

Attention and transformers

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- 1 Introduction
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- 3 The transformer architecture and its applications in computer vision
- 4 Discussion

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Transformers: a new revolution in deep learning?

- Transformers [Vaswani et al., 2017] have brought a break-through in natural language processing
 - Bidirectional Encoder Representations from Transformers (BERT, by Google [Brown et al., 2020])
 - Generative Pre-trained Transformer 3 (GPT-3, by OpenAI [Devlin et al., 2019]): 175 billion parameters.
- They contribute to the development of new natural language processing applications (translation, voice assistants, etc.)
- Will they do the same in image analysis?

NB: Our aim through this lesson is to (hopefully!) review the main ideas on attention and transformers, through selected examples. However, this overview is not exhaustive.

What are transformers?

Definition

A transformer is a neural network architecture module that allows the network to **adaptively focus its attention** on certain regions of the data.

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A transformer is a neural network architecture module that allows the network to **adaptively focus its attention** on certain regions of the data.

Transformers today

Nowadays, when people refer to the transformer, they generally mean the architecture proposed by Vaswani *et al.* in 2017 [Vaswani et al., 2017].

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- Attention in image analysis
- Attention with deep learning

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How do we look at an image?



Credits: Ilya Repin, An Unexpected Visitor, 1884.

How do we look at an image?



Tasks:

- Age of the characters?
- How long has the visitor been away?
- Memorize the objects in the scene.

Credits: Experiments on visual attention
[Yarbus, 1967]

Information used by human visual attention

- Bottom-up:
 - local features (orientation, intensity, junctions, colour, motion, etc.)
 - local features contrast
 - context
- Top-bottom: task related
- Construction of a single *saliency map*

Exploring the image



- Winner-takes all! We focus on the maximum of the saliency map.
- Inhibition of return: We explore the following maxima, at first avoiding those that have already been inspected

Why has visual attention evolved?

- Photoreceptor cells are expensive
- Processing power is limited
- Solution: concentrate the cells in a given region and use the gaze to optimize their use

Why has visual attention evolved?

- Photoreceptor cells are expensive
 - Processing power is limited
 - Solution: concentrate the cells in a given region and use the gaze to optimize their use
-
- The same arguments apply to artificial visual systems
 - + Some degree of invariance
 - + Interpretability

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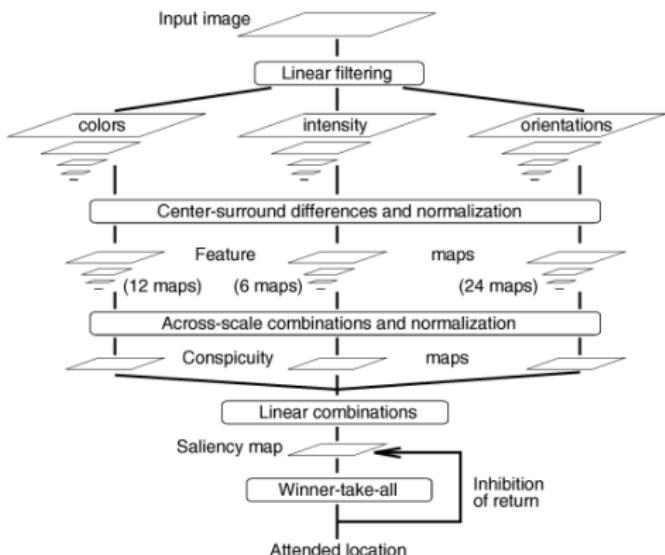
- Attention in human vision
- **Attention in image analysis**
- Attention with deep learning

3 The transformer architecture and its applications in computer vision

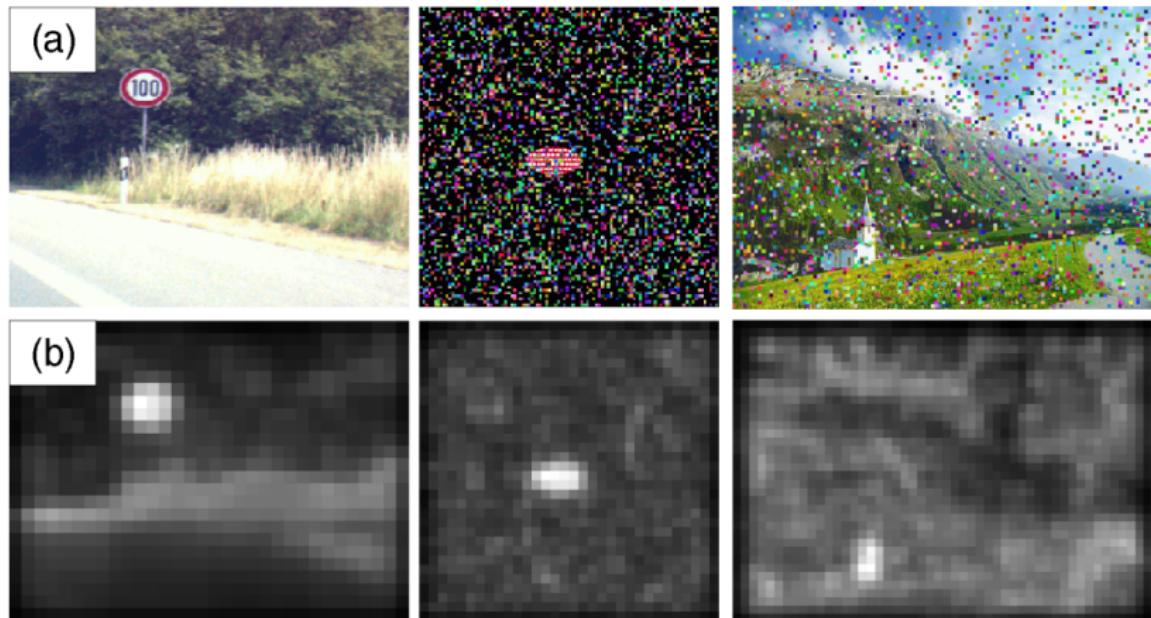
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A classical bottom-up model

- Itti et al. [Itti et al., 1998] proposed a model inspired by the primate visual system.
- It only uses low-level information.



