Shaping the future of AI from the history of Transformer

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AI is advancing so fast that it is hard to keep up

People spend a lot of time and energy catching up with the latest developments

But not enough attention goes to the old things

It is more important to <u>study the change itself</u>

What does it mean to study the change itself?

1. Identify the dominant driving forces behind the change

2. Understand the dominant driving forces

3. Predict the future trajectory

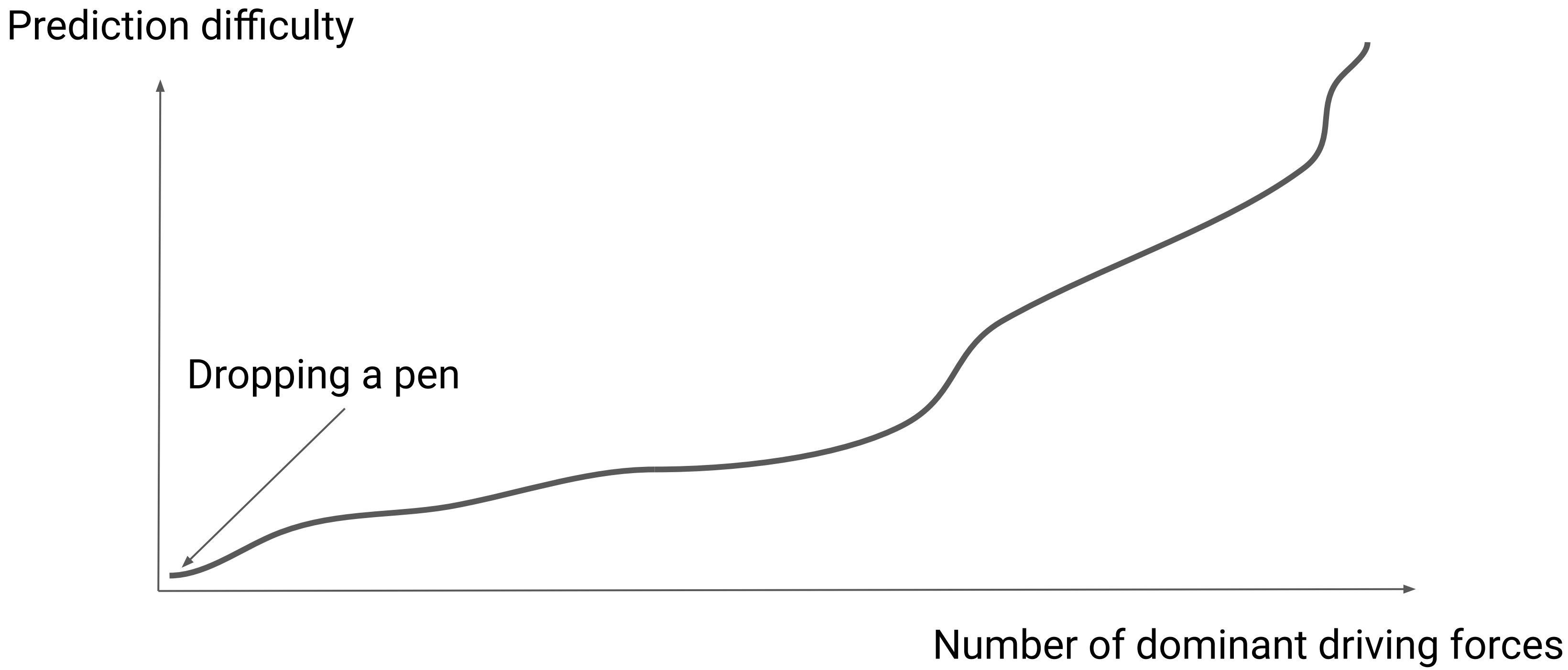
Toy experiment: dropping a pen

1. Identify the dominant driving forces: gravity

2. Understand gravity: Newtonian mechanics provides a good model

3. Predict the future trajectory of the pen $y(t) = \frac{1}{2}gt^2$

Predicting the future trajectory is difficult because there are many driving forces and the complexity of their interactions



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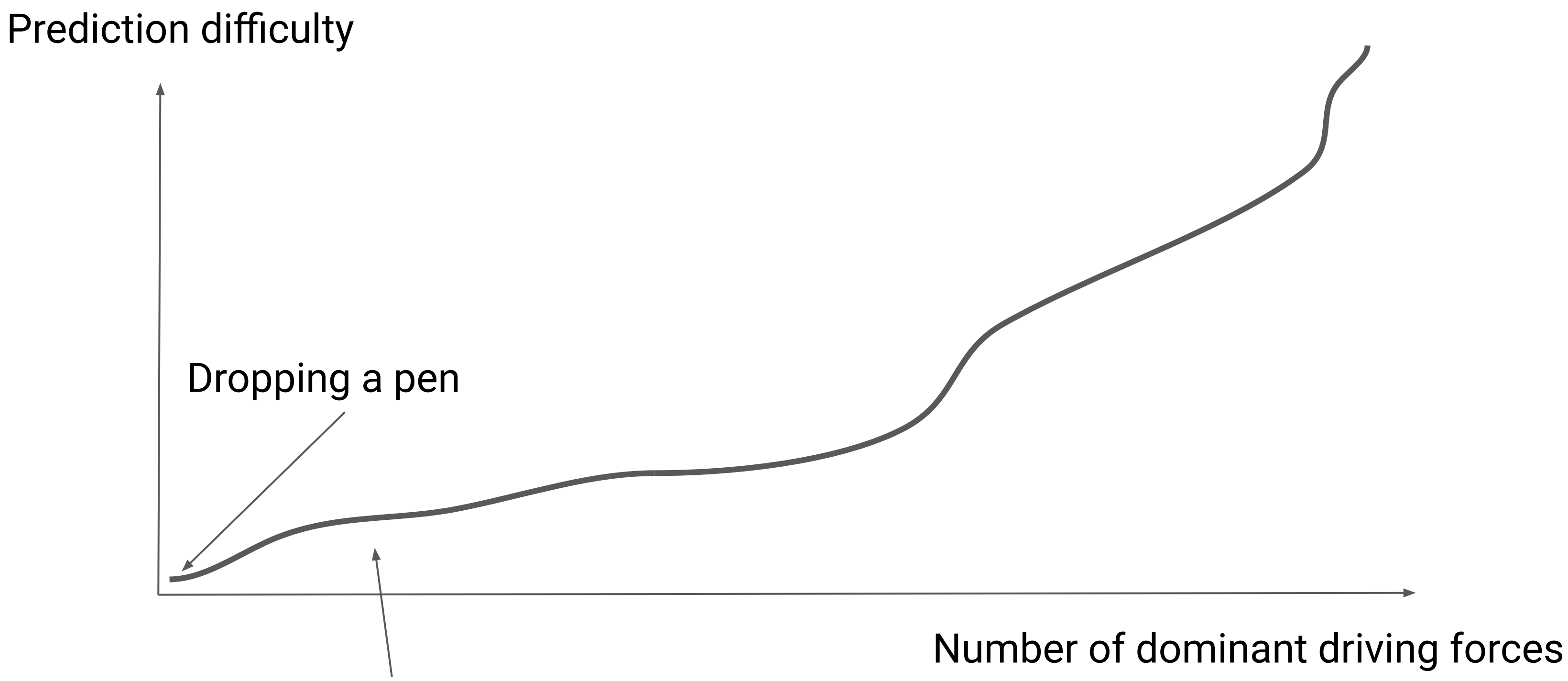
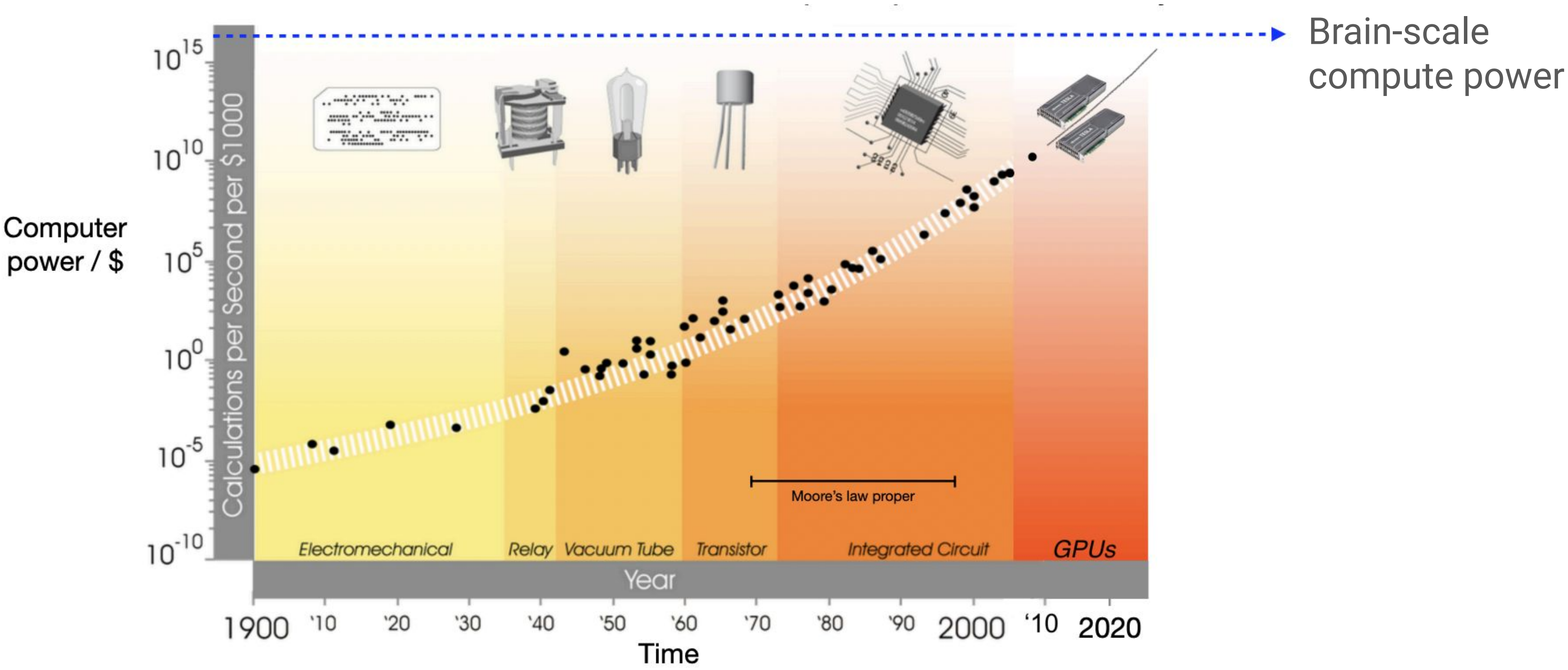


AI research is closer to the left than we feel



Roughly, 10x more compute every 5 years

Figure from Rich Sutton's [WAIC keynote]

The job of AI researchers is to teach machines how to “think”

One (unfortunately common) approach

Teach the machines how *we think* we think

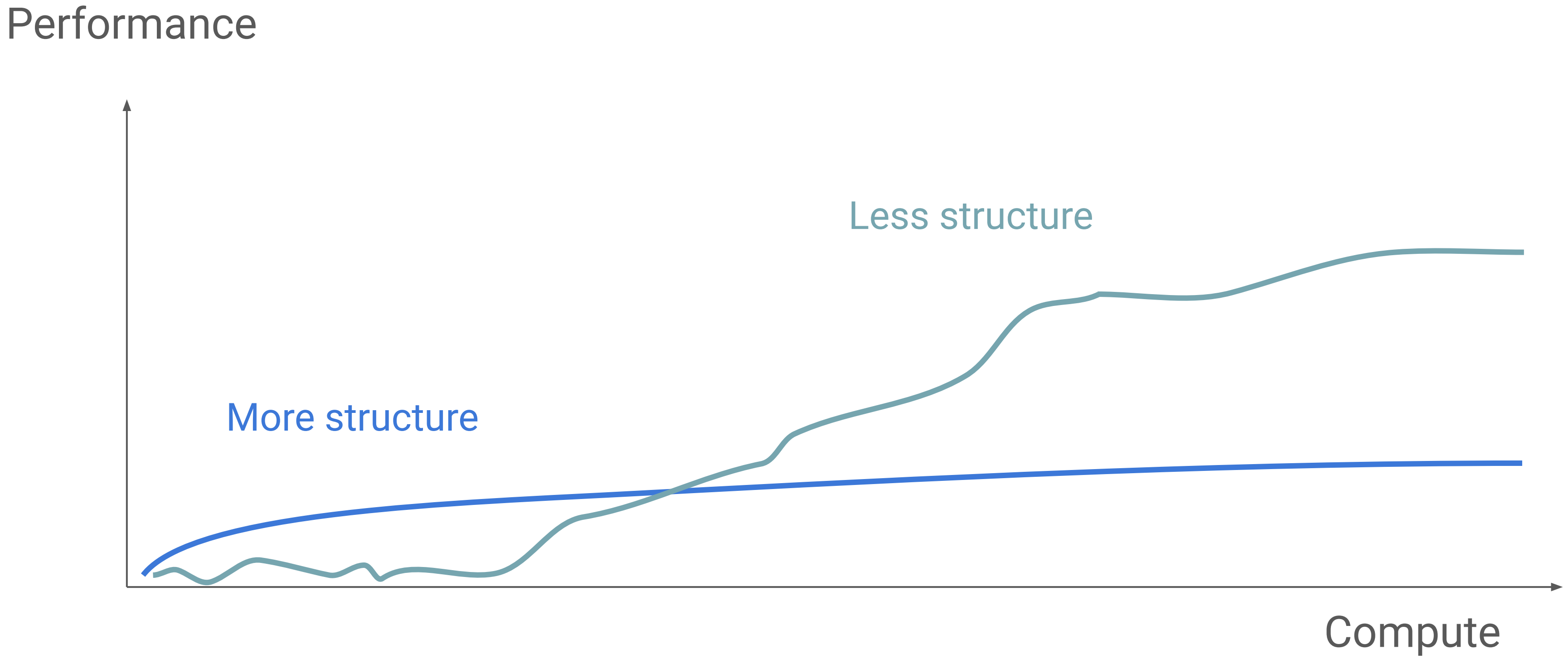
This approach poses structures to the problem, which can become the limitation when scaled up

The job of AI researchers is to teach machines how to "think"

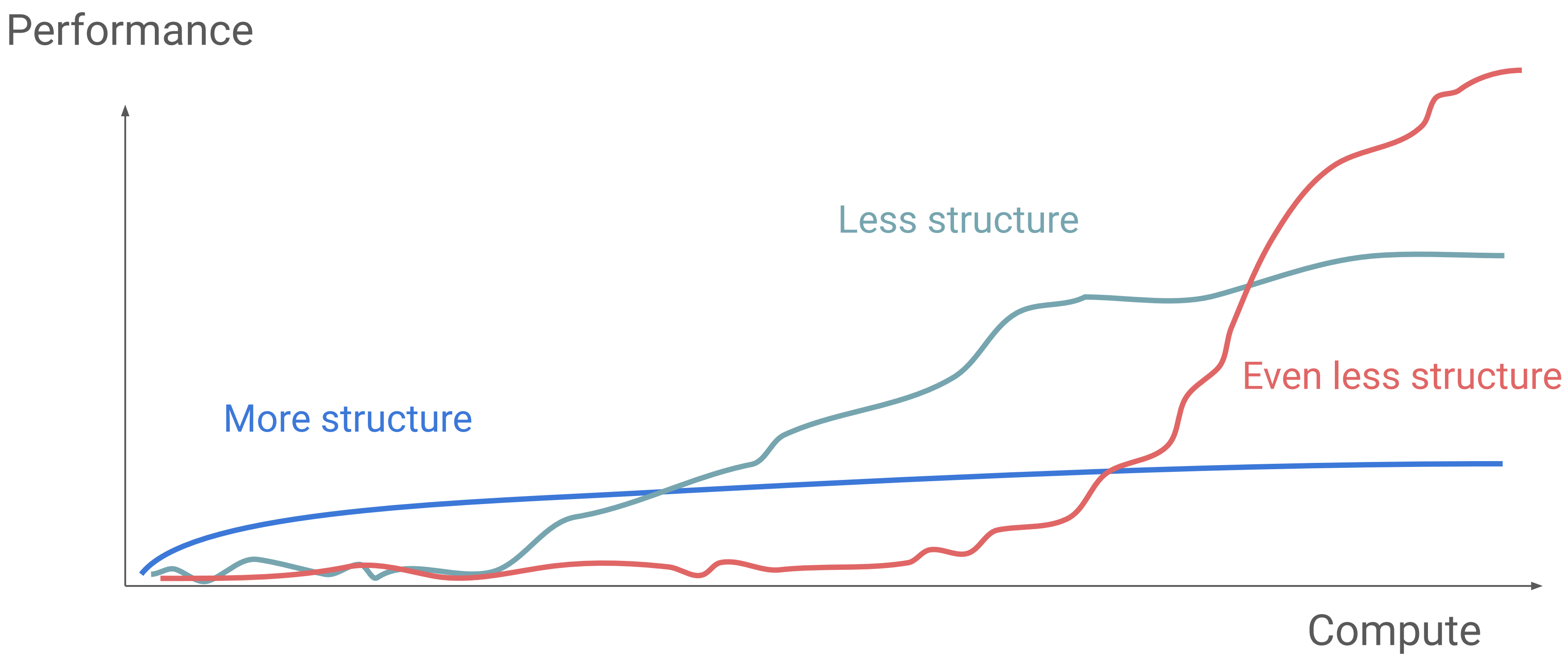
Bitter lesson: progress of AI in the past 70 years boils down to

