

Machine Learning

Lecture *Machine Learning* vom 24.3.2022

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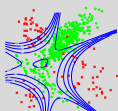


Image classification problem

Given an image - say 64×64 pixels with 3 color channels - predict a probability distribution over predefined classes e.g. *cat*, *dog*, *cow*, *plant*, One can then assign the image to the most likely class.

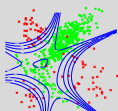


Image classification problem

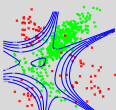
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Related problems

- Object detection
- Image segmentation
- Videos (i.e. timeseries of images) as input

A feature to classify a dog

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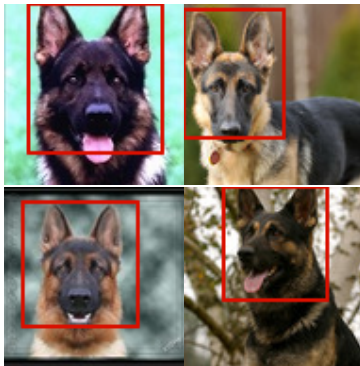
Convolutional Neural
Networks

Convolutional Layer

filter

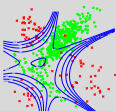


input images



Another feature to classify a dog

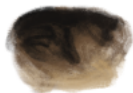
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Convolutional Neural
Networks

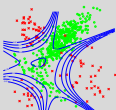
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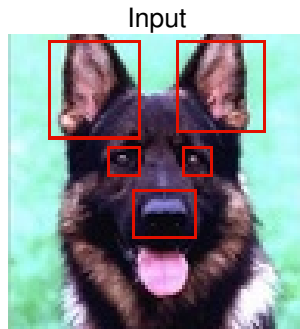


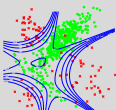
High- and low-level filters

The detection of complex high level filters depends on low-level filters.

Convolutional Neural
Networks

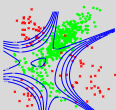
Convolutional Layer





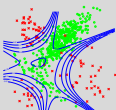
Problems with Fully Connected Artificial Neural Nets (only Dense layers)

- high number of parameters



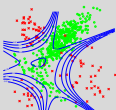
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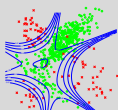
Problems with Fully Connected Artificial Neural Nets (only Dense layers)

- high number of parameters
- when images are input:
 - no notion of pixel neighborhoods
 - no translation invariance



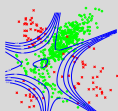
Idea of a CNN

- suppose we have K filters like in the previous slides



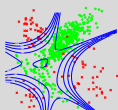
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- stacked layers can start with simple features (low-level) that contribute to the detection of more complex features (high-level)



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- each filter can detect some feature *somewhere* in the image
- stacked layers can start with simple features (low-level) that contribute to the detection of more complex features (high-level)
- prediction is based on the filters in the last layer

Cross-correlation (2-dimensional)

Definition 1

Let $A = (a_{ij})_{0 \leq i, j < m}$ be a square $m \times m$ -dimensional matrix and

$$B = (b_{ij})_{\substack{0 \leq i < h \\ 0 \leq j < w}}$$

be another matrix of shape $h \times w$.

The $h - m + 1 \times w - m + 1$ -dimensional matrix C with entries

$$c_{i,j} := \sum_{i'=0}^{m-1} \sum_{j'=0}^{m-1} a_{i',j'} \cdot b_{i+i',j+j'}$$

is the 2-dimensional **cross-correlation** of A and B . We write $C = A * B$.

