Science is to test ideas – Engineering is putting it into practice

Day 1 - Hot Ideas
01 Information Sciences meets Life Sciences
02 Data, Information and Knowledge
03 Decision Making and Decision Support
04 DSS: from Expert Systems to explainable AI

Day 2 - Cool Practice
05 Methods of Explainable-AI
Groupwork: Planning of a 500 bed Hospital - Bringing AI into the workflows
Plenary: Presenting of the developed concepts

Keywords
- Decision
- Cognition
- Intelligence
- Expected Utility Theory
- Probabilistic Inference
- Probabilistic Decision Theory
- Signal Detection Theory
- ROC curve
- Learning and Inference
- Naïve Bayes Classifier

Advance Organizer (1/2)
- Argmax/argmin = set of points for which f(x) attains the function's largest/smallest value.
- Brute Force = systematically computing all possible candidates for a solution and checking whether each candidate satisfies the problem's statement;
- Cognition = mental processes of gaining knowledge, comprehension, including thinking, attention, remembering, language understanding, decision making and problem-solving;
- Cognitive Science = interdisciplinary study of human information processing, including perception, language, memory, reasoning, and emotion;
- Confounding Variable = an unforeseen, unwanted variable that jeopardizes reliability and validity of a study outcome.
- Correlation coefficient = measures the relationship between pairs of interval variables in a sample, from $r = -1.00$ to $0.00$ (no correlation) to $r = 1.00$.
- Decision Making = a central cognitive process in every medical activity, resulting in the selection of a final choice of action out of alternatives; according to Shortliffe (2011) DM is still the key topic in medical informatics;
- Diagnosis = classification of a patient’s condition into separate and distinct categories that allow medical decisions about treatment and prognostic;
- Differential Diagnosis (DDx) = a systematic method to identify the presence of an entity where multiple alternatives are possible, and the process of elimination, or interpretation of the probabilities of conditions to negligible levels;
- Evidence-based medicine (EBM) = aiming at the best available evidence gained from the scientific method to clinical decision making. It seeks to assess the strength of evidence of the risks and benefits of treatments (including lack of treatment) and diagnostic tests. Evidence quality can range from meta-analyses and systematic reviews of double-blind, placebo-controlled clinical trials at the top end, down to conventional wisdom at the bottom; NOTE: Evidence (English) is NOT Evidence (Deutsch);
- Expected Utility Theory (EUT) = states that the decision maker selects between risky or uncertain prospects by comparing their expected utility values.
Advance Organizer (2/2)

- **External Validity**: the extent to which the results of a study are generalizable or transferable.
- **Hypothetico-Deductive Model (HDM)**: formulating a hypothesis in a form that could conceivably be falsified by a test of observable data, e.g., a test which shows results contrary to the prediction of the hypothesis is the falsification; a test that could but is not contrary to the hypothesis corroborates the theory – then you need to compare the explanatory value of competing hypotheses by testing how strong they are supported by their predictions.
- **Internal Validity**: the rigor with which a study was conducted (e.g., the design, the care taken to conduct measurements, and decisions concerning what was and was not measured).
- **PDCA = Plan-Do-Check-Act**: The so-called PDCA-cycle or Deming-wheel can be used to coordinate a systematic and continuous improvement. Every improvement starts with a goal and with a plan on how to achieve that goal, followed by action, measurement, and comparison of the gained output.
- **Perception**: sensory experience of the world, including the recognition of environmental stimuli and actions in response to these stimuli.
- **Qualitative Research**: empirical research exploring relationships using textual, rather than quantitative data, e.g., case study, observation, ethnography. Results are not considered generalizable, but sometimes at least transferable.
- **Quantitative Research**: empirical research exploring relationships using numeric data, e.g., surveys, quasi-experiments, experiments. Results should be generalized, although it is not always possible.
- **Reasoning**: cognitive (thought) processes involved in making medical decisions (clinical reasoning), medical problem solving, diagnostic reasoning, behind every action.
- **Receiver-operating characteristic (ROC)**: in signal detection theory this is a graphical plot of the sensitivity, or true positive rate, vs. false positive rate (1 – specificity or 1 – true negative rate), for a binary classifier system vs its discrimination threshold is varied.
- **Symbolic reasoning**: logical deduction
- **Triage**: process of judging the priority of patients’ treatments based on the severity of their condition.

