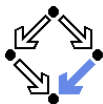
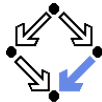


Hoare Calculus and Predicate Transformers

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1. The Hoare Calculus for Non-Loop Programs

2. Predicate Transformers

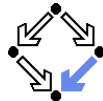
3. Partial Correctness of Loop Programs

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The Hoare Calculus

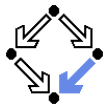


Calculus for reasoning about imperative programs.

- **“Hoare triple”**: $\{P\} c \{Q\}$
 - Logical propositions P and Q , program command c .
 - The Hoare triple is itself a logical proposition.
 - The Hoare calculus gives rules for constructing true Hoare triples.
- **Partial correctness** interpretation of $\{P\} c \{Q\}$:
 - “If c is executed in a state in which P holds, then it terminates in a state in which Q holds **unless it aborts or runs forever.**”
 - Program does not produce wrong result.
 - But program also need not produce **any** result.
 - Abortion and non-termination are not ruled out.
- **Total correctness** interpretation of $\{P\} c \{Q\}$:
 - “If c is executed in a state in which P holds, then it terminates in a state in which Q holds.”
 - Program produces the correct result.

We will use the partial correctness interpretation for the moment.

General Rule



$$\frac{P \Rightarrow P' \quad \{P'\} c \{Q'\} \quad Q' \Rightarrow Q}{\{P\} c \{Q\}}$$

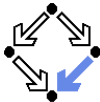
■ Logical derivation: $\frac{A_1 \ A_2}{B}$

- Forward: If we have shown A_1 and A_2 , then we have also shown B .
- Backward: To show B , it suffices to show A_1 and A_2 .

■ Interpretation of above sentence:

- To show that, if P holds, then Q holds after executing c , it suffices to show this for a P' weaker than P and a Q' stronger than Q .

Precondition may be weakened, postcondition may be strengthened.



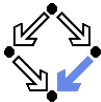
Special Commands

Commands modeling “emptiness” and abortion.

$$\{P\} \mathbf{skip} \{P\} \quad \{\mathbf{true}\} \mathbf{abort} \{\mathbf{false}\}$$

- The **skip** command does not change the state; if P holds before its execution, then P thus holds afterwards as well.
- The **abort** command aborts execution and thus trivially satisfies partial correctness.
 - Axiom implies $\{P\} \mathbf{abort} \{Q\}$ for arbitrary P, Q .

Useful commands for reasoning and program transformations.



Scalar Assignments

$$\{Q[e/x]\} x := e \{Q\}$$

■ Syntax

- Variable x , expression e .
- $Q[e/x] \dots Q$ where every free occurrence of x is replaced by e .

■ Interpretation

- To make sure that Q holds for x after the assignment of e to x , it suffices to make sure that Q holds for e before the assignment.

■ Partial correctness

- Evaluation of e may abort.

$$\begin{array}{l} \{x + 3 < 5\} \quad x := x + 3 \quad \{x < 5\} \\ \{x < 2\} \quad x := x + 3 \quad \{x < 5\} \end{array}$$



Array Assignments

$$\{Q[a[i \mapsto e]/a]\} \ a[i] := e \ \{Q\}$$

- An array is modelled as a **function** $a : I \rightarrow V$.
 - Index set I , value set V .
 - $a[i] = e$... array a contains at index i the value e .
- **Term** $a[i \mapsto e]$ (“array a updated by assigning value e to index i ”)
 - A new array that contains at index i the value e .
 - All other elements of the array are the same as in a .
- **Thus array assignment becomes a special case of scalar assignment.**
 - Think of “ $a[i] := e$ ” as “ $a := a[i \mapsto e]$ ”.

$$\{\underline{a[i \mapsto x]}[1] > 0\} \ a[i] := x \ \{a[1] > 0\}$$

Arrays are here considered as basic values (no pointer semantics).



Array Assignments

How to reason about $a[i \mapsto e]$?

$$\begin{aligned} & Q[\underline{a[i \mapsto e]}[j]] \\ & \rightsquigarrow \\ & (i = j \Rightarrow Q[e]) \wedge (i \neq j \Rightarrow Q[a[j]]) \end{aligned}$$

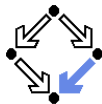
■ Array Axioms

$$\begin{aligned} i = j & \Rightarrow \underline{a[i \mapsto e]}[j] = e \\ i \neq j & \Rightarrow \underline{a[i \mapsto e]}[j] = a[j] \end{aligned}$$

$$\begin{array}{lll} \{ \underline{a[i \mapsto x]}[1] > 0 \} & a[i] := x & \{ a[1] > 0 \} \\ \{ (i = 1 \Rightarrow x > 0) \wedge (i \neq 1 \Rightarrow a[1] > 0) \} & a[i] := x & \{ a[1] > 0 \} \end{array}$$

Get rid of “array update terms” when applied to indices.

