COMP 4161
NICTA Advanced Course

Advanced Topics in Software Verification

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$$\{P\} \ldots \{Q\}$$

Slide 1

Last Time

- ➜ Calculations: also/finally
- ➜ [trans]-rules
- ➜ Code generation

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Content

[a] a1 due; [b] a2 due; [c] session break; [d] a3 due

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A CRASH COURSE IN SEMANTICS

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IMP - a small Imperative Language

Commands:

datatype com	=	SKIP	
	|	Assign loc aexp	(_ := _)
	|	Semi com com	(_; _)
	|	Cond bexp com com	(IF _ THEN _ ELSE _)
	|	While bexp com	(WHILE _ DO _ OD)

types loc = string
types state = loc $\Rightarrow$ nat

types aexp = state $\Rightarrow$ nat
types bexp = state $\Rightarrow$ bool

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Example Program

Usual syntax:

$B := 1;$
WHILE $A \neq 0$ DO
  $B := B * A;$
  $A := A - 1$
OD

Expressions are functions from state to bool or nat:

$B := (\lambda\sigma.\ 1);$
WHILE $(\lambda\sigma.\ \sigma\ A \neq 0)$ DO
  $B := (\lambda\sigma.\ \sigma\ B * \sigma\ A);$
  $A := (\lambda\sigma.\ \sigma\ A - 1)$
OD

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What does it do?

So far we have defined:

- **Syntax** of commands and expressions
- **State** of programs (function from variables to values)

Now we need: the meaning (semantics) of programs

How to define execution of a program?

- A wide field of its own
- Some choices:
  - Operational (inductive relations, big step, small step)
  - Denotational (programs as functions on states, state transformers)
  - Axiomatic (pre-/post conditions, Hoare logic)

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Structural Operational Semantics

$$\frac{}{\langle \mathsf{SKIP}, \sigma\rangle \longrightarrow \sigma}$$

$$\frac{e\ \sigma = v}{\langle \mathsf{x := e}, \sigma\rangle \longrightarrow \sigma[x \mapsto v]}$$

$$\frac{\langle c_1, \sigma\rangle \longrightarrow \sigma' \quad \langle c_2, \sigma'\rangle \longrightarrow \sigma''}{\langle c_1; c_2, \sigma\rangle \longrightarrow \sigma''}$$

$$\frac{b\ \sigma = \mathsf{True} \quad \langle c_1, \sigma\rangle \longrightarrow \sigma'}{\langle \mathsf{IF}\ b\ \mathsf{THEN}\ c_1\ \mathsf{ELSE}\ c_2, \sigma\rangle \longrightarrow \sigma'}$$

$$\frac{b\ \sigma = \mathsf{False} \quad \langle c_2, \sigma\rangle \longrightarrow \sigma'}{\langle \mathsf{IF}\ b\ \mathsf{THEN}\ c_1\ \mathsf{ELSE}\ c_2, \sigma\rangle \longrightarrow \sigma'}$$

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Structural Operational Semantics

$$\frac{b\ \sigma = \mathsf{False}}{\langle \mathsf{WHILE}\ b\ \mathsf{DO}\ c\ \mathsf{OD}, \sigma\rangle \longrightarrow \sigma}$$

$$\frac{b\ \sigma = \mathsf{True} \quad \langle c, \sigma\rangle \longrightarrow \sigma' \quad \langle \mathsf{WHILE}\ b\ \mathsf{DO}\ c\ \mathsf{OD}, \sigma'\rangle \longrightarrow \sigma''}{\langle \mathsf{WHILE}\ b\ \mathsf{DO}\ c\ \mathsf{OD}, \sigma\rangle \longrightarrow \sigma''}$$

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Demo: The Definitions in Isabelle

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Proofs about Programs

Now we know:

- ➜ What programs are: Syntax
- ➜ On what they work: State
- ➜ How they work: Semantics

So we can prove properties about programs

Example:
Show that example program from slide 6 implements the factorial.

lemma $\langle \mathsf{factorial}, \sigma\rangle \longrightarrow \sigma' \Longrightarrow \sigma' B = \mathsf{fac}\ (\sigma A)$

(where $\mathsf{fac}\ 0 = 1, \quad \mathsf{fac}\ (\mathsf{Suc}\ n) = (\mathsf{Suc}\ n) * \mathsf{fac}\ n$)

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Demo: Example Proof

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Too tedious

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Induction needed for each loop

Is there something easier?