Examples [Itti et al., 1998]



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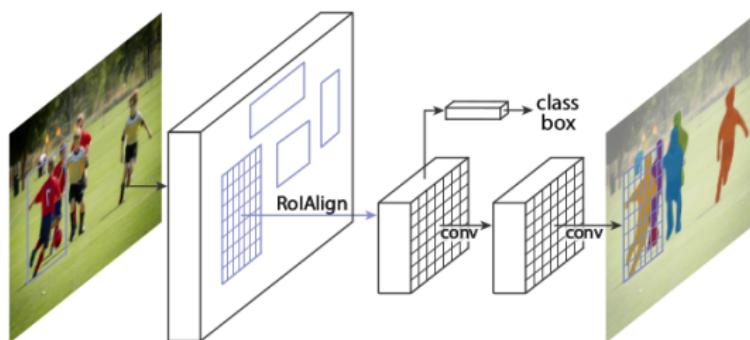
- Attention in human vision
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- **Attention with deep learning**

3 The transformer architecture and its applications in computer vision

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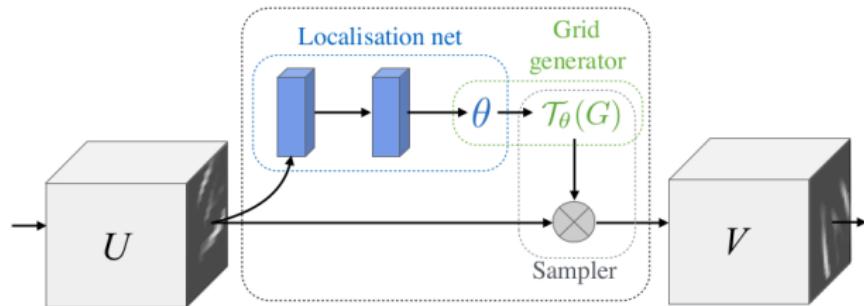
Region proposal networks [Ren et al., 2015]

- Detection and instance segmentation methods use region proposal networks, that can be interpreted as an attention mechanism.
- The region proposal network gives the coordinates of the rectangle and a probability that it contains an object.

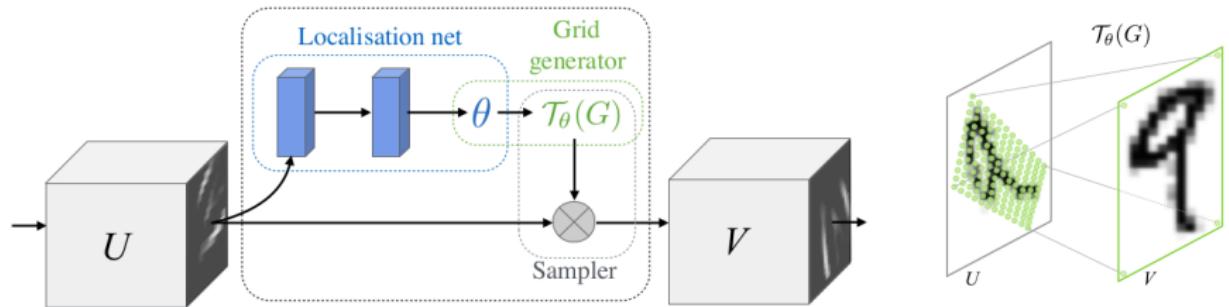


A region proposal module is used by mask R-CNN [He et al., 2017]

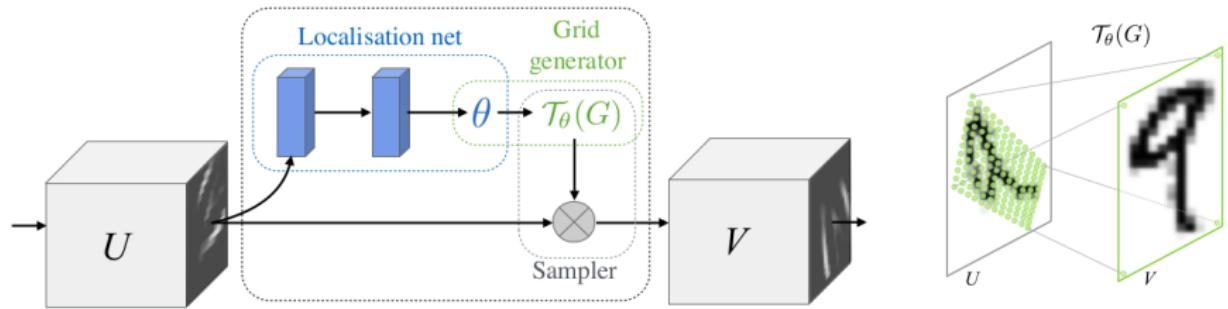
Spatial transformers [Jaderberg et al., 2016]



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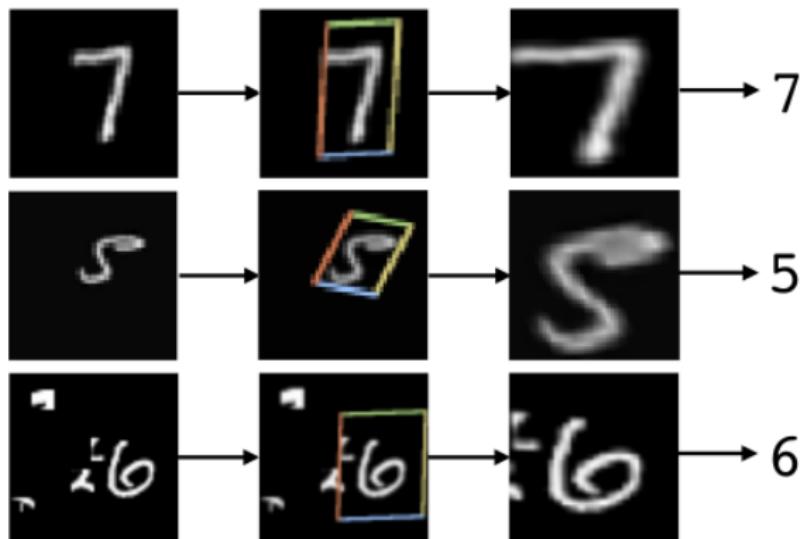