Command Sequences



$$\frac{\{P\} c_1 \{R_1\} \quad R_1 \Rightarrow R_2 \quad \{R_2\} c_2 \{Q\}}{\{P\} c_1; c_2 \{Q\}}$$

■ Interpretation

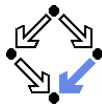
- To show that, if P holds before the execution of $c_1; c_2$, then Q holds afterwards, it suffices to show for some R_1 and R_2 with $R_1 \Rightarrow R_2$ that
 - if P holds before c_1 , that R_1 holds afterwards, and that
 - if R_2 holds before c_2 , then Q holds afterwards.

■ Problem: find suitable R_1 and R_2

- Typically $R_1 = R_2$.
- Easy in many cases (see later).

$$\frac{\{x + y - 1 > 0\} y := y - 1 \quad \{x + y > 0\} \quad \{x + y > 0\} x := x + y \quad \{x > 0\}}{\{x + y - 1 > 0\} y := y - 1; x := x + y \quad \{x > 0\}}$$

Conditionals



$$\frac{\{P \wedge b\} c_1 \{Q\} \quad \{P \wedge \neg b\} c_2 \{Q\}}{\{P\} \text{ if } b \text{ then } c_1 \text{ else } c_2 \{Q\}}$$

$$\frac{\{P \wedge b\} c \{Q\} \quad (P \wedge \neg b) \Rightarrow Q}{\{P\} \text{ if } b \text{ then } c \{Q\}}$$

■ Interpretation

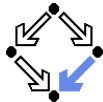
- To show that, if P holds before the execution of the conditional, then Q holds afterwards,
- it suffices to show that the same is true for each conditional branch, under the additional assumption that this branch is executed.

$$\frac{\{x \neq 0 \wedge x \geq 0\} y := x \quad \{y > 0\} \quad \{x \neq 0 \wedge x < 0\} y := -x \quad \{y > 0\}}{\{x \neq 0\} \text{ if } x \geq 0 \text{ then } y := x \text{ else } y := -x \quad \{y > 0\}}$$



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Backward Reasoning



Implication of rule for command sequences and rule for assignments:

$$\frac{\{P\} c \{Q[e/x]\}}{\{P\} c; x := e \{Q\}}$$

■ Interpretation

- If the last command of a sequence is an assignment, we can remove the assignment from the proof obligation.
- By multiple application, assignment sequences can be removed from the back to the front.

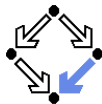
$$\begin{array}{l} \{P\} \\ x := x+1; \\ y := 2*x; \\ z := x+y \\ \{z = 15\} \end{array}$$

$$\begin{array}{l} \{P\} \\ x := x+1; \\ y := 2*x; \\ \{x + y = 15\} \end{array}$$

$$\begin{array}{l} \{P\} \\ x := x+1; \\ \{x + 2x = 15\} \\ (\Leftrightarrow 3x = 15) \\ (\Leftrightarrow x = 5) \end{array}$$

$$\begin{array}{l} \{P\} \\ \{x + 1 = 5\} \\ (\Leftrightarrow x = 4) \end{array}$$

$$P \Rightarrow x = 4$$

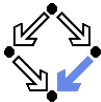


Weakest Preconditions

A calculus for “backward reasoning”.

- **Predicate transformer wp**
 - Function “wp” that takes a command c and a postcondition Q and returns a precondition.
 - Read $\text{wp}(c, Q)$ as “the weakest precondition of c w.r.t. Q ”.
- $\text{wp}(c, Q)$ is a **precondition** for c that ensures Q as a postcondition.
 - Must satisfy $\{\text{wp}(c, Q)\} c \{Q\}$.
- $\text{wp}(c, Q)$ is the **weakest** such precondition.
 - Take any P such that $\{P\} c \{Q\}$.
 - Then $P \Rightarrow \text{wp}(c, Q)$.
- **Consequence:** $\{P\} c \{Q\}$ iff $(P \Rightarrow \text{wp}(c, Q))$
 - We want to prove $\{P\} c \{Q\}$.
 - We may prove $P \Rightarrow \text{wp}(c, Q)$ instead.

