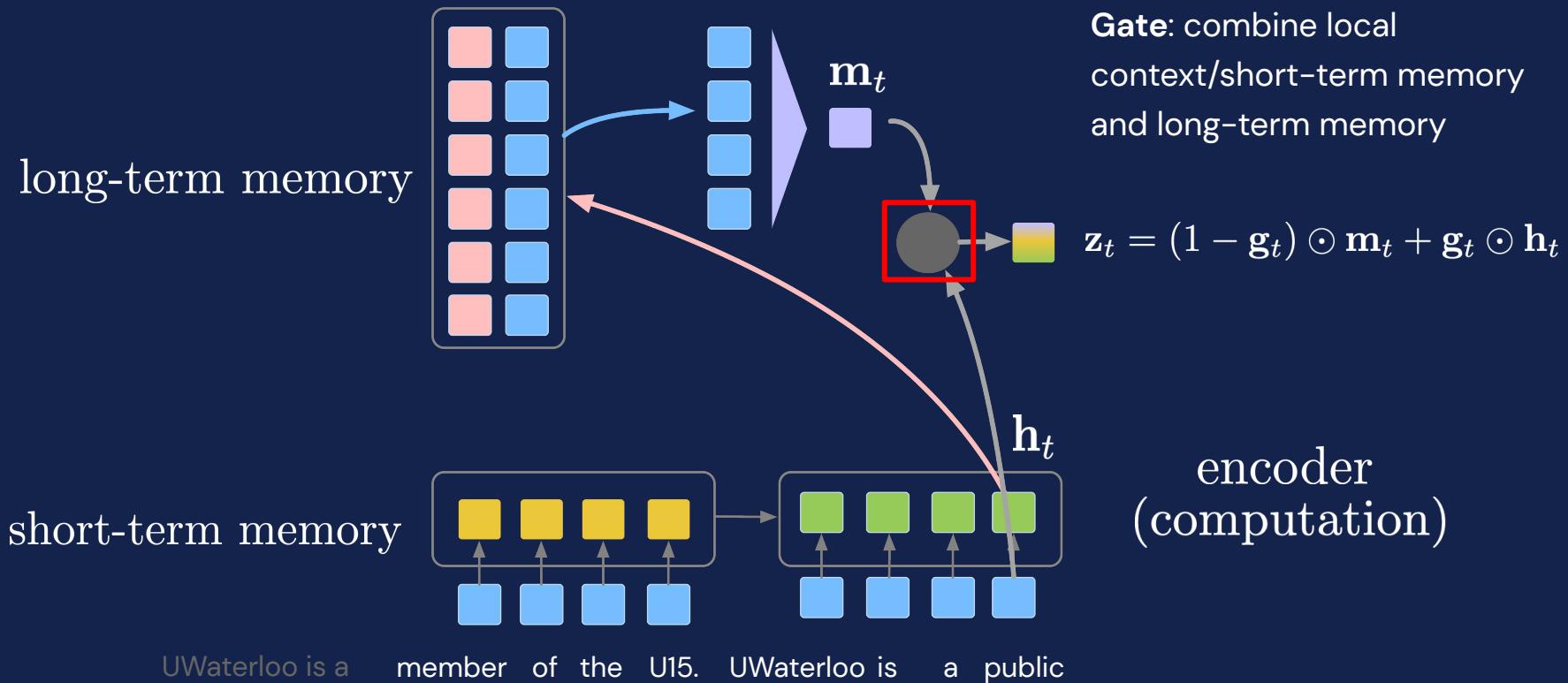
Language Model



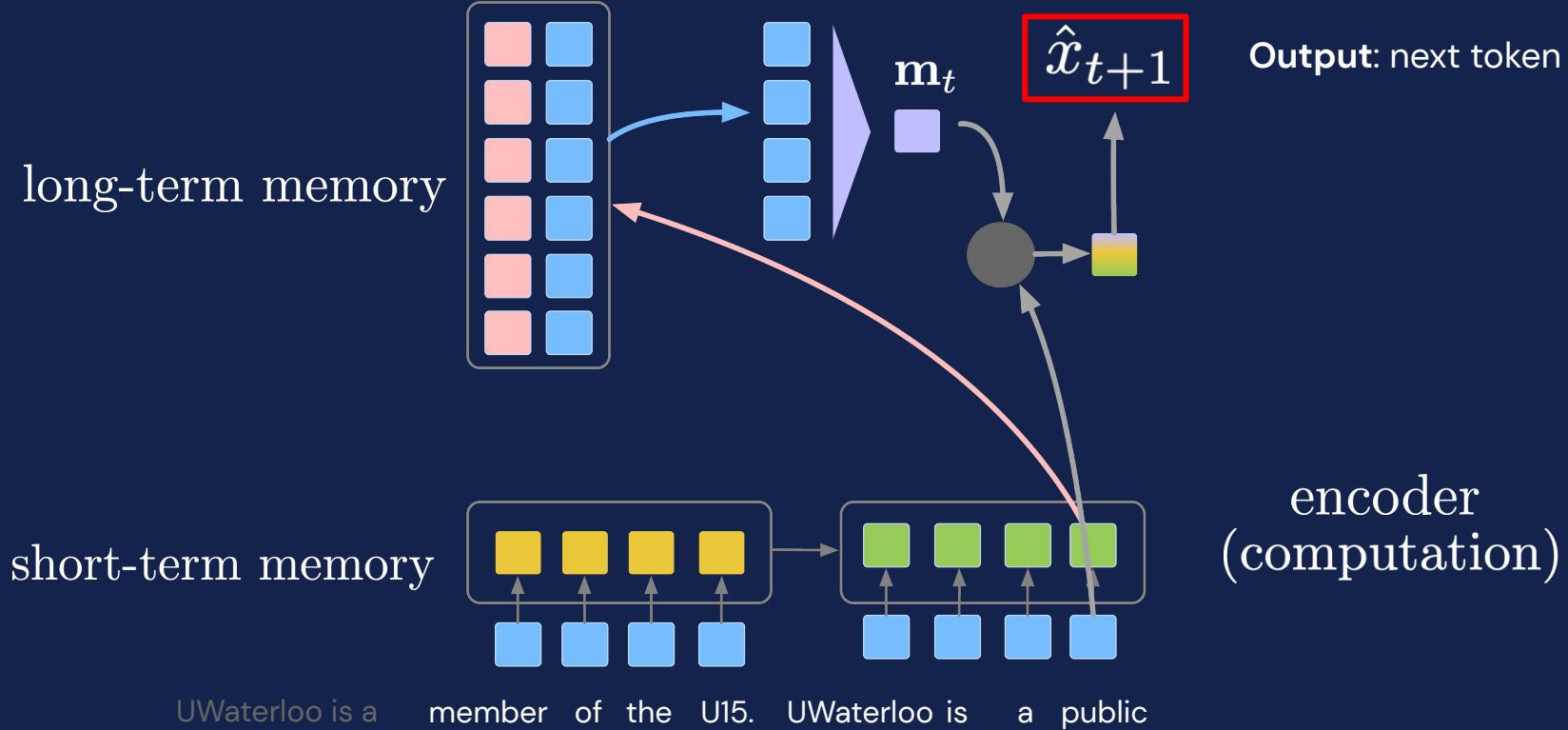
Language Model



Language Model



Language Model

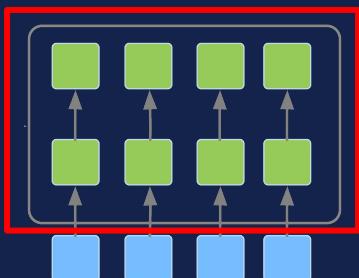


Language Model



Input: a sequence of tokens.

Language Model



Encoder: transformer
(Vaswani et al., 2017)
encoder
(computation)

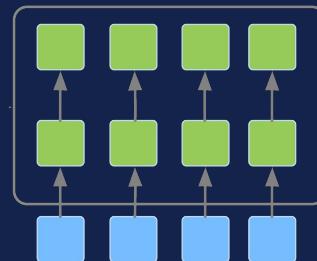
Language Model

Short-term memory:

transformer-XL (Dai et al., 2019)

Encoder: transformer
(Vaswani et al., 2017)

encoder
(computation)



UWaterloo is a

member of the U15.

