MSc Research Skills

Lecture: Scientific inference

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Topics

1. Types of scientific inference

2. Scientific explanation

3. Levels of certainty

4. The deductive-inductive scientific method

5. Logic in scientific explanation

Topic: Types of scientific inference

Science attempts to:

- reach **conclusions** . . .
- from **premises** and **observations** . . .
- using **rational argument**.

This is called **inference**.

Forms of inference

1. Purely **logical**
   - e.g. mathematical theorems from postulates
   - rigorous, by definition correct given the assumptions
2. **Deductive-inductive** ('hypothetic-deductive')
   - most common; *see below for details*
3. **Cause & effect**
   - if there is a direct time or action sequence
4. **Contributors & impacts**
   - a weaker form of cause & effect
   - correlation, causes can't be determined → correlation **statistics**

(continued . . .)

Forms of inference (2)

5. Inductive patterns: **classification**
   - organize observations, then determine why this grouping

6. **Case studies**
   - difficult to generalize, must identify idiosyncratic and universal factors

7. **Analogy**
   - conclusions from one system are used to predict in another system, without experiments or observations of the second system
   - must argue that the two systems are analogous

   (continued . . .)

Forms of inference (3)

8. **Probabilistic**

   - organizes knowledge in a predictive model, with each outcome given a computed probability of occurrence

9. **Functional**

   - e.g. an empirico-statistical model → “regression”
   - sufficient for prediction, but do not explain anything

10. **Systems explanations**; ‘black boxes’

    - input-output (**stimulus-response**) relations
    - sufficient for prediction, but do not explain anything

    (continued . . .)

Forms of inference (4)

11. (Expert) Judgement / **Wisdom** / Intuition . . .

    - holistic, can not be reduced to discrete steps of reasoning
    - by definition **not reproducible**

12. **Teleological**, ‘higher’ purpose, external cause.

    - things occur because they ‘want’ to (‘plants want to find sunlight, so they grow out of the soil and keep growing upwards’)
    - or because some ‘higher power’ wants them to occur (‘male and female He made them . . . ’)
    - **impossible to verify by scientific methods**

Topic: Scientific explanation

- To "explain" is to say **"why"** something happens or is observed

- This is ultimately an **existential** question:
  - philosophically related to **ontology**: questions of **existence**
  - interesting to the philosopher but not part of science.

- Applied science and engineering: more limited view of "why":
  - a coherent statement that allows **prediction**
  - related to **epistemology**: questions of **knowledge**
  - 'knowledge is power' ⟶ **prediction**

Explanation & causality

- An "explanation" is not very useful if it only **summarizes**
- It must also give some idea of the **causes**
- or at least **mechanisms**, at some level of understanding

Non-causal or non-mechanistic explanations give a very weak basis for **prediction** – only if we assume conditions do not change.

Proximate and ultimate causes

proximate cause: the immediate cause

e.g., “a gully formed **because** there was a large rainstorm”

- but this has a cause, which has a cause ...

  Cause of the rainstorm; pre-existing conditions for gully formation ...

- is there an **ultimate** (last) cause?

So, there are **levels** of explanation:

- increasingly-**general** in their mechanisms
- increasingly-**difficult** to establish

Topic: Levels of certainty

"Fact", "hypothesis", "theory" and "law"

- in common speech, difficult to distinguish
- in scientific discourse, these have distinct meanings . . .
- . . . with different **levels of certainty**

Facts

- A **fact** is something **directly observable** and **measurable**
- Always with some **measurement uncertainty**; no instrument is perfect
- The uncertainty is *not* from definition or interpretation, rather from measurement
- The uncertainty can be **quantified** (e.g. from instrument characteristics, sampling theory)

Hypotheses

This word is used in widely-divergent senses even in science. Here:

- A **hypothesis** is a **tentative theory** (see next)
- it is what we believe to be the true explanation or true state of nature
- based on **previous work** or **first principles**
- **Not yet tested**; must design experiments to test

Harvey (1969): 'logically consistent controlled speculation'

Oxford advanced learner's dictionary (1995):

> "[An] idea or a suggestion that is based on **known facts** and is used as a **basis for ... further investigation**."

