Course "Empirical Evaluation in Informatics"

The Scientific Method

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- Science and insight
- Informatics on the landscape of sciences
- The scientific method
- Variables, hypotheses, control
- Internal and external validity
- Validity, credibility, and relevance

"Empirische Bewertung in der Informatik"

Die wissenschaftliche Methode

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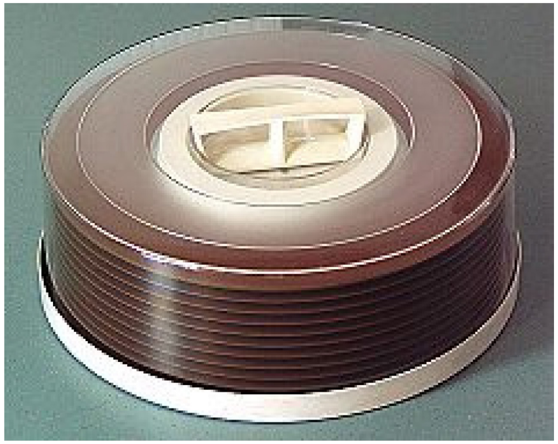
- Wissenschaft und Erkenntnismethoden
- Einordnung der Informatik
- Die wissenschaftliche Methode
- Variablen, Hypothesen, Kontrolle
- Interne und externe Gültigkeit
- Gültigkeit, Glaubwürdigkeit und Relevanz

Our goal

- In empirical evaluation, we have given a certain artifact or situation, e.g.
  - - a new (or old) design method or
  - - a new kind of hard disk, etc.



- and want to obtain an understanding of it

  often with respect to specific attributes, e.g.
  - - the effort for accommodating later requirements changes
  - - or the bandwidth and latency of data transfer to/from the disk

  or qualitatively, e.g.
  - - the process structure when introducing requirements changes
  - - how the disk fails when it dies

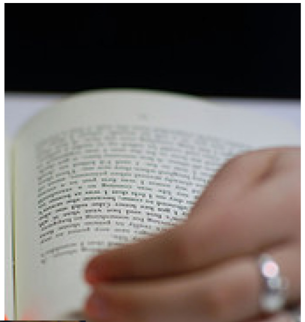
Obtaining understanding

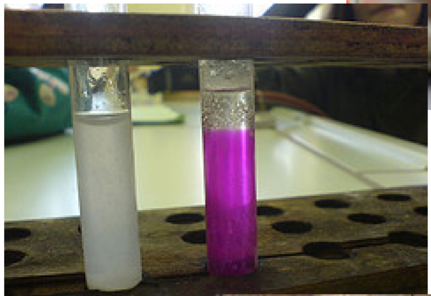
- There are different ways how people obtain understanding
  - by intuition (direct insight)
  - from some authority (tradition, teacher, book etc.)
  - by rational thought (reasoning, deduction)
  - by direct observation combined with induction
  - via the scientific method

- Each method *may* produce valid understanding
- No method can make *totally* sure that the understanding is valid
  - but the scientific method comes closest
  - and, just as important, has the best chance of convincing other people to accept the same understanding

The landscape of knowledge and science

- The arts
  - "Geisteswissenschaften"
  - Special case: Pure Mathematics
    - pure logic: principles of deduction are fixed, anything else is arbitrary
- The (natural) sciences
  - "Naturwissenschaften"
  - examines characteristics and behavior of the real world
  - Special case: the social sciences
    - "Sozialwissenschaften"
    - examines human behavior
- Engineering
  - "Ingenieurwissenschaften"
  - solves practical problems; interested in usefulness and cost





The landscape and T, C, E

T, C, E: Theory, Construction, Empiricism

- Mathematics
  - Mostly T
  - Auxiliary C and E have entered recently (computational math.)
- The (natural) sciences
  - T and E fertilize each other
  - Construction is purely auxiliary
- The social sciences
  - E drives T
  - Construction is usually only auxiliary
- Engineering
  - T, C, and E fertilize each other
  - Some T comes from from the natural sciences
  - Construction is the goal