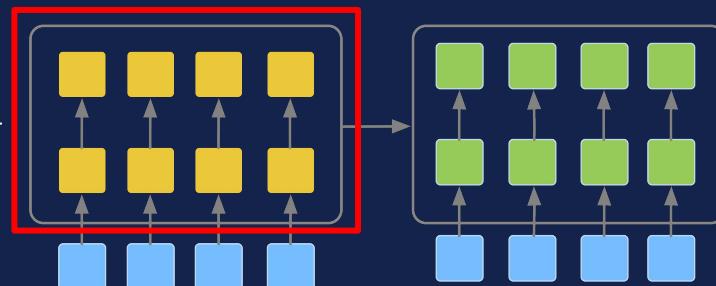
UWaterloo is a public

Language Model

Short-term memory:

transformer-XL (Dai et al., 2019)

short-term memory



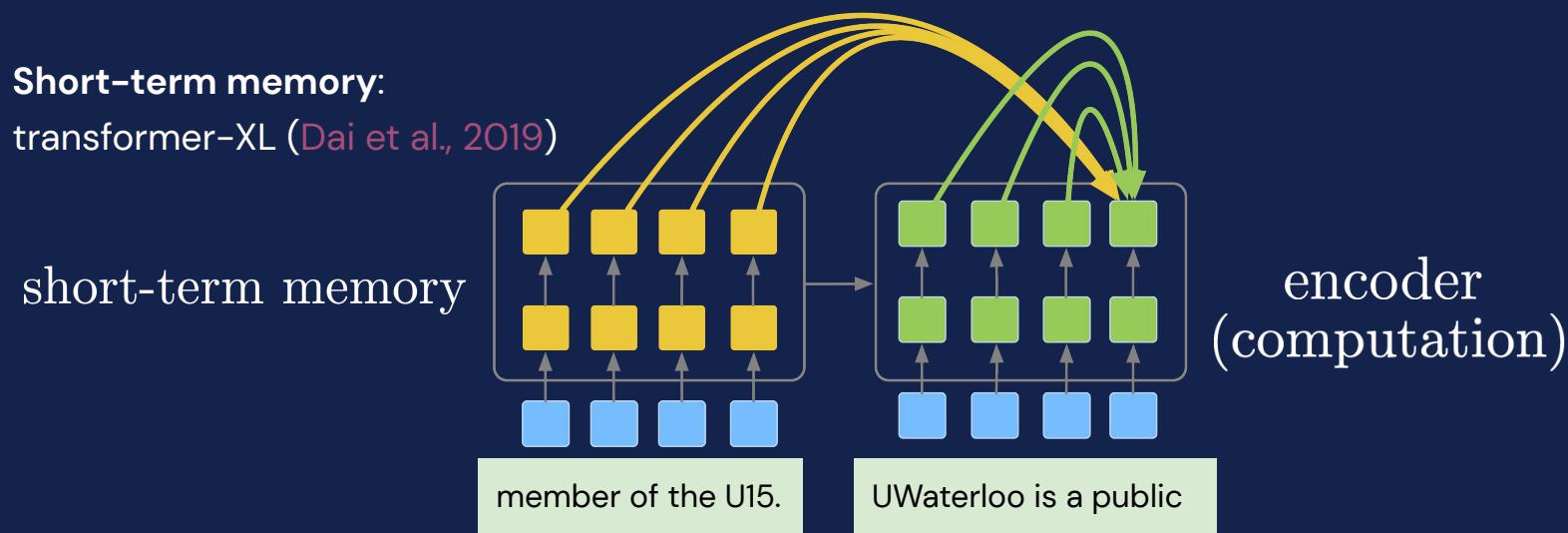
UWaterloo is a

member of the U15.

encoder
(computation)

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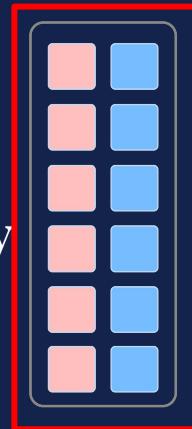
Language Model



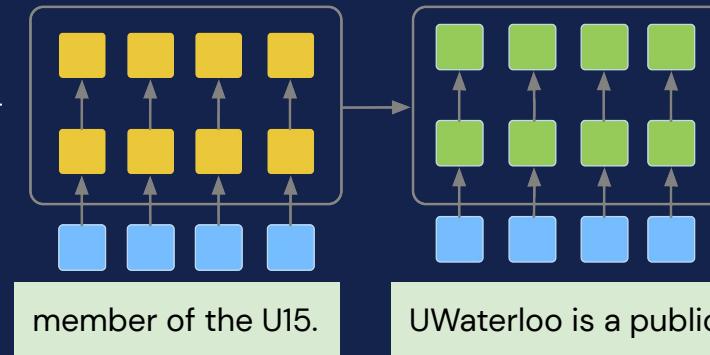
Language Model

Long-term memory:
key-value database

long-term memory



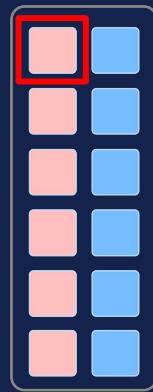
short-term memory



encoder
(computation)

Language Model

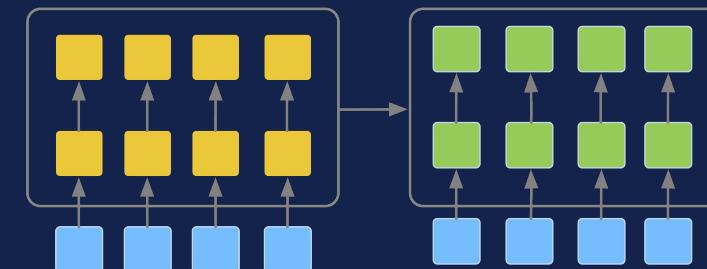
long-term memory



Key: compressed long-term context

Canada is a beautiful

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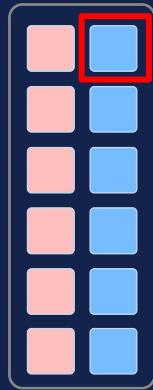
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UWaterloo is a public

encoder
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Language Model

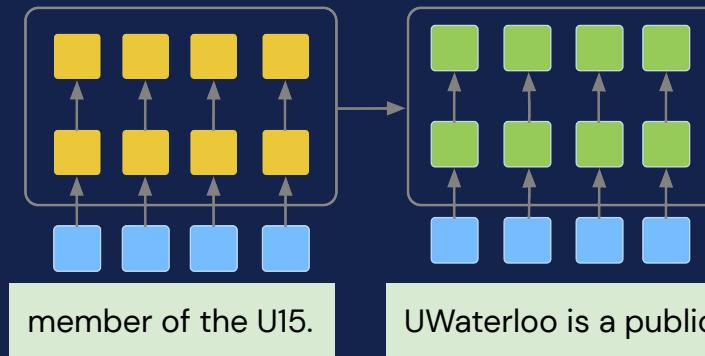
long-term memory



country

Value: output token for the respective context

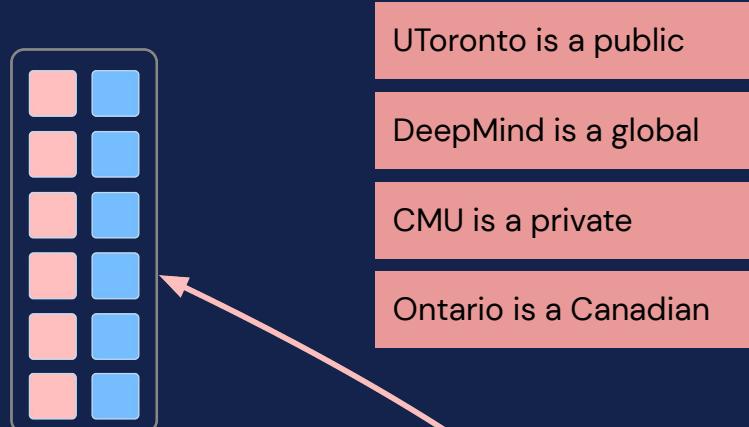
short-term memory



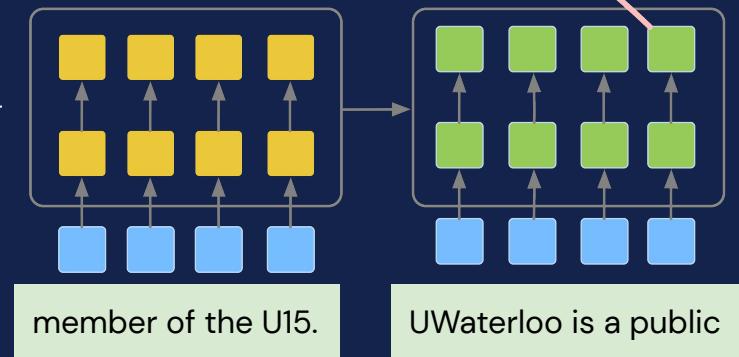
encoder
(computation)

