Hoare Semantics

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Objectives

You should be able to ...

- Explain the syntax of Hoare triples and relate them to small step semantics.
- Use a Hoare triple to show the correctness of a simple program.
- Explain the properties of the weakest precondition.

Review of Language Syntax

The Language

$$\begin{array}{rcl} S & ::= & \mathtt{skip} \\ & | & u := t \\ & | & S_1 ; S_2 \\ & | & \mathtt{if}\ B\ \mathtt{then}\ S_1\ \mathtt{else}\ S_2\ \mathtt{fi} \\ & | & \mathtt{while}\ B\ \mathtt{do}\ S_1\ \mathtt{od} \end{array}$$

- The `else` branch can be left off if the subexpression is simply a skip.
- $var(S)$ is the set of variable names appearing in S.
- $change(S)$ is the set of variables appearing on the LHS of `:=`.

Definition of $\rightarrow$

Skip and Assignment

$$< \mathtt{skip}, \sigma > \rightarrow < E, \sigma >$$

$$< u := t, \sigma > \rightarrow < E, \sigma[u := \sigma(t)] >$$

$$\frac{< S_1, \sigma > \rightarrow < S_2, \tau >}{< S_1 ; S, \sigma > \rightarrow < S_2 ; S, \tau >}$$

$$E ; S \equiv S$$

$$< \mathtt{if}\ B\ \mathtt{then}\ S_1\ \mathtt{else}\ S_2\ \mathtt{fi}, \sigma > \rightarrow < S_1, \sigma > \text{ where } \sigma \models B$$

$$< \mathtt{if}\ B\ \mathtt{then}\ S_1\ \mathtt{else}\ S_2\ \mathtt{fi}, \sigma > \rightarrow < S_2, \sigma > \text{ where } \sigma \models \neg B$$

$$< \mathtt{while}\ B\ \mathtt{do}\ S_1\ \mathtt{od}, \sigma > \rightarrow < S_1 ; \mathtt{while}\ B\ \mathtt{do}\ S_1\ \mathtt{od}, \sigma > \text{ where } \sigma \models B$$

$$< \mathtt{while}\ B\ \mathtt{do}\ S_1\ \mathtt{od}, \sigma > \rightarrow < E, \sigma > \text{ where } \sigma \models \neg B$$

Hoare Triples

- The $\rightarrow$ semantics gives us exact transformations, but sometimes we want something more general.
- Define $\{p\}S\{q\}$, where p and q are assertions, and S is a program:
  - $\models \{p\}S\{q\}$ – if p is true before the program runs, q will be true afterwards; if the program terminates. "Partial Correctness"
  - $\models_{tot} \{p\}S\{q\}$ – if p is true before the program runs, q will be true afterwards. Termination guaranteed. "Total Correctness"
- These are sometimes called *correctness formulas*.

Examples

- $\{x = 0\}x := x + 1\{x = 1\}$
- $\{x = 0\}x := x + 1\{x > 0\}$
- $\{x = 0\}x := x + 1\{true\}$

False formulas ...

- $\{x = 0\}x := x + 1\{x = 2\}$
- $\{x = 0\}x := x + 1\{x < 0\}$

What does this one mean? $\{x = 0\}x := x + 1\{false\}$

Axiom 1: Skip

$$\{p\}\texttt{skip}\,\{p\}$$

Axiom 2: Assignment

$$\{p[u := t]\}u := t\{p\}$$

- Is this what you expected?

$$\{y > 10\}x := y\{x > 10\}$$

Rule 3: Composition

$$\frac{\{p\}S_1\{r\}, \{r\}S_2\{q\}}{\{p\}S_1; S_2\{q\}}$$

Rule 4: Conditional

$$\frac{\{p \wedge B\}S_1\{q\}, \{p \wedge \neg B\}S_2\{q\}}{\{p\}\texttt{if } B \texttt{ then } S_1 \texttt{ else } S_2 \texttt{ fi } \{q\}}$$

- See Dijkstra's paper EWD 264.