Verification is reduced to the calculation of weakest preconditions.



Weakest Preconditions

The weakest precondition of each program construct.

$$\text{wp}(\text{skip}, Q) \Leftrightarrow Q$$

$$\text{wp}(\text{abort}, Q) \Leftrightarrow \text{true}$$

$$\text{wp}(x := e, Q) \Leftrightarrow Q[e/x]$$

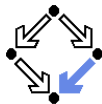
$$\text{wp}(c_1; c_2, Q) \Leftrightarrow \text{wp}(c_1, \text{wp}(c_2, Q))$$

$$\text{wp}(\text{if } b \text{ then } c_1 \text{ else } c_2, Q) \Leftrightarrow (b \Rightarrow \text{wp}(c_1, Q)) \wedge (\neg b \Rightarrow \text{wp}(c_2, Q))$$

$$\text{wp}(\text{if } b \text{ then } c, Q) \Leftrightarrow (b \Rightarrow \text{wp}(c, Q)) \wedge (\neg b \Rightarrow Q)$$

Alternative formulation of a program calculus.

Forward Reasoning



Sometimes, we want to derive a postcondition from a given precondition.

$$\{P\} x := e \{ \exists x_0 : P[x_0/x] \wedge x = e[x_0/x] \}$$

■ Forward Reasoning

- What is the maximum we know about the post-state of an assignment $x := e$, if the pre-state satisfies P ?
- We know that P holds for some value x_0 (the value of x in the pre-state) and that x equals $e[x_0/x]$.

$$\begin{aligned} & \{x \geq 0 \wedge y = a\} \\ & \quad x := x + 1 \\ & \{ \exists x_0 : x_0 \geq 0 \wedge y = a \wedge x = x_0 + 1 \} \\ & (\Leftrightarrow (\exists x_0 : x_0 \geq 0 \wedge x = x_0 + 1) \wedge y = a) \\ & (\Leftrightarrow x > 0 \wedge y = a) \end{aligned}$$

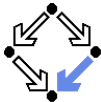


Strongest Postcondition

A calculus for forward reasoning.

- **Predicate transformer sp**
 - Function “sp” that takes a precondition P and a command c and returns a postcondition.
 - Read $\text{sp}(P, c)$ as “the strongest postcondition of c w.r.t. P ”.
- $\text{sp}(P, c)$ is a **postcondition** for c that is ensured by precondition P .
 - Must satisfy $\{P\} c \{\text{sp}(P, c)\}$.
- $\text{sp}(P, c)$ is the **strongest** such postcondition.
 - Take any P, Q such that $\{P\} c \{Q\}$.
 - Then $\text{sp}(P, c) \Rightarrow Q$.
- **Consequence:** $\{P\} c \{Q\}$ iff $(\text{sp}(P, c) \Rightarrow Q)$.
 - We want to prove $\{P\} c \{Q\}$.
 - We may prove $\text{sp}(P, c) \Rightarrow Q$ instead.

Verification is reduced to the calculation of strongest postconditions.



Strongest Postconditions

The strongest postcondition of each program construct.

$$\text{sp}(P, \mathbf{skip}) \Leftrightarrow P$$

$$\text{sp}(P, \mathbf{abort}) \Leftrightarrow \text{false}$$

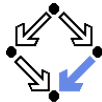
$$\text{sp}(P, x := e) \Leftrightarrow \exists x_0 : P[x_0/x] \wedge x = e[x_0/x]$$

$$\text{sp}(P, c_1; c_2) \Leftrightarrow \text{sp}(\text{sp}(P, c_1), c_2)$$

$$\text{sp}(P, \mathbf{if } b \mathbf{ then } c_1 \mathbf{ else } c_2) \Leftrightarrow \text{sp}(P \wedge b, c_1) \vee \text{sp}(P \wedge \neg b, c_2)$$

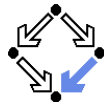
$$\text{sp}(P, \mathbf{if } b \mathbf{ then } c) \Leftrightarrow \text{sp}(P \wedge b, c) \vee (P \wedge \neg b)$$

The use of predicate transformers is an alternative/supplement to the Hoare calculus; this view is due to Dijkstra.



