

DOTE 6635: Artificial Intelligence for Business Research

Transformers

Renyu (Philip) Zhang

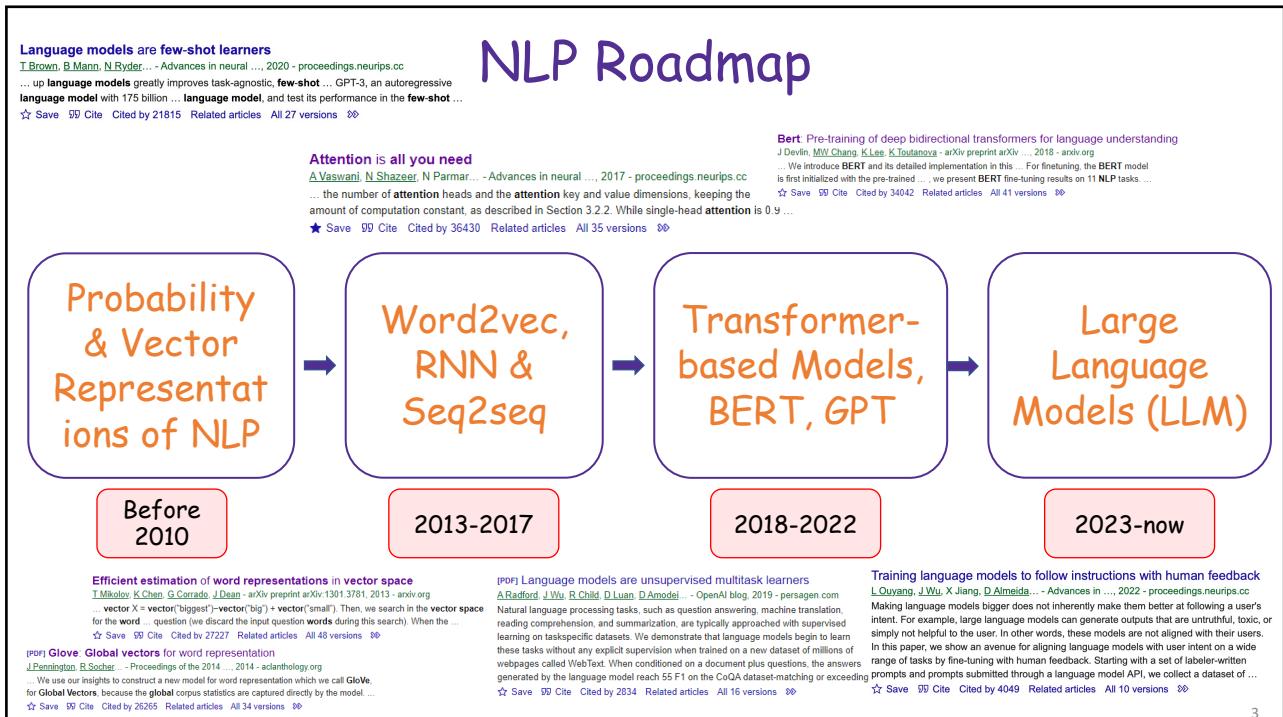
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Agenda

- Sequence-to-Sequence (Seq2seq) and Neural Machine Translation (NMT)
- Attention is All You Need
- Extensions, Adaptations, and Substitutes of Transformers

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**NOVEMBER
27
2024**

Announcing the NeurIPS 2024 Test of Time Paper Awards

COMMUNICATIONS CHAIRS 2024 / 2021 Conference

By Danielle Belgrave, Angela Fan, Ulrich Paquet, Jakub Tomczak, Cheng Zhang

We are honored to announce the Test of Time Paper Awards for NeurIPS 2024. This award is intended to recognize papers published 10 years ago at NeurIPS 2014 that have significantly shaped the research field since then, standing the test of time.

This year, we are making an exception to award two Test of Time papers given the undeniable influence of these two papers on the entire field. The awarded papers are:

- Generative Adversarial Nets
Ian Goodfellow, Jean Pouget-Abadie, Mehdi Mirza, Bing Xu, David Warde-Farley, Sherjil Ozair, Aaron Courville, Yoshua Bengio
- Sequence to Sequence Learning with Neural Networks
Ilya Sutskever, Oriol Vinyals, Quoc V. Le

Seq2Seq paper has passed the test of time!

Sequence to Sequence Learning with Neural Networks has been cited more than 27,000 times as of this blog post. With the current fast advances of large language models and foundation models in general, making a paradigm shift in AI and applications, the field has benefited from the foundation laid by this work. It is the cornerstone work that set the encoder-decoder architecture, inspiring later attention-based improvements leading to today's foundation model research.

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Neural Machine Translation (NMT)

Stanford CS224N: <https://web.stanford.edu/class/cs224n/>

- NMT is a way to do machine translation with a single end-to-end neural network: Sequence-to-sequence (**seq2seq**), which involves **2 RNNs**.
- Machine translation is **highly nontrivial** and once was a huge research field in CS and NLP.



1519年600名西班牙人在墨西哥登陆，去征服几百万人口的阿兹特克帝国，初次交锋他们损兵三分之二。

In 1519, six hundred Spaniards landed in Mexico to conquer the Aztec Empire **with a population of a few million**. They lost two thirds of their soldiers in the first clash.

[translate.google.com \(2009\)](#): 1519 600 Spaniards landed in Mexico, **millions of people to conquer the Aztec empire**, the first two-thirds of soldiers against their loss.

[translate.google.com \(2013\)](#): 1519 600 Spaniards landed in Mexico to conquer the Aztec empire, **hundreds of millions of people**, the initial confrontation loss of soldiers two-thirds.

[translate.google.com \(2015\)](#): 1519 600 Spaniards landed in Mexico, **millions of people to conquer the Aztec empire**, the first two-thirds of the loss of soldiers they clash.

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Seq2Seq for NMT

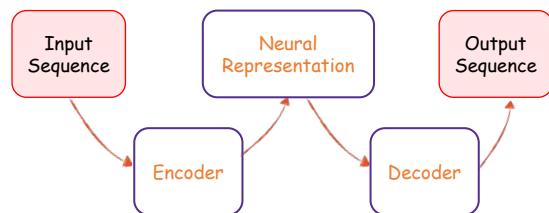
Stanford CS224N: <https://web.stanford.edu/class/cs224n/>

- Seq2seq is a **Conditional Language Model**:
 - Predicting the next word of the target sentence y conditioned on the source sentence x and prior texts.

$$P(y|x) = P(y_1|x) P(y_2|y_1, x) P(y_3|y_1, y_2, x) \dots \underbrace{P(y_T|y_1, \dots, y_{T-1}, x)}_{\text{Probability of next target word, given target words so far and source sentence } x}$$

Probability of next target word, given target words so far and source sentence x

- Encoder-decoder architecture: **Encoder** takes input and produces a **neural representation**; **Decoder** produces output based on that neural representation.
 - Seq2seq**: both input and output are **sequences**.
 - Summarization**: Long text \rightarrow short text
 - Dialogue**: previous utterances \rightarrow next utterance
 - Parsing**: Input text \rightarrow output parse as a sequence
 - Code generation**: Natural language \rightarrow Python code

