Specifying and Verifying Programs

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We will discuss two (closely interrelated) calculi.

- Hoare Calculus: $\{P\}\ c\ \{Q\}$
  - If command c is executed in a pre-state with property P and terminates, it yields a post-state with property Q.
    $\{x = a \land y = b\} x := x + y \{x = a + y \land y = b\}$
- Predicate Transformers: $\text{wp}(c, Q) = P$
  - If the execution of command c shall yield a post-state with property Q, it must be executed in a pre-state with property P.
    $\text{wp}(x := x + y, x = a + y \land y = b) = (x + y = a + y \land y = b)$

The Hoare calculs can be easily applied in manual verifications; for automation, the predicate transformers calculus is more suitable (both calculi can be also combined).

The Hoare Calculus

First/best-known calculus for program reasoning (C. A. R. Hoare, 1969).

- "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 (yet) 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.

The Rules of the Hoare Calculus

Hoare calculus rules are inference rules with Hoare triples as proof goals.

$$\frac{\{P_1\}\ c_1\ \{Q_1\}\ \ \dots\ \ \{P_n\}\ c_n\ \{Q_n\} \qquad VC_1,\dots,VC_m}{\{P\}\ c\ \{Q\}}$$

- Application of a rule to a triple $\{P\}\ c\ \{Q\}$ to be verified yields
  - other triples $\{P_1\}\ c_1\ \{Q_1\}\dots\{P_n\}\ c_n\ \{Q_n\}$ to be verified, and
  - formulas $VC_1,\dots,VC_m$ (the verification conditions) to be proved.
- Given a Hoare triple $\{P\}c\{Q\}$ as the root of the verification tree:
  - The rules are repeatedly applied until the leaves of the tree do not contain any more Hoare triples.
  - If all verification conditions in the tree can be proved, the root of the tree represents a valid Hoare triple.

The Hoare calculus generates verification conditions such that the validity of the conditions implies the validity of the original Hoare triple.

Weakening and Strengthening

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

- 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

$$\{P\}\ \textbf{skip}\ \{P\} \qquad \{\text{true}\}\ \textbf{abort}\ \{\text{false}\}$$

- 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 $\{P\}$ **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.
  - $Q[e/x]$ … 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.

$$\begin{array}{rcl} \{x+3<5\} & x := x+3 & \{x<5\} \\ \{x<2\} & x := x+3 & \{x<5\} \end{array}$$

Array Assignments

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

- An array is modelled as a function $a : I \to V$.
  - 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 "$a := a[i \mapsto e]$".

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

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

Array Assignments

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

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

- Array Axioms

$$i = j \Rightarrow \underline{a[i \mapsto e]}[j] = e$$
$$i \neq j \Rightarrow \underline{a[i \mapsto e]}[j] = a[j]$$

$$\{\underline{a[i \mapsto x]}[1] > 0\}\quad a[i] := x \quad \{a[1] > 0\}$$
$$\{(i = 1 \Rightarrow x > 0) \wedge (i \neq 1 \Rightarrow a[1] > 0)\}\quad a[i] := x \quad \{a[1] > 0\}$$

Get rid of "array update terms" when applied to indices.

Command Sequences

$$\frac{\{P\}\ c_1\ \{R\}\quad \{R\}\ c_2\ \{Q\}}{\{P\}\ c_1; c_2\ \{Q\}}$$

- 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 that
    - if P holds before c_1, that R holds afterwards, and that
    - if R holds before c_2, then Q holds afterwards.
- Problem: find suitable R.
  - Easy in many cases (see later).

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

The calculus itself does not indicate how to find intermediate property.

Conditionals

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

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

- 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.

$$\frac{\{x \neq 0 \wedge x \geq 0\}\ y := x\ \{y > 0\}\quad \{x \neq 0 \wedge x \not\geq 0\}\ y := -x\ \{y > 0\}}{\{x \neq 0\}\ \textbf{if}\ x \geq 0\ \textbf{then}\ y := x\ \textbf{else}\ y := -x\ \{y > 0\}}$$

Loops

$\{\text{true}\}$ **loop** $\{\text{false}\}$

$$\frac{\{I \wedge b\}\ c\ \{I\}}{\{I\}\ \textbf{while}\ b\ \textbf{do}\ c\ \{I \wedge \neg b\}}$$

- Interpretation:
  - The **loop** command does not terminate and thus trivially satisfies partial correctness.
    - Axiom implies $\{P\}$ **loop** $\{Q\}$ for arbitrary P, Q.
  - If it is the case that
    - I holds before the execution of the **while**-loop and
    - I also holds after every iteration of the loop body,

    then I holds also after the execution of the loop (together with the negation of the loop condition b).
    - I is a loop invariant.
- Problem:
  - Rule for **while**-loop does not have arbitrary pre/post-conditions P, Q.

In practice, we combine this rule with the strengthening/weakening-rule.

Loops (Generalized)

$$\frac{P \Rightarrow I \quad \{I \wedge b\}\ c\ \{I\} \quad (I \wedge \neg b) \Rightarrow Q}{\{P\}\ \textbf{while}\ b\ \textbf{do}\ c\ \{Q\}}$$

- Interpretation:
  - 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.

The calculus itself does not indicate how to find suitable loop invariant.

Example

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

$$\frac{\begin{array}{c}(n \geq 0 \wedge s = 0 \wedge i = 1) \Rightarrow I \\ \{I \wedge i \leq n\}\ s := s + i; i := i + 1\ \{I\} \\ (I \wedge i \not\leq n) \Rightarrow s = \sum_{j=1}^{n} j\end{array}}{\{n \geq 0 \wedge s = 0 \wedge i = 1\}\ \textbf{while}\ i \leq n\ \textbf{do}\ (s := s + i; i := i + 1)\ \{s = \sum_{j=1}^{n} j\}}$$

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

A Program Verification

- Verification of the following Hoare triple:

  $\{Input\}$ **while** $i \leq n$ **do** $(s := s + i; i := i + 1)$ $\{Output\}$
- Auxiliary predicates:

  $Input :\Leftrightarrow n \geq 0 \wedge s = 0 \wedge i = 1$

  $Output :\Leftrightarrow s = \sum_{j=1}^{n} j$

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

  $A :\Leftrightarrow Input \Rightarrow Invariant$

  $B :\Leftrightarrow Invariant \wedge i \leq n \Rightarrow Invariant[i + 1/i][s + i/s]$

  $C :\Leftrightarrow Invariant \wedge i \not\leq n \Rightarrow Output$

If the verification conditions are valid, the Hoare triple is true.

RISCAL: Checking Program Execution

```
val N:Nat; type number = ℕ[N]; type index = ℕ[N+1]; type result = ℕ[N·(1+N)/2];

proc summation(n:number): result
  requires n ≥ 0;
  ensures result = ∑j:number with 1 ≤ j ∧ j ≤ n. j;
{
  var s:result := 0;
  var i:index  := 1;
  while i ≤ n do
    invariant s = ∑j:number with 1 ≤ j ∧ j ≤ i-1. j;
    invariant 1 ≤ i ∧ i ≤ n+1;
  {
    s := s+i;
    i := i+1;
  }
  return s;
}
```

We check for some N the program execution; this implies that the invariant is not too strong.

RISCAL: Checking Verification Conditions

```
pred Input(n:number, s:result, i:index) ⇔
  n ≥ 0 ∧ s = 0 ∧ i = 1;
pred Output(n:number, s:result) ⇔
  s = ∑j:number with 1 ≤ j ∧ j ≤ n. j;
pred Invariant(n:number, s:result, i:index) ⇔
  (s = ∑j:number with 1 ≤ j ∧ j ≤ i-1. j) ∧ 1 ≤ i ∧ i ≤ n+1;

theorem A(n:number, s:result, i:index) ⇔
  Input(n, s, i) ⇒ Invariant(n, s, i);
theorem B(n:number, s:result, i:index) ⇔
  Invariant(n, s, i) ∧ i ≤ n ⇒ Invariant(n, s+i, i+1);
theorem C(n:number, s:result, i:index) ⇔
  Invariant(n, s, i) ∧ ¬(i ≤ n) ⇒ Output(n, s);
```

We check for some N that the verification conditions are valid; this also implies that the invariant is not too weak.

Another Program Verification

Verification of the following Hoare triple:

$\{olda = a \wedge oldx = x\}$

$i := 0; r := -1; n = |a|$
while $i < n \wedge r = -1$ **do**
  if $a[i] = x$
    then $r := i$
    else $i := i + 1$

$\{a = olda \wedge x = oldx \wedge$
$((r = -1 \wedge \forall i : 0 \leq i < |a| \Rightarrow a[i] \neq x) \vee$
$(0 \leq r < |a| \wedge a[r] = x \wedge \forall i : 0 \leq i < r \Rightarrow a[i] \neq x))\}$

$Invariant :\Leftrightarrow olda = a \wedge oldx = x \wedge n = |a| \wedge$
$0 \leq i \leq n \wedge \forall j : 0 \leq j < i \Rightarrow a[j] \neq x \wedge$
$(r = -1 \vee (r = i \wedge i < n \wedge a[r] = x))$

Find the smallest index r of an occurrence of value x in array a ($r = -1$, if x does not occur in a).

