CS477 Formal Software Development Methods

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

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DEMO

Algortihm for Proving Hoare Triples?

- Have seen in Isabelle that much of proving a Hoare triple is routine
- Will this always work?
- Why not automate the whole process?
  - Can't (always) calculate needed loop invariants
  - Can't (always) prove implications (side-conditions) in Rule of Consequence application
- Can we automate all but this?
- Yes! But how?

  1. Annotate all `while` loops with needed `invariants`

  2. Use routine to "roll back" post-condition to weakest precondition, gathering side-conditions as we go
- 2 called verification condition generation

Annotated Simple Imperative Language

- Give verification conditions for an annotated version of our simple imperative language
- Add a presumed invariant to each while loop

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

Example:

```
while y < n inv x = y * y
do
 x := (2 * y) + 1;
 y := y + 1
od
```

HOL Type for Deep Part of Embedding

```
datatype 'data annotated_command =
   AnnAssignCom "var_name" "'data exp"
                 (infix ":=" 110)
 | AnnSeqCom "'data annotated_command"
             "'data annotated_command"
             (infixl ";;" 109)
 | AnnCondCom "'data bool_exp"
               "'data annotated_command"
               "'data annotated_command"
      ("If _/ Then _/ Else _/ Fi" [70,70,70]70)
 | AnnWhileCom "'data bool_exp" "'data annotated_command"
      ("While _/ Inv _/  Do _/ Od" [70,70]70)
```

Hoare Logic for Annotated Programs

Assingment Rule

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

Rule of Consequence

$$\frac{P \Rightarrow P' \quad \{\!|P'|\!\}\ C\ \{\!|Q'|\!\} \quad Q' \Rightarrow Q}{\{\!|P|\!\}\ C\ \{\!|Q|\!\}}$$

Sequencing Rule

$$\frac{\{\!|P|\!\}\ C_1\ \{\!|Q|\!\} \quad \{\!|Q|\!\}\ C_2\ \{\!|R|\!\}}{\{\!|P|\!\}\ C_1;\ C_2\ \{\!|R|\!\}}$$

If Then Else Rule

$$\frac{\{\!|P \wedge B|\!\}\ C_1\ \{\!|Q|\!\} \quad \{\!|P \wedge \neg B|\!\}\ C_2\ \{\!|Q|\!\}}{\{\!|P|\!\}\ \mathit{if}\ B\ \mathit{then}\ C_1\ \mathit{else}\ C-2\ \{\!|Q|\!\}}$$

While Rule

$$\frac{\{\!|P \wedge B|\!\}\ C\ \{\!|P|\!\}}{\{\!|P|\!\}\ \mathit{while}\ B\ \mathit{inv}\ P\ \mathit{do}\ C\ \{\!|P \wedge \neg B|\!\}}$$

Defining Hoare Logic Rules

```
inductive ann_valid :: "'data bool_exp ⇒
'data annotated_command ⇒'data bool_exp ⇒bool"
("⦃_⦄_⦃_⦄" [60,60,60]60)where
AnnAssignmentAxiom:"⦃(P[x⇐e])⦄(x:=e) ⦃P⦄" |
AnnSequenceRule:
"⟦⦃P⦄C ⦃Q⦄; ⦃Q⦄C' ⦃R⦄⟧⟹⦃P⦄(C;;C')⦃R⦄" |
AnnRuleOfConsequence:
"⟦|⊨(P [⟶] P') ; ⦃P'⦄C⦃Q'⦄; |⊨(Q' [⟶] Q) ⟧
⟹⦃P⦄C⦃Q⦄" |
AnnIfThenElseRule:
"⟦⦃(P [∧] B)⦄C⦃Q⦄; ⦃(P[∧]([¬]B))⦄C'⦃Q⦄⟧
⟹⦃P⦄(If B Then C Else C' Fi)⦃Q⦄" |
AnnWhileRule:
"⟦⦃(P [∧] B)⦄C⦃P⦄⟧
⟹⦃P⦄(While B Inv P Do C Od)⦃(P [∧] ([¬]B))⦄"
```

Relation Between Two Languages

- Hoare Logic for Simple Imperative Programs and Hoare Logic to Annotated Programs almost the same
- What it precise relationship?
- First need precise relation between the two languages

Definition

$$\mathrm{strip}(v := e) \;=\; v := e$$
$$\mathrm{strip}(C_1\;;\;C_2) \;=\; \mathrm{strip}(C_1)\;;\;\mathrm{strip}(C_2)$$
$$\mathrm{strip}(\texttt{if}\ B\ \texttt{then}\ C_1\ \texttt{else}\ C_2\ \texttt{fi}) \;=\;$$
$$\qquad \texttt{if}\ B\ \texttt{then}\ \mathrm{strip}(C_1)\ \texttt{else}\ \mathrm{strip}(C_2)\ \texttt{fi}$$
$$\mathrm{strip}(\texttt{while}\ B\ \texttt{inv}\ P\ \texttt{do}\ C\ \texttt{od}) \;=\; \texttt{while}\ B\ \texttt{do}\ \mathrm{strip}(C)\ \texttt{od}$$

- We recursively remove all invariant annotations from all `while` loops

Relation Between Two Hoare Logics

Theorem

For all pre- and post-conditions P *and* Q*, and annotated programs* C*, if* $\{\!|P|\!\}\ C\ \{\!|Q|\!\}$*, then* $\{P\}\ strip(C)\ \{Q\}$*.*

Proof.

