Scientific research is divided into discovery and verification. We discuss the difference between research and development and between science and engineering. The research starts with the definition of the problem. After that a solution that is also called a hypothesis, theory, or system model should be found, implying some kind of causal relationship or correlation between variables. We present the conventional scientific or reductive approach of research. Not all problems can be solved reductively. Therefore a complementary systems approach will be presented in a later session. However, the reduction has been the reason for the success of the western culture since the 1600's after the remarkable work of Galileo, F. Bacon, Descartes, Newton and many others. It is based on the idea of dividing a large problem into several subproblems that are solved separately using the bottom up approach, inductive generalizations, or any other methods of discovery. (Continued)

(Continued) Scientific theories are shown to be deductive and causal structures having internal coherence. Usually in engineering a construction of the system is implemented to show that the theory is “working”. The correspondence of the theory with reality is verified by using the hypothetico-deductive method where some conclusions are deductively derived from the theory or hypothesis and they are compared with reality. In engineering research we start from performance criteria and performance requirements and therefore the hypothetico-deductive method must be slightly modified. Conceptual analysis will be emphasized before theories can be formed. Causality and correlation, deductive, inductive and abductive reasoning, strong inference, and the problem of induction will be explained in detail.
Summary of my lectures

- A doctor must be able to discover new scientific knowledge independently (lecture 1)
- Existing knowledge in the literature is best found through bibliographies, citations, and databases (lecture 2)
- All documents are written using a hierarchical top-down approach (lecture 3)
- In this lecture I show that the actual research is a learning process where the opposite bottom-up approach (reductive approach) is used (lecture 4)
- In my last lecture I show that also top-down approach (systems approach) can be useful to foster creativity and support learning (lecture 5)

Research methods: reductive approach

- Introduction
- Research & development
- Choosing a problem
- Formation of concepts and theories
- Order and creativity
- Empirical-inductive method
- Conclusions
Introduction

- Idea
- Literature review
- Problem and hypotheses
- Experiments/analysis
- System (prototype)
- Theory/paper (new knowledge)

Journey of Exploration: Columbus

- Problem: a new way to India
- Competing hypotheses: over the Atlantic (Spain), around Africa (Portugal)
What is Research All About: Problem and Hypothesis

- No general systematic deductive methods exist to discover hypotheses

Research and Development [Jain97]
- research: discover new knowledge (new regularities)
  - basic research (no specific application in mind)
  - applied research (ideas into operational form)
- development: systematic use of the existing knowledge
  - research and development are closely related
  - in research a prototype is often developed
Science, Technology and Engineering [Jain97]

- **science**: “organized knowledge of the physical or material world gained through observation and experimentation” [Random House79]
- **technology**: the ways we provide ourselves with the **material objects of our civilization**, application of scientific knowledge for practical ends in engineering, medicine, agriculture, etc.
- natural sciences and engineering sciences differ in the object of study
  - **natural sciences** (also called “science”, inc. physics, chemistry, and biology): objects in the nature
  - **engineering sciences**: objects (products, services, methods) not found in the nature, using results of mathematics and natural sciences

**Difference of science and engineering**

- In science we develop a theory for a phenomenon in nature
- In engineering we start from **requirements** (needs) and our aim is to have a product that fits these requirements, a theory is needed to explain and predict the performance
Scientific Method

- Scientific method is “a method of research, in which a problem is identified, relevant data are gathered, a hypothesis is formulated [= discovery], and the hypothesis is empirically tested [= verification]” [Random House99]
  - Problem is a question proposed for solution or discussion
  - Hypothesis is a provisional theory suggested as a solution to the problem: either a causal relationship or correlation between variables (correlation does not imply causality).

