technische universität dortmund

# Computational Intelligence

**Winter Term 2025/26**

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## Plan for Today



- Deep Neural Networks
  - Model
  - Training
- Convolutional Neural Networks
  - Model
  - Training



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## Deep Neural Networks (DNN)



DNN = Neural Network with > 3 layers

we know: L = 3 layers in MLP sufficient to describe arbitrary sets

**What can be achieved by more than 3 layers?**

information stored in weights of edges of network
→ more layers → more neurons → more edges → more information storable

**Which additional information storage is useful?**

traditionally : handcrafted features fed into 3-layer perceptron
modern viewpoint : let L-k layers learn the feature map, last k layers separate!

advantage:
human expert need not design features manually for each application domain

⇒ no expert needed, only observations!



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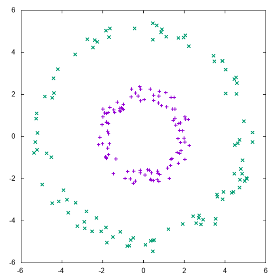
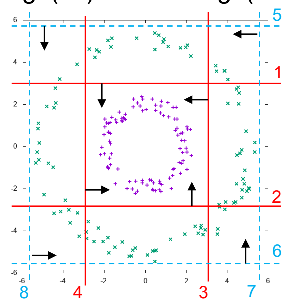
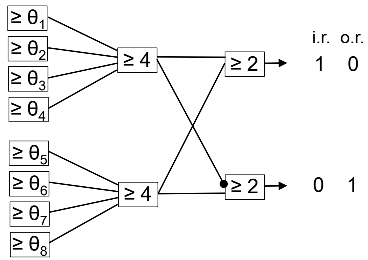
## Deep Neural Networks (DNN)



**example:** separate 'inner ring' (i.r.) / 'outer ring' (o.r.) / 'outside'






⇒ MLP with 3 layers and 12 neurons

**Is there a simpler way?**

observations $(x, y) \in \mathbb{R}^n \times \mathbb{B}$ feature map $F(x) = (F_1(x), \ldots, F_m(x)) \in \mathbb{R}^m$

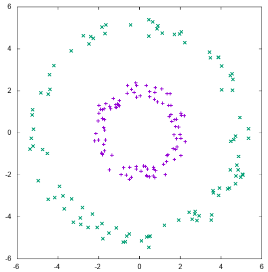
feature = measurable property of an observation or
numerical transformation of observed value(s)

⇒ find MLP on transformed data points (F(x), y)

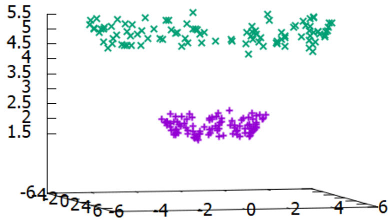
## Deep Neural Networks (DNN) — Lecture 13

**example:** separate ‘inner ring‘ / ‘outer ring‘

- feature map $F(x) = (x_1, x_2, \sqrt{x_1^2 + x_2^2}) \in \mathbb{R}^3$

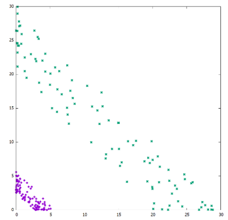


2D → 3D



- feature map $F(x) = (x_1^2, x_2^2) \in \mathbb{R}^2$

$x_1^2$, $x_2^2$ → $\boxed{\theta \geq 9}$ → $\begin{cases} 1: \text{outer} \\ 0: \text{inner} \end{cases}$





## Deep Neural Networks (DNN) — Lecture 13

**but:** how to find useful features?

→ typically designed by experts with domain knowledge

→ traditional approach in classification:
1. design & select appropriate features
2. map data to feature space
3. apply classification method to data in feature space

**modern approach via DNN:** learn feature map and classification simultaneously!

$x \rightarrow \underbrace{\boxed{\text{L – k layers}}}_{\text{feature map}} \rightarrow \underbrace{\boxed{\text{k layers}}}_{\text{classifier}} \rightarrow \hat{y}$

