

Machine Intelligence:: Deep Learning

Week 3

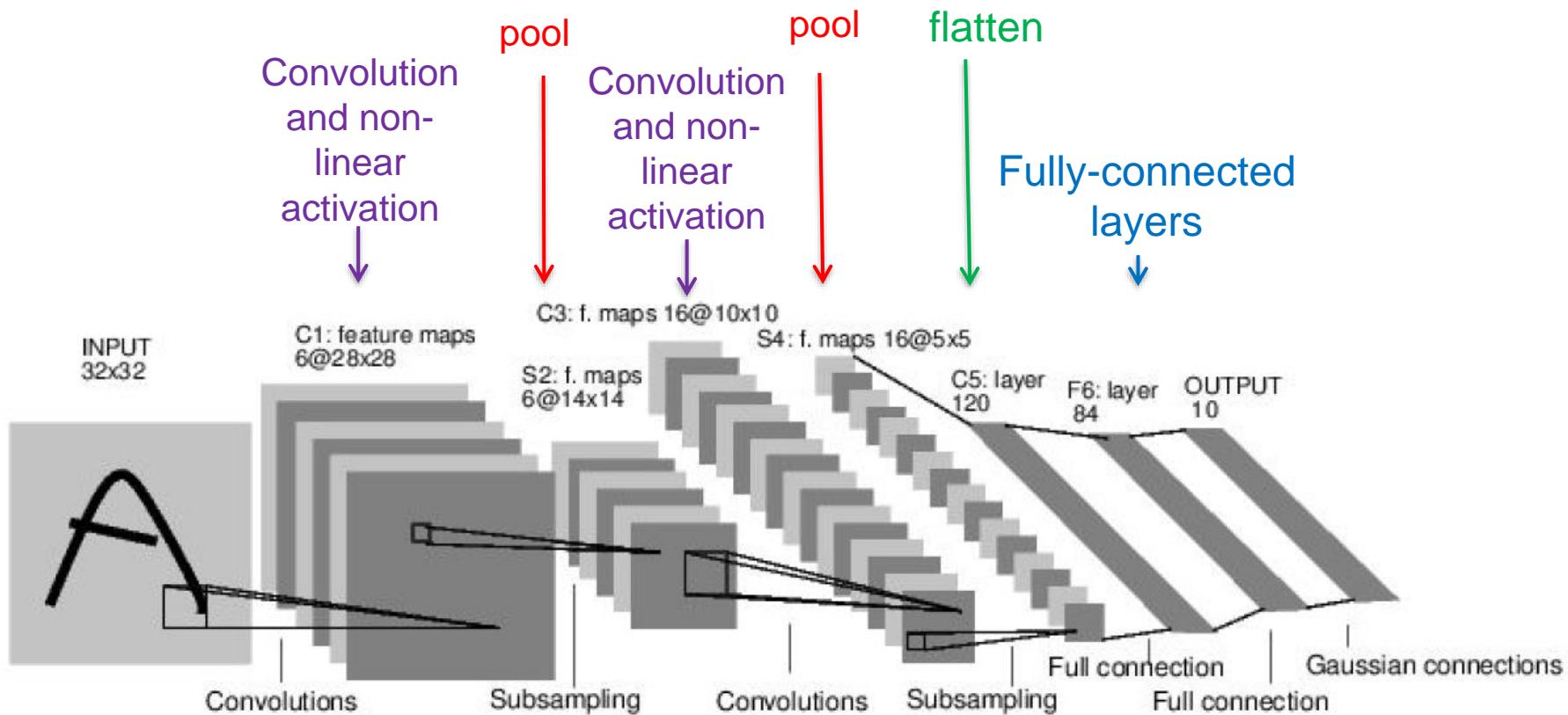
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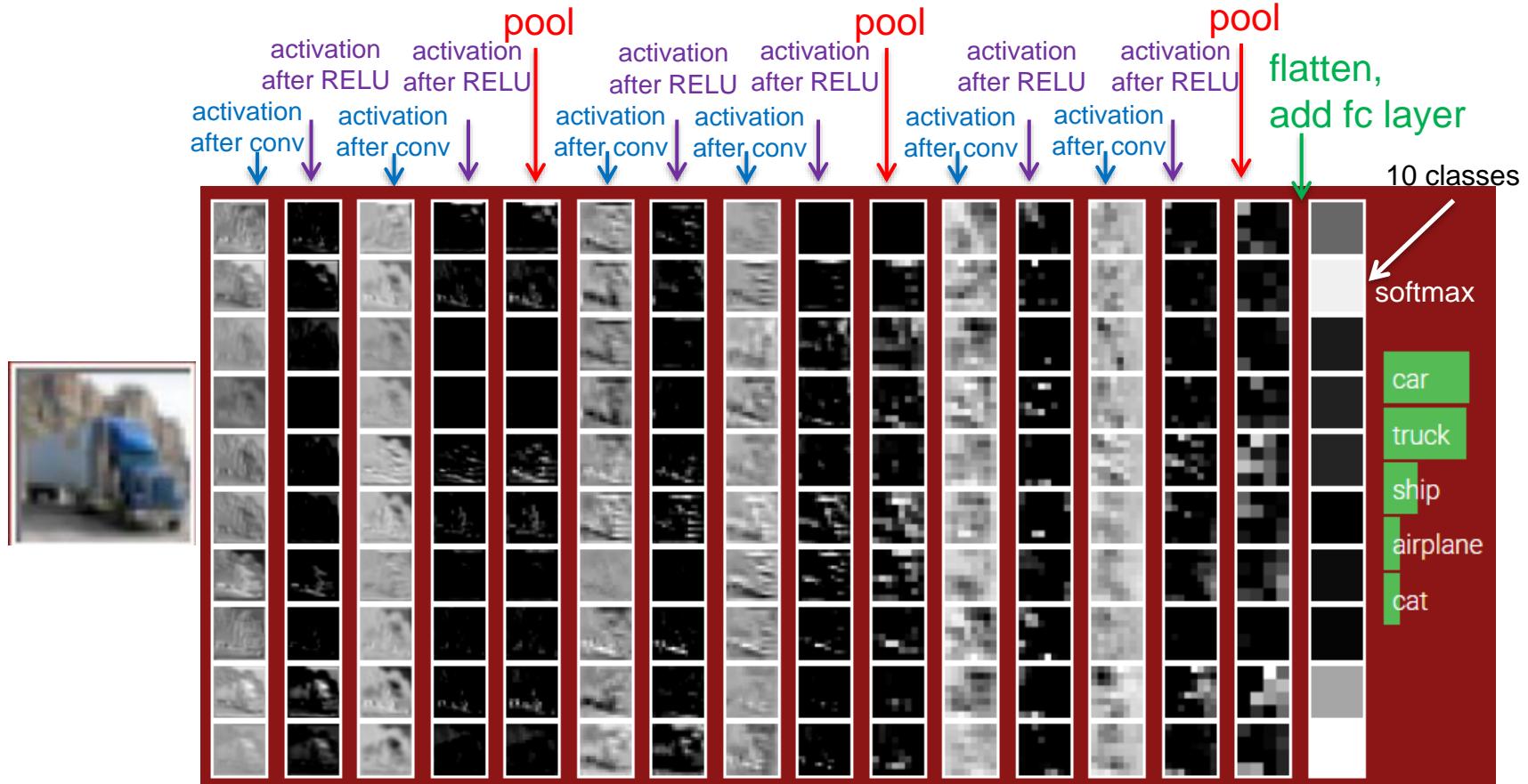
Topics of today

- Biological Inspiration of CNNs
- Tricks of the trade in CNNs
 - Standardizing / Batch-Norm
 - Dropout
- What does a CNN look at?
 - shining light into the black box
- Challenge winning CNN architectures
- DL with few data:
 - Transfer learning
 - Augmentation

Typical architecture of a simple CNN

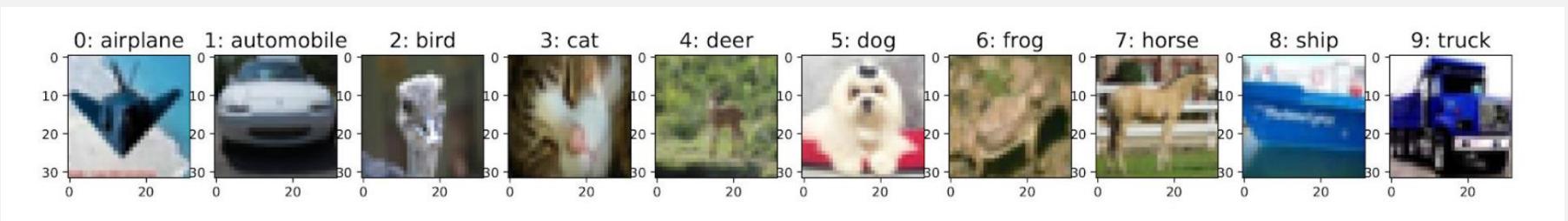


A CNN at work



Activation maps give insight on the spatial positions where the filter pattern was found in the input **one layer below** (in higher layers activation maps have no easy interpretation)
-> only the activation maps in the first hidden layer correspond directly to features of the input image.

Looking back at Homework: Develop a CNN for cifar10 data



Develop a CNN to classify cifar10 images (we have 10 classes)

Investigate the impact of standardizing the data on the performance

Notebook:

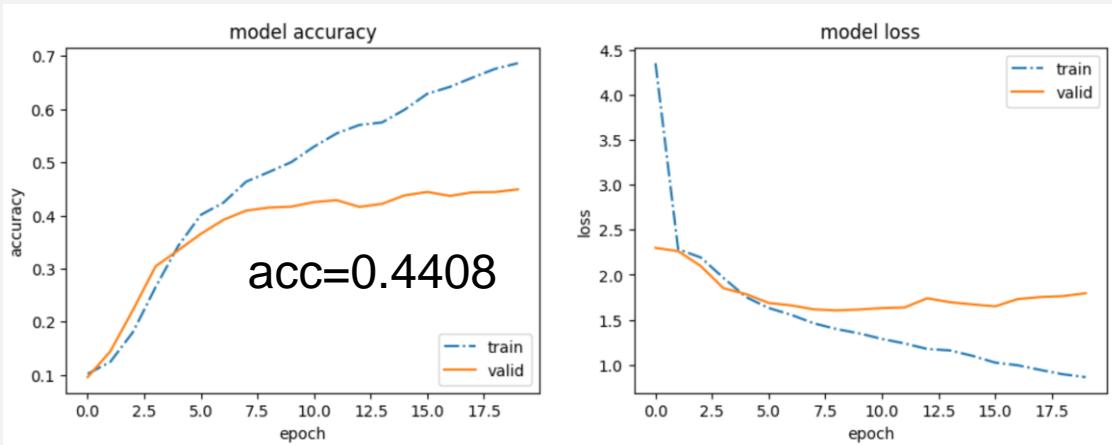
https://github.com/tensorchiefs/dl_course_2020/blob/master/notebooks/07_cifar10_norm_sol.ipynb

Take-home messages from the homework

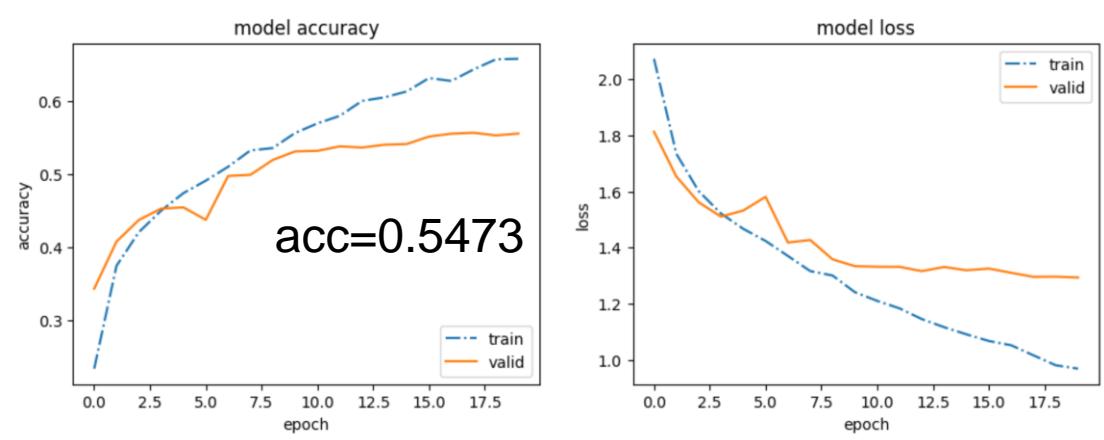


- DL does not need a lot of preprocessing, but working with standardized (small-valued) input data often helps.

Without standardizing
the input to the CNN

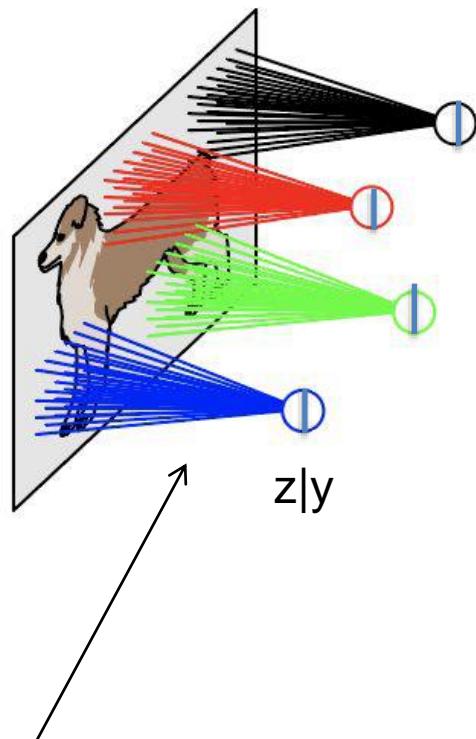


After standardizing
the input to the CNN

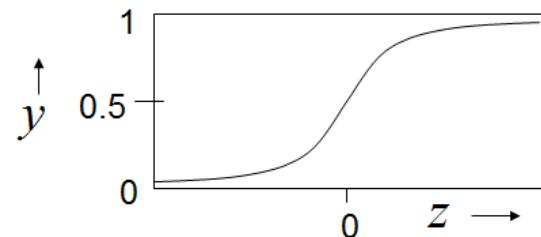


Shared weight and its consequences: standardize input

Locally connected neural net



$$z = b + \sum_i x_i w_i$$



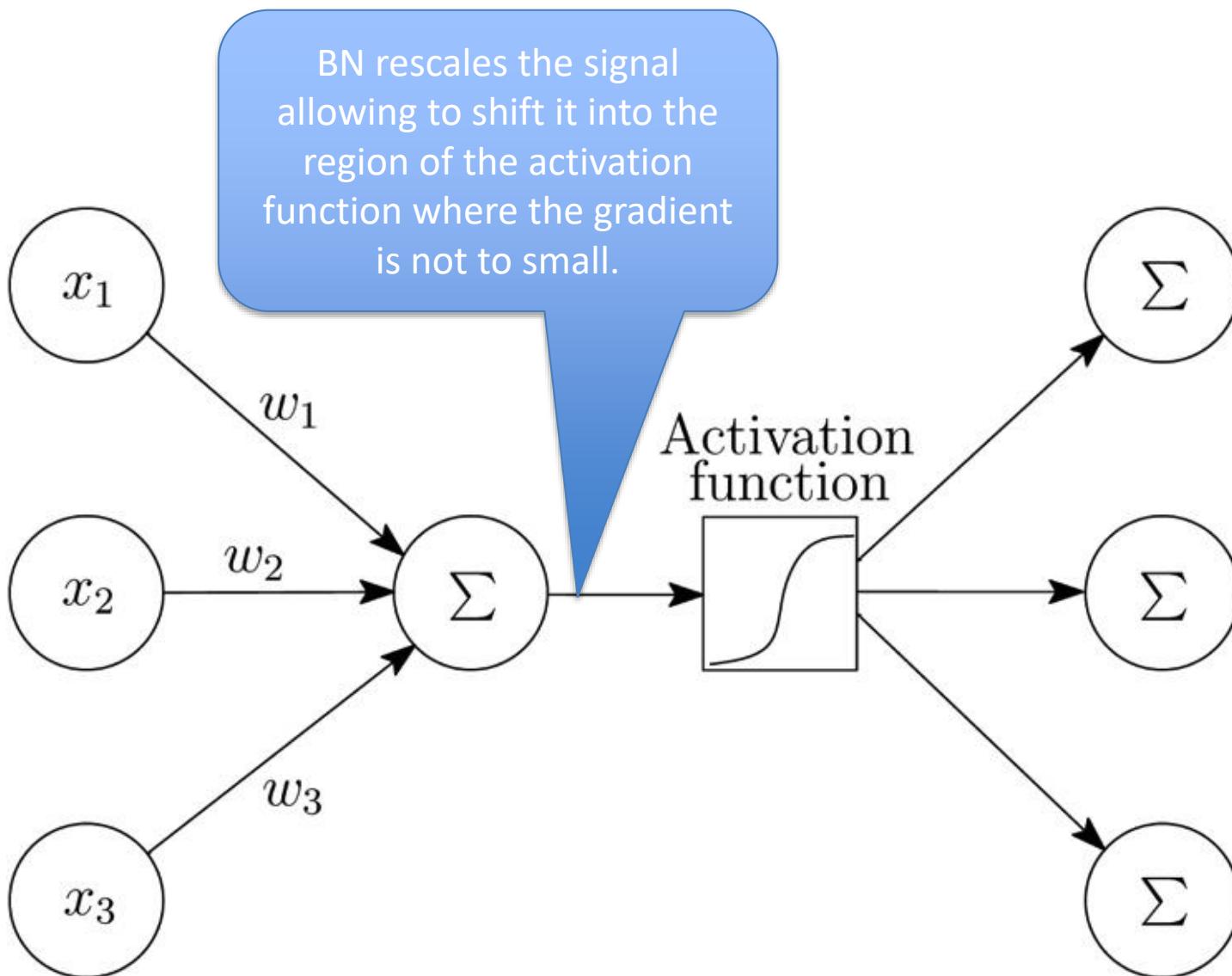
Shared weights: by using the same weights for each patch of the image

→ To get for many patches y -values close to the sweet-spot of the activation function, the x -values should not vary too much (it cannot be compensated by changed weights when weights are shared).