Scientific Methods

1. Nomothetic research (in natural sciences and engineering): the aim is to find general causal laws to explain phenomena, theories are usually axiomatic (deductive) systems or sets of models
   - the opposite is ideographic research trying to provide all possible explanations of a particular case, for example in history) [Nagel79]

2. Constructive research (in engineering): the solution of the problem is not only shown to exist but it is constructed [Pagels88]

3. Action research (in social sciences): the problem is solved by certain actions whose consequences are evaluated and new actions are specified (iterative improvement, trial and error)

4. Case study (in social sciences): an in-depth, longitudinal examination of a single instance or event, which is called a case

5. Questionnaire study (in social sciences): a series of questions are used for the purpose of gathering information, which is usually analyzed statistically
Critics Are Our Friends

- The aim of criticism is to show weaknesses and finally improve the quality of the work in international competition
  - Without criticism we would always compete in the “province league”
  - Do not prevent criticism although you may become angry because criticism hurts
- Criticism must be objective, impersonal, and pertinent
  - Ideally you should show what should be improved and how
- Start and finish with encouragement

Choosing a Problem [Loehle90]

- For success in research you need right problem, right timing, right approach [Hamming93], difficulty of problem and its likely payoff (not too easy, not too difficult)
- opportunities for you
  - other person is wrong (show what is right)
  - contradictory experiments
  - terminological confusion
- more experience needed to solve problems
  - discussions (most new ideas are generated by talking with others [Jain97])
  - experiments (start them early, use experimental-inductive approach)
  - literature (find out existing knowledge)
Induction and Deduction

- **Deductive reasoning (inference):**
  
  All humans are mortal (assumption or premise 1)
  
  Socrates is human (assumption or premise 2)
  
  ⇒ Socrates is mortal (conclusion)
  
  In deduction the conclusions are implied by the premises. The truth is necessarily preserved. There is no new information in the conclusions that would not be in the premises.

- **Inductive reasoning (inference):**
  
  All crows observed so far have been black (assumption or premise)
  
  ⇒ All crows are black (conclusion)
  
  In induction the truth is not necessarily preserved. The conclusions include more information than the premises.
Scientific and Mathematical Induction

Scientific induction
- Scientific induction presented on the previous slides is incomplete: truth is not necessarily preserved
- Scientific induction is based on regularity of the world (in time and space), thus generalizations and predictions are possible
- Scientific induction should not be mixed with mathematical induction

Mathematical induction:
- Mathematical induction is a special case of complete induction, used in mathematical proofs
- Complete induction is induction where all the special cases of the generalization are enumerated, actually a form of deduction [Niiniluoto83]

Abduction and Strong Inference

Abduction = inference to the best explanation
Strong inference = use of competing hypotheses
Summary: Types of reasoning

- **Deduction (top-down):** if the premises are true, the conclusion must be true, i.e., deduction preserves the truth (often proceeds from general to particular)
- **Induction (bottom-up):** the conclusion, though supported by the premises, does not follow from them necessarily, i.e., induction does not in general preserve the truth (often proceeds from particular to general)
  - **abduction:** inference to the best explanation, Russell’s chicken example
  - **strong inference:** use several competing hypotheses and select the best one, i.e., approximate for of abduction
  - **statistical inference** (Bayesian inference): Bayes’ theorem is used to infer the probability that the hypothesis is true

Criticism on Inductivism [Niiniluoto83]

- Induction does not preserve the truth as deduction does (Hume’s problem of induction)
- Strictly speaking, we cannot verify but only falsify hypotheses (Popper’s “solution” to the problem of induction).
- Often the new theory (hypothesis) is in conflict with the old theory and thus cannot be induced from the old theory (Kuhn’s revolutionary science).
- Hypothetico-deductive method is presently seen as the standard view of scientific reasoning. There are no systematic methods to find hypotheses.
- Induction is needed in everyday life (based on regularities in space and time).
Formation of Concepts and Theories

- We learn by induction (bottom up, generalization from examples to models) [Felder88]
- We present theories by deduction (top down, from models to results)

Concept Formation [Niiniluoto02]

Triangle (word)  “A closed plane figure having three angles and three sides” (definition)
Concept Formation [Honderich05] (2)