Glossary

- **CES = Central Executive System**
- **DDx = Differential Diagnosis**
- **DM = Decision Making**
- **DSS = Decision Support System**
- **EBM = Evidence-based medicine**
- **fMRI = functional Magnetic Resonance Image**
- **HDM = Hypothetico-Deductive Model**
- **IOM = Institute of Medicine**
- **LTS = Long Term Storage**
- **ME = Medical Error**
- **PDCA = Plan-Do-Check-Act**
- **QM = Quality Management**
- **ROC = Receiver Operating Characteristic**
- **RST = Rough Set Theory**
- **STS = Short Term Storage**
- **USTS = Ultra Short Term Storage (Sensory Register)**

Learning Goals: At the end of this lecture you ...

- ... are familiar with some principles and elements of human information processing;
- ... can discriminate between perception, cognition, thinking, reasoning & problem solving;
- ... have got insight into some basics of human decision making processes;
- ... got an overview of the Hypothetico-Deductive Method **HDM versus PCDA Deming approach**;
- ... have acquired some basics on modeling patient health and differential diagnosis.

Agenda for today

- **00 Reflection – follow-up from last lecture**
- **01 Cognition vs. Computation**
- **02 On Intelligence**
- **03 Human vs. Computer**
- **04 Human Information Processing**
- **05 Probabilistic Decision Theory**
00 Reflection

Key Challenges

- Medicine is an extremely complex application domain – dealing most of the time with uncertainties -> probable information!
- Key: Structure learning and prediction in large-scale biomedical networks with probabilistic graphical models
- Causality and Probabilistic Inference:
  - Uncertainties are present at all levels in health related systems
  - Data sets are noisy, mislabeled, atypical, dirty, wrong, etc. etc.
  - Even with data of high quality from different real-world sources requires processing uncertain information to make viable decisions.
- In the increasingly complicated settings of modern science, model structure or causal relationships may not be known a-priori [1].

Cognitive Science vs. Computer Science

- **Cognitive Science → human intelligence**
  - Study the principles of *human learning* to understand biological intelligence

- **Human-Computer Interaction → the bridge**
  - Interacting with algorithms that learn shall enhance user friendliness and let concentrate on problem solving - Opening the “black-box” to a “glass-box”

- **Computer Science → computational intelligence**
  - Study the principles of *machine learning* to understand artificial intelligence

**Why fitting Cognitive Science with Machine Learning?**

- CS aims to reverse engineer human intelligence;
- ML provides powerful sources of insight into how machine intelligence is possible.
- CS therefore raises challenges for, and draws inspiration from ML;
- ML could inspire new directions by novel insights about the human mind

**What is this: Cognitive Science?**

- “By 1960 it was clear that something interdisciplinary was happening. At Harvard we called it cognitive studies, at Carnegie-Mellon they called it information-processing psychology, and at La Jolla they called it cognitive science.”
  
  George A. Miller (1920-2012), Harvard University, well known for:

  - The magical number seven, plus or minus two: Some limits on our capacity for processing information.
  - *Stimuli and psychological events are examined from the standpoint of information theory. It is shown that the unaided observer is severely limited in terms of the amount of information he can receive, process, and remember. However, it is shown that by the use of various...*

**Some definitions (very incomplete)**

- **Intelligence**
  - Hundreds of controversial definitions – very hard to define;
  - For us: ability to solve problems, to make decisions and to acquire and apply knowledge and skills.

- **Learning**
  - Different definitions – relatively hard to define
  - Basically acquisition of knowledge through prior experience

- **Problem Solving**
  - Process of finding solutions to complex issues

- **Reasoning**
  - Ability of our mind to think and understand things

- **Decision Making**
  - Process of “de-ciding” (“ent-scheiden”) between alternative options

- **Sense Making**
  - Process of giving meaning to experience

- **Causality**
  - Relationship between cause and effect
What is learning?

**Learning:** mathematical and computational principles allowing one to learn from examples in order to acquire knowledge

- **adaptive behavior** change caused by experience
- to act successfully in a complex environment


02 On Intelligence
Typical Questions of Cognitive Science Research

- How do we process information?
- How do we learn and generalize?
- How do we solve problems?
- How do we reason and make decisions?
- How do we make predictions?
- How do we behave in new situations?

Intelligence

Do we understand how our brain works?

The Nobel Prize in Physiology or Medicine 2000

This book doubled in volume every decade ...


- Facts ≠ Knowledge, Descriptions ≠ Insight
- Our goal should be the opposite: To make this book shorter!

Motto of Google Deepmind: “Solving Intelligence ...”