Data Standardization

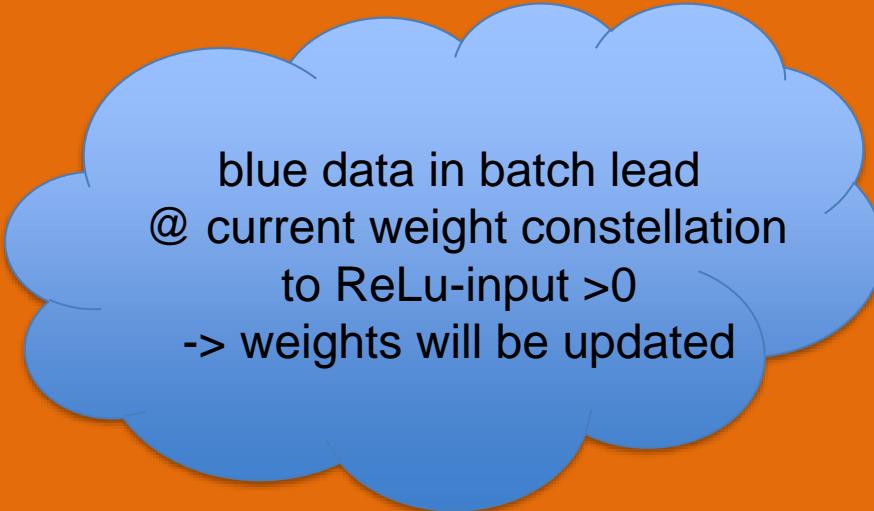
Batch Norm Layer

What is the idea of Batch-Normalization (BN)

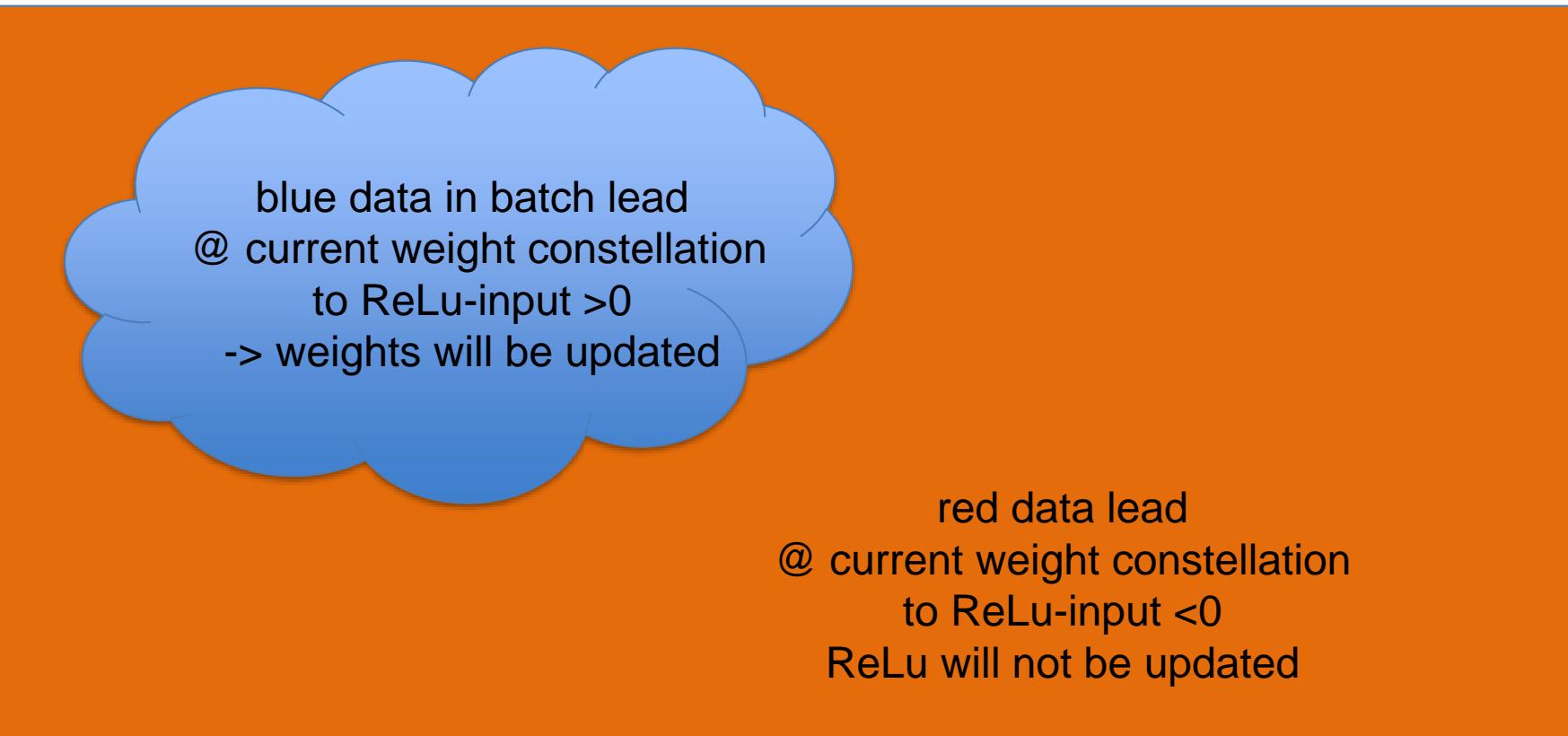


Why can batch-normalization help during training?

There is **no way to train=update-weights** when the data and weight constellation is such that for **all** data the input to the ReLu is <0 !



blue data in batch lead
@ current weight constellation
to ReLu-input >0
-> weights will be updated



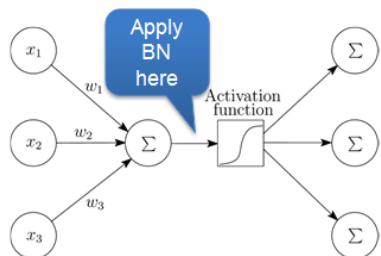
red data lead
@ current weight constellation
to ReLu-input <0
ReLU will not be updated

Depending on the data values, it can happen that there is no blue cloud and the NN is not trainable. This risk can be reduced when working with BN (or without BN with small learning rates).

Batch Normalization

- Idea: Introduce batch-norm layers between convolutions.

A BN layer performs a 2-step procedure with α and β as **learnable** parameter:



$$\text{Step 1: } \hat{x} = \frac{x - \text{avg}_{\text{batch}}(x)}{\text{stdev}_{\text{batch}}(x) + \epsilon}$$

$$\begin{aligned}\text{avg}(\hat{x}) &= 0 \\ \text{stdev}(\hat{x}) &= 1\end{aligned}$$

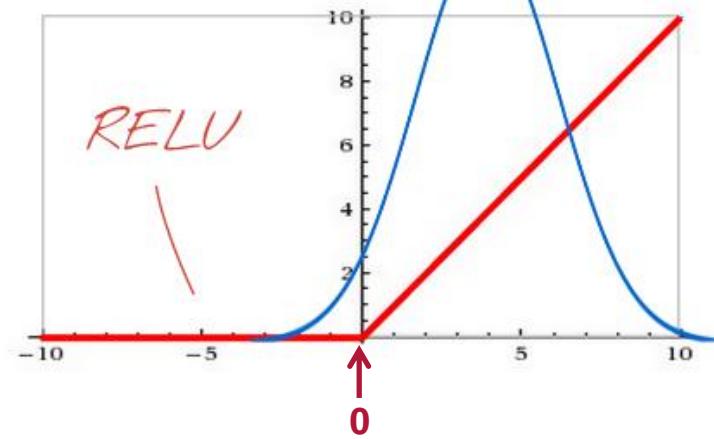
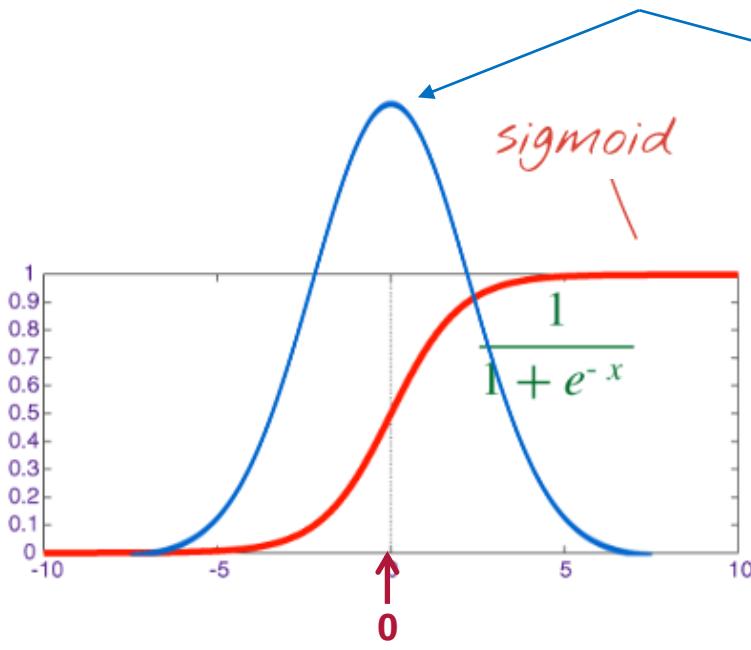
$$\text{Step 2: } BN(x) = \alpha \hat{x} + \beta$$

The learned parameters α and β determine how strictly the standardization is done. If the learned $\alpha = \text{stdev}(x)$ and the learned $\beta = \text{avg}(x)$, then the standardization performed in step 1 is undone in step 2 and $BN(x) = x$.

Batch Normalization is beneficial in many NN

After BN the input to the activation function is in the sweet spot

Observed distributions of signal after BN before going into the activation layer.



When using BN consider the following:

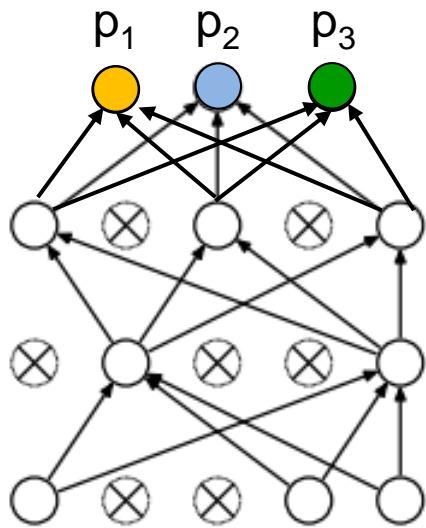
- Using a higher learning rate might work better
- Use less regularization, e.g. reduce dropout probability
- In the linear transformation the biases can be dropped (step 2 takes care of the shift)
- In case of ReLu only the shift β in steps 2 need to be learned (α can be dropped)

Image credits: Martin Gorner:

https://docs.google.com/presentation/d/e/2PACX-1vRouwj_3cYsmLrNNI3Uq5gv5-hYp_QFdeoan2GlxKgIZRSejozruAbVV0IMXBoPsINB7Jw92vJo2EAM/pub?slide=id.g187d73109b_1_2921

Dropout during training

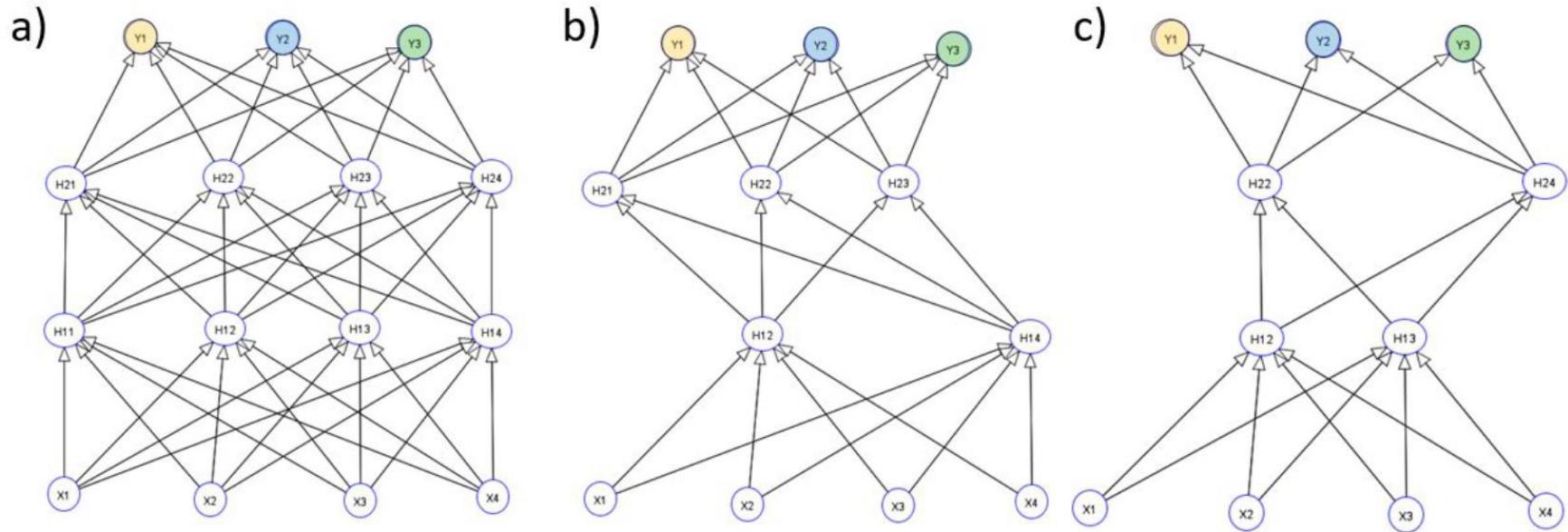
Dropout helps to fight overfitting



Using **dropout** during training implies:

- In each training step only weights to not-dropped units are updated → we train a sparse sub-model NN
- For predictions with the trained NN we freeze the weights corresponding to averaging over the ensemble of trained models we should be able to “reduce noise”, “overfitting”

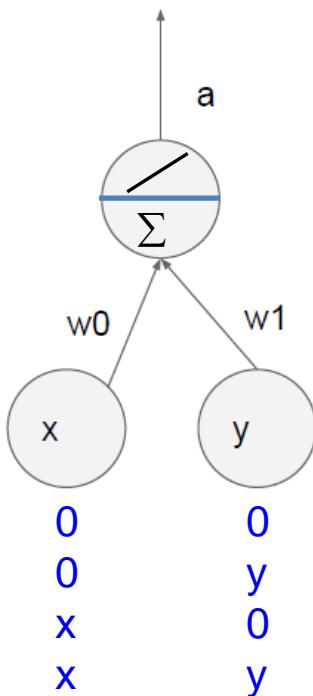
Dropout



Three NNs: a) shows the full NN with all neurons, b) and c) show two versions of a thinned NN where some neurons are dropped. Dropping neurons is the same as setting all connections that start from these neurons to zero

Dropout-trained NN are kind of NN ensemble averages

Use the trained net without dropout during test time



Q: Suppose no dropout during test time (x, y are never dropped to zero), but a dropout probability $p=0.5$ during training

What is the expected value for the output a of this neuron?

during test
w/o dropout:

$$a = w_0 * x + w_1 * y$$

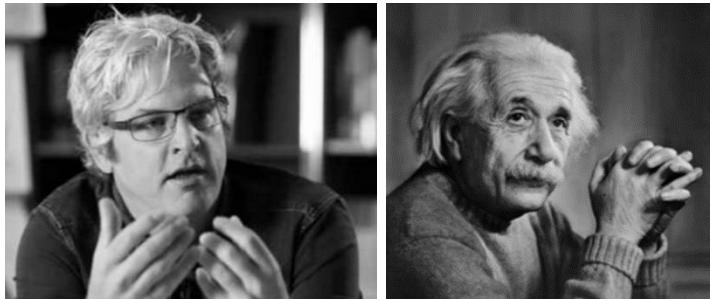
during training
with dropout
probability 0.5:

$$\begin{aligned} E[a] &= \frac{1}{4} * (w_0 * 0 + w_1 * 0 + \\ &\quad w_0 * 0 + w_1 * y + \\ &\quad w_0 * x + w_1 * 0 + \\ &\quad w_0 * x + w_1 * y) \\ &= \frac{1}{4} * (2 w_0 * x + 2 w_1 * y) \\ &= \frac{1}{2} * (w_0 * x + w_1 * y) \end{aligned}$$

