

Semantics and Verification of Software

Lecture 11: Axiomatic Semantics of WHILE IV (Semantic Equivalence)

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- 1 Recapitulation: Partial & Total Correctness Properties
- 2 Axiomatic Equivalence
- 3 Characteristic Assertions
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- 6 Summary: Axiomatic Semantics

Hoare Logic

Goal: syntactic derivation of valid partial correctness properties. Here $A[x \mapsto a]$ denotes the syntactic replacement of every occurrence of x by a in A .



Tony Hoare (* 1934)

Definition (Hoare Logic)

The **Hoare rules** are given by

$$\begin{array}{c} \text{(skip)} \frac{}{\{A\} \text{ skip } \{A\}} \qquad \text{(asgn)} \frac{}{\{A[x \mapsto a]\} x := a \{A\}} \\ \text{(seq)} \frac{\{A\} c_1 \{C\} \quad \{C\} c_2 \{B\}}{\{A\} c_1; c_2 \{B\}} \qquad \text{(if)} \frac{\{A \wedge b\} c_1 \{B\} \quad \{A \wedge \neg b\} c_2 \{B\}}{\{A\} \text{ if } b \text{ then } c_1 \text{ else } c_2 \{B\}} \\ \text{(while)} \frac{\{A \wedge b\} c \{A\}}{\{A\} \text{ while } b \text{ do } c \{A \wedge \neg b\}} \\ \text{(cons)} \frac{\models (A \Rightarrow A') \quad \{A'\} c \{B'\} \quad \models (B' \Rightarrow B)}{\{A\} c \{B\}} \end{array}$$

A partial correctness property is **provable** (notation: $\vdash \{A\} c \{B\}$) if it is derivable by the Hoare rules. In (while), A is called a **(loop) invariant**.

Proving Total Correctness

Goal: syntactic derivation of valid total correctness properties

Definition (Hoare Logic for total correctness)

The **Hoare rules** for total correctness are given by

$$\begin{array}{c} \text{(skip)} \frac{}{\{A\} \text{ skip } \{\Downarrow A\}} \qquad \text{(asgn)} \frac{}{\{A[x \mapsto a]\} x := a \{\Downarrow A\}} \\ \text{(seq)} \frac{\{A\} c_1 \{\Downarrow C\} \{C\} c_2 \{\Downarrow B\}}{\{A\} c_1; c_2 \{\Downarrow B\}} \qquad \text{(if)} \frac{\{A \wedge b\} c_1 \{\Downarrow B\} \{A \wedge \neg b\} c_2 \{\Downarrow B\}}{\{A\} \text{ if } b \text{ then } c_1 \text{ else } c_2 \{\Downarrow B\}} \\ \text{(while)} \frac{\models (i \geq 0 \wedge A(i+1) \Rightarrow b) \quad \{i \geq 0 \wedge A(i+1)\} c \{\Downarrow A(i)\} \quad \models (A(0) \Rightarrow \neg b)}{\{\exists i. i \geq 0 \wedge A(i)\} \text{ while } b \text{ do } c \{\Downarrow A(0)\}} \\ \text{(cons)} \frac{\models (A \Rightarrow A') \quad \{A'\} c \{\Downarrow B'\} \quad \models (B' \Rightarrow B)}{\{A\} c \{\Downarrow B\}} \end{array}$$

where $i \in LVar$.

A total correctness property is **provable** (notation: $\vdash \{A\} c \{\Downarrow B\}$) if it is derivable by the Hoare rules. In case of (while), $A(i)$ is called a **(loop) invariant**.

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Definition 4.1: $\mathfrak{O}[\cdot] : Cmd \rightarrow (\Sigma \dashrightarrow \Sigma)$ given by

$$\mathfrak{O}[c](\sigma) = \sigma' \iff \langle c, \sigma \rangle \rightarrow \sigma'$$

Definition 4.2: Two statements $c_1, c_2 \in Cmd$ are **operationally equivalent** (notation: $c_1 \sim c_2$) if

$$\mathfrak{O}[c_1] = \mathfrak{O}[c_2].$$

Theorem 7.5: For every $c \in Cmd$,

$$\mathfrak{O}[c] = \mathfrak{C}[c],$$

i.e., $\mathfrak{O}[\cdot] = \mathfrak{C}[\cdot]$.