Spatial transformers [Jaderberg et al., 2016]

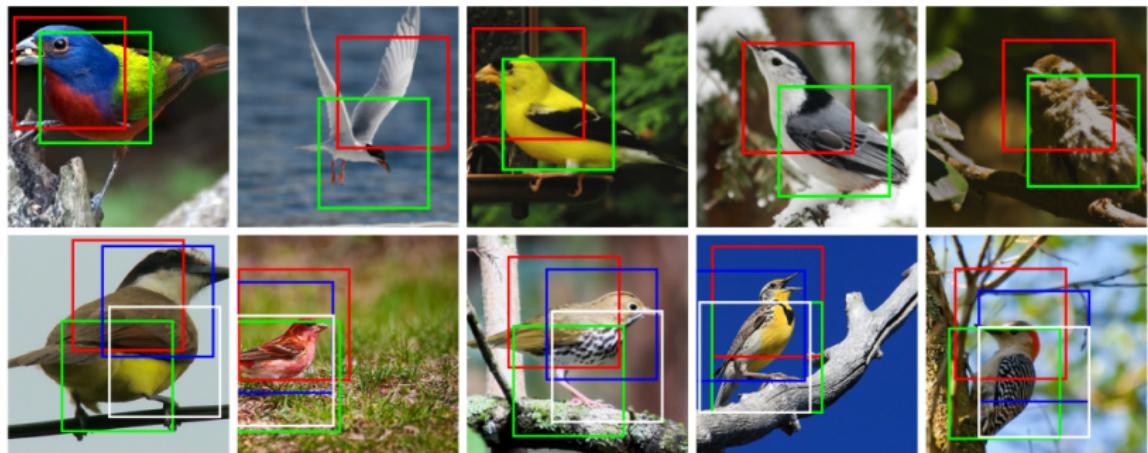


- This module can be added to any convolutional network
- End-to-end learning

Spatial transformers illustration



Spatial transformers with multiple heads



Remarks

- Note that in the first row one transformer tends to focus on the bird's head, while the second is centered on the body
- In the second row, the specialization is less apparent

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Transformer avatars

Some examples

- Graph transformers [Lecun et al., 1998]
- Transforming auto-encoders [Hinton et al., 2011]
- Spatial transformers [Jaderberg et al., 2016]

The transformer [Vaswani et al., 2017].

Today, when people refer to the transformer, they generally mean the architecture proposed by Vaswani et al. in 2017.

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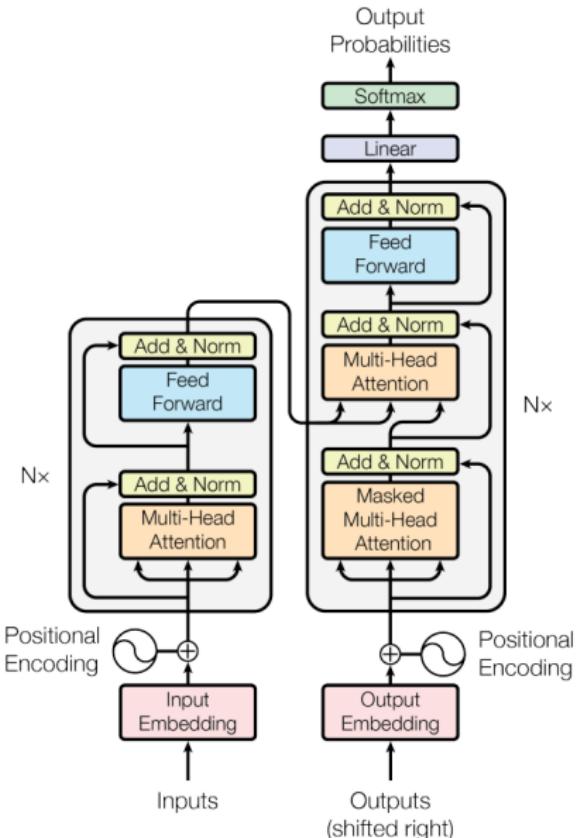
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The rise of transformers