- Develop progressively more general methods with weaker modeling assumptions
- Add more data and computation (i.e. scale up)

The more structure, the less scalable the method is



However, we can't just go for the most general method



Inspired by the conversation with Beomjoon Kim

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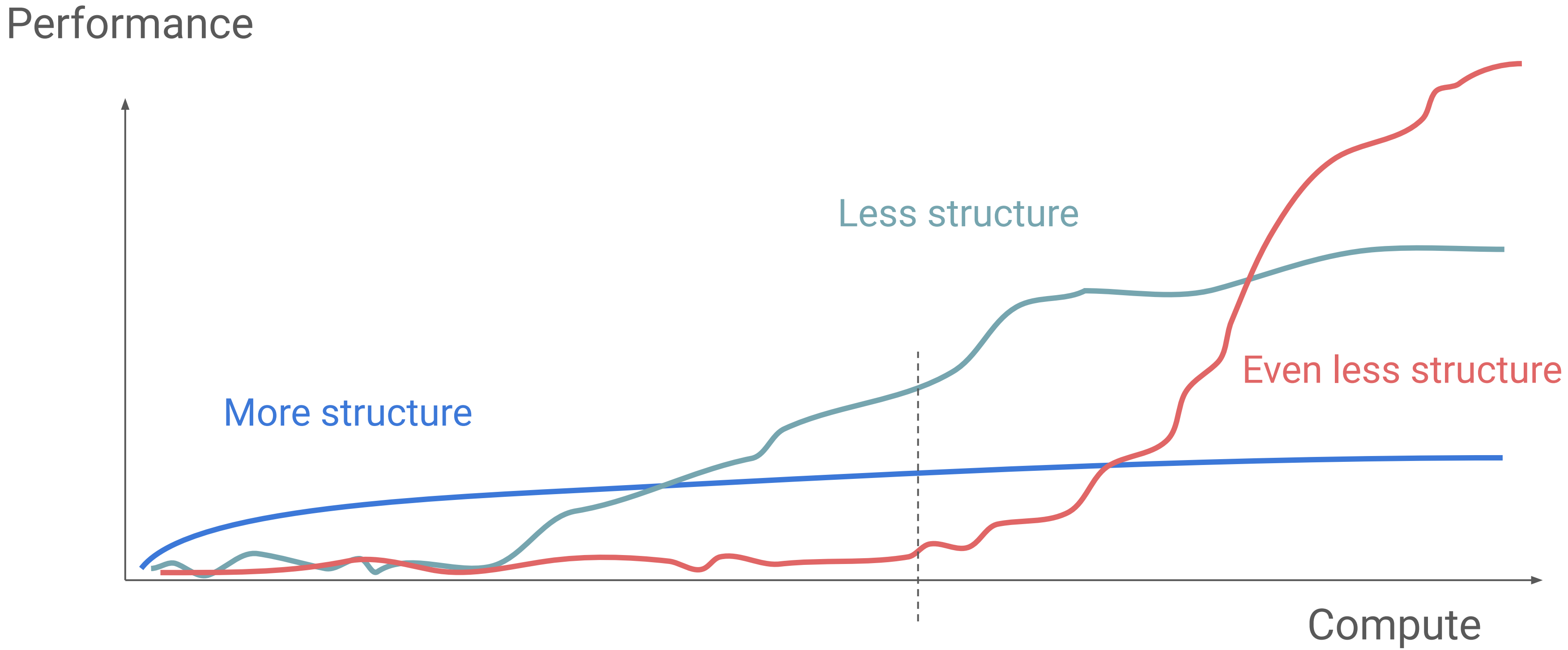
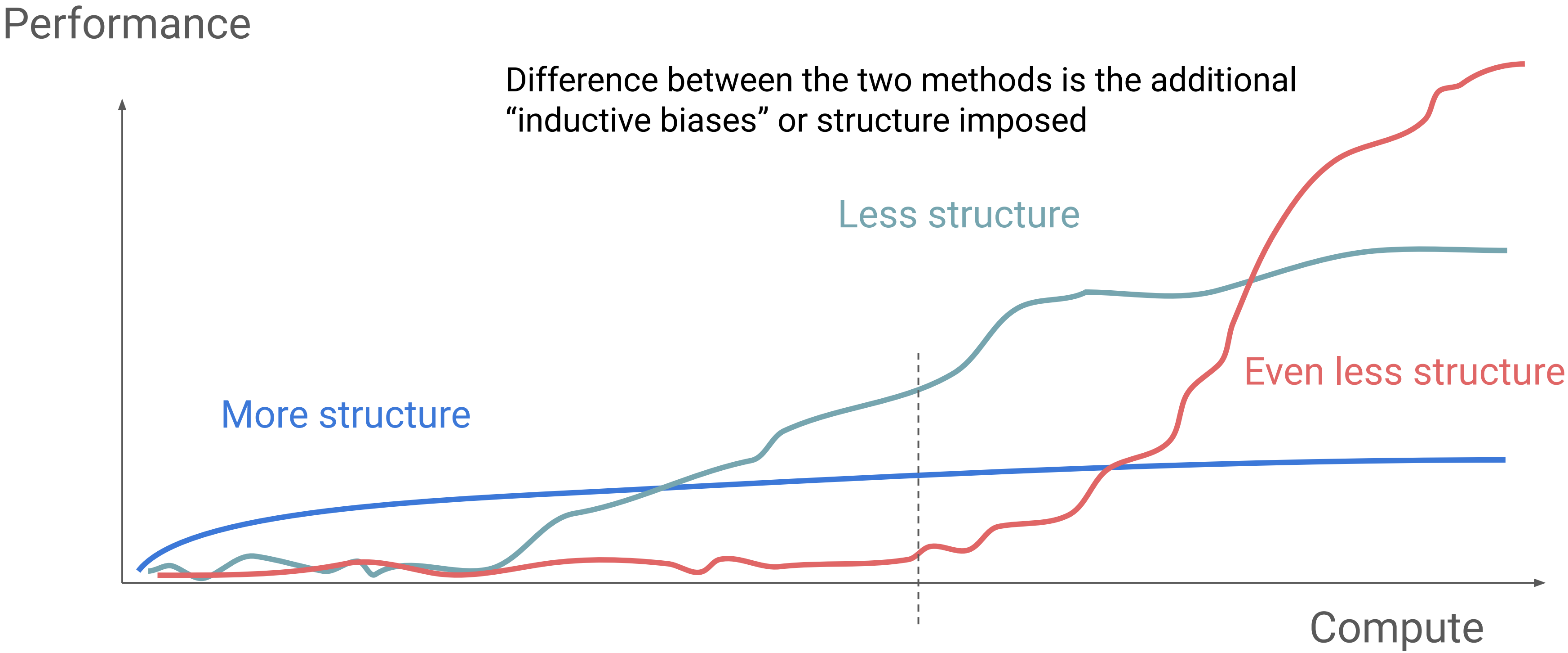


If we are here, we should choose "Less structure". But remember to undo later

Inspired by the conversation with Beomjoon Kim

However, we can't just go for the most general method



If we are here, we should choose "Less structure". But remember to undo later

Inspired by the conversation with Beomjoon Kim

Adding optimal inductive bias for a given level of compute, data, algorithmic development and architecture is critical

These are shortcuts that will hinder further scaling later on. Remove them later.

As a community we do the former well but not the latter

Implications of bitter lesson

What is better in the long term almost always looks worse now

This is somewhat unique to the AI research. If clever modeling techniques and fancy math were the driving force, it would have been completely different story

Summary

We identified the dominant driving force: exponentially cheaper compute and scaling

1

Now we need to understand it better

2

For that we will go to back to early history of Transformer and analyze key structures added by researchers and their motivations.

Then we will see how these structures became less relevant with now that more compute and better algorithm is available

Transformer architectures variants

1. Encoder-decoder
2. Encoder-only
3. Decoder-only (least structure)

Process	Shape
“Unicode characters like emojis may be split.”	[ ]

Process	Shape
Unicode characters like emojis may be split. [7085, 2456, 836, 470, 3975, 284, 530, 11241, 25, 773, 452, 12843, 13]	[length]
⬆ Tokenization	⬆
"Unicode characters like emojis may be split."	[ ]

Process | **Shape**

2.3	-3.2	8.3	5.4	2.1	3.9	-8.9	3.8	3.9	3.3
4.5	5.9	4.5	7.1	1.0	5.3	5.0	3.1	0.7	5.0
…	…	…	…	…	…	…	…	…	…
3.8	1.2	3.8	9.0	9.3	3.1	4.2	0.8	9.2	5.8

`[d_model, length]`

Embedding

`Unicode characters like emojis may be split.`

`[7085, 2456, 836, 470, 3975, 284, 530, 11241, 25, 773, 452, 12843, 13]`

`[length]`

Tokenization

"Unicode characters like emojis may be split."

`[]`

Process

Shape

3.2	-2.3	3.8	4.5	1.2	9.3	-9.8	8.3	9.3	3.3
5.4	9.5	5.4	1.7	0.1	3.5	0.5	1.3	7.0	0.5
…	…	…	…	…	…	…	…	…	…
8.3	2.1	8.3	0.9	3.9	1.3	2.4	8.0	2.9	8.5

`[d_model, length]`

Sequence model

2.3	-3.2	8.3	5.4	2.1	3.9	-8.9	3.8	3.9	3.3
4.5	5.9	4.5	7.1	1.0	5.3	5.0	3.1	0.7	5.0
…	…	…	…	…	…	…	…	…	…
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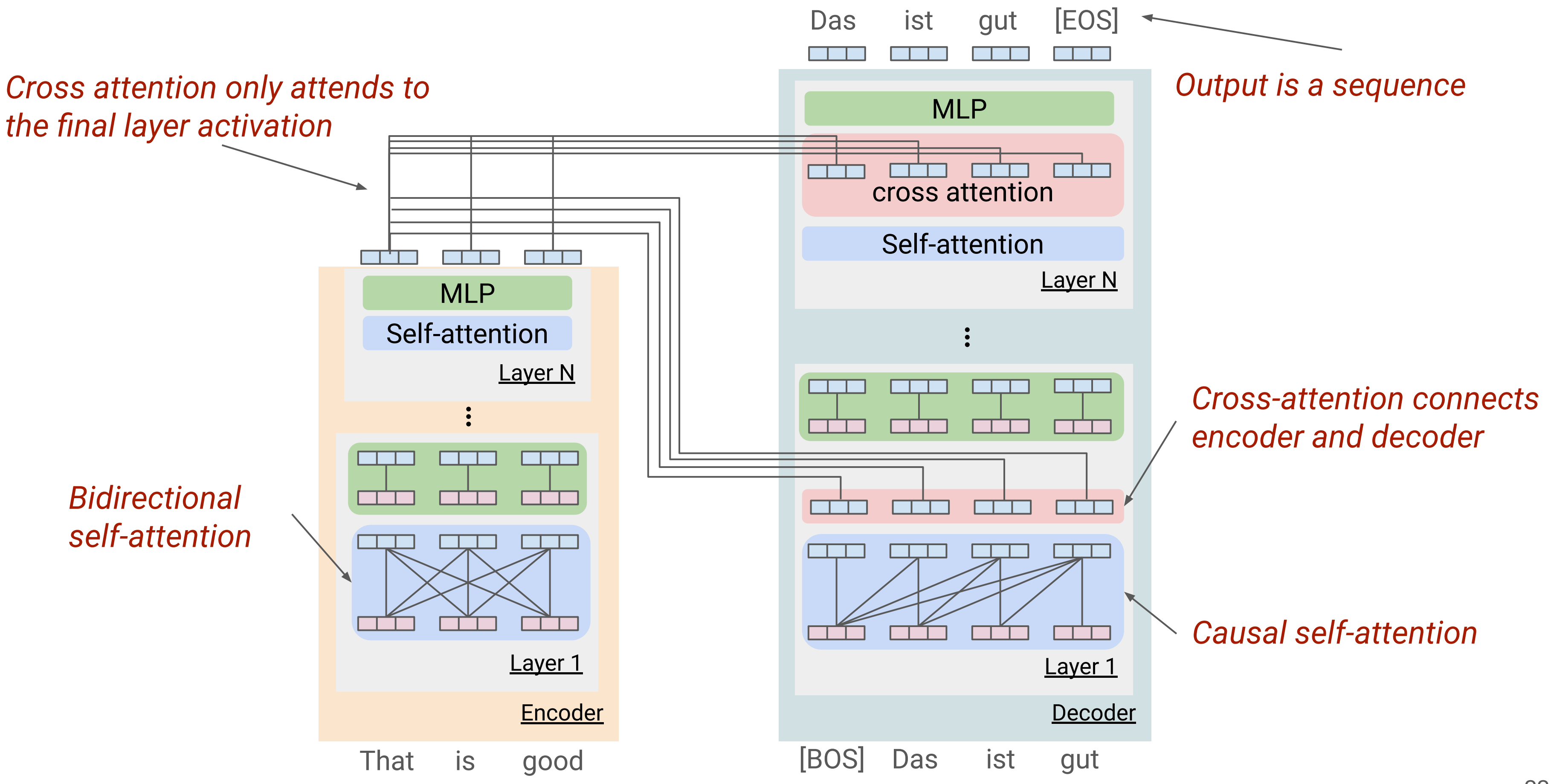
[Tokenization](#)

"Unicode characters like emojis may be split."