In the axiomatic semantics, two statements have to be considered equivalent if they are **indistinguishable** w.r.t. partial correctness properties:

Definition 11.1 (Axiomatic equivalence)

Two statements $c_1, c_2 \in Cmd$ are called **axiomatically equivalent** (notation: $c_1 \approx c_2$) if, for all assertions $A, B \in Assn$,

$$\models \{A\} c_1 \{B\} \iff \models \{A\} c_2 \{B\}.$$

Example 11.2

We show that

$\text{while } b \text{ do } c \approx \text{if } b \text{ then } (c; \text{while } b \text{ do } c) \text{ else skip}$

(cf. Lemma 4.3). Let $A, B \in \text{Assn}$:

$$\begin{aligned} & \models \{A\} \text{while } b \text{ do } c \{B\} \\ \iff & \vdash \{A\} \text{while } b \text{ do } c \{B\} \quad (\text{Theorem 9.4, 10.3}) \\ \iff & \text{ex. } C \in \text{Assn} \text{ such that } \vdash (A \Rightarrow C), \vdash (C \wedge \neg b \Rightarrow B), \\ & \quad \vdash \{C\} \text{while } b \text{ do } c \{C \wedge \neg b\} \quad (\text{rule (cons)}) \\ \iff & \text{ex. } C \in \text{Assn} \text{ such that } \vdash (A \Rightarrow C), \vdash (C \wedge \neg b \Rightarrow B), \\ & \quad \vdash \{C \wedge b\} c \{C\} \quad (\text{rule (while)}) \\ \iff & \text{ex. } C \in \text{Assn} \text{ such that } \vdash (A \Rightarrow C), \vdash (C \wedge \neg b \Rightarrow B), \\ & \quad \vdash \{C \wedge b\} c; \text{while } b \text{ do } c \{C \wedge \neg b\} \quad (\text{rule (seq)}), \\ & \quad \vdash \{C \wedge \neg b\} \text{skip} \{C \wedge \neg b\} \quad (\text{rule (skip)}) \\ \iff & \text{ex. } C \in \text{Assn} \text{ such that } \vdash (A \Rightarrow C), \vdash (C \wedge \neg b \Rightarrow B), \\ & \quad \vdash \{C\} \text{if } b \text{ then } (c; \text{while } b \text{ do } c) \text{ else skip} \{C \wedge \neg b\} \quad (\text{rule (if)}) \\ \iff & \vdash \{A\} \text{if } b \text{ then } (c; \text{while } b \text{ do } c) \text{ else skip} \{B\} \quad (\text{rule (cons)}) \\ \iff & \models \{A\} \text{if } b \text{ then } (c; \text{while } b \text{ do } c) \text{ else skip} \{B\} \\ & \quad (\text{Theorem 9.4, 10.3}) \end{aligned}$$

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The following results are based on the following **encoding of states** by assertions:

Definition 11.3

Given a finite subset of program variables $X \subseteq \text{Var}$ and a state $\sigma \in \Sigma$, the **characteristic assertion of σ w.r.t. X** is given by

$$\text{State}(\sigma, X) := \bigwedge_{x \in X} (x = \underbrace{\sigma(x)}_{\in \mathbb{Z}}) \in \text{Assn}$$

Moreover, we let $\text{State}(\perp, X) := \text{false}$.

Characteristic Assertions II

Programs and characteristic state assertions are obviously related in the following way:

Corollary 11.4

Let $c \in \text{Cmd}$, and let $\text{FV}(c) \subseteq \text{Var}$ denote the set of all variables occurring in c . Then, for every finite $X \supseteq \text{FV}(c)$ and $\sigma \in \Sigma$,

$$\{\text{State}(\sigma, X)\} \subset \{\text{State}(\mathfrak{C}[c]\sigma, X)\}$$

Example 11.5 (Factorial program)

For $c := (y := 1; \text{while } \neg(x = 1) \text{ do } (y := y * x; x := x - 1))$, $X = \{x, y\}$, $\sigma(x) = 3$, and $\sigma(y) = 0$, we obtain

$$\begin{aligned}\text{State}(\sigma, X) &= (x = 3 \wedge y = 0) \\ \text{State}(\mathfrak{C}[c]\sigma, X) &= (x = 1 \wedge y = 6)\end{aligned}$$

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Now we can show that considering **total** rather than partial correctness properties yields the same notion of equivalence:

Theorem 11.6

Let $c_1, c_2 \in \text{Cmd}$. The following propositions are equivalent:

- ① $\forall A, B \in \text{Assn} : \models \{A\} c_1 \{B\} \iff \models \{A\} c_2 \{B\}$
- ② $\forall A, B \in \text{Assn} : \models \{A\} c_1 \{\Downarrow B\} \iff \models \{A\} c_2 \{\Downarrow B\}$

Proof.

on the board



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Theorem 11.7

Axiomatic and operational/denotational equivalence coincide, i.e., for all $c_1, c_2 \in \text{Cmd}$,

$$c_1 \approx c_2 \iff c_1 \sim c_2.$$

Proof.

on the board



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- Formalized by **partial/total correctness properties**
- Inductively defined by **Hoare Logic** proof rules
- Technically involved (especially loop invariants)
 ⇒ machine support (**proof assistants**) indispensable for larger programs
- **Equivalence** of axiomatic and operational/denotational semantics
- **Software engineering** aspect: integrated development of program and proof (cf. assertions in Java)