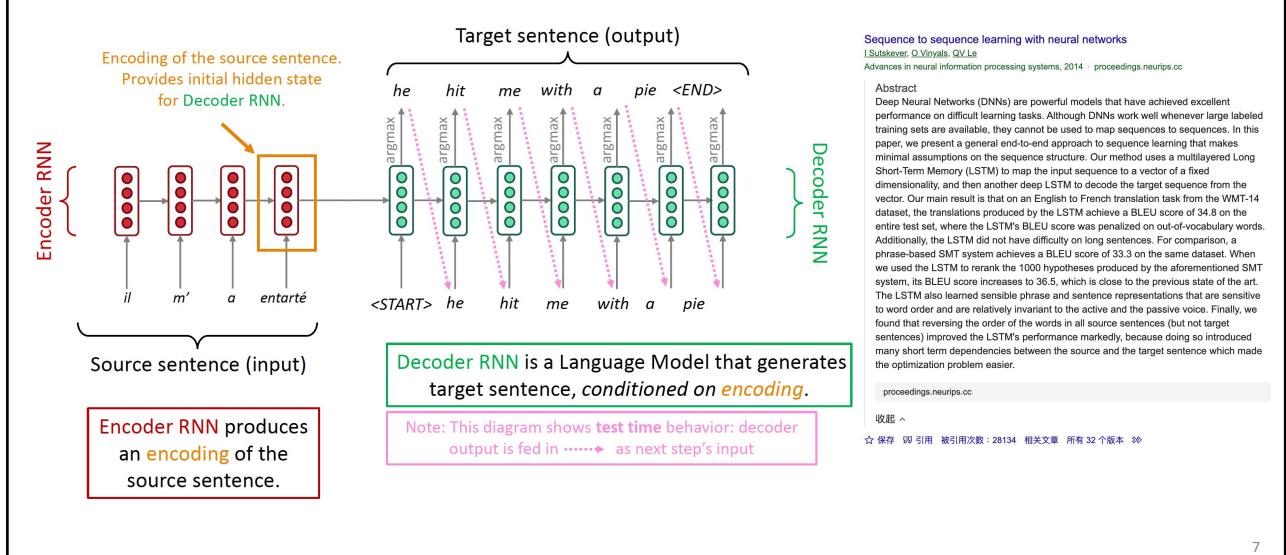


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Seq2Seq Architecture

Stanford CS224N: <https://web.stanford.edu/class/cs224n/>
 Scribed notes of last year: https://github.com/rphilipzhang/AI-PhD-S24/blob/main/Notes/Scribed_Notes-AI-PhD-S24.pdf

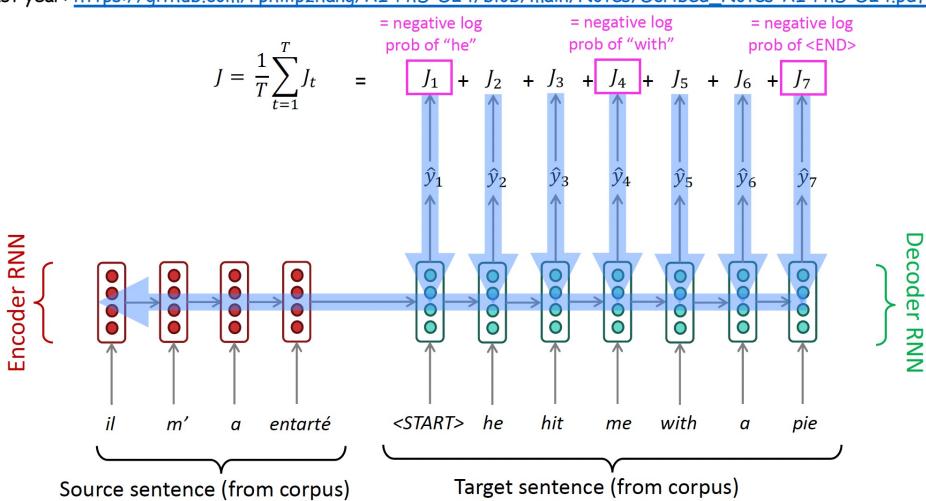


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Seq2Seq Training

Stanford CS224N: <https://web.stanford.edu/class/cs224n/>
 Scribed notes of last year: https://github.com/rphilipzhang/AI-PhD-S24/blob/main/Notes/Scribed_Notes-AI-PhD-S24.pdf



Seq2seq is optimized as a single system. Backpropagation operates "end-to-end".

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NMT: The First Major Success of DL-NLP

Stanford CS224N: <https://web.stanford.edu/class/cs224n/>

- NMT transformed from a **mere research attempt** in 2014 to the **leading standard** in 2016.
- 2014: The Seq2seq paper.
- 2016: Adopted by Google Translate.
- 2018: Adopted by everyone.



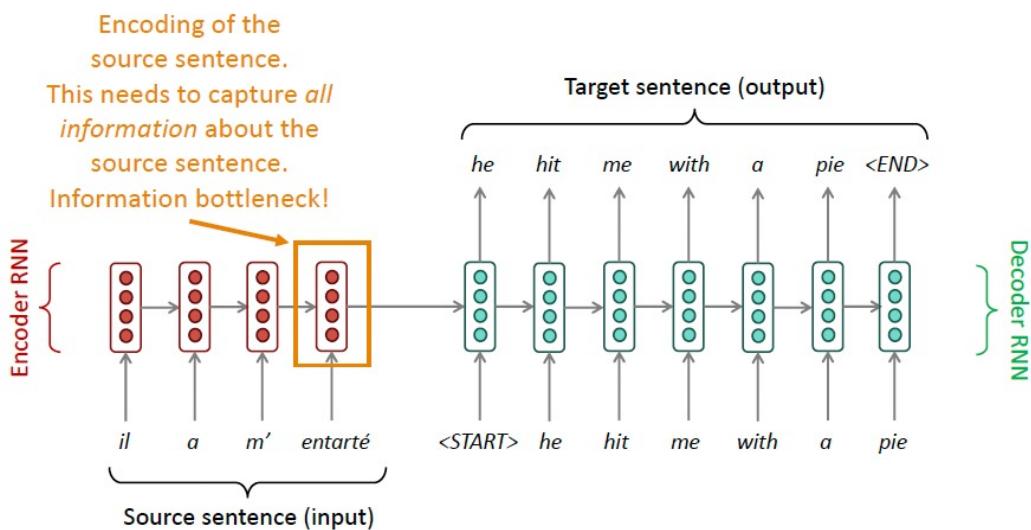
- The original statistical machine translation (SMT) system, built by **hundreds** of engineers over **many years**, soon outperformed by NMT trained by **small groups** of engineers in a **few months**.

