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Being a researcher

The research process

Outline

- Does a standard research process exist?
- What is a research result?
- Does a scientific method exist?
- From conjectures to results: trial and error
- Different approaches to research
- Different validations of research results

Research area

software engineering

Research topic

software testing

automatic test
data generation
via symbolic execution

Research problem

Research result

Dissemination

Research area, topic, problem

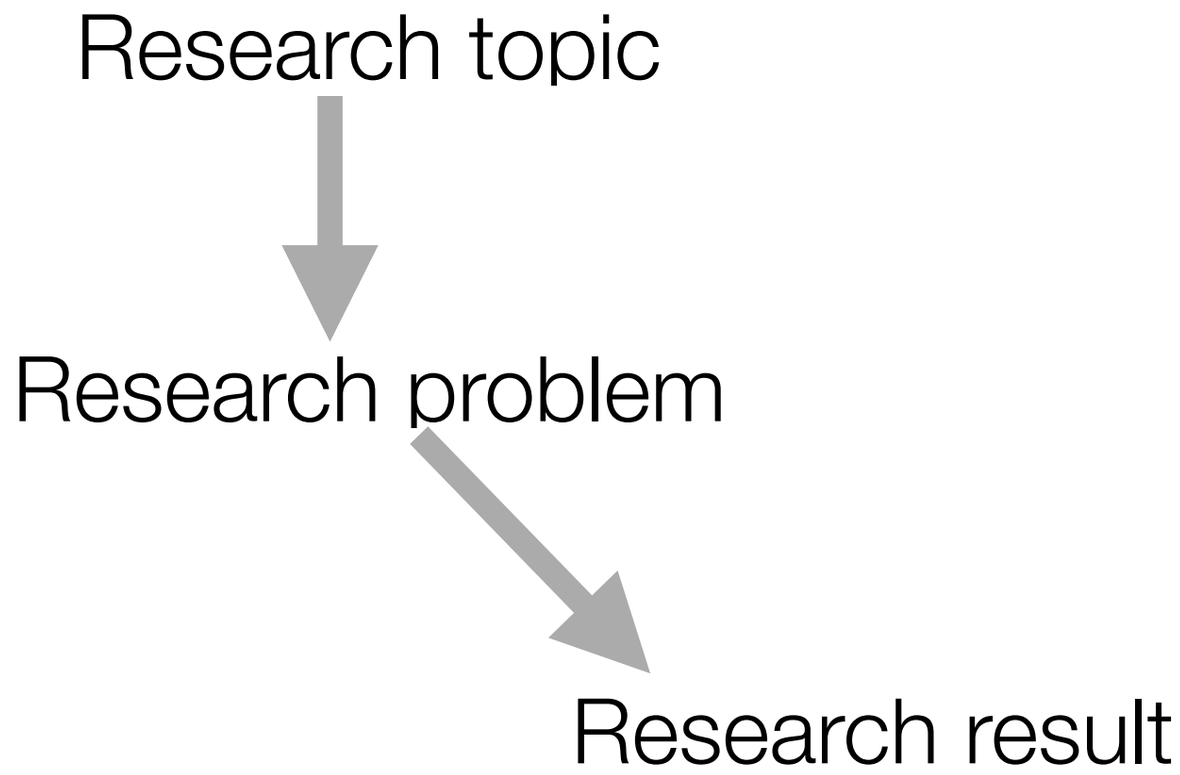
- A research area has long term objectives
- It has an associated research community
- Knowing a research community (and being known in it) is important
  - helps you developing your own agenda
- A research area has its own culture
- Topics are medium term objectives
- Research problems are manageable units that can lead to a single (or few) results

Research result

- A dissemination unit describing new knowledge
- It has a value as a unit
- Most common form is a written report, a paper
- But also, and increasingly more so, an artifact
- From research artifact to pre-competitive prototype to product/business

Research method

- How do we move in this space?