“Solve intelligence – then solve everything else”

Demis Hassabis, 22 May 2015
The Royal Society, Future Directions of Machine Learning Part 2

CS vs ML did NOT harmonize in the past

- Cognitive Science had its focus on specific experimental paradigms because it was embedded deeply in Psychology and Linguistics; and aimed to be cognitively/neurally plausible ...
- ML had its focus on standard learning problems and tried to optimize in the range of 1% because it was embedded in Computer Engineering; and aimed to have working systems whether mimicking the human brain or not ...
Cerebellum: big memory to support motor learning
Neocortex: big memory flexibly learns statistical structure from input patterns
Hippocampus: big memory encoding memory traces via Hebbian learning
Example Vision: process of discovering properties (what, where) of things in the real-world from 3D-images (on 2D)
Vision = information processing task + rich internal representation
Understanding of vision requires multiple levels of analysis: computational – algorithmic and physical (hardware)


Cognitive Science versus Machine Learning

- Human learning
- Categorization
- Causal learning
- Function learning
- Representations
- Language
- Experiment design

- Machine learning
- Density estimation
- Graphical models
- Regression
- Nonparametric Bayes
- Probabilistic grammars
- Inference algorithms

"People who are interested in machine learning should be cognitive scientists and vice versa." Joshua Tenenbaum, MIT
http://web.mit.edu/cocosci/josh.html

Is the human brain a inference engine?

- Learning concepts from examples (babies!)
- Causal inference and reasoning
- Predicting everyday events
- Even little children solve complex problems unconsciously, effortlessly, and ... successfully!

Compare your best Machine Learning algorithm with a seven year old child!

03 Human versus Computer

03 Human vs. Computer

Problem Solving: Humans vs. Computers

When is the human *) better?
- *) human intelligence/natural intelligence/human mind/human brain/ learning
- Natural Language Translation/Curation
  Computers cannot understand the context of sentences [3]
- Unstructured problem solving
  Without a pre-set of rules, a machine has trouble solving the problem, because it lacks the creativity required for it [1]
- NP-hard Problems
  Processing times are often exponential and makes it almost impossible to use machines for it, but human make heuristic decisions which are often not perfect but sufficiently good [4]

When is the computer **) better?
- **) Computational intelligence, Artificial intelligence/soft computing/ML
- High-dimensional data processing
  Humans are very good at dimensions less or equal than 3, but computers can process data in arbitrarily high dimensions
- Rule-Based environments
  Difficulties for humans in rule-based environments often come from not recognizing the correct goal in order to select the correct procedure or set of rules [2]
- Image optimization
  Machine can look at each pixel and apply changes without human personal biases, and with more speed [1]

Comparison: Human vs. Computer

<table>
<thead>
<tr>
<th>Superiority</th>
<th>Human</th>
<th>Computer</th>
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</thead>
<tbody>
<tr>
<td>Sensitiveness for stimuli (visual, auditory, tactile, olfactory)</td>
<td>Precise Counting and Measuring of physical entities</td>
<td></td>
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<tr>
<td>Ability for inductive Reasoning and complex Problem Solving</td>
<td>Deductive Operations, formal Logic, Application of Rules</td>
<td></td>
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<tr>
<td>Creating of networked knowledge and storage for a long-time</td>
<td>Storage of huge amounts of data which are not necessarily connected</td>
<td></td>
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<tr>
<td>Flexibility in decisions, even in totally new situations</td>
<td>Reliable reaction to unambiguous input signals</td>
<td></td>
</tr>
<tr>
<td>Discovering of ambiguous signals even when distorted</td>
<td>Reliable performance over long periods without tiredness</td>
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</tbody>
</table>

Human Cognitive capacities of Inference and Prediction

- Similarity [1]
- Representativeness and evidential support
- Causal judgment [2]
- Coincidences and causal discovery
- Clinical diagnostic inference [3]
- Predicting the future


Important: Statistics meet Knowledge

- 1. How does abstract knowledge guide learning and inference from sparse data?
  - (Approximate) Bayesian inference in probabilistic models.
- 2. What are the forms and contents of that knowledge?
  - Probabilities defined over a range of structured representations: graphs, grammars, predicate logic, schemas...
- 3. How is that knowledge itself acquired?
  - Hierarchical Bayesian models, with inference at multiple levels of abstraction (“learning to learn”). Learning as (hierarchical Bayesian) program induction.

Central Question:
How does our mind get so much out of so little?


Humans learn from very few examples...

Decision trees are coming from Clinical Practice


Expected Utility Theory $E(U|d)$

For a single decision variable an agent can select $D = d$ for any $d \in \text{dom}(D)$.