Informatics on the landscape

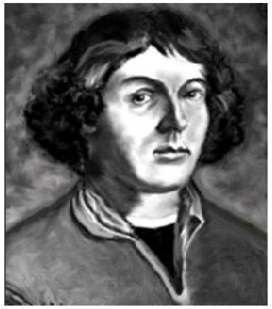
- Informatics has its roots in
  - Mathematics: logic, formal languages
  - Engineering: constructing computers
- Today, the larger part is clearly engineering
  - (In this course, we look at this part only)
- However, the engineering is not purely technical:
  - The artifacts have to be used by people
    - and building them involves people, too
  - Brings psychology, sociology, and politics into play
- Hence, Informatics needs a lot of empiricism

Mathematics vs. natural science

- Historically, all of science was philosophy
  - at least in the western culture
  - Greek philosophers
- and much of that was mathematics
- The notion that nature could be understood by pure thought (rationalism) was prevalent in the middle ages
- The idea that observation and experimentation was necessary to understand the world began to get accepted during the renaissance

Early empiricists

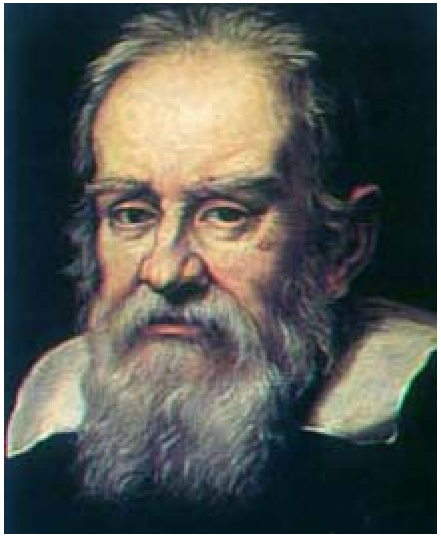
- Some of the earliest modern empiricists were the astronomers Kopernikus, Kepler, Brahe, and Galilei
  - around 1500–1600