Rule 5: Loop

$$\frac{\{p \wedge B\}S\{p\}}{\{p\}\texttt{while } B \texttt{ do } S \texttt{ od } \{p \wedge \neg B\}}$$

Rule 6: Consequence

- This one you will use a *lot*.

$$\frac{p \to p_1, \{p_1\}S\{q_1\}, q_1 \to q}{\{p\}S\{q\}}$$

Skip, Assignment, and Sequence

$$\{p\}\mathbf{skip}\ \{p\}$$

$$\{p[u := t]\}u := t\{p\}$$

$$\frac{\{p\}S_1^*\{r\}, \{r\}S_2^*\{q\}}{\{p\}S_1^*; \{r\}S_2^*\{q\}}$$

- Example

$\{y = 20, x = 10\}$
$t := x;$
$\{y = 20, t = 10\}$
$x := y;$
$\{x = 20, t = 10\}$
$y := t$
$\{x = 20, y = 10\}$

If, Consequence

$$\frac{\{p \wedge B\}S_1^*\{q\}, \{p \wedge \neg B\}S_2^*\{q\}}{\{p\}\mathbf{if}\ B\ \mathbf{then}\ \{p \wedge B\}S_1^*\{q\}\ \mathbf{else}\ \{p \wedge \neg B\}S_2^*\{q\}\ \mathbf{fi}\ \{q\}}$$

$$\frac{p \rightarrow p_1, \{p_1\}S^*\{q_1\}, q_1 \rightarrow q}{\{p\}\{p_1\}S^*\{q_1\}\{q\}}$$

Activity

Try to verify the following program.

$$\{true\}\ \begin{array}{l}\mathbf{if}\ x > y\ \mathbf{then}\ m := x\ \mathbf{fi}\ ;\\ \mathbf{if}\ x < y\ \mathbf{then}\ m := y\ \mathbf{fi}\end{array}\ \{m = max(x, y)\}$$

(Hint: actually, it's not true!)

The Verification

$\{true\}$
$\mathbf{if}\ x > y\ \mathbf{then}\ m := x\ \mathbf{fi}\ ;$
$\mathbf{if}\ x < y\ \mathbf{then}\ m := y\ \mathbf{fi}$
$\{m = max(x, y)\}$

The Verification

$\{true\}$
if $x > y$ **then** $m := x$ **fi** ;
if $x < y$ **then** $\{y = max(x,y)\}m := y\{m = max(x,y)\}$
else $\{m = max(x,y)\}$**skip** $\{m = max(x,y)\}$ **fi**
$\{m = max(x,y)\}$

The Verification

$\{true\}$
if $x > y$ **then** $m := x$ **fi** ;
$\{P \equiv x < y \wedge y = max(x,y) \vee x > y \wedge m = max(x,y)\}$
if $x < y$ **then** $\{y = max(x,y)\}m := y\{m = max(x,y)\}$
else $\{m = max(x,y)\}$**skip** $\{m = max(x,y)\}$ **fi**
$\{m = max(x,y)\}$

The Verification

$\{true\}$
if $x > y$ **then** $\{P[x = max(x,y)]\}m := x\{P\}$
else $\{P\}$**skip** $\{P\}$ **fi** ;
$\{P \equiv x < y \wedge y = max(x,y) \vee x > y \wedge m = max(x,y)\}$
if $x < y$ **then** $\{y = max(x,y)\}m := y\{m = max(x,y)\}$
else $\{m = max(x,y)\}$**skip** $\{m = max(x,y)\}$ **fi**
$\{m = max(x,y)\}$

The Verification

$\{true\}$
$\{x > y \wedge x = max(x,y) \vee x < y \wedge y = max(x,y) \vee x = y \wedge m = max(x,y)\}$
if $x > y$ **then** $\{P[x = max(x,y)]\}m := x\{P\}$
else $\{P\}$**skip** $\{P\}$ **fi** ;
$\{P \equiv x < y \wedge y = max(x,y) \vee x \geq y \wedge m = max(x,y)\}$
if $x < y$ **then** $\{y = max(x,y)\}m := y\{m = max(x,y)\}$
else $\{m = max(x,y)\}$**skip** $\{m = max(x,y)\}$ **fi**
$\{m = max(x,y)\}$