Introduction to Artificial Neural Networks and Deep Learning

18. February, ACLS ZHAW Life Sciences

Organisation (ACLS Module Description)

- "Neural Networks and Deep Learning" Module of the Master in "Applied Computational Life Sciences"
- 2 h lectures a week, 1 h exercises a week
  60 h: 28 h contact lessons; 14 h guided exercises; 18 h self-study
- Lectures (30%)
  Guided exercises (20%)
  Self-study (50%)
- The course requires a solid background in mathematics, as usually taught at the Bachelor's level, especially in:
  - statistics
  - probability theory
  - basic linear algebra
- The module and associated practical exercises will be taught using Python and Keras/Tensorflow (Tensorflow 2) for Python.
  Familiarity with basic programming in Python is required.
- Written exam (no computer) (70%)
  Graded **group work** (30%)
- New lecture notes! (please report mistakes, etc.)

Learning Outcomes (ACLS Module Description)

The objective of the module is to provide the students with a working knowledge of current artificial neural network (ANN) and deep learning (DL) techniques and apply them to problems in the field of life sciences.
After completing the module, students will be able to:

1. judge on the advantages and disadvantages of different ANN and DL architectures and corresponding applications
2. adapt and apply suitable ANN and DL techniques to problems in life sciences
3. learn about new methods in the field on their own
4. reflect the usage of ANN and DL in a life sciences context.

Learning Outcomes

This course is pretty standard, but deems important to:

1. know about the background of ANN & DL,
2. get the basics (mathematics) right,
3. master Keras/Tensorflow and Python,
4. form an informed opinion on AI.

Timeline (provisional)

1. **18.2** Introduction: Motivation, Biological Foundations, The Concept of Learning, History
2. **25.2** The Mathematical Basics (Thomas Ott)
3. **3.3** The Mathematical Basics (Thomas Ott)
4. **10.3** The Perceptron I: Binary Classifiers, Learning Rule
5. **17.3** The Perceptron II: Gradient Descent, Tasks & Performance
6. **24.3** Multilayer Networks I, Intro to Deep Learning, Intro to Tensorflow 2
7. **31.4** Multilayer Networks II
8. **7.4** Multilayer Networks III
9. **14.4** Autoencoders, VAEs (Thomas Ott)
10. **21.4** Convolutional Networks
11. **28.4** GANs (Self-Study)
12. **5.5** Recurrent Networks & LSTM
13. **12.5** Natural Language Processing
14. **19.5** Philosophy & Ethics of AI
15. **26.5** Group work discussion

First Chapter: Learning Outcomes

After the first chapter

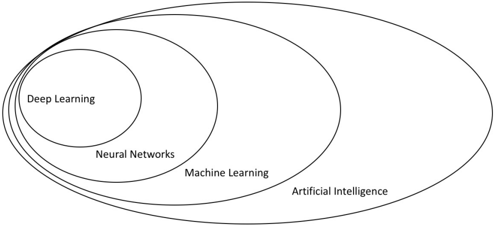
1. you know why the field of artificial neural networks matters and can tell this to others
2. you can explain the basic biological motivations and the historical background to the field
3. you can derive a first basic artificial neuron model
4. you know basic learning concepts and can point them out in real-word situations
5. you know and can name the main applications fields.

Motivation

1. Artificial neural networks (ANN) are biologically inspired computing systems.
2. Conventional computing systems: write fixed programs to solve a task
3. ANN can *learn* to solve a task:
   generate a program from data
   change the program given new data
   generalise to new cases
4. ANN are more flexible, adaptive and general than conventional computing systems.

What Is the Field of ANN?

- Intersection of many fields: computational neuroscience, cognitive science, artificial intelligence, computer science, software engineering, mathematics and physics.
- Overarchin

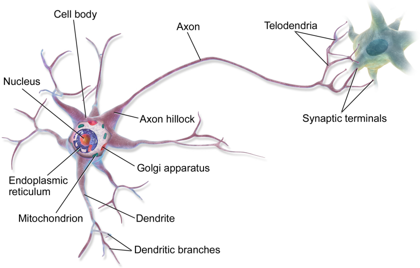


- Field of AI: long history.
  Nowadays: Thriving research field & and the big “tech companies” and many start-ups are dedicated to AI research/applications.

ANN and Biology

1. Understanding how biological or neural systems work can help to discover and design novel algorithms.
2. Brains are extremely good at difficult tasks like vision but e.g. perform poor in arithmetics: $31 \cdot 64 = ?$
3. The brain is difficult to study: complicated and living system
4. Theoretical models and computer simulations necessary to advance its understanding.