Kopernikus

Brahe

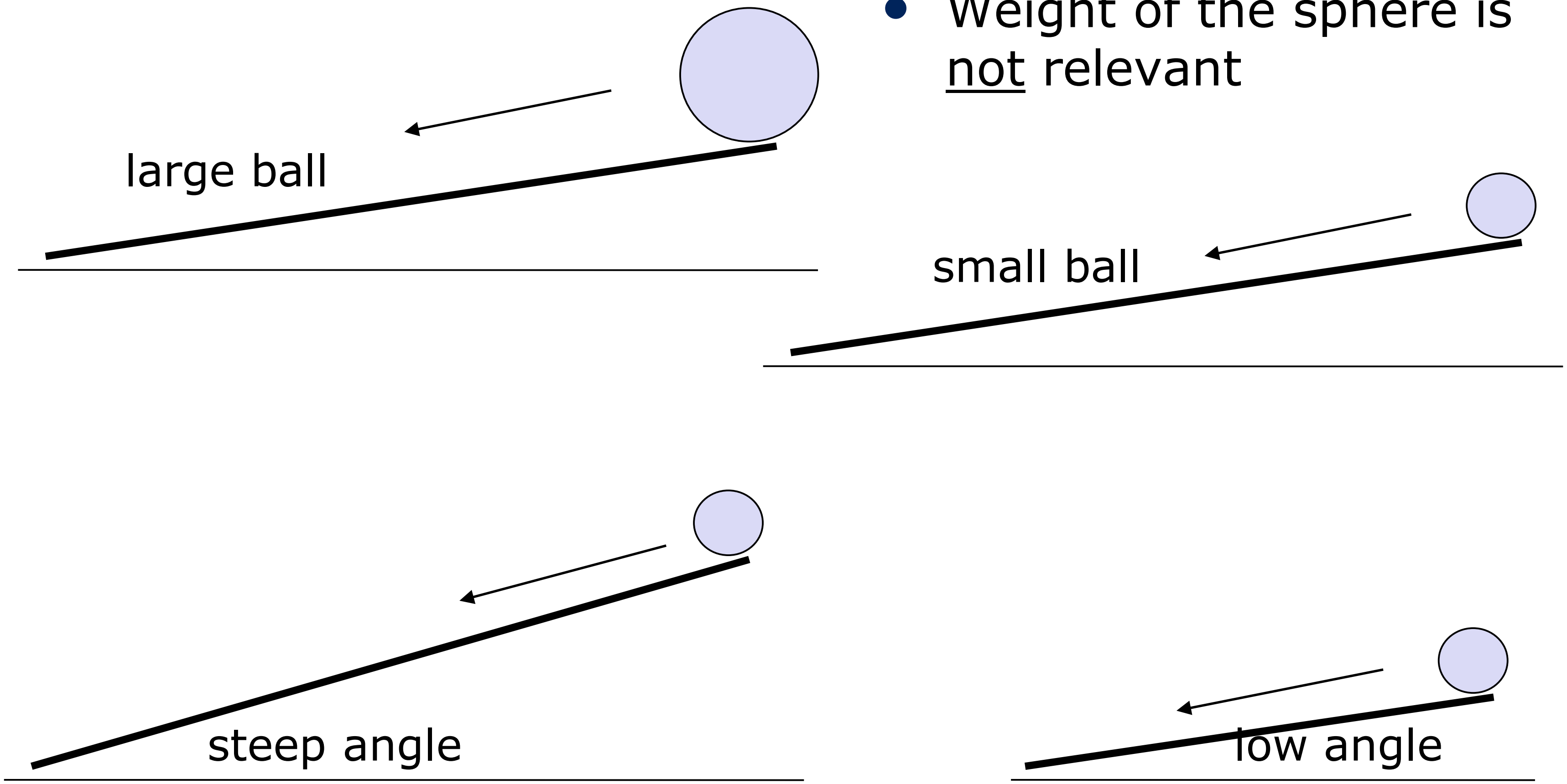
- One of the first modern experimental scientists was Galileo Galilei
  - At the time, it was generally accepted that heavy objects fell down faster than lighter ones
    - as claimed by Aristotle (384–322 BC)
  - Galilei did not believe this and experimented with brass spheres, inclined planes, and water clocks (1589–1604)
    - He systematically varied the weight of the ball and the steepness of the plane and found weight-independent acceleration
    - These were controlled experiments



Galilei

Galilei's experiments

- Weight of the sphere is not relevant



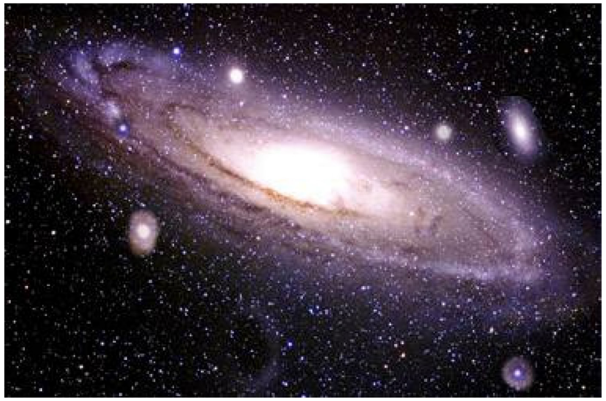
The scientific method

- Since Galilei, physics and other sciences work according to this model:
  - Formulate a theory T about
    how (some aspect of) the real world behaves
  - Design and conduct experiments X for testing this theory

- Is accepted in all subjects where experimentation is possible
  - Natural sciences: Physics, chemistry, biology, medicine etc.
  - Engineering
  - Parts of many social sciences (such as economics, sociology, etc.)