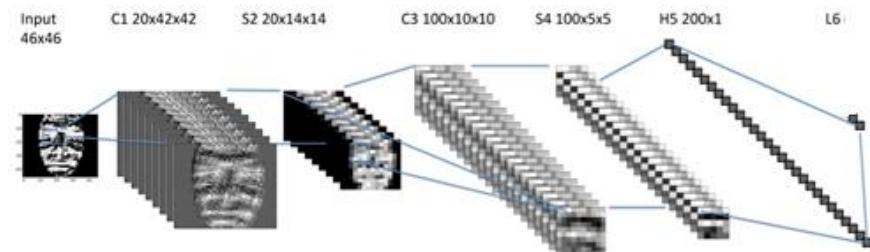
=> To get same expected output in training and test time, we reduce the weights during test time by multiplying them by the dropout probability $p=0.5$

Another intuition: Why “dropout” can be a good idea

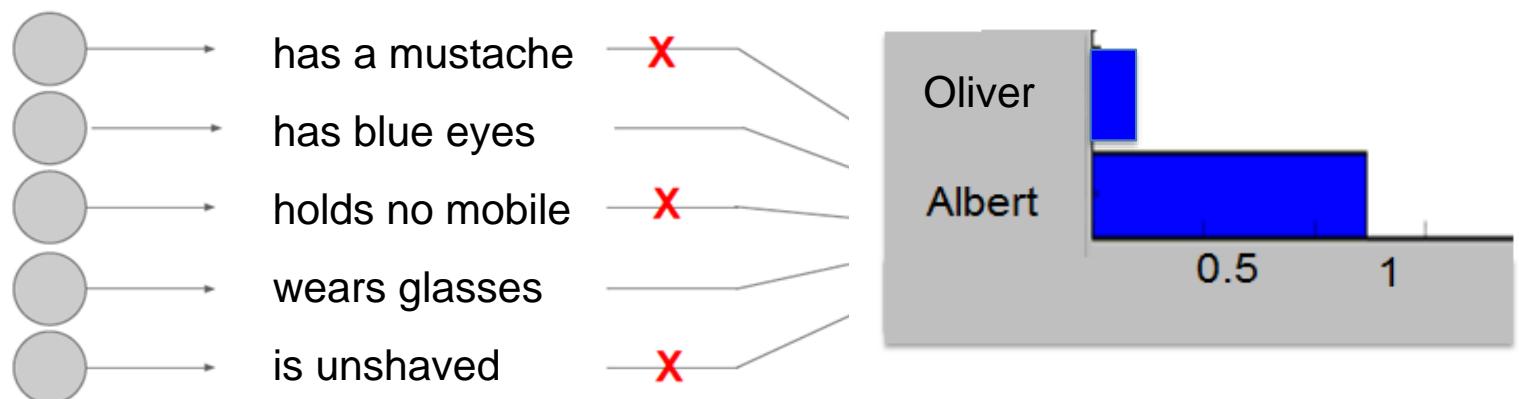
The training data consists of many different pictures of Oliver and Einstein



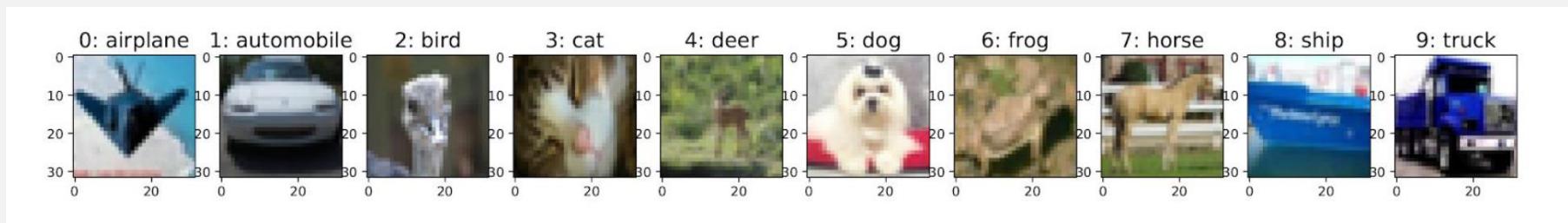
We need a huge number of neurons to extract good features which help to distinguish Oliver from Einstein



Dropout forces the network to learn redundant and independent features



Can batchnorm and dropout improve performance?



Notebook:

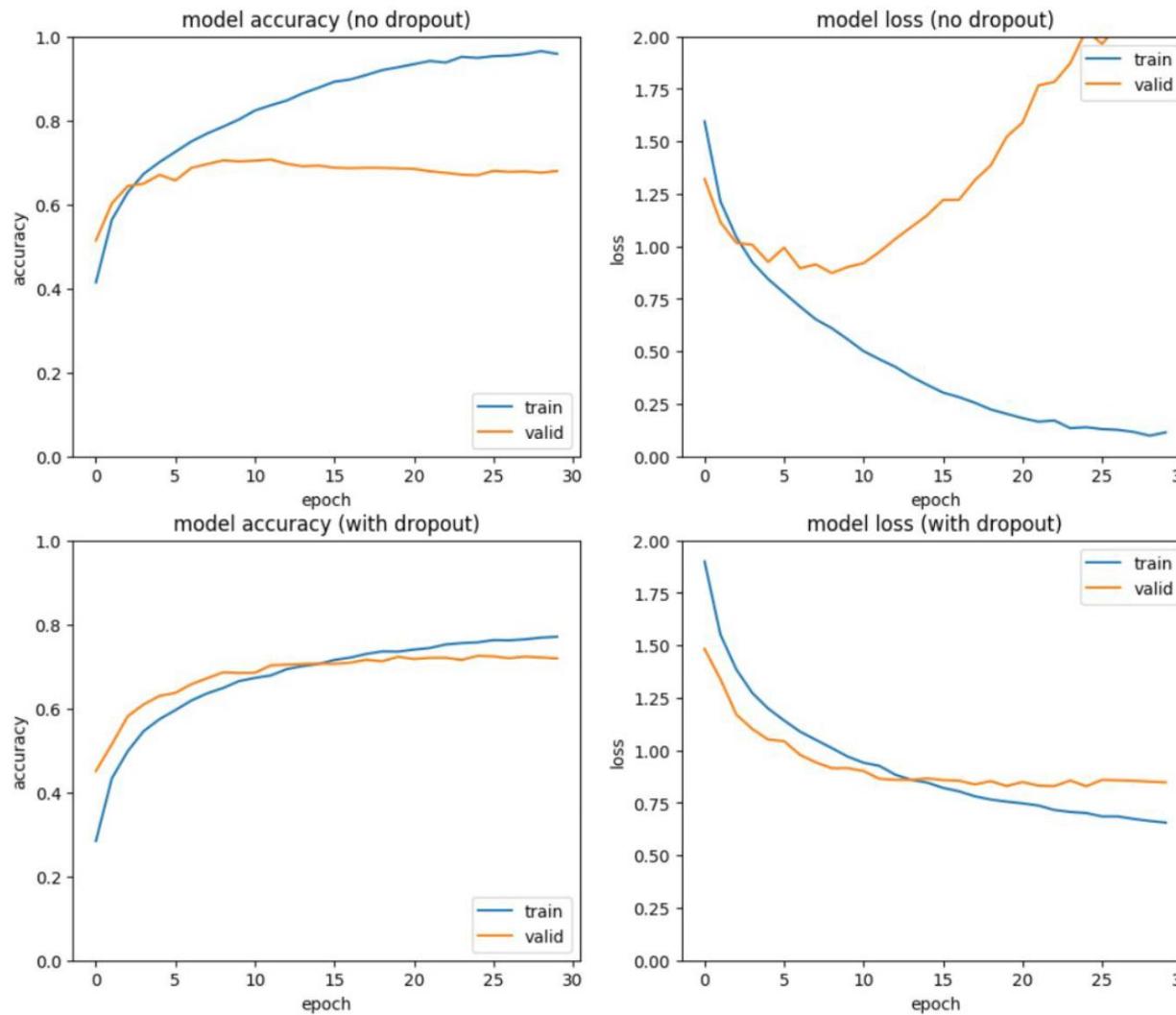
https://github/tensorchiefs/dl_course_2020/blob/master/notebooks/08_cifar10_tricks.ipynb

cnn from scratch

cnn from scratch with dropout

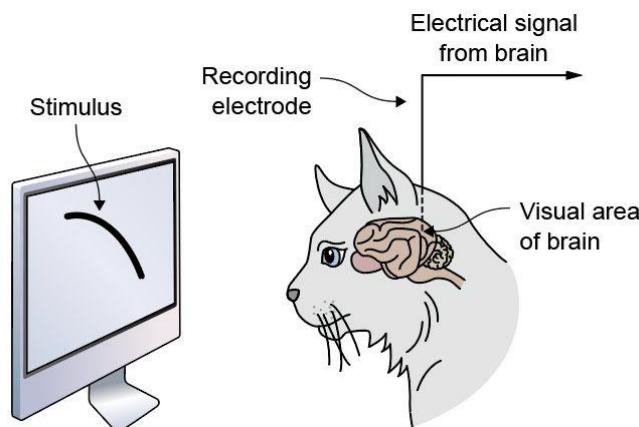
cnn from scratch with batchnorm

Dropout fights overfitting in a CIFAR10 CNN

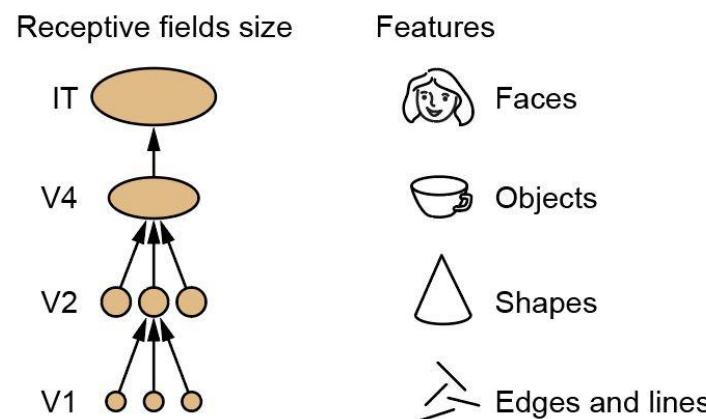
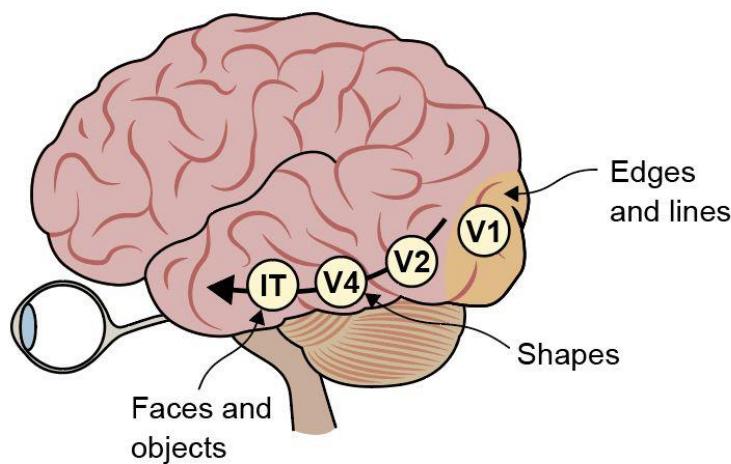


Biological Inspiration of CNNs

How does the brain respond to visually received stimuli?

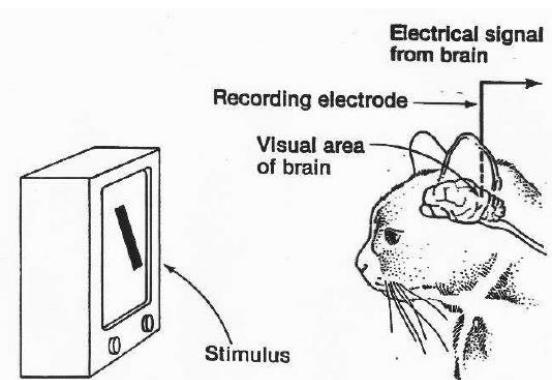


Setup of the experiment of Hubel and Wiesel in late 1950s in which they discovered **neurons** in the visual cortex that **responded** when moving **edges** were shown to the cat.

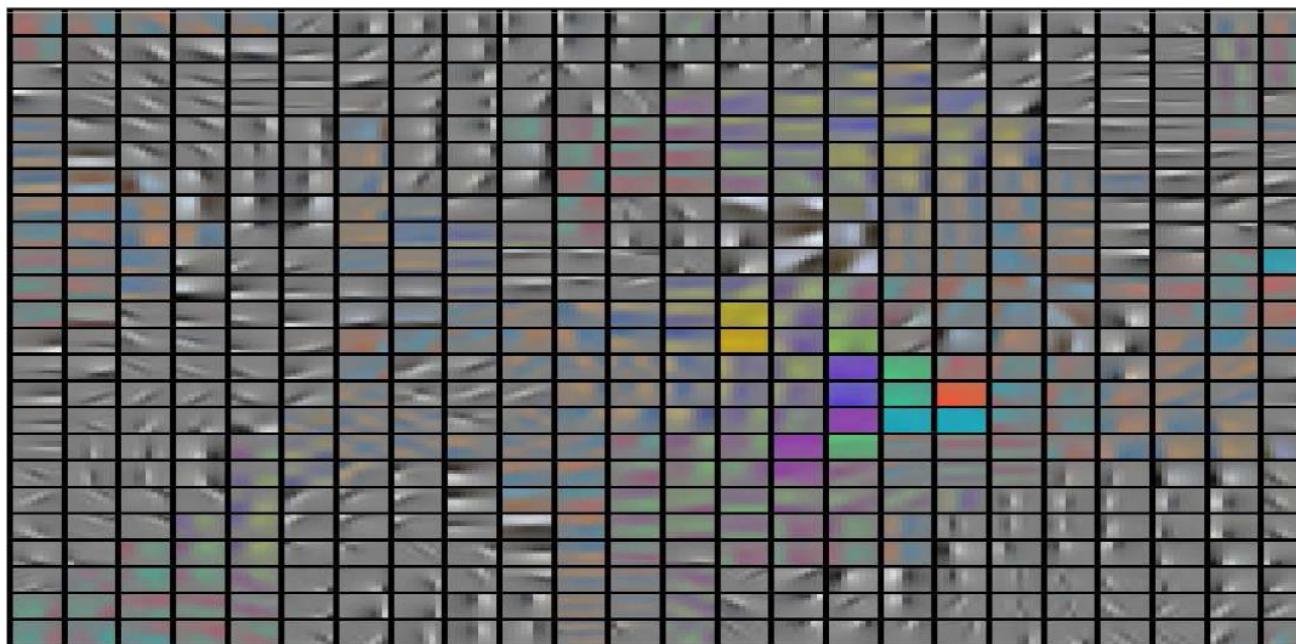
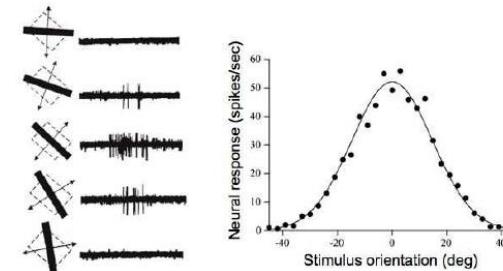


Organization of the visual cortex in a brain, where neurons in different regions respond to more and more complex stimuli

Compare neurons in brain region V1 in first layer of a CNN



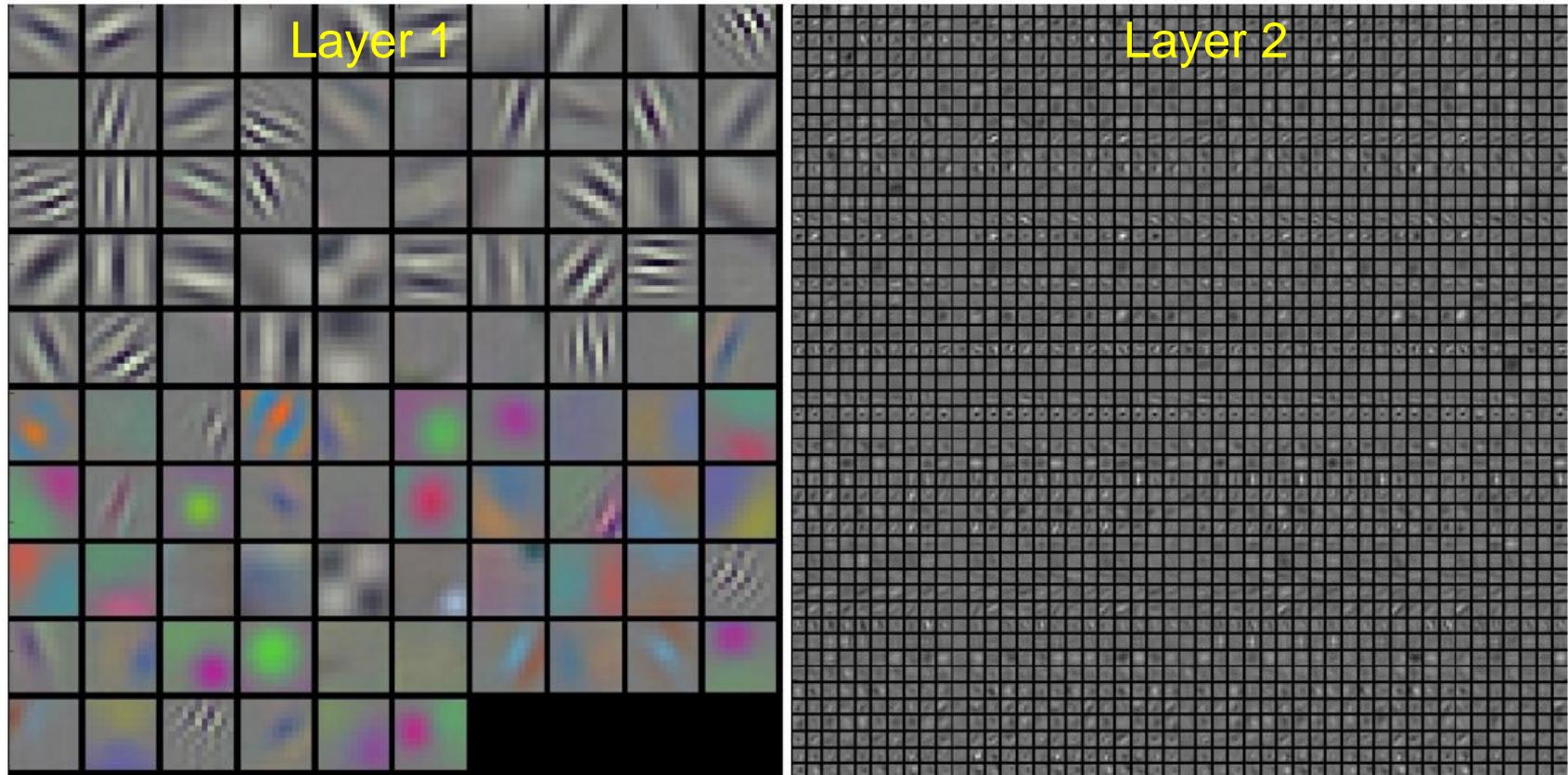
V1 physiology: orientation selectivity



Neurons in brain region V1 and neurons in 1. layer of a CNN respond to similar patterns