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Example 2

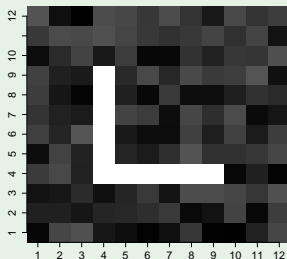
$m = 2$, $h = 4$, $w = 5$.

$$A = \begin{pmatrix} 1 & -1 \\ 2 & -3 \end{pmatrix} \quad B = \begin{pmatrix} 2 & -3 & 0 & 2 & -1 \\ 0 & 1 & 4 & 0 & 1 \\ 2 & -2 & 7 & 3 & 0 \\ -1 & 0 & 1 & 0 & 4 \end{pmatrix} \quad C = \begin{pmatrix} 2 & -13 & 6 & 0 \\ 9 & -28 & 9 & 5 \\ 2 & -12 & 6 & -9 \end{pmatrix}$$

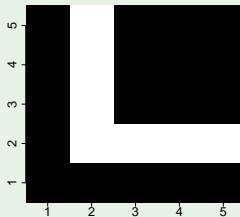
Cross-Correlation of an Image

$$\begin{pmatrix} 0.56 & 0.54 & 0.59 & 0.41 & 0.56 & 0.54 & 0.45 & 0.50 & 0.44 & 0.58 & 0.44 & 0.54 \\ 0.48 & 0.42 & 0.53 & 0.48 & 0.53 & 0.46 & 0.42 & 0.52 & 0.60 & 0.52 & 0.56 & 0.52 \\ 0.40 & 0.56 & 0.56 & 0.42 & 0.51 & 0.55 & 0.58 & 0.47 & 0.55 & 0.53 & 0.51 & 0.57 \\ 0.40 & 0.44 & 0.58 & 1.00 & 0.51 & 0.47 & 0.51 & 0.43 & 0.54 & 0.48 & 0.56 & 0.46 \\ 0.53 & 0.42 & 0.58 & 1.00 & 0.59 & 0.55 & 0.56 & 0.43 & 0.57 & 0.52 & 0.53 & 0.52 \\ 0.44 & 0.53 & 0.45 & 1.00 & 0.51 & 0.43 & 0.43 & 0.53 & 0.49 & 0.42 & 0.52 & 0.57 \\ 0.41 & 0.51 & 0.53 & 1.00 & 0.46 & 0.43 & 0.54 & 0.42 & 0.57 & 0.42 & 0.53 & 0.53 \\ 0.43 & 0.49 & 0.49 & 1.00 & 0.48 & 0.46 & 0.56 & 0.48 & 0.50 & 0.54 & 0.56 & 0.57 \\ 0.45 & 0.49 & 0.44 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 0.46 & 0.59 & 0.58 \\ 0.59 & 0.45 & 0.50 & 0.48 & 0.48 & 0.60 & 0.46 & 0.41 & 0.46 & 0.55 & 0.57 & 0.40 \\ 0.56 & 0.48 & 0.45 & 0.57 & 0.55 & 0.49 & 0.48 & 0.45 & 0.47 & 0.50 & 0.58 & 0.43 \\ 0.41 & 0.48 & 0.44 & 0.54 & 0.43 & 0.55 & 0.52 & 0.54 & 0.55 & 0.43 & 0.53 & 0.59 \end{pmatrix}$$

“filter” A



input image B



$$\begin{pmatrix} -1 & 4 & -1 & -1 & -1 \\ -1 & 4 & -1 & -1 & -1 \\ -1 & 4 & -1 & -1 & -1 \\ -1 & 4 & 4 & 4 & 4 \\ -1 & -1 & -1 & -1 & -1 \end{pmatrix}$$

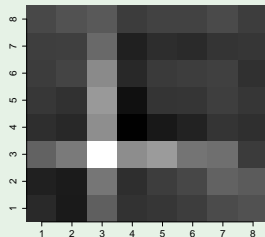
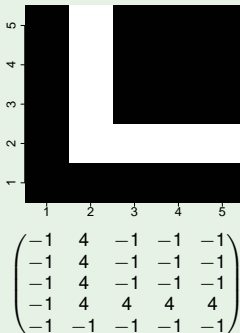
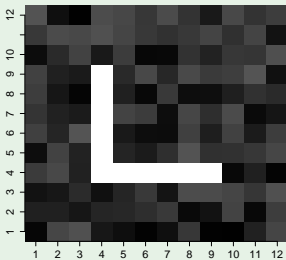
output image