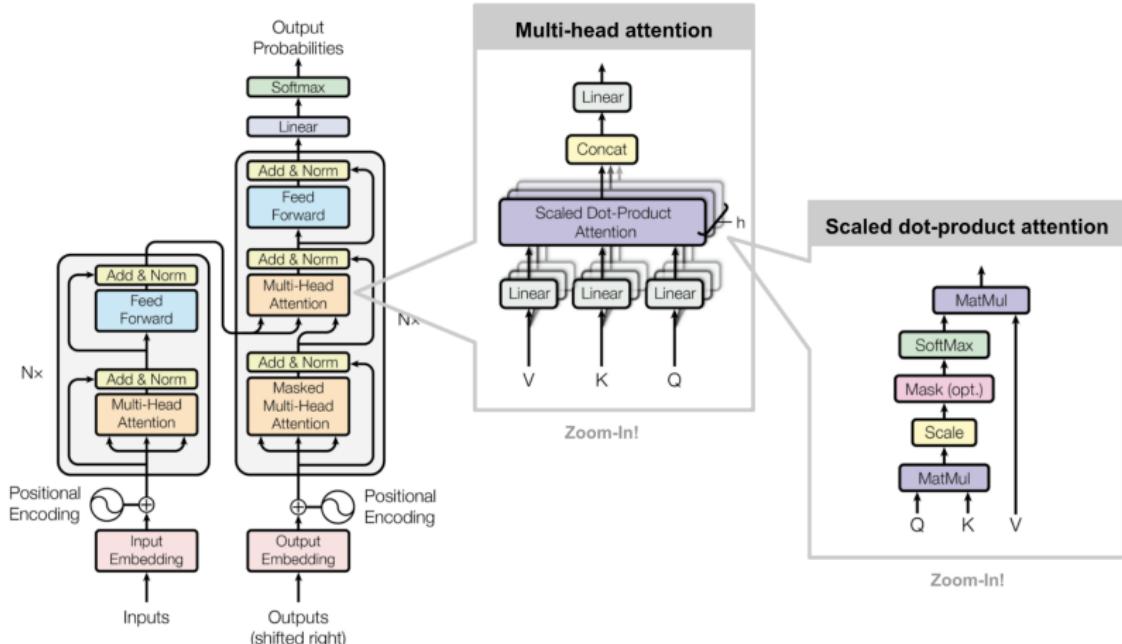
The paper that started it all

Vaswani et al., Attention is all you need, Neurips 2017.

This architecture was developed for text processing.



Architecture [Vaswani et al., 2017]



Credits: <https://lilianweng.github.io/lil-log/2018/06/24/attention-attention.html>

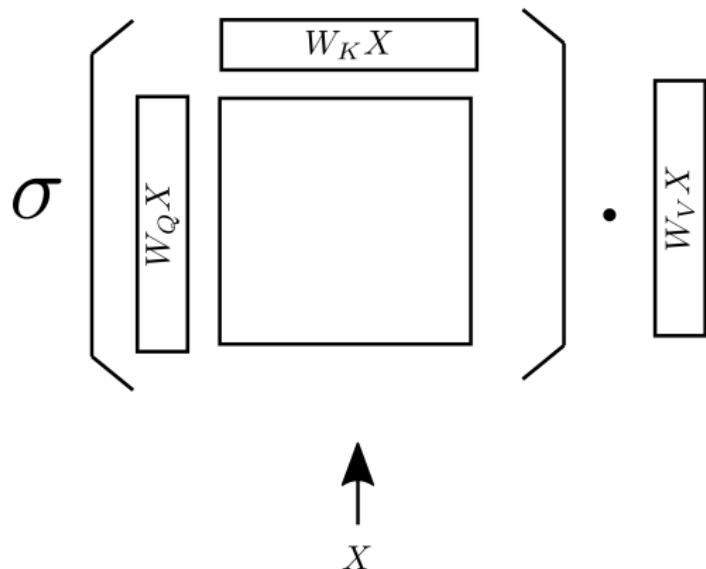
Scaled dot-product attention

Definition

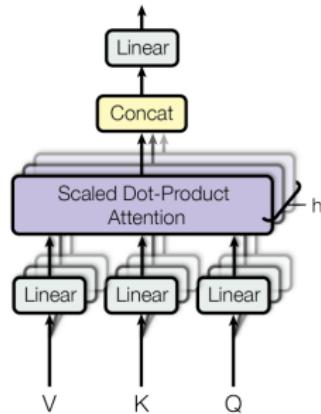
$$Att(Q, K, V) = \sigma \left(\frac{QK^t}{\sqrt{d_K}} \right) V$$

- V : values; K : keys; Q : queries.
- d_K is the length of K .
- σ : row-wise soft-max.

Self-attention

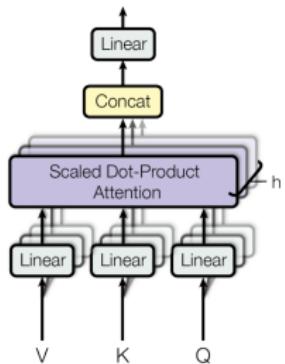


Multi-head attention



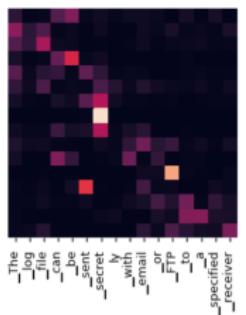
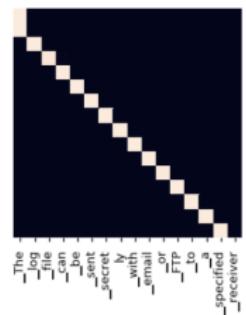
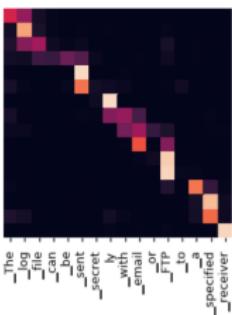
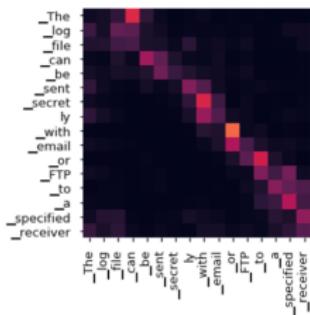
- Matrices W_Q , W_V and W_V are learnable.
- h heads work in parallel.

Dot-product self-attention illustration



In the case of self-attention:

- $V = K = Q = X$



Credits:
<https://nlp.seas.harvard.edu/2018/04/03/a/>

Success of transformers in natural language processing

- Bidirectional Encoder Representations from Transformers (BERT, by Google [Brown et al., 2020])
- Generative Pre-trained Transformer 3 (GPT-3, by OpenAI [Devlin et al., 2019]): 175 billion parameters.