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Information Bottleneck in RNN

Stanford CS224N: <https://web.stanford.edu/class/cs224n/>



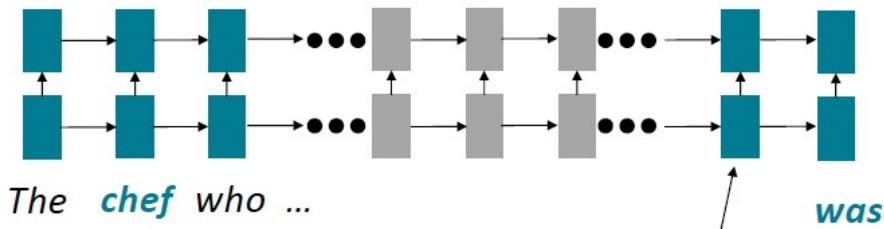
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Issue with RNN: Linear Interaction Distance

Stanford CS224N: <https://web.stanford.edu/class/cs224n/>

- Human languages are intrinsically NOT linearly ordered.



Info of *chef* has gone through
 $O(\text{sequence length})$ many layers!

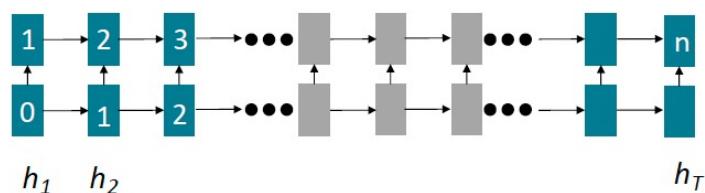
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Issue with RNN: Non-parallelizability

Stanford CS224N: <https://web.stanford.edu/class/cs224n/>

- Forward and backward passes both have $O(\text{sequence length})$ unparallelizable operations.
 - GPUs can perform independent small computations quickly in a large scale.
 - Future hidden states cannot be computed (in full) before past RNN hidden states have been computed.
 - Cannot scale with a very large dataset.



Numbers indicate min # of steps before a state can be computed

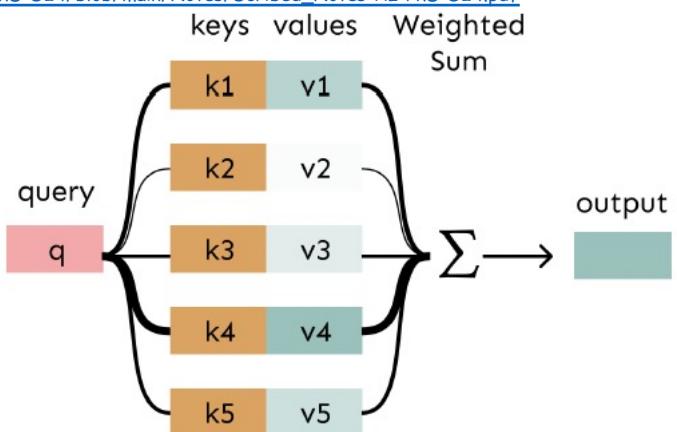
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Attention as a Very General DL Technique

Scribed notes of last year: https://github.com/rphilipzhang/AI-PhD-S24/blob/main/Notes/Scribed_Notes-AI-PhD-S24.pdf
Stanford CS224N: <https://web.stanford.edu/class/cs224n/>

- **Attention:** Given a set of vector values and a vector of query, attention is a technique to compute a weighted sum of the values dependent on the query.
 - The weighted sum is a **selective summary** of the information contained in the values, where the query determines which **values to focus on**.
 - A **fixed-size representation** of an arbitrary set of representations (values), dependent on some other representation (query).
- In **seq2seq + attention**, each decoder hidden state (query) attends to all the encoder hidden states (values)..



Neural machine translation by jointly learning to align and translate

D Bahdanau, K Cho, Y Bengio - arXiv preprint arXiv:1409.0473, 2014 - arxiv.org

... 3 LEARNING TO ALIGN AND TRANSLATE In this section, we propose a novel architecture for **neural machine translation**. The new architecture consists of a bidirectional RNN as an ...

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A Family of Attention Models

Stanford CS224N: <https://web.stanford.edu/class/cs224n/>

Name	Alignment score function	Citation
Content-base attention	$\text{score}(\mathbf{s}_t, \mathbf{h}_i) = \text{cosine}[\mathbf{s}_t, \mathbf{h}_i]$	Graves2014
Additive(*)	$\text{score}(\mathbf{s}_t, \mathbf{h}_i) = \mathbf{v}_a^\top \tanh(\mathbf{W}_a[\mathbf{s}_t; \mathbf{h}_i])$ $\alpha_{t,i} = \text{softmax}(\mathbf{W}_a \mathbf{s}_t)$	Bahdanau2015
Location-Base	Note: This simplifies the softmax alignment to only depend on the target position.	Luong2015
General	$\text{score}(\mathbf{s}_t, \mathbf{h}_i) = \mathbf{s}_t^\top \mathbf{W}_a \mathbf{h}_i$ where \mathbf{W}_a is a trainable weight matrix in the attention layer.	Luong2015
Dot-Product	$\text{score}(\mathbf{s}_t, \mathbf{h}_i) = \mathbf{s}_t^\top \mathbf{h}_i$	Luong2015
Scaled Dot-Product(^)	$\text{score}(\mathbf{s}_t, \mathbf{h}_i) = \frac{\mathbf{s}_t^\top \mathbf{h}_i}{\sqrt{n}}$ Note: very similar to the dot-product attention except for a scaling factor; where n is the dimension of the source hidden state.	Vaswani2017

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- Attention is All You Need
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Attention is All You Need

Stanford CS224N: <https://web.stanford.edu/class/cs224n/>
<https://peterbloem.nl/blog/transfomers>

- Transformer: No RNN architecture, just attention mechanism.
- Self-attention: To generate y_t , we need to pay attention to $y_{\leftarrow t}$.

$$w'_{ij} = \frac{q_i^T k_j}{\sqrt{k}}$$

Query	Key	Value
$q_i = W_q x_i$	$k_i = W_k x_i$	$v_i = W_v x_i$
$w'_{ij} = q_i^T k_j$		
$w_{ij} = \text{softmax}(w'_{ij})$		
$y_i = \sum_j w_{ij} v_j$		

Why does it work?

Attention is all you need

A Vaswani, N Shazeer, N Parmar... - Advances in neural ... , 2017 - proceedings.neurips.cc
 ... to attend to all positions in the decoder up to and including that position. We need to prevent
 ... We implement this inside of scaled dot-product attention by masking out (setting to $-\infty$) ...
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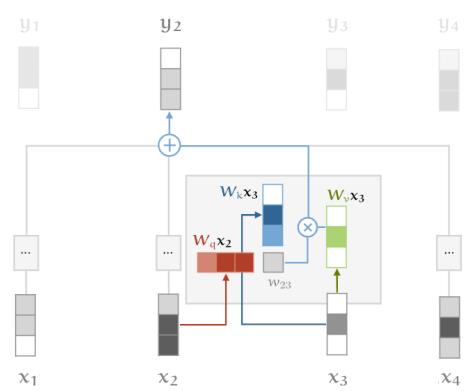


Illustration of the self-attention with key, query and value transformations.