RISCAL: Checking Program Execution

```
val N:ℕ; val M:ℕ;
type index = ℤ[-1,N]; type elem = ℕ[M]; type array = Array[N,elem];

proc search(a:array, x:elem): index
  ensures (result = -1 ∧ ∀i:index. 0 ≤ i ∧ i < N ⇒ a[i] ≠ x) ∨
          (0 ≤ result ∧ result < N ∧
            a[result] = x ∧ ∀i:index. 0 ≤ i ∧ i < result ⇒ a[i] ≠ x);
{
  var i:index = 0;
  var r:index = -1;
  while i < N ∧ r = -1 do
    invariant 0 ≤ i ∧ i ≤ N ∧ ∀j:index. 0 ≤ j ∧ j < i ⇒ a[j] ≠ x;
    invariant r = -1 ∨ (r = i ∧ i < N ∧ a[r] = x);
  {
    if a[i] = x
      then r := i;
      else i := i+1;
  }
  return r;
}
```

We check for some N, M the program execution.

The Verification Conditions

$$Input :\Leftrightarrow olda = a \wedge oldx = x \wedge n = length(a) \wedge i = 0 \wedge r = -1$$

$$\begin{aligned} Output :\Leftrightarrow\ & a = olda \wedge x = oldx \wedge \\ & ((r = -1 \wedge \forall i : 0 \le i < length(a) \Rightarrow a[i] \ne x) \vee \\ & \ (0 \le r < length(a) \wedge a[r] = x \wedge \forall i : 0 \le i < r \Rightarrow a[i] \ne x)) \end{aligned}$$

$$\begin{aligned} Invariant :\Leftrightarrow\ & olda = a \wedge oldx = x \wedge n = |a| \wedge \\ & 0 \le i \le n \wedge \forall j : 0 \le j < i \Rightarrow a[j] \ne x \wedge \\ & (r = -1 \vee (r = i \wedge i < n \wedge a[r] = x)) \end{aligned}$$

$$\begin{aligned} & A :\Leftrightarrow Input \Rightarrow Invariant \\ & B_1 :\Leftrightarrow Invariant \wedge i < n \wedge r = -1 \wedge a[i] = x \Rightarrow Invariant[i/r] \\ & B_2 :\Leftrightarrow Invariant \wedge i < n \wedge r = -1 \wedge a[i] \ne x \Rightarrow Invariant[i+1/i] \\ & C :\Leftrightarrow Invariant \wedge \neg(i < n \wedge r = -1) \Rightarrow Output \end{aligned}$$

The verification conditions A, B_1, B_2, C must be valid.

RISCAL: Checking Verification Conditions

```
pred Input(i:index, r:index) ⇔ i = 0 ∧ r = -1;
pred Output(a:array, x:elem, i:index, r:index) ⇔
  (r = -1 ∧ ∀i:index. 0 ≤ i ∧ i < N ⇒ a[i] ≠ x) ∨
  (0 ≤ r ∧ r < N ∧ a[r] = x ∧ ∀i:index. 0 ≤ i ∧ i < r ⇒ a[i] ≠ x);
pred Invariant(a:array, x:elem, i:index, r:index) ⇔
  0 ≤ i ∧ i ≤ N ∧ (∀j:index. 0 ≤ j ∧ j < i ⇒ a[j] ≠ x) ∧
  (r = -1 ∨ (r = i ∧ i < N ∧ a[r] = x));

theorem A(a:array, x:elem, i:index, r:index) ⇔
  Input(i, r) ⇒ Invariant(a, x, i, r);
theorem B1(a:array, x:elem, i:index, r:index) ⇔
  Invariant(a, x, i, r) ∧ i < N ∧ r = -1 ∧ a[i] = x ⇒
    Invariant(a, x, i, i);
theorem B2(a:array, x:elem, i:index, r:index) ⇔
  Invariant(a, x, i, r) ∧ i < N ∧ r = -1 ∧ a[i] ≠ x ⇒
    Invariant(a, x, i+1, r);
theorem C(a:array, x:elem, i:index, r:index) ⇔
  Invariant(a, x, i, r) ∧ ¬(i < N ∧ r = -1) ⇒
    Output(a, x, i, r);
```

We check for some N, M that the verification conditions are valid.

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.

$\{P\}$	$\{P\}$	$\{P\}$	$\{P\}$	$P \Rightarrow x = 4$
x := x+1;	x := x+1;	x := x+1;	$\{x + 1 = 5\}$	
y := 2*x;	y := 2*x;	$\{x + 2x = 15\}$	$(\Leftrightarrow x = 4)$	
z := x+y	$\{x + y = 15\}$	$(\Leftrightarrow 3x = 15)$		
$\{z = 15\}$		$(\Leftrightarrow x = 5)$		

Weakest Preconditions

A calculus for "backward reasoning" (E.W. Dijkstra, 1975).

- Predicate transformer wp
  - Function "wp" that takes a command c and a postcondition Q and returns a precondition.
  - Read wp(c, Q) as "the weakest precondition of c w.r.t. Q".
- wp(c, Q) is a precondition for c that ensures Q as a postcondition.
  - Must satisfy $\{\text{wp}(c, Q)\}\ c\ \{Q\}$.
- 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.

$$\begin{aligned}
&\text{wp}(\textbf{skip}, Q) = Q\\
&\text{wp}(\textbf{abort}, Q) = \text{true}\\
&\text{wp}(x := e, Q) = Q[e/x]\\
&\text{wp}(c_1; c_2, Q) = \text{wp}(c_1, \text{wp}(c_2, Q))\\
&\text{wp}(\textbf{if } b \textbf{ then } c_1 \textbf{ else } c_2, Q) = (b \Rightarrow \text{wp}(c_1, Q)) \wedge (\neg b \Rightarrow \text{wp}(c_2, Q))\\
&\text{wp}(\textbf{if } b \textbf{ then } c, Q) \Leftrightarrow (b \Rightarrow \text{wp}(c, Q)) \wedge (\neg b \Rightarrow Q)\\
&\text{wp}(\textbf{while } b \textbf{ do } c, Q) = \ldots
\end{aligned}$$

Loops represent a special problem (see later).

Example

$$\begin{aligned}
WP &= \text{wp}(\textbf{if } \text{a[i]} < \text{x } \textbf{then } \{\text{a[i] := a[i-1]; i := i-1}\}, a[i+1] = b)\\
&= (a[i] < x \Rightarrow WP_1) \wedge (\neg(a[i] < x) \Rightarrow a[i+1] = b)\\
&\equiv (a[i] < x \Rightarrow WP_1) \wedge (a[i] \geq x \Rightarrow a[i+1] = b)
\end{aligned}$$

$$\begin{aligned}
WP_1 &= \text{wp}(\{\text{a[i] := a[i-1]; i := i-1}\}, a[i+1] = b)\\
&= \text{wp}(\text{a[i] := a[i-1]}, a[(i-1)+1] = b)\\
&\equiv \text{wp}(\text{a[i] := a[i-1]}, a[i] = b)\\
&= \text{wp}(\text{a := a[i} \mapsto \text{a[i-1]]}, a[i] = b)\\
&= a[i \mapsto a[i-1]][i] = b\\
&\equiv (i = i \Rightarrow a[i-1] = b) \wedge (i \neq i \Rightarrow a[i] = b)\\
&\equiv a[i-1] = b
\end{aligned}$$

$$WP \equiv \underline{(a[i] < x \Rightarrow a[i-1] = b) \wedge (a[i] \geq x \Rightarrow a[i+1] = b)}$$

Forward Reasoning

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

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

- 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 $e[x_0/x]$.

$$\begin{array}{c} \{x \geq 0 \land y = a\} \\ x := x + 1 \\ \{\exists x_0 : x_0 \geq 0 \land y = a \land x = x_0 + 1\} \\ (\Leftrightarrow (\exists x_0 : x_0 \geq 0 \land x = x_0 + 1) \land y = a) \\ (\Leftrightarrow x > 0 \land y = a) \end{array}$$

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 $\text{sp}(c, P)$ as "the strongest postcondition of c w.r.t. P".
- $\text{sp}(c, P)$ is a postcondition for c that is ensured by precondition P.
  - Must satisfy $\{P\}\ c\ \{\text{sp}(c, P)\}$.
- $\text{sp}(c, P)$ is the strongest such postcondition.
  - Take any P, Q such that $\{P\}\ c\ \{Q\}$.
  - Then $\text{sp}(c, P) \Rightarrow Q$.
- Consequence: $\{P\}\ c\ \{Q\}$ iff $(\text{sp}(c, P) \Rightarrow Q)$.
  - We want to prove $\{P\}\ c\ \{Q\}$.
  - We may prove $\text{sp}(c, P) \Rightarrow Q$ instead.

Verification is reduced to the calculation of strongest postconditions.