Not a linear, sequential process

Spectrum of possibilities

The problem is given to you

The problem is "in the air"

You have to find your problem

A brief historical tour on the "research method" (mostly based on natural sciences)

Understanding the context

- Natural sciences: where experiments lead to new knowledge
- Research is an experimental exploratory activity
- Similar focus can be in social sciences, in health sciences, or may concern certain aspects of engineering and constructive research

Francis Bacon (1561-1626) as a landmark point

- Early days of science (until 16th century)
  - Truth lay all around us
  - It is there to be taken, if we can **observe** things as they really are, without prejudice and preconception
- Francis Bacon and the role of experimentation
  - We cannot rely on luck of observations, but need to be proactive
  - We must instead devise happenings and contrive experiments

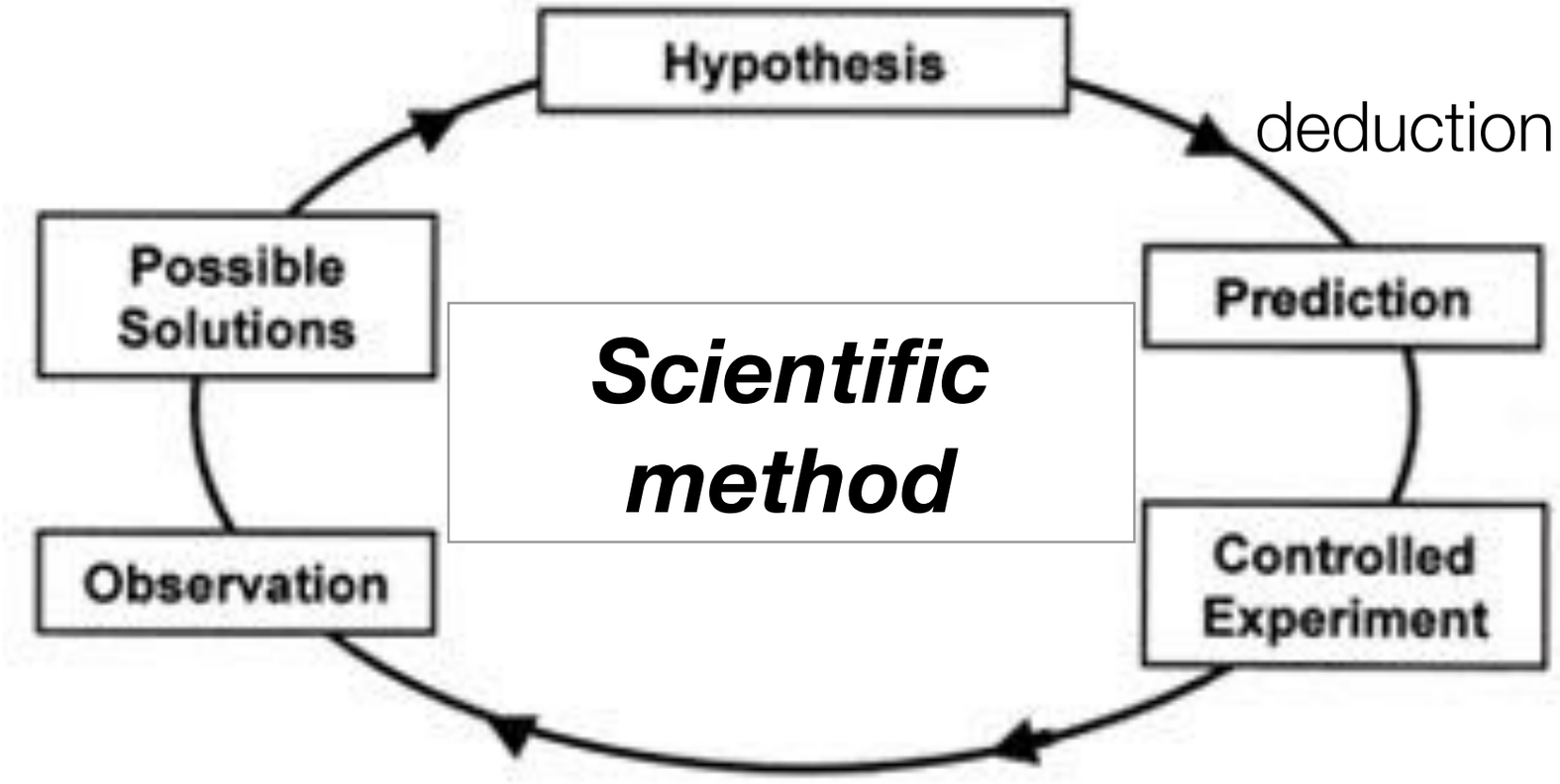
The inductive method

- Science is based on
  - collection of observations concerning a certain phenomenon X, obtained through experiments
  - inference of a general rule describing future manifestations of X
- The inductive method has no logical consistency, since observations cannot be exhaustive in general

Galileo Galilei (1564-1642): the origin of modern science

- The role of experiments in creating knowledge
- Knowledge formulated as a hypothesis
- A Galilean experiment is a **critical** one
  - it discriminates between possibilities
  - it is the proof to which we expose our hypotheses or the implications that follow from them ("il cimento")

The role of deduction



Prove vs disprove

- Experiments should be designed not to **prove** anything to be true —a hopeless effort— but rather to refute a null hypothesis (that which denies the validity of the hypothesis under investigation)

- For positive experiments we can only say that they are consistent with the hypotheses under experimental evaluation, NOT that they prove the hypotheses

- *No amount of experimentation can ever prove me right; a single experiment can prove me wrong (A. Einstein)*

- Karl Popper, and the efficacy of falsification as opposed to verification

Discovery: 3 main kinds of logical inference at play (1)

- Deduction
  - a the process of reasoning from one or more statements (premises) to reach a logically certain conclusion (aka syllogism)