The scientific method:
Limits of applicability

- The scientific method is problematic where experiments cannot be performed
  - for technical or ethical reasons
  - must rely on observation plus induction then (qualitative + quantitative argumentation)

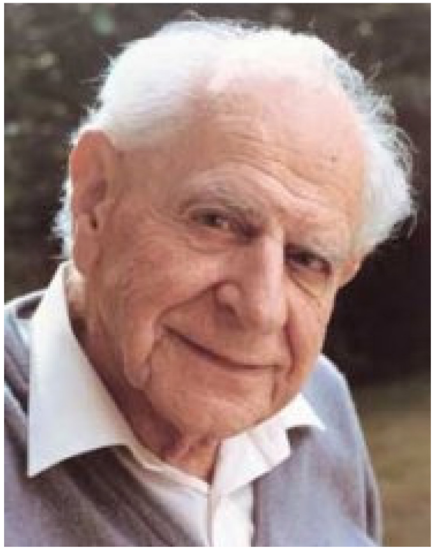


- It is unsuitable when there are too many factors involved to formulate a precise theory, e.g.
  - social sciences
  - socio-technical systems
  - software engineering
  - again, must rely on observation plus induction then (qualitative research methods)

The scientific method: Scientific vs. unscientific theories

- Note the following:
  - T is called a *scientific theory* only if it predicts something specifically and hence can be tested
  - Even if T is wrong, it may happen that the results of X are as expected
  - But if X contradicts predictions of T, then T must be false

- This view of science was suggested by Karl Popper (1904–1994)
  - It is the prevalent scientific paradigm today
  - In this view, theories cannot be directly confirmed, only refuted
  - If a theory cannot be refuted for a long time, it will gradually be accepted as confirmed
    - example: special theory of relativity
  - https://www.youtube.com/watch?v=-X8Xfl0JdTQ
    - good explanation in 9 minutes



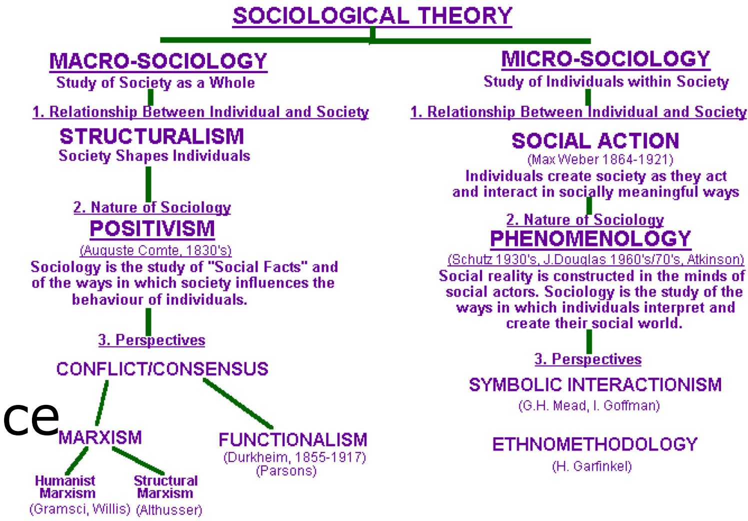
Pre-theoretical empiricism

- In many areas, too little is known for formulating a plausible, testable theory
  - In particular where people are involved and the situation is complex
    - social sciences, socio-technical systems, software engineering
- A different, qualitative style of empiricism is useful then:
  - Observe things that lead to hypotheses from which one could build theories
  - Often these observations have to be qualitative rather than quantitative in order to be useful
    - Qualitative research is a large and interesting branch of research methodology
    - but not the topic of this course (half-exception: Case Studies)

Hard science vs. soft science

- Many people claim that a subject is a science only if it produces theories that are precise and reliable
  - "hard science", such as physics formulas

- and hence claim that subjects involving human behavior are not scientific
  - "soft science"
    - This attitude could be called "physics envy"
- This is not true: The scientifc principle can be applied
  - but the theories will be more complex and make weaker (e.g. probabilistic) predictions
- Hard science is simpler than soft science
  - That is why it is farther advanced



SOCIOLOGICAL THEORY

MACRO-SOCIOLOGY
Study of Society as a Whole

1. Relationship Between Individual and Society
STRUCTURALISM
Society Shapes Individuals

2. Nature of Sociology
POSITIVISM
(Auguste Comte, 1830's)
Sociology is the study of "Social Facts" and of the ways in which society influences the behaviour of individuals.