Strongest Postconditions

The strongest postcondition of each program construct.

$$\begin{array}{l} \text{sp}(\textbf{skip}, P) = P \\ \text{sp}(\textbf{abort}, P) = \text{false} \\ \text{sp}(x := e, P) = \exists x_0 : P[x_0/x] \land x = e[x_0/x] \\ \text{sp}(c_1; c_2, P) = sp(c_2, sp(c_1, P)) \\ \text{sp}(\textbf{if } b \textbf{ then } c_1 \textbf{ else } c_2, P) \Leftrightarrow \text{sp}(c_1, P \land b) \lor \text{sp}(c_2, P \land \neg b) \\ \text{sp}(\textbf{if } b \textbf{ then } c, P) = \text{sp}(c, P \land b) \lor (P \land \neg b) \\ \text{sp}(\textbf{while } b \textbf{ do } c, P) = \ldots \end{array}$$

Forward reasoning as a (less-known) alternative to backward-reasoning.

Example

$$\begin{array}{rl} SP & = \text{sp}(\textbf{if } \text{a[i]} < \text{x} \textbf{ then } \{\text{a[i] := a[i-1]; i := i-1}\}, a[i] = b) \\ & = SP_1 \lor (a[i] = b \land \neg(a[i] < x)) \equiv SP_1 \lor (a[i] = b \land a[i] \geq x) \\ & \equiv SP_1 \lor (b \geq x \land a[i] = b) \\ SP_1 & = \text{sp}(\{\text{a[i] := a[i-1]; i := i-1}\}, a[i] = b \land a[i] < x) \\ & \equiv \text{sp}(\{\text{a[i] := a[i-1]; i := i-1}\}, a[i] = b \land b < x) \\ & = \text{sp}(\text{i:=i-1}, SP_2) \\ SP_2 & = \text{sp}(\text{a[i]:=a[i-1]}, a[i] = b \land b < x) \\ & = \text{sp}(\text{a:=a[i} \mapsto \text{a[i-1]]}, a[i] = b \land b < x) \\ & = \exists a_0 : a_0[i] = b \land b < x \land a = a_0[i \mapsto a_0[i-1]] \\ & \equiv b < x \land \exists a_0 : a_0[i] = b \land a = a_0[i \mapsto a_0[i-1]] \\ & \equiv b < x \land a[i] = a[i-1] \\ SP_1 & \equiv \text{sp}(\text{i:=i-1}, b < x \land a[i] = a[i-1]) \\ & = \exists i_0 : b < x \land a[i_0] = a[i_0 - 1] \land i = i_0 - 1 \\ & \equiv b < x \land \exists i_0 : a[i_0] = a[i_0 - 1] \land i_0 = i + 1 \\ & \equiv b < x \land a[i+1] = a[(i+1) - 1] \equiv b < x \land a[i+1] = a[i] \\ SP & \equiv \underline{(b < x \land a[i+1] = a[i]) \lor (b \geq x \land a[i] = b)} \end{array}$$

Hoare Calc. and Predicate Transformers

In practice, often a combination of the calculi is applied.

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

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

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

Predicate transformers are applied to reduce the verification of a program to the Hoare-style verification of loops.

Weakest Liberal Preconditions for Loops

Why not apply predicate transformers to loops?

$$\mathrm{wp}(\textbf{loop}, Q) = \mathrm{true}$$
$$\mathrm{wp}(\textbf{while}\ b\ \textbf{do}\ c, Q) = L_0(Q) \wedge L_1(Q) \wedge L_2(Q) \wedge \ldots$$

$$L_0(Q) = \mathrm{true}$$
$$L_{i+1}(Q) = (\neg b \Rightarrow Q) \wedge (b \Rightarrow \mathrm{wp}(c, L_i(Q)))$$

- 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: $L_i(Q) = \mathrm{wp}(\mathrm{if}_i, Q)$
  $\mathrm{if}_0 = \textbf{loop}$
  $\mathrm{if}_{i+1} = \textbf{if}\ b\ \textbf{then}\ (c; \mathrm{if}_i)$

Example

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

$$\begin{aligned}
L_0(Q) &= \mathrm{true}\\
L_1(Q) &= (i \not< n \Rightarrow Q) \wedge (i < n \Rightarrow \mathrm{wp}(i := i+1, \mathrm{true}))\\
&\Leftrightarrow (i \not< n \Rightarrow Q) \wedge (i < n \Rightarrow \mathrm{true})\\
&\Leftrightarrow (i \not< n \Rightarrow Q)\\
L_2(Q) &= (i \not< n \Rightarrow Q) \wedge (i < n \Rightarrow \mathrm{wp}(i := i+1, i \not< n \Rightarrow Q))\\
&\Leftrightarrow (i \not< n \Rightarrow Q) \wedge\\
&\qquad (i < n \Rightarrow (i+1 \not< n \Rightarrow Q[i+1/i]))\\
L_3(Q) &= (i \not< n \Rightarrow Q) \wedge (i < n \Rightarrow \mathrm{wp}(i := i+1,\\
&\qquad (i \not< n \Rightarrow Q) \wedge (i < n \Rightarrow (i+1 \not< n \Rightarrow Q[i+1/i]))))\\
&\Leftrightarrow (i \not< n \Rightarrow Q) \wedge\\
&\qquad (i < n \Rightarrow ((i+1 \not< n \Rightarrow Q[i+1/i]) \wedge\\
&\qquad\quad (i+1 < n \Rightarrow (i+2 \not< n \Rightarrow Q[i+2/i]))))
\end{aligned}$$

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":
  - $\forall i \in \mathbb{N} : \mathrm{wp}(\textbf{while}\ b\ \textbf{do}\ c, Q) \Rightarrow L_i(Q)$.
  - $\forall P : (\forall i \in \mathbb{N} : P \Rightarrow L_i(Q)) \Rightarrow (P \Rightarrow \mathrm{wp}(\textbf{while}\ b\ \textbf{do}\ c, Q))$.
- We can only compute weaker approximation $L_i(Q)$.
  - $\mathrm{wp}(\textbf{while}\ b\ \textbf{do}\ c, Q) \Rightarrow L_i(Q)$.
- We want to prove $\{P\}\ \textbf{while}\ b\ \textbf{do}\ c\ \{Q\}$.
  - This is equivalent to proving $P \Rightarrow \mathrm{wp}(\textbf{while}\ b\ \textbf{do}\ c, Q)$.
  - Thus $P \Rightarrow L_i(Q)$ must hold as well.
- If we can prove $\neg(P \Rightarrow L_i(Q))$, ...
  - $\{P\}\ \textbf{while}\ b\ \textbf{do}\ c\ \{Q\}$ 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.

Preconditions for Loops with Invariants

$$\begin{aligned}&\mathrm{wp}(\textbf{while } b \textbf{ do invariant } I;\ c^{x,\cdots}, Q) = \\ &\quad \textbf{let } oldx = x, \ldots \textbf{ in} \\ &\quad I \land (\forall x, \ldots : I \land b \Rightarrow wp(c, I)) \land \\ &\quad (\forall x, \ldots : I \land \neg b \Rightarrow Q)\end{aligned}$$

- Loop body c only modifies variables $x, \ldots$
- Loop is annotated with invariant I.
  - May refer to new values $x, \ldots$ of variables after every iteration.
  - May refer to original values $oldx, \ldots$ when loop started execution.
- Generated verification condition ensures:
  1. I holds in the initial state of the loop.
  2. I is preserved by the execution of the loop body c.
  3. When the loop terminates, I ensures postcondition Q.

This precondition is only "weakest" relative to the invariant.

Example

$$\textbf{while } i \leq n \textbf{ do } (s := s + i; i := i + 1)$$

$$c^{s,i} := (s := s + i; i := i + 1)$$
$$I :\Leftrightarrow s = olds + \left(\sum_{j=oldi}^{i-1} j\right) \land oldi \leq i \leq n + 1$$

- Weakest precondition:

$$\begin{aligned}&\mathrm{wp}(\textbf{while } i \leq n \textbf{ do invariant } I;\ c^{s,i}, Q) = \\ &\quad \textbf{let } olds = s, oldi = i \textbf{ in} \\ &\quad I \land (\forall s, i : I \land i \leq n \Rightarrow I[i+1/i][s+i/s]) \land \\ &\quad (\forall s, i : I \land \neg(i \leq n) \Rightarrow Q)\end{aligned}$$

- Verification condition:

$$n \geq 0 \land i = 1 \land s = 0 \Rightarrow \mathrm{wp}(\ldots, s = \textstyle\sum_{j=1}^{n} j)$$

Many verification systems implement (a variant of) this calculus.

Termination

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

$$\{\text{false}\}\ \textbf{loop}\ \{\text{false}\} \qquad \frac{I \Rightarrow t \geq 0 \quad \{I \land b \land t = N\}\ c\ \{I \land t < N\}}{\{I\}\ \textbf{while } b \textbf{ do } c\ \{I \land \neg b\}}$$

$$\frac{P \Rightarrow I \quad I \Rightarrow t \geq 0 \quad \{I \land b \land t = N\}\ c\ \{I \land t < N\} \quad (I \land \neg b) \Rightarrow Q}{\{P\}\ \textbf{while } b \textbf{ do } c\ \{Q\}}$$

- 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 measure t (term 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 as the domain of t.