  - In deductive inferences, what is inferred is necessarily true if the premises from which it is inferred are true; that is, the truth of the premises guarantees the truth of the conclusion: it is a **proof**
- *modus ponens* is a classical example
  - from P —> Q (major premise) and P (minor premise) we deduce Q
- but also, from P—>Q and Q—>R we deduce P—>R

A-symmetry of proof

- Consider P —> Q (major premise) and P (minor premise) from which we deduce Q

- If we know Q, we cannot derive P—>Q and Q

- For example, knowing that Socrates is mortal and that all men are mortal, we cannot derive that he is a man (Socrates could be a fish)

- However, we know that if Q is false than either P—>Q or Q are wrong!

Limited practical use of deduction

- Typical example of deduction
  - All As are Bs, a is an A —> a is a B
- In practice we often do inferences that are not logically justified, but "make sense"
  - “Most people living in Chelsea are rich” and “John lives in Chelsea” —> “John is (likely to be) rich”
    - truth of the first sentence is not guaranteed (but likely)
    - it is logically compatible with the truth of the premises that John is a member of (the minority of non-)rich inhabitants of Chelsea
- You know that John and Jill decided to split, someone tells you he has seen them jogging together all week, you may deduce they are back together
  - but maybe they were running together to decide about divorce details

The need for "non-necessary inferences"

- Philosophers have long discussed and tried to distinguish between **induction** and **abduction**
  - goes back to C.S. Peirce
- No universally agreed definition of the two terms exists

Discovery: 3 main kinds of logical inference at play (2)

- Induction: inference of a generalized conclusion from particular instances

  - a process of reasoning in which the premises are viewed as supplying some evidence for the truth of the conclusion

  - while the conclusion of a deductive argument is certain, the truth of the conclusion of an inductive argument may be probable, based upon the evidence given

Example

- **DEDUCTION**
  - *Major premise* All beans in bag B are white
  - *Minor premise* These beans come from bag B
  - *Conclusion (observation)* These beans are white
- **INDUCTION**
  - *Minor premise* These beans come from bag B
  - *Observation* These beans are white
  - *Major premise* All beans in bag B are white

Diacovery: 3 main kinds of logical inference at play (3)