3. Perspectives
CONFLICT/CONSENSUS

MARXISM

Humanist Marxism (Gramsci, Willis)

Structural Marxism (Althusser)

FUNCTIONALISM
(Durkheim, 1855-1917)
(Parsons)

MICRO-SOCIOLOGY
Study of Individuals within Society

1. Relationship Between Individual and Society
SOCIAL ACTION
(Max Weber 1864-1921)
Individuals create society as they act and interact in socially meaningful ways

2. Nature of Sociology
PHENOMENOLOGY
(Schutz 1930's, J.Douglas 1960's/70's, Atkinson)
Social reality is constructed in the minds of social actors. Sociology is the study of the ways in which individuals interpret and create their social world.

3. Perspectives
SYMBOLIC INTERACTIONISM
(G.H. Mead, I. Goffman)

ETHNOMETHODOLOGY
(H. Garfinkel)

Terminology of Empiricism

- When we empirically investigate something quantitatively
  - we characterize the situation by a set of ***input variables***
    - often quantitative or categorical
    - e.g. "team size = 4" or "design method used = A"
  - and the observations by a set of ***output variables***
  - If we choose the value of at least one input variable, the study is called an ***experiment***
- The act of consciously manipulating the values of input variables is one important aspect of ***control***
- Every empirical study assumes that there is some systematic relationship between inputs and outputs
  - If we have a certain expectation about this relationship, this is called a ***hypothesis***
  - Any additional factors influencing the outputs are called ***extraneous variables***

Example: Case study

- Assume we want to evalute a design method A
- We pick a representative team of people
  - a capable, but not unrealistically clever team
- We pick a task of interest
  - a "normal" one: not unusually small or large or difficult or …
- We have them do the design using method A
  - (hopefully they receive some training beforehands…)
- We see what happens (using many sources of observations):
  - What goes well?
  - What goes not so well?
  - How good is the resulting design?

Control in the case study

- This case study has little control
  - We have controlled the task to be done and the method to be used
    - (and even this is unusual for a case study)
  - but not the capabilities of the people
    - Precisely how intelligent, knowledgable, interested etc. are they?
  - Worse, we cannot judge the results without comparing them to other results

- Hence, it is not so clear what the results mean

Example: Controlled experiment

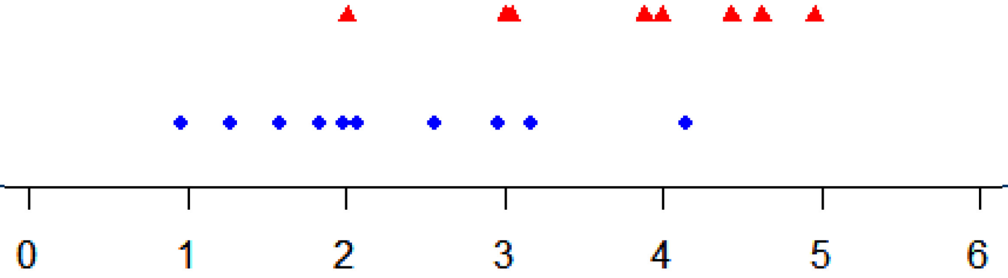
- This time, we compare design methods A and B
- Again, we pick a task T and a set of people P
    - but this time a large set of people
    - we train all of them equally well in both methods
- But now we use separate teams working with A or with B
- and have 20 different teams solve T with each method
    - People are assigned to the teams at random
- We compare the average result obtained by the method A teams and method B teams

Control in the controlled experiment

Important!

