CS477 Formal Software Dev Methods

Elsa L Gunter
2112 SC, UIUC
egunter@illinois.edu
http://courses.engr.illinois.edu/cs477

Slides based in part on previous lectures
by Mahesh Vishwanathan, and by Gul Agha

February 27, 2020

Floyd-Hoare Logic

- Also called Axiomatic Semantics
- Based on formal logic (first order predicate calculus)
- Logical system built from axioms and inference rules
- Mainly suited to simple imperative programming languages
- Ideas applicable quite broadly

Floyd-Hoare Logic

- Used to formally prove a property (post-condition) of the state (the values of the program variables) after the execution of program, assuming another property (pre-condition) of the state holds before execution

Floyd-Hoare Logic

- Goal: Derive statements of form

$$\{P\}\ C\ \{Q\}$$

  - P, Q logical statements about state, P precondition, Q postcondition, C program
- Example:

$$\{x = 1\}\ x := x + 1\ \{x = 2\}$$

Floyd-Hoare Logic

- **Approach:** For each type of language statement, give an axiom or inference rule stating how to derive assertions of form

$$\{P\}\ C\ \{Q\}$$

  where C is a statement of that type
- Compose axioms and inference rules to build proofs for complex programs

Partial vs Total Correctness

- An expression $\{P\}\ C\ \{Q\}$ is a partial correctness statement
- For total correctness must also prove that C terminates (i.e. doesnt run forever)
  - Written: $[P]\ C\ [Q]$
- Will only consider partial correctness here

Simple Imperative Language

- We will give rules for simple imperative language

$$\begin{array}{l}\langle command\rangle \ ::= \ \langle variable\rangle := \langle term\rangle \\ \mid \langle command\rangle; \ \ldots; \ \langle command\rangle \\ \mid \textit{if} \ \langle statement\rangle \ \textit{then} \ \langle command\rangle \ \textit{else} \ \langle command\rangle \\ \mid \textit{while} \ \langle statement\rangle \ \textit{do} \ \langle command\rangle\end{array}$$

- Could add more features, like for-loops

Substitution

- Notation: $P[e/v]$ (sometimes $P[v \to e]$)
- Meaning: Replace every v in P by e
- Example:

$$(x + 2)[y - 1/x] = ((y - 1) + 2)$$

The Assignment Rule

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

Example:

$$\frac{}{\Big\{ \quad ? \quad \Big\} \ x \ := \ y \ \{ \ x \ = 2 \}}$$

The Assignment Rule

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

Example:

$$\frac{}{\Big\{ \boxed{} = 2 \Big\} \ x \ := \ y \ \{ \boxed{x} = 2 \}}$$

The Assignment Rule

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

Example:

$$\frac{}{\Big\{ \boxed{y} = 2 \Big\} \ x \ := \ y \ \{ \boxed{x} = 2 \}}$$

The Assignment Rule

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

Examples:

$$\frac{}{\{y = 2\} \ x \ := \ y \ \{x = 2\}}$$

$$\frac{}{\{y = 2\} \ x \ := \ 2 \ \{y = x\}}$$

$$\frac{}{\{x + 1 = n + 1\} \ x \ := \ x + 1 \ \{x = n + 1\}}$$

$$\frac{}{\{2 = 2\} \ x \ := \ 2 \ \{x = 2\}}$$

The Assignment Rule – Your Turn

- What is the weakest precondition of

$$x := x + y \{x + y = wx\}?$$

$$\{ \quad ? \quad \}$$
$$x := x + y$$
$$\{x + y = wx\}$$

The Assignment Rule – Your Turn

- What is the weakest precondition of

$$x := x + y \{x + y = wx\}?$$

$$\{ (x + y) + y = w(x + y) \}$$
$$x := x + y$$
$$\{x + y = wx\}$$

Precondition Strengthening

$$\frac{(P \Rightarrow P') \qquad \{P'\}\ C\ \{Q\}}{\{P\}\ C\ \{Q\}}$$

- Meaning: If we can show that P implies P' (*i.e.* $(P \Rightarrow P')$ and we can show that $\{P\}\ C\ \{Q\}$, then we know that $\{P\}\ C\ \{Q\}$
- P is stronger than P' means $P \Rightarrow P'$

