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Proof Techniques

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Learning Outcomes

Unit 1: *Proof Techniques*

1. Know logical *proof strategies* for proving implications, set inclusions, set equalities, and quantified statements.
2. Be able to use *mathematical induction* in simple proofs.
3. Know techniques for *proving termination* and *correctness* of procedures.

Outline

1 Proof Techniques

- 1.1 Digression: Random Shuffle
- 1.2 Proof Templates
- 1.3 Mathematical Induction
- 1.4 Correctness Proofs

1.1 Digression: Random Shuffle

Random shuffle

- ▶ **Goal:** Put an array $A[0..n)$ of n numbers into random order.
More precisely: Any ordering of the elements $A[0], \dots, A[n-1]$ should be equally likely.
- ▶ A natural approach yields the following code

```
1 procedure myShuffle( $A[0..n)$ )  
2   for  $i := 0, \dots, n-1$   
3      $r := \text{randomInt}([0..n))$  // A uniformly random number  $r$  with  $0 \leq r < n$ .  
4     Swap  $A[i]$  and  $A[r]$  // Swap  $A[i]$  to random position.  
5   end for
```

- ▶ Intuitively: All elements are moved to a random index, so the order is random . . . right?

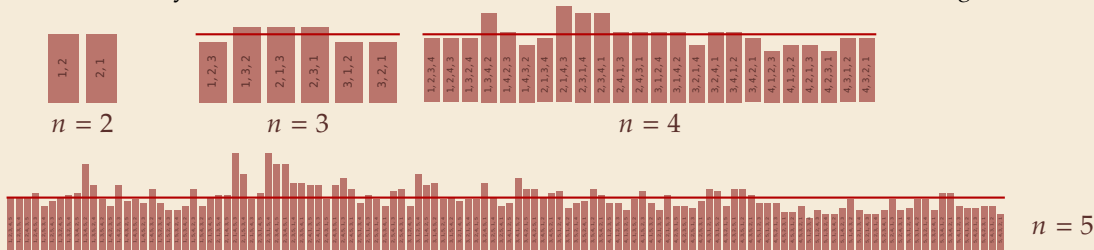
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5   end for
```

← **WRONG!**
DO NOT USE

- ▶ Intuitively: All elements are moved to a random index, so the order is random ... right????



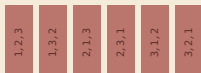
Correct shuffle

- ▶ interestingly, a very small change corrects the issue

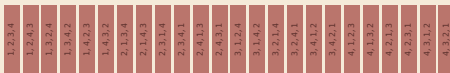
```
1 procedure shuffleKnuthFisherYates( $A[0..n]$ )  
2   for  $i := 0, \dots, n - 1$   
3      $r := \text{randomInt}([i..n])$   
4     Swap  $A[i]$  and  $A[r]$   
5   end for
```



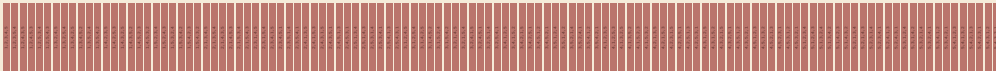
$n = 2$



$n = 3$



$n = 4$



$n = 5$

- ▶ looks good ...
- ▶ ... but how can we convince ourselves that it is correct, *beyond any doubt*?

1.2 Proof Templates

What is a *formal* proof?

A formal proof (in a logical system) is a **sequence of statements** such that each statement

1. is an *axiom* (of the logical system), OR
2. follows from previous statements using the *inference rules* (of the logical system).

Among experts: Suffices to *convince a human* that a formal proof *exists*.

But: Use formal logic as guidance against faulty reasoning. \rightsquigarrow bulletproof



Notation:

- ▶ Statements: $A \equiv$ "it rains", $B \equiv$ "the street is wet".
- ▶ Negation: $\neg A$ "Not A "
- ▶ And/Or: $A \wedge B$ " A and B "; $A \vee B$ " A or B or both"
- ▶ Implication: $A \Rightarrow B$ "If A , then B "; $\neg A \vee B$
- ▶ Equivalence: $A \Leftrightarrow B$ " A holds true *if and only if* ('iff') B holds true."; $(A \Rightarrow B) \wedge (B \Rightarrow A)$

Implications

To prove $A \Rightarrow B$, we can

- ▶ directly derive B from A *direct proof*
- ▶ prove $(\neg B) \Rightarrow (\neg A)$ *indirect proof, proof by contraposition*
- ▶ assume $A \wedge \neg B$ and derive a contradiction *proof by contradiction, reductio ad absurdum*
- ▶ distinguish cases, i. e., separately prove
 $(A \wedge C) \Rightarrow B$ and $(A \wedge \neg C) \Rightarrow B$. *proof by exhaustive case distinction*

Equivalences

To prove $A \Leftrightarrow B$,

we prove both implications $A \Rightarrow B$ and $B \Rightarrow A$ separately.

(Often, one direction is much easier than the other.)

Set Inclusion and Equality

To prove that a set S contains a set R , i. e., $R \subseteq S$,
we prove the implication $x \in R \Rightarrow x \in S$.

To prove that two sets S and R are equal, $S = R$,
we prove both inclusions, $S \subseteq R$ and $R \subseteq S$ separately.

1.3 Mathematical Induction

Quantified Statements

Notation

- ▶ Statements with parameters: $A(x) \equiv$ “ x is an even number.”
- ▶ Existential quantifiers: $\exists x : A(x)$ “There exists some x , so that $A(x)$.”
- ▶ Universal quantifiers: $\forall x : A(x)$ “For all x it holds that $A(x)$.”

Note: $\forall x : A(x)$ is equivalent to $\neg \exists x : \neg A(x)$

Quantifiers can be nested, e. g., ε - δ -criterion for limits:

$$\lim_{x \rightarrow \xi} f(x) = a \quad :\Leftrightarrow \quad \forall \varepsilon > 0 \exists \delta > 0 : (|x - \xi| < \delta) \Rightarrow |f(x) - a| < \varepsilon.$$


To prove $\exists x : A(x)$, we simply list an example ξ such that $A(\xi)$ is true.

For-all statements

To prove $\forall x : A(x)$, we can

- ▶ derive $A(x)$ for an “arbitrary but fixed value of x ”, or,
- ▶ for $x \in \mathbb{N}_0$, use **induction**, i. e.,
 - ▶ prove $A(0)$, *induction basis*, and
 - ▶ prove $\forall n \in \mathbb{N}_0 : A(n) \Rightarrow A(n + 1)$ *inductive step*

More general variants of induction:

- ▶ complete/strong induction
inductive step shows $(A(0) \wedge \cdots \wedge A(n)) \Rightarrow A(n + 1)$
- ▶ structural/transfinite induction
works on any *well-ordered* set, e. g., binary trees, graphs, Boolean formulas, strings, . . .

no infinite strictly decreasing chains

1.4 Correctness Proofs

Formal verification

► verification: prove that a program computes the correct result

↪ not our key focus in CS 566

but same techniques are useful for *reasoning* about algorithms

Here:

1. Prove that loop or recursive call eventually *terminates*.
2. Prove that a *loop* computes the *correct* result.

Proving termination

To prove that a recursive procedure $\text{proc}(x_1, \dots, x_m)$ eventually terminates, we

- ▶ define a *potential* $\Phi(x_1, \dots, x_m) \in \mathbb{N}_0$ of the parameters
(Note: $\Phi(x_1, \dots, x_m) \geq 0$ by definition!)
- ▶ prove that every recursive call decreases the potential, i. e.,
any recursive call $\text{proc}(y_1, \dots, y_m)$ inside $\text{proc}(x_1, \dots, x_m)$ satisfies

$$\begin{aligned}\Phi(y_1, \dots, y_m) &< \Phi(x_1, \dots, x_m) && \text{which means} \\ \Phi(y_1, \dots, y_m) &\leq \Phi(x_1, \dots, x_m) - \mathbf{1}\end{aligned}$$

\rightsquigarrow $\text{proc}(x_1, \dots, x_m)$ terminates because
we can only strictly *decrease* the (integral) potential
a *finite* number of times from its initial value

- ▶ Can use same idea for a loop: show that potential decreases in each iteration.
 \rightsquigarrow see tutorials for an example.

Loop invariants

Goal: Prove that a *post condition* holds after execution of a (terminating) loop.