The Biological Neuron



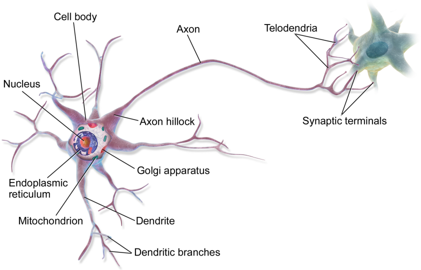
Anatomy

Neuron: specialized cell, basic computional and communication unit

Different types of neurons, usually consisting of a cell body, dendrites and a axon

- Axon: reaches from the cell body, via the axon hill, to other neurons
- Synapse: point of contact to dendrites
- Dendrites: usually branch multiple times, receiving inputs from a number of other neurons

The Biological Neuron



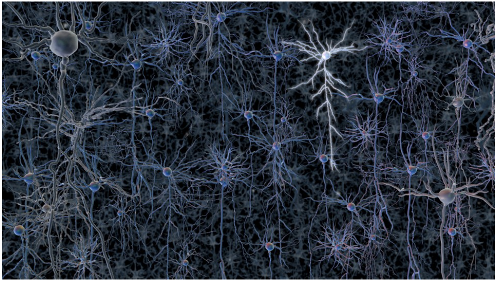
Functionality

1. Axon hillock: synaptic inputs (postsynaptic potentials) are summed and once a triggering threshold is exceeded, an action potential is generated.
2. Action potential: propagates as a wave along the axon.
3. Action potentials reaches the synapse: a neurotransmitter is released thereby passing a chemical signal to the dendrites or soma of another neuron.
4. Postsynaptically, the chemical (electrical) signal causes an excitatory or inhibitory membrane potential.
   The excitatory potential make the postsynaptic neuron more likely to fire an action potential while an inhibitory potential makes a neuron less likely to generate an action potential.

From the Biological Neuron to Artificial Neurons

- Synapses play a crucial role in regard to memory:
  the connection between two neurons is strengthened when both neurons are active. The strength of the connections relates to the storage of information, i.e. memory.
- Mathematical neuron models:
  - Integrate-and-fire model
  - Hodgkin-Huxley model
  - Models by Rulkov and Izhikevich
- Which level of description?
- Neurons in ANN mimic only certain aspects of their biological counterparts.

Biological Neural Networks



- Biological neural network: Interconnected biological neurons
- Human brain: estimated 86 billion neurons and 16 billion neurons in the cerebral cortex.
  In comparison, the number of stars in the milky way is estimated to be 200-400 billion.
- Cat:
  Primates:
  Elephants:
  Some whales and dolphins:
- Each human neuron has on average around 1000 synaptic connections to other neurons. Thus, there are around $10^{14} = 100$ trillion connections in the brain.

From the Biological Neuron to Artificial Neurons

(Action potential description)

From the Biological Neuron to Artificial Neurons

Task Based on the information on biological neurons:
1. Write down your own, simplified neuron model.
2. Point out its limitations vis-à-vis real biological neurons.

What is Learning?

- ANN & DL systems do not follow a specific written program: they learn how to solve a task.
- Learning: loosely based on insights from learning in biological neural networks and in cognitive science.

Three types of learning:

- Supervised learning
- Unsupervised learning
- Reinforcement learning

What is Learning?

Supervised learning

- Learning with a “teacher”that gives “feedback”
- Feedback from *labelled data*: to each input example there is a desired output example called *target*
- *Training* the network: learn to output the target by comparing output with the target via a *cost function*
- Aim: *generalise* to unseen cases
- Widely used for classification or pattern recognition tasks and for regression or function approximation tasks.

What is Learning?

Unsupervised learning

- Learning without a "teacher": no feedback to the network
- Main goal: find good low- or high-dimensional representation of the data
- Representation can be used for supervised or reinforcement learning
- Another aim: find clusters or certain patterns in the data
- There are also variants between super- and unsupervised learning called *semi-supervised learning*.

Reinforcement learning

- Learning with a “teacher”that gives only indirectly some feedback: no labelled data
- Learn how to take actions in some environment in order to maximise some sort of reward
- Action performed: the environment generates observation data and reward in form of a cost function
- Rewards may be delayed or partly missing
- Discover actions that minimise long-term cost

What is Learning?

Task Name real-world examples of supervised, unsupervised and reinforcement learning.

When Do We Need Neural Network Learning?

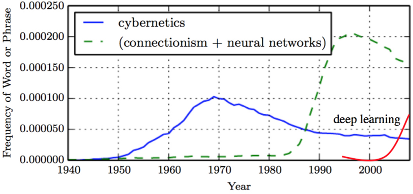
- Real-world problems: often complex and not easily describable in mathematical form.
- If describable mathematically: equations may not be solvable or it may be computationally too expensive.
- Often not clear what kind of underlying process generates the data.
- Biological systems: can “solve” problems that are hard for conventional computing machines.
- Example: recognising familiar faces under varying conditions etc.
- Neural network learning aims to close gap between cognitive faculties and conventional programming.