Precondition Strengthening

- Examples:

$$\frac{x = 3 \Rightarrow x < 7 \qquad \{x < 7\}\ x := x + 3\ \{x < 10\}}{\{x = 3\}\ x := x + 3\ \{x < 10\}}$$

$$\frac{True \Rightarrow (2 = 2) \qquad \{2 = 2\}\ x := 2\ \{x = 2\}}{\{True\}\ x := 2\ \{x = 2\}}$$

$$\frac{x = n \Rightarrow x + 1 = n + 1 \qquad \{x + 1 = n + 1\}\ x := x + 1\ \{x = n + 1\}}{\{x = n\}\ x := x + 1\ \{x = n + 1\}}$$

Which Inferences Are Correct?

$$\frac{\{x > 0 \wedge x < 5\}\ x := x * x\ \{x < 25\}}{\{x = 3\}\ x := x * x\ \{x < 25\}}$$

$$\frac{\{x = 3\}\ x := x * x\ \{x < 25\}}{\{x > 0 \wedge x < 5\}\ x := x * x\ \{x < 25\}}$$

$$\frac{\{x * x < 25\}\ x := x * x\ \{x < 25\}}{\{x > 0 \wedge x < 5\}\ x := x * x\ \{x < 25\}}$$

Which Inferences Are Correct?

$$\frac{\{x > 0 \wedge x < 5\}\ x := x * x\ \{x < 25\}}{\{x = 3\}\ x := x * x\ \{x < 25\}}\ YES$$

$$\frac{\{x = 3\}\ x := x * x\ \{x < 25\}}{\{x > 0 \wedge x < 5\}\ x := x * x\ \{x < 25\}}$$

$$\frac{\{x * x < 25\}\ x := x * x\ \{x < 25\}}{\{x > 0 \wedge x < 5\}\ x := x * x\ \{x < 25\}}$$

Which Inferences Are Correct?

$$\frac{\{x > 0 \land x < 5\}\ x\ :=\ x * x\ \{x < 25\}}{\{x = 3\}\ x\ :=\ x * x\ \{x < 25\}}\ \mathit{YES}$$

$$\frac{\{x = 3\}\ x\ :=\ x * x\ \{x < 25\}}{\{x > 0 \land x < 5\}\ x\ :=\ x * x\ \{x < 25\}}\ \mathit{NO}$$

$$\frac{\{x * x < 25\}\ x\ :=\ x * x\ \{x < 25\}}{\{x > 0 \land x < 5\}\ x\ :=\ x * x\ \{x < 25\}}$$

Which Inferences Are Correct?

$$\frac{\{x > 0 \land x < 5\}\ x\ :=\ x * x\ \{x < 25\}}{\{x = 3\}\ x\ :=\ x * x\ \{x < 25\}}\ \mathit{YES}$$

$$\frac{\{x = 3\}\ x\ :=\ x * x\ \{x < 25\}}{\{x > 0 \land x < 5\}\ x\ :=\ x * x\ \{x < 25\}}\ \mathit{NO}$$

$$\frac{\{x * x < 25\}\ x\ :=\ x * x\ \{x < 25\}}{\{x > 0 \land x < 5\}\ x\ :=\ x * x\ \{x < 25\}}\ \mathit{YES}$$

Post Condition Weakening

$$\frac{\{P\}\ C\ \{Q'\} \qquad Q' \Rightarrow Q}{\{P\}\ C\ \{Q\}}$$

- Example:

$$\frac{\{x + y = 5\}\ x := x + y\ \{x = 5\} \qquad (x = 5) \Rightarrow (x < 10)}{\{x + y = 5\}\ x := x + y\ \{x < 10\}}$$