Example

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

$$\frac{\begin{array}{c}(n \ge 0 \wedge i = 1 \wedge s = 0) \Rightarrow I \quad \color{red}{I \Rightarrow n - i + 1 \ge 0} \\ \{I \wedge i \le n \wedge \color{red}{n - i + 1 = N}\}\ s := s + i; i := i + 1\ \{I \wedge \color{red}{n - i + 1 < N}\} \\ (I \wedge i \not\le n) \Rightarrow s = \sum_{j=1}^{n} j\end{array}}{\{n \ge 0 \wedge i = 1 \wedge s = 0\}\ \textbf{while}\ i \le n\ \textbf{do}\ (s := s + i; i := i + 1)\ \{s = \sum_{j=1}^{n} j\}}$$

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

Termination in RISCAL

```
while i ≤ n do
  invariant s = ∑j:number with 1 ≤ j ∧ j ≤ i-1. j;
  invariant 1 ≤ i ∧ i ≤ n+1;
  decreases n+1-i;
{
  s := s+i;
  i := i+1;
}

fun Termination(n:number, s:result, i:index): number =
  n+1-i;
theorem T(n:number, s:result, i:index) ⇔
  Invariant(n, s, i) ⇒ Termination(n, s, i) ≥ 0;
theorem B(n:number, s:result, i:index) ⇔
  Invariant(n, s, i) ∧ i ≤ n ⇒
    Invariant(n, s+i, i+1) ∧
    Termination(n, s+i, i+1) < Termination(n, s, i);
```


Termination in RISCAL

```
while i < N ∧ r = -1 do
  invariant 0 ≤ i ∧ i ≤ N;
  invariant ∀j:index. 0 ≤ j ∧ j < i ⇒ a[j] ≠ x;
  invariant r = -1 ∨ (r = i ∧ i < N ∧ a[r] = x);
  decreases if r = -1 then N-i else 0;
{
  if a[i] = x
    then r := i;
    else i := i+1;
}

fun Termination(a:array, x:elem, i:index, r:index): index =
  if r = -1 then N-i else 0;
theorem T(a:array, x:elem, i:index, r:index) ⇔
  Invariant(a, x, i, r) ⇒ Termination(a, x, i, r) ≥ 0;
theorem B1(a:array, x:elem, i:index, r:index) ⇔
  Invariant(a, x, i, r) ∧ i < N ∧ r = -1 ∧ a[i] = x ⇒
    Invariant(a, x, i, i) ∧
    Termination(a, x, i, i) < Termination(a, x, i, r);
theorem B2(a:array, x:elem, i:index, r:index) ⇔ ...
```


Weakest Preconditions for Loops

$\text{wp}(\textbf{loop}, Q) = \color{red}{\text{false}}$
$\text{wp}(\textbf{while}\ b\ \textbf{do}\ c, Q) = L_0(Q) \vee L_1(Q) \vee L_2(Q) \vee \ldots$

$L_0(Q) = \color{red}{\text{false}}$
$L_{i+1}(Q) = (\neg b \Rightarrow Q) \wedge (b \Rightarrow \text{wp}(c, L_i(Q)))$

- 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: $L_i(Q) \Leftrightarrow \text{wp}(\text{if}_i, Q)$

  $\text{if}_0 = \textbf{loop}$
  $\text{if}_{i+1} = \textbf{if}\ b\ \textbf{then}\ (c; \text{if}_i)$

Example

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

$$L_0(Q) = \text{false}$$
$$L_1(Q) = (i \not< n \Rightarrow Q) \land (i < n \Rightarrow \; wp(i := i+1, L_0(Q)))$$
$$\Leftrightarrow (i \not< n \Rightarrow Q) \land (i < n \Rightarrow \; \text{false})$$
$$\Leftrightarrow i \not< n \land Q$$
$$L_2(Q) = (i \not< n \Rightarrow Q) \land (i < n \Rightarrow \; wp(i := i+1, L_1(Q)))$$
$$\Leftrightarrow (i \not< n \Rightarrow Q) \land (i < n \Rightarrow (i+1 \not< n \land Q[i+1/i]))$$
$$L_3(Q) = (i \not< n \Rightarrow Q) \land (i < n \Rightarrow \; \text{wp}(i := i+1, L_2(Q)))$$
$$\Leftrightarrow (i \not< n \Rightarrow Q) \land (i < n \Rightarrow \; ((i+1 \not< n \Rightarrow Q[i+1/i]) \land (i+1 < n \Rightarrow (i+2 \not< n \land Q[i+2/i]))))$$

...

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":
  - $\forall i \in \mathbb{N} : L_i(Q) \Rightarrow \text{wp}(\textbf{while } b \textbf{ do } c, Q)$.
  - $\forall P : (\forall i \in \mathbb{N} : L_i(Q) \Rightarrow P) \Rightarrow (\text{wp}(\textbf{while } b \textbf{ do } c, Q) \Rightarrow P)$.
- We can only compute a stronger approximation $L_i(Q)$.
  - $L_i(Q) \Rightarrow \text{wp}(\textbf{while } b \textbf{ do } c, Q)$.
- We want to prove $\{P\}\ c\ \{Q\}$.
  - It suffices to prove $P \Rightarrow \text{wp}(\textbf{while } b \textbf{ do } c, Q)$.
  - 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.

Weakest Precondition with Measures

$$\text{wp}(\textbf{while } b \textbf{ do invariant } I; \textbf{decreases } t;\; c^{x,\cdots}, Q) =$$
$$\textbf{let } oldx = x, \ldots \textbf{ in}$$
$$I \land (\forall x, \ldots : I \land b \Rightarrow wp(c, I)) \land$$
$$(\forall x, \ldots : I \land \neg b \Rightarrow Q) \land$$
$$(\forall x, \ldots : I \Rightarrow t \geq 0) \land$$
$$(\forall x, \ldots : I \land b \Rightarrow \texttt{let } T = t \texttt{ in } wp(c, t < T))$$

- Loop body c only modifies variables $x, \ldots$
- Loop is annotated with termination measure (term) t.
  - May refer to new values $x, \ldots$ of variables after every iteration.
- Generated verification condition ensures:
  1. t is non-negative before/after every loop iteration.
  2. t is decremented by the execution of the loop body c.

Also here any well-founded ordering may be used as the domain of t.

Example

$$\textbf{while } i \leq n \textbf{ do } (s := s+i; i := i+1)$$

$$c^{s,i} := (s := s+i; i := i+1)$$
$$I :\Leftrightarrow s = olds + \left(\sum_{j=oldi}^{i-1}\right) \land oldi \leq i \leq n+1$$
$$t := n+1-i$$

- Weakest precondition:

$$\text{wp}(\textbf{while } i \leq n \textbf{ do invariant } I;\; c^{s,i}, Q) =$$
$$\textbf{let } olds = s, oldi = i \textbf{ in}$$
$$I \land (\forall s, i : I \land i \leq n \Rightarrow I[s+i/s, i+1/i]) \land$$
$$(\forall s, i : I \land \neg(i \leq n) \Rightarrow Q) \land$$
$$(\forall s, i : I \Rightarrow t \geq 0) \land$$
$$(\forall s, i : I \land i \leq n \Rightarrow \texttt{let } T = n+1-i \texttt{ in } n+1-(i+1) < T)$$

- Verification condition:

$$n \geq 0 \land i = 1 \land s = 0 \Rightarrow \text{wp}(\ldots, s = \textstyle\sum_{j=1}^{n} j)$$

Abortion

New rules to prevent abortion.

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

- 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

$D(0) = \text{true}.$
$D(1) = \text{true}.$
$D(x) = \text{true}.$
$D(a[i]) = D(i) \wedge 0 \leq i < \text{length}(a).$
$D(e_1 + e_2) = D(e_1) \wedge D(e_2).$
$D(e_1 * e_2) = D(e_1) \wedge D(e_2).$
$D(e_1 / e_2) = D(e_1) \wedge D(e_2) \wedge e_2 \neq 0.$
$D(\text{true}) = \text{true}.$
$D(\text{false}) = \text{true}.$
$D(\neg b) = D(b).$
$D(b_1 \wedge b_2) = D(b_1) \wedge D(b_2).$
$D(b_1 \vee b_2) = D(b_1) \wedge D(b_2).$
$D(e_1 < e_2) = D(e_1) \wedge D(e_2).$
$D(e_1 \leq e_2) = D(e_1) \wedge D(e_2).$
$D(e_1 > e_2) = D(e_1) \wedge D(e_2).$
$D(e_1 \geq e_2) = D(e_1) \wedge D(e_2).$

Assumes that expressions have already been type-checked.

Abortion

Slight modification of existing rules.

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

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

$$\frac{I \Rightarrow (t \geq 0 \wedge D(b)) \quad \{I \wedge b \wedge t = N\}\ c\ \{I \wedge t < N\}}{\{I\}\ \textbf{while}\ b\ \textbf{do}\ c\ \{I \wedge \neg b\}}$$

Expressions must be defined in any context.