**proven:** MLP can approximate any continuous map with arbitrary accuracy



## Deep Multi-Layer Perceptrons — Lecture 13

**contra:**
- danger: overfitting
  → need larger training set (expensive!)
  → optimization needs more time
- response landscape changes
  → more sigmoidal activiations
  → gradient vanishes
  → small progress in learning weights

**countermeasures:**
- regularization / dropout
  → data augmentation
  → parallel hardware (multi-core / GPU)
- not necessarily bad
  → change activation functions
  → gradient does not vanish
  → progress in learning weights

**vanishing gradient:** (underlying principle)

forward pass $y = f_3(f_2(f_1(x;\, w_1);\, w_2);\, w_3)$ $\qquad f_i \approx$ activation function

backward pass $(f_3(f_2(f_1(x;\, w_1);\, w_2);\, w_3))' =$
$f_3'(f_2(f_1(x;w_1);w_2);w_3) \cdot f_2'(f_1(x;w_1);w_2) \cdot f_1'(x;w_1)$ ***chain rule!***

→ repeated multiplication of values in (0,1) → 0

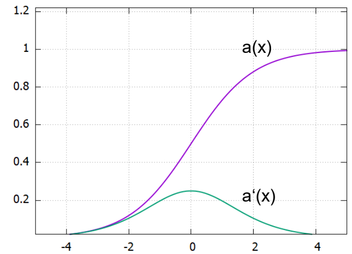


## Deep Multi-Layer Perceptrons — Lecture 13

**vanishing gradient:** $a(x) = \dfrac{e^x}{e^x + 1} = \dfrac{1}{1 + e^{-x}} \quad \rightarrow \quad a'(x) = a(x) \cdot (1 - a(x))$

$\forall x \in \mathbb{R}: \; a(x) \cdot (1 - a(x)) \leq \dfrac{1}{4} \;\Leftrightarrow\; \left(a(x) - \dfrac{1}{2}\right)^2 \geq 0$ ☑

$\Rightarrow$ gradient $a'(x) \in [0, \frac{1}{4}]$




principally: desired property in learning process!
if weights stabilize such that neuron almost always either fires [i.e., a(x) ≈ 1] or not fires [i.e., a(x) ≈ 0] then gradient ≈ 0 and the weights are hardly changed

⇒ leads to convergence in the learning process!

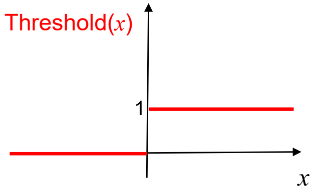
while learning, updates of weights via partial derivatives:

$$\frac{\partial f(w,u;x,z^*)}{\partial w_{ij}} = 2 \sum_{k=1}^{K} [a(u_k' y) - z_k^*] \cdot \underbrace{a'(u_k' y)}_{\leq \frac{1}{4}} \cdot u_{jk} \cdot \underbrace{a'(w_j' x)}_{\leq \frac{1}{4}} \cdot x_i \qquad \text{(L= 2 layers)}$$

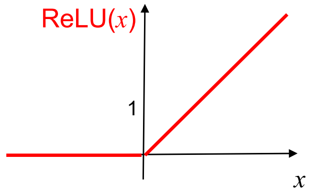
⇒ in general $f_{w_{ij}} = O(4^{-L}) \rightarrow 0$ as $L\uparrow$ $\qquad L \leq 3$: effect neglectable; but $L \gg 3$ ☒

## non-sigmoid activation functions

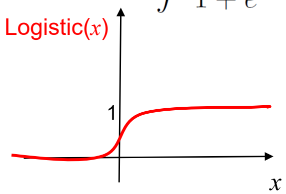
$$\int \mathbb{1}_{[x\geq 0]}(x)\,dx = \left\{ \begin{array}{ll} 0 & \text{if } x<0 \\ x & \text{if } x \geq 0 \end{array} \right\} = \max\{0,x\} = \text{ReLU}(x)$$