Theories – strong definition

A **theory** is a **conceptual framework** which:

- **explains** existing facts;
- allows **predictions**; and
- is in principle **falsifiable**
  - if it is false, there is some way to demonstrate that
  - some experiment or observation could contradict it or force its modification

Harvey (1969): 'highly articulate systems of statements of **enormous explanatory power**'

Theories – weak definition

Some theories are **impossible to falsify**, because they **do not make predictions** that can be tested.

Many macro-economic and macro-social theories ("theory of human nature") are in this category. They predict, but the world is so complicated that it is unclear whether, when the prediction fails, it is the fault of the theory, or that the boundary conditions of theory have been exceeded.

Still, these theories must explain existing facts.

There tend to be more **ideological** aspects to such theories.

Example – Thomas theorem

“If men define situations as real, they are real in their consequences.”

— Thomas, W.I. & D.S. Thomas (1928) *The child in America: Behavior problems and programs*. New York: Knopf, pp. 571-572

(sorry about the ‘men’ . . .)

1. What predictions does this make?

2. How can this be falsified?

Laws

A **law** is theory with **overwhelming evidence**, including the conditions under which it is true.

Classic example: Newton's laws of motion (1687)

- precise mathematical statements, consistenly-applied to bodies of all sizes and at all distances
- **limiting conditions**: velocities must be low compared to the speed of light, so that relativistic effects are not significant.

In fields such as geography, it is quite unlikely we can formulate laws in the same sense as in physics; it is perhaps better to speak of **'law-like statements'**.

E.g. "von Thünen's law" of land use related to distance to markets

Topic: The deductive-inductive scientific method

This is the best-known and most productive scientific method.

We start with a simplified version and then see how it works in practice.