Visualize the weights used in filters

Filter weights from a trained Alex Net

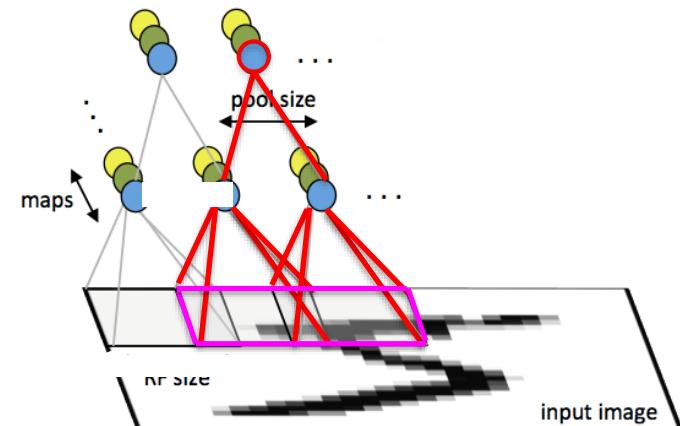
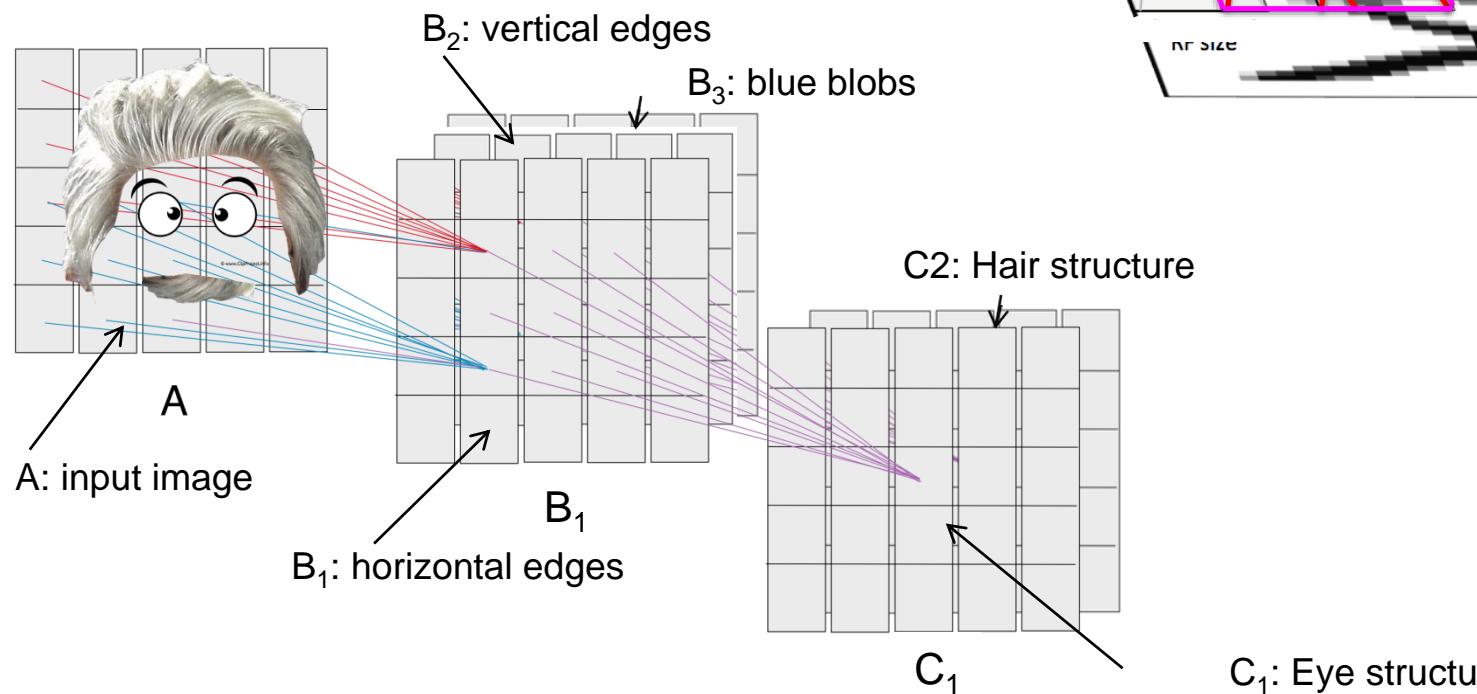


Only in layer 1 the filter pattern correspond to extracted patterns in the image.

In higher layers we can only check if patterns look noisy, which would indicate that the network that hasn't been trained for long enough, or possibly with a too low regularization strength that may have led to overfitting.

The receptive field

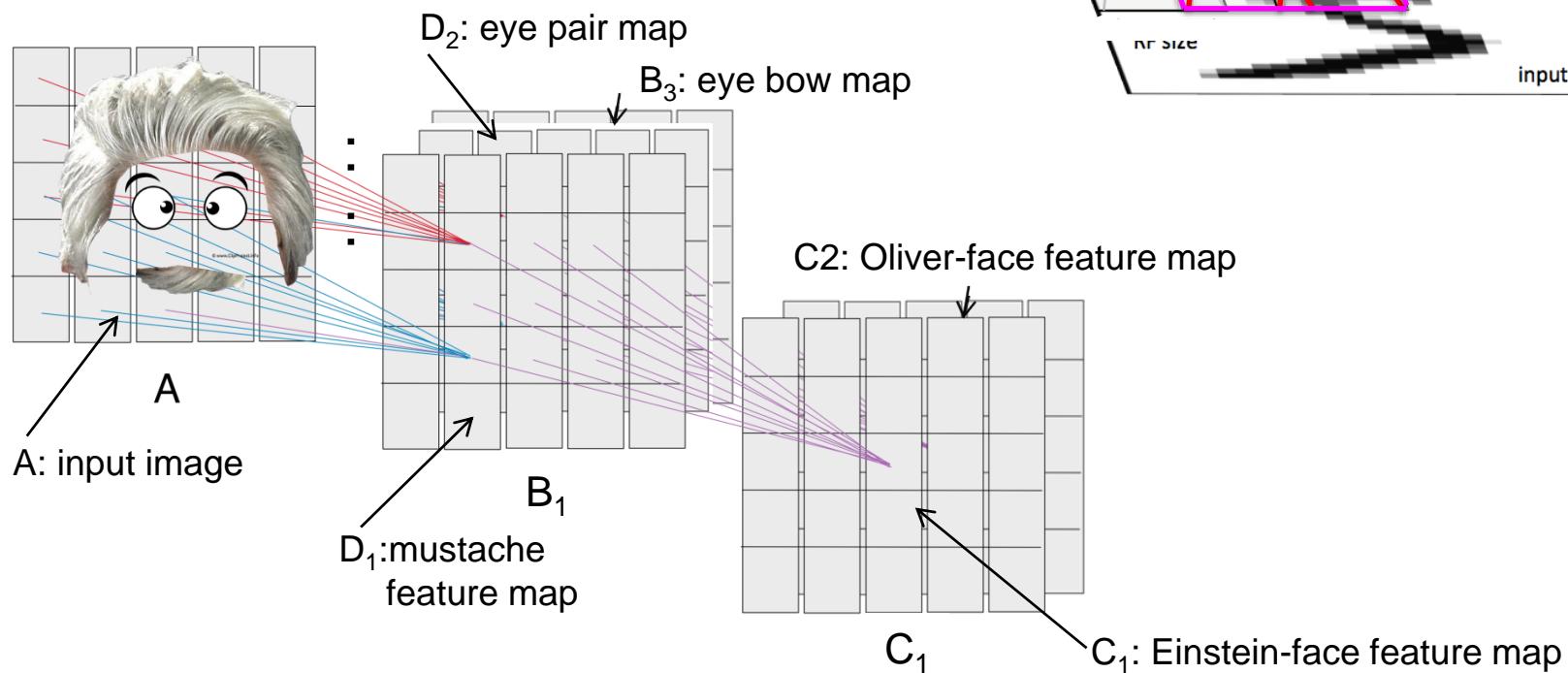
For each pixel of a feature map we can determine the connected area in the input image – this area in the input image is called receptive field.



An activation map gets activated by a certain structure of the feature maps one layer below, which by itself depends on the input of a lower layer etc and finally on the input image. Activation maps close to the input image are activated by simple structures in the image, higher maps by more complex image structures.

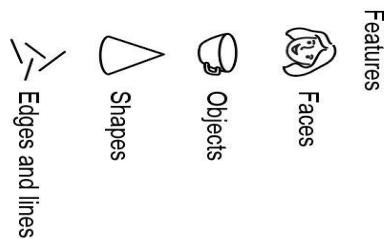
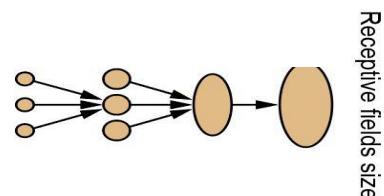
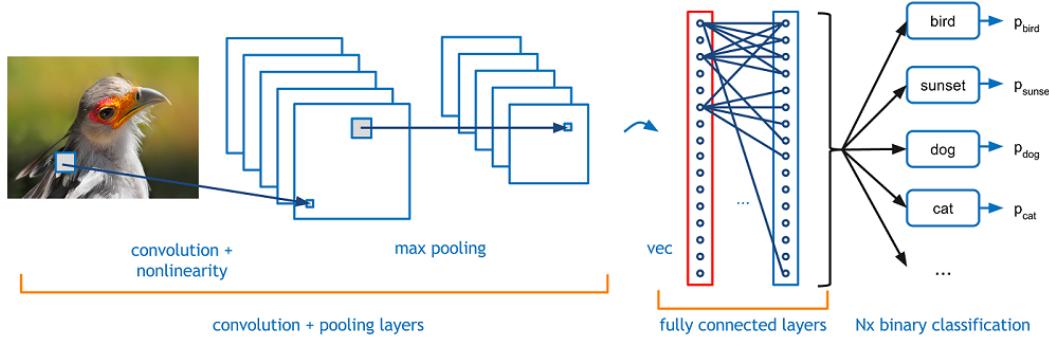
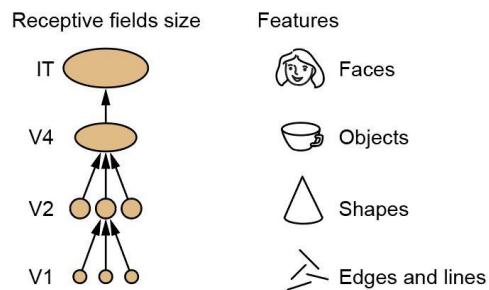
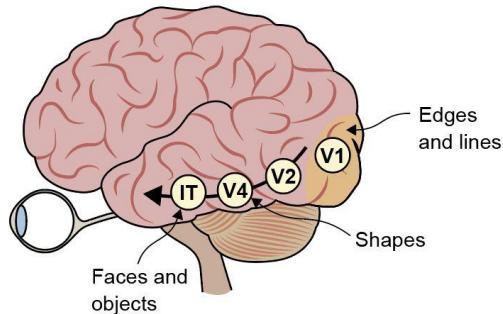
The receptive field

The receptive field gets larger and larger when going further away from the input

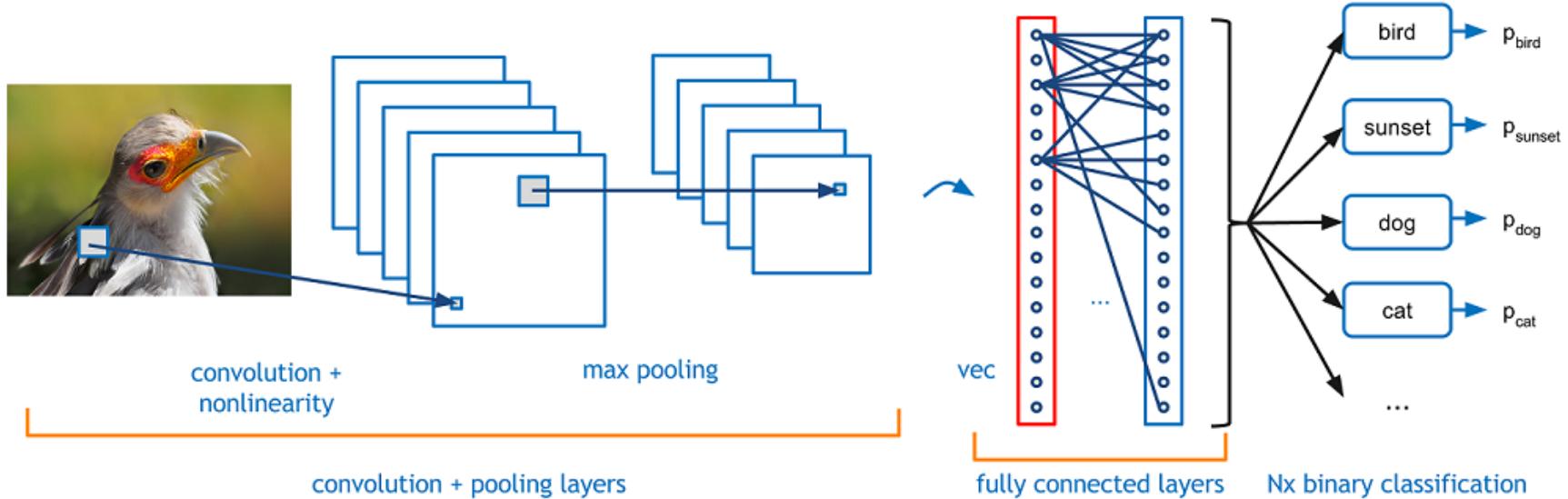


Filter cascade across different channels can capture relative position of different features in input image. Einstein-face-filter will have a high value at expected mustache position.

Weak analogies between brain and CNNs architecture



Convolutional part in CNN as representation learning



In a classical CNN we start with convolution layers and end with fc layers.

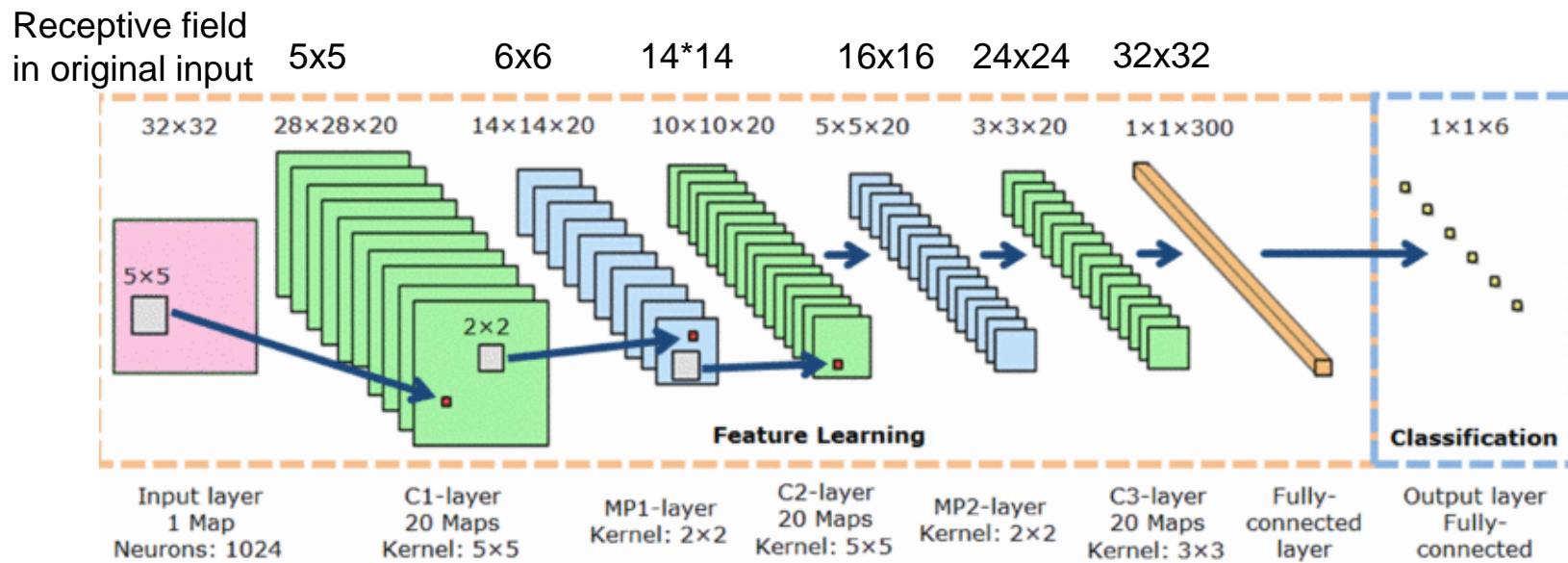
The task of the convolutional layers is to extract useful features from the image which might appear at arbitrary positions in the image.