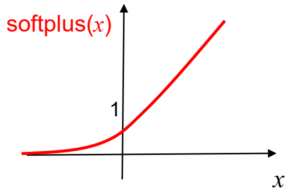

$\Rightarrow$




$$\int \frac{e^x}{1+e^x}\,dx = \log(1+e^x) = \text{softplus}(x)$$




$\Rightarrow$








## dropout

- applied for regularization (against overfitting)
- can be interpreted as inexpensive approximation of **bagging**

↓

aka: bootstrap aggregating, model averaging, ensemble methods

create k training sets by drawing with replacement
train k models (with own exclusive training set)
combine k outcomes from k models (e.g. majority voting)

- parts of network are effectively switched off
  e.g. multiplication of outputs with 0,
  e.g. use inputs with prob. 0.8 and inner neurons with prob. 0.5
- gradient descent on switching parts of network
  → artificial perturbation of greediness during gradient descent
- can reduce computational complexity if implemented sophistically





## data augmentation (counteracts overfitting)

→ extending training set by slightly perturbed true training examples

- best applicable if inputs are **images**: translate, rotate, add noise, resize, …


original image


rotated


resized


noisy


noisy + rotated

- if x is **real vector** then adding e.g. small gaussian noise
  → here, utility disputable (artificial sample may cross true separating line)

**extra costs** for acquiring additional annotated data are **inevitable**!





## stochastic gradient descent

- partitioning of training set B into **(mini-) batches** of size b

| traditionally: 2 extreme cases | | now: |
|---|---|---|
| update of weights | | update of weights |
| - after each training example | b = 1 | - after b training examples where 1 < b < \|B\| |
| - after all training examples | b = \|B\| | |

- search in subspaces → counteracts greediness → better generalization
- accelerates optimization methods (parallelism possible)

**choice of batch size b**
b large ⇒ better approximation of gradient
b small ⇒ better generalization

b also depends on available hardware
b too small ⇒ multi-cores underemployed

often b ≈ 100 (empirically)

## cost functions

- *regression*

  N training samples $(x_i, y_i)$

  insist that $f(x_i;\ \theta) = y_i$ for i=1,…, N

  if $f(x;\ \theta)$ linear in $\theta$ then $\theta^T x_i = y_i$ for i=1,…, N or $X\,\theta = y$

  ⇒ best choice for $\theta$: least square estimator (LSE)

  ⇒ $(X\,\theta - y)^T (X\,\theta - y) \to \min\limits_{\theta}!$

  in case of MLP: $f(x;\ \theta)$ is <u>nonlinear</u> in $\theta$

  ⇒ best choice for $\theta$: (nonlinear) least square estimator; aka TSSE

  ⇒ $\sum\limits_i (f(x_i;\ \theta) - y_i)^2 \to \min\limits_{\theta}!$





## cost functions

- *classification*

  N training samples $(x_i, y_i)$ where $y_i \in \{ 1, \dots, C \}$, C = #classes

  → want to estimate probability of different outcomes for unknown sample

  → decision rule: choose class with highest probability (given the data)

  <u>idea</u>: use maximum likelihood estimator (MLE)

  = estimate unknown parameter $\theta$ such that likelihood of sample $x_1, \dots, x_N$ gets maximal as a function of $\theta$

  <u>likelihood function</u>

  $$L(\theta; x_1, \dots, x_N) := f_{X_1,\dots,X_N}(x_1, \dots, x_N; \theta) = \prod_{i=1}^{N} f_X(x_i; \theta) \to \max_{\theta}!$$





**here**: random variable $X \in \{1, \dots, C\}$ with $P\{ X = i \} = q_i$ (true, but unknown)

→ we use relative frequencies of training set $x_1, \dots, x_N$ as estimator of $q_i$

$$\hat{q}_i = \frac{1}{N} \sum_{j=1}^{N} \mathbb{1}_{[x_j = i]}$$ ⇒ there are $N \cdot \hat{q}_i$ samples of class $i$ in training set

