Scientific reasoning: General rules

Methods of Scientific Working (for Crop Sciences) (3502-440)

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1 Motivation

In previous chapters, we introduced the philosophical basis of scientific working, in particular the scientific method. However, as scientists, we often begin our research with a specific problem or natural phenomenon we plan to investigate. The type of phenomenon then defines to some degrees the methods that are suitable and available for its investigation. Such research projects are then applications of scientific reasoning in which observations are made or theoretical models are developed to understand natural phenomena.

For this reason, it is necessary to know the key principles of scientific reasoning to achieve robust conclusions about nature, and how they are derived from the concepts of the philosophy of science, in particular the scientific method. In other words, how can the abstracts concepts and considerations be translated to concrete methods or process for the scientific investigation of a specific phenomenon? For this purpose, we introduce the most important concepts of scientific reasoning, which include **deduction**, **induction**, **evidence** and **arguments**.

Much research starts with evidence, which can be broadly defined as observations about nature. Several types of evidence exist:

- Examples
- Facts
- Analogies
- Experimental studies

The **goal of scientific research** is to make statements about nature. Such statements are made in form of an argument. There are rules and conventions for making an argument, which are derived from formal logic and common sense. Furthermore, there is a need to differentiate arguments from evidence.

The purpose of this lecture is to introduce the key principles of scientific reasoning, which are based on the four principles mentioned above. The discussion is kept general and bent towards a philosophical, conceptual approach, but we will use example from crop science for illustration.

We will also introduce formal logical arguments as an important tool of deductive scientific inference. While such formal arguments are rarely used in daily scientific practice they are very useful in formalizing scientific reasoning and are central concepts that underly computer hardware and software that are the foundation of the modern digital era.

2 Deductive reasoning

We first discuss the difference between deductive and inductive arguments.

2.1 Definition of deductive reasoning

We begin with a deductive argument and the following table is an example of such a deductive argument:

Premise 1	All plants contain DNA
Premise 2	Maize is a plant
Conclusion	Maize contains DNA

Deductive arguments have several properties:

A valid deductive argument consists of **premises** and **conclusions**. In a deductive argument, the premises already contain the conclusions. If the premises are true, the conclusions are also true. Therefore, a deductive argument reasons from general to the specific.

Here is another example of an argument:

Premise 1	400 out of 800 wheat plants are randomly sampled.
Premise 2	DNA was observed in all 400 sampled wheat plants.
Conclusion	The other 400 wheat plants have DNA, too.

This argument is not a deductive, but an inductive argument because the /premises do not contain/ the conclusion. By comparing deductive and inductive arguments, one may raise the question whether deductive arguments are of any use, because we can learn nothing new from deductive arguments, contrary to inductive arguments.

The key problem of science is that we can only gather knowledge about observed entities. Using this knowledge to infer information about non-observed entities of the same kind is induction. But if we

postulate general models or hypotheses, we can deduct conclusions from these. This is a first main use of deduction in science. Keep in mind: The conclusions are only true, if the model or hypotheses (the premises) are true. Induction will often lead to new models or hypotheses, from which one can deduct conclusions that can serve as predictions for further inductive arguments, and so on according to Aristotle's iterative process of deductions and inductions (inductive-deductive method). Another use of deduction is **model testing** and **model selection**, which is the comparison of different models to explain observed phenomena (See chapter on models.

2.2 Grosseteste's Method of Verification and Falsification

Robert Grosseteste (Oxford, c. 1168-1280; Wikipedia) provided a refinement of Aristotle's inductive-deductive method, which he called *Method of Verification and Falsification*. It works as follows: Given a model or hypothesis, deduct conclusions from it. They can then be tested in a controlled experiment. If the outcome from the experiment does not agree with the conclusion from the theory, it has to be discarded or refined. However, one can not verify ('proof') a theory by empirical evidence, but only falsify it (Karl Popper, 1902-1994; Wikipedia). The falsification of theories is the second main use of deduction. Positive (supporting) evidence for a theory can be used only in an inductive manner.

In the following we have a simple example of a falsification.

Assume that you are a person who grew up in Central Europe and saw only modern hybrid maize varieties with yellow cobs, which are predominant type of cobs in Europe. Based on your experience, you may generate the following **hypothesis**: *All maize cobs are yellow*.

Given this hypothesis, it is sufficient to find a single maize cob that is not yellow to falsify the hypothesis as in Figure 1. This photograph is sufficient to falsify the hypothesis that all maize cobs are yellow.

Figure 1: A basket with maize cobs from different maize landraces cultivated in Peru. Photo: Karl Schmid.