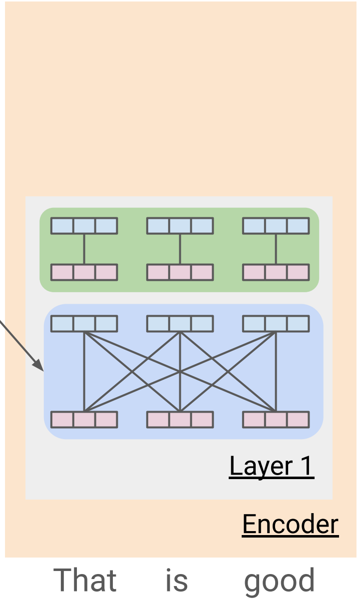
`[]`

Encoder-decoder



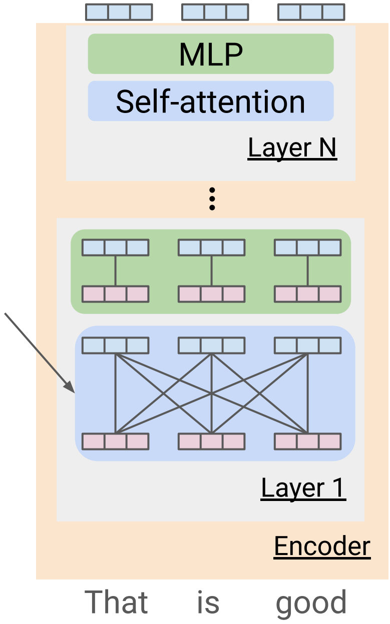
Encoder-decoder

Bidirectional self-attention

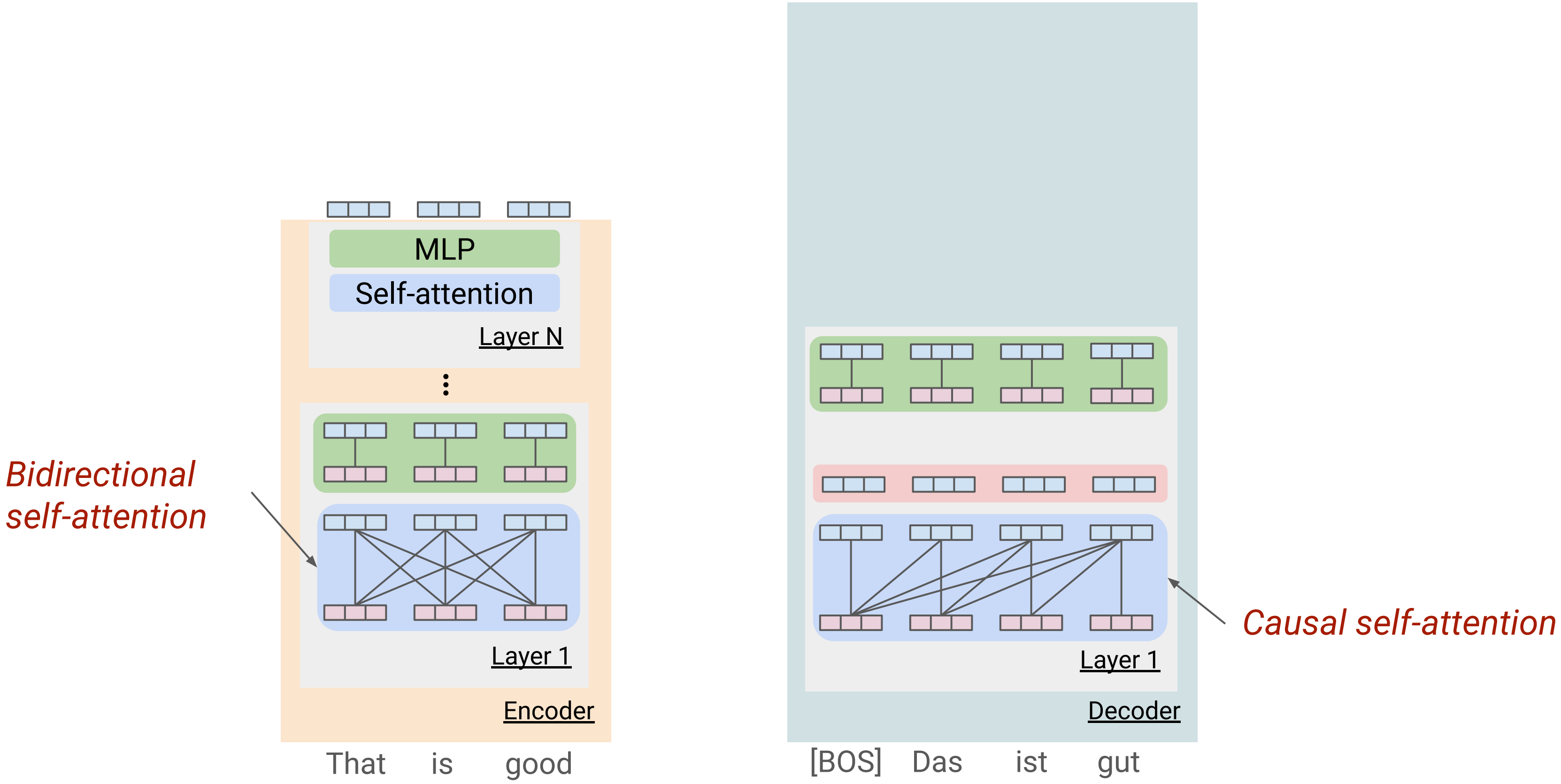


Encoder-decoder

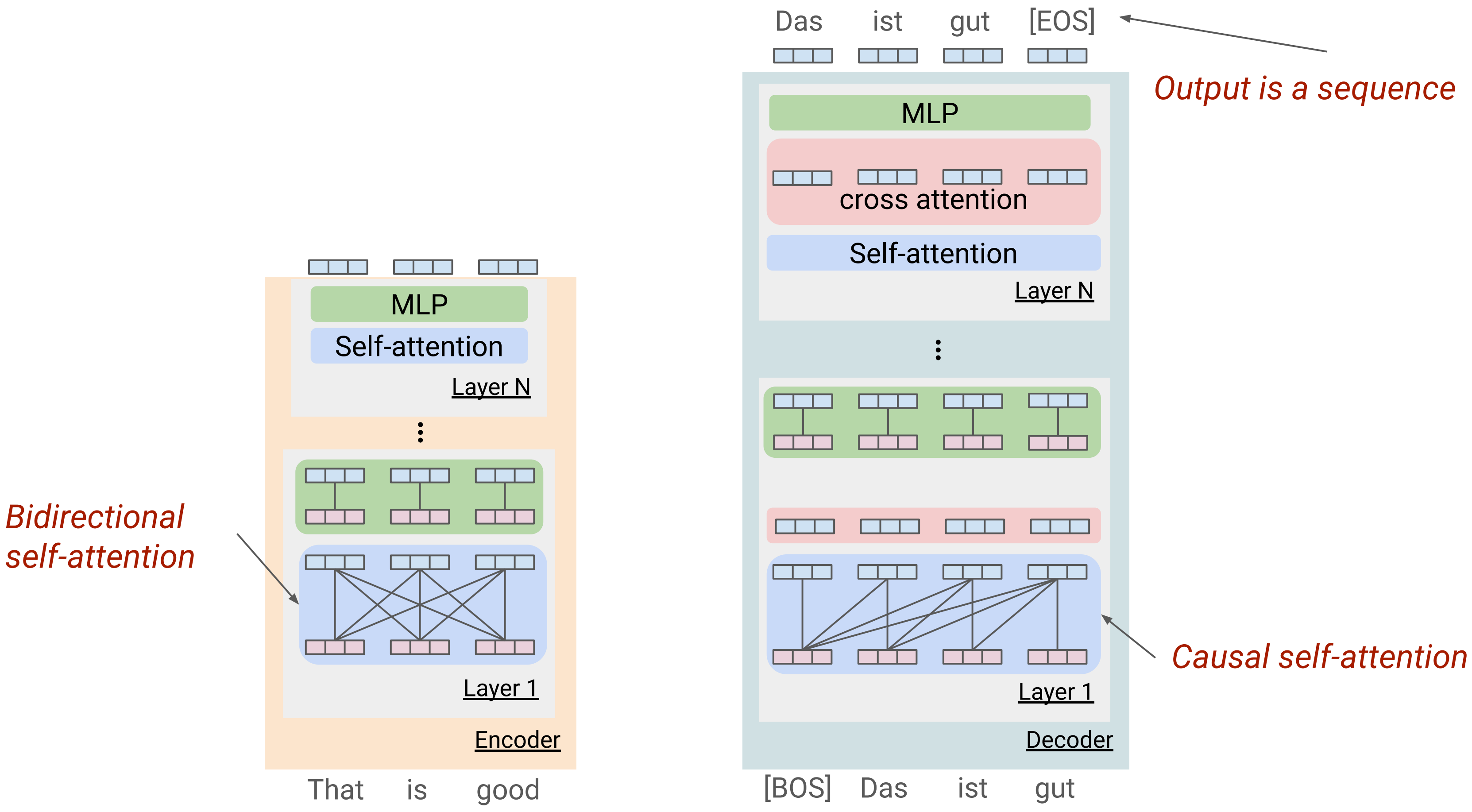
Bidirectional self-attention



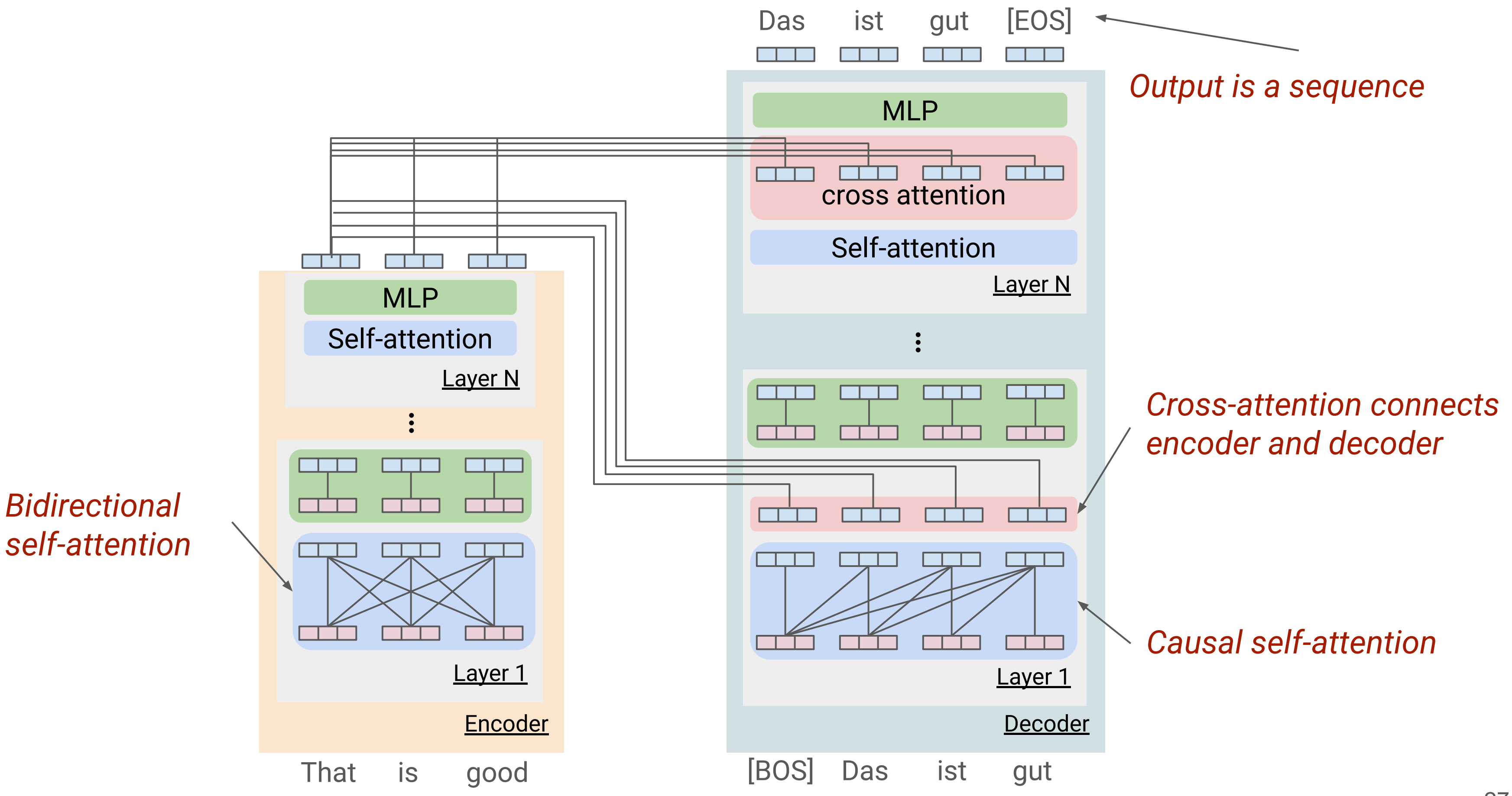
Encoder-decoder



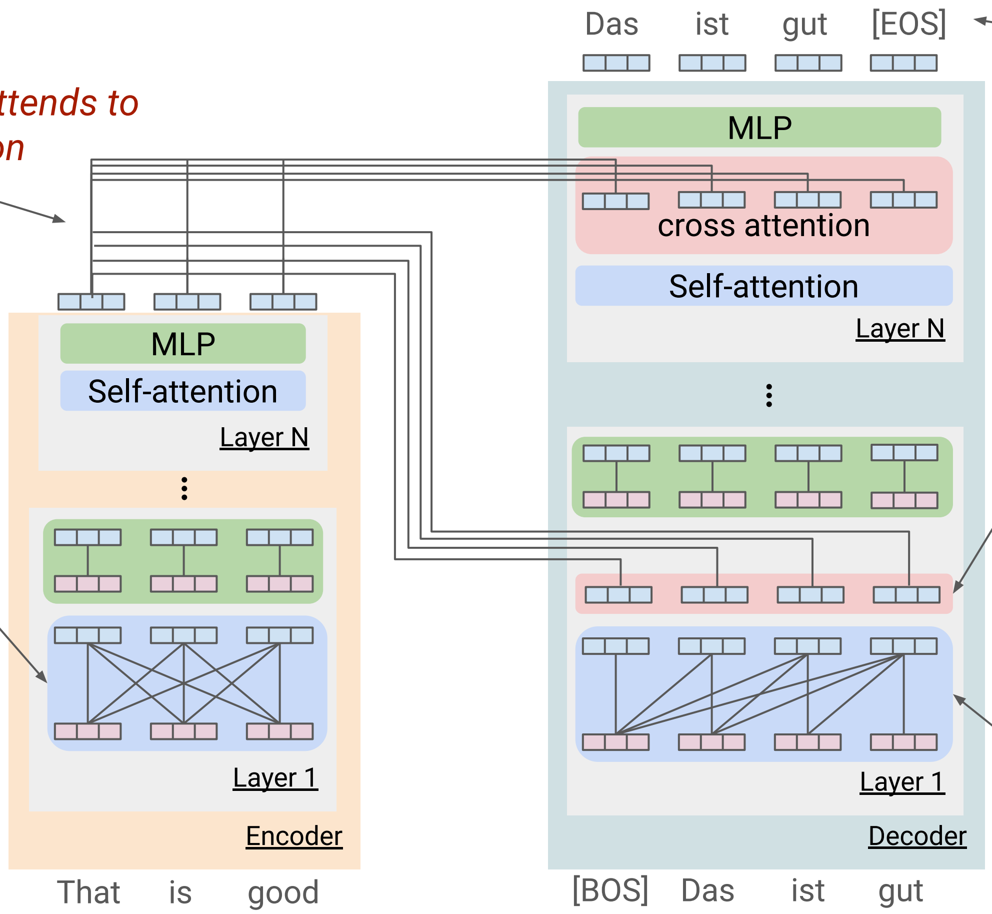
Encoder-decoder



Encoder-decoder



Encoder-decoder



Cross attention only attends to the final layer activation

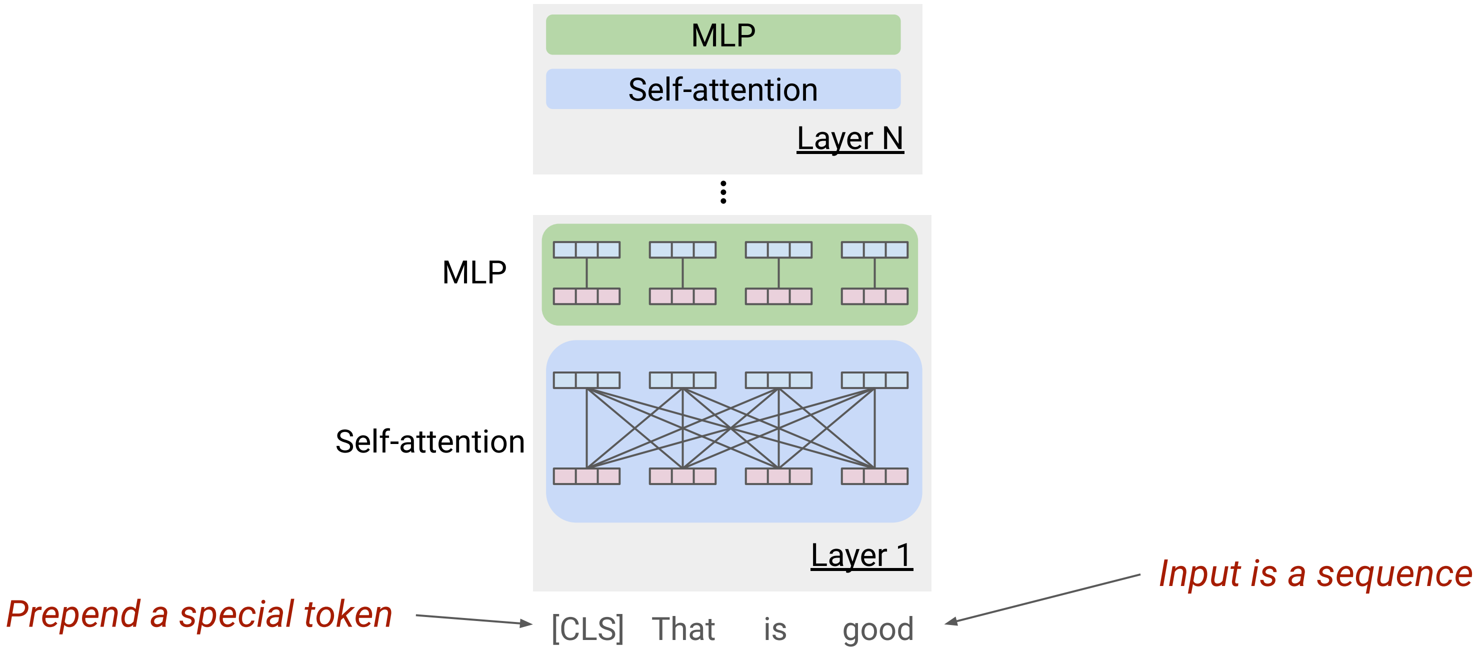
Output is a sequence

Cross-attention connects encoder and decoder

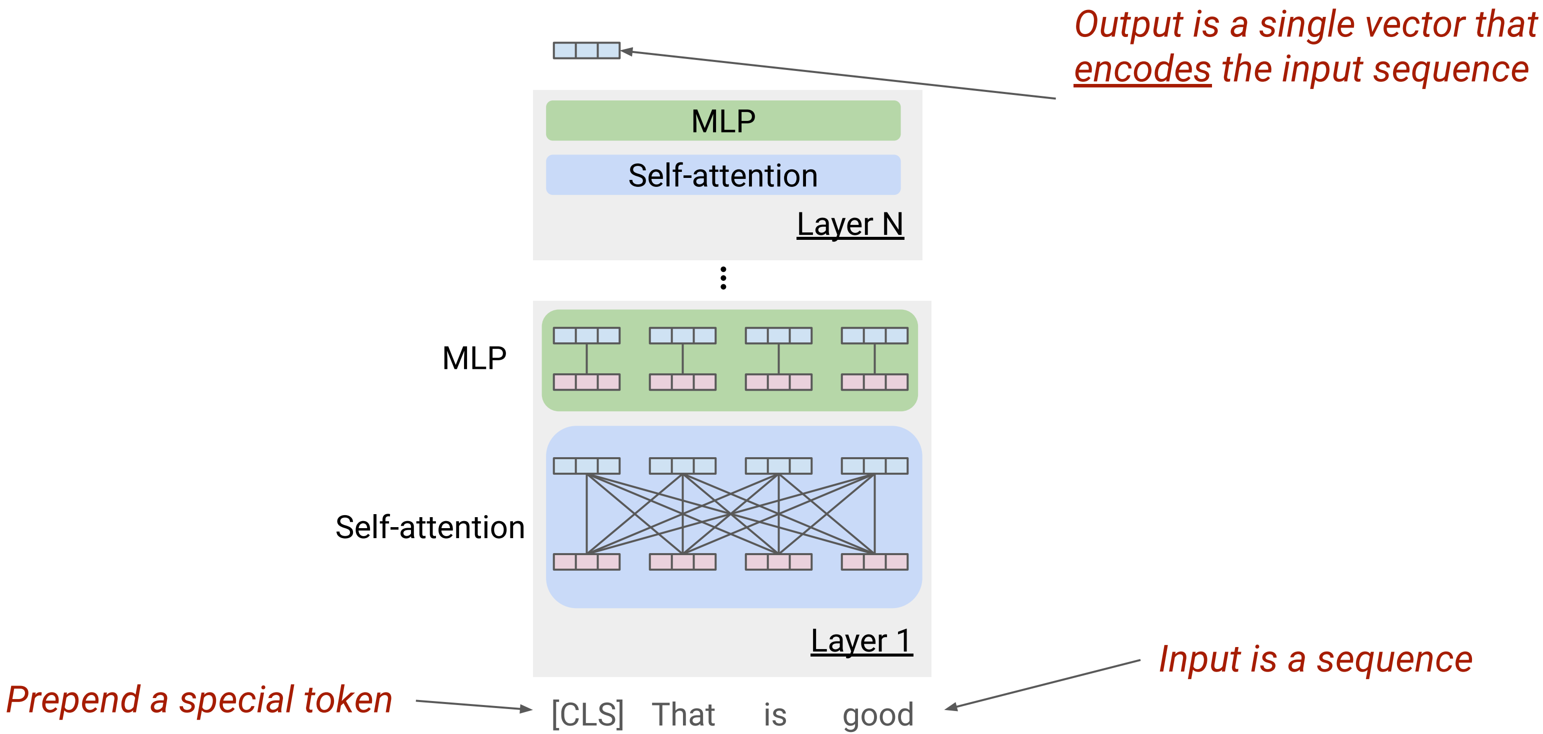
Bidirectional self-attention

Causal self-attention

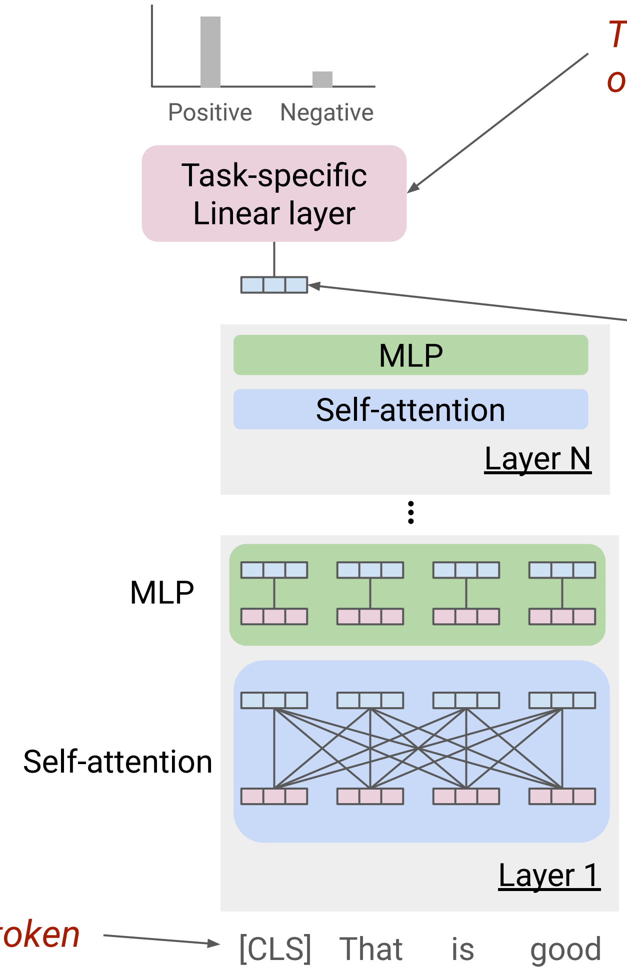
Encoder-only



Encoder-only



Encoder-only