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The Hoare Calculus and Loops



$$\{ \text{true} \} \text{ loop } \{ \text{false} \} \quad \frac{P \Rightarrow I \quad \{ I \wedge b \} c \quad \{ I \} \quad (I \wedge \neg b) \Rightarrow Q}{\{ P \} \text{ while } b \text{ do } c \quad \{ Q \}}$$

■ Interpretation:

- The **loop** command does not terminate and thus trivially satisfies partial correctness.

- Axiom implies $\{ P \} \text{ loop } \{ Q \}$ for arbitrary P, Q .

- To show that, if before the execution of a **while**-loop the property P holds, after its termination the property Q holds, it suffices to show for some property I (the **loop invariant**) that

- I holds before the loop is executed (i.e. that P implies I),

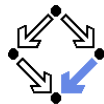
- if I holds when the loop body is entered (i.e. if also b holds), that after the execution of the loop body I still holds,

- when the loop terminates (i.e. if b does not hold), I implies Q .

■ Problem: find appropriate loop invariant I .

- Strongest relationship between all variables modified in loop body.

Example



$$I :\Leftrightarrow s = \sum_{j=1}^{i-1} j \wedge 1 \leq i \leq n + 1$$

$$(n \geq 0 \wedge i = 1 \wedge s = 0) \Rightarrow I$$

$$\{I \wedge i \leq n\} s := s + i; i := i + 1 \{I\}$$

$$(I \wedge i \not\leq n) \Rightarrow s = \sum_{j=1}^n j$$

$$\{n \geq 0 \wedge i = 1 \wedge s = 0\} \text{ while } i \leq n \text{ do } (s := s + i; i := i + 1) \{s = \sum_{j=1}^n j\}$$

The invariant captures the “essence” of a loop; only by giving its invariant, a true understanding of a loop is demonstrated.

Practical Aspects



We want to verify the following program:

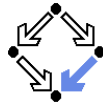
$$\{P\} c_1; \mathbf{while} \ b \ \mathbf{do} \ c; c_2 \ \{Q\}$$

- Assume c_1 and c_2 do not contain loop commands.
- It suffices to prove

$$\{\text{sp}(P, c_1)\} \mathbf{while} \ b \ \mathbf{do} \ c \ \{\text{wp}(c_2, Q)\}$$

Verification of loops is the core of most program verifications.

Weakest Liberal Preconditions for Loops



$\text{wp}(\text{loop}, Q) \Leftrightarrow \text{true}$

$\text{wp}(\text{while } b \text{ do } c, Q) \Leftrightarrow \forall i \in \mathbb{N} : L_i(Q)$

$L_0(Q) :\Leftrightarrow \text{true}$

$L_{i+1}(Q) :\Leftrightarrow (\neg b \Rightarrow Q) \wedge (b \Rightarrow \text{wp}(c, L_i(Q)))$

■ Interpretation

- Weakest precondition that ensures that loops stops in a state satisfying Q , unless it aborts or runs forever.

■ Infinite sequence of predicates $L_i(Q)$:

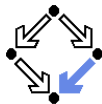
- Weakest precondition that ensures that **after less than i iterations** the state satisfies Q , unless the loop aborts or does not yet terminate.

■ Alternative view: $L_i(Q) \Leftrightarrow \text{wp}(\text{if}_i, Q)$

$\text{if}_0 := \text{loop}$

$\text{if}_{i+1} := \text{if } b \text{ then } (c; \text{if}_i)$

Example



$\text{wp}(\text{while } i < n \text{ do } i := i + 1, Q)$

$L_0(Q) \Leftrightarrow \text{true}$

$L_1(Q) \Leftrightarrow (i \not< n \Rightarrow Q) \wedge (i < n \Rightarrow \text{wp}(i := i + 1, \text{true}))$

$\Leftrightarrow (i \not< n \Rightarrow Q) \wedge (i < n \Rightarrow \text{true})$

$\Leftrightarrow (i \not< n \Rightarrow Q)$

$L_2(Q) \Leftrightarrow (i \not< n \Rightarrow Q) \wedge (i < n \Rightarrow \text{wp}(i := i + 1, i \not< n \Rightarrow Q))$

$\Leftrightarrow (i \not< n \Rightarrow Q) \wedge$

$(i < n \Rightarrow (i + 1 \not< n \Rightarrow Q[i + 1/i]))$

$L_3(Q) \Leftrightarrow (i \not< n \Rightarrow Q) \wedge (i < n \Rightarrow \text{wp}(i := i + 1,$