2.3 Use of deduction in mathematics

Mathematics is the field of scientific enquiry that is almost entirely based on deduction. Only a small set of assumptions called **axioms** are set to be true, and very other conclusion is deducted from axioms. For mathematical theories an important goal ist to make the set of axioms required as small as possible. For nearly all possible conclusions, one can theoretically deduct from axioms whether they are true or not. One exception is Kurt Gödel's first **incompleteness theorem** (Wikipedia). It states that there are conclusions, which cannot be shown to be either true nor false (or that there are contradictions).

2.4 Structure of deductive arguments

Deductive arguments can be expressed in a formal logical structures. There are different areas of formal logic, of which **propositional logic** is the simplest.

2.5 Propositional logic

In propositional logic, composite statements can be build up from **propositions** and **operators**. Propositions are simple statements like *Plants have DNA*, *Trees are plants* or *Trees have DNA* (here symbolized by A, B and C), which are either true or false. Operators are used to express relationships between the elements of a statement. Some important operators are shown in the following table:

Operator:| and | or | implies | equals | not (negation)
Symbol: | $\wedge$ | $\vee$ | $\rightarrow$ | $=$ | $\neg$

The 'implies' operator $A \rightarrow B$ is often expressed as *If A, then B*. Using these operators, statements can be translated into formal logic:

Statement	Formal logic
If plants have DNA and trees are plants, then trees have DNA:	$(A \wedge B) \rightarrow C$
If trees have no DNA, then trees are no plants:	$\neg C \rightarrow \neg B$
If trees have no DNA, then trees are no plants or plants have no DNA:	$\neg C \rightarrow (\neg A \vee \neg B)$
If trees have DNA and trees are plants, then plants have DNA:	$(C \wedge B) \rightarrow A$

Note that these sentences are just composite statements and do not have a conclusion yet!

The next step is therefore to construct logical arguments. In propositional logic, a logical argument is a list of statements (composite or simple), where the last statement is the conclusion, the rest are the premises. The conclusion is marked with the symbol $\therefore$ ('therefore').

An argument is valid if whenever all premises are true, also the conclusion is true. For small arguments, this can be done with a **truth table**: To all propositions present in the argument, assign all combinations of true and false. Then, for each combination check whether the statements in the argument are true or false. The argument is valid if every such combination that makes all premises true also makes the conclusion true. The following table shows an application of a truth table of the argument: $A, B, (A \wedge B) \rightarrow C \therefore C$.

Using this table, we check whether the argument is a valid logical argument, or not. The criterion for this decision is that there is no row in which the proposition (equal to premiss) is true and the conclusion is not.

```
julia> using TruthTables
julia> @truthtable (A ^ B) -> C full = true
TruthTable

|   A   |   B   |   C   | A ^ B | A ^ B --> C |
-------------------------------------------------
| true  | true  | true  | true  | true        |
| true  | true  | false | true  | false       |
| true  | false | true  | false | true        |
| true  | false | false | false | true        |
| false | true  | true  | false | true        |
| false | true  | false | false | true        |
| false | false | true  | false | true        |
| false | false | false | false | true        |
```

The one combination in row 1, which renders all premises (A, B, C) true also makes the conclusion ($(A \wedge B) \rightarrow C$) true. This combination is then a valid logical argument.

By using truth tables, one can validate complex arguments.

2.6 How to work with propositional logic

Working with propositional logic involves the following steps. First, check whether you are making a deductive or non-deductive argument:

- **Deductive argument**: If premises are true the conclusions are inevitably true
- **Nondeductive argument**: Conclusion is beyond premises → Induction

Second, check whether the premises are clear or well definable to construct a deductive argument. In real life examples, this is often not the case. Third, split a complex argument into simpler and valid rules or equalities to construct a deductive argument. Forth, use *building blocks* (frequently occurring logical patterns) for inference rules/equalities (p, q are statements):

Name	Definition
Modus ponens	$p, p \rightarrow q \therefore q$
Modus tollens	$\neg q, p \rightarrow q \therefore \neg p$
Modus tollens (as equality)	$(p \rightarrow q) = (\neg q \rightarrow \neg p)$
De Morgan's Rule 1	$\neg(p \wedge q) = \neg q \vee \neg p$
De Morgan's Rule 2	$\neg(p \vee q) = \neg q \wedge \neg p$

There are many more of these patterns:

Modus ponens: The mode of putting: put p, get q

- If p then q.
- $p.$
- Therefore, q.

Modus tollens: The mode of taking: take q, take p

- If p then q.
- Not $q.$
- Therefore, not p.