Abortion

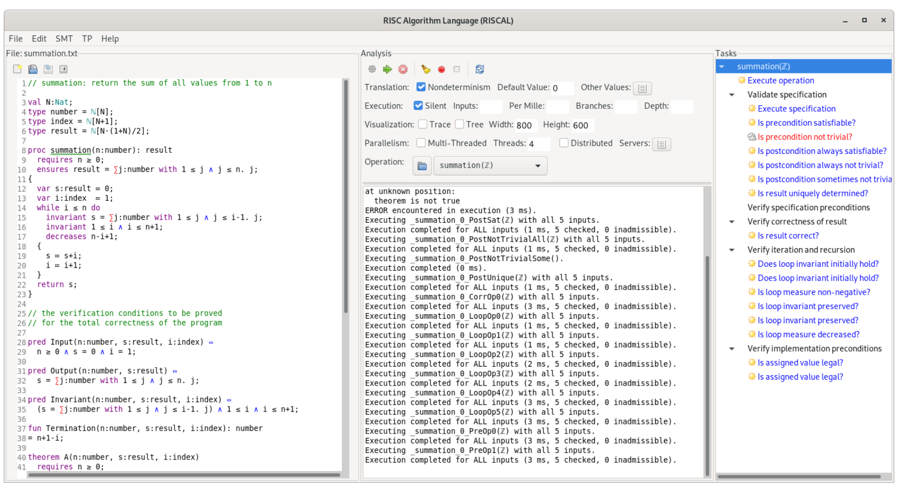
Similar modifications of weakest preconditions.

$$\begin{aligned}
&\text{wp}(\textbf{abort}, Q) = \text{false} \\
&\text{wp}(x := e, Q) = Q[e/x] \wedge D(e) \\
&\text{wp}(\textbf{if } b \textbf{ then } c_1 \textbf{ else } c_2, Q) = \\
&\quad D(b) \wedge (b \Rightarrow \text{wp}(c_1, Q)) \wedge (\neg b \Rightarrow \text{wp}(c_2, Q)) \\
&\text{wp}(\textbf{if } b \textbf{ then } c, Q) = D(b) \wedge (b \Rightarrow \text{wp}(c, Q)) \wedge (\neg b \Rightarrow Q) \\
&\text{wp}(\textbf{while } b \textbf{ do } c, Q) = (L_0(Q) \vee L_1(Q) \vee L_2(Q) \vee \ldots)
\end{aligned}$$

$$\begin{aligned}
&L_0(Q) = \text{false} \\
&L_{i+1}(Q) = D(b) \wedge (\neg b \Rightarrow Q) \wedge (b \Rightarrow \text{wp}(c, L_i(Q)))
\end{aligned}$$

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

RISCAL and Verification Conditions



RISCAL implements (a variant of) the wp-calculus for VC generation.

RISCAL Verification Conditions

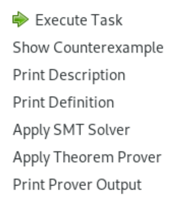
RISCAL splits Dijkstra's single condition $\mathit{Input} \Rightarrow \mathit{wp}(C, \mathit{Output})$ into many "fine-grained" verification conditions:

- Implementation preconditions
  - Well-definedness of commands and loop annotations.
  - One condition for every partial function/predicate application.
- Is result correct?
  - One condition for every `ensures` clause.
- Does loop invariant initially hold? Is loop invariant preserved?
  - Partial correctness.
  - One condition for every `invariant` clause.
- Is loop measure non-negative? Is loop measure decreased?
  - Termination.
  - One condition for every `decreases` clause.

Click on a condition to see the affected commands; if the procedure contains conditionals, a condition is generated for each execution branch.

Checking Verification Conditions

- Double-click a condition to have it checked.
  - Checked conditions turn from red to blue.
- Right-click a condition to see a pop-up menu.
  - Check verification condition (same as double-click)
  - Show variable values that invalidate condition.
  - Print relevant program information (e.g. invariant).
  - Print verification condition itself.
  - Apply SMT solver for faster checking (see menu "SMT").



Example: is loop invariant preserved?

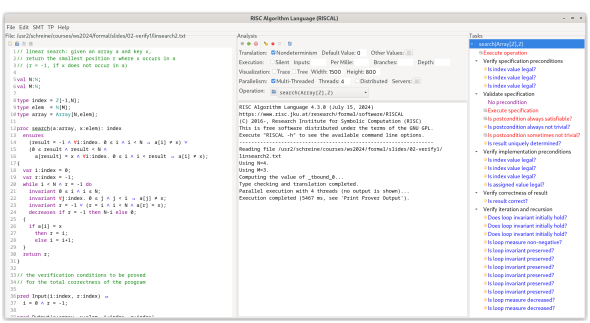
```
s = (∑j:number with (1 ≤ j) ∧ (j ≤ (i-1)). j)

theorem _summation_0_LoopOp3(n:number)
requires n ≥ 0;
 ⇔ ∀s:result,i:index. ((((s = (∑j:number with (1 ≤ j)∧(j ≤ (i-1)). j))
    ∧ ((1 ≤ i) ∧ (i ≤ (n+1)))) ∧ (i ≤ n)) ⇒
        (let s = s+i in (let i = i+1 in
          (s = (∑j:number with (1 ≤ j) ∧ (j ≤ (i-1)). j)))));
```

Important: check models with *small* type sizes.

Proving Verification Conditions

RISCAL also integrates the RISCTP interface to various theorem provers.

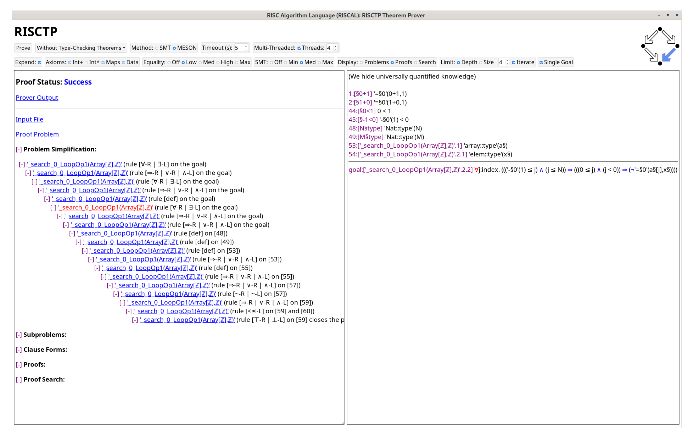
- Menu "TP" and menu entry "Apply Theorem Prover"
  - Tries to prove verification condition for *arbitrary* type sizes.
  - "Apply Prover to All Theorems": multiple proofs (in parallel).
  - "Print Prover Output": shows details of proof attempt.
  - "Open Theorem Prover GUI": open the RISTP web interface.



Many (but typically not all) automatic proof attempts may succeed.

Example: Linear Search

Does the quantified loop invariant initially hold?



Proof method MESON: proof problem is already closed by simplification.

Example: Linear Search

Does the quantified loop invariant initially hold?

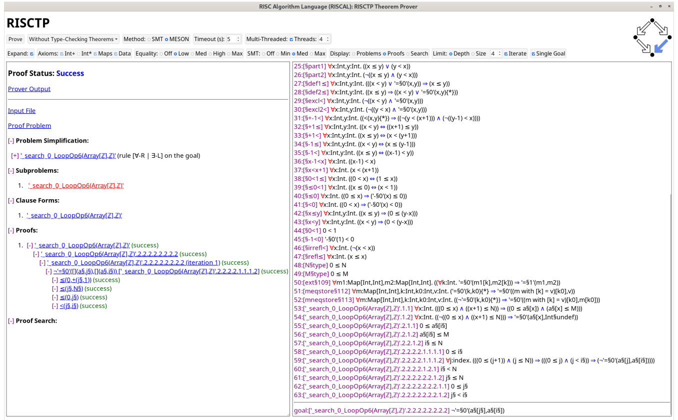
(We hide universally quantified knowledge)

```
1:[§0+1] '=§0'(0+1,1)
2:[§1+0] '=§0'(1+0,1)
44:[§0<1] 0 < 1
45:[§-1<0] '-§0'(1) < 0
48:[N§type] 0 ≤ N
49:[M§type] 0 ≤ M
55:['_search_0_LoopOp1(Array[ℤ],ℤ)'.2.1.1] 0 ≤ x§
56:['_search_0_LoopOp1(Array[ℤ],ℤ)'.2.1.2] x§ ≤ M
57:['_search_0_LoopOp1(Array[ℤ],ℤ)'.2.2.1.1] 0 ≤ (j§+1)
58:['_search_0_LoopOp1(Array[ℤ],ℤ)'.2.2.1.2] j§ ≤ N
59:['_search_0_LoopOp1(Array[ℤ],ℤ)'.2.2.2.1.1] 0 ≤ j§
60:['_search_0_LoopOp1(Array[ℤ],ℤ)'.2.2.2.1.2] j§ < 0
-----------------------------------------------
goal:['_search_0_LoopOp1(Array[ℤ],ℤ)'.2.2.2.2] ¬'=§0'(a§[j§],x§)
```

In the next (and final) step, it is recognized that the assumptions $0 \leq j§$ and $j§ \leq 0$ are inconsistent.