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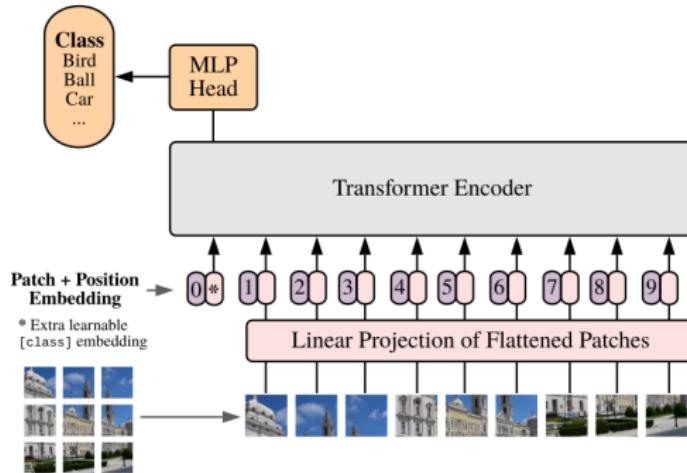
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- **Vision transformer**
- Shifted window transformer
- Transformers for image segmentation

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ViT: the vision transformer [Dosovitskiy et al., 2021]



Remarks

- Only uses the transformer encoder
- Directly takes as inputs image patches
- Achieves state-of-the-art results when pre-trained on very large databases (Google's JFT-300M dataset)

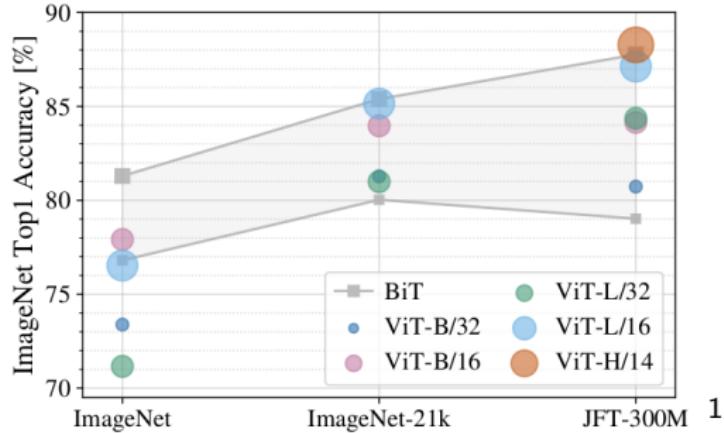
ViT results

	Ours-JFT (ViT-H/14)	Ours-JFT (ViT-L/16)	Ours-I21K (ViT-L/16)	BiT-L (ResNet152x4)	Noisy Student (EfficientNet-L2)
ImageNet	88.55 ± 0.04	87.76 ± 0.03	85.30 ± 0.02	87.54 ± 0.02	88.4/88.5*
ImageNet ReaL	90.72 ± 0.05	90.54 ± 0.03	88.62 ± 0.05	90.54	90.55
CIFAR-10	99.50 ± 0.06	99.42 ± 0.03	99.15 ± 0.03	99.37 ± 0.06	—
CIFAR-100	94.55 ± 0.04	93.90 ± 0.05	93.25 ± 0.05	93.51 ± 0.08	—
Oxford-IIIT Pets	97.56 ± 0.03	97.32 ± 0.11	94.67 ± 0.15	96.62 ± 0.23	—
Oxford Flowers-102	99.68 ± 0.02	99.74 ± 0.00	99.61 ± 0.02	99.63 ± 0.03	—
VTAB (19 tasks)	77.63 ± 0.23	76.28 ± 0.46	72.72 ± 0.21	76.29 ± 1.70	—
TPUv3-core-days	2.5k	0.68k	0.23k	9.9k	12.3k

Remarks

- Models pre-trained on JFT-300M
- Note the required processing power

ViT results



- ViT-H/14 requires 2500 TPUv3-core-days for pre-training
- But: “Training data-efficient image transformers & distillation through attention” [Touvron et al., 2021].

¹BiT: Big transfer [Kolesnikov et al., 2020]

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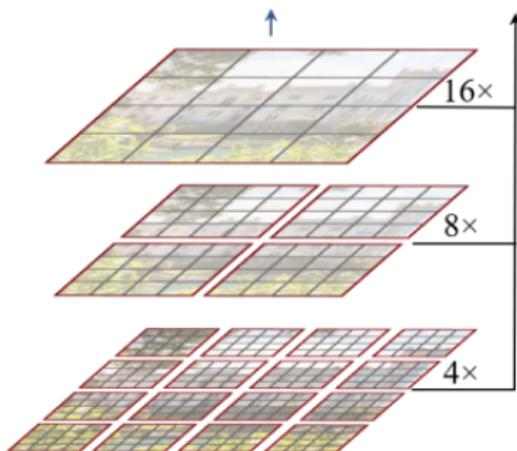
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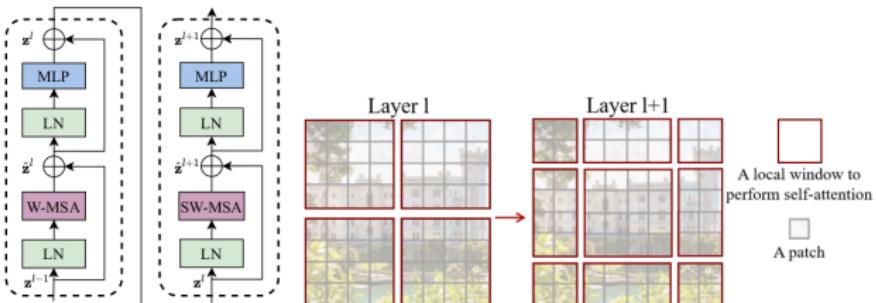
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Shifted window (SWIN) transformer [Liu et al., 2021]