$$C = A * B$$

Cross-Correlation of an Image

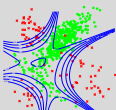
$$\begin{pmatrix} 0.56 & 0.54 & 0.59 & 0.41 & 0.56 & 0.54 & 0.45 & 0.50 & 0.44 & 0.58 & 0.44 & 0.54 \\ 0.48 & 0.42 & 0.53 & 0.48 & 0.53 & 0.46 & 0.42 & 0.52 & 0.60 & 0.52 & 0.56 & 0.52 \\ 0.40 & 0.56 & 0.56 & 0.42 & 0.51 & 0.55 & 0.58 & 0.47 & 0.55 & 0.53 & 0.51 & 0.57 \\ 0.40 & 0.44 & 0.58 & 1.00 & 0.51 & 0.47 & 0.51 & 0.43 & 0.54 & 0.48 & 0.56 & 0.46 \\ 0.53 & 0.42 & 0.58 & 1.00 & 0.59 & 0.55 & 0.56 & 0.43 & 0.57 & 0.52 & 0.53 & 0.52 \\ 0.44 & 0.53 & 0.45 & 1.00 & 0.51 & 0.43 & 0.43 & 0.53 & 0.49 & 0.42 & 0.52 & 0.57 \\ 0.41 & 0.51 & 0.53 & 1.00 & 0.46 & 0.43 & 0.54 & 0.42 & 0.57 & 0.42 & 0.53 & 0.53 \\ 0.43 & 0.49 & 0.49 & 1.00 & 0.48 & 0.46 & 0.56 & 0.48 & 0.50 & 0.54 & 0.56 & 0.57 \\ 0.45 & 0.49 & 0.44 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 1.00 & 0.46 & 0.59 & 0.58 \\ 0.59 & 0.45 & 0.50 & 0.48 & 0.48 & 0.60 & 0.46 & 0.41 & 0.46 & 0.55 & 0.57 & 0.40 \\ 0.56 & 0.48 & 0.45 & 0.57 & 0.55 & 0.49 & 0.48 & 0.45 & 0.47 & 0.50 & 0.58 & 0.43 \\ 0.41 & 0.48 & 0.44 & 0.54 & 0.43 & 0.55 & 0.52 & 0.54 & 0.55 & 0.43 & 0.53 & 0.59 \end{pmatrix}$$

“filter” A



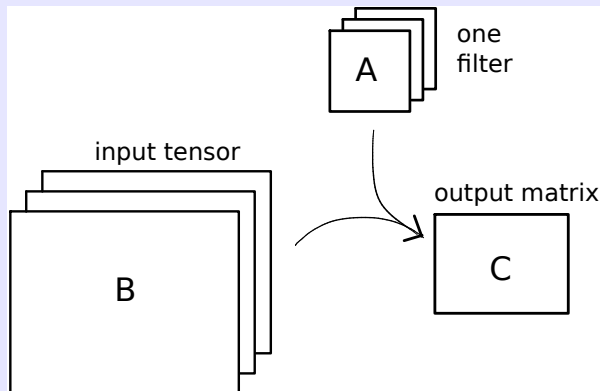
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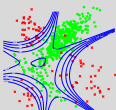
$$\begin{pmatrix} 6.6 & 7.4 & 5.0 & 4.19 & 4.7 & 4.3 & 4.7 & 5.2 \\ 6.2 & 7.9 & 8.8 & 4.56 & 5.3 & 5.4 & 4.6 & 6.2 \\ 5.2 & 5.9 & 9.2 & 3.27 & 4.6 & 5.2 & 3.8 & 5.6 \\ 4.7 & 5.2 & 12.1 & 2.57 & 4.6 & 5.0 & 4.0 & 5.5 \\ 4.4 & 4.1 & 11.0 & 0.85 & 2.0 & 3.7 & 3.1 & 5.1 \\ 7.7 & 9.3 & 19.3 & 11.13 & 11.9 & 10.8 & 8.4 & 7.2 \\ 2.7 & 2.7 & 9.6 & 3.69 & 4.4 & 5.7 & 5.4 & 6.7 \\ 3.7 & 3.1 & 7.9 & 4.14 & 4.8 & 5.2 & 5.3 & 6.0 \end{pmatrix}$$



3-dimensional input

- Want to
 - 1 use multiple filters in parallel and
 - 2 stack several (convolutional) layers.
- Also, color images are naturally encoded as 3-dimensional (each pixel has a red, green and blue value).
- Solution: Define convolution for 3-dimensional tensor input as well.