Example: Linear Search

Is the quantified loop invariant preserved by the first conditional branch?



Problem is closed by simplification, proof search, and SMT solving.

Example: Linear Search

Is the quantified loop invariant preserved by the first conditional branch?

Goal: ¬'=§0'([](a§,j§),[](a§,i§)) ['_search_0_LoopOp6(Array[ℤ],ℤ)'.2.2.2.2.1.1.1.2] (proof depth: 0, proof size: 1)

```
Goal: ¬'=§0'([](a§,j§),[](a§,i§))

To prove the goal, we assume its negation

[1] '=§0'([](a§,j§),[](a§,i§))

and show a contradiction. For this, consider knowledge ['_search_0_LoopOp6(Array[ℤ],ℤ)'.2.2.2.2.1.1.1.2] with the following instance:

  ∀j@113:index. ≤(0,+(j@113,1)) ∧ ≤(j@113,N§) ∧ ≤(0,j@113) ∧ <(j@113,i§) ∧ '=§0'([](a§,j@113),[](a§,i§)) ⇒ ⊥

Assumption [1] matches the literal '=§0'([](a§,j@113),[](a§,i§)) on the left side of this clause by the following substitution:

  j@113 → j§

Therefore, applying this substitution and dropping the literal, we know:

  ≤(0,+(j§,1)) ∧ ≤(j§,N§) ∧ ≤(0,j§) ∧ <(j§,i§) ⇒ ⊥

Therefore, to show a contradiction, we prove this subgoal:

  ≤(0,+(j§,1)) ∧ ≤(j§,N§) ∧ ≤(0,j§) ∧ <(j§,i§)
------------------------------------------------------------------------------------------
SUCCESS: goal ¬'=§0'([](a§,j§),[](a§,i§)) ['_search_0_LoopOp6(Array[ℤ],ℤ)'.2.2.2.2.1.1.1.2] has been proved with the following substitution:

  j@113 → j§
```

Invariant has to be instantiated with constant $j§$ for variable j.

Example: Linear Search

Is the quantified loop invariant preserved by the first conditional branch?

Goal: ≤(0,+(j§,1)) (proof depth: 1, proof size: 2)

```
Goal: ≤(0,+(j§,1))

Assumptions:

[1] '=§0'([](a§,j§),[](a§,i§))

The goal has been proved by the SMT solver: the solver states by the output

  unsat

the unsatisfiability of the negated goal in conjunction with this knowledge:

['_search_0_LoopOp6(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.1.1] ≤(0,j§)
------------------------------------------------------------------------------------------
SUCCESS: goal ≤(0,+(j§,1)) has been proved with the following substitution:

  j@113 → j§
```

Option "SMT: Med": subgoals are closed by the SMT solver.

Example: Linear Search

Is the quantified loop invariant preserved by the first conditional branch?

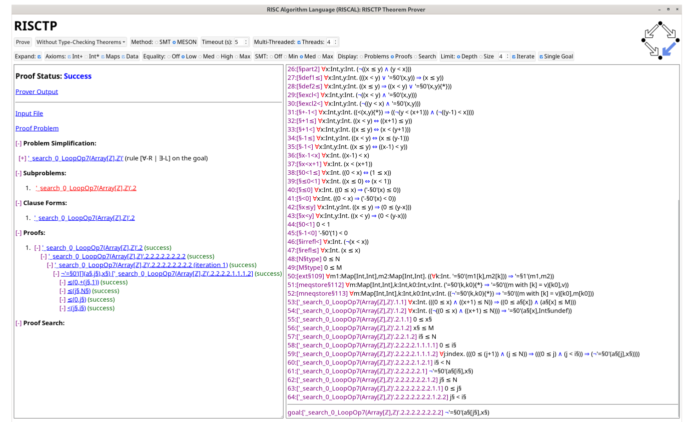
Proof problem: '_search_0_LoopOp6(Array[ℤ],ℤ)'

```
The problem has been closed by the SMT solver: the solver states by the output

  unsat

the unsatisfiability of these clauses that arise from the negation of the theorem to be proved:

['_search_0_LoopOp6(Array[ℤ],ℤ)'.2.2.2.2.1.1.1.2] ∀j:index. ≤(0,+(j,1)) ∧ ≤(j,N§) ∧ ≤(0,j) ∧ <(j,i§) ∧ '=§0'([](a§,j),[](a§,i§)) ⇒ ⊥
['_search_0_LoopOp6(Array[ℤ],ℤ)'.2.2.2.2.2.2.1.2] ≤(j§,N§)
['_search_0_LoopOp6(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.1.1] ≤(0,j§)
['_search_0_LoopOp6(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.1.2] <(j§,i§)
['_search_0_LoopOp6(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2] '=§0'([](a§,j§),[](a§,i§))

In more detail, the solver states the unsatisfiability of these clause instances:

['_search_0_LoopOp6(Array[ℤ],ℤ)'.2.2.2.2.1.1.1.2.1] ≤(0,+(j§,1)) ∧ ≤(j§,N§) ∧ ≤(0,j§) ∧ <(j§,i§) ∧ '=§0'([](a§,j§),[](a§,i§)) ⇒ ⊥
['_search_0_LoopOp6(Array[ℤ],ℤ)'.2.2.2.2.2.2.1.2] ≤(j§,N§)
['_search_0_LoopOp6(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.1.1] ≤(0,j§)
['_search_0_LoopOp6(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.1.2] <(j§,i§)
['_search_0_LoopOp6(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2] '=§0'([](a§,j§),[](a§,i§))

Thus the theorem is valid.
------------------------------------------------------------------------------------------
SUCCESS: goal '_search_0_LoopOp6(Array[ℤ],ℤ)' has been proved.
```

Option “SMT: Max”: a proof outline is produced by the SMT solver.

Example: Linear Search

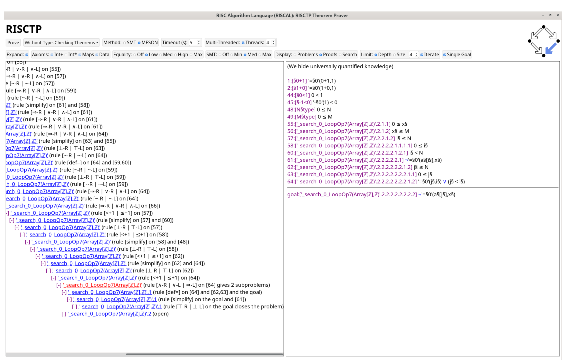
Is quantified loop invariant preserved by the second conditional branch?



Problem is closed by simplification, proof search, and SMT solving.

Example: Linear Search

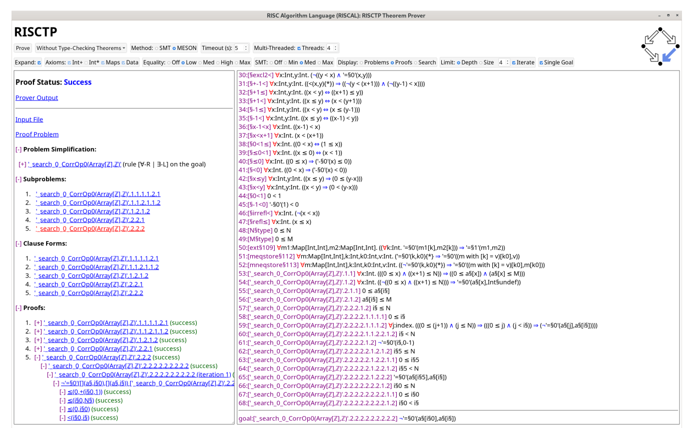
Is quantified loop invariant preserved by the second conditional branch?



Proof with knowledge $j \leq i$ is split into one case $j = i$ (which is closed by simplification) and one case $j < i$ (which is closed by proof search as in the first conditional branch).

Example: Linear Search

Is result correct?



Problem is decomposed into five subproblems closed by proof search.