- Abduction
  - inference to explanatory hypothesis (or hypotheses for selection of those best worth trying)
  - starts with an observation or set of observations then seeks to find a plausible explanation
  - often described as like a detective's identification of a criminal by piecing together evidence at a crime scene
  - has a remnant of uncertainty or doubt, which is expressed in retreat terms such as "best available" or "most likely", although not all uses of the terms abduction and inference to the best explanation are exactly equivalent

Example

- **DEDUCTION**
  - *Major premise* All beans in bag B are white
  - *Minor premise* These beans come from bag B
  - *Conclusion (observation)* These beans are white
- **ABDUCTION**
  - *Observation* These beans are white
  - *Major premise* All beans in bag B are white
  - *Minor premise* These beans come from bag B

A calculus for discovery cannot exist

- Every discovery starts with an **imaginative** preconception of what the truth might be, a hypothesis
- Experiments are acts undertaken to test a hypothesis, or conjecture
- A hypothesis is the starting point of the research process from problem to result
- Formulating a hypothesis requires ingenuity, it is not just inferred
- Use of deduction to generate consequences (predictions) from hypotheses
- Refutation of predictions may lead to a new hypothesis: the process of trial and error
- A theory is valid until it is refuted

Qualitative research

- Discover underlying meanings and patterns of relationships without using or developing mathematical models
- Qualitative methods involve fieldwork which could include interviews or personal observations
    - psychologist seeking in-depth understanding of human behavior and the reasons that govern such behavior , understanding of human experience, decision making
    - sociologists/political scientists seeking understanding of government and social programs
- Usually small sample sizes
- Experiments not necessarily repeatable
- Often an initial step, followed by quantitative research

Quantitative research

- Develop models, theories, and hypotheses describing a phenomenon
- Quantitative methods involve measuring something that will help develop the model/theory/hypothesis
- Heavily based on mathematics
- Often large samples needed
- Experiments must be repeatable

Results of quantitative research

- Consider hypothesis "beans come from bag B". Given a white bean, the inference may be wrong because the bean is white but does not come from bag B. It can be wrong because we have falsely assumed that no non-white beans are in bag B.
  - true positives (this bean is white and from bag B)
  - false positives (this bean is white, but not from bag B)
  - negatives (this bean is not white and not from bag B)
  - false negatives (this bean is not white and from bag B)

Precision and recall

$$\text{Precision} = \frac{tp}{tp + fp}$$

$$\text{Recall} = \frac{tp}{tp + fn}$$

Perfect precision and recall score 1

Ubiquitous precision and recall

- Applied in many contexts
- Search of relevant documents, image recognition, etc
- Precision is true positives (i.e. the number of items correctly labeled as belonging to the positive class) divided by the total number of elements labeled as belonging to the positive class (i.e. the sum of true positives and false positives, which are items incorrectly labeled as belonging to the class).
- Recall is the number of true positives divided by the total number of elements that actually belong to the positive class (i.e. the sum of true positives and false negatives, which are items which were not labeled as belonging to the positive class but should have been).

Other kinds of scientific research

- Theoretical research
  - typical of Mathematics
    - develops new theories, mostly validated by theorems
- Constructive research
  - typical of Engineering
    - develops new artifacts, new processes
- Often research has components of all kinds

Failures as drivers

- Falsification, failures, errors are key progress factors also in theory and constructive research

- Much engineering research based on reducing/ eliminating failures in earlier artifacts

- E.g., steam engines, turbine engines, bridge design…

- E.g., type safe languages and type checking

Research in ICST

- Encompasses all kinds
  - Experimental
    - How do programmers work?
    - Where are most likely bugs
    - How does a protocol perform?
  - Theory, e.g.
    - computability and complexity theory
    - semantics and property proofs
    - security models
  - Construction
    - new languages, new interfaces, new image recognizers, new development tools, new development processes ..
- Often a single research (area) requires a combination of theory/experimentation/construction

Summary

- How did understanding of scientific discovery evolve?
- The myth of the method: there is no standard approach to discovery
- Main logic reasoning involved in discovery
- Experimental, theoretical, and constructive research: often all together
- The role of falsification