- Classes of definitions
  - **Ostensive definition** (“pseudodefinition”, elementary terms are explained by examples to avoid an endless loop of definitions (Locke), “blue is the color of the sky”) [Rosenberg00]
  - **Dictionary definition** (meaning explained as established in a language, “compexity refers to the number of parts and their interconnections”)
  - **Stipulative definition** (definition by agreement, “complexity is measured by size, delay, energy, and cost”)
- A definition names a **wider class** to which something belongs and **distinguishing properties** (“triangle is a closed plane figure [wider class] having three angles and three sides [distinguishing properties]”)

### Comparison of Theories

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<th>Model-based theory</th>
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<tr>
<td>Definitions &amp; Axioms</td>
<td>Definitions &amp; Model and assumptions</td>
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<td>Rules of inference</td>
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**Taxonomy of Theories [Rosenberg00]**

1. **Axiomatic systems** – ideal form of theory
   - *theorems* are derived deductively (= analysis) from definitions and axioms
   - two forms: Hilbertian axiomatic systems in formal sciences (mathematics, logic, set theory, computer science) and hypothetico-deductive systems in empirical sciences

2. **Theories based on sets of theoretical models**
   - results are derived by *analysis* (deduction) from the definitions and assumptions of the model
   - usually used in science and engineering, for example ideal gas, Bohr model of atom

**Theoretical Model and IMRAD Structure [Day98], [Rosenberg00]**

- **Introduction**
- **Materials and methods**
- **Results**
- **Discussion**

<table>
<thead>
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<td>Rules of verification</td>
<td>Rules of verification</td>
</tr>
</tbody>
</table>
**Axiomatic Systems**

Hilbertian axiomatic system  |  Hypothetico-deductive system
--- | ---
Axioms | Axioms (model)
Deduction | Deduction
Theorems | Results
Synthesis | Analysis

---

**Taxonomy of Axiomatic Systems** [Niiniluoto02]

**Hilbertian axiomatic systems**
- used on formal sciences
- no interpretation made
- the axioms are assumptions and initially the **theorems are** hypotheses or **conjectures**, which are proved by deriving them deductively from axioms
- examples: logic, arithmetics, geometry, set theory, probability theory

**Hypothetico-deductive systems**
- used in empirical sciences
- interpretations made
- initially **axioms are hypotheses** that are verified indirectly by comparing the results with reality
- examples: Newtonian mechanics, quantum mechanics, hypothetico-deductive systems are used also in biology and social sciences
Creativity: On the Edge of Order and Chaos

- You must have something on which to build (order, systematic work) and something to move (chaos, flexibility)
- Ways to improve creativity: analogies, symmetries, relations, extremes, opposites
- Working habits: well defined problem, quiet time (“lazyness”), new environment, mental barriers avoided [Loehle90]

Creativity Can Be Improved

- Define your problem carefully.
- Respect criticism and follow the instructions. Avoid group think by criticism.
- Follow ethical rules. Emphasize integrity.
- Appreciate publicity. Do not accept wildcat business (“hämärä puuha”).
- Respect independence and accept dissimilarity (diversity).
Sources of Knowledge [Honderich05]

- deductive and inductive reasoning
- experience, observation and experiment, improved instruments [Derry99]
- analogy [Bohm87], [Feynman98]
- abduction (Russel’s chicken [Deutsch98]), intuition, imagination, dream (Descartes: reductionism [Wilson99], Kekulé: benzene [Hudson92], Mendeleyev: periodic system of elements [Strathern00])
- patterns and discrepancies in data, serendipity [Derry02]
- wild guess [Loseee01], brainstorming [Davis97], telepathy, clairvoyance, precognition, etc.