Example: Linear Search

Is result correct?

```
proc search(a:array, x:elem): index
  ensures
    (result = -1 ∧ ∀i:index. 0 ≤ i ∧ i < N ⇒ a[i] ≠ x) ∨
    (0 ≤ result ∧ result < N ∧ a[result] = x ∧ ∀i:index. 0 ≤ i ∧ i < result ⇒ a[i] ≠ x);
```

(We hide universally quantified knowledge)

```
1:[§0+1] '=§0'(0+1,1)
2:[§1+0] '=§0'(1+0,1)
44:[§0<1] 0 < 1
45:[§-1<0] '-§0'(1) < 0
48:[N§type] 0 ≤ N
49:[M§type] 0 ≤ M
55:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.1.1] 0 ≤ x§
56:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.1.2] x§ ≤ M
57:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.1.1] 0 ≤ (i§+1)
58:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.1.2] i§ ≤ N
59:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.1.1] 0 ≤ (r§+1)
60:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.1.2] r§ ≤ N
61:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.1.1.1] 0 ≤ i§
63:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.1.2] '=§0'(r§,'-§0'(1)) ∨ (('=§0'(r§,i§) ∧ (i§ < N)) ∧ '=§0'(a§[r§],x§))
64:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.2] ¬((i§ < N) ∧ '=§0'(r§,'-§0'(1)))
65:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.1] ¬('=§0'(r§,'-§0'(1)) ∧ (∀i:index. ((('-§0'(1) ≤ i) ∧ (i ≤ N)) ⇒ (((0 ≤ i) ∧ (i < N)) ⇒ (¬'=§0'(a§[i],x§))))))
----------------------------------------
goal:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2] (((0 ≤ r§) ∧ (r§ < N)) ∧ '=§0'(a§[r§],x§)) ∧ (∀i:index. ((('-§0'(1) ≤ i) ∧ (i ≤ N)) ⇒ (((0 ≤ i) ∧ (i < r§)) ⇒ (¬'=§0'(a§[i],x§)))))
```

At first, the decomposition yields the second part of the disjunction as the goal (with the negation of the first part as knowledge).

Example: Linear Search

Is result correct?

```
(((0 ≤ r§) ∧ (r§ < N)) ∧ '=§0'(a§[r§],x§)) ∧ (∀i:index. ((('-§0'(1) ≤ i) ∧ (i ≤ N)) ⇒ (((0 ≤ i) ∧ (i < r§)) ⇒ (¬'=§0'(a§[i],x§)))))
```

The further decomposition yields four subproblems with the following goals which are then decomposed into five open subproblems as follows:

- $(0 \leq r) \rightsquigarrow$ 2 subproblems, 1 closed, 1 open: subproblem 1.
- $(r < N) \rightsquigarrow$ 3 subproblems, 2 closed, 1 open: subproblem 2.
- $(a[r] = x) \rightsquigarrow$ 2 subproblems, 1 closed, 1 open: subproblem 3.
- $(\forall i\colon \ldots\ a[i] \neq x) \rightsquigarrow$ 4 subproblems, 2 closed, 2 open: subproblems 4, 5.

We show the derivation and solution of subproblem 5.

Example: Linear Search

Is result correct?

(We hide universally quantified knowledge)

```
1:[§0+1] '=§0'(0+1,1)
2:[§1+0] '=§0'(1+0,1)
44:[§0<1] 0 < 1
45:[§-1<0] '-§0'(1) < 0
48:[N§type] 0 ≤ N
49:[M§type] 0 ≤ M
55:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.1.1] 0 ≤ x§
56:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.1.2] x§ ≤ M
57:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.1.1] 0 ≤ (i§+1)
58:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.1.2] i§ ≤ N
59:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.1.1] 0 ≤ (r§+1)
60:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.1.2] r§ ≤ N
61:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.1.1.1] 0 ≤ i§
63:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.1.2] '=§0'(r§,'-§0'(1)) ∨ (('=§0'(r§,i§) ∧ (i§ < N)) ∧ '=§0'(a§[r§],x§))
64:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.2] ¬((i§ < N) ∧ '=§0'(r§,'-§0'(1)))
65:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.1] ¬('=§0'(r§,'-§0'(1)) ∧ (∀i:index. ((('-§0'(1) ≤ i) ∧ (i ≤ N)) ⇒ (((0 ≤ i) ∧ (i < N)) ⇒ (¬'=§0'(a§[i],x§))))))
----------------------------------------
goal:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2] ∀i:index. ((('-§0'(1) ≤ i) ∧ (i ≤ N)) ⇒ (((0 ≤ i) ∧ (i < r§)) ⇒ (¬'=§0'(a§[i],x§))))
```

The last of the four initial subproblems (the goal is to show that value x does not occur in array a at any index less than result r).

Example: Linear Search

Is result correct?

(We hide universally quantified knowledge)

```
1:[§0+1] '=§0'(0+1,1)
2:[§1+0] '=§0'(1+0,1)
44:[§0<1] 0 < 1
45:[§-1<0] '-§0'(1) < 0
48:[N§type] 0 ≤ N
49:[M§type] 0 ≤ M
55:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.1.1] 0 ≤ x§
56:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.1.2] x§ ≤ M
57:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.1.1] 0 ≤ (i§+1)
58:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.1.2] i§ ≤ N
59:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.1.1] 0 ≤ (r§+1)
60:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.1.2] r§ ≤ N
61:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.1.1.1] 0 ≤ i§
63:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.1.2] '=§0'(r§,'-§0'(1)) ∨ (('=§0'(r§,i§) ∧ (i§ < N)) ∧ '=§0'(a§[r§],x§))
64:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.2] ¬((i§ < N) ∧ '=§0'(r§,'-§0'(1)))
65:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.1] ¬('=§0'(r§,'-§0'(1)) ∧ (∀i:index. ((('-§0'(1) ≤ i) ∧ (i ≤ N)) ⇒ (((0 ≤ i) ∧ (i < N)) ⇒ (¬'=§0'(a§[i],x§))))))
66:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.1.1] 0 ≤ (i§0+1)
67:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.1.2] i§0 ≤ N
68:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2.1.1] 0 ≤ i§0
69:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2.1.2] i§0 < r§
----------------------------------------
goal:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2.2] ¬'=§0'(a§[i§0],x§)
```

The subproblem after further decomposition; now a case split is going to be performed on disjunction formula 63.

Example: Linear Search

Is result correct?

```
(We hide universally quantified knowledge)

1:[§0+1] '=§0'(0+1,1)
2:[§1+0] '=§0'(1+0,1)
44:[§0<1] 0 < 1
45:[§-1<0] '-§0'(1) < 0
48:[N§type] 0 ≤ N
49:[M§type] 0 ≤ M
55:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.1.1] 0 ≤ x§
56:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.1.2] x§ ≤ M
57:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.1.1] 0 ≤ (i§+1)
58:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.1.2] i§ ≤ N
59:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.1.1] 0 ≤ (r§+1)
60:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.1.2] r§ ≤ N
61:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.1.1.1] 0 ≤ i§
63:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.1.2.2] ('=§0'(r§,i§) ∧ (i§ < N)) ∧ '=§0'(a§[r§],x§)
64:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.2] ¬((i§ < N) ∧ '=§0'(r§,'-§0'(1)))
65:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.1] ¬('=§0'(r§,'-§0'(1)) ∧ (∀i:index. ((('-§0'(1) ≤ i) ∧ (i ≤ N)) ⇒ (((0 ≤ i) ∧ (i < N)) ⇒ (¬'=§0'(a§[i],x§))))))
66:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.1.1] 0 ≤ (i§0+1)
67:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.1.2] i§0 ≤ N
68:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2.1.1] 0 ≤ i§0
69:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2.1.2] i§0 < r§
-----------------------------------------------------------------
goal:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2.2] ¬'=§0'(a§[i§0],x§)
```

The second case: result *r* equals loop variable *i* which is less than array length *N* and *x* occurs at index *r* in *a*.

Example: Linear Search

Is result correct?

```
(We hide universally quantified knowledge)

1:[§0+1] '=§0'(0+1,1)
2:[§1+0] '=§0'(1+0,1)
44:[§0<1] 0 < 1
45:[§-1<0] '-§0'(1) < 0
48:[N§type] 0 ≤ N
49:[M§type] 0 ≤ M
55:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.1.1] 0 ≤ a§[i§]
56:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.1.2] a§[i§] ≤ M
57:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.1.1] 0 ≤ (i§+1)
58:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.1.2] i§ ≤ N
59:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.1.1.1] 0 ≤ i§
61:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.1.2.2.1.2] i§ < N
62:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.2] ¬'=§0'(i§,0-1)
63:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.1] ¬('=§0'(i§,'-§0'(1)) ∧ (∀i:index. ((('-§0'(1) ≤ i) ∧ (i ≤ N)) ⇒ (((0 ≤ i) ∧ (i < N)) ⇒ (¬'=§0'(a§[i],a§[i§]))))))
64:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.1.1] 0 ≤ (i§0+1)
65:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.1.2] i§0 ≤ N
66:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2.1.1] 0 ≤ i§0
67:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2.1.2] i§0 < i§
-----------------------------------------------------------------
goal:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2.2] ¬'=§0'(a§[i§0],a§[i§])
```

After further simplification, another case split is performed on the negated conjunction formula 63 (equivalent to a disjunction of negated formulas).

Example: Linear Search

Is result correct?

```
(We hide universally quantified knowledge)

1:[§0+1] '=§0'(0+1,1)
2:[§1+0] '=§0'(1+0,1)
44:[§0<1] 0 < 1
45:[§-1<0] '-§0'(1) < 0
48:[N§type] 0 ≤ N
49:[M§type] 0 ≤ M
55:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.1.1] 0 ≤ a§[i§]
56:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.1.2] a§[i§] ≤ M
57:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.1.1] 0 ≤ (i§+1)
58:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.1.2] i§ ≤ N
59:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.1.1.1] 0 ≤ i§
61:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.1.2.2.1.2] i§ < N
62:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.2] ¬'=§0'(i§,0-1)
63:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.1.2] ¬(∀i:index. ((('-§0'(1) ≤ i) ∧ (i ≤ N)) ⇒ (((0 ≤ i) ∧ (i < N)) ⇒ (¬'=§0'(a§[i],a§[i§])))))
64:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.1.1] 0 ≤ (i§0+1)
65:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.1.2] i§0 ≤ N
66:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2.1.1] 0 ≤ i§0
67:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2.1.2] i§0 < i§
-----------------------------------------------------------------
goal:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2.2] ¬'=§0'(a§[i§0],a§[i§])
```

The second case: given constant *i*§, array *a* holds at some index *i* greater equal 0 and less than *N* value *a*[*i*§].