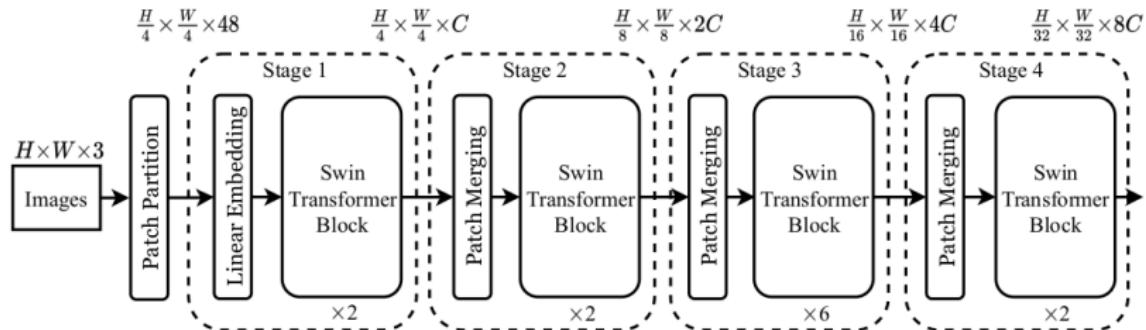
- The transformer modules are applied within each window
- Hierarchical approach: patches are merged at some levels
- The model uses **shifted windows**

SWIN blocks



- Multi-headed self-attention with regular (W-MSA) and shifted (SW-MSA) windowing configurations are applied alternatively

SWIN architecture

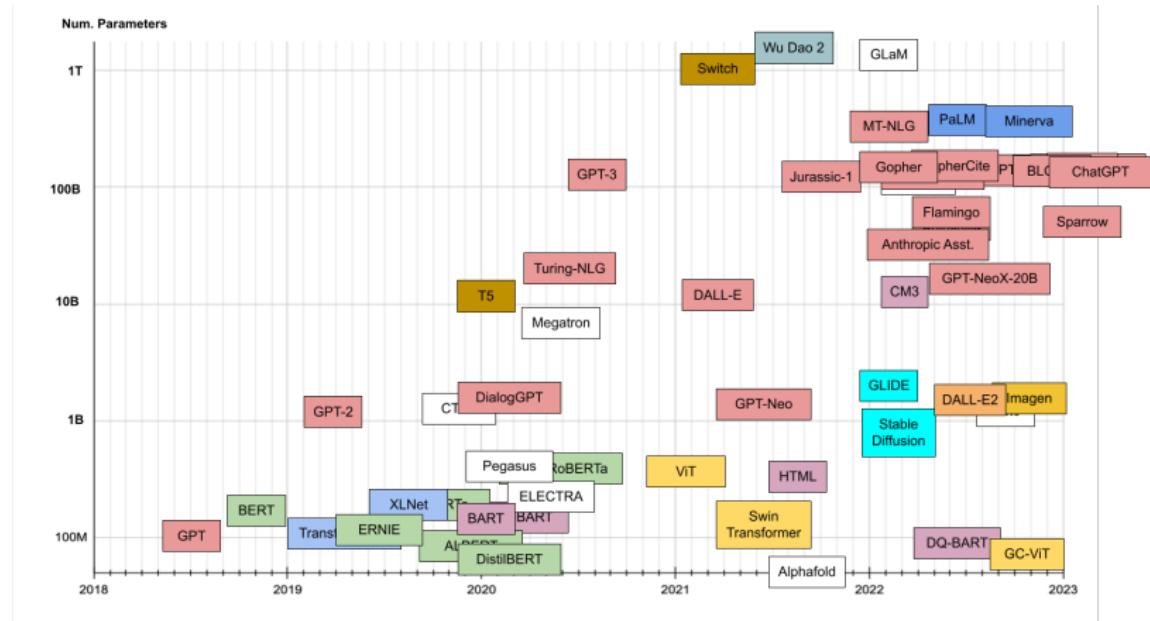


Results

The Swin transformer obtains better results than previous methods on:

- ImageNet 1k and 22k classification
- COCO object detection and image segmentation
- ADE20k semantic segmentation

Transformers chronology [Amatriain, 2023]



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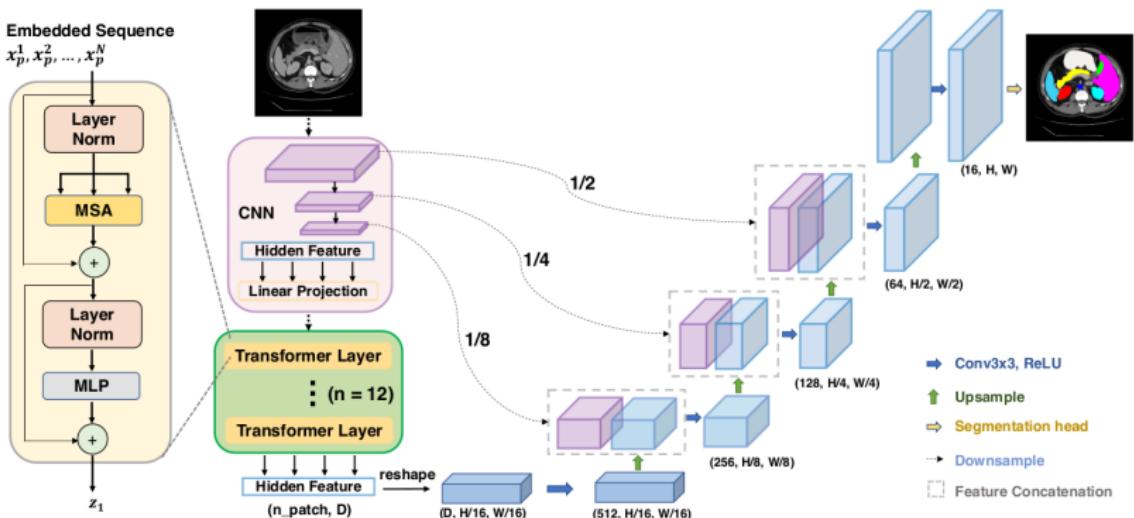
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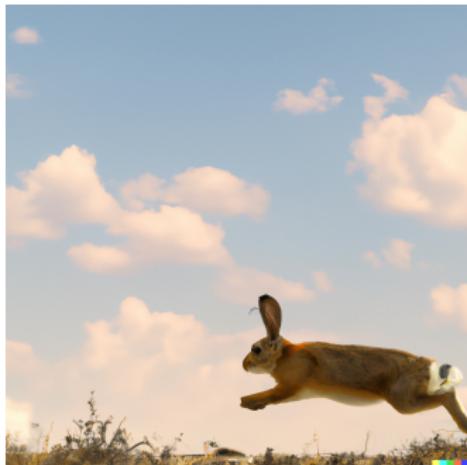
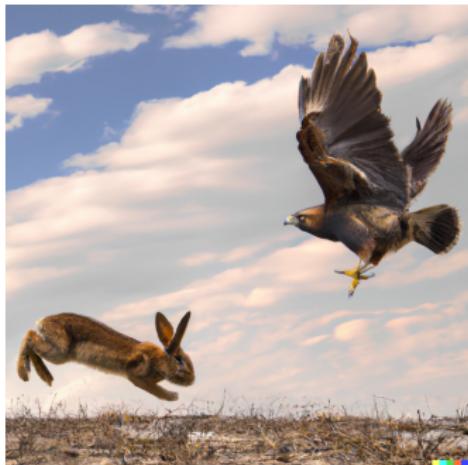
TransUNet [Chen et al., 2021]