The task of the fc layer is to use these extracted features for classification.

What input does activate a feature map in the CNN part or a neuron in the last layer?

The receptive field is growing from layer to layer

The receptive field of a neuron is the area in the original input image that impact the value of this neuron – “that can be seen by this neuron”.



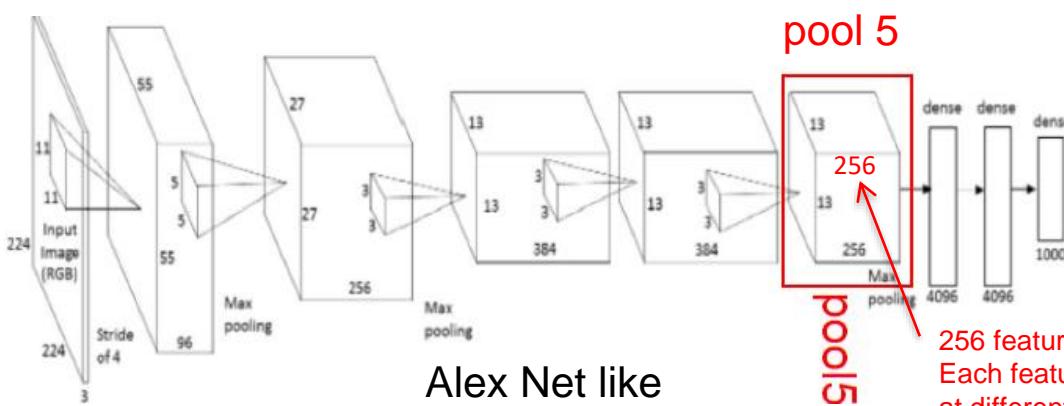
Neurons from feature maps in higher layers have a larger receptive field than neurons sitting in feature maps closer to the input.

Code to determine size of receptive field: <http://stackoverflow.com/questions/35582521/how-to-calculate-receptive-field-size>

Visualize patches yielding high values in activation maps



Figure 4: Top regions for six pool₅ units. Receptive fields and activation values are drawn in white. Some units are aligned to concepts, such as people (row 1) or text (4). Other units capture texture and material properties, such as dot arrays (2) and specular reflections (6).



<http://cs231n.github.io/understanding-cnn/>

Here we show image patches that activate maps in layer 5 most.

256 feature maps generated by 256 different 3x3 filters. Each feature map consists of equivalent neurons looking at different positions of the input volume.

What kind of image (patches) excites a certain neuron corresponding to a large activation in a feature map?

10 images from data set leading to high signals 6 feature maps of **conv6**



10 images from data set leading to high signals 6 feature maps of **conv9**



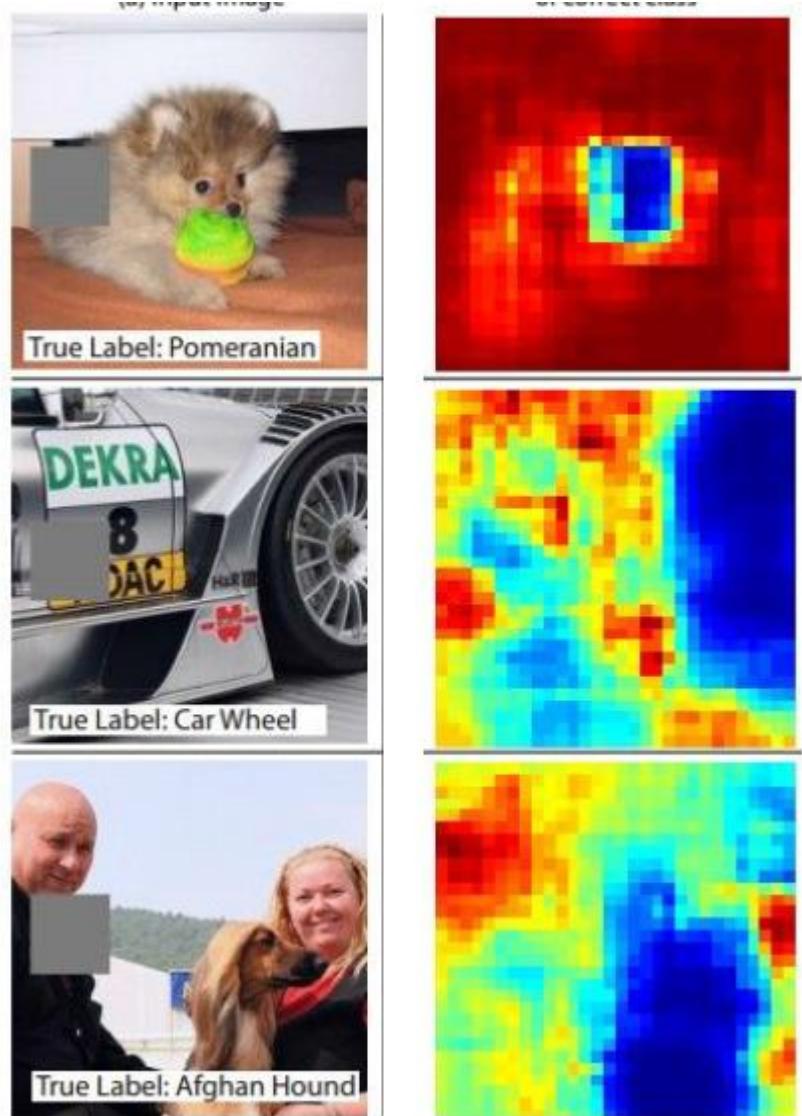
What in the input image was important for the prediction?

Which pixels are important for the classification?

Occlusion experiments

Occlude part of the image with a mask and check for each position of the mask how strongly the score for the correct class is changing.

Warning:
Usefulness depends on application...



Occlusion experiments [\[Zeiler & Fergus 2013\]](#)

image credit: cs231n

Which pixels are important for the classification?

LIME: Local Interpretable Model-agnostic Explanations

Idea:

- 1) perturb interpretable features of the instance – e.g. randomly delete super-pixels in an image and track as perturbation vector such as $(0,1,1,0,\dots,1)=x$.
- 2) Classify perturbed instance by your model, here a CNN, and track the achieved classification-score= y
- 3) Identify for which features/super-pixels the presence in the perturbed input version are important to get a high classification score (use RF or lasso for $y \sim x$)



(a) Husky classified as wolf



(b) Explanation

-> presence of snow was used to distinguish wolf and husky

-> Explain the CNN classification by showing instance-specific important features
visualize important feature allows to judge the individual classification



(a) Original Image



(b) Explaining Electric guitar

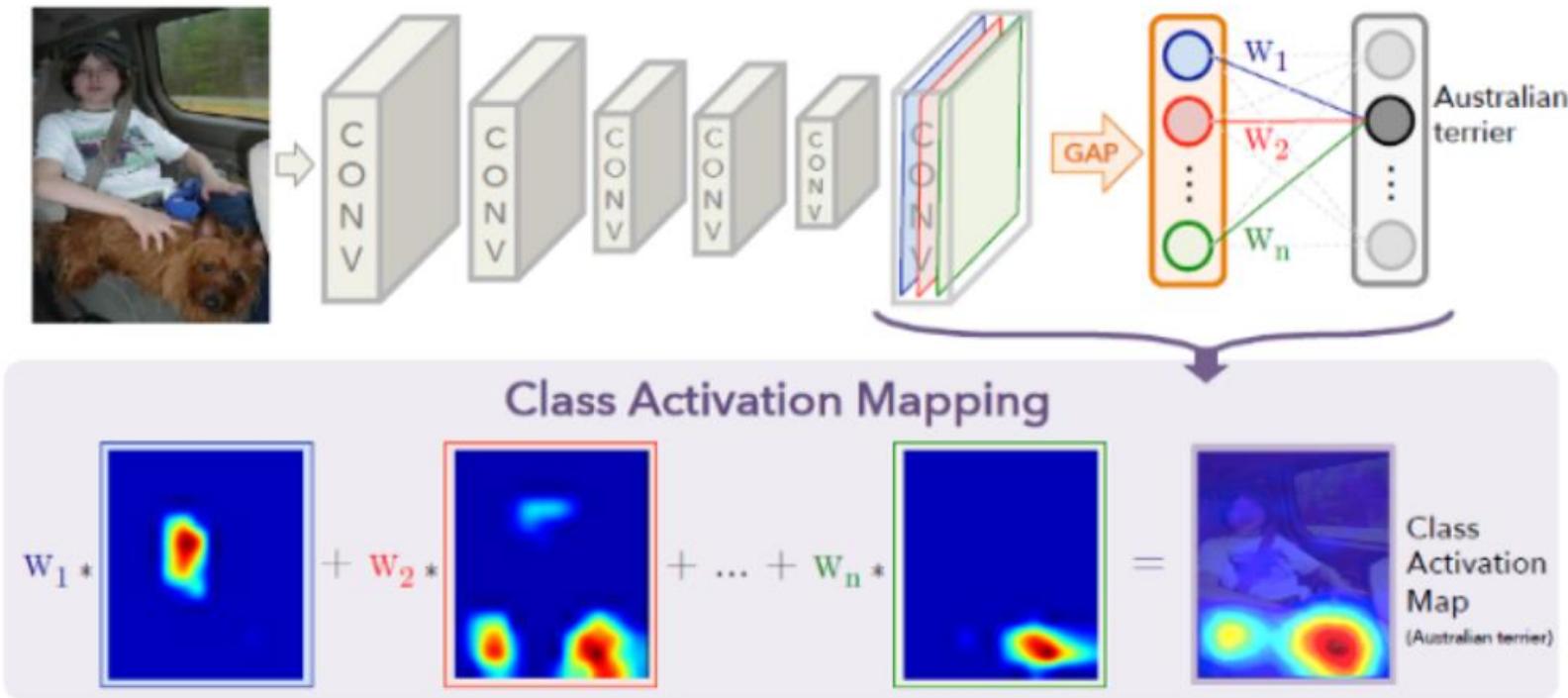


(c) Explaining Acoustic guitar



(d) Explaining Labrador

Class Activation Mapping (CAM)



We compute the CAM by multiplying each feature map of the final convolution layer with the corresponding weight connected to the neuron of the winning class.

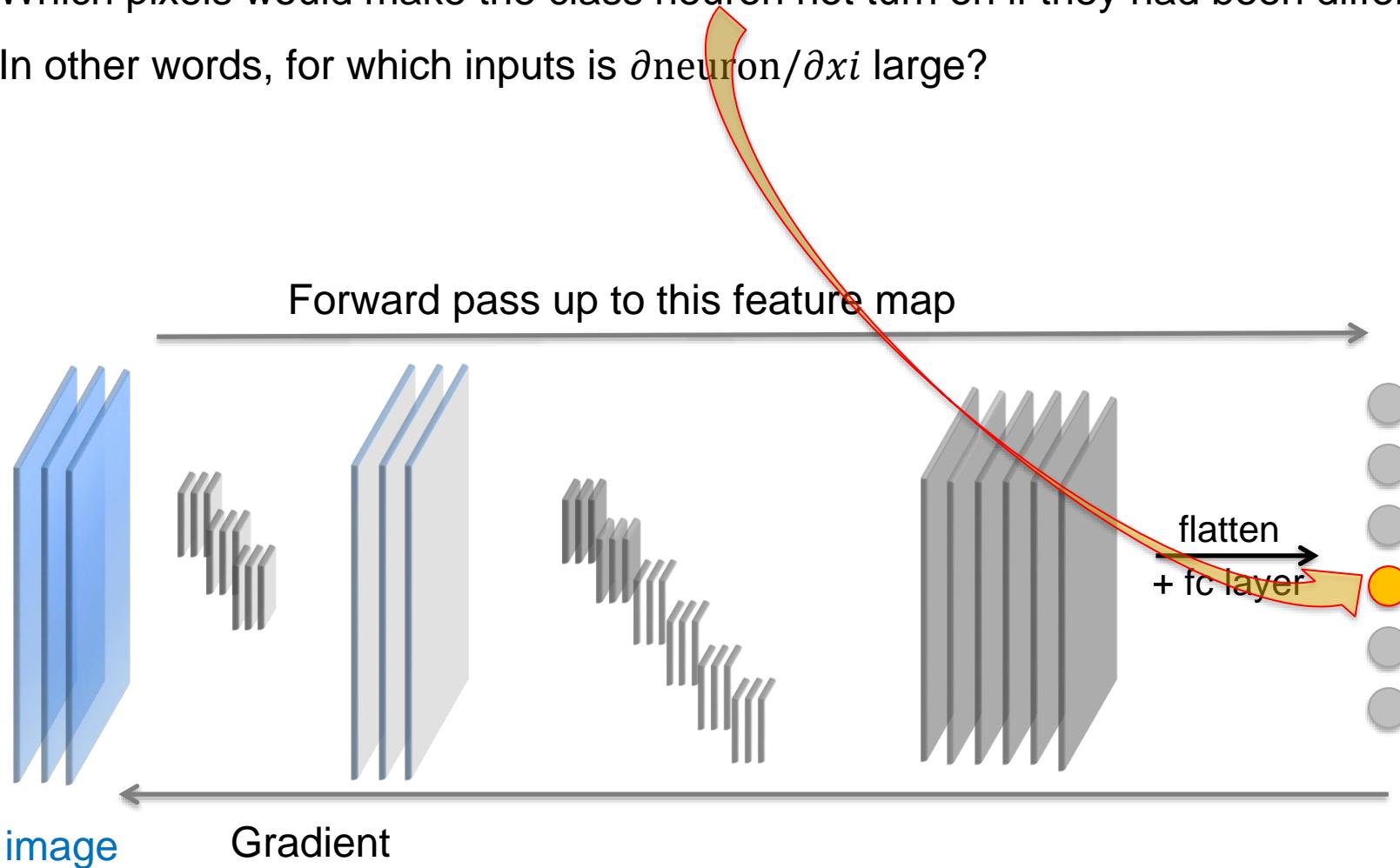
<https://arxiv.org/abs/1512.04150>

<https://towardsdatascience.com/class-activation-mapping-using-transfer-learning-of-resnet50-e8ca7cf657e>

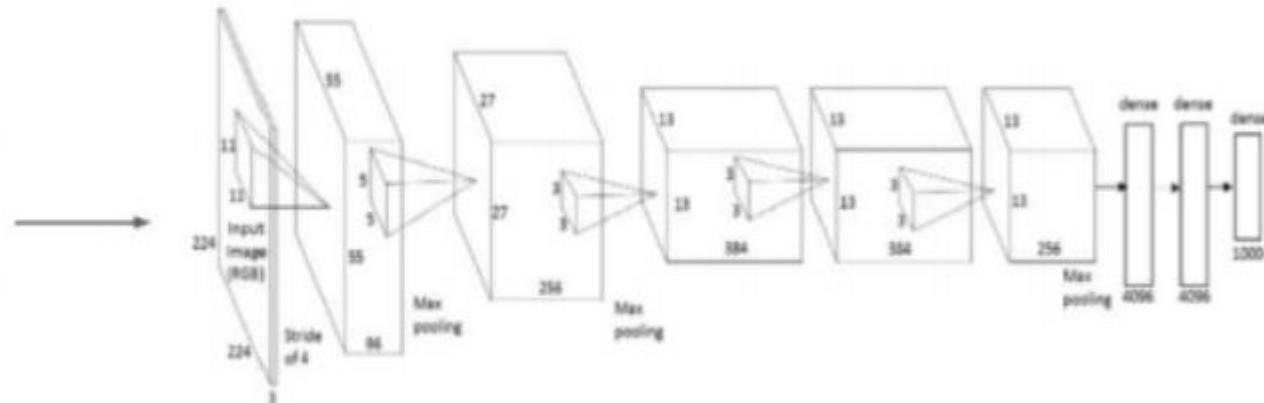
Gradient Backpropagation

Which pixels would make the class neuron not turn on if they had been different?