Language Model

long-term memory



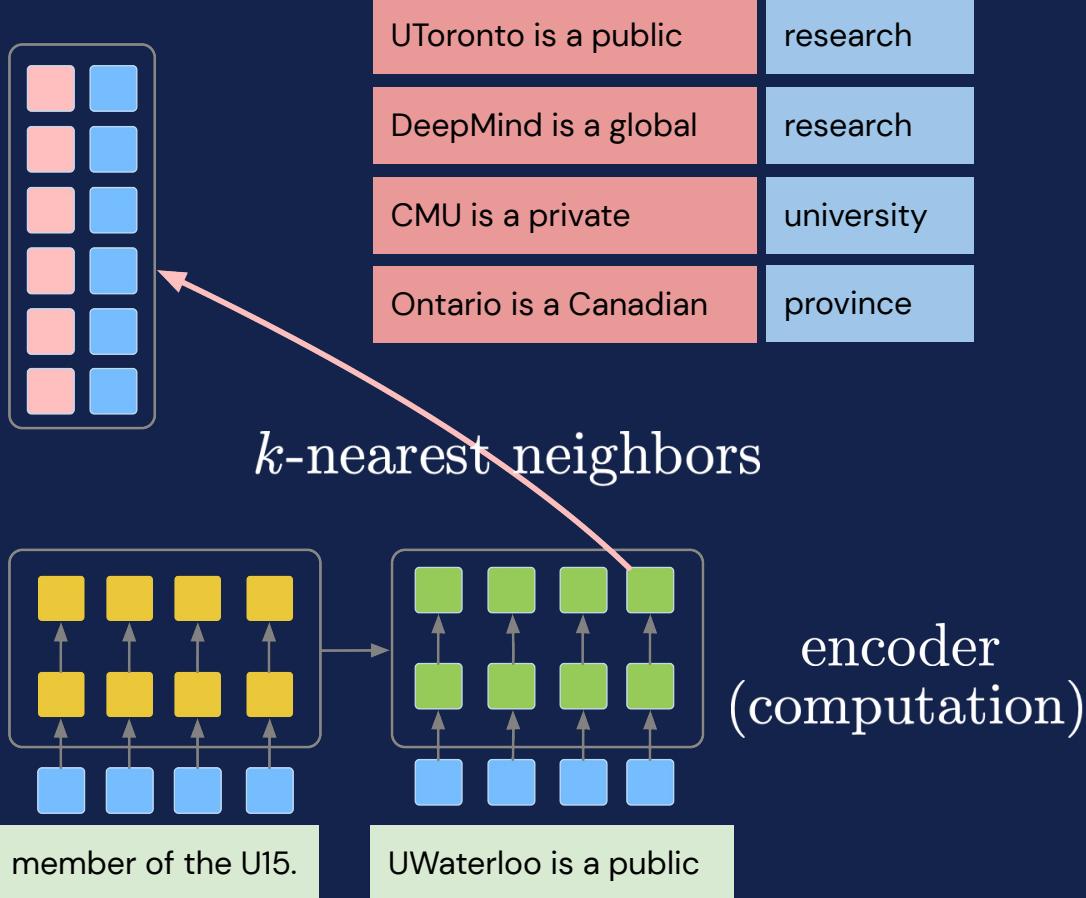
short-term memory



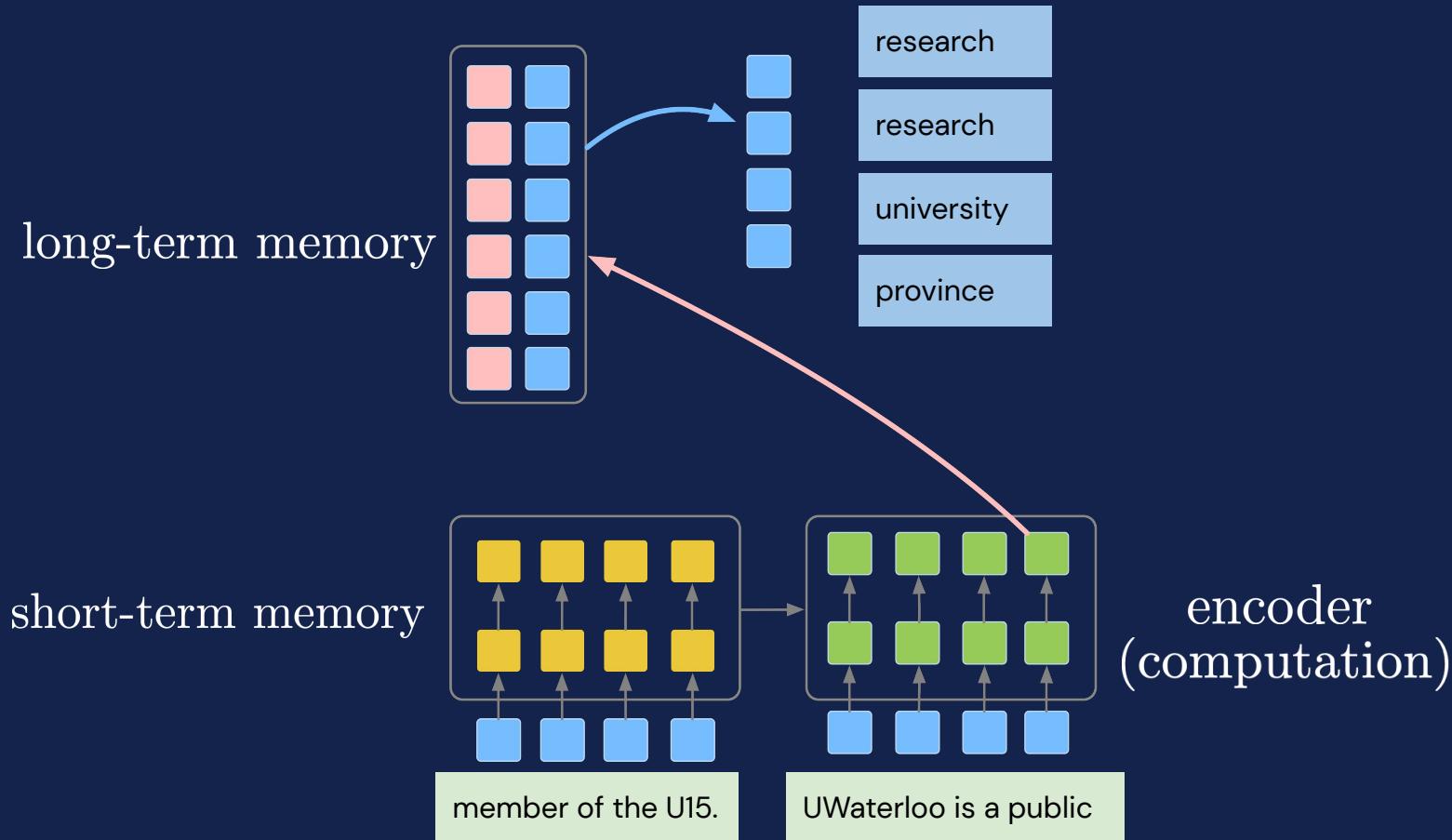
k -nearest neighbors

Language Model

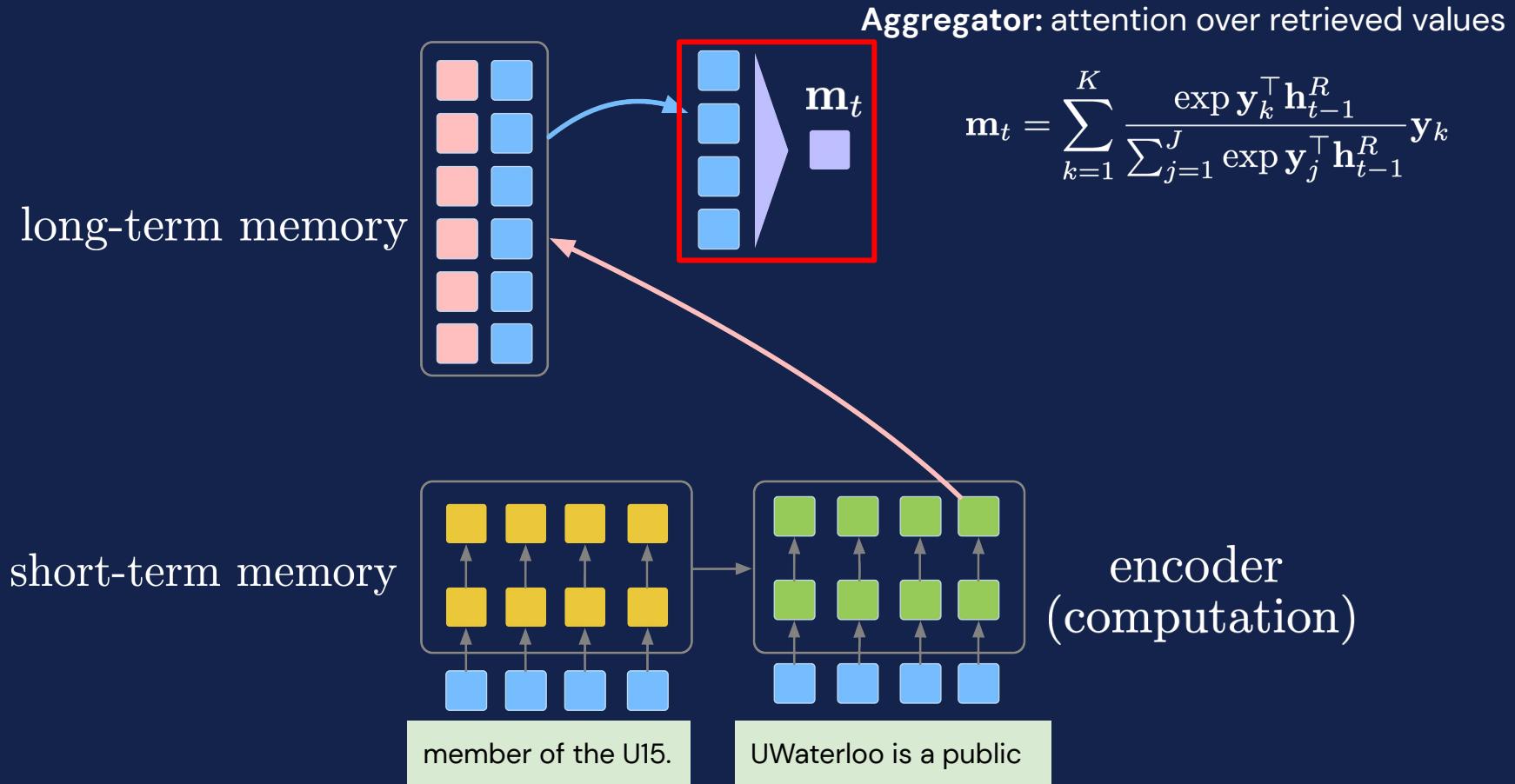
long-term memory



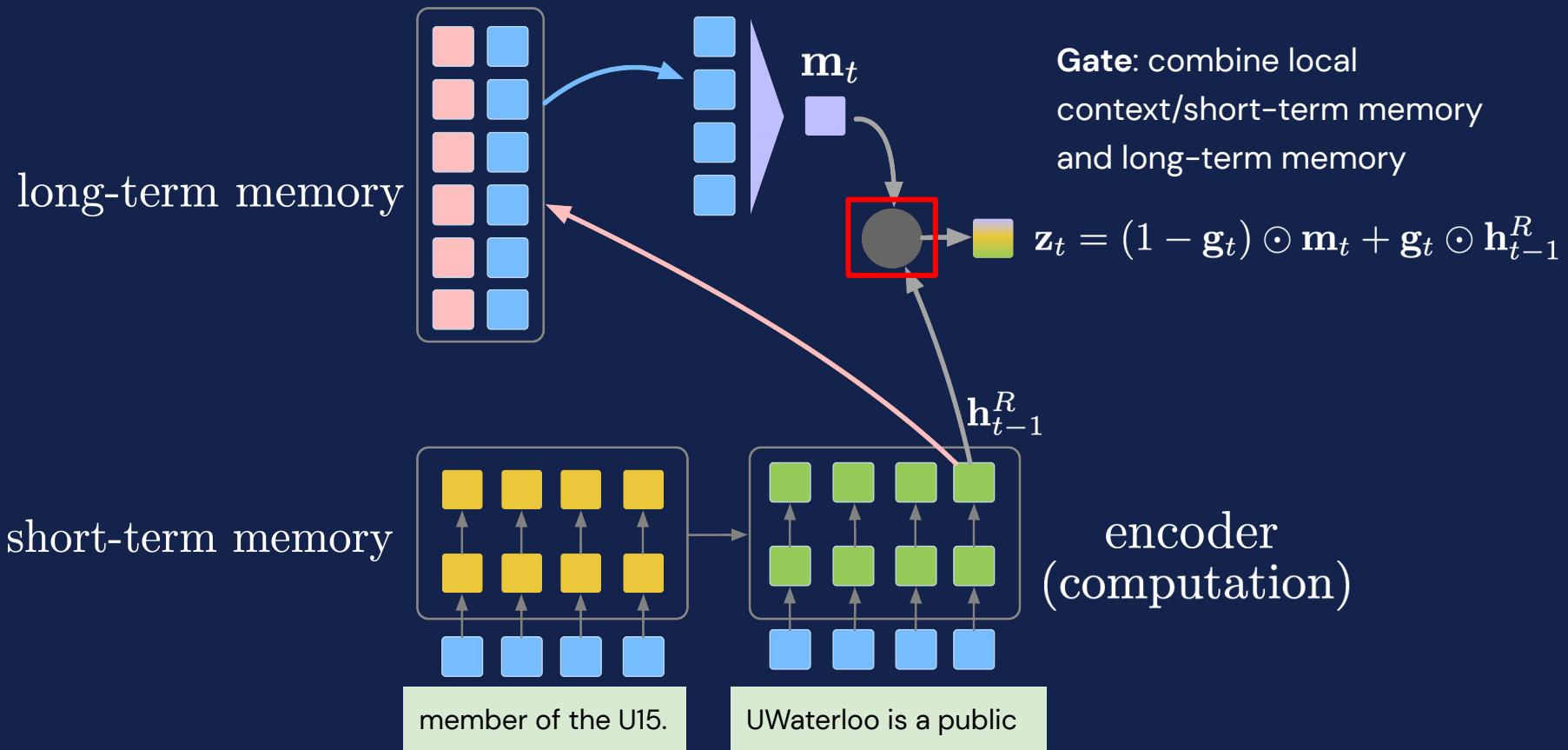
Language Model