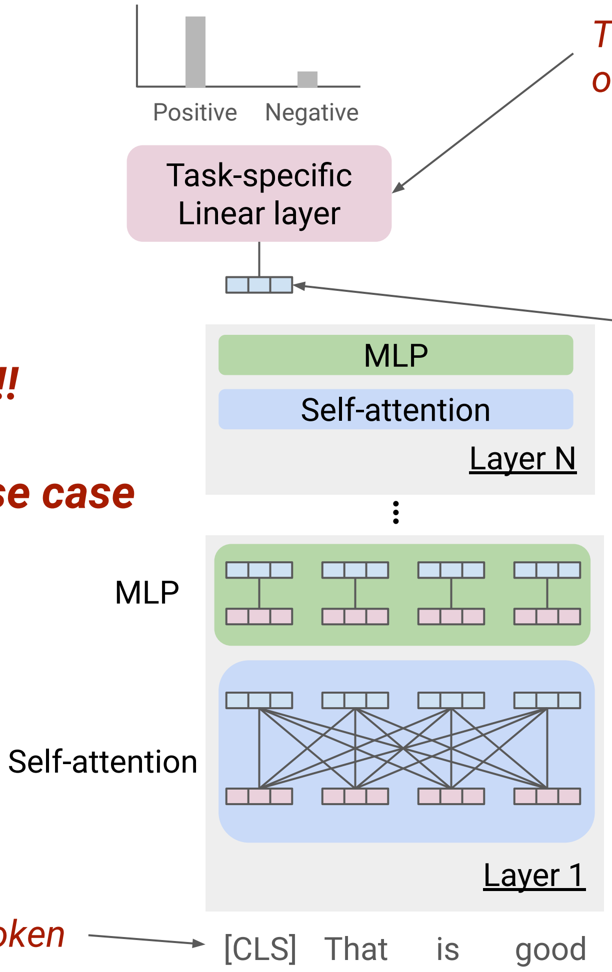
Task-specific layer is necessary to map output vector to classification label space

Output is a single vector that encodes the input sequence

Input is a sequence

Prepend a special token

Encoder-only



Task-specific layer is necessary to map output vector to classification label space

Output is a single vector that encodes the input sequence

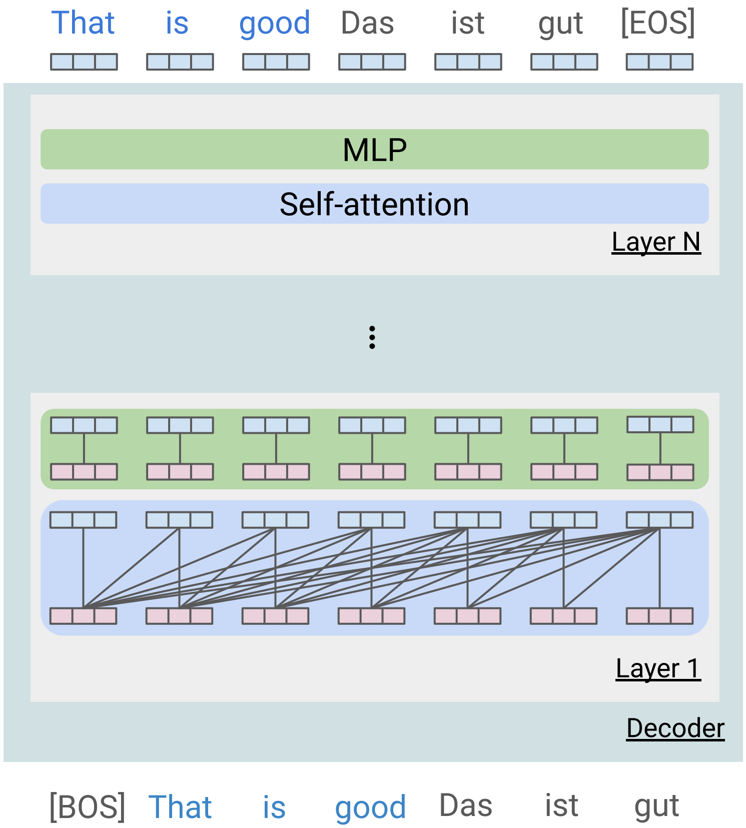
Can't generate a sequence!!

Deal breaker for general use case

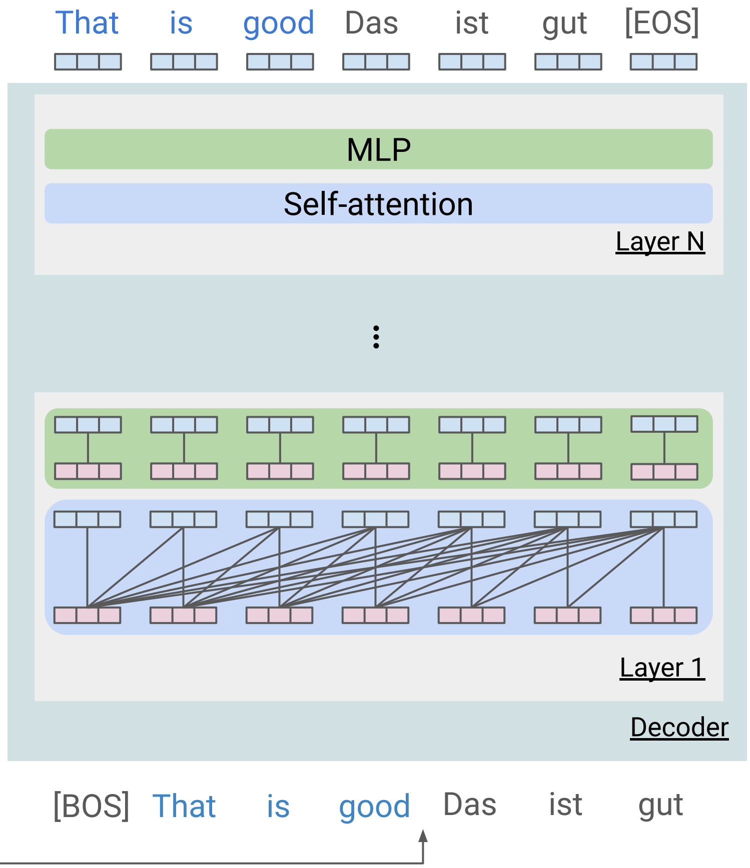
Prepend a special token

Input is a sequence

Decoder-only

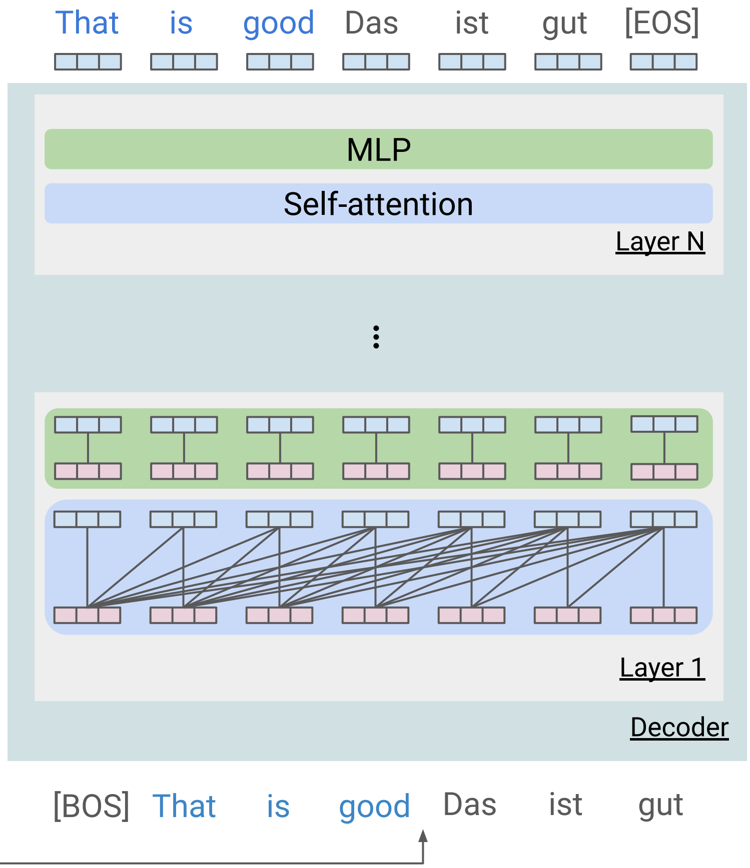


Decoder-only



Input and target are concatenated

Decoder-only



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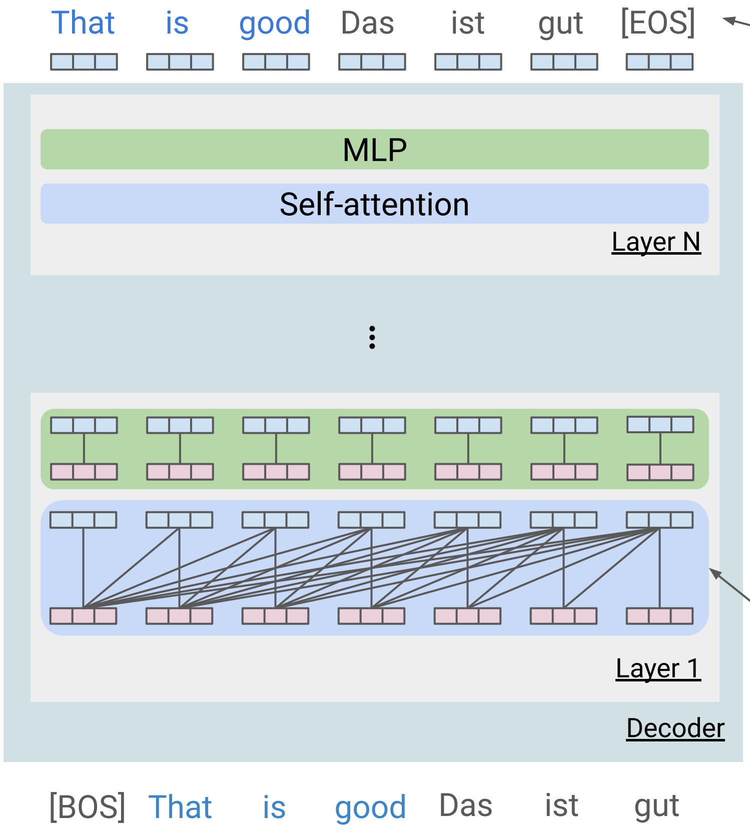
Decoder-only