Novelty and Paradigm

Paradigm is an unquestioned theory or set of beliefs, existing world-view (concept introduced by T. Kuhn in 1962) [Honderich05]. Novel results outside the present paradigm are often rejected by the scientific community.
Scientific Method [Honderich05], [Pagels88]

- Scientific method is divided into two parts:
  - **Discovery**: divide and conquer (reduction), iterative improvement, empirical-inductive method, systems approach (next lecture)
  - **Verification**: hypothetico-deductive method

- Modern scientific method by Galileo includes mathematical analysis (*coherence* of the theory) and experiments (*correspondence* with reality), in engineering the solution must also be practical (pragmatic)
  - Best theories are deductive systems (either axiomatic systems or causal theoretical models)
  - Methods of discovery are controversial (no systematic method of discovery exists)

Methods of Discovery

- Traditional methods of problem solving [Pagels88]
  - **Divide and conquer** (reduction, break a large problem into simpler subproblems and try to solve them)
  - **Iterative improvement** (guess a solution and then try to improve it)

- Traditional methods need a complementary “holistic” method that is also called **systems approach** (example: working of an airplane)
Reductive Method of Discovery [Wilson99], [Pagels88]

- Break the problem down and then generalize the results (“divide and conquer”)
- “Practical people often balk at this approach [reduction, idealizations] since the idealized situations may be so far removed from those of use as to appear highly academic.” [Wilson90]
- We present the results explicitly by deduction (top down), but we learn through induction (bottom up)

Empirical-Inductive Method of Discovery [Kragh02]

- Problem is divided into subproblems (this is called reduction)
- Hypothesis (system model) is derived by using experience (often analogies used)
Iterative Method of Discovery [Pagels88]

- You must work iteratively since the problem and hypotheses are initially not very clear (a chicken and egg problem)
- In the beginning it is difficult to understand the literature
- Experience is gained by own experiments and discussions
- Reporting and publishing will improve the quality of research
In engineering a hypothesis (defined in system specifications) is usually an idea of the relationship between the cause and effect (defined in system requirements).

Theoretical model is always only an approximation of observation in real world (prototypes include tacit knowledge [Leppälä03], e.g., Stradivarius violin).

- Backwards and downwards causality are in suspect in natural science.
- Scientific theories are deterministic and deductive (relativity theory) or probabilistic (quantum theory) [Nagel79].
- Scientific theories describe (question how?) but do not strictly speaking explain (question why?).
Division of a System into Parts and Properties — Different Views [Honderich05]

- **system** is a combination of parts forming a unitary whole
- **complexity** refers to number of parts and their relations

**Reality**

Pendulum

Prototype

Parts

Performance

T period

l length

Experimental

Theoretical

Aarne Mämmelä 25.9.2007
**Theory**

Simple pendulum

System model

Parts

Performance (statistics)

**T**

**T** period

**l** length

Assumptions:
- small amplitude
- no friction

Definitions:
- \( g \) is gravitational acceleration (\( 9.81 \text{ m/s}^2 \))

**Reality and Theory**

Reality

Prototype

Parts

Performance

**T** period

**l** length

Assumptions:
- small amplitude
- no friction

Definitions:
- \( g \) is gravitational acceleration (\( 9.81 \text{ m/s}^2 \))

Theory

System model

Parts

Performance (statistics)

**T** period

**l** length

**T** = \( 2\pi \sqrt{\frac{l}{g}} \)
Experiment (Set of Tests) [Wohlin00]

Tests are either deterministic or statistical
One independent variable is changed and other independent variables are set at a fixed level
In this way the factors affecting the system can be determined

Example: Factors Affecting Performance

Reductionism helps you to test your models.
Use reference data from simplified analysis or literature.
The scientific verification method is called **hypothetico-deductive method** [Honderich05]: the theoretical model acts as a hypothesis, which is verified indirectly by comparing the results given by the theoretical model with the corresponding experimental results given by the reality. (Deduction \( \Rightarrow \) internal coherence, verification \( \Rightarrow \) correspondence with reality.)