The expected utility of decision $D = d$ is

$$E(U \mid d) = \sum_{x_1, \ldots, x_n} P(x_1, \ldots, x_n \mid d) U(x_1, \ldots, x_n, d)$$

An optimal single decision is the decision $D = d_{\text{max}}$ whose expected utility is maximal:

$$d_{\text{max}} = \arg \max_{d \in \text{dom}(D)} E(U \mid d)$$


A few certainties

- Cognition as probabilistic inference
  - Visual perception, language acquisition, motor learning, associative learning, memory, attention, categorization, reasoning, causal inference, decision making, theory of mind
- Learning concepts from examples
- Learning and applying intuitive theories (balancing complexity vs. fit)

Modeling basic cognitive capacities as intuitive Bayes

- Similarity
- Representativeness and evidential support
- Causal judgement
- Coincidences and causal discovery
- Diagnostic inference
- Predicting the future


Drawn by Human or Machine Learning Algorithm?

A Bayesian program learning (BPL) framework, capable of learning a large class of visual concepts from just a single example and generalizing in ways that are mostly indistinguishable from people

How does our mind get so much out of so little?


General Model of Human Information Processing


Learning and Inference

$d \ldots \text{data}$
$h \ldots \text{hypotheses}$

\[ p(h|d) = \frac{p(d|h)p(h)}{\sum_{h' \in H} p(d|h')p(h')} \]

Problem in $\mathbb{R}^n \rightarrow \text{complex}$
05 Probabilistic Decision Theory

“It is remarkable that a science which began with the consideration of games of chance should have become the most important object of human knowledge.”

Pierre Simon de Laplace, 1812

06 How to make decisions in an domain of uncertainty

Signal Detection Theory (SDT)

Image source: Staffordshire University Computing Futures Museum http://www.fcct.staffs.ac.uk/jdw1/wcfm/malvern.htm


Signal Detection Theory on the MDM process

Two doctors, with equally good training, looking at the same CT scan, will have the same information ... but they may have a different bias/criteria!
Decision Making Process - Signal Detection

Remember: Two doctors, with equally good training, looking at the same CT scan data, will have the same information ... but they may gain different knowledge due to bias/criteria.


Receiver Operating Characteristics (ROC curve)

http://gru.stanford.edu/doku.php/tutorials/ict

\( d' = 1 \) (lots of overlap)

- Hits = 97.5%
- False alarms = 34%

\( d' = 3 \) (not much overlap)

- Hits = 84%
- False alarms = 20%

\( d' = 2 \)

- Hits = 84%
- False alarms = 50%

\( d' = 0 \)

https://kennis-research.shinyapps.io/ROC-Curves

Slide 7-23 Information Acquisition and criteria - bias

- **Information acquisition**: In the CT data, e.g. healthy lungs have a characteristic shape; the presence of a tumor might distort that shape (= anomaly).
- Tumors have different image characteristics: brighter or darker, different texture, etc.
- With proper training a doctor learns what kinds of things to look for, so with more practice/training they will be able to acquire more (and more reliable) information.
- Running another test (e.g., MRI) can be used to acquire more (relevant) information.
- The effect of information is to increase the likelihood of getting either a hit or a correct rejection, while reducing the likelihood of an outcome in the two error boxes (slide 33).
- **Criterion**: Additionally to relying on technology/testing, the medical profession allows doctors to use their own judgment.
- Different doctors may feel that the different types of errors are not equal.
- For example, a doctor may feel that missing an opportunity for early diagnosis may mean the difference between life and death.
- A false alarm, on the other hand, may result only in a routine biopsy operation. They may chose to err toward “yes” (tumor present) decisions.
- Other doctors, however, may feel that unnecessary surgeries (even routine ones) are very bad (expensive, stress, etc.).
- They may chose to be more conservative and say “no” (no tumor) more often. They will miss more tumors, but they will be doing their part to reduce unnecessary surgeries. And they may feel that a tumor, if there really is one, will be picked up at the next check-up.