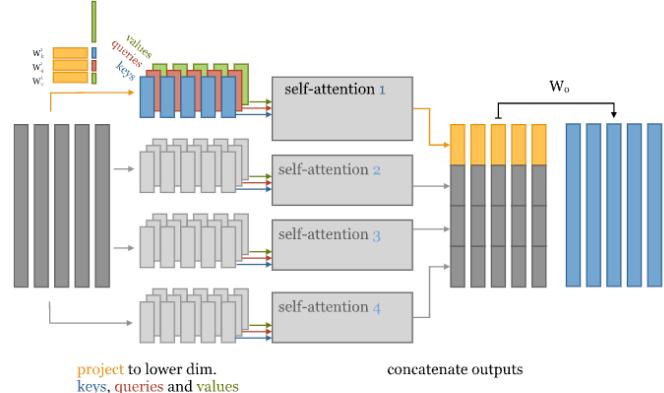
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Multi-head Attention

Stanford CS224N: <https://web.stanford.edu/class/cs224n/>
<https://peterbloem.nl/blog/transfomers>

- Multi-head attention is a way to **speed up the training procedure**.
- Instead of using a large matrix to compute all attentions, we can **compute multiple attention matrices and concatenate the final vectors**.
- Allows for **parallel computing**: Deploy attention mechanisms to multiple computing cores in parallel and sum them up at the end.
- Input dim = 256, 8 attention heads, each with 32 dimensions.



The basic idea of multi-head self-attention with 4 heads. To get our **keys**, **queries** and **values**, we project the input down to vector sequences of smaller dimension.

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Position Encoding

Stanford CS224N: <https://web.stanford.edu/class/cs224n/>
<https://peterbloem.nl/blog/transfomers>

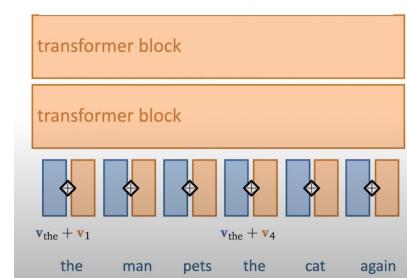
- **Position embeddings**: Position vectors which are learned.
- **Position encoding**: The function from position to vector.
- The final input of the model is the **sum of word embeddings and position embeddings**.

word embeddings:

v_{the} , v_{man} , v_{pets} , v_{cat} , v_{again}

position embeddings:

v_1 , v_2 , v_3 , v_4 , v_5 , ...



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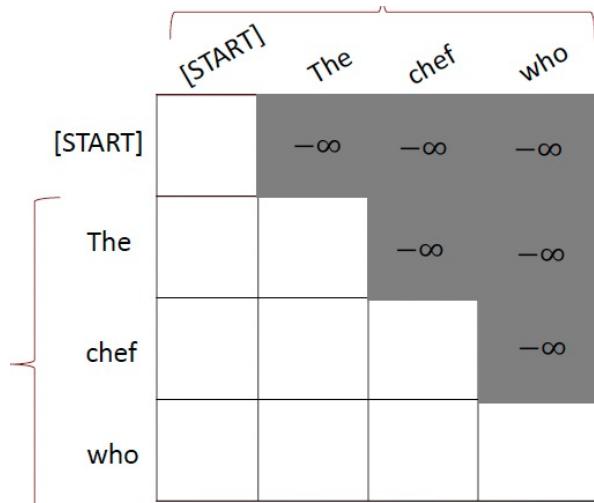
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Auto-Regression

Stanford CS224N: <https://web.stanford.edu/class/cs224n/>
<https://peterbloem.nl/blog/transformers>

- Self-supervised learning for transformers.
- To use self-attention in decoders, we need to mask the future.
- Inefficient implementation: Change the set of keys and queries to include only past words.
- Parallelizable implementation: Mask out attention to future words by setting the weight to -inf.

$$w'_{ij} = \begin{cases} q_i^T k_j, j \leq i \\ -\infty, j > i \end{cases}$$



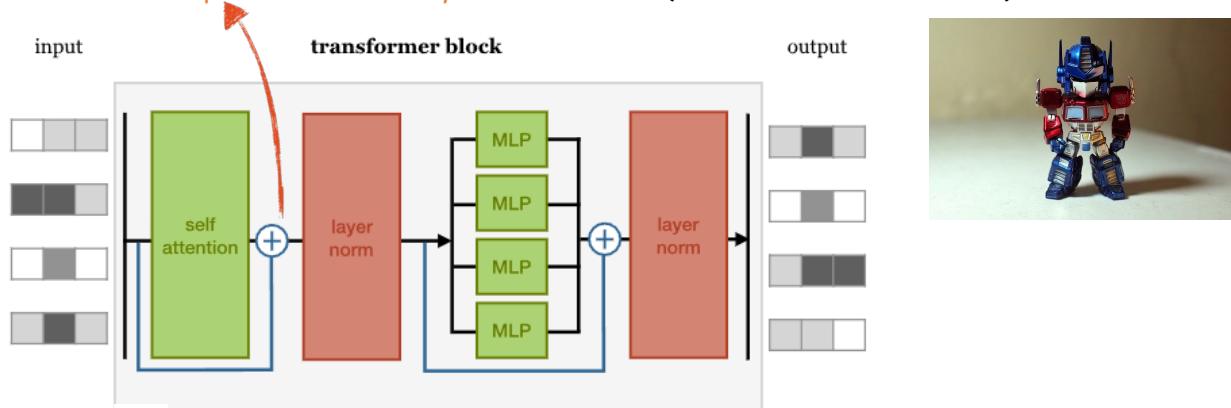
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Transformer

Stanford CS224N: <https://web.stanford.edu/class/cs224n/>
<https://peterbloem.nl/blog/transformers>

- Transformer = Multi-head self-attention + MLP + position encoding + autoregression
- Need to add skip-connection and layer normalization (the order does not matter).



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Layer Normalization

Stanford CS224N: <https://web.stanford.edu/class/cs224n/>
<https://peterbloem.nl/blog/transfomers>

- **Layer normalization:** A trick to help models train faster.
- Cut down on uninformative variation in hidden values by normalizing to unit mean and standard deviation within each layer: Normalized gradients.
- Let $x \in \mathbb{R}^d$ be an individual (word) vector in the model.
- Let $\mu = \sum_{j=1}^d x_j$; this is the mean; $\mu \in \mathbb{R}$.
- Let $\sigma = \sqrt{\frac{1}{d} \sum_{j=1}^d (x_j - \mu)^2}$; this is the standard deviation; $\sigma \in \mathbb{R}$.
- Let $\gamma \in \mathbb{R}^d$ and $\beta \in \mathbb{R}^d$ be learned “gain” and “bias” parameters. (Can omit!)
- Then layer normalization computes:

$$\text{output} = \frac{x - \mu}{\sqrt{\sigma + \epsilon}} * \gamma + \beta$$

Normalize by scalar mean and variance Modulate by learned elementwise gain and bias