$(i \not< n \Rightarrow Q) \wedge (i < n \Rightarrow (i + 1 \not< n \Rightarrow Q[i + 1/i])))$

$\Leftrightarrow (i \not< n \Rightarrow Q) \wedge$

$(i < n \Rightarrow ((i + 1 \not< n \Rightarrow Q[i + 1/i]) \wedge$

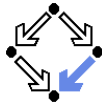
$(i + 1 < n \Rightarrow (i + 2 \not< n \Rightarrow Q[i + 2/i])))$



Weakest Liberal Preconditions for Loops

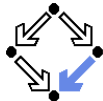
- Sequence $L_i(Q)$ is monotonically increasing in strength:
 - $\forall i \in \mathbb{N} : L_{i+1}(Q) \Rightarrow L_i(Q)$.
- The weakest precondition is the “lowest upper bound”:
 - $\forall i \in \mathbb{N} : \text{wp}(\text{while } b \text{ do } c, Q) \Rightarrow L_i(Q)$.
 - $\forall P : (\forall i \in \mathbb{N} : P \Rightarrow L_i(Q)) \Rightarrow (P \Rightarrow \text{wp}(\text{while } b \text{ do } c, Q))$.
- We can only compute weaker **approximation** $L_i(Q)$.
 - $\text{wp}(\text{while } b \text{ do } c, Q) \Rightarrow L_i(Q)$.
- We want to prove $\{P\} \text{ while } b \text{ do } c \{Q\}$.
 - This is equivalent to proving $P \Rightarrow \text{wp}(\text{while } b \text{ do } c, Q)$.
 - Thus $P \Rightarrow L_i(Q)$ must hold as well.
- If we can prove $\neg(P \Rightarrow L_i(Q))$, ...
 - $\{P\} \text{ while } b \text{ do } c \{Q\}$ does **not** hold.
 - If we fail, we may try the easier proof $\neg(P \Rightarrow L_{i+1}(Q))$.

Falsification is possible by use of approximation L_i , but verification is not.



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Total Correctness of Loops



Hoare rules for **loop** and **while** are replaced as follows:

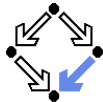
$$\frac{\begin{array}{c} P \Rightarrow I \quad I \Rightarrow t \geq 0 \\ \{I \wedge b \wedge t = N\} c \{I \wedge t < N\} \quad (I \wedge \neg b) \Rightarrow Q \end{array}}{\{P\} \text{ while } b \text{ do } c \{Q\}}$$

- New interpretation of $\{P\} c \{Q\}$.
 - If execution of c starts in a state where P holds, then execution **terminates** in a state where Q holds, unless it aborts.
 - Non-termination is ruled out, abortion not (yet).
 - The **loop** command thus does not satisfy total correctness.
- **Termination term t (type-checked to denote an integer)**.
 - Becomes smaller by every iteration of the loop.
 - But does not become negative.
 - Consequently, the loop must eventually terminate.

The initial value of t limits the number of loop iterations.

Any well-founded ordering may be used for the domain of t .

Example



$$I :\Leftrightarrow s = \sum_{j=1}^{i-1} j \wedge 1 \leq i \leq n + 1$$

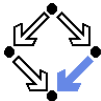
$$(n \geq 0 \wedge i = 1 \wedge s = 0) \Rightarrow I \quad I \Rightarrow n - i + 1 \geq 0$$

$$\{I \wedge i \leq n \wedge n - i + 1 = N\} s := s + i; i := i + 1 \quad \{I \wedge n - i + 1 < N\}$$

$$(I \wedge i \not\leq n) \Rightarrow s = \sum_{j=1}^n j$$

$$\{n \geq 0 \wedge i = 1 \wedge s = 0\} \text{ while } i \leq n \text{ do } (s := s + i; i := i + 1) \quad \{s = \sum_{j=1}^n j\}$$

In practice, termination is easy to show (compared to partial correctness).



Weakest Preconditions for Loops

$\text{wp}(\text{loop}, Q) \Leftrightarrow \text{false}$

$\text{wp}(\text{while } b \text{ do } c, Q) \Leftrightarrow \exists i \in \mathbb{N} : L_i(Q)$

$L_0(Q) :\Leftrightarrow \text{false}$

$L_{i+1}(Q) :\Leftrightarrow (\neg b \Rightarrow Q) \wedge (b \Rightarrow \text{wp}(c, L_i(Q)))$

■ New interpretation

- Weakest precondition that ensures that the loop terminates in a state in which Q holds, unless it aborts.