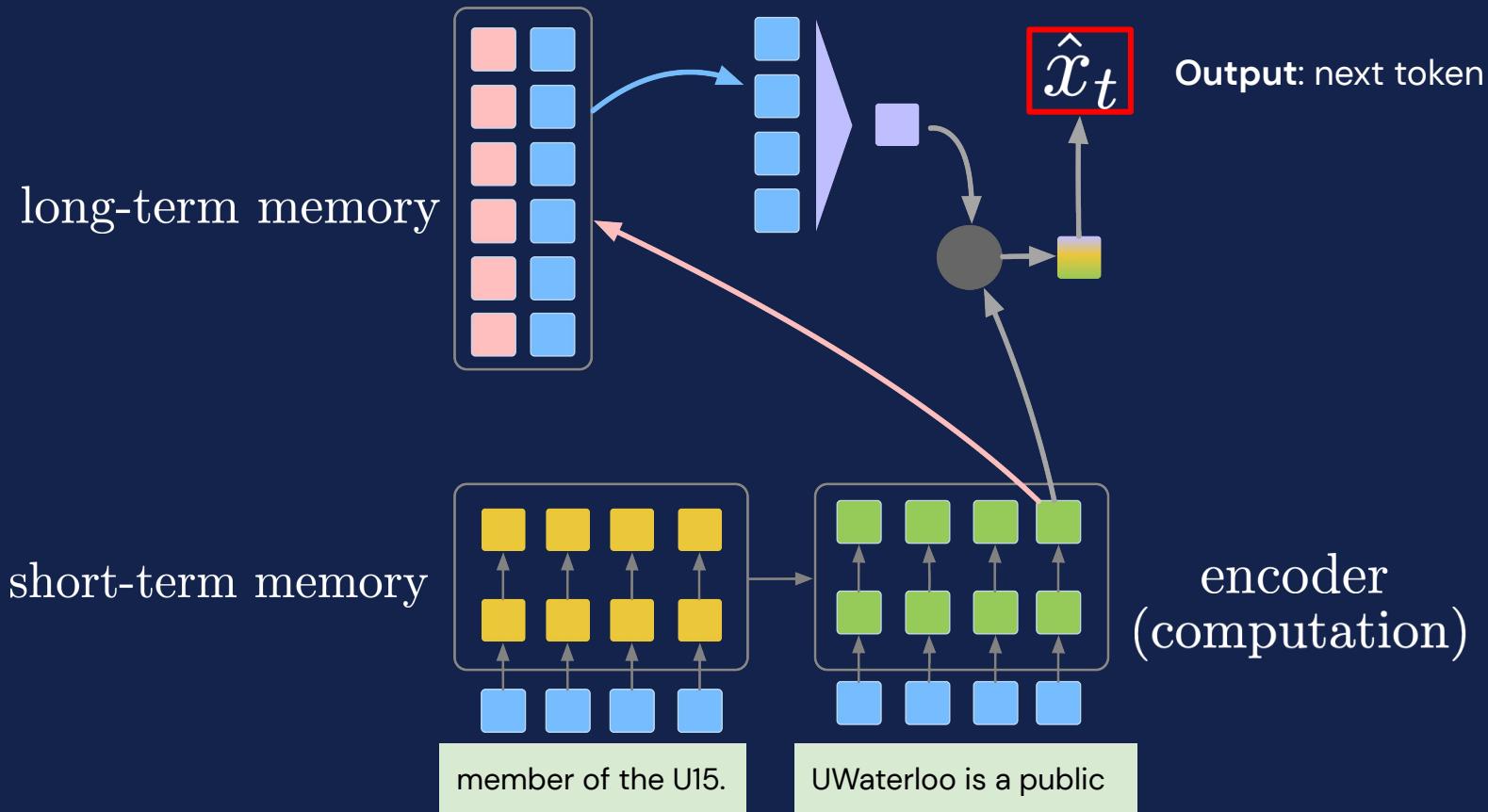
Language Model



Language Model



Language Model



Experiments

- Word-level language modeling.
 - WikiText-103 English (Merity et al., 2016).
 - WMT 2019 English: <http://www.statmt.org/wmt19/>.
- Character-level language modeling.
 - enwik8: <http://prize.hutter1.net>.