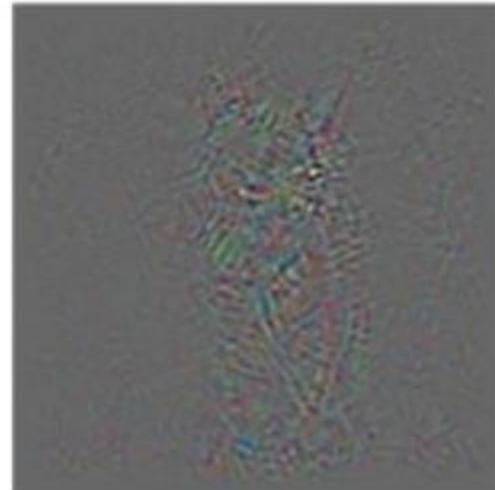
In other words, for which inputs is $\partial \text{neuron} / \partial x_i$ large?



Gradient Backpropagation

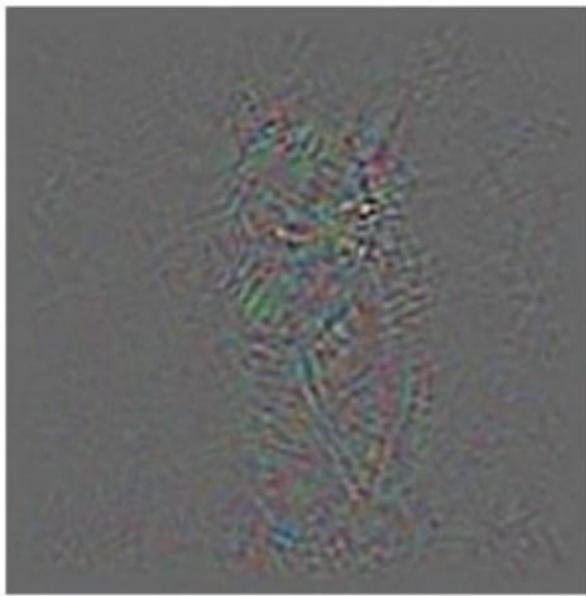


- 1) Do a forward pass with the image
- 2) Compute the gradient of the winning class neuron using backprop

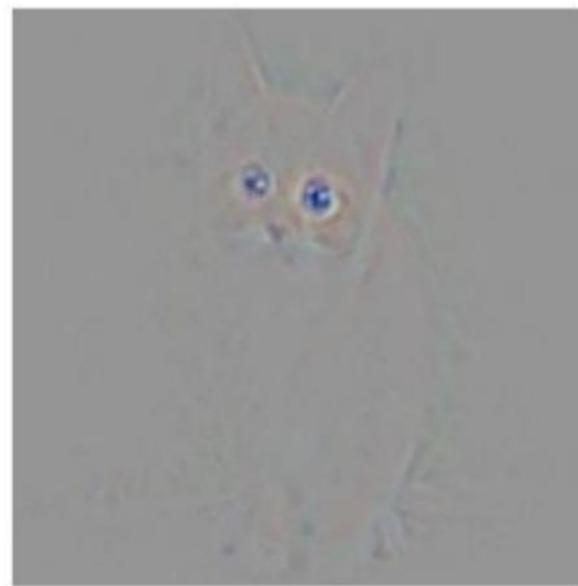


Guided Gradient Backpropagation

- We are **only interested to see which image features the neuron detects**, not in what kind of stuff it doesn't detect
- So **only propagating positive gradients** (set all the negative gradients to 0)

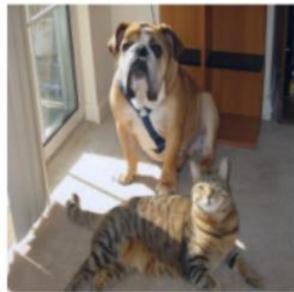


Backprop



Guided Backprop

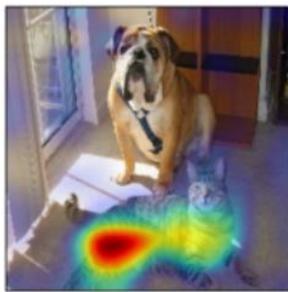
What in the image was important for the prediction?



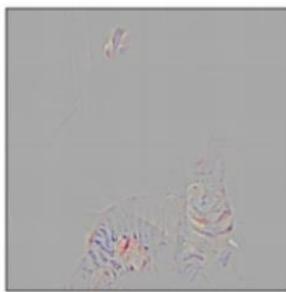
(a) Original Image



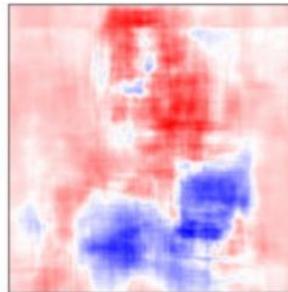
(b) Guided Backprop 'Cat'



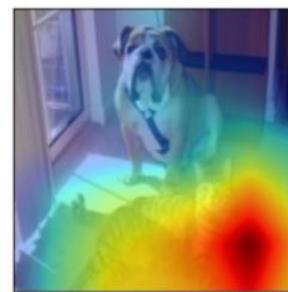
(c) Grad-CAM 'Cat'



(d) Guided Grad-CAM 'Cat'



(e) Occlusion map 'Cat'



(f) ResNet Grad-CAM 'Cat'



(g) Original Image



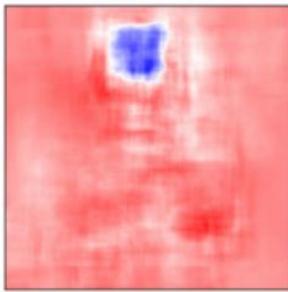
(h) Guided Backprop 'Dog'



(i) Grad-CAM 'Dog'



(j) Guided Grad-CAM 'Dog'



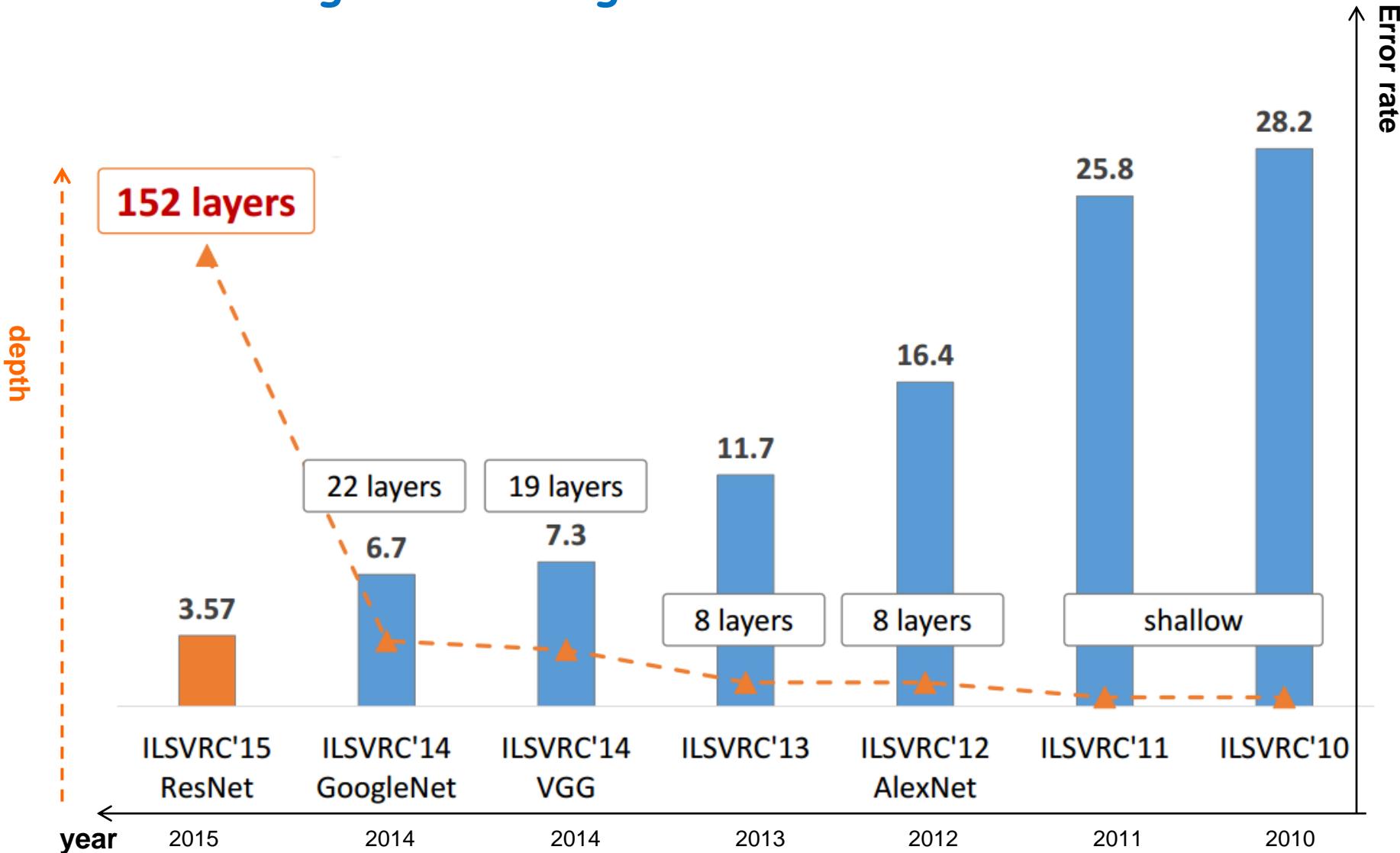
(k) Occlusion map 'Dog'



(l) ResNet Grad-CAM 'Dog'

Challenge winning CNN architectures

Review of ImageNet winning CNN architectures



LeNet-5 1998: first CNN for ZIP code recognition

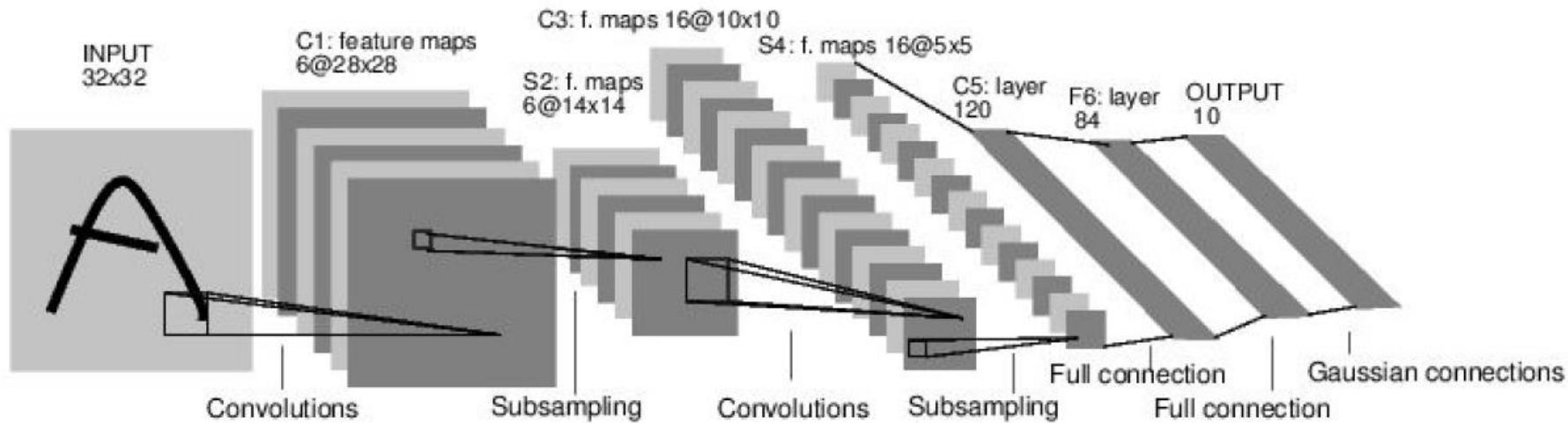


Image credits: <http://yann.lecun.com/exdb/publis/pdf/lecun-98.pdf>

Conv filters were **5x5**, applied at stride 1

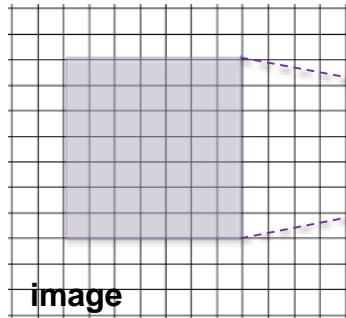
Subsampling (Pooling) layers were **2x2** applied at stride 2
i.e. architecture is [CONV-POOL-CONV-POOL-CONV-FC]

The trend in modern CNN architectures goes to small filters

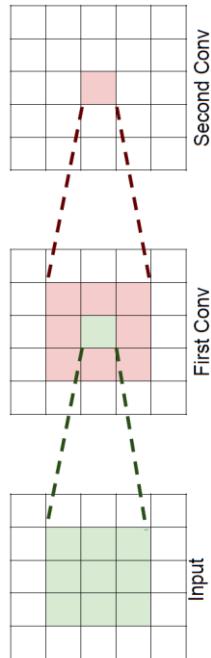
Why do modern architectures use very small filters?

Determine the receptive field in the following situation:

- 1) Suppose we have one
7x7 conv layers (stride 1)
49 weights



Answer1): 7x7



- 2) Suppose we stack two
3x3 conv layers (stride 1)

Answer 2): 5x5

				x
			x	

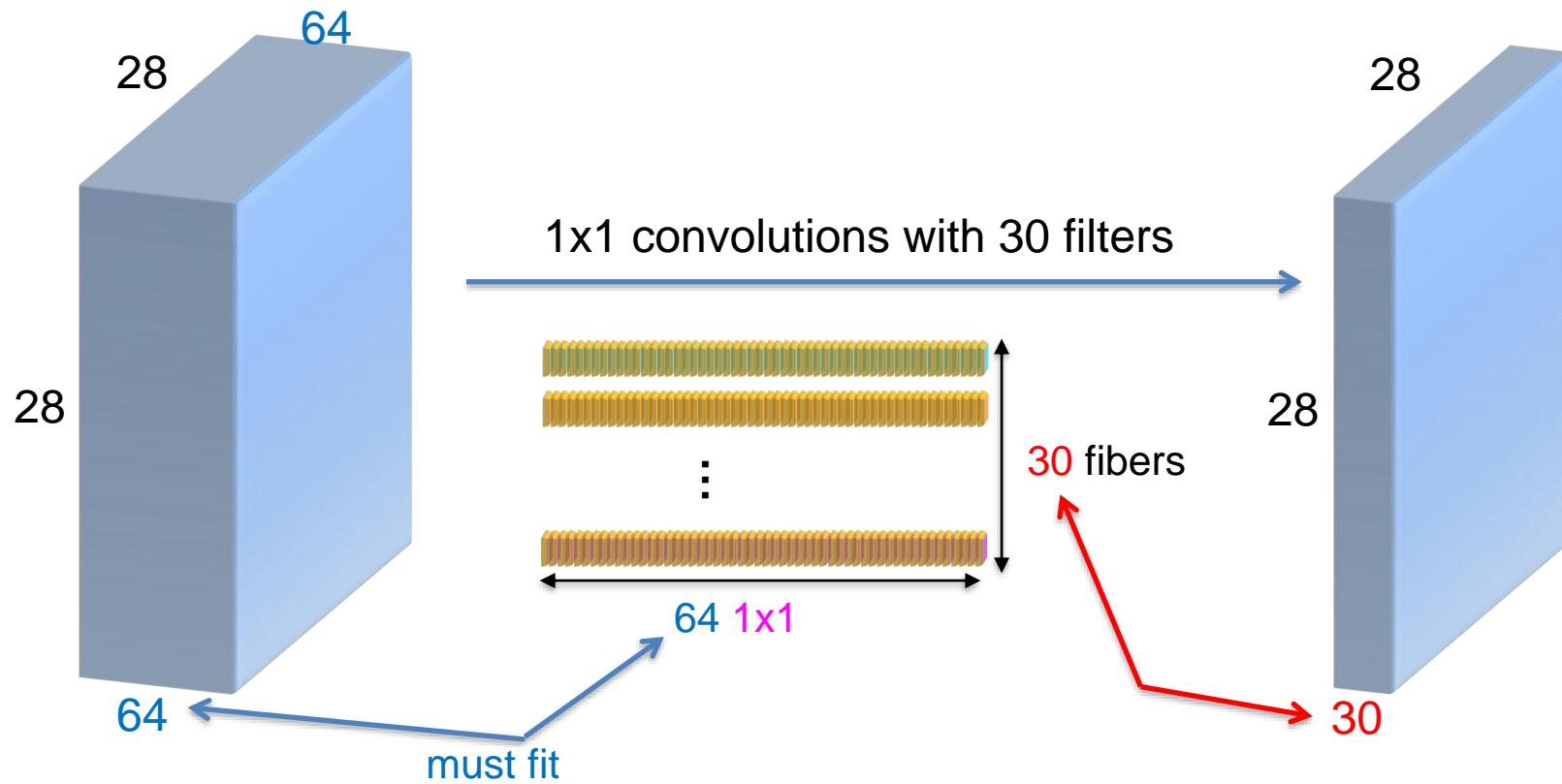
- 3) Suppose we stack three
3x3 conv layers (stride 1)
 $3 \times 9 = 27$ weights