### Hypothetico-Deductive Method of Verification

- **Practice**
  - Prototype
  - Results
- **Analogy**
- **Theory**
- **Hypothesis**
  - Deduction
  - Analysis (top-down)
  - Synthesis (bottom-up)
- **Verification**
  - Experimental
  - Results
  - Theoretical

### Theory Construction in Science

- **Experiments**
- **Natural object**
- **Observations**
- **Verification (HD method)**
- **Hypothesis (theoretical model)**
- **Theory construction**
- **The finding of the hypothesis is a nonlinear process (it can be made systematic only in very specific cases)**
- **There are several possible hypotheses that are good approximations of the reality (for example Kepler/Galileo, Newton, Einstein)**
System Design in Engineering

- Natural object is replaced by requirements that describe user needs.
- The requirements describe the properties of the expected system. The system is verified against the requirements, but finally validated in the field tests (perhaps not all needs are not included in the requirements).

Brief History of Scientific Method [Losee01]

- c. 585 BC Regularity of nature, deduction (Thales of Miletus)
- c. 320 BC Induction and deduction, axiomatic system, classification (Aristotle)
- c. 200 BC Library at Alexandria
- 1011 Experimental method (Ibn al-Haytham or Alhazen or Alhacen)
- 1327 Occam’s razor: principle of parsimony (William of Occam)
- 1620 Empirical-inductive method (F. Bacon, Novum Organum)
- 1637 Reductionism (R. Descartes, Discourse on Method)
- 1638 Modern scientific method (G. Galilei, Two New Sciences)
- 1660 Scientific society (Royal Academy)
- c. 1665 Hypothetico-deductive method (R. Boyle), the term later suggested by W. Whewell
- 1665 Scientific journal (Royal Academy)
- 1687 I. Newton, Principia
- 1739 Problem of induction and causality (D. Hume)
Brief History of Scientific Method [Losee01]

- 1840 W. Whewell, *The Philosophy of the Inductive Sciences*
- 1856 Positivism (A. Comte)
- 1878 Abduction: inference to the best explanation (C. S. Peirce)
- 1927 Uncertainty principle (W. Heisenberg)
- 1929 Logical positivism or logical empirism (Vienna Circle)
- 1931 Incompleteness theorem (K. Gödel)
- 1934 Falsification (K. Popper, *The Logic of Scientific Discovery*, originally in German)
- c. 1940 Systems analysis (L. von Bertalanffy)
- c. 1940 Systems engineering (Bell Telephone Laboratories)
- c. 1945 Analytical philosophy of science (Carnap, Hempel, Nagel, Quine)
- 1946 Electronic computer (ENIAC)
- 1962 Paradigms (T. Kuhn, *The Structure of Scientific Revolutions*)
- 1962 A. D. Hall, *A Methodology for Systems Engineering*
- 1963 Deterministic chaos (E. Lorenz)
- 1964 Strong inference: competitive hypotheses (J. R. Platt)

Conclusions (1)

- Idea
- Literature review
- Problem and hypotheses
- Experiments/analysis
- System (prototype)
- Theory/paper (new knowledge)
Conclusions (2)

- **Experience (analogies)**
- **Question (problem)**
- **Answer (hypothesis)**
- **Criticism (testing)**

Conclusions (3)

- use **bottom-up (inductive) approach** in research, which is essentially a learning process
- use **top-down (deductive) approach** in technical documents (reviews, monographs), this will make the presentation compact and easy to follow for experts (use IMRAD structure)
- use bottom-up approach in teaching (tutorials, textbooks), and integrate results by using the top-down approach
- remember that a doctoral thesis is not a textbook (writing a textbook is a large challenge), write the thesis for experts in the field
Conclusions (4): Iterative research method

Conclusions (5): Theory and practice

- A good research project emphasizes theoretical results (usually system models) and uses prototypes for verification and validation of the new results.
Abbreviations

- AWGN = additive white Gaussian noise
- HD = hypothetico-deductive

References (1)

References (2)


References (3)

- I. Niiniluoto, Tieteellinen päättely ja selittäminen. Otava, 1983
References (4)