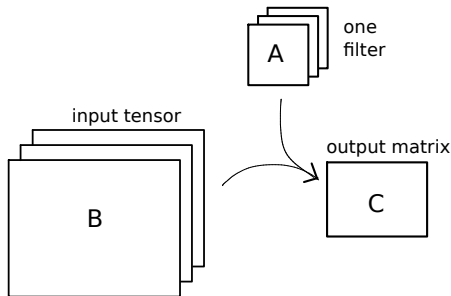
3-dimensional cross-correlation

Let $B = (b_{ijk})_{\substack{0 \leq i < h \\ 0 \leq j < w \\ 0 \leq k < d}}$ be a tensor of shape $h \times w \times d$ and

let $A = (a_{ijk})_{\substack{0 \leq i, j < m \\ 0 \leq k < d}}$ be another tensor ("filter").

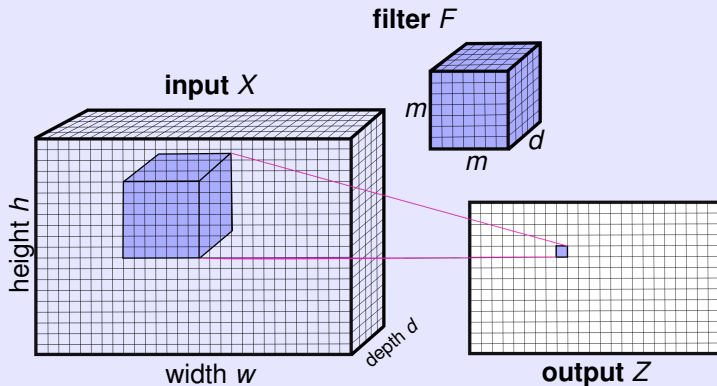
The **cross-correlation** of A and B is then the $h - m + 1 \times w - m + 1$ -dimensional matrix $C = A * B$ with entries

$$c_{i,j} := \sum_{i'=0}^{m-1} \sum_{j'=0}^{m-1} \sum_{k=0}^{d-1} a_{i',j',k} \cdot b_{i+i',j+j',k}.$$



Deep Learning for Computer Vision

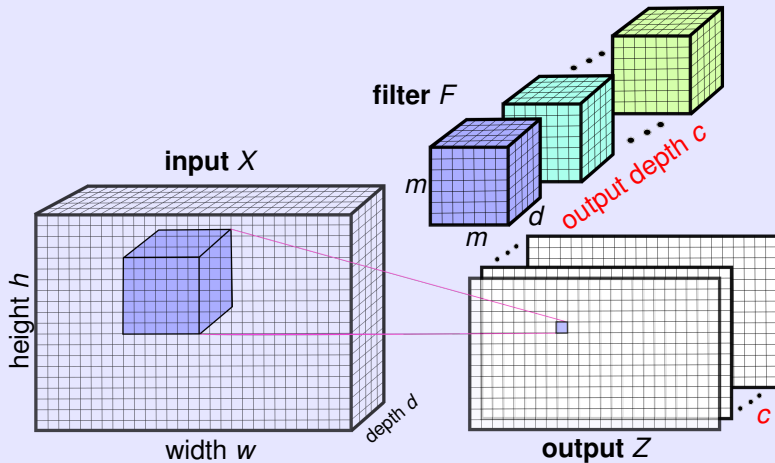
Convolutional Layer



$$Z_{i,j} = \sum_{i'=0}^{m-1} \sum_{j'=0}^{m-1} \sum_{k=0}^{d-1} X_{i+i', j+j', k} \cdot f_{i', j', k}$$