Output is a sequence

Causal self-attention

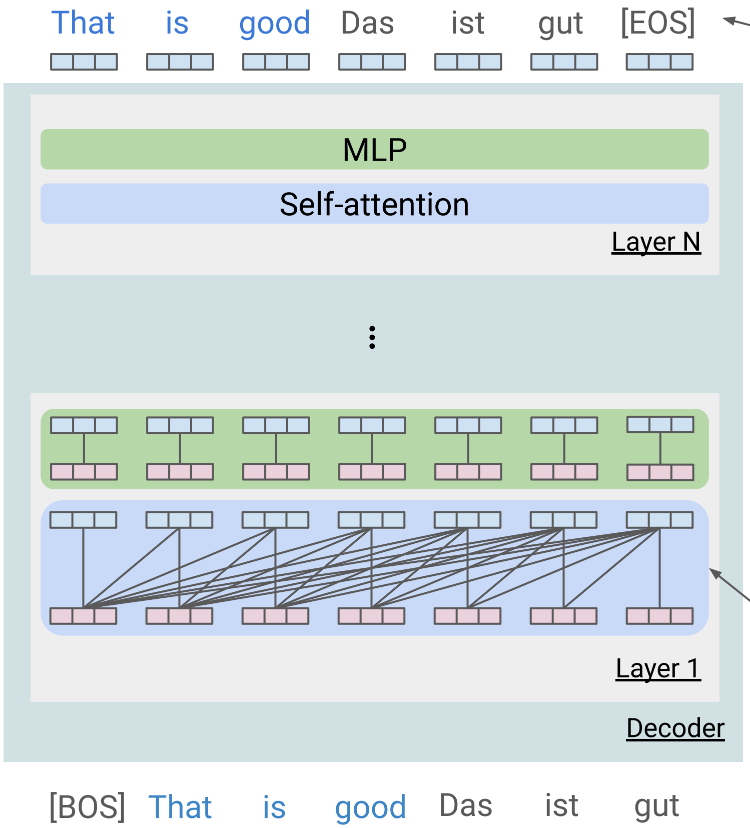
Input and target are concatenated

Decoder-only

Key design features

Self attention also serves the role of cross-attention

Same set of parameters apply to both input and target sequences



Output is a sequence

Causal self-attention

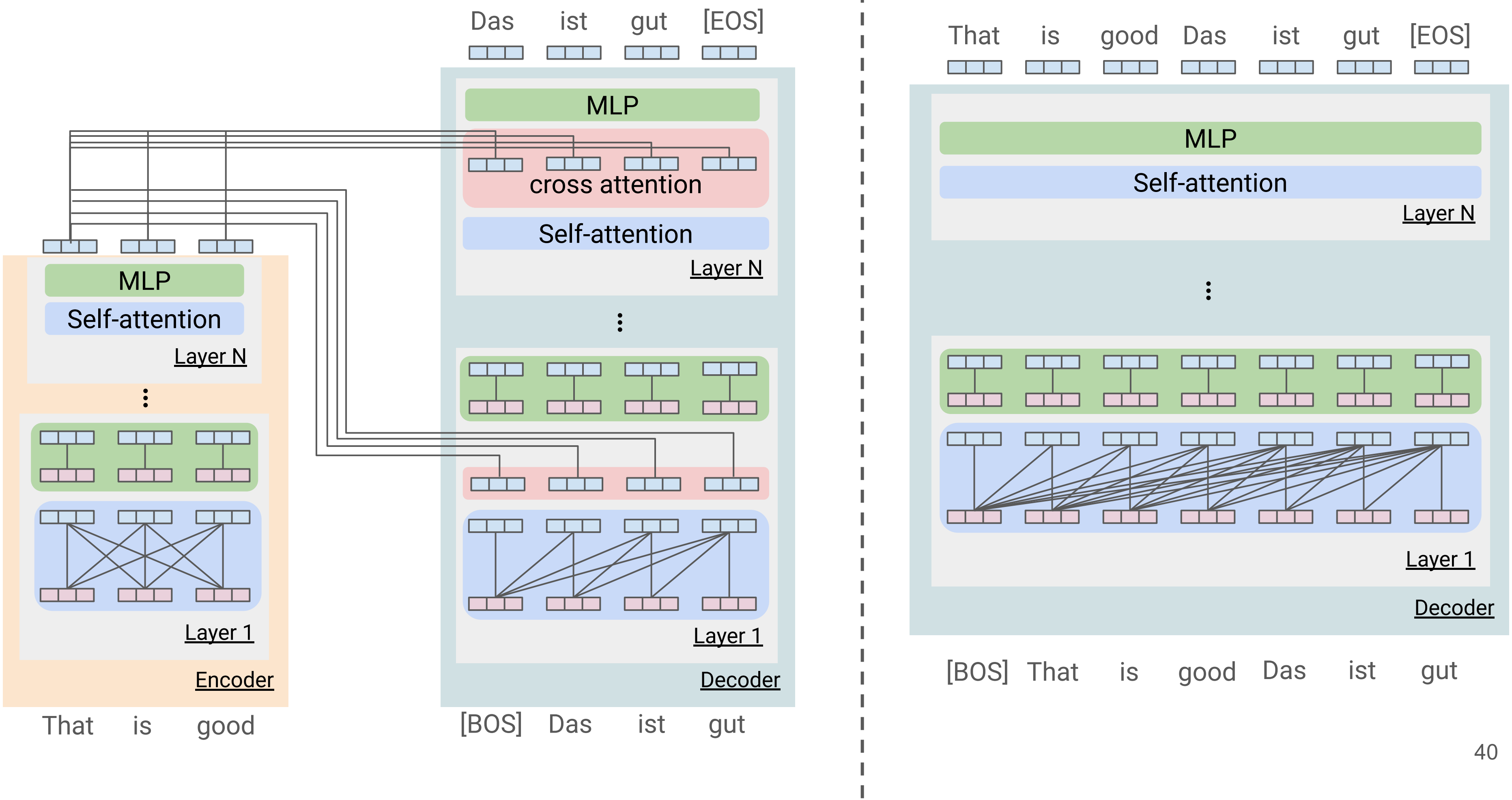
Input and target are concatenated

How different are encoder-decoder and decoder-only architectures?

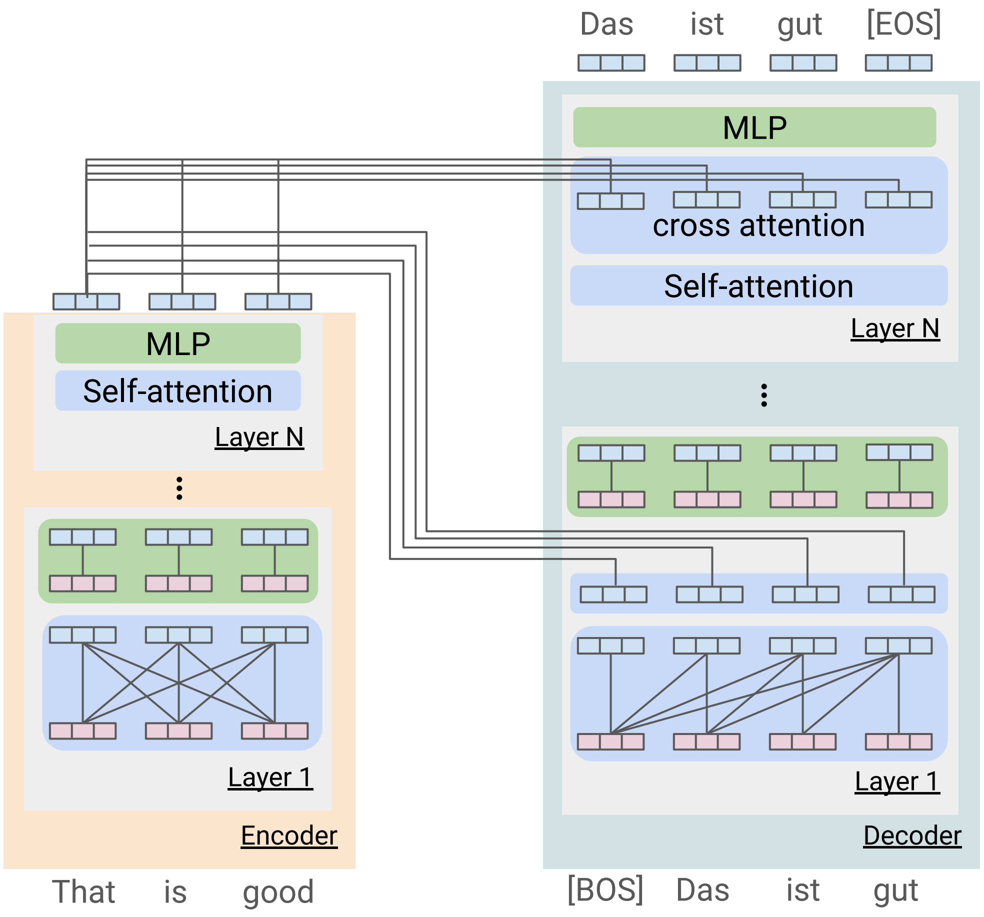
Let’s try to transform encoder-decoder into decoder-only

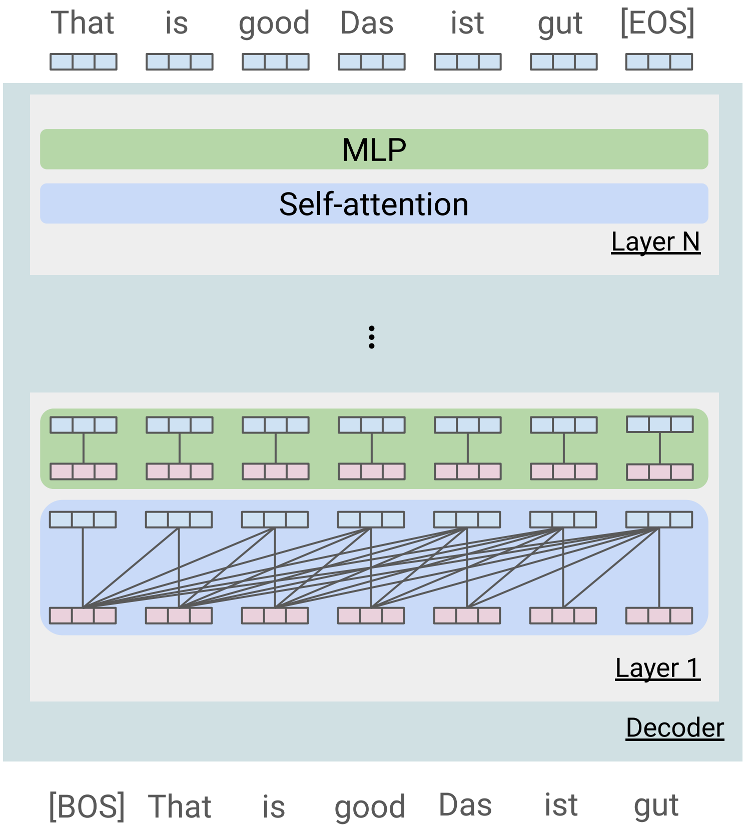
Summary of the differences

	Encoder-decoder	Decoder-only
Additional cross attention		
Parameter sharing		
Target-to-input attention pattern		
Input attention		


Das
ist
gut
[EOS]
MLP
cross attention
Self-attention
Layer N
Layer 1
Decoder
[BOS]
Das
ist
gut
MLP
Self-attention
Layer N
Layer 1
Encoder
That
is
good
That
is
good
Das
ist
gut
[EOS]
MLP
Self-attention
Layer N
Layer 1
Decoder
[BOS]
That
is
good
Das
ist
gut

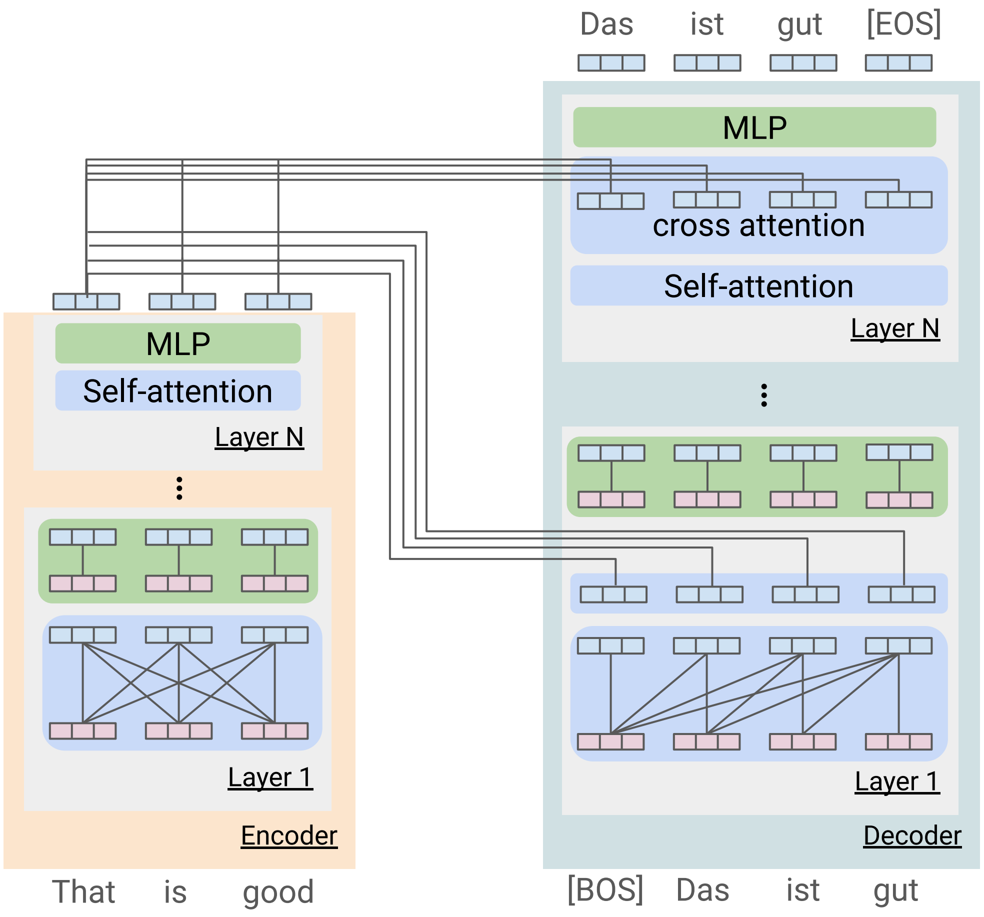
1. Share cross and self-attention parameters