⇒ the neural network should output $\hat{p}$ as close as possible to $\hat{q}$ ! [actually: to q]

likelihood $L(\hat{p}; x_1, \dots, x_N) = \prod\limits_{k=1}^{N} P\{X_k = x_k\} = \prod\limits_{i=1}^{C} \hat{p}_i^{N\cdot\hat{q}_i} \to \max!$

$$\log L = \log \left( \prod_{i=1}^{C} \hat{p}_i^{N\cdot\hat{q}_i} \right) = \sum_{i=1}^{C} \log \hat{p}_i^{N\cdot\hat{q}_i} = N \underbrace{\sum_{i=1}^{C} \hat{q}_i \cdot \log \hat{p}_i}_{-H(\hat{q},\hat{p})} \to \max!$$

⇒ maximizing $\log L$ leads to same solution as minimizing **cross-entropy** $H(\hat{q}, \hat{p})$





in case of *classification*

use softmax function $P\{y = j \,|\, x\} = \dfrac{e^{w_j^T x + b_j}}{\sum_{i=1}^{C} e^{w_i^T x + b_i}}$ in output layer

→ multiclass classification: probability of membership to class j = 1, …, C

→ class with maximum excitation w'x+b has maximum probabilty

→ decision rule: element x is assigned to class with maximum probability

## Convolutional Neural Networks (CNN)

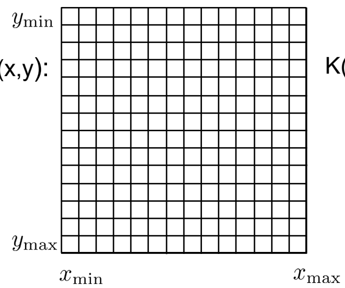


most often used in graphical applications (2-D input; also possible: k-D tensors)

**layer of CNN = 3 stages**

1. convolution
2. nonlinear activation (e.g. ReLU)
3. pooling

I(x,y):




K(i,j):

| | $-\delta$ | | $\delta$ | |
|---|---|---|---|---|
| | -1 | -2 | -1 | $-\delta$ |
| | 1 | 1 | 1 | |
| | -2 | 1 | -2 | $\delta$ |

example

**1. Convolution**

local filter / kernel K(i, j) applied to each cell of image I(x, y)

$$S(x,y) = (K * I)(x,y) = \sum_{i=-\delta}^{\delta} \sum_{j=-\delta}^{\delta} I(x+i, y+j) \cdot K(i,j)$$

ranges:
- without padding: $x = x_{\min} + \delta, \ldots, x_{\max} - \delta,\ y = y_{\min} + \delta, \ldots, y_{\max} - \delta$



## Convolutional Neural Networks (CNN)



**example:** edge detection with Sobel kernel

→ two convolutions

$$K_x = \begin{pmatrix} -1, & 0, & 1 \\ -2, & 0, & 2 \\ -1, & 0, & 1 \end{pmatrix} \quad K_y = \begin{pmatrix} -1, & -2, & -1 \\ 0, & 0, & 0 \\ 1, & 2, & 1 \end{pmatrix}$$

yields $S_x$ yields $S_y$

$$S(x,y) = \sqrt{S_x(x,y)^2 + S_y(x,y)^2}$$

original image I(x,y)

image S(x,y) after convolution



## Convolutional Neural Networks



**filter / kernel**

well known in image processing; typically hand-crafted!

<u>here:</u> values of filter matrix learnt in CNN !

actually: many filters active in CNN

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

e.g. horizontal line detection

**stride**

= distance between two applications of a filter (horizontal $s_h$ / vertical $s_v$)

→ leads to smaller images if $s_h$ or $s_v > 1$

**padding**

= treatment of border cells if filter does not fit in image

- “valid“ : apply only to cells for which filter fits → leads to smaller images
- “same“ : add rows/columns with zero cells; apply filter to all cells (→ same size)



## Convolutional Neural Networks



**2. nonlinear activation**

a(x) = ReLU($x^T$ W + c)