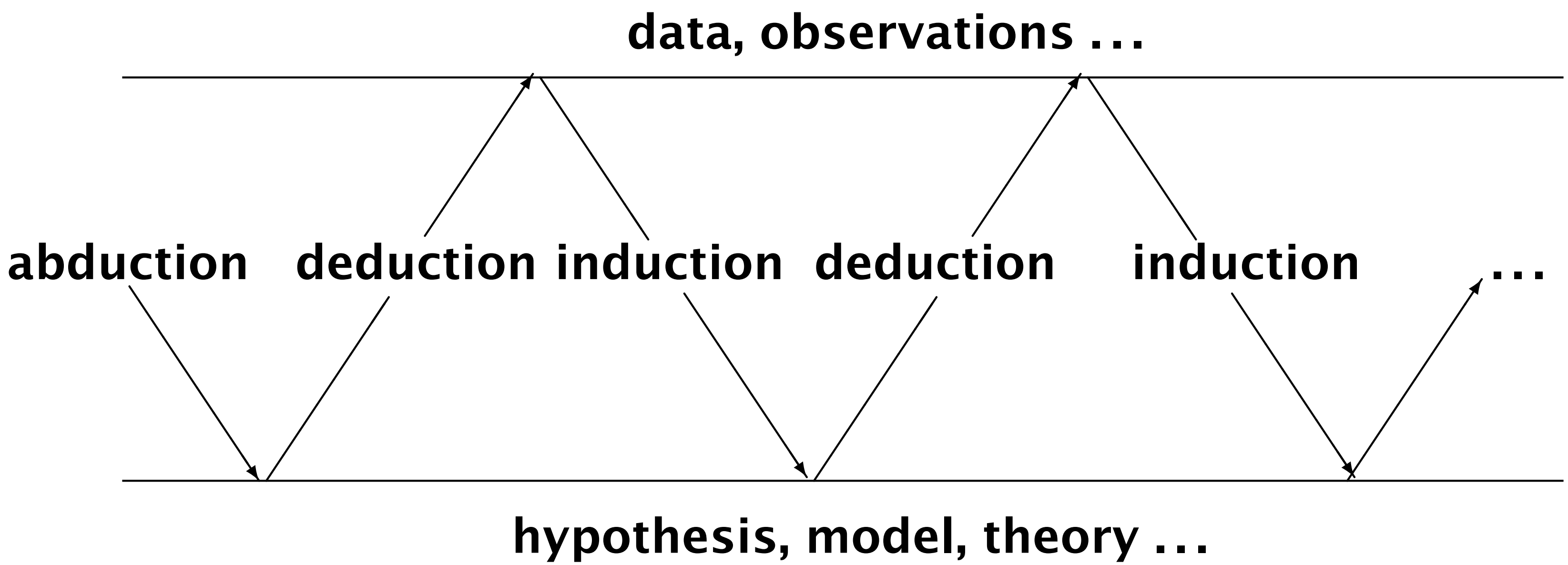
Steps of the simple version

1. **Observe**; synthesize general knowledge of the world;
2. **Invent a theory** to explain the observations $\Longrightarrow$ ***abduction***;
3. Use the theory to **make predictions** $\Longrightarrow$ ***deduction***;
4. **Design experiments** or **observations** to test these predictions;
5. **Modify the theory** in the light of results $\Longrightarrow$ ***induction***.

Repeat from step 3 **until** you can't think of any new predictions that might falsify or modify the theory.

Box's diagram

A never-ending process . . .



modified from:

Box, G. E. P.; Hunter, W. G.; & Hunter, J. S. 1978. *Statistics for experimenters*. New York: Wiley

Abductive step

Synthesize previous knowledge and first principles into a **tentative theory**

- i.e. a **hypothesis**
- Arrive at a **‘reasoned speculation’**

This is done during the research **proposal / design** phase.

> “Based on what I know from previous experience, and what I can observe, I formulate the following hypothesis: . . . ”,

Note no systematic experiments or observations have (yet) been made

So, the hypothesis is based on common knowledge, general principles, and any observations that are available.

Deductive steps

From existing theory or hypothesis **to** design a new experiment or set of observations, with expected results:

> "If my theory is true, and if I do this experiment (or make these observations), I should obtain these results."

Inductive steps

Compare hypothesis/theory to the results from experiments/observations

Modify hypothesis/theory as necessary

In extreme cases **abandon** theory and start over: **Paradigm shift**

> “My experiment did not give all the expected results. (My observations are not all as I expected.) However, if I modify my theory this way, then the experiment (observations), as well as my previous knowledge, would fit this new theory”.

or:

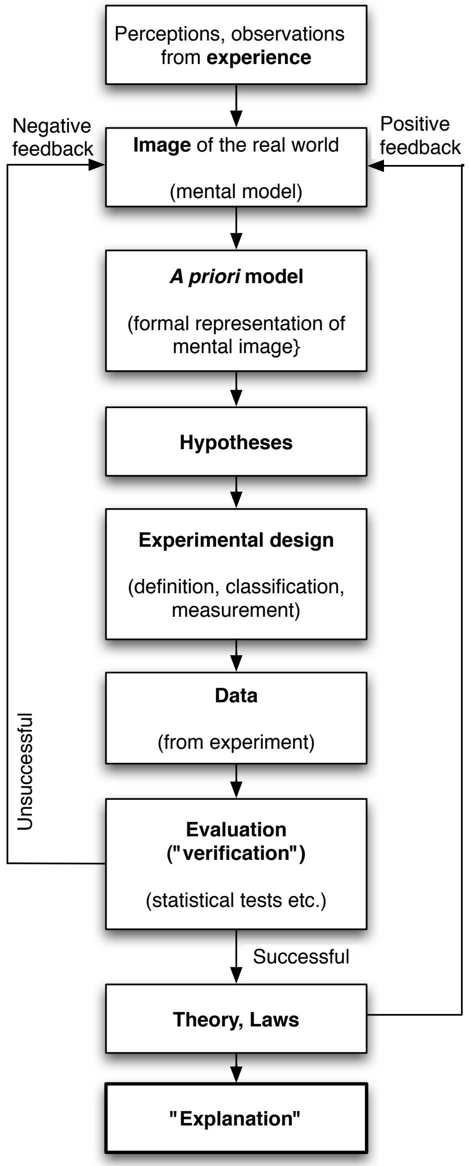
> “My results make no sense in view of my current hypothesis. I have to abandon it and formulate a new one”.