Deep Learning for Computer Vision

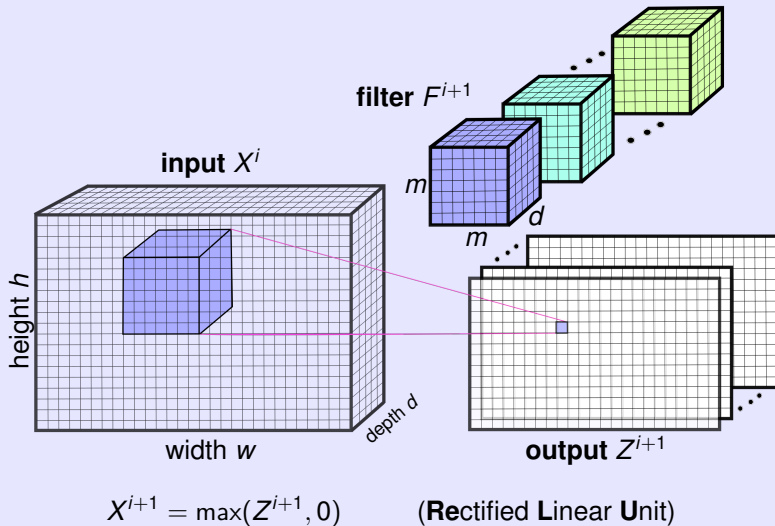
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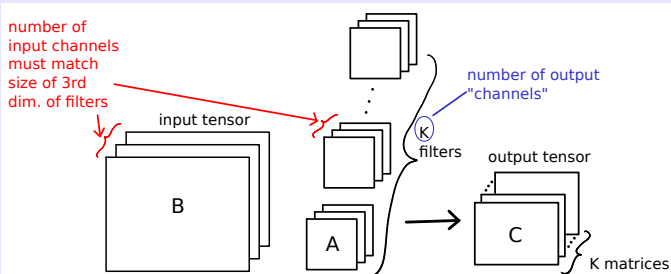
$$Z_{i,j,r} = \sum_{i'=0}^{m-1} \sum_{j'=0}^{m-1} \sum_{k=0}^{d-1} x_{i+i',j+j',k} \cdot f_{i',j',k,r} + \underset{\text{bias}}{b_r}$$

Deep Learning for Computer Vision

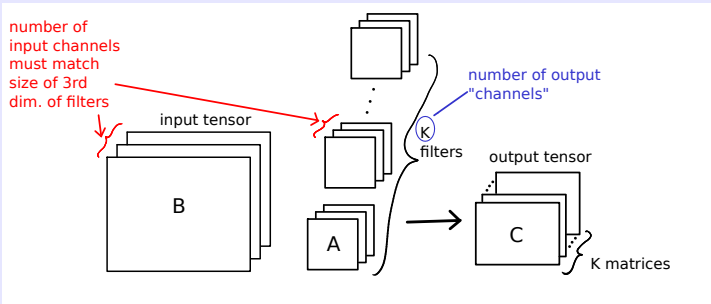
Convolutional Layer



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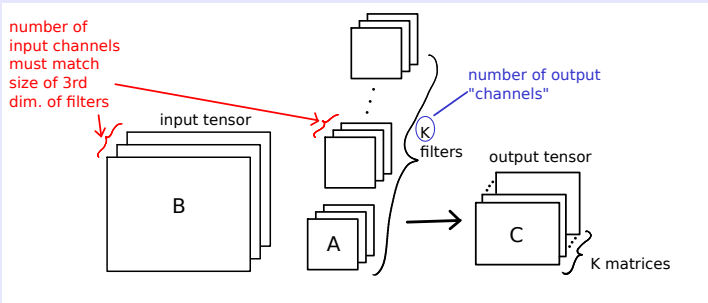


Convolutional Layer



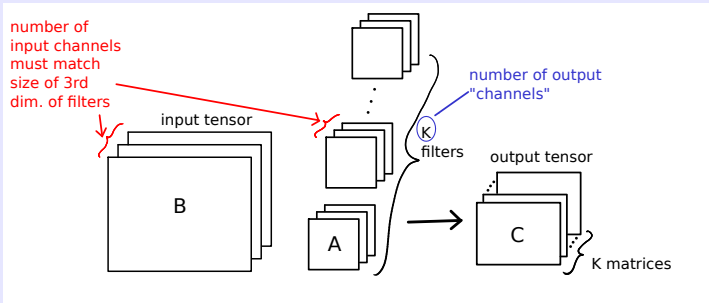
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Convolutional Layer