Experiments

Perplexity (1-inf), lower is better

	Base	TXL	kNN-LM	Ours
WikiText-103	21.8	19.1	18.0	17.6*
WMT	16.5	15.5	15.2	14.1

Transformer: Vaswani et al., 2017

Transformer-XL: Dai et al., 2019

kNN-LM: Khandelwal et al., 2020

Experiments

BPC (0-inf), lower is better

	Base	TXL	kNN-LM	Ours
enwik8	1.05	1.01	1.02	1.00

Transformer: Vaswani et al., 2017

Transformer-XL: Dai et al., 2019

kNN-LM: Khandelwal et al., 2020

Analysis

Liberal Democrat leader Jo Swinson has said she would work with Donald Trump in government as

Analysis

What's in the long-term memory?

Elizabeth Warren on Friday proposed \$20 trillion in spending over the next decade to provide health care for every American without raising taxes on the middle class.

Analysis

What's in the long-term memory?

For

Perhaps
Like
Elizabeth Warren

on Friday proposed \$ 20 trillion in

spending over the next decade to provide health care

every American without raising taxes on the middle class

Analysis

What's in the long-term memory?

For Warren
Warren
Perhaps Warren
Like Warren
Elizabeth Warren on Friday proposed \$20 trillion in

spending over the next decade to provide health care
every American without raising taxes on the middle class

Analysis

What's in the long-term memory?

For Warren &
Perhaps Warren may
Like Warren has
Elizabeth Warren ,
spending over the next decade to provide health care
every American without raising taxes on the middle class

Analysis

What's in the long-term memory?

For Warren & Wednesday
Warren may Tuesday
Perhaps Warren has Sunday
Like Warren , Monday
Elizabeth Warren on Friday proposed \$ 20 trillion in

spending over the next decade to provide health care

every American without raising taxes on the middle class

Analysis

What's in the long-term memory?

For Warren & Wednesday briefly a 5 billion to
Warren may Tuesday praised wiping 16 trillion in
Perhaps Warren has Sunday stood breaking 10 billion for
Like Warren , Monday defended using 166 trillion in
Elizabeth Warren on Friday proposed \$ 20 trillion in

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Analysis

What's in the long-term memory?

For Warren & Wednesday briefly a 5 billion to
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grants in 10 course eight . fight even care
funding over the next three . upgrade them cover
funds over 10 next five in improve American -
, over a next 10 , invest a insur.
spending over the next decade to provide health care

every American without raising taxes on the middle class

Analysis

What's in the long-term memory?

For	Warren	&	Wednesday	briefly	a	5	billion	to
	Warren	may	Tuesday	praised	wiping	16	trillion	in
Perhaps	Warren	has	Sunday	stood	breaking	10	billion	for
Like	Warren	,	Monday	defended	using	166	trillion	in
Elizabeth	Warren	on	Friday	proposed	\$	20	trillion	in
grants	in	10	course	eight	.	fight	even	care
funding	over	the	next	three	.	upgrade	them	cover
funds	over	10	next	five	in	improve	American	-
,	over	a	next	10	,	invest	a	insur.
spending	over	the	next	decade	to	provide	health	care
more	community	as	the	rates	.	the	middle	class
everyone	child	,	a	taxes	on	the	wealthy	class
some	baby	,	co	taxes	.	the	middle	class
every	American	by	triggering	taxes	on	all	middle	class
every	American	without	raising	taxes	on	the	middle	class

Takeaways

- A language model that adaptively combines local context, short-term memory, and long-term memory.

Takeaways

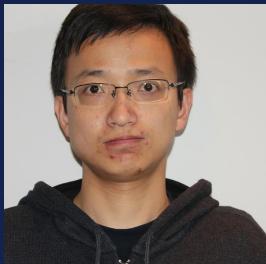
- A language model that adaptively combines local context, short-term memory, and long-term memory.
- A variant of the models for question answering (**de Masson d'Autume et al., NeurIPS 2019**)



Cyprien



Sebastian



Lingpeng



Dani

Future Directions



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

Future Directions



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Training Paradigms

Model Architectures

Future Directions



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

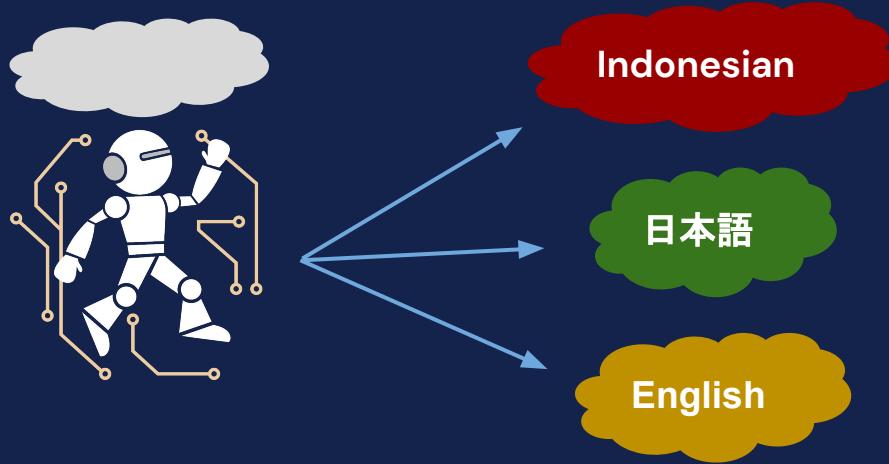
Training Paradigms

Model Architectures

Future Directions



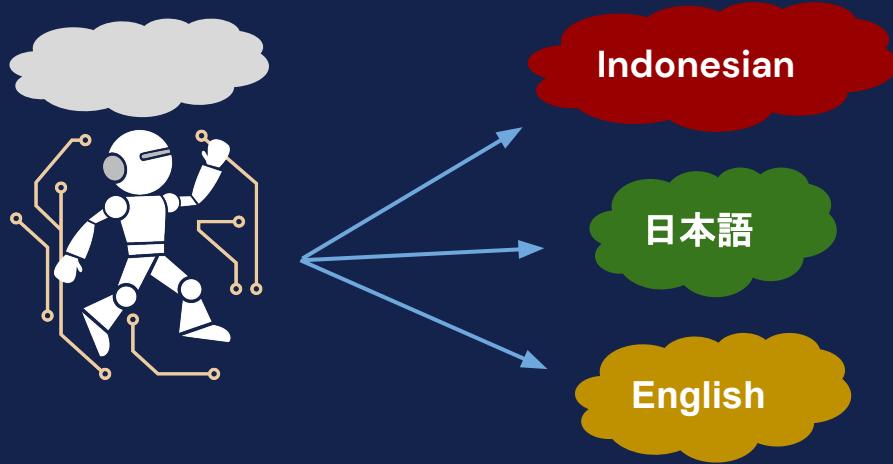
A language model that continually learns in an efficient way to perform multiple complex tasks in many languages.