Layer normalization

JL Ba, JR Kiros, GE Hinton - arXiv preprint arXiv:1607.06450, 2016 - arxiv.org
... , we transpose batch **normalization** into **layer normalization** by computing the mean and variance used for **normalization** from all of the summed inputs to the neurons in a **layer** on a ...
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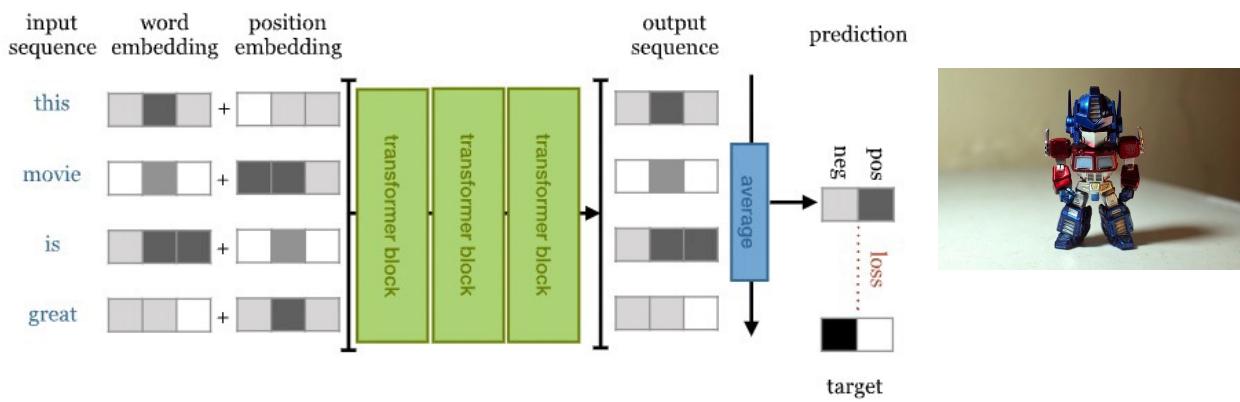
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Classification Transformer

Stanford CS224N: <https://web.stanford.edu/class/cs224n/>
<https://peterbloem.nl/blog/transfomers>

- Directly train a classifier on top of a transformer.



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Attention is All You Need

Stanford CS224N: <https://web.stanford.edu/class/cs224n/>
<https://peterbloem.nl/blog/transfomers>

- Input: Sequence in language one and Sequence in language two.
- Architecture: Encoder + Decoder
- 8 heads, 512 embedding dimensions, 2048 sentence length
- Trained on 8 GPUs for 5 days.

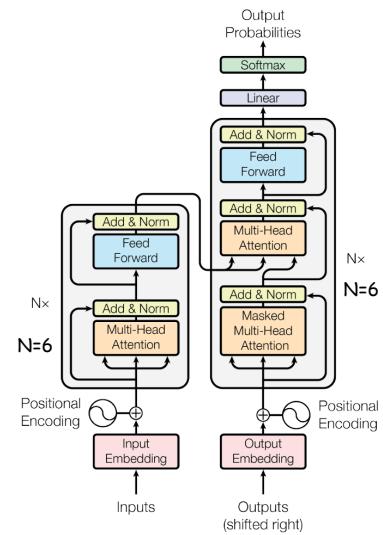


Figure 1: The Transformer - model architecture.

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Attention is All You Need

Stanford CS224N: <https://web.stanford.edu/class/cs224n/>
<https://peterbloem.nl/blog/transfomers>

Machine Translation

Model	BLEU		Training Cost (FLOPs)	
	EN-DE	EN-FR	EN-DE	EN-FR
ByteNet [18]	23.75			
Deep-Att + PosUnk [39]		39.2		$1.0 \cdot 10^{20}$
GNMT + RL [38]	24.6	39.92	$2.3 \cdot 10^{19}$	$1.4 \cdot 10^{20}$
ConvS2S [9]	25.16	40.46	$9.6 \cdot 10^{18}$	$1.5 \cdot 10^{20}$
MoE [32]	26.03	40.56	$2.0 \cdot 10^{19}$	$1.2 \cdot 10^{20}$
Deep-Att + PosUnk Ensemble [39]		40.4		$8.0 \cdot 10^{20}$
GNMT + RL Ensemble [38]	26.30	41.16	$1.8 \cdot 10^{20}$	$1.1 \cdot 10^{21}$
ConvS2S Ensemble [9]	26.36	41.29	$7.7 \cdot 10^{19}$	$1.2 \cdot 10^{21}$
Transformer (base model)	27.3	38.1	$3.3 \cdot 10^{18}$	
Transformer (big)	28.4	41.8	$2.3 \cdot 10^{19}$	

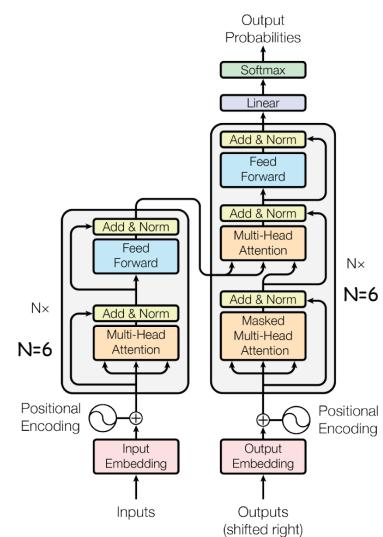


Figure 1: The Transformer - model architecture.

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Application of Transformer: Polarized Framing of Immigration

PNAS

RESEARCH ARTICLE | COMPUTER SCIENCES

OPEN ACCESS

Computational analysis of 140 years of US political speeches reveals more positive but increasingly polarized framing of immigration

Dallas Card ^{a,b,1}, Serina Chang^a, Chris Becker^b, Julia Mendelsohn^b, Rob Voigt^{d,e}, Leah Boustan^{c,f}, Ran Abramitzky ^{c,g}, and Dan Jurafsky ^{c,h}

Edited by Joseph Fene, Northwestern University, Evanston, IL; received November 10, 2021; accepted June 15, 2022

Editorial Board Member Kenneth W. Wachter

July 29, 2022 | 119(31) e2120510119 | <https://doi.org/10.1073/pnas.2120510119>

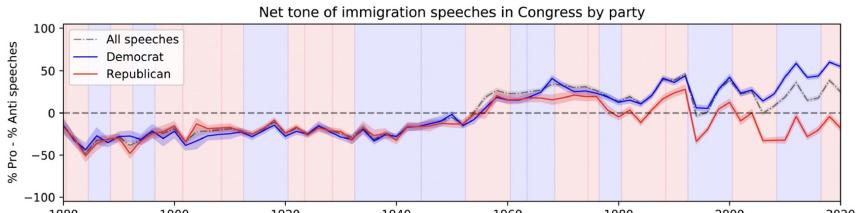
Significance

In the first comprehensive quantitative analysis of the past 140 yr of US congressional and presidential speech about immigration, we identify a dramatic rise in proimmigration attitudes beginning in the 1940s, followed by a steady decline among Republicans (relative to Democrats) over the past 50 yr. We also reveal divergent usage of positive (e.g., families) and negative (e.g., crime) frames—over time, by party, and between frequently mentioned European and non-European groups. Finally, to capture more suggestive language, we introduce a method for measuring implicit dehumanizing metaphors long associated with immigration (animals, cargo, etc.) and show that such metaphorical language has been significantly more common in speeches by Republicans than Democrats in recent decades.