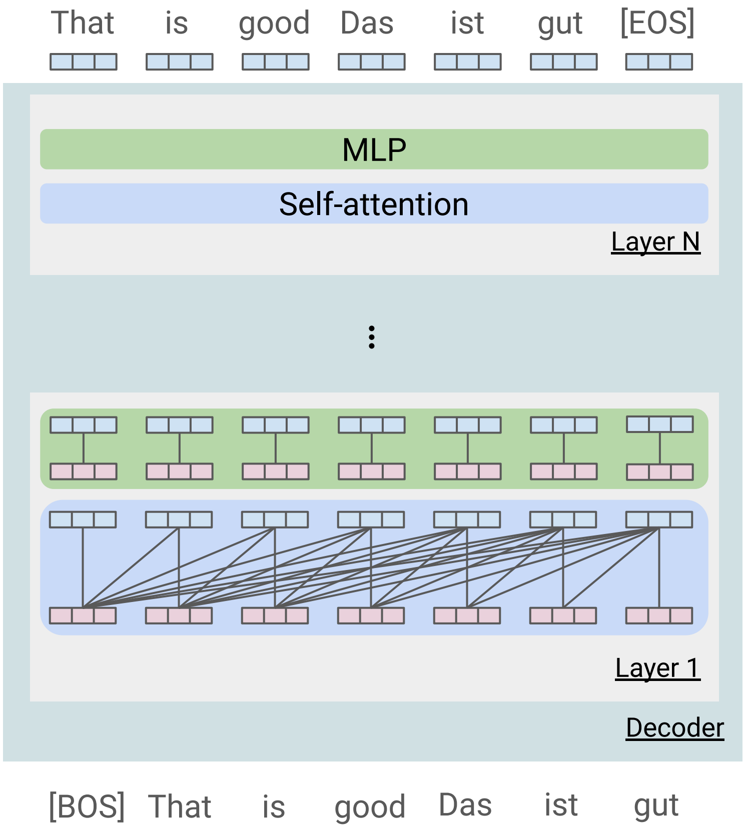




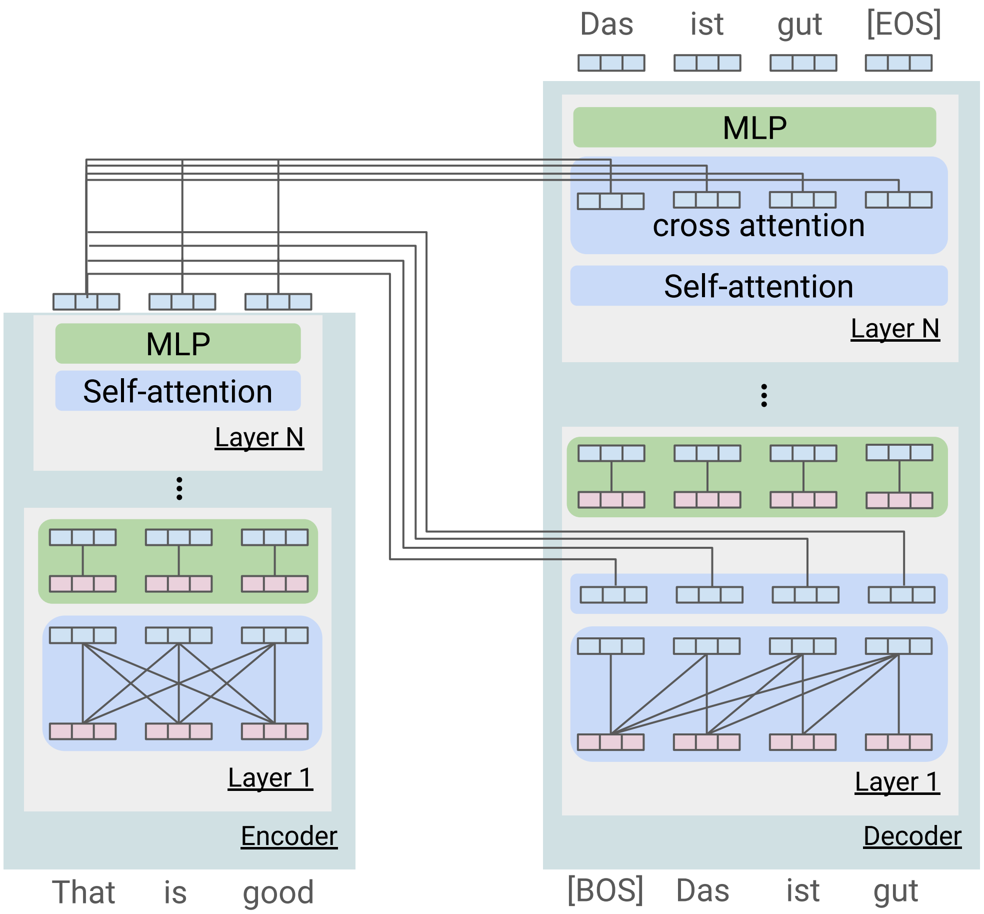
Summary of the differences

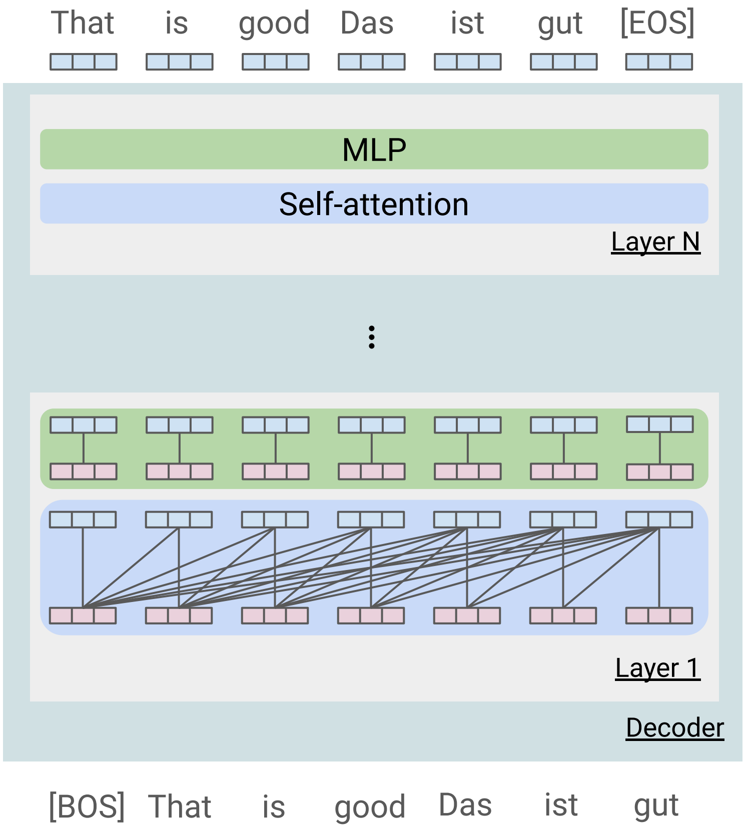
	Encoder-decoder	**Decoder-only**
Additional cross attention	Separate cross attention	Self-attention serving both roles
Parameter sharing		
Target-to-input attention pattern		
Input attention		


Das ist gut [EOS]
MLP
cross attention
Self-attention
Layer N
MLP
Self-attention
Layer N
Layer 1
Encoder
Layer 1
Decoder
That is good
[BOS] Das ist gut


That is good Das ist gut [EOS]
MLP
Self-attention
Layer N
Layer 1
Decoder
[BOS] That is good Das ist gut

2. Share encoder and decoder parameters





Summary of the differences

	Encoder-decoder	**Decoder-only**
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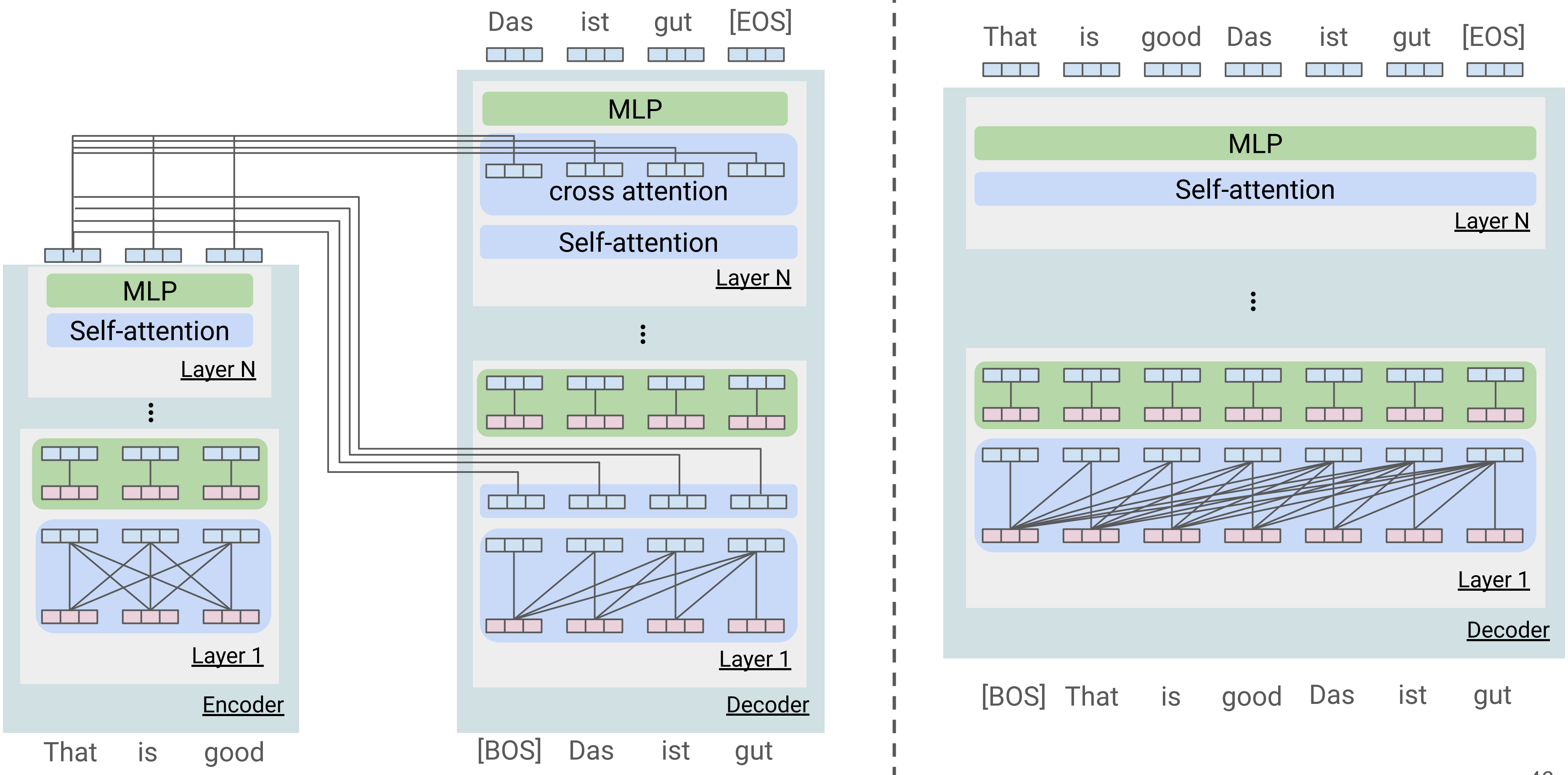
Input attention		



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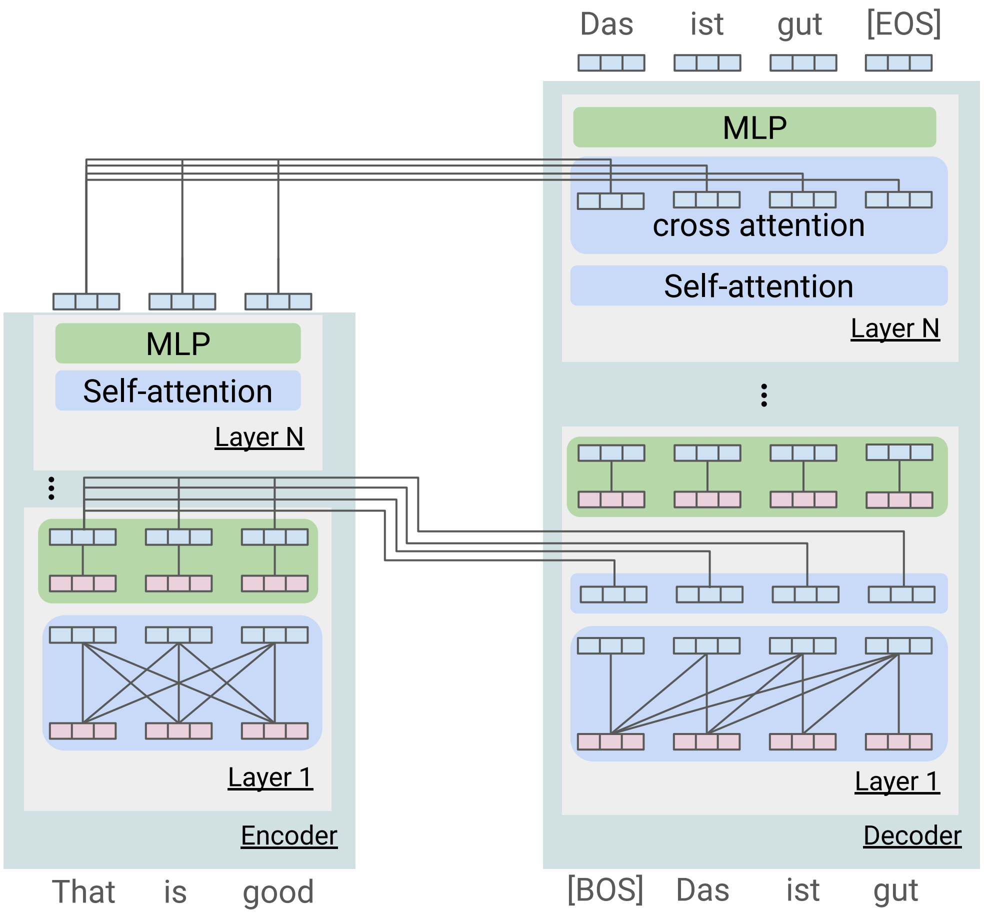
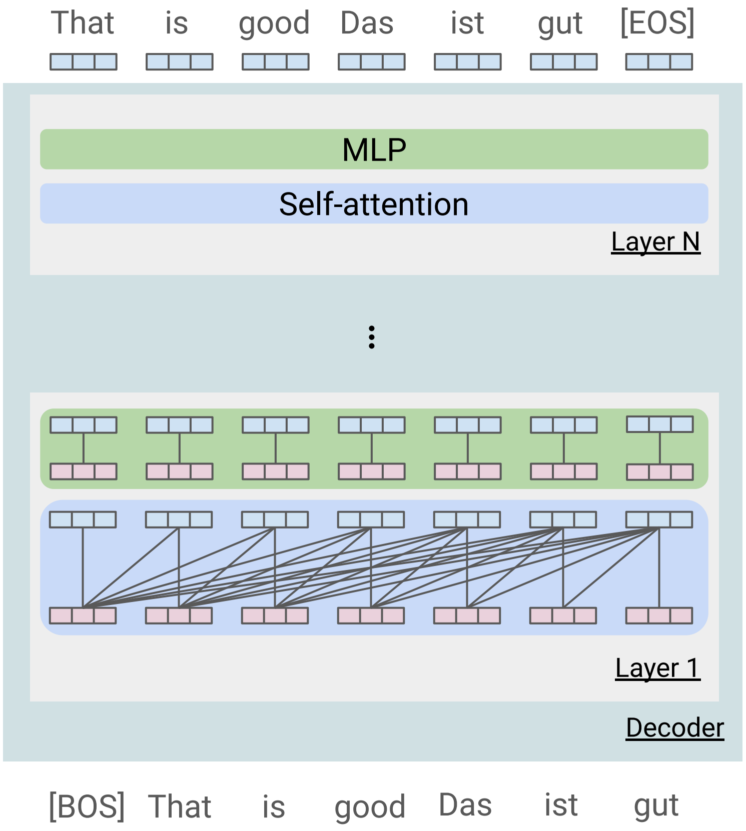
3. Decoder layer l attends to encoder layer l