(Sketch) Use rule induction on proof of $\{\!|P|\!\}\ C\ \{\!|Q|\!\}$; in case of While Rule, erase invariant □

Relation Between Two Hoare Logics

Theorem

For all pre- and post-conditions P and Q, and unannotated programs C, if $\{P\}\ C\ \{Q\}$, then there exists an annotated program S such that $C = strip(S)$ and $\{\!|P|\!\}\ S\ \{\!|Q|\!\}$.

Proof.

(Sketch) Use rule induction on proof of $\{P\}\ C\ \{Q\}$; in case of While Rule, add invariant from precondition as invariant to command. □

Weakest Precondition

Question: Given post-condition Q, and annotated program C, what is the most general pre-condition P such that $\{\!|P|\!\}\ C\ \{\!|Q|\!\}$?

Answer: Weakest Precondition

Definition

$$\text{wp}\ (x := e)\ Q = Q[x \Leftarrow e]$$
$$\text{wp}\ (C_1; C_2)\ Q = \text{wp}\ C_1\ (\text{wp}\ C_2\ Q)$$
$$\text{wp}\ (\texttt{if}\ B\ \texttt{then}\ C_1\ \texttt{else}\ C_2\ \texttt{fi})\ Q = (B \wedge (\text{wp}\ C_1\ Q)) \vee ((\neg B) \wedge (\text{wp}\ C_2\ Q))$$
$$\text{wp}\ (\texttt{while}\ B\ \texttt{inv}\ P\ \texttt{do}\ C\ \texttt{od})\ Q = P$$

Assumes, without verifying, that P is the correct invariant

Weakest Justification

Weakest in weakest precondition means any other valid precondition implies it:

Theorem

For all annotated programs C, and pre- and post-conditions P and Q, if $\{\!|P|\!\}\ C\ \{\!|Q|\!\}$ then $P \Rightarrow wp\ C\ Q$.

- Proof somewhat complicated
- Uses induction on the structure of C
- In each case, want to assert triple proof must have used rule for that construct (e.g. Sequence Rule for sequences)
- Can't because of Rule Of Consequence
- Must induct on proof (rule induction) - in each case
- Uses:

Lemma

$\forall C\ P\ Q.\ (P \Rightarrow Q) \Rightarrow (wp\ C\ P \Rightarrow wp\ C\ Q)$

What About Precondition?

Question: Do we have $\{\!|\text{wp } C\ Q|\!\}\ C\ \{\!|Q|\!\}$?

Answer: Not always - need to check while-loop side-conditions – verification conditions

Question: How to calculate verification conditions?

Definition

$\text{vcg } (x := e)\ Q = \text{true}$
$\text{vcg } (C_1; C_2)\ Q = (\text{vcg } C_1\ (\text{wp } C_2\ Q)) \wedge (\text{vcg } C_2\ Q)$
$\text{vcg } (\texttt{if } B \texttt{ then } C_1 \texttt{ else } C_2 \texttt{ fi})\ Q = (\text{vcg } C_1\ Q) \wedge (\text{vcg } C_2\ Q)$
$\text{vcg } (\texttt{while } B \texttt{ inv } P \texttt{ do } C \texttt{ od})\ Q =$
$((P \wedge B) \Rightarrow (\text{wp } C\ P)) \wedge (\text{vcg } C\ P) \wedge ((P \wedge (\neg B)) \Rightarrow Q)$

Verification Condition Guarantees wp Precondition

Theorem

$vcg\ C\ Q \Rightarrow \{\!|wp\ C\ Q|\!\}\ C\ \{\!|Q|\!\}$

Proof.

(Sketch)

- Induct on structure of C
- For each case, wind back as we did in specific examples:
  - Assignment: wp C Q exactly what is needed for Assignment Axiom
  - Sequence: Follows from inductive hypotheses, all elim, and modus ponens
  - If_Then_Else: Need to use Precondition Strengthening with each branch of conditional; wp and inductive hypotheses give the needed side conditions
  - While: Need to use Postcondition Weakening, While Rule and Precondition Strengthening

□

Verification Condition Guarantees wp Precondition

Corollary

$((P \Rightarrow wp\ C\ Q) \land (vcg\ C\ Q)) \Rightarrow \{\!|P|\!\}\ C\ \{\!|Q|\!\}$

This amounts to a method for proving Hoare triple $\{P\}\ C\ \{Q\}$:

1. Annotate program with loop invariants (reduces to showing $\{\!|P|\!\}\ C\ \{\!|Q|\!\}$
2. Calculate wp C Q and vcg C Q (automated)
3. Prove $P \Rightarrow$ wp C Q and vcg C Q

Basic outline of interaction with Boogie: Human does 1, Boogie does 2, Z3 / Simplify / Isabelle + human / ... does 3

For more infomation

- http://research.microsoft.com/en-us/projects/boogie/
- http://research.microsoft.com/en-us/um/people/moskal/pdf/hol-boogie.pdf
- http://www.cl.cam.ac.uk/research/hvg/Isabelle/dist/library/HOL/HOL-Hoare/index.html