The ANN & DL Approach (Supervised Learning)

- Collect large amount of data with examples.
- Learn to reproduce examples and to generalise to new examples.
- Learning produces a "program" that solves a task.
- The program may change whenever new data is available.
- Resulting "program": may not easily be interpretable.

History

- Idea of building intelligent machines, studying the functioning of the human mind and brain, has a long scientific and philosophical history going back to ancient thinkers.
- Field of machine learning and artificial neural network theory: cybernetics in the 1940s-1960s, connectionism starting in the 1980s and the recent trend deep learning.



History

Some milestones in the field:

- 1943 The McCulloch-Pitts neuron developed by Warren McCulloch and Frank Pitts was an early model of a neuron, that is, the first artificial neuron model.
- 1948 The work of Norbert Wiener, especially his book *Cybernetics: Or Control and Communication in the Animal and the Machine* is considered to be the beginning of modern artificial intelligence research.
- 1953 The perceptron invented by Frank Rosenblatt was the first neuron model that could learn to solve a task by updating its weights according to input-output examples.
- 1960 The ADALINE neural network by Widrow and Hoff is an evolution of the perceptron that can learn by gradient descent.
- 1969 The book *Perceptrons* by Minsky and Papert discussed critically the perceptron concept and is perceived to have led to a decline in ANN research. This is called the “first AI winter”.
- 1980s Development of the Neocognitron by Fukushima, a hierarchical multilayer ANN that inspired convolutional neural networks.

History

Some milestones in the field:

- **1990s** Kernel machines and graphical models lead to a further decline in neural networks research.
  This is called the “second AI winter”.
- **1997** Long short-term memory (LSTM) network by Hochreiter and Schmidhuber.
- **90s/00s** Development of convolutional neural networks by LeCun et al. and others which found many applications especially in vision processing tasks.
- **2006/7** Deep learning “officially” starts with Hinton, Bengio, LeCun and others.
- **2010s** DL takes off: many breakthrough applications lead to a DL and AI hype.
  Media, businesses and politics speculate on an “AI revolution”.
- **2020s** Your time!

Is it all a hype?

Is it all a hype?

The hype may (and likely will) recede, but the sustained economic and technological impact of deep learning will remain. In that sense, deep learning could be analogous to the internet: it may be overly hyped up for a few years, but in the longer term it will still be a major revolution that will transform our economy and our lives.

I'm particularly optimistic about deep learning because even if we were to make no further technological progress in the next decade, deploying existing algorithms to every applicable problem would be a game changer for most industries.

François Chollet

Some ANN/DL/RL Applications

- Convolutional neural networks are successfully used in **object recognition** and **object labelling**.
- Deep feedforward neural network and recurrent neural networks are widely used in **speech recognition task**.
- Neural network technologies are heavily used in the problem field of processing large natural language data.
  This involves tasks such as **machine translation**, **chatbots**, **semantic extraction**.
  (www.deepl.com/translator)
  (Cleverbot)
- ANN/DL are used in **recommender systems** and **online learning**.

Some ANN/DL/RL Applications

- Neural networks with reinforcement learning are also heavily used in **robotics** and **self-autonomous driving**.
  (Tesla Self-Driving)
  (Tesla Object Recognition)
- RL/DL is used in **video games**, both for generating them as well as playing them.
  Neural networks nowadays perform better than the human counterparts in **board games** such as chess and go.
  (AlphaZero)
  (Anand on AlphaZero)
  RL/DL is a very interesting approach for many **scientific tasks**.
  (Protein folding)
- **Generative models** such as generative adversarial networks (GANs) can produce high-quality data such as images. (This person does not exist.)
- Supervised and unsupervised neural networks are successfully used in **data analytics** such as feature extracting tasks or pattern analysis.
  AI systems may even be developed as a **self-programming technology**.

Disclaimer and Literature

These lecture notes were devised and written for the course "Artificial Neural Networks & Deep Learning" in the Master's programme Applied Computational Life Sciences at the University of Applied Sciences (ZHAW). The lecture notes are intended only for internal use and shall not be distributed.

These lecture notes are partly based on the book by Hertz, Krogh and Palmer, the lectures notes by Hinton et al., the book by Goodfellow, Bengio and Courville, the book by Chollet and research articles mentioned in the text.

The theory and application of ANN & DL is a very active field with many online sources on theory, applications and software codes. Go find out yourself!

Implementation of a Simple Artificial Neuron

Task

Implement a simple artificial neuron and compute the AND function with it.

1. Use Python (3.5-3.7) (use Anaconda)
2. Implement the artificial neuron as discussed, without numpy
3. Implement the same neuron with numpy
4. Write a function implementing the artificial neuron