■ New interpretation of $L_i(Q)$

- Weakest precondition that ensures that the loop terminates **after less than i iterations** in a state in which Q holds, unless it aborts.

■ Preserves property: $\{P\} c \{Q\}$ iff $(P \Rightarrow \text{wp}(c, Q))$

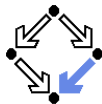
- Now for **total correctness** interpretation of Hoare calculus.

■ Preserves alternative view: $L_i(Q) \Leftrightarrow \text{wp}(\text{if}_i, Q)$

$\text{if}_0 := \text{loop}$

$\text{if}_{i+1} := \text{if } b \text{ then } (c; \text{if}_i)$

Example



$wp(\mathbf{while} \ i < n \ \mathbf{do} \ i := i + 1, Q)$

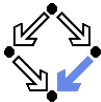
$L_0(Q) :\Leftrightarrow \text{false}$

$L_1(Q) :\Leftrightarrow (i \not< n \Rightarrow Q) \wedge (i < n \Rightarrow wp(i := i + 1, L_0(Q)))$
 $\Leftrightarrow (i \not< n \Rightarrow Q) \wedge (i < n \Rightarrow \text{false})$
 $\Leftrightarrow i \not< n \wedge Q$

$L_2(Q) :\Leftrightarrow (i \not< n \Rightarrow Q) \wedge (i < n \Rightarrow wp(i := i + 1, L_1(Q)))$
 $\Leftrightarrow (i \not< n \Rightarrow Q) \wedge$
 $\quad i < n \Rightarrow (i + 1 \not< n \wedge Q[i + 1/i])$

$L_3(Q) :\Leftrightarrow (i \not< n \Rightarrow Q) \wedge (i < n \Rightarrow wp(i := i + 1, L_2(Q)))$
 $\Leftrightarrow (i \not< n \Rightarrow Q) \wedge$
 $\quad (i < n \Rightarrow ((i + 1 \not< n \Rightarrow Q[i + 1/i]) \wedge$
 $\quad\quad (i + 1 < n \Rightarrow (i + 2 \not< n \wedge Q[i + 2/i])))$

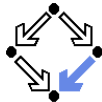
...



Weakest Preconditions for Loops

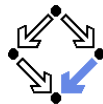
- Sequence $L_i(Q)$ is now monotonically **decreasing** in strength:
 - $\forall i \in \mathbb{N} : L_i(Q) \Rightarrow L_{i+1}(Q)$.
- The weakest precondition is the “greatest lower bound”:
 - $\forall i \in \mathbb{N} : L_i(Q) \Rightarrow \text{wp}(\mathbf{while\ } b \ \mathbf{do\ } c, Q)$.
 - $\forall P : (\forall i \in \mathbb{N} : L_i(Q) \Rightarrow P) \Rightarrow (\text{wp}(\mathbf{while\ } b \ \mathbf{do\ } c, Q) \Rightarrow P)$.
- We can only compute a stronger approximation $L_i(Q)$.
 - $L_i(Q) \Rightarrow \text{wp}(\mathbf{while\ } b \ \mathbf{do\ } c, Q)$.
- We want to prove $\{P\} c \{Q\}$.
 - It suffices to prove $P \Rightarrow \text{wp}(\mathbf{while\ } b \ \mathbf{do\ } c, Q)$.
 - It thus also suffices to prove $P \Rightarrow L_i(Q)$.
 - If proof fails, we may try the easier proof $P \Rightarrow L_{i+1}(Q)$

However, verifications are typically not successful with any finite approximation of the weakest precondition.



-
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 4. Total Correctness of Loop Programs
 - 5. Abortion**
 6. Procedures

Abortion



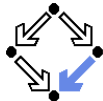
New rules to prevent abortion.

$$\begin{aligned} & \{\text{false}\} \mathbf{abort} \{\text{true}\} \\ & \{Q[e/x] \wedge D(e)\} x := e \{Q\} \\ & \{Q[a[i \mapsto e]/a] \wedge D(e) \wedge 0 \leq i < \text{length}(a)\} a[i] := e \{Q\} \end{aligned}$$

- New interpretation of $\{P\} c \{Q\}$.
 - If execution of c starts in a state, in which property P holds, then it does not abort and eventually terminates in a state in which Q holds.
- Sources of abortion.
 - Division by zero.
 - Index out of bounds exception.

$D(e)$ makes sure that every subexpression of e is well defined.