Future Directions



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



Learning cross-lingual
transferable representations

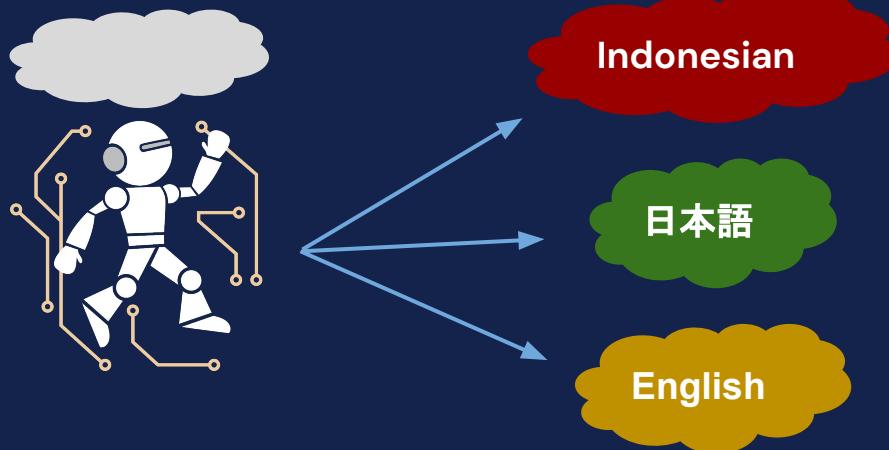
Artetxe et al., ACL 2020



Future Directions



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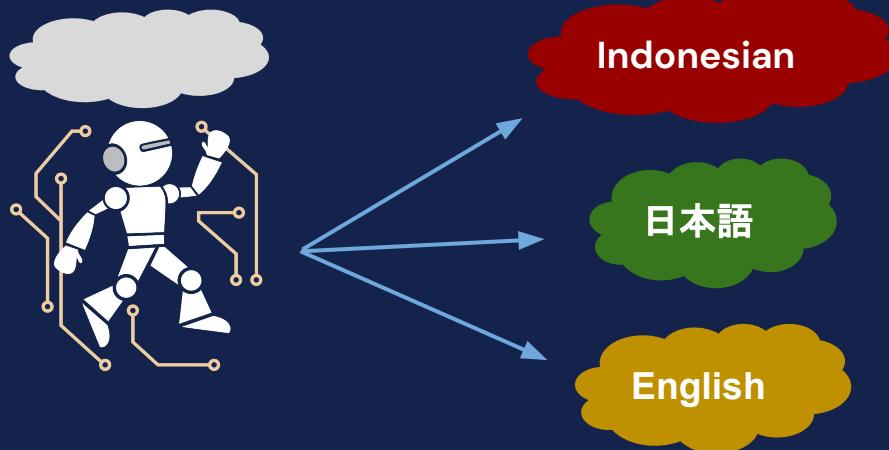
Distributionally Robust Optimization

$$\min_{\theta} \sup_q \mathbb{E}_{(x,y) \sim q} \mathcal{L}_{\theta}(x, y)$$

Future Directions



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Distributionally Robust Optimization

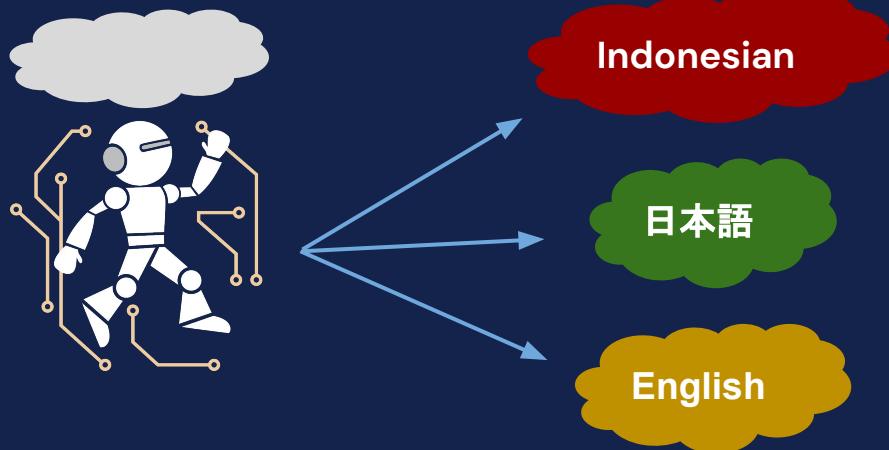
$$\min_{\theta} \sup_q \mathbb{E}_{(x,y) \sim q} \mathcal{L}_{\theta}(x, y)$$

Language

Future Directions



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Distributionally Robust Optimization

$$\min_{\theta} \sup_q \mathbb{E}_{(x,y) \sim q} \mathcal{L}_{\theta}(x, y)$$

Ensuring that a language model works equally well across languages (important for fairness)

Future Directions



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Training Paradigms

Model Architectures

Future Directions



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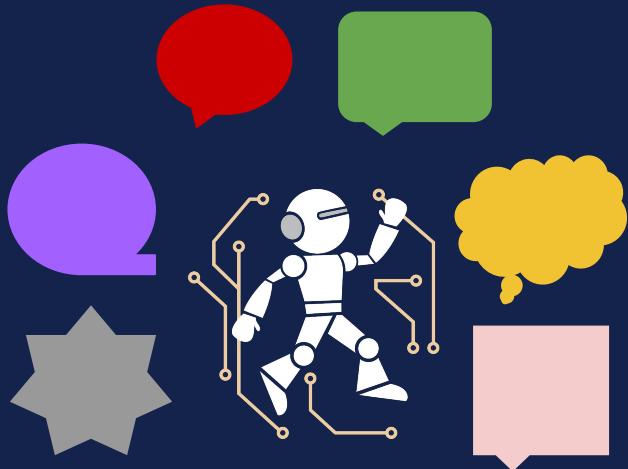
Training Paradigms

Model Architectures

Future Directions



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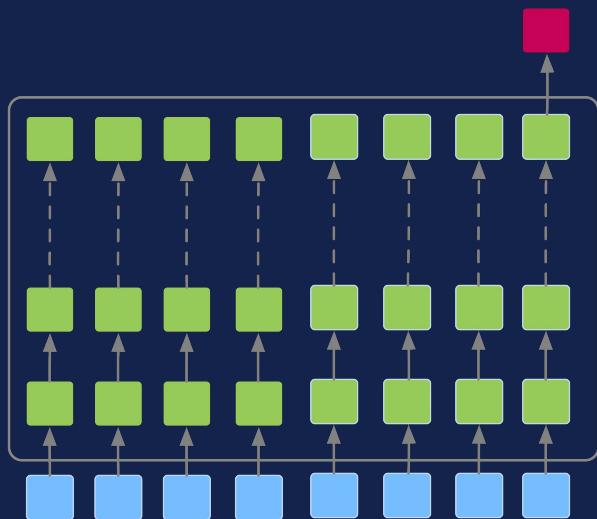


Integration of data from various sources and modalities.

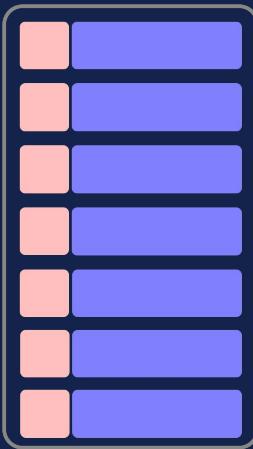
Future Directions



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Computation

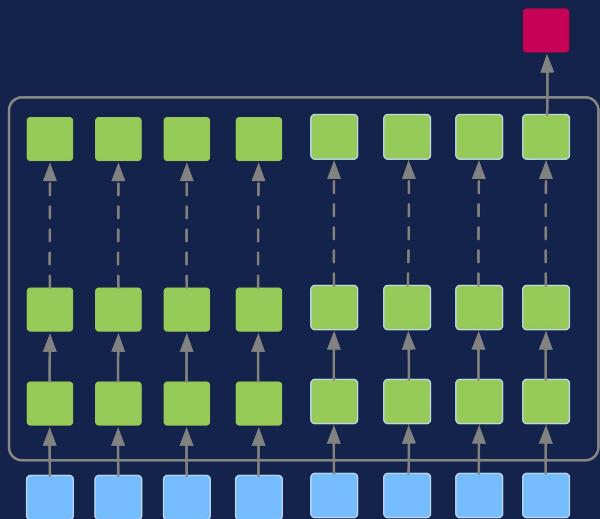


Storage

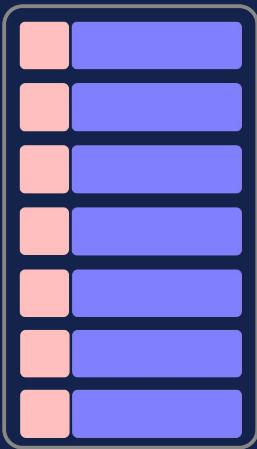
Future Directions



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Computation



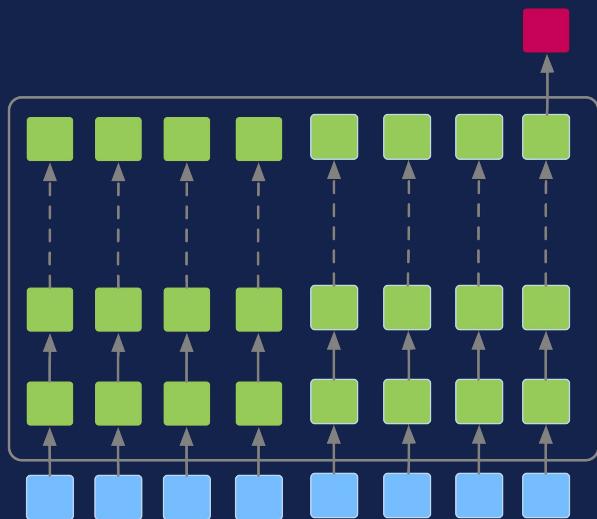
Storage



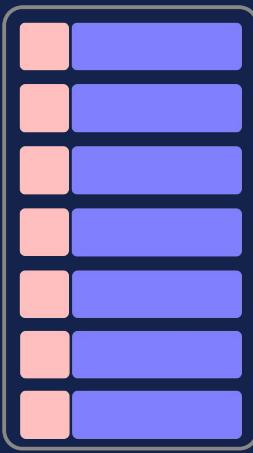
Future Directions



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Computation



Storage

A screenshot of a profile page for Cristiano Ronaldo. At the top, there is a grid of five small images showing him in various poses. Below the images, his name "Cristiano Ronaldo" is displayed in a large, bold black font, followed by the subtitle "Portuguese footballer". A link "cristianoronaldo.com" is provided. In the bottom right corner of the profile area, there is a "More images" button with a camera icon. The main content area contains the following biographical information:

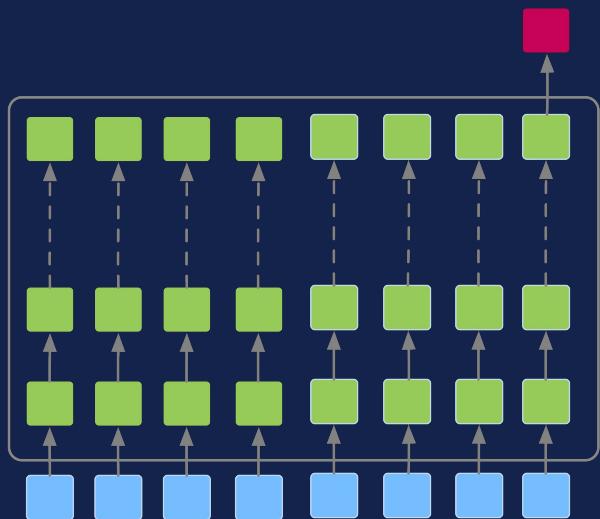
- Born: 5 February 1985 (age 36 years), Hospital Dr. Nélio Mendonça, Funchal, Portugal
- Height: 1.87 m
- Partner: Georgina Rodríguez (2017–)
- Salary: 31 million EUR (2019)
- Children: Cristiano Ronaldo Jr., Alana Martina dos Santos Aveiro, Eva Maria Dos Santos, Mateo Ronaldo
- Current teams: Juventus F.C. (#7 / Forward), Portugal national football team (#7 / Forward)

At the bottom right of the slide, there is a small "Wikipedia" logo.

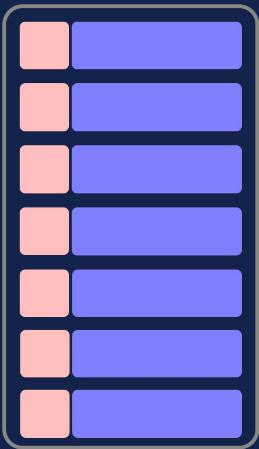
Future Directions



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Computation



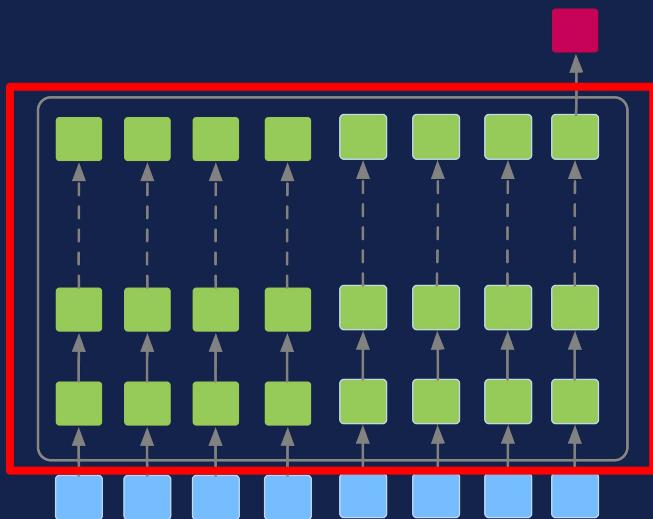
Storage

↑ computational efficiency

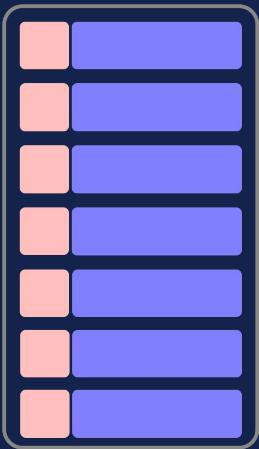
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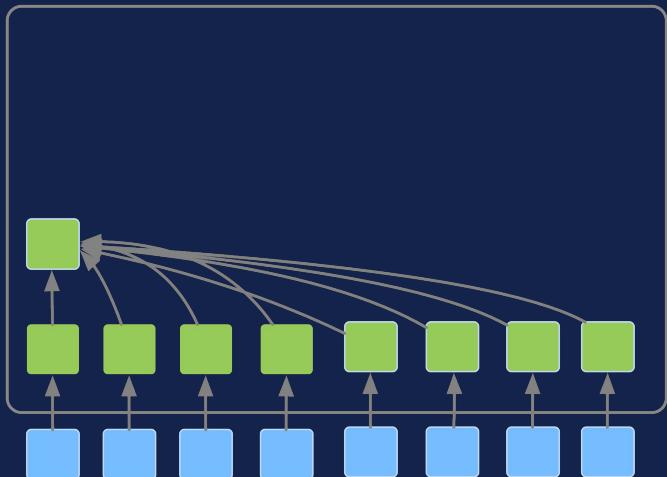
Storage

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Random Feature Attention

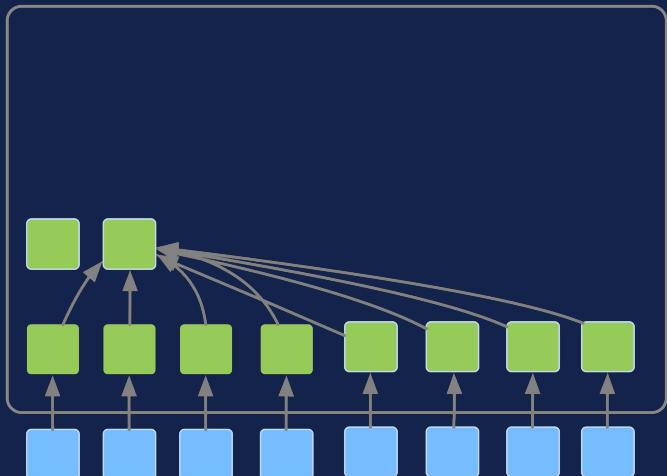
Peng et al., ICLR 2021



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Random Feature Attention

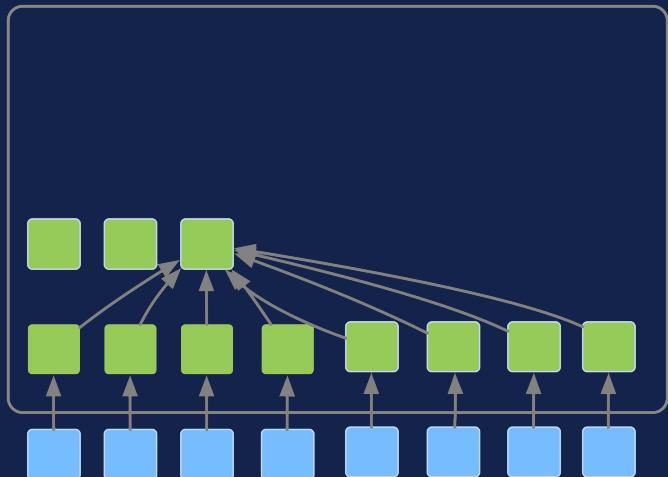
Peng et al., ICLR 2021



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Random Feature Attention

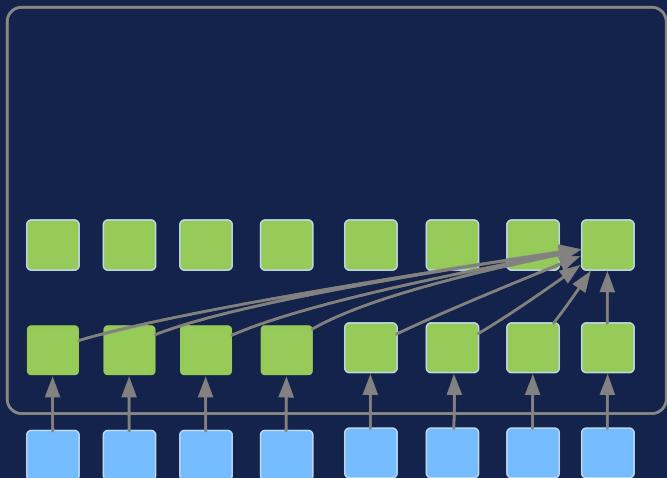
Peng et al., ICLR 2021



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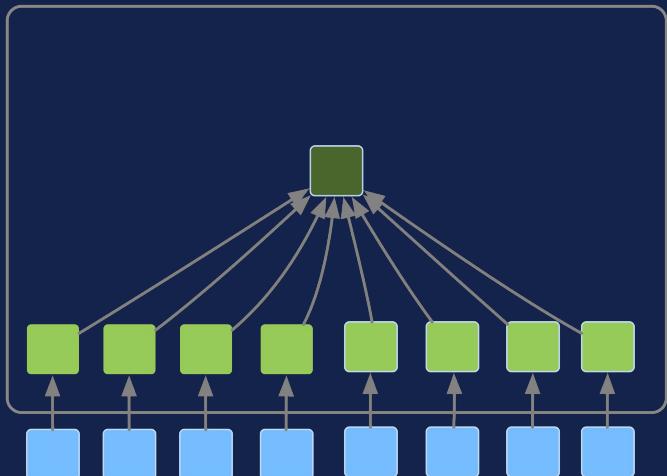
Peng et al., ICLR 2021