A more sophisticated view

Harvey (1969) emphasizes the asymmetric roles of “successful” and “unsuccessful” experiments, i.e. those that confirmed or contradicted the hypotheses

- **unsuccessful**
  - must **re-consider** mental and formal models of the world
  - they may be **really wrong**
  - the **hypotheses** for the following experiments must be at least **adjusted**, if not **abandoned**
- **successful**
  - this **confirms** the mental and formal models so far
  - allows them to be **expanded** (generalized, or applied to more phenomena).
  - able to upgrade **hypothesis** into a **theory**
  - or even a **law**

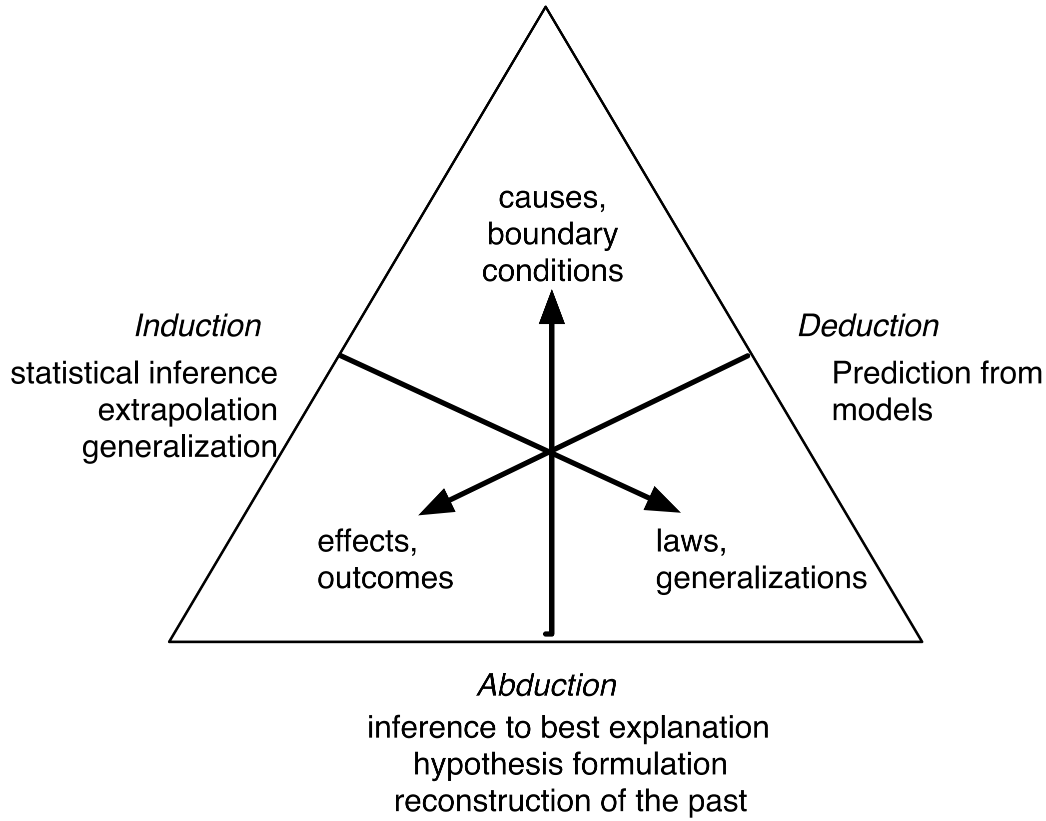
(see flow chart on next page)