Answer 3): 7x7

						x
			x			

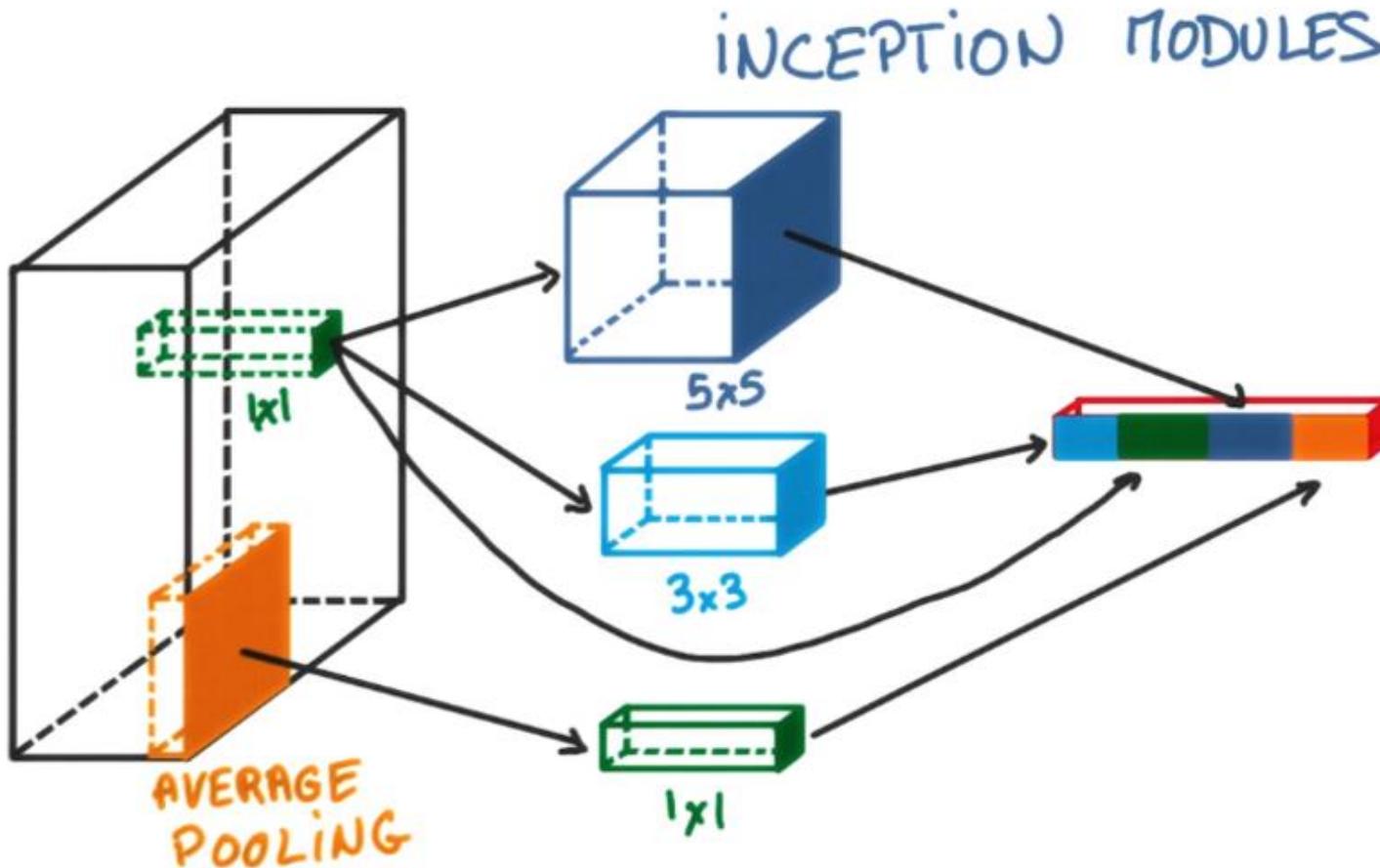
We need less weights for the same receptive field when stacking small filters!

Go to the extreme: What is about filter size 1? 1x1 convolutions act only in depth dimension



1x1 convolution act along a “fiber” in depth dimension across the channels.
→ efficient way to reduce/change the depth dimension
→ simultaneously introduce more non-linearity

The idea of inception modules



Between two layers just **do several operations in parallel**: pooling and 1×1 conv, and 3×3 and 5×5 . “same”-conv and concatenate them together.
Benefit: total number of parameters is small, yet performance better.

How to concatenate tensors of different dimensions?

DepthConcat needs to make the tensor the same in all, but the depth dimension:

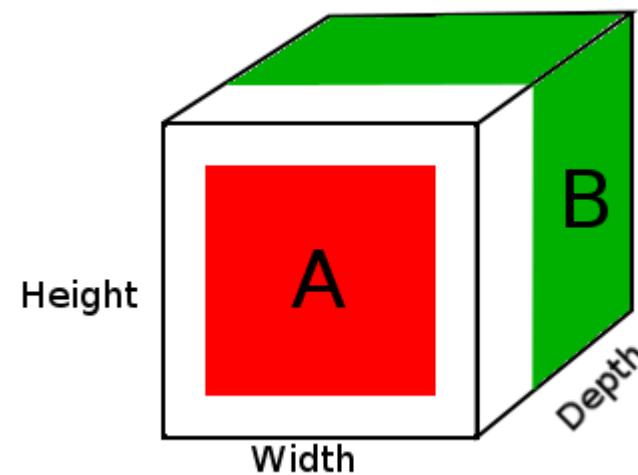
To deal with different output dimensions, the largest spatial dimension is selected and zero-padding around the smaller dimensions is added.

Usually depth gets large!
Do 1x1 conv afterwards!

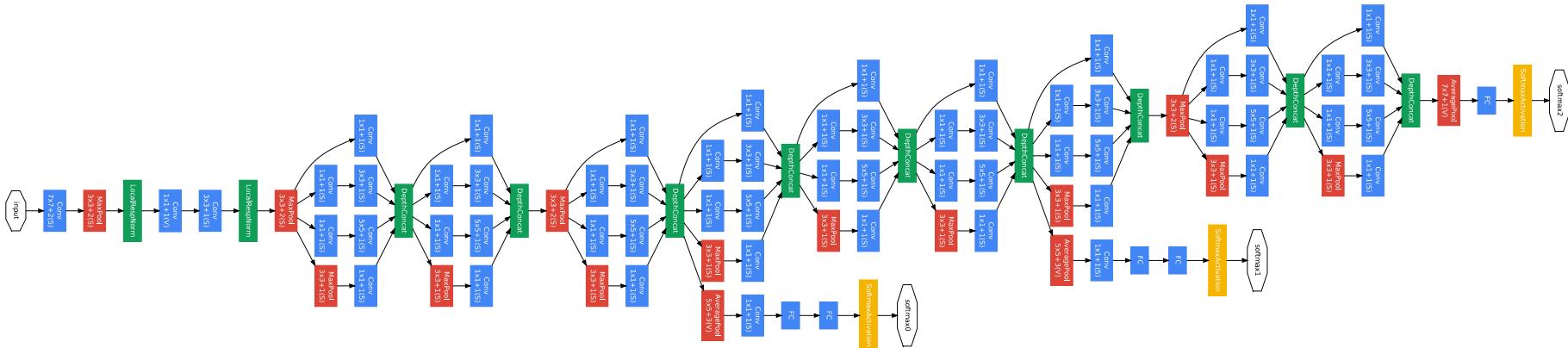
Pseudo code for an example:

```
A = tensor of size (14, 14, 2)  
B = tensor of size (16, 16, 3)  
result = DepthConcat([A, B])
```

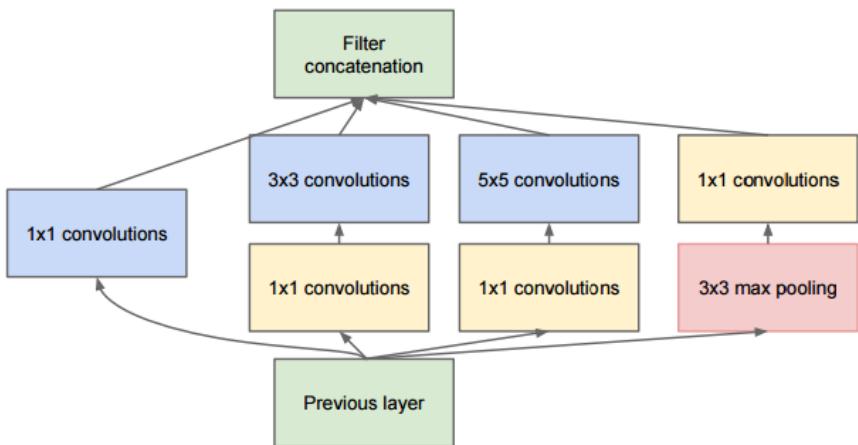
where result will have a height of 16, width of 16 and a depth of 5 ($2 + 3$)



Winning architecture (GoogLeNet, 2014)

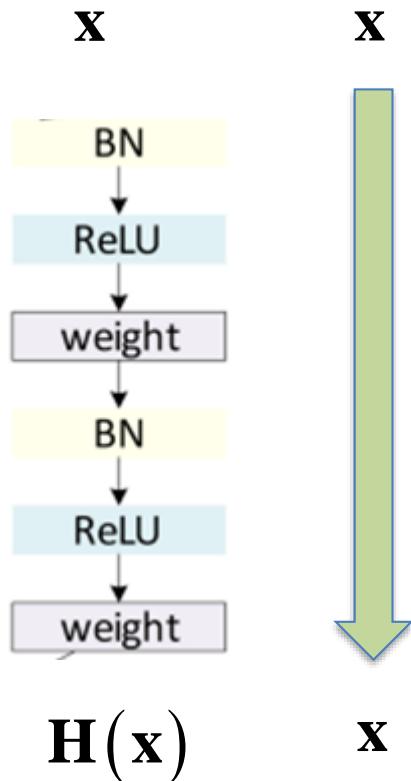


The inception module (convolutions and maxpooling)



Few parameters, hard to train.
Comments see [here](#)

Highway Networks: providing a highway for the gradient



Idea: Use nonlinear transform T to determine how much of the output y is produced by H or the identity mapping. Technically we do that by:

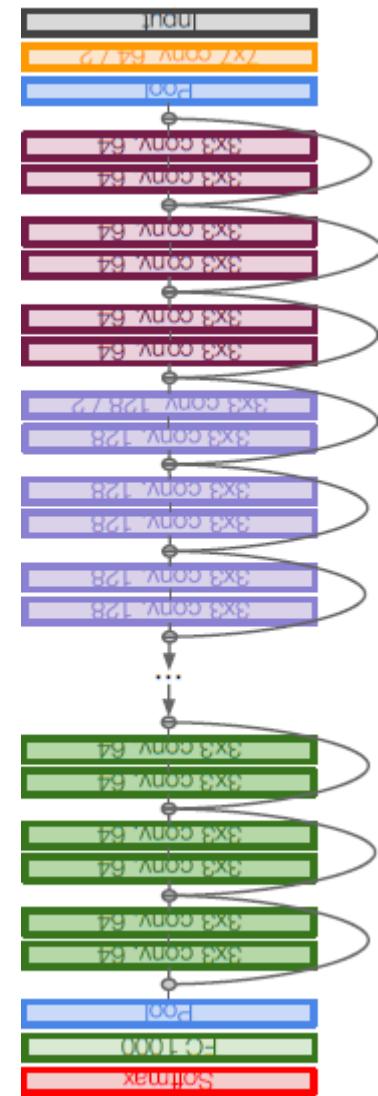
$$y = H(x, \mathbf{W}_H) \cdot T(x, \mathbf{W}_T) + x \cdot (1 - T(x, \mathbf{W}_T)).$$

Special case:

$$y = \begin{cases} x, & \text{if } T(x, \mathbf{W}_T) = 0 \\ H(x, \mathbf{W}_H), & \text{if } T(x, \mathbf{W}_T) = 1 \end{cases}$$

This opens a highway for the gradient:

$$\frac{dy}{dx} = \begin{cases} \mathbf{I}, & \text{if } T(x, \mathbf{W}_T) = 0, \\ H'(x, \mathbf{W}_H), & \text{if } T(x, \mathbf{W}_T) = 1. \end{cases}$$

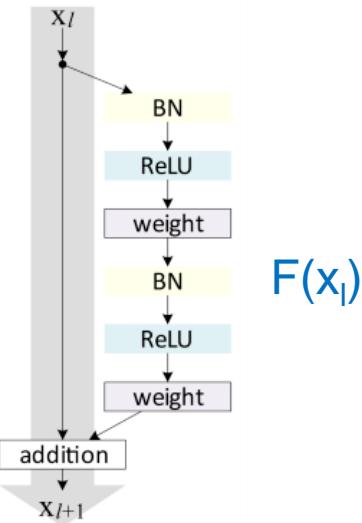


"ResNet" from Microsoft 2015 winner of imageNet

152
layers

ResNet basic design (VGG-style)

- add shortcut connections every two
- all 3x3 conv (almost)



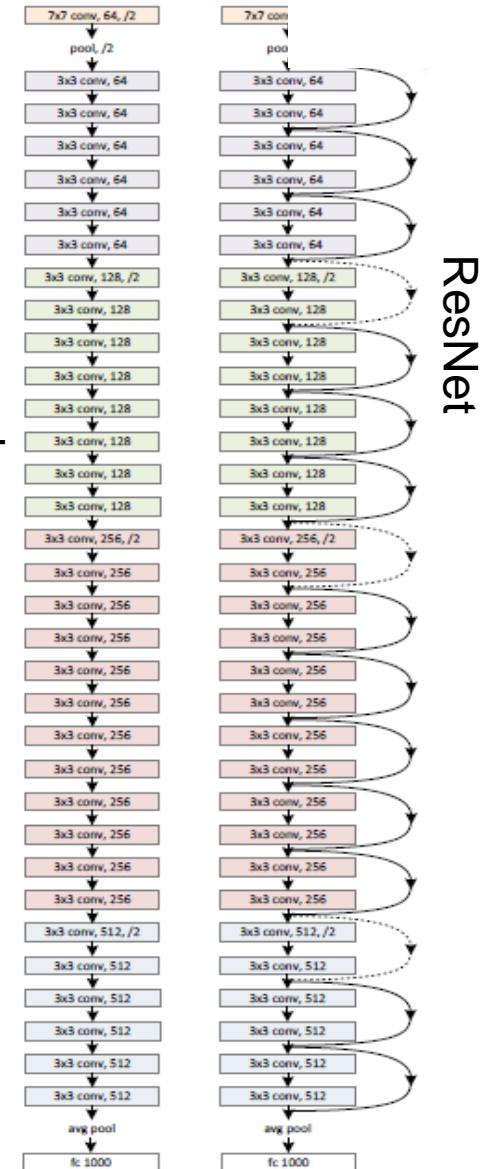
$$H(x_i) = x_{i+1} = x_i + F(x_i)$$

$F(x)$ is called "residual" since it only learns the "delta" which is needed to add to x to get $H(x)$

152 layers:
Why does this train at all?

This deep architecture
could still be trained, since
the gradients can skip
layers which diminish the
gradient!

plain VGG



“Oxford Net” or “VGG Net” 2nd place

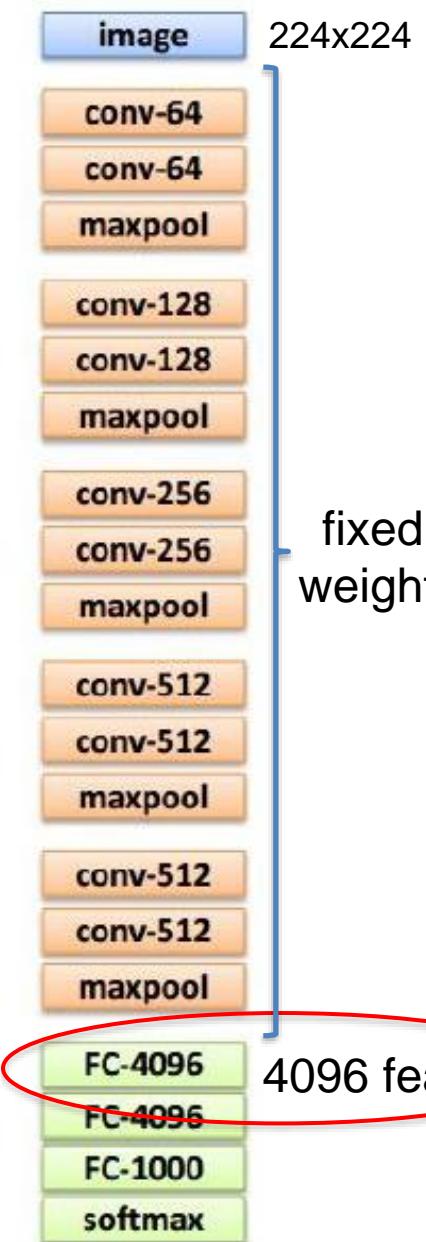
- 2nd place in the imageNet challenge
- More traditional, easier to train
- More weights than GoogLeNet
- Small pooling
- Stacked 3x3 convolutions before maxpooling
-> large receptive field
- no strides (stride 1)
- ReLU after conv. and FC (batchnorm was not used)
- Pre-trained model is available



<http://arxiv.org/abs/1409.1556>

What to do in case of limited data?