- This time we have controlled all variables:
  - task and method as before
  - the comparison to method B allows for interpreting the results
  - replication turns all kinds of individual differences into a noise signal
    - we will get different results for different teams although they are using the same condition
    - but given enough teams, the differences cancel out
  - random group assignment avoids systematic accumulations of individual differences
    - e.g. if more capable people favor working with method A

- Hence, we can decide whether A works better than B
  - at least for this kind of people, in this setting, and for this task



Internal and external validity

Important!

- Internal validity (important for credibility)
  - the degree to which the observed results were caused by only the intended input variables
  - rather than extraneous variables
- External validity (important for relevance)
  - the degree to which the results can be generalized to other circumstances
    - in our example: other people, settings, and tasks
- Improving external validity *tends* to reduce internal validity
  - because it will often strengthen the influence of extraneous variables

Threats to internal validity

- Have all plausible extraneous variables been controlled completely?
- Has the act of observing influenced the observations?
- Are the measurements done correctly?
- Are the results that are compared really comparable?

Important!

A more general concept is *construct validity*:

- Do my measurements really represent the characteristic that I want to observe?
  - e.g. does the number of pages of a design document really represent the size of a design task?
  - (Construct validity can be considered to encompass both internal and external validity. We do not use the term much.)

Threats to external validity

Important!

- The results rely on specific characteristics of the task
  - e.g. task is unusually well suited for method A, but not for B
- The results rely on specific characteristics of the people
  - e.g. they have an unrealistically good understanding of method A, because they were thoroughly taught by its inventor

- The results rely on specific characteristics of the experimental setting
  - e.g. the subjects were enthusiastic about A, but not B.
- The threat is worst if those special characteristics are uncommon

Credibility, relevance, validity

- Credibility is achieved when
  - there is high internal validity
  - there is a reasonable amount of external validity
    - in particular: no bias of the task
  - there is no doubt that both is the case

Important!

- Relevance is achieved when
  - the question investigated is of general interest and
  - there is enough external validity

Qualitative vs. quantitative research

- In complex settings (e.g., software engineering, socio-technical systems) understanding which factors must occur in a theory is difficult
    - because there are so many involved
    - and they interrelate in many ways

- Until we have this understanding, qualitative research is more useful than quantitative research
    - because it helps more in identifying the factors
    - whereas quantitative research involving ill-chosen sets of factors will mislead

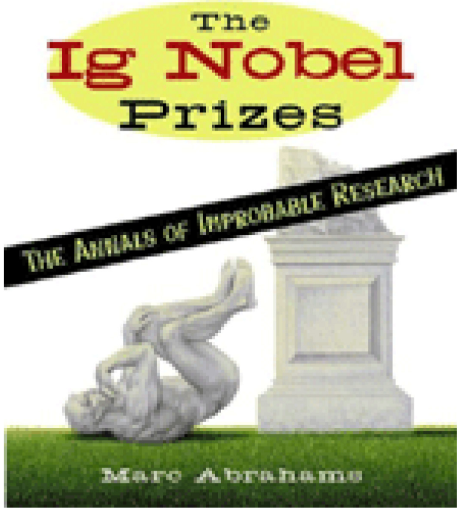
Judging empirical results

- Some fraction of the empirical results in scientific publications is dubious or wrong
- Outside of science, this is even much worse

- How can we discriminate valid results from dubious ones?
- The following questions help:
  - How do they know this?
    - in particular: Are the conclusions warranted by the facts?
  - What has not been said (but should have)?
  - Is this information really relevant?

(More about this in the next lecture)

Other results are correct but hardly relevant:



Summary

- Our goal is insight into objective facts and relationships

- The most powerful method for this is the scientific method:
  - Formulate a theory, derive hypotheses
  - Test them by experiments
    - Can only refute the theory, not prove it!

- It is accepted wherever experiments are possible
  - and can be approximated in many further settings
  - In Informatics, control in the experiments is often incomplete

- The goal is high internal and external validity
  - because they are key to good credibility and relevance

- Results should be judged by these criteria

Thank you!