Perceptions, observations from **experience**
Negative feedback
Image of the real world
(mental model)
Positive feedback
***A priori* model**
(formal representation of mental image}
Hypotheses
Experimental design
(definition, classification, measurement)
Data
(from experiment)
Unsuccessful
Evaluation ("verification")
(statistical tests etc.)
Successful
Theory, Laws
"Explanation"

Topic: Logic in scientific explanation

- Abduction
- Deduction
- Induction
- Assumptions

Three kinds of explanation



modified from: Kleinhans, M.; Buskes, C.; & de Regt, H. 2010. *Philosophy of earth science*. In Allhoff, F. (ed.), *Philosophy of the sciences: a guide*, pp. 213–236. Wiley-Blackwell

Abduction

Propose a hypothesis from common knowledge, first principles, and available observations (perhaps the results of other people's experiments).

> **Example**: If we go to the market and see some red apples displayed for sale, and behind them a large crate of red apples, we can infer (by abduction) that the loose apples were taken from that crate.
>
> Note that there are many other possible explanations for the presence of those loose apples; there is no logical necessity that they came from the crate. Note also that we've done nothing to prove or disprove the hypothesis.

Introduced by C. S. Pierce, early 1900's

Not a strictly logical approach, but succeeds often enough (humans are good at abduction) and is the only way to discover new truths.

Deduction

Specialise from a general law to a specific case

- Logically true (internally)
- That's why contradictory evidence invalidates (at least part of) the general law
- Provides ideas for **experiments** or **observations**
- "If this theory is true, then the following should occur or be observed"
- If not observed, the theory is **falsified** and should be abandoned or modified

Example: At the market we see a crate of red apples, and buy a bag of apples taken from that crate. When we get home, without looking in the bag, we can deduce that any apple that we take out of our bag will be red.

Note that if a selected apple is not red, our premise must be false: the apples in our bag were not in fact taken from the crate. We have **falsified** our theory.

Induction

Generalise from observations to theories

- From a **particular** set of observations to a **universal** statement (**hypotheses**, **theories** and **laws**)
- An inductive argument does *not* assert that its conclusion is necessarily true (Logic: the **premises** of the argument do not **entail** the **conclusion**)
  - **If** the premises are true, it strongly **suggests** the conclusion is true, but this is not a logical proof (there could be other explanations)

Example: We have a closed bag of apples which may be of any colour. We pick one without looking, it is red. We pick another, it is also red. We continue in this way, and after a number of apples have been picked, we infer by induction that the apples in this bag all came from the crate of red apples.

At this point we have a theory, and can then make a deduction (the next apple we pick will be red), which can be falsified by experiment.

Relation between modes of reasoning

"**Abduction** is the process of forming an explanatory hypothesis. It is the only logical operation which introduces any new idea; for **induction** does nothing but determine a value, and **deduction** merely evolves the necessary consequences of a pure hypothesis"
— C.S. Pierce, *Harvard Lectures on Pragmatism* (1903)

Assumptions

- **Taken as true** in the context of this research
- **If they are not true, the research is not valid**
- **Can not be tested** within the time, budget or experimental design
- Often difficult to express, “taken for granted” at many levels
- Established laws are often taken as assumptions, without explicit mention
  * we don’t repeat the laws of universal gravitation each time we model landslide hazard
- The more problematical should be made explicit
- Could an **assumption** be a good **research question**?

Final thoughts

How we really “know” anything or “prove” something is a very tricky concept.

This has two fundamental causes:

1. the **complexity** of the systems being studied;
2. the **humanity** of the researchers.

So: **careful reasoning** and **constant self-examination** of logic and assumptions.