**3. pooling**

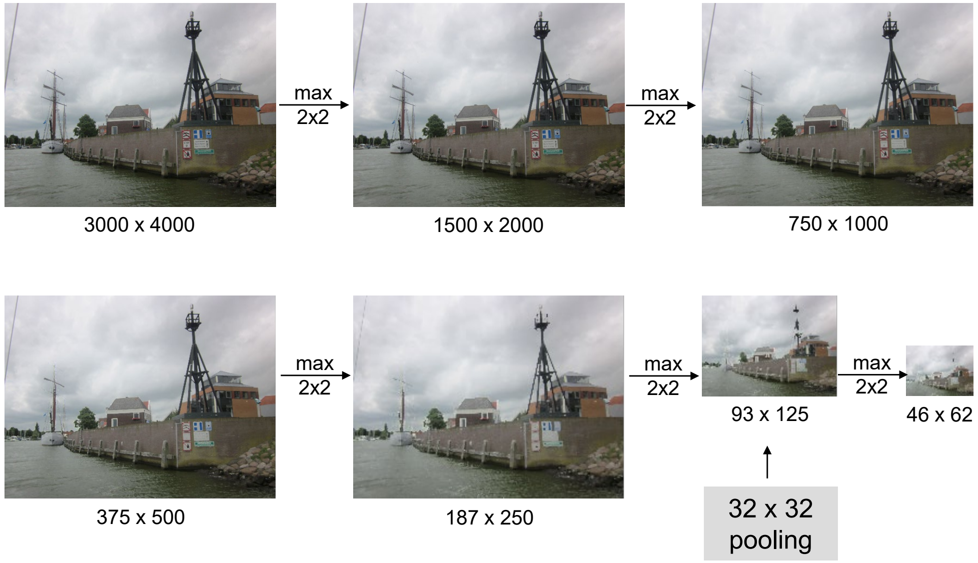
in principle: summarizing statistic of nearby outputs

e.g. **max-pooling** m(i,j) = max( I(i+a, j+b) : a,b = -δ, …, 0, … δ ) for δ > 0

- also possible: mean, median, matrix norm, …

- can be used to reduce matrix / output dimensions

**example:** max-pooling 2x2 (iterated), stride = 2





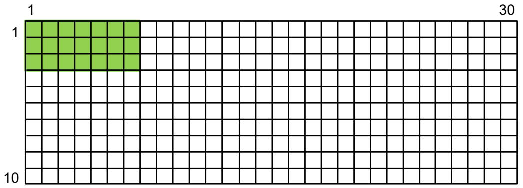



**Pooling with Stride**

$c_{in}$ : columns of input
$r_{in}$ : rows of input
$f_c$ : columns of filter
$f_r$ : rows of filter
$s_c$ : stride for columns
$s_r$ : stride for rows

image size : $r_{in} \times c_{in}$
filter size : $f_r \times f_c$

<u>assumptions:</u>
$f_c \le c_{in}$
$f_r \le f_{in}$
**`padding = valid`**




How often fits the filter in image horizontally?

$pos_1 = 1$
$pos_2 = pos_1 + s_c$
$pos_3 = pos_2 + s_c = (pos_1 + s_c) + s_c = pos_1 + 2 \cdot s_c$
$\vdots$
$pos_k = pos_1 + (k-1) \cdot s_c$

thus, find largest k such that

$$pos_1 + (k-1) \cdot s_c + (f_c - 1) \le c_{in}$$
$$\Leftrightarrow \quad (k-1) \cdot s_c + f_c \le c_{in}$$
$$\Leftrightarrow \quad k \le (c_{in} - f_c) / s_c + 1 \qquad \text{(integer division!)}$$

$$\Rightarrow \quad k = \left\lfloor \frac{c_{in} - f_c}{s_c} \right\rfloor + 1 = c_{out}$$

[ analog reasoning for rows! ]