We classify and analyze 200,000 US congressional speeches and 5,000 presidential communications related to immigration from 1880 to the present. Despite the salience of antiimmigration rhetoric today, we find that political speech about immigration is now much more positive on average than in the past, with the shift largely taking place between World War II and the passage of the Immigration and Nationality Act in 1965. However, since the late 1970s, political parties have become increasingly polarized in their expressed attitudes toward immigration, such that Republican speeches today are as negative as were those of the 1920s, an era of significant immigration restriction and immigration quotas. Using an approach based on contextual embeddings of text, we find that modern Republicans are significantly more likely to use language that is suggestive of metaphors long associated with immigration, such as “animals” and “cargo,” and make greater use of frames like “crime” and “legality.” The tone of speeches also differs strongly based on which nationalities are mentioned, with a striking similarity between how Mexican immigrants are framed today and how Chinese immigrants were framed during the era of Chinese exclusion in the late 19th century. Overall, despite more favorable attitudes toward immigrants and the formal elimination of race-based restrictions, nationality is still a major factor in how immigrants are spoken of in Congress.

[immigration](#) | [metaphor](#) | [dehumanization](#) | [framing](#) | [Congress](#)

- Finetune RoBERTa to classify congressional speeches as proimmigration, antiimmigration or neutral.
- Quantitative analysis of 140 years of US congressional and presidential speech about immigration



Computational analysis of 140 years of US political speeches reveals more positive but increasingly polarized framing of immigration

O.Card, S.Chang, C.Becker, J.Mendelsohn, R.Voigt, L.Boustan, R.Abramitzky, D.Jurafsky

Proceedings of the National Academy of Sciences, 2022 | National Acad Sciences

We classify and analyze 200,000 US congressional speeches and 5,000 presidential communications related to immigration from 1880 to the present. Despite the salience of antiimmigration rhetoric today, we find that political speech about immigration is now much more positive on average than in the past, with the shift largely taking place between World War II and the passage of the Immigration and Nationality Act in 1965. However, since the late 1970s, political parties have become increasingly polarized in their

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Application of Transformer: Remote Work

Remote Work across Jobs, Companies, and Space

Stephen Hansen, Peter John Lambert, Nicholas Bloom,
Steven J. Davis, Raffaella Sadun & Bledi Taska

WORKING PAPER 31007 DOI 10.3386/w31007 ISSUE DATE March 2023

The pandemic catalyzed an enduring shift to remote work. To measure and characterize this shift, we examine more than 250 million job vacancy postings across five English-speaking countries. Our measurements rely on a state-of-the-art language-processing framework that we fit, test, and refine using 30,000 human classifications. We achieve 99% accuracy in flagging job postings that say new employees can work remotely one or more days per week rose more than three-fold in the U.S. and by a factor of five or more in Australia, Canada, New Zealand and the U.K. These developments are highly non-uniform across and within cities, industries, occupations, and companies. Even when zooming in on employers in the same industry competing for talent in the same occupations, we find large differences in the share of job postings that explicitly offer remote work.

- Use DistilBERT pre-trained on 1 M text chunks of job vacancy postings to measure the work-from-homeness of the 250 M jobs (Work from Home Algorithmic Measure), achieving 99% accuracy that outperforms dictionary-based methods.
- The number of WFM jobs has risen significantly since 2019 and it differs w.r.t. different industries.

Remote work across jobs, companies, and space

S Hansen, PJ Lambert, N Bloom, SJ Davis, R Sadun... - 2023 - nber.org

The pandemic catalyzed an enduring shift to remote work. To measure and characterize this shift, we examine more than 250 million job vacancy postings across five English-speaking countries. Our measurements rely on a state-of-the-art language-processing framework that we fit, test, and refine using 30,000 human classifications. We achieve 99% accuracy in flagging job postings that advertise hybrid or fully remote work, greatly outperforming dictionary methods and also outperforming other machine-learning methods. From 2019 to ...

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Text as Data

Journal of Economic Literature 2019, 57(3), 535–574
<https://doi.org/10.1257/jel.20181020>

Text as Data^{*}

MATTHEW GENTZKOW, BRYAN KELLY, AND MATT TADDY*

An ever-increasing share of human interaction, communication, and culture is recorded as digital text. We provide an introduction to the use of text as an input to economic research. We discuss the features that make text different from other forms of data, offer a practical overview of relevant statistical methods, and survey a variety of applications. (JEL C38, C55, LS2, Z13)

0. Pre-processing:

1. Represent raw text \mathcal{D} as a numerical array \mathbf{C} ;
2. Map \mathbf{C} to predicted values $\hat{\mathbf{V}}$ of unknown outcomes \mathbf{V} ; and
3. Use $\hat{\mathbf{V}}$ in subsequent descriptive or causal analysis.

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Text Algorithms in Economics

Annual Review of Economics

Text Algorithms in Economics

Elliott Ash¹ and Stephen Hansen^{2,3}

¹Center for Law and Economics, ETH Zurich, Zurich, Switzerland

²Department of Economics, University College London, London, United Kingdom; email: stephen.hansen@ucl.ac.uk

³Centre for Economic Policy Research, London, United Kingdom

Keywords

text as data, topic models, word embeddings, large language models, transformer models

Abstract

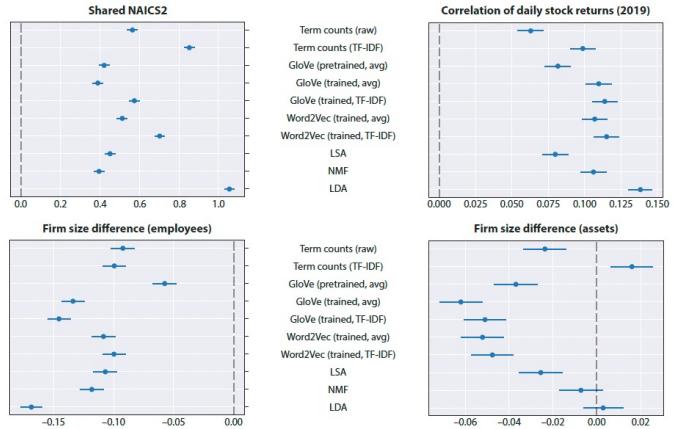
This article provides an overview of the methods used for algorithmic text analysis in economics, with a focus on three key contributions. First, we introduce methods for representing documents as high-dimensional count vectors over vocabulary terms, for representing words as vectors, and for representing word sequences as embedding vectors. Second, we define four core empirical tasks that encompass most text-as-data research in economics and enumerate the various approaches that have been taken so far to accomplish these tasks. Finally, we flag limitations in the current literature, with a focus on the challenge of validating algorithmic output.