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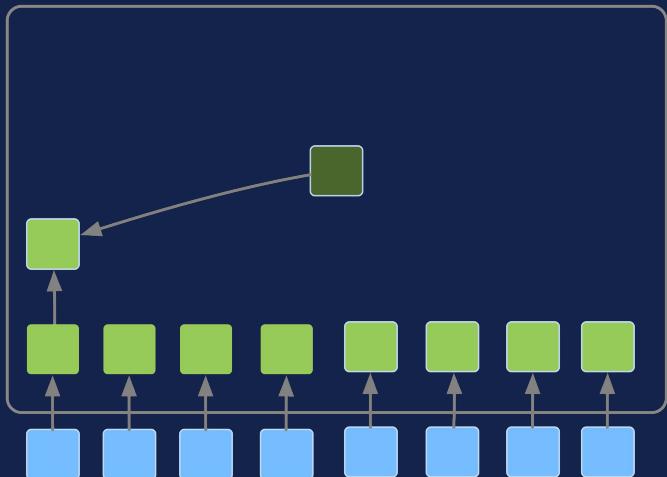
Peng et al., ICLR 2021



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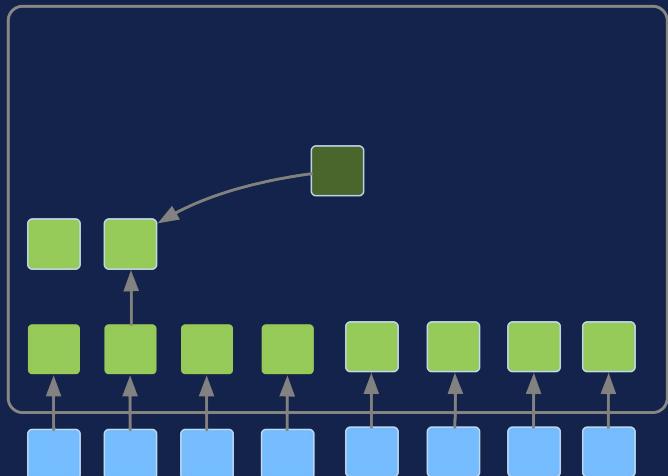
Peng et al., ICLR 2021



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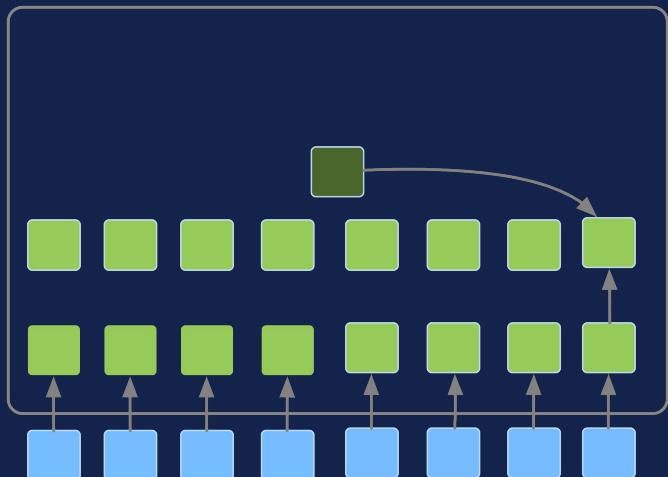
Peng et al., ICLR 2021



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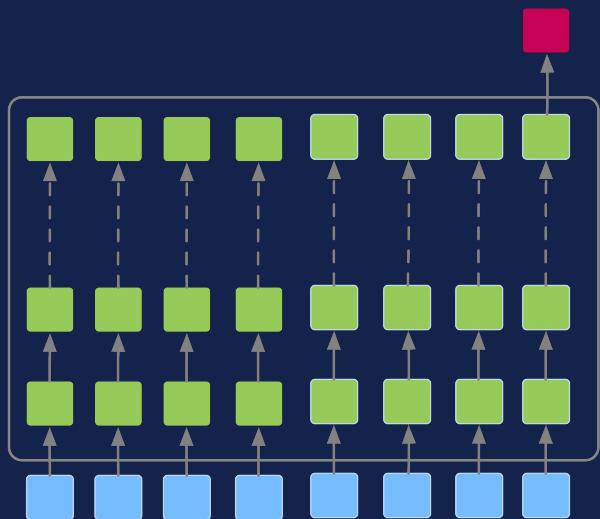
Peng et al., ICLR 2021



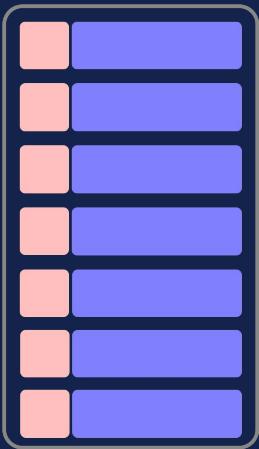
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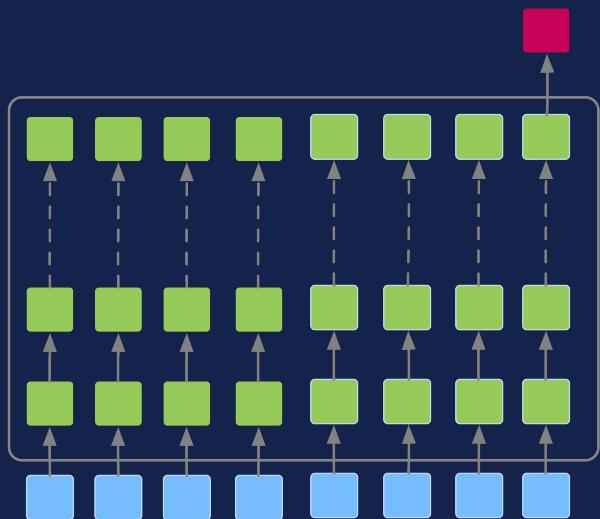
Storage

↑ computational efficiency

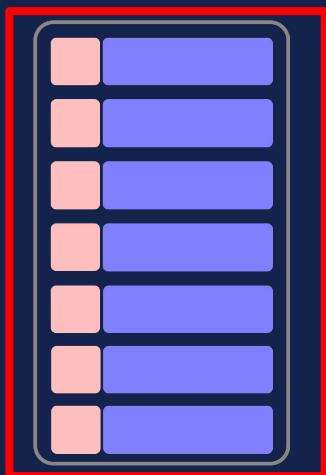
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Computation



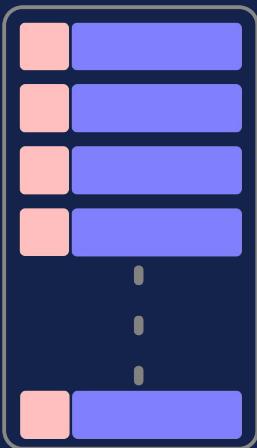
Storage

↑ computational efficiency

Future Directions



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Storage

Learning what to remember and forget

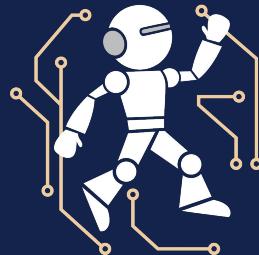


Constant-size memory

Future Directions



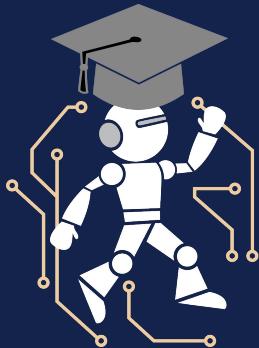
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Future Directions



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tack გნორჩაჲალითჟიოს Danke
ありがとうございました Salamat
grazie **Thank you** multumesc நன்றி
ধন্যবাদ Terima kasih Dankie 감사합니다 Merci
Спасибо شکرا جزیلا σας ευχαριστώ
teşekkür ederim 谢謝 cảm ơn bạn

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

Background

Our semiparametric language model architecture is
designed to mitigate these problems