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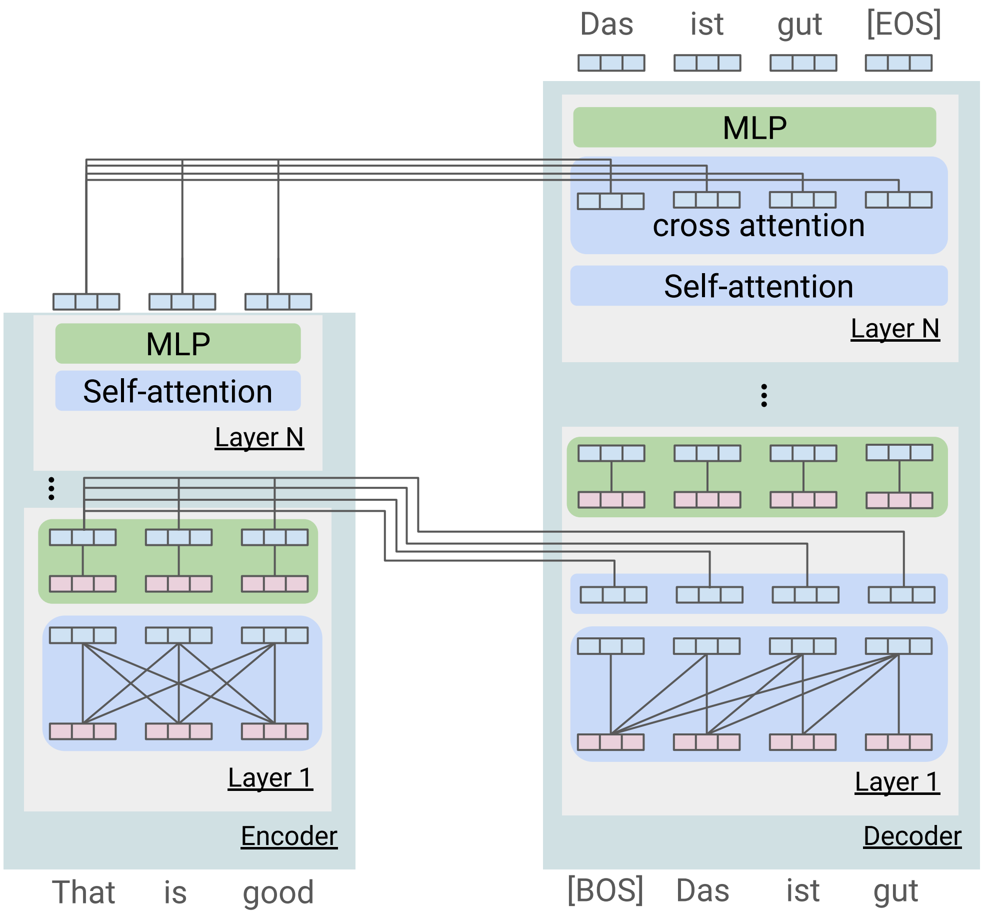
Input attention		

* input attention can be bidirectional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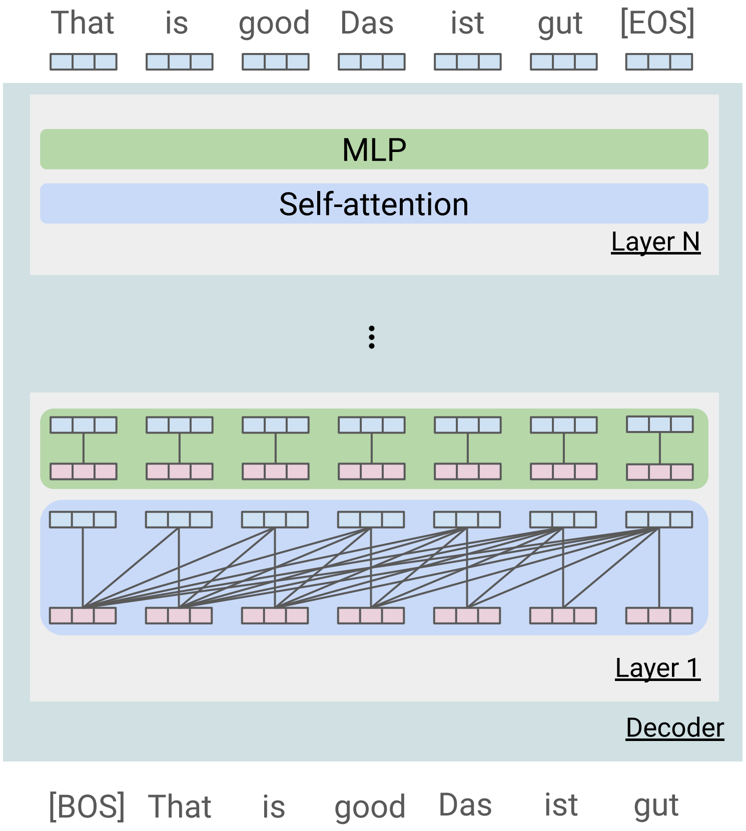
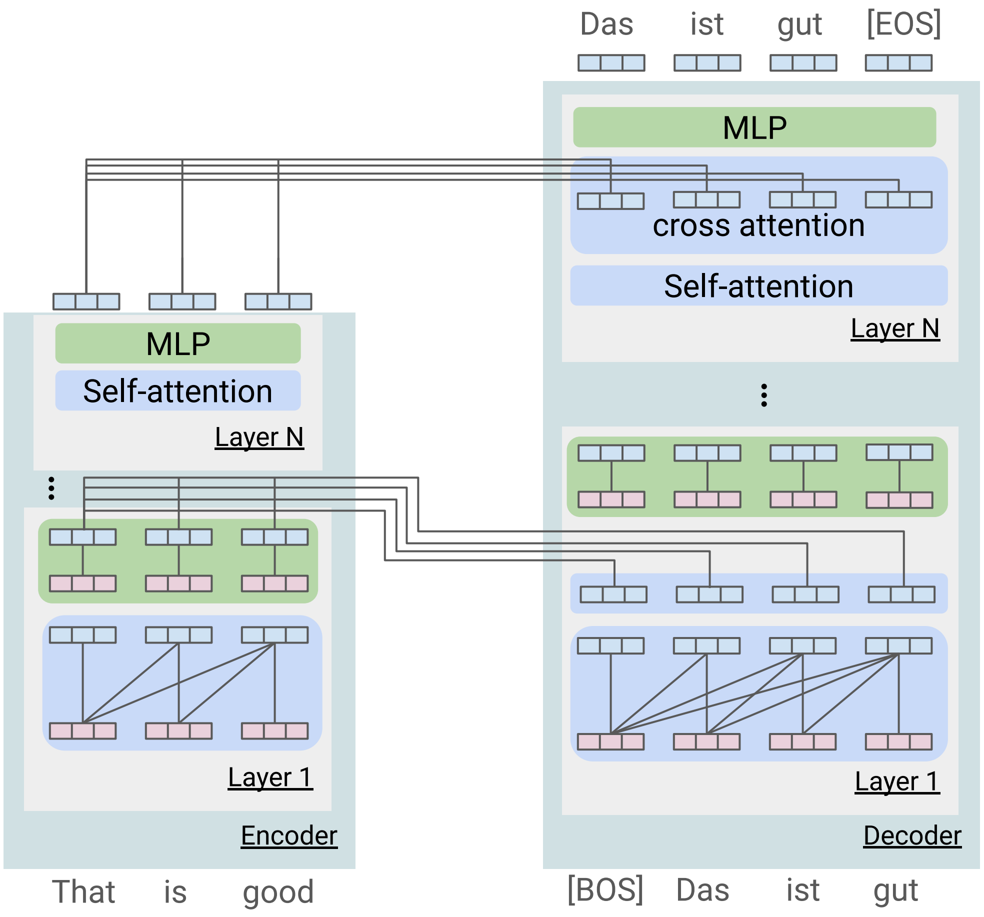
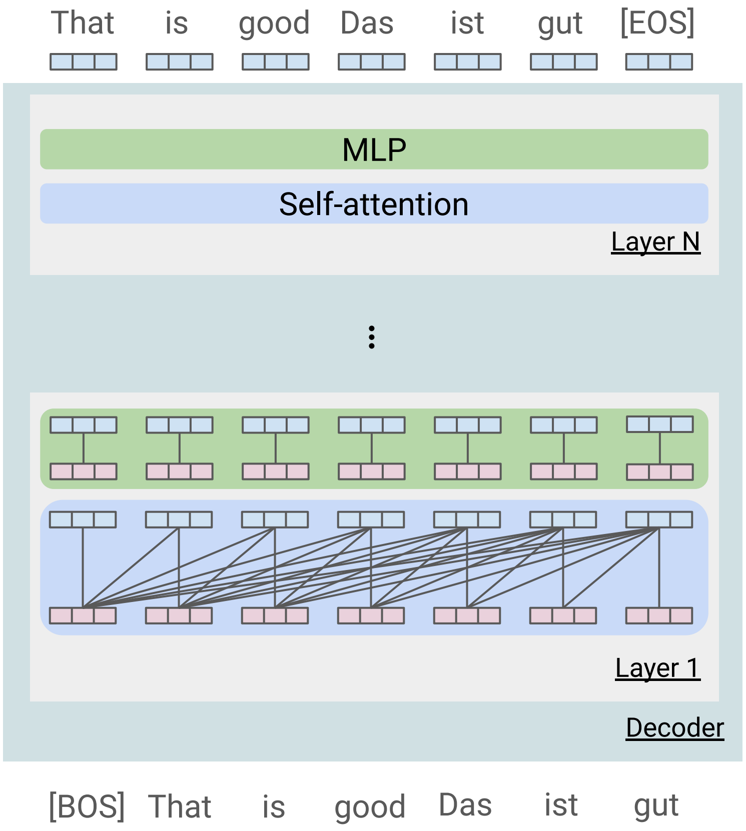

That is good Das ist gut [EOS]
MLP
Self-attention
Layer N
Layer 1
Decoder
[BOS] That is good Das ist gut

4. Make encoder self-attention causal





Summary of the differences

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Input attention	Bidirectional	Unidirectional*

* input attention can be bidirectional

Additional structures in encoder-decoder compared to decoder-only

1. Input and target sequences are sufficiently different that using separate parameters can be effective

2. The target element can attend to the fully encoded representation of the input

3. When encoding the input sequence, all-to-all interaction among the sequence elements is preferred

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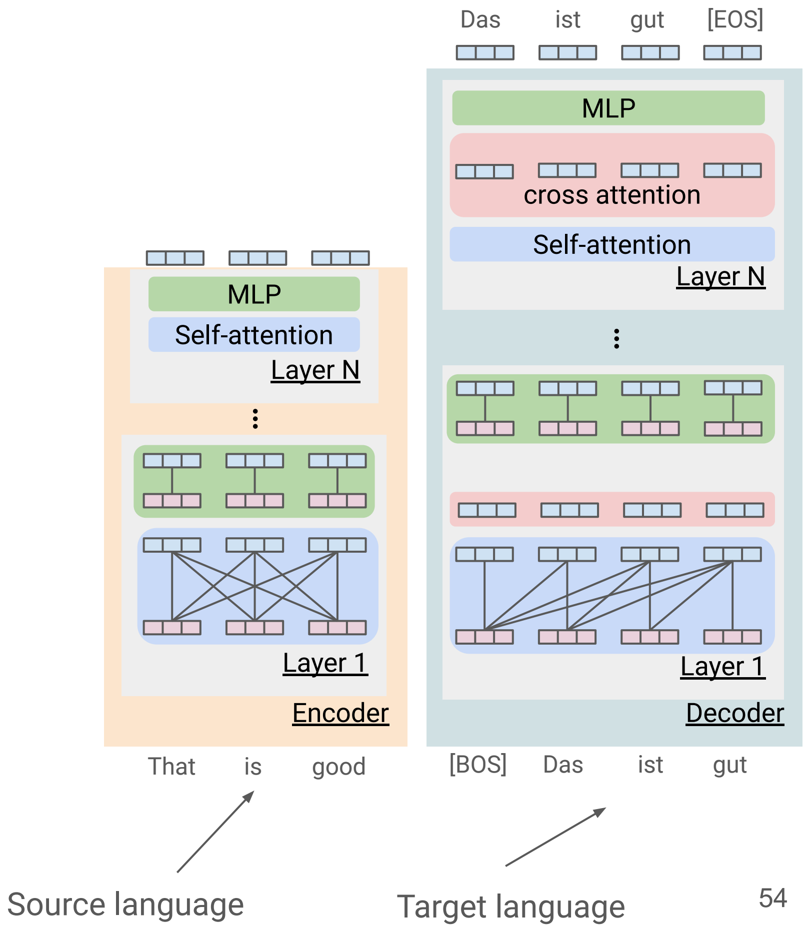
Example 1: machine translation

When Transformer was introduced in 2017, translation was a popular and difficult task

Input and target are in different languages

If the only goal is to learn translation, separate parameters make sense



Example 1: machine translation

When Transformer was introduced in 2017, translation was a popular and difficult task

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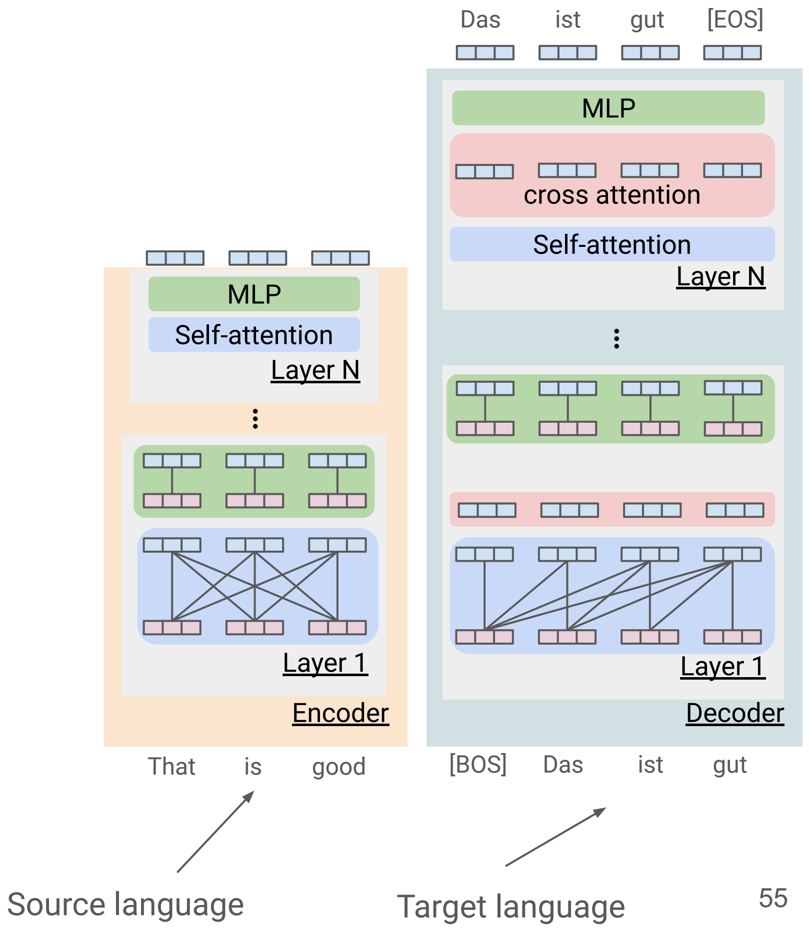
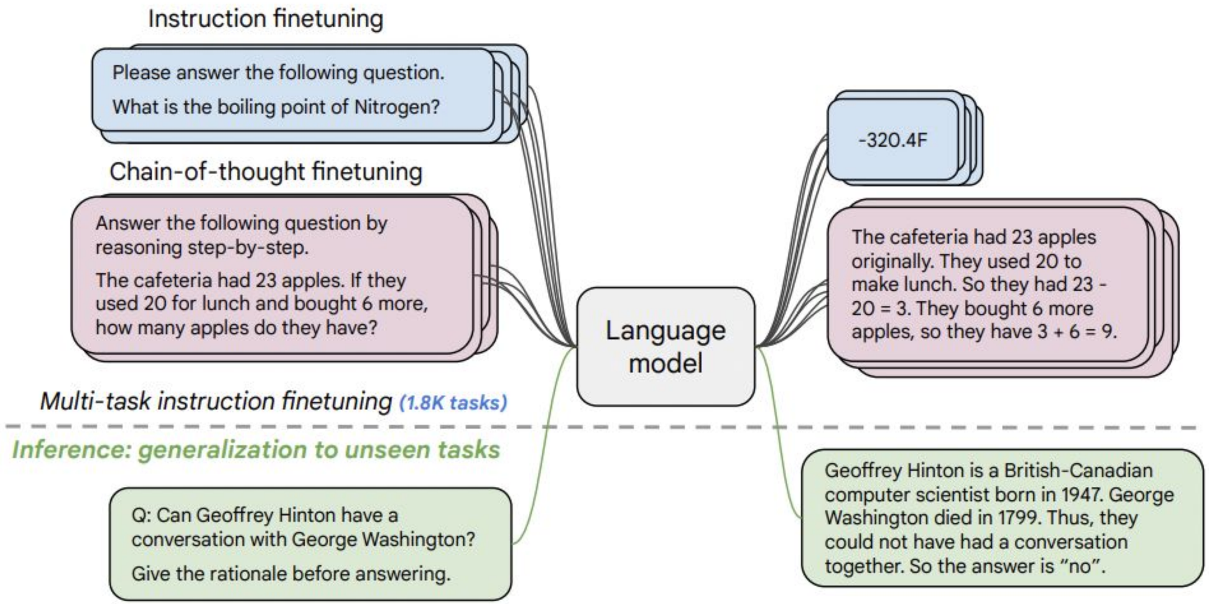
If the only goal is to learn translation, separate parameters make sense

Modern language models learn the world knowledge

Separate parameters for knowledge just expressed in different languages? 🤔



Example 2: instruction finetuning with academic datasets



[Scaling Instruction-Finetuned Language Models](#)
Hyung Won Chung, Le Hou, Shayne Longpre, Barret Zoph, Yi Tay, William Fedus et al. (2022)

Example 2: instruction finetuning with academic datasets

Params	Model	Norm. avg.
80M	T5-Small	-9.2
	Flan-T5-Small	-3.1 (**+6.1**)
250M	T5-Base	-5.1
	Flan-T5-Base	6.5 (**+11.6**)
780M	T5-Large	-5.0
	Flan-T5-Large	13.8 (**+18.8**)
3B	T5-XL	-4.1
	Flan-T5-XL	19.1 (**+23.2**)
11B	T5-XXL	-2.9
	Flan-T5-XXL	23.7 (**+26.6**)
8B	PaLM	6.4
	Flan-PaLM	21.9 (**+15.5**)
62B	PaLM	28.4
	Flan-PaLM	38.8 (**+10.4**)
540B	PaLM	49.1
	Flan-PaLM	58.4 (**+9.3**)
62B	cont-PaLM	38.1
	Flan-cont-PaLM	46.7 (**+8.6**)
540B	U-PaLM	50.2
	Flan-U-PaLM	59.1 (**+8.9**)

Encoder-decoder

Decoder-only

Encoder-decoder models had much bigger gain!