Definedness of Expressions



$D(0) :\Leftrightarrow \text{true}.$

$D(1) :\Leftrightarrow \text{true}.$

$D(x) :\Leftrightarrow \text{true}.$

$D(a[i]) :\Leftrightarrow D(i) \wedge 0 \leq i < \text{length}(a).$

$D(e_1 + e_2) :\Leftrightarrow D(e_1) \wedge D(e_2).$

$D(e_1 * e_2) :\Leftrightarrow D(e_1) \wedge D(e_2).$

$D(e_1 / e_2) :\Leftrightarrow D(e_1) \wedge D(e_2) \wedge e_2 \neq 0.$

$D(\text{true}) :\Leftrightarrow \text{true}.$

$D(\text{false}) :\Leftrightarrow \text{true}.$

$D(\neg b) :\Leftrightarrow D(b).$

$D(b_1 \wedge b_2) :\Leftrightarrow D(b_1) \wedge D(b_2).$

$D(b_1 \vee b_2) :\Leftrightarrow D(b_1) \wedge D(b_2).$

$D(e_1 < e_2) :\Leftrightarrow D(e_1) \wedge D(e_2).$

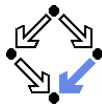
$D(e_1 \leq e_2) :\Leftrightarrow D(e_1) \wedge D(e_2).$

$D(e_1 > e_2) :\Leftrightarrow D(e_1) \wedge D(e_2).$

$D(e_1 \geq e_2) :\Leftrightarrow D(e_1) \wedge D(e_2).$

Assumes that expressions have already been type-checked.

Abortion



Slight modification of existing rules.

$$\frac{\{P \wedge b \wedge D(b)\} c_1 \{Q\} \quad \{P \wedge \neg b \wedge D(b)\} c_2 \{Q\}}{\{P\} \text{ if } b \text{ then } c_1 \text{ else } c_2 \{Q\}}$$

$$\frac{\{P \wedge b \wedge D(b)\} c \{Q\} \quad (P \wedge \neg b \wedge D(b)) \Rightarrow Q}{\{P\} \text{ if } b \text{ then } c \{Q\}}$$

$$\frac{P \Rightarrow I \quad I \Rightarrow (T \in \mathbb{N} \wedge D(b)) \quad \{I \wedge b \wedge T = t\} c \{I \wedge T < t\} \quad (I \wedge \neg b) \Rightarrow Q}{\{P\} \text{ while } b \text{ do } c \{Q\}}$$

Expressions must be defined in any context.



Abortion

Similar modifications of weakest preconditions.

$$\text{wp}(\mathbf{abort}, Q) \Leftrightarrow \text{false}$$

$$\text{wp}(x := e, Q) \Leftrightarrow Q[e/x] \wedge D(e)$$

$$\text{wp}(\mathbf{if } b \mathbf{ then } c_1 \mathbf{ else } c_2, Q) \Leftrightarrow$$

$$D(b) \wedge (b \Rightarrow \text{wp}(c_1, Q)) \wedge (\neg b \Rightarrow \text{wp}(c_2, Q))$$

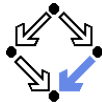
$$\text{wp}(\mathbf{if } b \mathbf{ then } c, Q) \Leftrightarrow D(b) \wedge (b \Rightarrow \text{wp}(c, Q)) \wedge (\neg b \Rightarrow Q)$$

$$\text{wp}(\mathbf{while } b \mathbf{ do } c, Q) \Leftrightarrow \exists i \in \mathbb{N} : L_i(Q)$$

$$L_0(Q) :\Leftrightarrow \text{false}$$

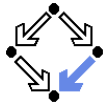
$$L_{i+1}(Q) :\Leftrightarrow D(b) \wedge (\neg b \Rightarrow Q) \wedge (b \Rightarrow \text{wp}(c, L_i(Q)))$$

$\text{wp}(c, Q)$ now makes sure that the execution of c does not abort but eventually terminates in a state in which Q holds.



-
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Procedure Specifications



global g ;
requires Pre ;
ensures $Post$;
 $o := p(i) \{ c \}$

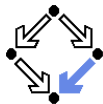
- Specification of a procedure p implemented by a command c .
 - Input parameter i , output parameter o , global variable g .
 - Command c may read/write i , o , and g .
 - Precondition Pre (may refer to i, g).
 - Postcondition $Post$ (may refer to i, o, g, g_0).
 - g_0 denotes the value of g before the execution of p .