Text algorithms in economics

E. Ash, S. Hansen - Annual Review of Economics, 2023 - annualreviews.org
... methods used for algorithmic text analysis in economics, with ... encompass most text-as-data research in economics and ... with a focus on the challenge of validating algorithmic output. ...

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- **Four problems:** (I) Measuring document similarity; (II) Concept detection; (III) How concepts are related; (IV) Associating text with metadata.
- **Two challenges:** (I) Validation; (II) Interpretability.
- **One future:** Large Language Models.



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Agenda

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ViT (2020)

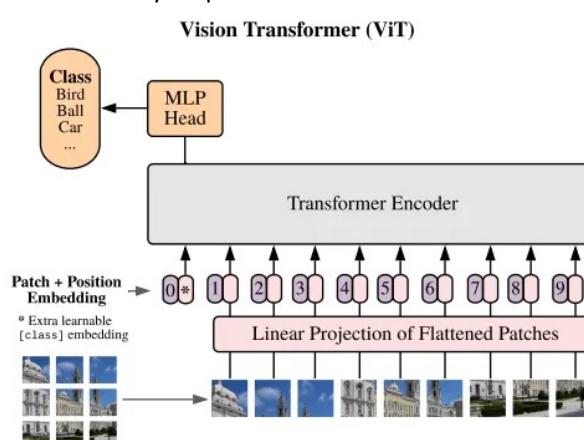
An image is worth 16x16 words: Transformers for image recognition at scale
[A Dosovitskiy, L Beyer, A Kolesnikov... - arXiv preprint arXiv ..., 2020 - arxiv.org](#)

... To do so, we split an image into patches and provide the sequence of ... Image patches are treated the same way as tokens (words) in an NLP application. We train the model on image ...
☆ 保存 回引用 被引用次数 : 32273 相关文章 所有 17 个版本 ≈≈

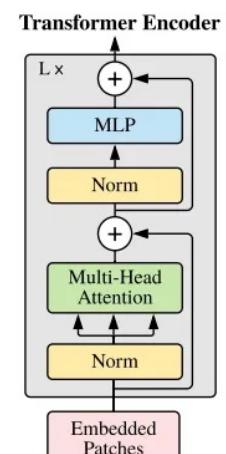
- Transformer encoders can also effectively process image.
- Decompose images into patches of 16 by 16 pixels. Patch = token.

Transformer lacks the inductive biases of CNN:
 Translation invariance and locality.

It may be smart to combine CNN and transformers.



Reference: http://cs231n.stanford.edu/slides/2023/lecture_9.pdf



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ViT vs. ResNet

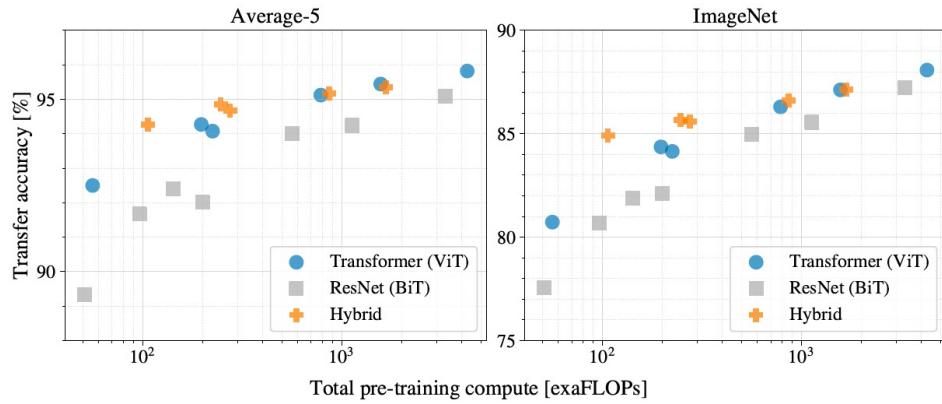


Figure 5: Performance versus pre-training compute for different architectures: Vision Transformers, ResNets, and hybrids. Vision Transformers generally outperform ResNets with the same computational budget. Hybrids improve upon pure Transformers for smaller model sizes, but the gap vanishes for larger models.

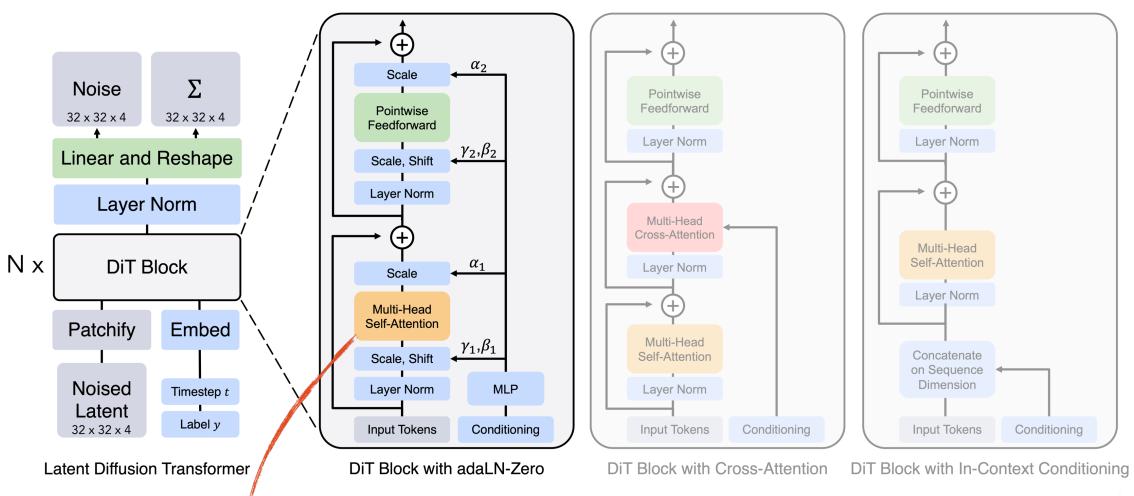
Attention is all you need, again!

Reference: http://cs231n.stanford.edu/slides/2023/lecture_9.pdf

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Diffusion Transformer (DiT)



Replace the U-Net in latent diffusion models (LDMs) with a transformer.