Rule of Consequence

$$\frac{P \Rightarrow P' \qquad \{P'\}\ C\ \{Q'\} \qquad Q' \Rightarrow Q}{\{P\}\ C\ \{Q\}}$$

- Logically equivalent to the combination of Precondition Strengthening and Postcondition Weakening
- Uses $P \Rightarrow P$ and $Q \Rightarrow Q$

Sequencing

$$\frac{\{P\}\ C_1\ \{Q\} \qquad \{Q\}\ C_2\ \{R\}}{\{P\}\ C_1;\ C_2\ \{R\}}$$

- Example:

$$\frac{\{z = z \land z = z\}\ x := z\ \{x = z \land z = z\} \quad \{x = z \land z = z\}\ y := z\ \{x = z \land y = z\}}{\{z = z \land z = z\}\ x := z;\ y := z\ \{x = z \land y = z\}}$$

If Then Else

$$\frac{\{P \land B\}\ C_1\ \{Q\} \qquad \{P \land \neg B\}\ C_2\ \{Q\}}{\{P\}\ \mathit{if}\ B\ \mathit{then}\ C_1\ \mathit{else}\ C_2\ \{Q\}}$$

- Example:

  $\{y = a\}\ \mathit{if}\ x < 0\ \mathit{then}\ y := y - x\ \mathit{else}\ y := y + x\ \{y = a + |x|\}$

  By If_Then_Else Rule suffices to show:
  - (1) $\{y = a \land x < 0\}\ y := y - x\ \{y = a + |x|\}$ and
  - (4) $\{y = a \land \neg(x < 0)\}\ y := y + x\ \{y = a + |x|\}$

(1) $\{y = a \land x < 0\}\ y := y - x\ \{y = a + |x|\}$

$$\frac{(3)\ \ (y = a \land x < 0) \Rightarrow (y - x = a + |x|) \qquad (2)\ \ \{y - x = a + |x|\}\ y := y - x\ \{y = a + |x|\}}{(1)\ \ \{y = a \land x < 0\}\ y := y - x\ \{y = a + |x|\}}$$

- (1) reduces to (2) and (3) by Precondition Strengthening
- (2) instance of Assignment Axiom
- (3) holds since $x < 0 \Rightarrow |x| = -x$

(4) $\{y = a \land \neg(x < 0)\}\ y := y + x\ \{y = a + |x|\}$

$$\frac{(6)\ \ (y = a \land \neg(x < 0)) \Rightarrow (y + x = a + |x|) \qquad (5)\ \ \{y + x = a + |x|\}\ y := y + x\ \{y = a + |x|\}}{(4)\ \ \{y = a \land \neg(x < 0)\}\ y := y + x\ \{y = a + |x|\}}$$

- (4) reduces to (5) and (6) by Precondition Strengthening
- (5) Follows from Assignment Axiom
- (6) since $\neg(x < 0) \Rightarrow |x| = x$

If Then Else

$$\frac{(1)\ \ \{y = a \land x < 0\}\ y := y - x\ \{y = a + |x|\} \qquad (4)\ \ \{y = a \land \neg(x < 0)\}\ y := y + x\ \{y = a + |x|\}}{\{y = a\}\ \textit{if}\ x < 0\ \textit{then}\ y := y - x\ \textit{else}\ y := y + x\ \{y = a + |x|\}}$$

by the If_Then_Else Rule

While

We need a rule to be able to make assertions about *while* loops.