Decision Making Process vs. Data Mining process

Repetition Bayes Foundations

What is the simplest mathematical operation for us?

\[ p(x) = \sum_x (p(x, y)) \]

How do we call repeated adding?

\[ p(x, y) = p(y|x) * p(x) \]

Laplace (1773) showed that we can write:

\[ p(x, y) = p(y|x) * p(x) \]

Now we introduce a third, more complicated operation:

\[ \frac{p(x, y)}{p(y)} = \frac{p(y|x) * p(x)}{p(y)} \]

We can reduce this fraction by \( p(y) \) and we receive what is called Bayes rule:

\[ p(x, y) = \frac{p(y|x) * p(x)}{p(y)} \]

\[ p(h|d) = \frac{p(d|h) * p(h)}{p(d)} \]

Bayes Law of Total Probability = data modelling

| d ... data; h ... hypothesis | \( P(h|d) = \frac{P(d|h)P(h)}{P(d)} \) |
|-------------------------------|---------------------------------|
| \( P(h) \):                  | prior belief (probability of hypothesis \( h \) before seeing any data) |
| \( P(d|h) \):                | likelihood (probability of the data if the hypothesis \( h \) is true) |
| \( P(d) = \sum_h P(d|h)P(h) \): data evidence (marginal probability of the data) |
| \( P(h|d) \):                | posterior (probability of hypothesis \( h \) after having seen the data \( d \)) |

posterior = \( \frac{\text{likelihood} * \text{prior}}{\text{evidence}} \)

- evidence = marginal likelihood = “normalization”
- Remember: The inverse probability allows to infer unknowns, learn from data and make predictions ... machine learning!

Always Remember: Learning and Inference

\[ p(h|d) = \frac{p(d|h) * p(h)}{\sum_{h \in H} p(d|h') * p(h')} \]

Bayes Rule for Medical Diagnosis

<table>
<thead>
<tr>
<th>Symptoms</th>
<th>Likelihood</th>
<th>Bayes’ Rule</th>
</tr>
</thead>
<tbody>
<tr>
<td>p(symptoms</td>
<td>disease)</td>
<td>p(disease)</td>
</tr>
<tr>
<td>p(disease)</td>
<td>p(symptoms)</td>
<td></td>
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</tbody>
</table>

\[ p(\text{disease} | \text{symptoms}) = \frac{p(\text{symptoms} | \text{disease})p(\text{disease})}{p(\text{symptoms})} \]

Bayesian Inference

Key
Chickenpox = $\theta_c$
Smallpox = $\theta_s$
Symptoms = $x$

$p(x|\theta_c) = 0.8$
$p(x|\theta_s) = 0.9$

Bayes’ Rule

$p(\theta|x) = \frac{p(x|\theta)p(\theta)}{p(x)}$

$p(\theta|x) = \frac{0.8 \times 0.1}{0.81} = 0.081$
$p(\theta|x) = \frac{0.9 \times 0.001}{0.081} = 0.011$

Prior probability of $\theta_c$
Posterior probability of $\theta_c$

Prior probability of $\theta_s$
Posterior probability of $\theta_s$

Practical Example: Diagnoses

- Your MD has bad news and good news for you.
- Bad news first: You are tested positive for a serious disease, and the test is 99% accurate if you are infected (T)
- Good news: It is a rare disease, striking 1 in 10,000 (D)
- How worried would you now be?

$$p(x|d) = \frac{\text{likelihood} \times \text{prior} \times p(x)}{\text{evidence}}$$

$$p(h|d) = \frac{p(d|h)p(h)}{p(d)}$$

$p(T=1|D=1) = p(d|h) = 0.99$ and
$p(D=1) = p(h) = 0.0001$

$$p(D=1|T=1) = \frac{(0.99)(0.0001)}{(1-0.99)(1-0.0001)+0.99(0.0001)} = 0.0098$$

Conclusion

Let the human do what the human can do better:
Natural Language Translation/Curation

- Computers cannot understand the context of sentences [3]

- Unstructured problem solving
  - Without a pre-set of rules, a machine has trouble solving the problem, because it lacks the creativity required for it [1]

- NP-hard Problems
  - Processing times are often exponential and makes it almost impossible to use machines for it, but human make heuristic decisions which are often not perfect but sufficiently good [4]

Thank you!
Appendix

Reasoning Foundations of Medical Diagnosis

Symbolic logic, probability, and value theory aid our understanding of how physicians reason.

Robert S. Ledley and Lee B. Lusted

The purpose of this article is to analyze the simplified reasoning processes inherent in medical diagnosis. The importance of this problem has received recent emphasis by the increasing interest in the use of computer programs as an aid to medical diagnostic processes. The results of the study indicate that the computer may be used as an aid to medical diagnostic procedures, but it must be properly designed and used to be effective.


The Quiz-Slide will be shown during the course.

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The probabilistic model expresses general knowledge about a situation.

The inference algorithm uses the model to answer queries, given evidence.

The answers to queries are framed as probabilities of different outcomes.

The evidence contains specific information about a situation.

The queries express the things that will help you make a decision.

By D telescopes, Practical probabilistic programming (Manning Publications Co, 2016)