The following example is an application of *modus tollens*[1]

Sherlock Holmes says:

> A dog was kept in the stables, and yet, though someone had been in and had fetched out a horse, [the dog] had not barked.... Obviously the ... visitor was someone whom the dog knew well.

These thoughts can be expressed as *modus tollens*:

- If the visitor were a stranger (s), then the dog would have barked (b)
- The dog did not bark.
- Therefore, the visitor was not a stranger.
- if s then b.
- Not-b.
- Therefore, not-s.

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[1]The example was taken from Weston (2008), p. 29.

2.7 Predicate logic

Predicate logic is another approach to deductive statements. A typical statement of predicate logic is the following:

Premise:	All trees have DNA, the plant in front of lecture room S09 is a tree
Conclusion:	This tree has DNA

What is new: Statements are not only true or false, but are true for all (or one) members of a **class of objects**. There is a new type of operators that are called **quantifiers**. They are 'For all' (∀) and 'there exists at least one' (∃). The basis of falsification is then: The negation of *All trees have DNA* is *There exists at least one tree that doesn't have DNA*

These (admittedly superficial) examples were presented to demonstrate the role of formal logic in science. It should be noted that in contrast to mathematics or computer science, such formal considerations are hardly ever used in biological research, but they help to understand the key concepts and principles of conducting a correct scientific reasoning. Formal logic is also highly useful to test whether some arguments or statements are correct, mistakes (blunders) or fallacies as shown below.

3 Inductive reasoning

Induction is the complement of deduction, which we can illustrate with the following example:

- Assume a population fo 800 wheat plants
- 400 plants were tested whether they contain DNA

Analysis by induction:

DNA was found in 400 of 800 observed wheat plants	Premise 1

The other 400 wheat plants have DNA, too Conclusion

What are the characteristics of an inductive argument?

An inductive argument consists of premises and conclusions. The premises **do not** contain the conclusions. If the premises are true, the conclusions are not necessarily true. However, in a reasonable inductive argument the conclusions will be true with a **high probability**. Induction reasons from specific to general. In other words, it reasons from the observed to the unobserved.

There are several modes of induction:

- Induction from **sample to population**: Inferential statistics is required to test how much the sample resembles the population.
- Induction from **history to presence/future**: In this case, a prediction is required: Which model is the best to predict the future from the past?
- From **entities to similar entities**: Which entities are comparable? For example, the basic principles of inheritance should apply to maize and rice. Can we model the inheritance of a particular gene in the same manner in maize than in rice?

Wheat is the importance of induction in scientific studies? Often it is easier, cheaper or only possible to analyse a sample instead of a whole population of objects. By definition, induction is the basis of any prediction for future events.

Induction provides the foundation for models, hypotheses or theories. From these, deductive inference for unobserved objects is possible, which leads to the (by now) well known iteration of induction and deduction

The following table shows the key differences between induction and deduction:

	Deduction	Induction
Conclusion	Contained in premises	Extension of premises
Truth	Certain	Probable
Direction	General Model → Reality	Reality → General Model

3.1 Presuppositions of induction

Inductive inference makes several presuppositions:

Uniformity of nature Universe is governed by general laws. Objects which are *identical* should act the same way under the same circumstances.

Parsimony or law of limited variety of nature Things represent one another in relevant aspects and are not unlimited in their variety. Induction is *within* classes of objects

David Hume criticised induction. It is known as **Hume's problem**: Uniformity of Nature can neither be justified by induction nor deduction.

A scientist's approach to this problem is that induction works good enough in general, but one should be aware of its limitations. Uniformity of nature refers both to the perception and the existence of nature. On a more mundane level, much of plant breeding and plant cultivation tests the rule for uniformity of nature (in field trials, for example), by estimating the effect of the environment of a character of interest such as crop yield.

It should be noted that Hume's argument is essentially a philosophical one, based on abstract reasoning, whereas an estimation of environmental effects in a field trial is a pragmatic approach to quantify the effect of environmental variation, or as one may call it *variability of nature*.

3.2 Statistics is the combination of induction and mathematics

We can express the quality of an inductive argument: If the premises are true, the conclusion should also be true with high probability. What is probability? How can you measure its value? We use a mathematical model which describes both premises and conclusion (think about sample and population). From this model, we deduce the probability of the conclusion, or at least estimate the bounds (limits) of the probability of the conclusion. This branch of mathematics is called **statistics**. Therefore, applied induction *is* statistics.