- Inference rule because we can only draw conclusions if we know something about the body
- Lets start with:

$$\frac{\{\ ?\ \}\ C\ \{\ ?\ \}}{\{\ ?\ \}\ \textit{while}\ B\ \textit{do}\ C\ \{P\}}$$

While

- Loop may never execute
- To know P holds after, it had better hold before
- Second approximation:

$$\frac{\{\ ?\ \}\ C\ \{\ ?\ \}}{\{P\}\ \textit{while}\ B\ \textit{do}\ C\ \{P\}}$$

While

- Loop may execute C; enf of loop is of C
- P holds at end of *while* means P holds at end of loop C
- P holds at start of *while*; loop taken means $P \land B$ holds at start of C
- Third approximation:

$$\frac{\{P \land B\}\ C\ \{P\}}{\{P\}\ \textit{while}\ B\ \textit{do}\ C\ \{P\}}$$

While

- Always know $\neg B$ when *while* loop finishes
- Final While rule:

$$\frac{\{P \wedge B\}\ C\ \{P\}}{\{P\}\ while\ B\ do\ C\ \{P \wedge \neg B\}}$$

While

$$\frac{\{P \wedge B\}\ C\ \{P\}}{\{P\}\ while\ B\ do\ C\ \{P \wedge \neg B\}}$$

- P satisfying this rule is called a loop invariant
- Must hold before and after the each iteration of the loop

While

- While rule generally used with precondition strengthening and postcondition weakening
- No algorithm for computing P in general
- Requires intuition and an understanding of why the program works

Example

Prove:

$$\begin{array}{l} \{n \geq 0\} \\ x := 0;\ \ y := 0; \\ while\ x < n\ do \\ (y := y + ((2 * x) + 1); \\ \ x := x + 1) \\ \{y = n * n\} \end{array}$$

Example

- Need to find P that is true before and after loop is executed, such that

$$(P \wedge \neg(x < n)) \Rightarrow y = n * n$$

Example

- First attempt:

$$y = x * x$$

- Motivation:
- Want $y = n * n$
- x counts up to n
- **Guess:** Each pass of loop calcuates next square

Example

By Post-condition Weakening, suffices to show:

(1) $\{n \geq 0\}$
$x := 0;\ y := 0;$
while $x < n$ *do*
$(y := y + ((2 * x) + 1);\ x := x + 1)$
$\{y = x * x \wedge \neg(x < n)\}$

and

(2) $(y = x * x \wedge \neg(x < n)) \Rightarrow (y = n * n)$

Problem with (2)

- Want (2) $(y = x * x \wedge \neg(x < n)) \Rightarrow (y = n * n)$
- From $\neg(x < n)$ have $x \geq n$
- Need $x = n$
- Don't know this; from this could have $x > n$
- Need stronger invariant
- Try ading $x \leq n$
- Then have $((x \leq n) \wedge \neg(x < n)) \Rightarrow (x = n)$
- Then have $x = n$ when loop done

Example

Second attempt:

$$P = ((y = x * x) \wedge (x \leq n))$$

Again by Post-condition Weakening, sufices to show:

(1) $\{n \geq 0\}$
$x := 0;\ y := 0;$
while $x < n$ *do*
$(y := y + ((2 * x) + 1);\ x := x + 1)$
$\{(y = x * x) \wedge (x \leq n) \wedge \neg(x < n)\}$

and

(2) $((y = x * x) \wedge (x \leq n) \wedge \neg(x < n)) \Rightarrow (y = n * n)$

Proof of (2)

- $(\neg(x < n)) \Rightarrow (x \geq n)$
- $((x \geq n) \wedge (x \leq n)) \Rightarrow (x = n)$
- $((x = n) \wedge (y = x * x)) \Rightarrow (y = n * n)$

Example

- For (1), set up While Rule using Sequencing Rule
- By Sequencing Rule, suffices to show

(3) $\{n \geq 0\}\ x := 0;\ y := 0\ \{(y = x * x) \wedge (x \leq n)\}$

and

(4) $\{(y = x * x) \wedge (x \leq n)\}$
while $x < n$ *do*
$(y := y + ((2 * x) + 1);\ x := x + 1)$
$\{(y = x * x) \wedge (x \leq n) \wedge \neg(x < n)\}$

Proof of (4)