Example: Linear Search

Is result correct?

```
(We hide universally quantified knowledge)

1:[§0+1] '=§0'(0+1,1)
2:[§1+0] '=§0'(1+0,1)
44:[§0<1] 0 < 1
45:[§-1<0] '-§0'(1) < 0
48:[N§type] 0 ≤ N
49:[M§type] 0 ≤ M
55:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.1.1] 0 ≤ a§[i§]
56:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.1.2] a§[i§] ≤ M
57:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.1.2] i§ ≤ N
58:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.1.1.1] 0 ≤ i§
60:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.1.2.2.1.2] i§ < N
61:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.2] ¬'=§0'(i§,0-1)
62:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.1.2.1.2] i§5 ≤ N
63:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.1.2.2.1.1] 0 ≤ i§5
64:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.1.2.2.1.2] i§5 < N
65:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.1.2.2.2] '=§0'(a§[i§5],a§[i§])
66:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.1.2] i§0 ≤ N
67:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2.1.1] 0 ≤ i§0
68:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2.1.2] i§0 < i§
-----------------------------------------------------------------
goal:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2.2] ¬'=§0'(a§[i§0],a§[i§])
```

After further simplification, we have subproblem 5.

Example: Linear Search

Is result correct?

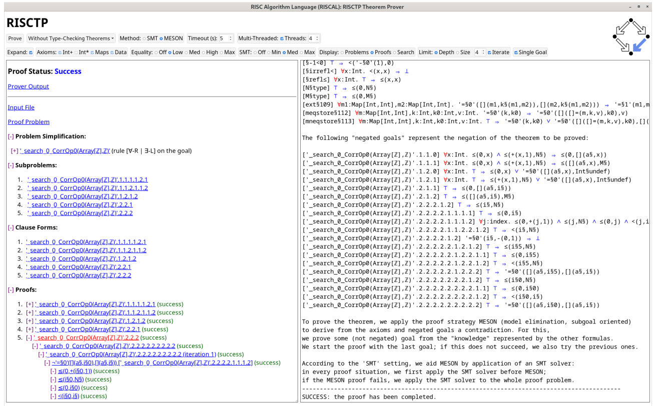
53:['_search_0_CorrOp0(Array[ℤ],ℤ)'.1.1] ∀x:Int. (((0 ≤ x) ∧ ((x+1) ≤ N)) ⇒ ((0 ≤ a§[x]) ∧ (a§[x] ≤ M)))
54:['_search_0_CorrOp0(Array[ℤ],ℤ)'.1.2] ∀x:Int. ((¬((0 ≤ x) ∧ ((x+1) ≤ N))) ⇒ '=§0'(a§[x],Int§undef))
55:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.1.1] 0 ≤ a§[i§]
56:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.1.2] a§[i§] ≤ M
57:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.1.2] i§ ≤ N
58:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.1.1.1] 0 ≤ i§
59:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.1.1.2] ∀j:index. (((0 ≤ (j+1)) ∧ (j ≤ N)) ⇒ (((0 ≤ j) ∧ (j < i§)) ⇒ (¬'=§0'(a§[j],a§[i§]))))
60:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.1.2.2.1.2] i§ < N
61:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.2] ¬'=§0'(i§,0-1)
62:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.1.2.1.2] i§5 ≤ N
63:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.1.2.2.1.1] 0 ≤ i§5
64:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.1.2.2.1.2] i§5 < N
65:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.1.2.2.2] '=§0'(a§[i§5],a§[i§])
66:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.1.2] i§0 ≤ N
67:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2.1.1] 0 ≤ i§0
68:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2.1.2] i§0 < i§

goal:['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2.2] ¬'=§0'(a§[i§0],a§[i§])

Subproblem 5 with the quantified formulas (except for the theory axioms).

Example: Linear Search

Is result correct?



The problem is closed by proof search and SMT solving.

Example: Linear Search

Is result correct?

Goal: ¬'=§0'([](a§,i§0),[](a§,i§)) ['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.1.1.2] (proof depth: 0, proof size: 1)

```
Goal: ¬'=§0'([](a§,i§0),[](a§,i§))

To prove the goal, we assume its negation

[1] '=§0'([](a§,i§0),[](a§,i§))

and show a contradiction. For this, consider knowledge ['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.1.1.2] with the following instance:

  ∀j@113:index. ≤(0,+(j@113,1)) ∧ ≤(j@113,N§) ∧ ≤(0,j@113) ∧ <(j@113,i§) ∧ '=§0'([](a§,j@113),[](a§,i§)) ⇒ ⊥

Assumption [1] matches the literal '=§0'([](a§,j@113),[](a§,i§)) on the left side of this clause by the following substitution:

  j@113 → i§0

Therefore, applying this substitution and dropping the literal, we know:

  ≤(0,+(i§0,1)) ∧ ≤(i§0,N§) ∧ ≤(0,i§0) ∧ <(i§0,i§) ⇒ ⊥

Therefore, to show a contradiction, we prove this subgoal:

  ≤(0,+(i§0,1)) ∧ ≤(i§0,N§) ∧ ≤(0,i§0) ∧ <(i§0,i§)
------------------------------------------------------------------------------------------
SUCCESS: goal ¬'=§0'([](a§,i§0),[](a§,i§)) ['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.1.1.2] has been proved with the following substitution:

  j@113 → i§0
```

Invariant has to be instantiated with constant $i§0$ for variable j.

Example: Linear Search

Is result correct?

Goal: ≤(0,+(i§0,1)) (proof depth: 1, proof size: 2)

```
Goal: ≤(0,+(i§0,1))

Assumptions:

[1] '=§0'([](a§,i§0),[](a§,i§))

The goal has been proved by the SMT solver: the solver states by the output

  unsat

the unsatisfiability of the negated goal in conjunction with this knowledge:

['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2.1.1] ≤(0,i§0)
------------------------------------------------------------------------------------------
SUCCESS: goal ≤(0,+(i§0,1)) has been proved with the following substitution:

  j@113 → i§0
```

Option "SMT: Med": the subproblems are closed by the SMT solver.

Example: Linear Search

Is result correct?

Proof problem: '_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2

```
The problem has been closed by the SMT solver: the solver states by the output

  unsat

the unsatisfiability of these clauses that arise from the negation of the theorem to be proved:

['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.1.1.2] ∀j:index. ≤(0,+(j,1)) ∧ ≤(j,N§) ∧ ≤(0,j) ∧ <(j,i§) ∧ '=§0'([](a§,j),[](a§,i§)) ⇒ ⊥
['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.1.2] ≤(i§0,N§)
['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2.1.1] ≤(0,i§0)
['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2.1.2] <(i§0,i§)
['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2.2.2] '=§0'([](a§,i§0),[](a§,i§))

In more detail, the solver states the unsatisfiability of these clause instances:

['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.1.1.1.2.2] ≤(0,+(i§0,1)) ∧ ≤(i§0,N§) ∧ ≤(0,i§0) ∧ <(i§0,i§) ∧ '=§0'([](a§,i§0),[](a§,i§)) ⇒ ⊥
['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.1.2] ≤(i§0,N§)
['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2.1.1] ≤(0,i§0)
['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2.1.2] <(i§0,i§)
['_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2.2.2.2.2.2.2.2] '=§0'([](a§,i§0),[](a§,i§))

Thus the theorem is valid.
-------------------------------------------------------------------------------------------
SUCCESS: goal '_search_0_CorrOp0(Array[ℤ],ℤ)'.2.2.2 has been proved.
```

Option “SMT: Max”: a proof outline is produced by the SMT solver.

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:

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

- Alternative:

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

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.

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

- $Pre[e/i]$ 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.
- $Post[\ldots]$ 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

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

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

Explicit naming of old/new values required.

Example

- Procedure specification:

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

- Procedure call:

  $\{g \geq 0 \land g = N \land b \geq 0\}$
  $x = p(b+1)$
  $\{g \cdot (b+1) \leq N < (g+1) \cdot (b+1)\}$

- To be proved:

$$\begin{aligned}
&g \geq 0 \land g = N \land b \geq 0 \Rightarrow \\
&\quad D(b+1) \land g \geq 0 \land b+1 > 0 \land \\
&\quad \forall x', g' : \\
&\qquad g = g' \cdot (b+1) + x' \land 0 \leq x' < b+1 \Rightarrow \\
&\qquad\quad g' \cdot (b+1) \leq N < (g'+1) \cdot (b+1)
\end{aligned}$$