```
1 // (A) before loop
2 while cond do
3   // (B) before body
4   body
5   // (C) after body
6 end while
7 // (D) after loop
```

For that, we

- ▶ find a *loop invariant* I (that's the tough part!)
- ▶ prove that I holds at (A)
- ▶ prove that $I \wedge \textit{cond}$ at (B) imply I at (C)
- ▶ prove that $I \wedge \neg \textit{cond}$ imply the desired post condition at (D)

Note: I holds before, during, and after the loop execution, hence the name.

Loop invariant – Example

► loop condition: $cond \equiv j < n$

► post condition (in line 13):

$$curMax = \max_{k \in [0..n-1]} A[k]$$

► loop invariant:

$$I \equiv curMax = \max_{k \in [0..j-1]} A[k] \wedge j \leq n$$

We have to proof:

(i) I holds at (A)

(ii) $I \wedge cond$ at (B) $\Rightarrow I$ at (C)

(iii) $I \wedge \neg cond \Rightarrow$ post condition

```
1  procedure arrayMax( $A, n$ )
2      // input: array of  $n$  elements,  $n \geq 1$ 
3      // output: the maximum element in  $A[0..n-1]$ 
4       $curMax := A[0]$ ;  $j := 1$ 
5      // (A)
6      while  $j < n$  do
7          // (B)
8          if  $A[j] > curMax$ 
9               $curMax := A[j]$ 
10              $j := j + 1$ 
11             // (C)
12         end while
13         // (D)
14         return  $curMax$ 
```

Loop invariant – Example