Scalable diffusion models with transformers

W Peebles, S Xie - Proceedings of the IEEE/CVF ..., 2023 - openaccess.thecvf.com

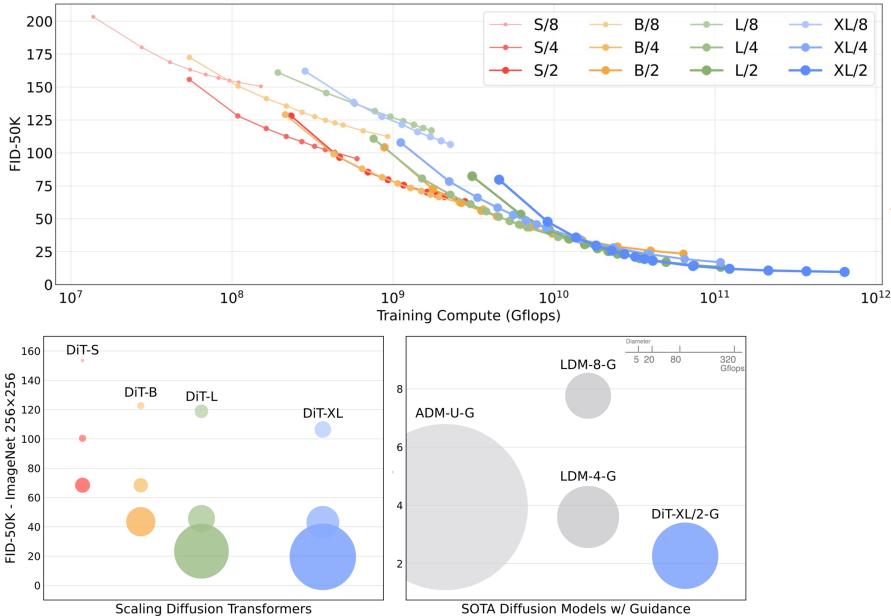
... We train latent diffusion models of images, replacing the commonly-used U-Net ... a transformer that operates on latent patches. We analyze the scalability of our Diffusion Transformers (...

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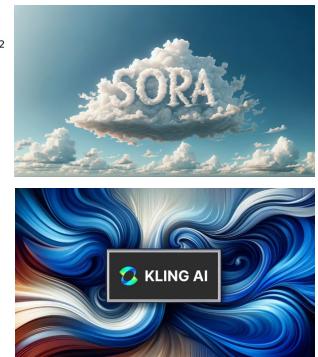
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Diffusion Transformer (DiT) Performances



Attention is all you need again!

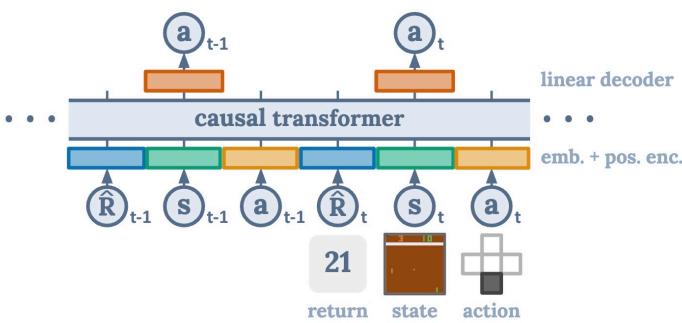
The bitter/sweet lesson:
scaling laws.



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Decision Transformer



- Mainstream RL: Learn value function or policy gradient.
- Decision transformer: Directly learn the **next action** based on an **auto-regressive model**.
- Multi-modal transformer: (reward to go, state, action)

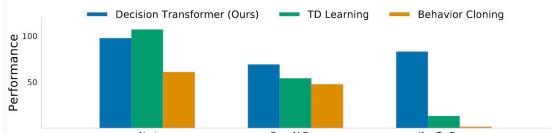


Figure 1: Decision Transformer architecture¹. States, actions, and returns are fed into modality-specific linear embeddings and a positional episodic timestep encoding is added. Tokens are fed into a GPT architecture which predicts actions autoregressively using a causal self-attention mask.

Reinforcement learning as **conditional sequence modeling**, like language models

Decision transformer: Reinforcement learning via sequence modeling
[L.Chen, K.Lu, A.Rajeswaran, K.Lee... - Advances in neural ... , 2021 - proceedings.neurips.cc](#)
 ... of the **Transformer** architecture, and associated advances in language modeling such as GPT-x and BERT. In particular, we present **Decision Transformer**, ..., **Decision Transformer** simply ...
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BC Applied to Inventory Management

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A Practical End-to-End Inventory Management Model with Deep Learning

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Keywords: end-to-end decision-making • inventory management • deep learning • e-commerce

MANAGEMENT SCIENCE
Vol. 69, No. 2, February 2023, pp. 708–723
ISSN 0025-1909 (print), ISSN 1526-5501 (online)

• Use multi-quantile RNNs to provide end-to-end predictions from features to the optimal inventory decisions, whereas most of the literature applies the predict-then-optimize paradigm.

• A field experiment shows that the e2e approach substantially reduces the inventory costs compared with some naïve benchmarks.

• Behavioral cloning (BC) applied to an MDP, with uncertainty completely removed.

A practical end-to-end inventory management model with deep learning

M.Qi, Y.Shi, Y.Qi, C.Ma, R.Yuan, D.Wu, Z.J.Shen

Management Science, 2023 pubsonline.informs.org

We investigate a data-driven multiperiod inventory replenishment problem with uncertain demand and vendor lead time (VLT) with accessibility to a large quantity of historical data. Different from the traditional two-step predict-then-optimize (PTO) solution framework, we propose a one-step end-to-end (E2E) framework that uses deep learning models to output the suggested replenishment amount directly from input features without any intermediate step. The E2E model is trained to capture the behavior of optimal dynamic programming solution under historical observations without any prior assumptions on the distributions of the demand and the VLT. By conducting a series of thorough numerical experiments using real data from a well-known e-commerce company, we demonstrate the advantages of the proposed E2E model over conventional PTO frameworks. We also conduct a field experiment with JD.com, and the results show that our new algorithm reduces holding cost, stockout cost, total inventory cost, and turnover rate substantially compared with PTOs or current practice. For the supply chain management industry, our E2E model shortens the process of transitioning to automatic inventory management solution with the possibility to generalize and scale. The concept of E2E, which uses the input information directly for the ultimate goal, can also be useful in practice for other supply chain management circumstances.

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No Free Lunch: Quadratic Training Cost

- Training (and inference) cost of transformer: $O(n^2)$; cost of training RNN: $O(n)$.
 - Inference memory of transformer: $O(n)$; that of RNN: $O(1)$.
- Sparse Attention** reduces the full pairwise attention calculations (such as sliding windows, fixed patterns, etc.) to lower computational complexity to $O(nk)$; e.g., "Generating Long Sequences with Sparse Transformers" (2019)
- Low-Rank Approximation** approximates the attention matrix using low-rank decomposition to reduce the computational complexity to $O(nk)$; e.g., "Lformer: Self-Attention with Linear Complexity" (2020)
- Kernel Methods** approximate self-attention calculations to reduce the complexity to $O(n\log n)$; e.g., "Performer: Efficient Transformer with Linear Complexity" (2021)
- Local Attention** uses sliding window-based attention to reduce the complexity to $O(nk)$; e.g., "Longformer: The Long-Document Transformer" (2020)
- Mixture of Experts (MoE)** uses multiple expert models and activate only a few at a time, adopted by the SOTA LLMs such as DeepSeek-V3; e.g., "Switch Transformers: Scaling to Trillion Parameter Models with Simple and Efficient Sharded Training"
- Linear recurrence for parallel training** optimizes RNN architecture with parallelization; e.g., Mamba: Linear-Time Sequence Modeling with Selective State Spaces (2023)
 - Empirically, not as competitive as transformers for in-context learning.

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