By While Rule

$$\frac{(5)\ \{(y = x * x) \wedge (x \leq n) \wedge (x < n)\}\ \ y := y + ((2 * x) + 1);\ x := x + 1\ \ \{(y = x * x) \wedge (x \leq n)\}}{\{(y = x * x) \wedge (x \leq n)\}\ \textit{while}\ x < n\ \textit{do}\ (y := y + ((2 * x) + 1);\ x := x + 1)\ \{(y = x * x) \wedge (x \leq n) \wedge \neg(x < n)\}}$$

Proof of (5)

By Sequencing Rule

(6) $\{(y = x * x) \wedge (x \leq n) \wedge (x < n)\}$
$y := y + ((2 * x) + 1)$
$\{(y = (x + 1) * (x + 1)) \wedge ((x + 1) \leq n)\}$

(7) $\{(y = (x + 1) * (x + 1)) \wedge ((x + 1) \leq n)\}$
$x := x + 1$
$\{(y = x * x) \wedge (x \leq n)\}$

$$\frac{(6) \quad (7)}{\{(y = x * x) \wedge (x \leq n) \wedge (x < n)\}\; y := y + ((2 * x) + 1);\; x := x + 1\; \{(y = x * x) \wedge (x \leq n)\}}$$

(7) holds by Assignment Axiom

Proof of (6)

By Precondition Strengthening

(8) $((y = x * x) \wedge (x \leq n) \wedge (x < n)) \Rightarrow (((y + ((2 * x) + 1)) = (x + 1) * (x + 1)) \wedge ((x + 1) \leq n))$

(9) $\{((y + ((2 * x) + 1)) = ((x + 1) * (x + 1))) \wedge ((x + 1) \leq n)\}$
$y := y + ((2 * x) + 1)$
$\{(y = (x + 1) * (x + 1)) \wedge ((x + 1) \leq n)\}$

$$\frac{(8) \quad (9)}{\{(y = x * x) \wedge (x \leq n) \wedge (x < n)\}\; y := y + ((2 * x) + 1)\; \{(y = (x + 1) * (x + 1)) \wedge ((x + 1) \leq n)\}}$$

Have (9) by Assignment Axiom

Proof of (8)

- (Assuming x integer) $(x < n) \Rightarrow ((x + 1) \leq n)$
- $(y = x * x) \Rightarrow$ $((y + ((2 * x) + 1))$
  $= ((x * x) + ((2 * x) + 1))$
  $= ((x + 1) * (x + 1)))$
- That finishes (8), and thus (6) and thus (5) and thus (4) (*while*)
- Need (3) $\{n \geq 0\}\; x := 0;\; y := 0\; \{(y = x * x) \wedge (x \leq n)\}$

Proof of (3)

By Sequencing

(10) $\{n \geq 0\}$
$x := 0$
$\{(0 = x * x) \wedge (x \leq n)\}$

(11) $\{(0 = x * x) \wedge (x \leq n)\}$
$y := 0$
$\{(y = x * x) \wedge (x \leq n)\}$

$$\frac{(10) \quad (11)}{\{n \geq 0\}\; x := 0;\; y := 0\; \{(y = x * x) \wedge (x \leq n)\}}$$

Have (11) by Assignment Axiom

Proof of (10)

By Precondition Strengthening

(12) $(n \geq 0) \Rightarrow ((0 = 0 * 0) \wedge (0 \leq n))$

(13) $\{(0 = 0 * 0) \wedge (0 \leq n)\}$
$x := 0$
$\{(0 = x * x) \wedge (x \leq n)\}$

$$\frac{(12) \quad (13)}{\{n \geq 0\}\; x := 0;\; y := 0\; \{(0 = x * x) \wedge (x \leq n)\}}$$

- For (12), $0 = 0 * 0$ and $(n \geq 0) \Leftrightarrow (0 \leq n)$
- Have (13) by Assignment Axiom
- Finishes (10), thus (3), thus (1)