Discrete Mathematics in Computer Science

A2. Proofs I

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What is a Proof?

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What is a statement?

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Notes:

- set of preconditions is sometimes empty
- often, “assumptions” is used instead of “preconditions”; slightly unfortunate because “assumption” is also used with another meaning ($\rightsquigarrow$ cf. indirect proofs)

Examples of Mathematical Statements

Examples (some true, some false):

- "Let $p \in \mathbb{N}_0$ be a prime number. Then p is odd."
- "There exists an even prime number."
- "Let $p \in \mathbb{N}_0$ with $p \geq 3$ be a prime number. Then p is odd."
- "All prime numbers $p \geq 3$ are odd."
- "For all sets A, B, C: $A \cap (B \cup C) = (A \cap B) \cup (A \cap C)$"

What are the preconditions, what are the conclusions?

On what Statements can we Build the Proof?

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We can use:

- axioms: statements that are assumed to always be true
  in the current context
- theorems and lemmas: statements that were already proven
  - lemma: an intermediate tool
  - theorem: itself a relevant result
- premises: assumptions we make
  to see what consequences they have

What is a Logical Step?

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Each step directly follows

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For a formal definition, we would need formal logics.

The Role of Definitions

Definition

A set is an unordered collection of distinct objects.

The objects in a set are called the elements of the set.

We write $x \in S$ to indicate that x is an element of set S, and $x \notin S$ to indicate that S does not contain x.

The set that does not contain any objects is the *empty set* $\emptyset$.

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- A definition introduces an abbreviation.
- Whenever we say "set", we could instead say "an unordered collection of distinct objects" and vice versa.
- Definitions can also introduce notation.

Disproofs

- A disproof (refutation) shows that a given mathematical statement is false by giving an example where the preconditions are true, but the conclusion is false.
- This requires deriving, in a sequence of proof steps, the opposite (negation) of the conclusion.

A Word on Style

A proof should help the reader to see why the result must be true.

- A proof should be easy to follow.
- Omit unnecessary information.
- Move self-contained parts into separate lemmas.
- In complicated proofs, reveal the overall structure in advance.
- Have a clear line of argument.

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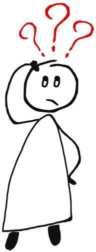
Recommended reading (ADAM additional ressources):

- "Some Remarks on Writing Mathematical Proofs" (John M. Lee)
- "§1. Minicourse on technical writing" of "Mathematical Writing" (Donald E. Knuth, Tracy Larrabee, and Paul M. Roberts)

Questions



Questions?

Proof Strategies

Common Forms of Statements

Many statements have one of these forms:

1. "All $x \in S$ with the property P also have the property Q."
2. "A is a subset of B."
3. "For all $x \in S$: x has property P iff x has property Q."
4. "$A = B$", where A and B are sets.

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In the following, we will discuss some typical proof/disproof strategies for such statements.

Proof Strategies

1. "All $x \in S$ with the property P also have the property Q."
   "For all $x \in S$: if x has property P, then x has property Q."
   - To prove, assume you are given an arbitrary $x \in S$ that has the property P.
     Give a sequence of proof steps showing that x must have the property Q.
   - To disprove, find a counterexample, i. e., find an $x \in S$ that has property P but not Q and prove this.

Proof Strategies

2. "A is a subset of B."
   - To prove, assume you have an arbitrary element $x \in A$ and prove that $x \in B$.
   - To disprove, find an element in $x \in A \setminus B$ and prove that $x \in A \setminus B$.

Proof Strategies

3. "For all $x \in S$: x has property P iff x has property Q."
   ("iff": "if and only if")
   - To prove, separately prove "if P then Q" and "if Q then P".
   - To disprove, disprove "if P then Q" or disprove "if Q then P".

Proof Strategies

4. "$A = B$", where A and B are sets.
   - To prove, separately prove "$A \subseteq B$" and "$B \subseteq A$".
   - To disprove, disprove "$A \subseteq B$" or disprove "$B \subseteq A$".

Proof Techniques

most common proof techniques:

- direct proof
- indirect proof (proof by contradiction)
- contrapositive
- mathematical induction
- structural induction

Direct Proof

Direct Proof

Direct Proof

Direct derivation of the statement by deducing or rewriting.

Direct Proof: Example

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Indirect Proof

Indirect Proof

Indirect Proof (Proof by Contradiction)

- Make an assumption that the statement is false.
- Derive a contradiction from the assumption together with the preconditions of the statement.
- This shows that the assumption must be false given the preconditions of the statement, and hence the original statement must be true.

Indirect Proof: Example

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Proof by Contrapositive

Contrapositive

(Proof by) Contrapositive

Prove "If A, then B" by proving "If not B, then not A."

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(Proof by) Contrapositive

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Examples:

- Prove "For all $n \in \mathbb{N}_0$: if n^2 is odd, then n is odd" by proving "For all $n \in \mathbb{N}_0$, if n is even, then n^2 is even."
- Prove "For all $n \in \mathbb{N}_0$: if n is not a square number, then $\sqrt{n}$ is irrational" by proving "For all $n \in \mathbb{N}_0$: if $\sqrt{n}$ is rational, then n is a square number."

Contrapositive: Example

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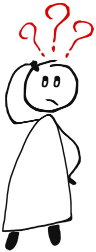
Questions



Questions?

Excursus: Computer-assisted Theorem Proving

Computer-assisted Proofs

- Computers can help proving theorems.
- Computer-aided proofs have for example been used for proving theorems by exhaustion.
- Example: Four color theorem

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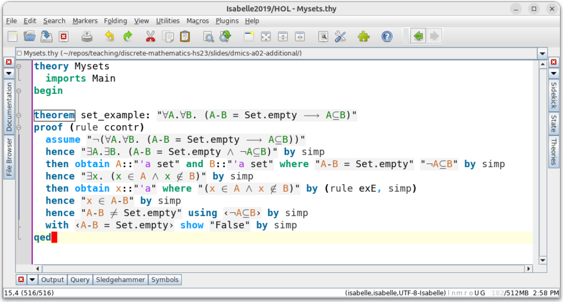
- Example theorem provers: Isabelle/HOL, Lean

Example



⇝ Demo

Summary

Summary

- A proof should convince the reader by logical steps of the truth of some mathematical statement.
- There are standard strategies for proving some common forms of statements, e.g. some property of all elements of a set.
- Direct proof: derive statement by deducing or rewriting.
- Indirect proof: derive contradiction from the assumption that the statement is false.
- Proof by contrapositive: Prove "If A, then B" by proving "If not B, then not A.".