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Task: segment the rabbits that are in danger



Credits: Images generated by DALL.E2

Discussion

Convolutional neural networks

- Convolutional networks are based on two inductive biases:

Transformers

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Convolutional neural networks

- Convolutional networks are based on two inductive biases:
 - Locality

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Transformers

- Transformers, like fully connected layers, do not make any assumptions on the data structure

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Transformers

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 - Localization is brought by a positional encoding

Discussion

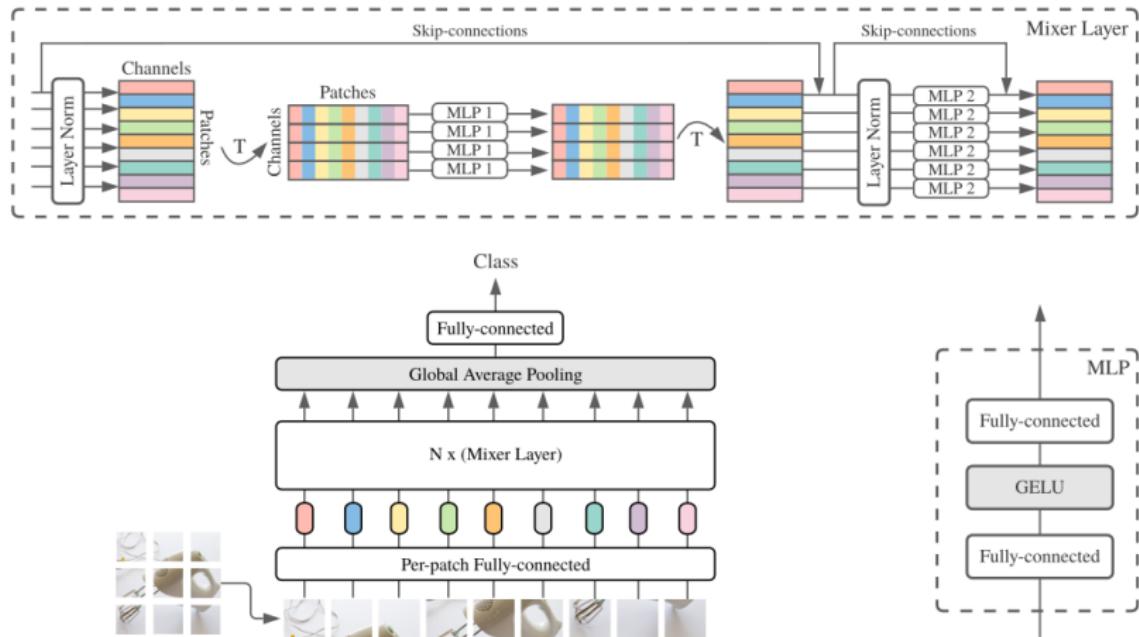
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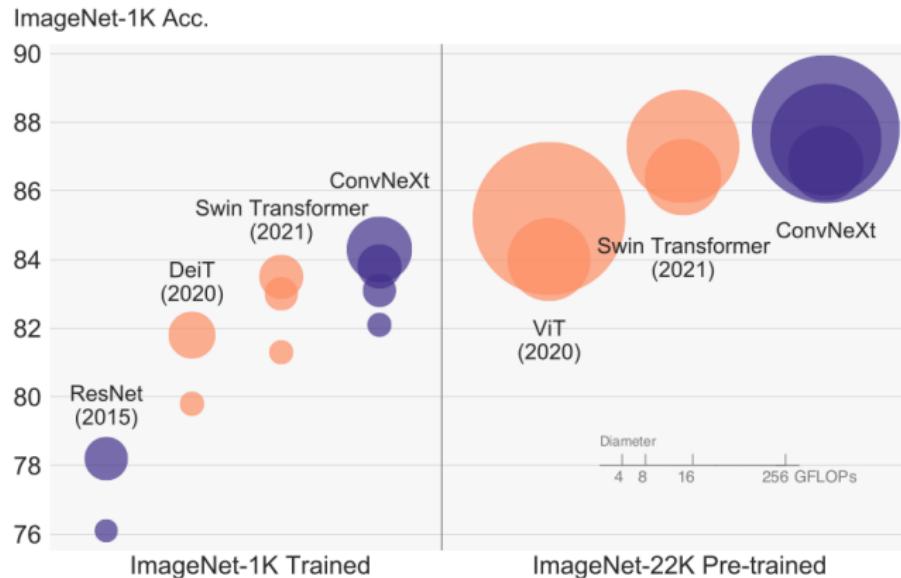
- Transformers, like fully connected layers, do not make any assumptions on the data structure
 - Localization is brought by a positional encoding
- Are transformers a smart way of analysing images with fully connected layers?