Use pre-trained CNNs for feature generation



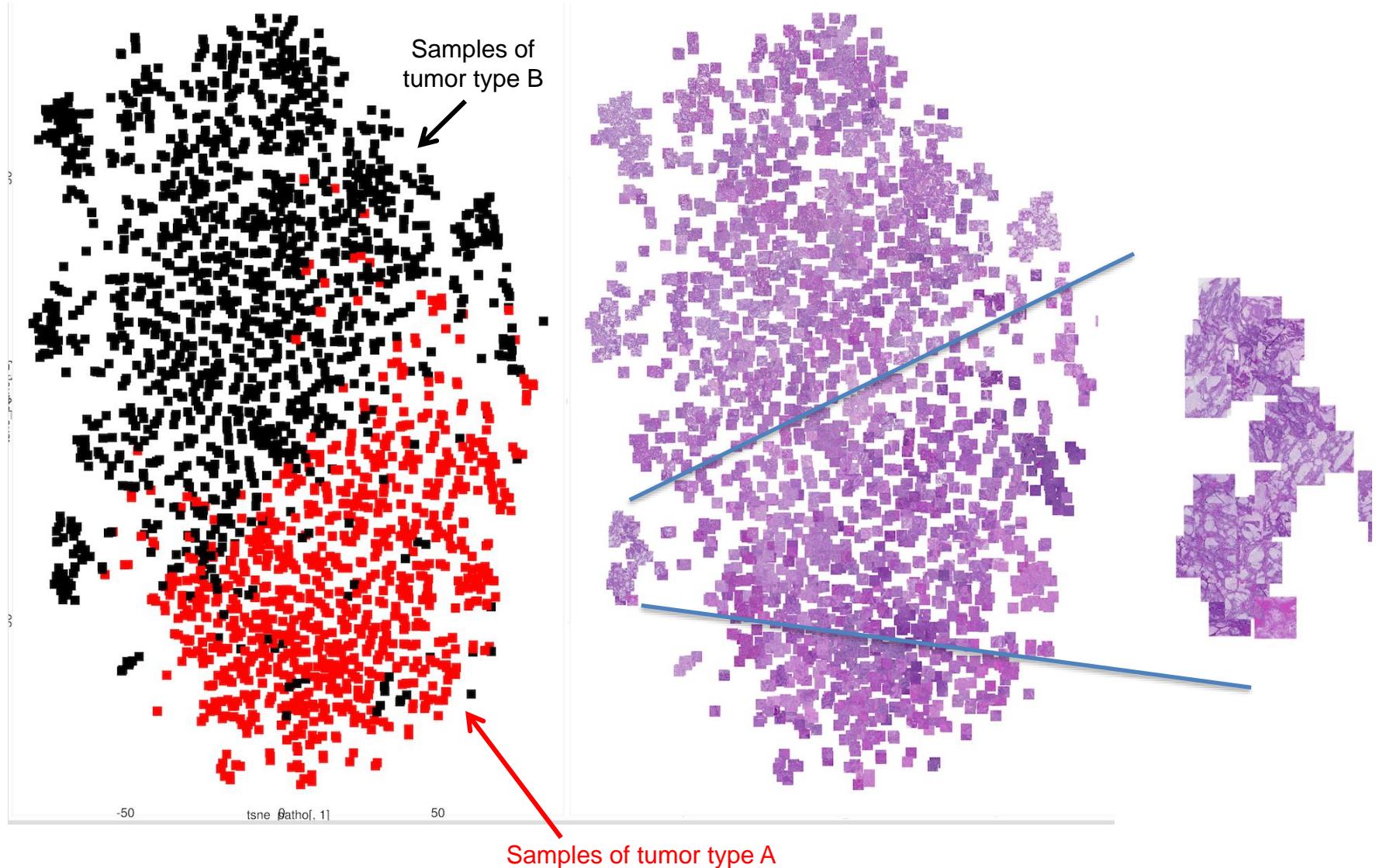
- Load a pre-trained CNN – e.g.g VGG16
- Resize image to required size (224x224 for VGG16)
- Rescaling of the pixel values to “VGG range”
- Do a forward pass and **fetched features** that are used as CNN representations, dump these features into a file on disk
- Use these CNN features as input to a simple classifier – e.g. fc NN, RF, SVM ...
(here it is easily possible to adapt to the new number of class labels)

Number features depends on input shape

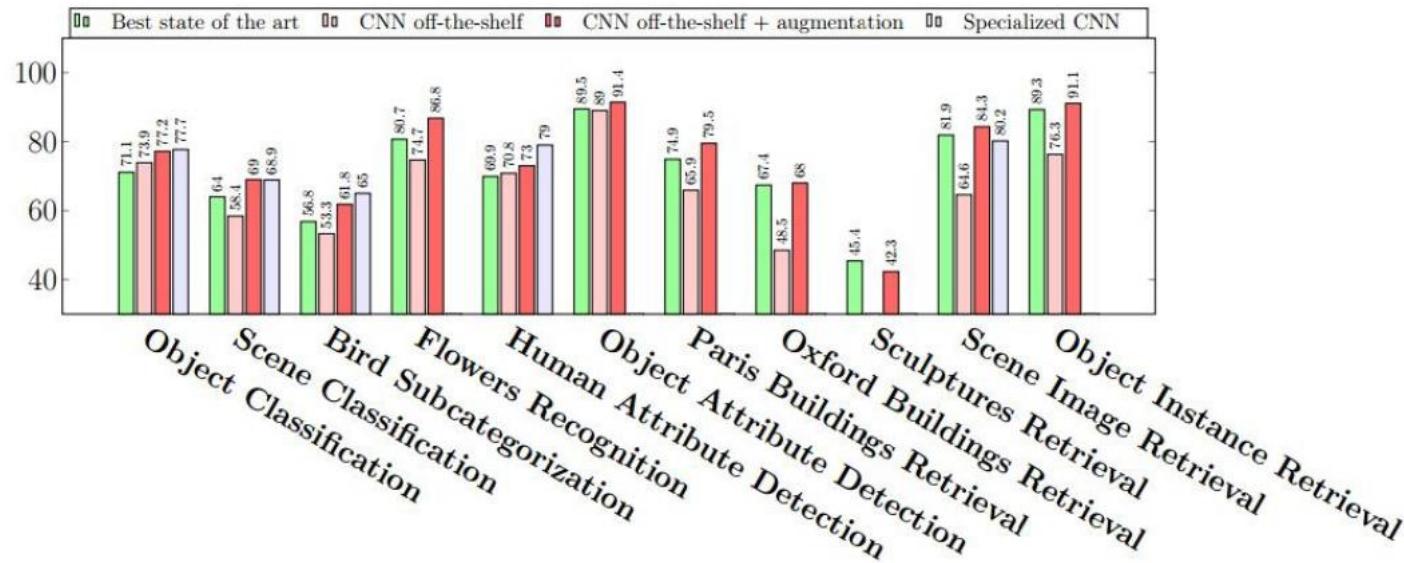
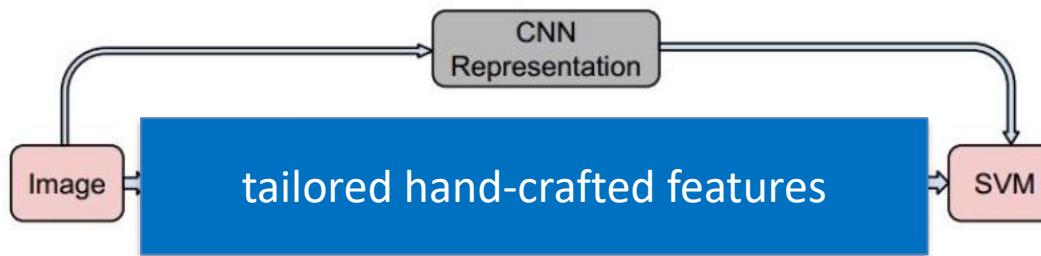
4096 feature

Fetch this CNN feature vector for each image

Are VGG features useful?



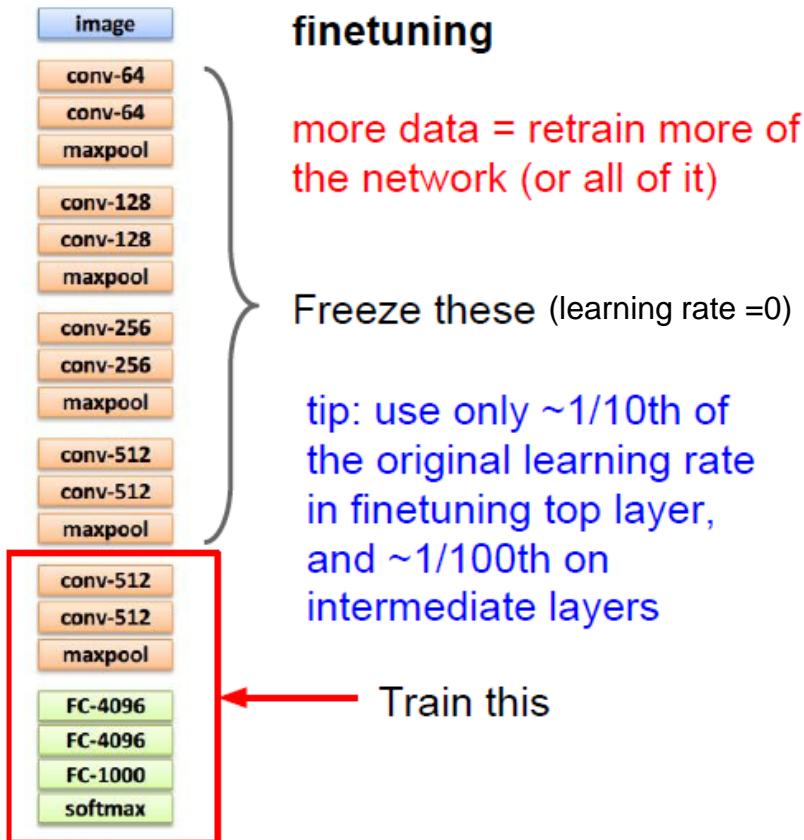
Performance of off-the-shelf CNN features when compared to tailored hand-crafted features



“Astonishingly, we report consistent superior results compared to the highly tuned state-of-the-art systems in all the visual classification tasks on various datasets.”

Transfer learning beyond using off-shelf CNN feature

e.g. medium data set (<1M images)



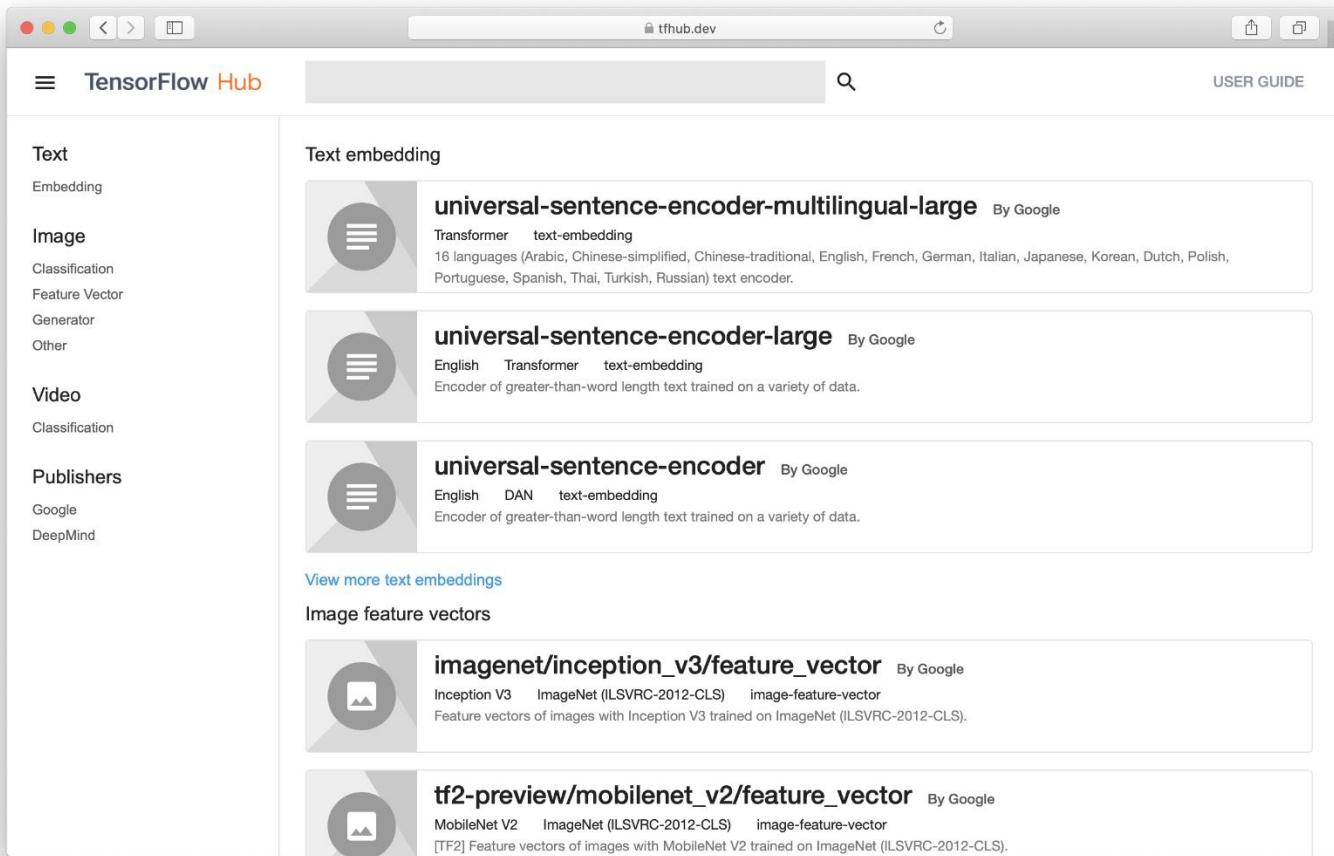
The strategy for fine-tuning depends on the size of the data set and the type of images:

	Similar task (to imageNet challenge)	Very different task (to imageNet challenge)
little data	Extract CNN representation of one top fc layer and use these features to train an external classifier	You are in trouble - try to extract CNN representations from different stages and use them as input to new classifier
lots of data	Fine-tune a few layers including few convolutional layers	Fine-tune a large number of layers

Hint: first retrain only fully connected layer, only then add convolutional layers for fine-tuning.

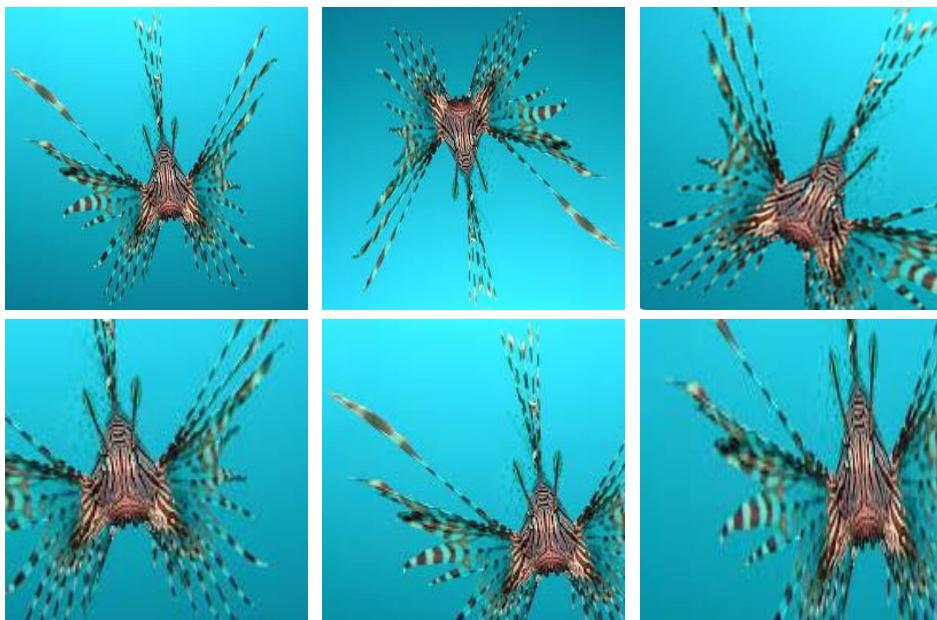
Where to find pretrained networks

- <https://tfhub.dev/>



Fighting overfitting by Data augmentation ("always" done): "generate more data" on the fly during fitting the model

- Rotate image within an angle range
- Flip image: left/right, up, down
- resize
- Take patches from images
-



Data augmentation in Keras:

```
from keras.preprocessing.image import ImageDataGenerator

datagen = ImageDataGenerator(
    rotation_range=10,
    width_shift_range=0.1,
    height_shift_range=0.1,
    horizontal_flip=True,
    vertical_flip=True,
    #zoom_range=[0.1,0.1]
)

train_generator = datagen.flow(
    x = X_train_new,
    y = Y_train,
    batch_size = 128,
    shuffle = True)

history = model.fit_generator(
    train_generator,
    samples_per_epoch = X_train_new.shape[0],
    epochs = 400,
    validation_data = (X_valid_new, Y_valid),
    verbose = 2, callbacks=[checkpointer]
)
```

Summary

- NNs are loosely inspired by the structure of the brain.
 - When going deep the receptive field increases (~layer 5 sees whole input)
 - Deeper layer respond to more complex feature in the input
- Trick of the trade to get deep CNN trained:
 - Stack enough layers and use small kernels (3x3)
 - Use dropout during training to avoid overfitting
 - Standardize your input data
 - Use batch-norm to get into the sweet-spot of the activation function (ReLU)
 - Use skip connections to avoid gradient vanishing
- We can/should visualize which parts in the image were important for the prediction
- In case of few data
 - use data augmentation
 - use a pretrained CNN (eg imageNet VGG) as feature extractor or for finetuning
 - Always use a simple baseline model (eg RF) as benchmark