A key problem of statistics is: How to choose a suitable mathematical model? Here, we already have to make an inductive step of choosing a model given our knowledge of the premises and the conclusion. Statistics has two major branches (we assume here induction from a sample to a population):

- Estimation of parameters
- Testing of models

3.3 Estimation in statistics

Estimate parameters of the population using parameter values from the sample.

For example, estimate mean 1,000 grain weight in a population of a wheat elite line by measuring the trait in a sample and computing an estimate from the data.

There are certain quality criteria for such a statistical estimation:

Confidence interval Give a range of parameter values so that the correct population parameter lies in this range with a certain probability.
Small intervals are a sign of a good estimation.
Unbiasedness If you repeat the estimation in a lot of samples, the mean value of all estimations is the population value.
Consistence If you enlarge your sample, the estimation gets better because of a lower estimation error.

3.4 Testing of models in statistics

The testing of models involves the following steps:

1. Develop a model or hypothesis about a phenomenon in a population
2. Get a sample for the population
3. Use data from sample and a procedure to decide whether a hypothesis or model is correct

There are two main schools of thinking how to come up with such a procedure

- **Frequentist school:** Test only a single hypothesis and choose an inference rule that the decision based on the sample will be correct for many other samples drawn from the population → Focus on the testing method.
- **Bayesian school:** Among multiple hypotheses, choose the one with the highest probability given the observed data → Focus on the hypothesis.

The difference between both schools will be discussed later.

4 An application of induction and deduction

The iteration of induction and deduction can be nicely demonstrated with the Hardy-Weinberg-Equilibrium (HWE), which is a fundamental principle of population genetics. The HWE allows to calculate the frequency of genotypes in a population under certain assumptions (premises) using a simple formula.

Briefly, the HWE states that if certain conditions of a population such as an infinite (or very large) size and random mating are met, the frequencies of a genotype frequencies (combinations of individual alleles such as AA, Aa, aa) can be calculated from the allele frequencies (e.g., p for allele A and q for allele a) at locus A.

The formula for calculation is the following

Genotype	AA	Aa	aa
Frequency	p^2	$2pq$	q^2

We can now define two different problems that are either solved with deduction, or induction.

Problem 1. Assume that a very large plant population is in Hardy-Weinberg equilibrium at a locus.

From this population 100 individuals are sampled.

→ Which genotype frequencies at this locus can be **expected** in the sample?

⇒ Deduction with the Hardy-Weinberg-Formula

Problem 2. A sample of 100 plants from a population are genotyped. → What are the **observed** genotype frequencies in the population? ⇒ Induction: Is the population in Hardy-Weinberg equilibrium? Approach: Compare observed with expected frequencies.

These types of quantitative inference (both deductive and inductive) need a mathematical model describing the relationship between sample and population that are given by the mathematical formulae of the HWE.

5 Summary

- Deduction reasons from general to specific
- Any conclusions from valid deductive arguments are true
- Uses of deduction: Deduct hypotheses from theoretical models or falsify theories
- The validity of logical arguments can be checked with a truth table
- Deduction is often applied incorrectly. This misuse results in unjustified conclusions.
- Induction derives general claims from a sample of observations
- The general claim is not true *per se*, but only /likely/ true (with high probability)
- The scientific method is built from the interplay of deduction and incduction
- Statistics is the application and quantification of induction

6 Key concepts

- Argument
- Deductive argument *versus* inductive argument
- Proposition, statement, conclusion
- Propositional logic
- Uniformity and Hume's problem
- Statistics as applied inductive reasoning

7 Further reading

- Weston (2009) *A rulebook for arguments.* 4th edition. Hackett Publishing Company. 88p. Excellent short and very accessible introduction into making arguments. See Chapters II, III, IV, V, VI, VII.
- Gauch (2002) *Scientific Method in Practice.* Cambridge University Press. Chapters 5 and 7.
- Priest (2000) *Logic - A Very Short Introduction* Oxford University Press.
- Wikipedia entry on propositional logic: Link

8 Review questions

1. Why is deduction important for doing science?

2. Can you verify a deductive argument by an experiment?

3. We have the hypothesis that a certain disease is caused by either a deleterious recessive allele at locus A or at locus B. The disease is very rare. We are not really sure whether the hypothesis is true. Design an experiment to try to falsify this hypothesis.

5. What are the key differences between inductive and deductive arguments? Is deduction superior to induction, or are they complementary in scientific thinking?

6. Why is the uniformity of nature (UoN) assumption so important in the use of induction?

7. Do you know some examples in agriculture in which the assumption of a uniformity of nature is violated?

8. What is the use of statistics in inductive arguments?

References

Weston A. 2008. A rulebook for arguments. Hackett Publishing.