■ Proof obligation

$$\{ Pre \wedge i_0 = i \wedge g_0 = g \} c \{ Post[i_0/i] \}$$

Proof of the correctness of the implementation of a procedure with respect to its specification.

Example



■ Procedure specification:

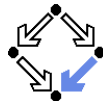
global g
requires $g \geq 0 \wedge i > 0$
ensures $g_0 = g \cdot i + o \wedge 0 \leq o < i$
 $o := p(i) \{ o := g \% i; g := g / i \}$

■ Proof obligation:

$\{g \geq 0 \wedge i > 0 \wedge i_0 = i \wedge g_0 = g\}$
 $o := g \% i; g := g / i$
 $\{g_0 = g \cdot i_0 + o \wedge 0 \leq o < i_0\}$

A procedure that divides g by i and returns the remainder.

Procedure Calls



A call of p provides actual input argument e and output variable x .

$$x := p(e)$$

Similar to assignment statement; we thus first give an alternative (equivalent) version of the assignment rule.

- Original:

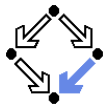
$$\frac{\{D(e) \wedge Q[e/x]\}}{x := e} \{Q\}$$

- Alternative:

$$\frac{\{D(e) \wedge \forall x' : x' = e \Rightarrow Q[x'/x]\}}{x := e} \{Q\}$$

The new value of x is given name x' in the precondition.

Procedure Calls



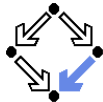
From this, we can derive a rule for the correctness of procedure calls.

$$\frac{\{D(e) \wedge Pre[e/i] \wedge \forall x', g' : Post[e/i, x'/o, g'/g_0, g'/g] \Rightarrow Q[x'/x, g'/g]\}}{x := p(e) \{Q\}}$$

- $Pre[e/i]$ refers to the values of the actual argument e (rather than to the formal parameter i).
- x' and g' denote the values of the vars x and g after the call.
- $Post[...]$ refers to the argument values before and after the call.
- $Q[x'/x, g'/g]$ refers to the argument values after the call.

Modular reasoning: rule only relies on the *specification* of p , not on its implementation.

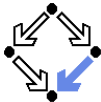
Corresponding Predicate Transformers



$$\begin{aligned} \text{wp}(x = p(e), Q) &\Leftrightarrow \\ &D(e) \wedge \text{Pre}[e/i] \wedge \\ &\forall x', g' : \\ &\quad \text{Post}[e/i, x'/o, g/g_0, g'/g] \Rightarrow Q[x'/x, g'/g] \end{aligned}$$

$$\begin{aligned} \text{sp}(P, x = p(e)) &\Leftrightarrow \\ &\exists x_0, g_0 : \\ &\quad P[x_0/y, g_0/g] \wedge \\ &\quad (\text{Pre}[e[x_0/x, g_0/g]/i, g_0/g] \Rightarrow \text{Post}[e[x_0/x, g_0/g]/i, x/o]) \end{aligned}$$

Explicit naming of old/new values required.



Example

■ Procedure specification:

global g

requires $g \geq 0 \wedge i > 0$

ensures $g_0 = g \cdot i + o \wedge 0 \leq o < i$

$o = p(i) \{ o := g \% i; g := g / i \}$

■ Procedure call:

$\{g \geq 0 \wedge g = N \wedge b \geq 0\}$

$x = p(b + 1)$

$\{g \cdot (b + 1) \leq N < (g + 1) \cdot (b + 1)\}$

■ To be proved:

$g \geq 0 \wedge g = N \wedge b \geq 0 \Rightarrow$

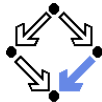
$D(b + 1) \wedge g \geq 0 \wedge b + 1 > 0 \wedge$

$\forall x', g' :$

$g = g' \cdot (b + 1) + x' \wedge 0 \leq x' < b + 1 \Rightarrow$

$g' \cdot (b + 1) \leq N < (g' + 1) \cdot (b + 1)$

Not Yet Covered



- Primitive data types.
 - `int` values are actually finite precision integers.
- More data and control structures.
 - `switch`, `do-while` (easy); `continue`, `break`, `return` (more complicated).
 - Records can be handled similar to arrays.
- Recursion.
 - Procedures may not terminate due to recursive calls.
- Exceptions and Exception Handling.
 - Short discussion in the context of ESC/Java2 later.
- Pointers and Objects.
 - Here reasoning gets complicated.
- ...

The more features are covered, the more complicated reasoning becomes.