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Floyd/Hoare

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Idea: describe meaning of program by pre/post conditions

Examples:

$\{\text{True}\} \quad x := 2 \quad \{x = 2\}$

$\{y = 2\} \quad x := 21 * y \quad \{x = 42\}$

$\{x = n\} \quad \text{IF } y < 0 \text{ THEN } x := x + y \text{ ELSE } x := x - y \quad \{x = n - |y|\}$

$\{A = n\} \quad \text{factorial} \quad \{B = \text{fac } n\}$

Proofs: have rules that directly work on such triples

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Meaning of a Hoare-Triple

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$$\{P\} \quad c \quad \{Q\}$$

What are the assertions P and Q?

- ➜ Here: again functions from state to bool (shallow embedding of assertions)
- ➜ Other choice: syntax and semantics for assertions (deep embedding)

What does $\{P\}\ c\ \{Q\}$ mean?

Partial Correctness:

$\models \{P\}\ c\ \{Q\} \quad \equiv \quad (\forall \sigma\ \sigma'.\ P\ \sigma \wedge \langle c, \sigma\rangle \longrightarrow \sigma' \Longrightarrow Q\ \sigma')$

Total Correctness:

$\models \{P\}\ c\ \{Q\} \quad \equiv \quad (\forall \sigma.\ P\ \sigma \Longrightarrow \exists \sigma'.\ \langle c, \sigma\rangle \longrightarrow \sigma' \wedge Q\ \sigma')$

This lecture: partial correctness only (easier)

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Hoare Rules

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$$\frac{}{\{P\} \quad \text{SKIP} \quad \{P\}} \qquad \frac{}{\{P[x \mapsto e]\} \quad x := e \quad \{P\}}$$

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

$$\frac{\{P \wedge b\}\ c_1\ \{Q\} \quad \{P \wedge \neg b\}\ c_2\ \{Q\}}{\{P\} \quad \text{IF } b \text{ THEN } c_1 \text{ ELSE } c_2 \quad \{Q\}}$$

$$\frac{\{P \wedge b\}\ c\ \{P\} \quad P \wedge \neg b \Longrightarrow Q}{\{P\} \quad \text{WHILE } b \text{ DO } c \text{ OD} \quad \{Q\}}$$

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

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Hoare Rules

$$\frac{}{\vdash \{P\}\quad \text{SKIP}\quad \{P\}} \qquad \frac{}{\vdash \{\lambda\sigma.\ P\ (\sigma(x := e\ \sigma))\}\quad x := e\quad \{P\}}$$

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

$$\frac{\vdash \{\lambda\sigma.\ P\ \sigma \wedge b\ \sigma\}\ c_1\ \{R\} \quad \vdash \{\lambda\sigma.\ P\ \sigma \wedge \neg b\ \sigma\}\ c_2\ \{Q\}}{\vdash \{P\}\quad \text{IF } b \text{ THEN } c_1 \text{ ELSE } c_2\quad \{Q\}}$$

$$\frac{\vdash \{\lambda\sigma.\ P\ \sigma \wedge b\ \sigma\}\ c\ \{P\} \quad \bigwedge\sigma.\ P\ \sigma \wedge \neg b\ \sigma \Longrightarrow Q\ \sigma}{\vdash \{P\}\quad \text{WHILE } b \text{ DO } c \text{ OD}\quad \{Q\}}$$

$$\frac{\bigwedge\sigma.\ P\ \sigma \Longrightarrow P'\ \sigma \quad \vdash \{P'\}\ c\ \{Q'\} \quad \bigwedge\sigma.\ Q'\ \sigma \Longrightarrow Q\ \sigma}{\vdash \{P\}\quad c\quad \{Q\}}$$

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Are the Rules Correct?

Soundness: $\vdash \{P\}\ c\ \{Q\} \Longrightarrow \models \{P\}\ c\ \{Q\}$

Proof: by rule induction on $\vdash \{P\}\ c\ \{Q\}$

Demo: Hoare Logic in Isabelle

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