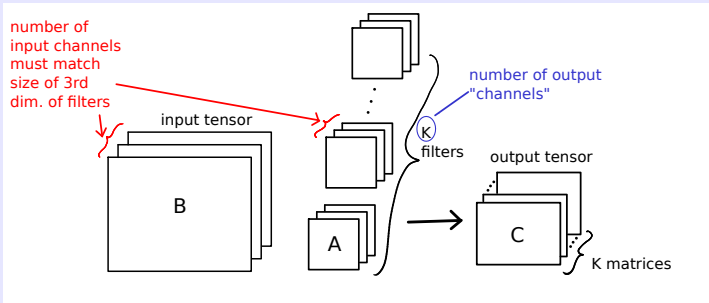
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- Stride (Schrittweite) s : Skip $s - 1$ positions in each direction when 'sliding' A over $B \Rightarrow$ decreases output layer size up to a factor of s^2 .

Convolutional Layer



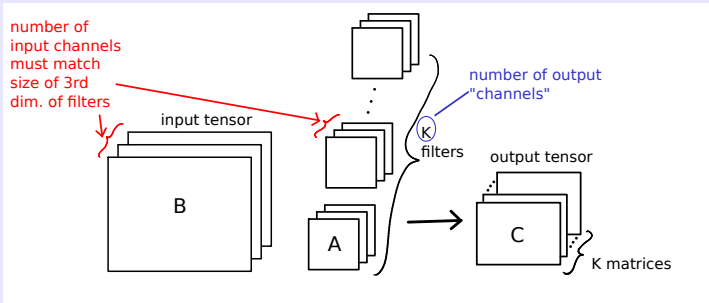
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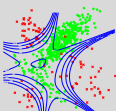


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- Convolution is a special case of a fully-connected layer, in which certain parameters are shared (*parameter sharing*).
- Output neurons of convolution can detect lower-level features like ("lower left corner", "pupil") and be combined in deeper layers.

Convolutional Neural
Networks

Convolutional Layer

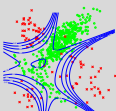
Pooling-Layers

Max-Pooling (`tf.keras.layers.MaxPool2D`)

- similar to a convolutional layer
- requires a `pool_size` m like the filter size
- does not have any parameters
- computes output

$$Z_{i,j,r} = \max_{\substack{i' \in [0, m) \\ j' \in [0, m)}} X_{s \cdot i + i', s \cdot j + j', r}$$

- is usually applied with a **stride** $s \geq 2$ and therefore reduces height and width
- often $s = m$, can have different strides for each dimension
- intuition:

Convolutional Neural
Networks

Convolutional Layer

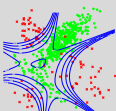
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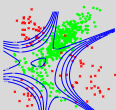
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With an analogous definition, **average pooling** *averages* over regions of size $m \times m$, but is used less often.

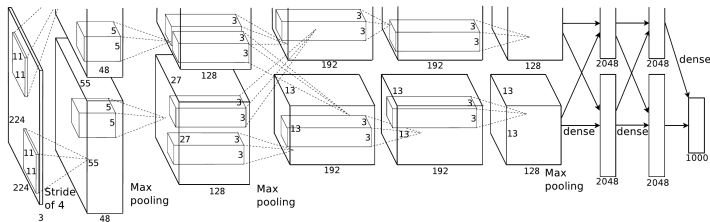
Convolutional Neural
Networks

Convolutional Layer

Multi-Layered CNN example

Photo classification

- CNN from 2012 (“AlexNet”)
- classification into 1000 categories



Alex Krizhevsky, Ilya Sutskever and Geoffrey Hinton, "ImageNet Classification with Deep Convolutional Neural Networks", NIPS, 2012