MLPs is all you need [Tolstikhin et al., 2021]



And the winner is ...

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Competition is still ongoing [Liu et al., 2022]...

References |

- [Amatriain, 2023] Amatriain, X. (2023). Transformer models: an introduction and catalog. [arXiv:2302.07730 \[cs\]](https://arxiv.org/abs/2302.07730).
- [Brown et al., 2020] Brown, T. B., Mann, B., Ryder, N., Subbiah, M., Kaplan, J., Dhariwal, P., Neelakantan, A., Shyam, P., Sastry, G., Askell, A., Agarwal, S., Herbert-Voss, A., Krueger, G., Henighan, T., Child, R., Ramesh, A., Ziegler, D. M., Wu, J., Winter, C., Hesse, C., Chen, M., Sigler, E., Litwin, M., Gray, S., Chess, B., Clark, J., Berner, C., McCandlish, S., Radford, A., Sutskever, I., and Amodei, D. (2020). Language Models are Few-Shot Learners. [arXiv:2005.14165 \[cs\]](https://arxiv.org/abs/2005.14165). arXiv: 2005.14165.
- [Chen et al., 2021] Chen, J., Lu, Y., Yu, Q., Luo, X., Adeli, E., Wang, Y., Lu, L., Yuille, A. L., and Zhou, Y. (2021). TransUNet: Transformers Make Strong Encoders for Medical Image Segmentation. [arXiv:2102.04306 \[cs\]](https://arxiv.org/abs/2102.04306).
- [Devlin et al., 2019] Devlin, J., Chang, M.-W., Lee, K., and Toutanova, K. (2019). BERT: Pre-training of Deep Bidirectional Transformers for Language Understanding. [arXiv:1810.04805 \[cs\]](https://arxiv.org/abs/1810.04805). arXiv: 1810.04805.
- [Dosovitskiy et al., 2021] Dosovitskiy, A., Beyer, L., Kolesnikov, A., Weissenborn, D., Zhai, X., Unterthiner, T., Dehghani, M., Minderer, M., Heigold, G., Gelly, S., Uszkoreit, J., and Houlsby, N. (2021). An Image is Worth 16x16 Words: Transformers for Image Recognition at Scale. In [arXiv:2010.11929 \[cs\]](https://arxiv.org/abs/2010.11929). arXiv: 2010.11929.

References II

- [He et al., 2017] He, K., Gkioxari, G., Dollár, P., and Girshick, R. (2017). Mask R-CNN. *arXiv:1703.06870 [cs]*. arXiv: 1703.06870.
- [Hinton et al., 2011] Hinton, G. E., Krizhevsky, A., and Wang, S. D. (2011). Transforming Auto-Encoders. In Honkela, T., Duch, W., Girolami, M., and Kaski, S., editors, *Artificial Neural Networks and Machine Learning – ICANN 2011*, Lecture Notes in Computer Science, pages 44–51, Berlin, Heidelberg. Springer.
- [Itti et al., 1998] Itti, L., Koch, C., and Niebur, E. (1998). A model of saliency-based visual attention for rapid scene analysis. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, 20(11):1254–1259. Conference Name: IEEE Transactions on Pattern Analysis and Machine Intelligence.
- [Jaderberg et al., 2016] Jaderberg, M., Simonyan, K., Zisserman, A., and Kavukcuoglu, K. (2016). Spatial Transformer Networks. *arXiv:1506.02025 [cs]*. arXiv: 1506.02025.
- [Kolesnikov et al., 2020] Kolesnikov, A., Beyer, L., Zhai, X., Puigcerver, J., Yung, J., Gelly, S., and Houlsby, N. (2020). Big Transfer (BiT): General Visual Representation Learning. In *European Conference on Computer Vision*.
- [Lecun et al., 1998] Lecun, Y., Bottou, L., Bengio, Y., and Haffner, P. (1998). Gradient-based learning applied to document recognition. *Proceedings of the IEEE*, 86(11):2278–2324.

References III

- [Liu et al., 2021] Liu, Z., Lin, Y., Cao, Y., Hu, H., Wei, Y., Zhang, Z., Lin, S., and Guo, B. (2021). Swin Transformer: Hierarchical Vision Transformer Using Shifted Windows. *pages* 10012–10022.
- [Liu et al., 2022] Liu, Z., Mao, H., Wu, C.-Y., Feichtenhofer, C., Darrell, T., and Xie, S. (2022). A ConvNet for the 2020s. *pages* 11976–11986.
- [Ren et al., 2015] Ren, S., He, K., Girshick, R., and Sun, J. (2015). Faster R-CNN: Towards Real-Time Object Detection with Region Proposal Networks. *Advances in Neural Information Processing Systems*, 28:91–99.
- [Tolstikhin et al., 2021] Tolstikhin, I., Houlsby, N., Kolesnikov, A., Beyer, L., Zhai, X., Unterthiner, T., Yung, J., Steiner, A., Keysers, D., Uszkoreit, J., Lucic, M., and Dosovitskiy, A. (2021). MLP-Mixer: An all-MLP Architecture for Vision. *arXiv:2105.01601 [cs]*. arXiv: 2105.01601.
- [Touvron et al., 2021] Touvron, H., Cord, M., Douze, M., Massa, F., Sablayrolles, A., and Jégou, H. (2021). Training data-efficient image transformers & distillation through attention. *arXiv:2012.12877 [cs]*. arXiv: 2012.12877.
- [Vaswani et al., 2017] Vaswani, A., Shazeer, N., Parmar, N., Uszkoreit, J., Jones, L., Gomez, A. N., Kaiser, L., and Polosukhin, I. (2017). Attention is All you Need. *Advances in Neural Information Processing Systems*, 30.

References IV

[Yarbus, 1967] Yarbus, A. L. (1967). Eye Movements During Perception of Complex Objects. In Yarbus, A. L., editor, *Eye Movements and Vision*, pages 171–211. Springer US, Boston, MA.