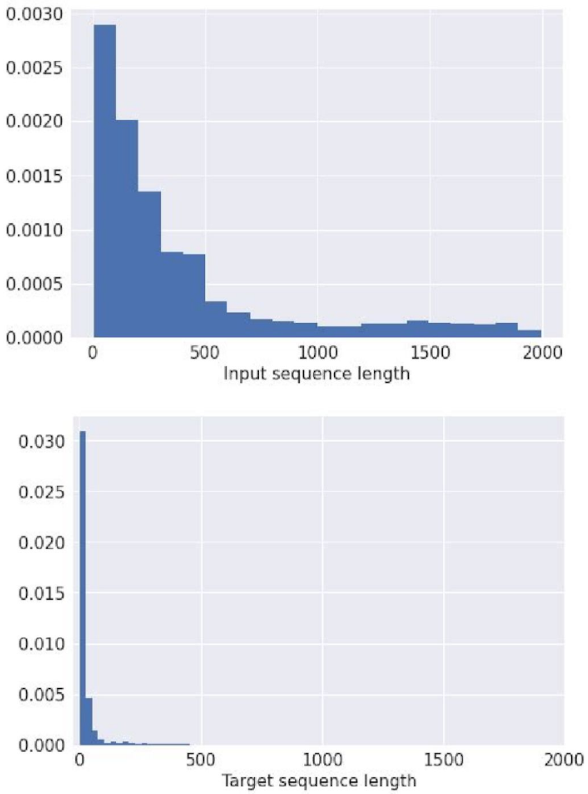
Example 2: instruction finetuning with academic datasets

Academic datasets have distinctive length distribution: long input and short target

This is due to inherent difficulty of grading long text

Hypothesis
Having separate parameters for longer text in input and shorter text in target was an effective *structure*

No longer a good structure as more interesting language model use cases have longer generation



Length distribution of finetuning datasets

Additional structures in encoder-decoder compared to decoder-only

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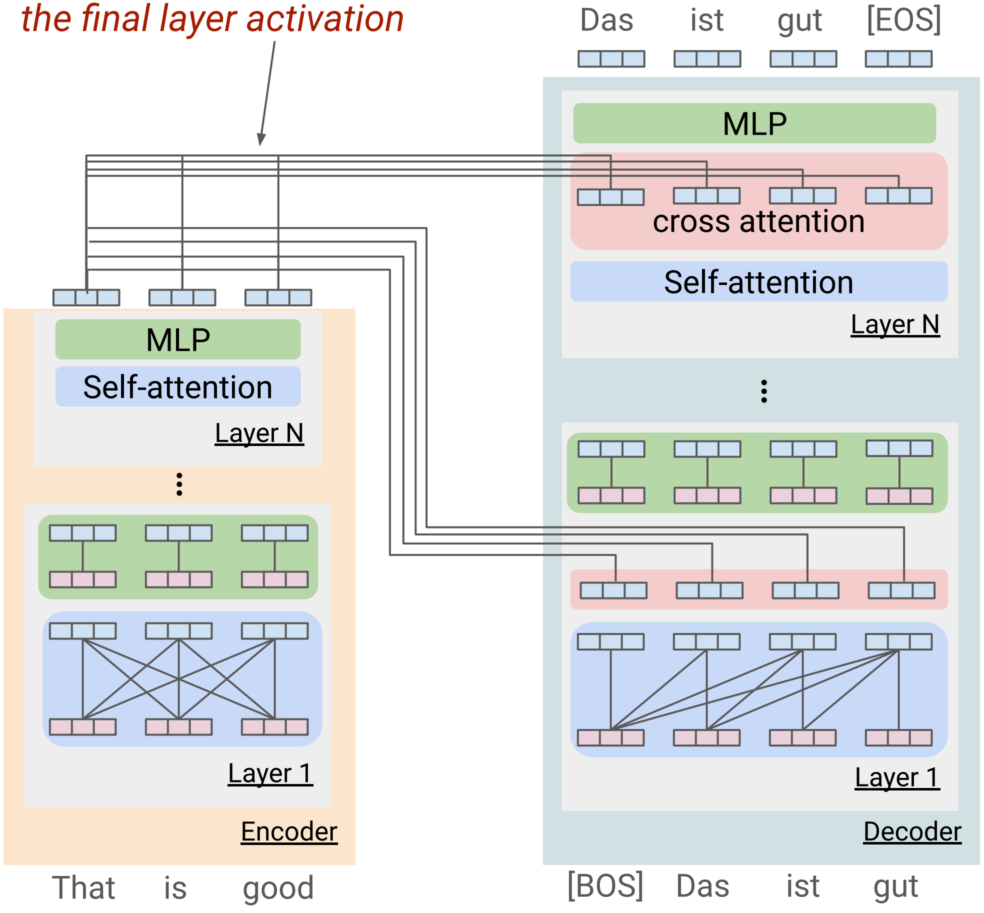
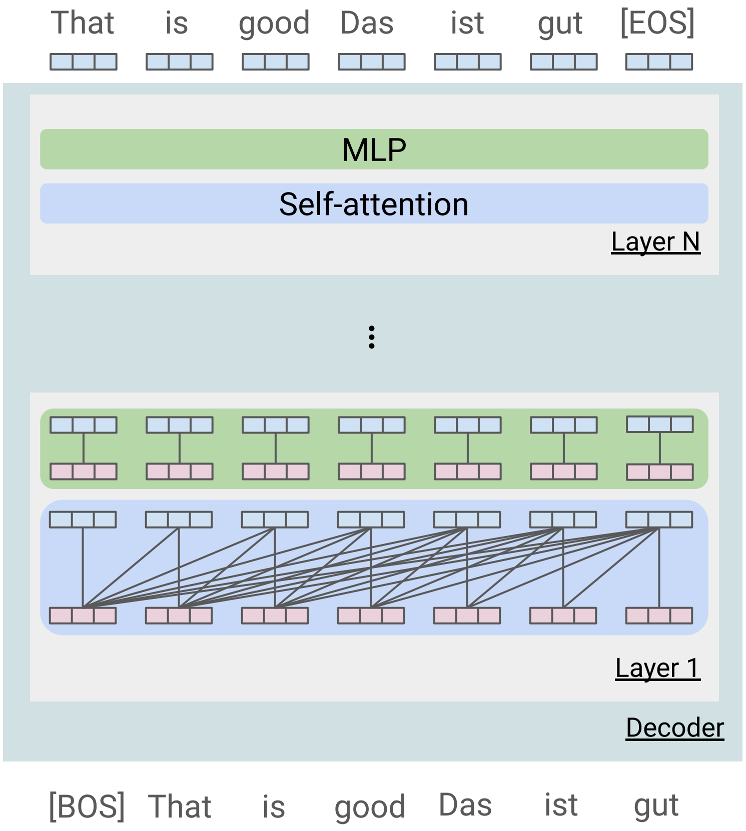
Cross attention only attends to the final layer activation





In deep neural networks, the bottom and top layers encode information at a different level of granularity

For example, in computer vision, the bottom layers learn to encode edges and the top layers learn higher level features (e.g. cat face)

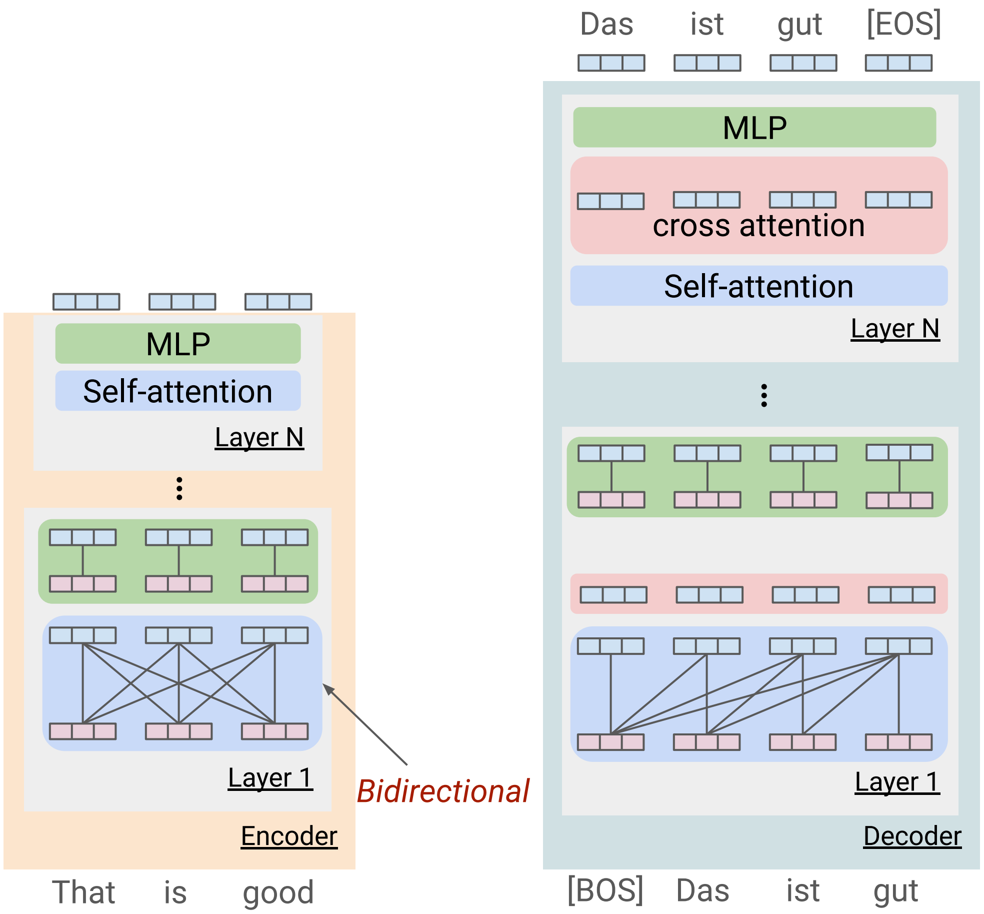
Can decoder only attending to the final layer of encoder be an *information bottleneck* if encoder is sufficiently deep? 🤔

Additional structures in encoder-decoder compared to decoder-only

1. Input and target sequences are sufficiently different that using separate parameters can be effective

2. The target element can attend to the fully encoded representation of the input

3. When encoding the input sequence, all-to-all interaction among the sequence elements is preferred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MLP
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Self-attention
Layer N
Layer 1
Decoder
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Self-attention
Layer N
Layer 1
Encoder
Bidirectional
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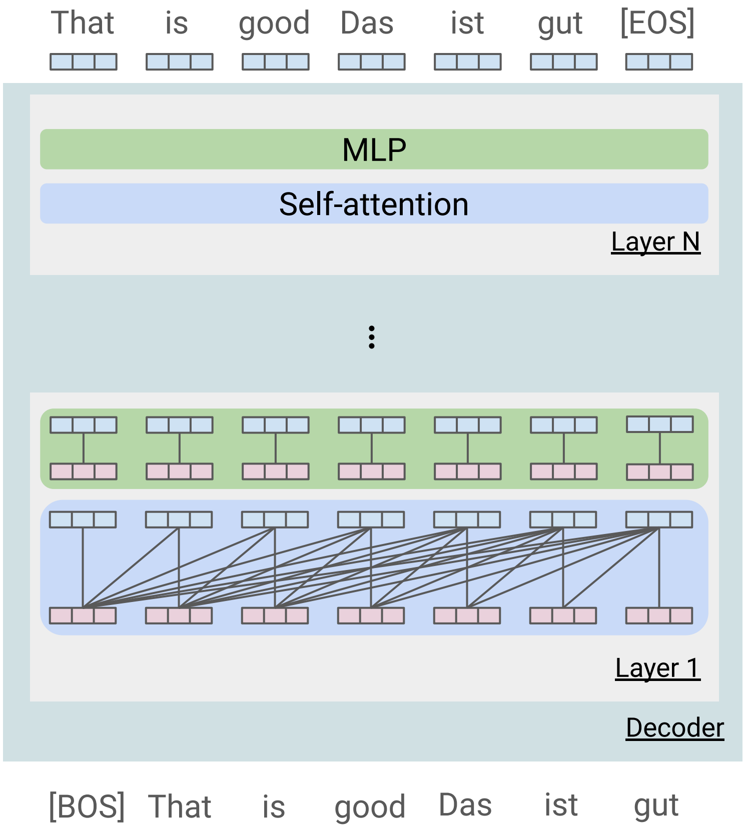
good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Self-attention
Layer N
Layer 1
Decoder
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(Highly anecdotal) At sufficient scale, bidirectionality doesn’t seem to matter much

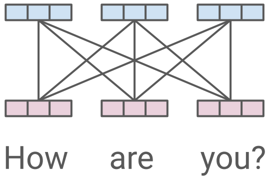
Bidirectionality brings in engineering challenges for multi-turn chat application

At every turn, the new input has to be encoded again; for unidirectional attention, only the newly added message needs to be encoded.

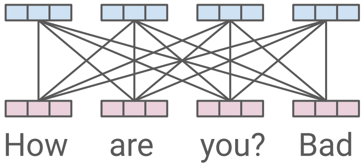
Input attention pattern for multi-turn conversation

Bidirectional

USER
How are you?



ASSISTANT
Bad



USER
Why?

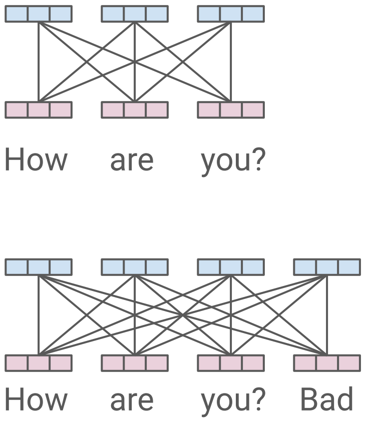
Input attention pattern for multi-turn conversation

USER
How are you?

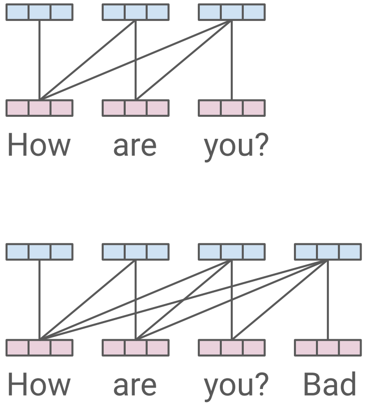
ASSISTANT
Bad

USER
Why?

Bidirectional



Unidirectional



Conclusion

Identify the dominant driving force as exponentially cheaper compute and associated scaling

Analyzed additional structure of encoder-decoder from the perspective of scaling

Hopefully this perspective and analysis can be useful for understanding what is happening today and predict the future trajectory