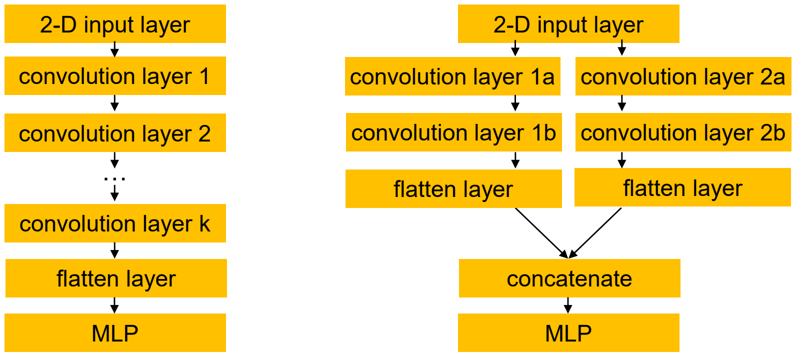




**CNN architecture:**

- several consecutive convolution layers (also parallel streams); possibly dropouts
- flatten layer (→ converts k-D matrix to 1-D matrix required for MLP input layer)
- fully connected MLP

**examples:**







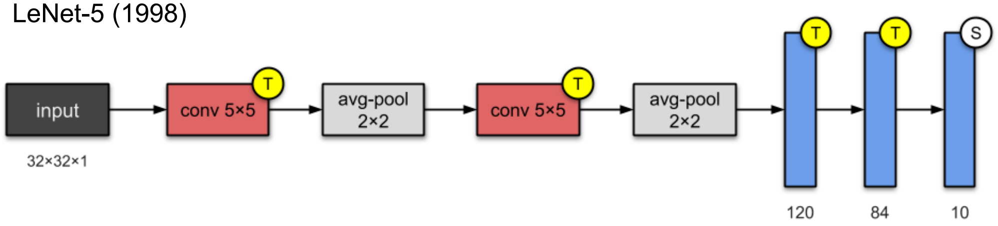

**Popular CNN Architectures** `https://towardsdatascience.com`

| Name | Year | Depth | #Params |
|---|---|---|---|
| LeNet | 1998 | | |
| AlexNet | 2012 | | > 60 M |
| VGG16 | 2014 | 23 | > 23 M |
| Inception-v1 | 2014 | | |
| ResNet50 | 2014 | | > 25 M |
| Inception-v3 | 2015 | 159 | |
| Xception | 2016 | 126 | > 22 M |
| InceptionResNet | 2017 | 572 | > 55 M |
| … | | | |

## Popular CNN Architectures

https://towardsdatascience.com

LeNet-5 (1998)




T = tanh
S = softmax

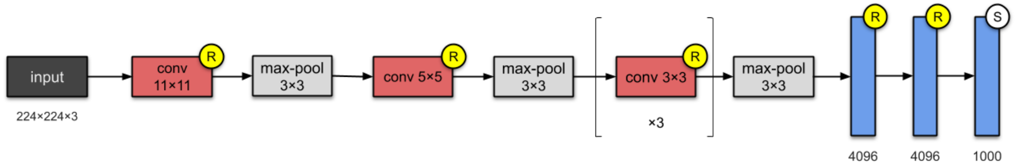




## Popular CNN Architectures

https://towardsdatascience.com

AlexNet (2012)




T = tanh
R = ReLU
S = softmax

Used dropout

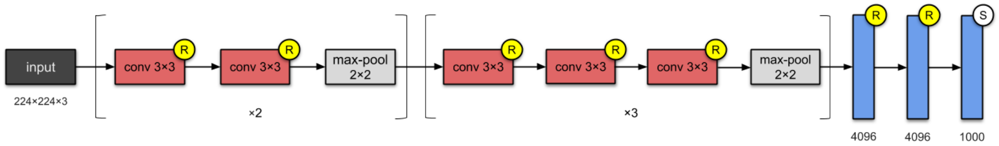




## Popular CNN Architectures

https://towardsdatascience.com

VGG-16 (2014)




T = tanh
R = ReLU
S = softmax

Deeper than AlexNet