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Review of formal proof techniques

Why do we need proofs in CS.

specification ⟹ SW

How do we know that the SW respects the specification?

specification ⟹ formal specification

SW ⟵ satisfies? ⟶ formal specification

satisfies? < testing
⋮
proving = understanding how a complex program works

Deductive proofs:

- start from a set H of hypotheses (i.e., given statements)
- show that if H is true, the a conclusion C is also true
- this is done through a sequence of steps:
  - for every step a new fact follows from H and/or previously proved facts by some accepted logical principle
  - the final fact of the sequence is C

Note: the hypothesis H may be either true or false

What we have proved when we go from H to C is:
"if H then C"

Note2: H and C may depend on parameters that affect their truth-value

Example: "If n is even, then n^2 is even"

What does it mean that n is even?

There is an integer k s.t. $n = 2k$.

H : n is even (note: H has n as parameter)

by Def. : there exist k s.t. $n = 2k$

by rules of mult. : $n^2 = (2\cdot k)^2 = 2^2 \cdot k^2 = 2\cdot(2\cdot k^2)$

by integer arithm. $2\cdot k^2 = h$ is an integer

by Def. : $n^2 = 2\cdot h$ is even

Other ways of stating if-then statements:

if H then C

H implies C

H only if C   C if H

whenever H holds, also C holds

If-and-only-if statements:

A if-and-only-if B

if part: A if B , i.e. if B then A

only-if part: A only-if B i.e. if A then B

To prove "A iff B", we must prove both the "If part" and the "Only-if part"

Example: $\lfloor x \rfloor$ = greatest integer $\leq x$
floor x

$\lceil x \rceil$ = least integer $\geq x$
ceiling x

Prove: Let x be a real number.

Then $\lfloor x \rfloor = \lceil x \rceil$ iff x is an integer.

Proof:

"If-part": we assume x is an integer and prove $\lfloor x \rfloor = \lceil x \rceil$

We use the definition: if x is an integer $\lfloor x \rfloor = x$

$\lceil x \rceil = x$

$\Rightarrow \lfloor x \rfloor = \lceil x \rceil$

"Only-if part": we assume $\lfloor x \rfloor = \lceil x \rceil$ and prove that x is an integer

Def of floor: $\lfloor x \rfloor \leq x$ (1)

" ceiling: $\lceil x \rceil \geq x$ (2)

Hypothesis: $\lfloor x \rfloor = \lceil x \rceil$ (3)

Substituting $\lceil x \rceil$ in place of $\lfloor x \rfloor$, we get from (1)

$\lceil x \rceil \leq x$ and with (2) and arithmetic laws,

we get $\lceil x \rceil = x$

Since $\lceil x \rceil$ is an integer, so is x

Other forms of proofs:

- Proving equivalences of sets

e.g. show that the language accepted by A_1 is the same as " A_2

To show $E = F$ we have to show

expressions representing sets

1) $E \subseteq F$, i.e. if $x \in E$ then $x \in F$

2) $F \subseteq E$, i.e. if $x \in F$ then $x \in E$

Example: $\underbrace{R \cup (S \cap T)}_{E} = \underbrace{(R \cup S) \cap (R \cup T)}_{F}$

1) If $x \in R \cup (S \cap T)$ then $x \in (R \cup S) \cap (R \cup T)$

   See HMU Figure 1.5

2) If $x \in (R \cup S) \cap (R \cup T)$ then $x \in R \cup (S \cap T)$

   See HMU Figure 1.6

- Contrapositive:

To prove: "if H then C"

we can prove its contrapositive: "if not C, then not H"

We can easily see that a statement and its contrapositive are logically equivalent (i.e., either both true, or both false)

4 cases:

H	C	if H then C	if not C then not H
true	true	true	true
true	false	false	false
false	true	true	true
false	false	true	true

Example: "if n is even, then n^2 is even"

contrapositive: "if n^2 is not even, then n is not even"

Don't confuse contrapositive, with converse.

Note: To prove an iff statement, we prove a statement and its converse

- Proof by contradiction:

To prove "if H then C"
prove that "H and not C implies falsehood"

Example: H = "U is an infinite set
S is a finite subset of U
T is the complement of S wrt U"

C = "T is infinite"

Proof by contradiction of "if H then C"

Assume H and not C, i.e. H and T is finite.

(A set S is finite iff there is an integer n s.t. $|S| = n$ ← number of elements of S)

S is finite ⇒ there is n s.t. $|S| = n$
T is finite ⇒ ... m $|T| = m$

From H we know: $\left.\begin{array}{l} S \cup T = U \\ S \cap T = \emptyset \end{array}\right\} |S \cup T| = |U| = n+m$

⇒ U is finite, which is a contradiction

- Proof by counterexample:

- to prove something is not a theorem is often easier than to prove something is a theorem

It is sufficient to provide a counterexample

e.g. All odd numbers > 1 are prime

9 is not, which is a counterexample

Proof by induction:

Basic proof technique when dealing with recursively defined objects

- integers:
  - 0 is an integer
  - if n is an integer, then $n+1$ is an integer
  - nothing else is an integer

- strings
  - ε is a string
  - if x is a string and $a \in \Sigma$, then $x \cdot a$ is a string
  - nothing else is a string

- binary trees
  - a single node is a BT
  - if N is a single node and T_1, T_2 are BT then $\begin{array}{ccc} & N & \\ / & & \backslash \\ T_1 & & T_2 \end{array}$ is a BT
  - nothing else is a BT

Induction on integers:

We want to prove a statement $S(n)$ about integer n.

We show:

1) We show $S(i)$, for some specific integer i (e.g. $i=0$) (base step)

2) We assume $n \geq i$ and show "if $S(n)$ then $S(n+1)$" (inductive step)

We then resort to the Induction Principle

If we prove $S(i)$ and we prove that
for all $n \geq i$ "$S(n)$ implies $S(n+1)$"
then we can conclude $S(n)$ for all $n \geq i$

N.B. The IP cannot be proved

Example: For all $n \geq 0$ $\sum_{i=1}^{n} i = \frac{n(n+1)}{2}$ (*)

base case $n = 0$: $\sum_{i=1}^{0} i = 0$

inductive case: assume $n \geq 0$

we must prove that (*) implies $\sum_{i=1}^{n+1} i = \frac{(n+1)(n+2)}{2}$

(*) is called the inductive hypothesis

$$\sum_{i=1}^{n+1} i = \sum_{i=1}^{n} i + (n+1) \underset{\text{by IH}}{=} \frac{n \cdot (n+1)}{2} + (n+1) =$$

$$= \frac{n \cdot (n+1)}{2} + \frac{2 \cdot (n+1)}{2} = \frac{(n+2) \cdot (n+1)}{2}$$

Generalization of the basic induction scheme

1) We can use several base cases, i.e. we prove $S(i), S(i+1), \ldots, S(j)$ for some $j > i$

2) In proving $S(n)$, we use all of $S(i), S(i+1), \ldots, S(n)$ (strong induction)