COMP4161
Advanced Topics in Software Verification

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

Gerwin Klein, Miki Tanaka, Johannes Åman Pohjola, Rob Sison

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Content

➜ Foundations & Principles

- Intro, Lambda calculus, natural deduction [1,2]
- Higher Order Logic, Isar (part 1) [2,3[a]]
- Term rewriting [3,4]

➜ Proof & Specification Techniques

- Inductively defined sets, rule induction [4,5]
- Datatype induction, primitive recursion [5,7]
- General recursive functions, termination proofs [7[b]]
- Proof automation, Isar (part 2) [8]
- Hoare logic, proofs about programs, invariants [8,9]
- C verification [9,10]
- Practice, questions, exam prep [10[c]]

[a] a1 due; [b] a2 due; [c] a3 due

A Crash Course in Semantics

(For more,
see Concrete Semantics)

IMP - a small Imperative Language

Commands:

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

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type_synonym state	$=$	vname $\Rightarrow$ nat

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type_synonym vname = string
type_synonym state = vname $\Rightarrow$ nat

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

Example Program

Usual syntax:

$$
\begin{array}{l}
B := 1; \\
\text{WHILE } A \neq 0 \text{ DO} \\
\quad B := B * A; \\
\quad A := A - 1 \\
\text{OD}
\end{array}
$$

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$$

Expressions are functions from state to bool or nat:

$$
\begin{array}{l}
B := (\lambda\sigma.\ 1); \\
\text{WHILE } (\lambda\sigma.\ \sigma\ A \neq 0) \text{ DO} \\
\quad B := (\lambda\sigma.\ \sigma\ B * \sigma\ A); \\
\quad A := (\lambda\sigma.\ \sigma\ A - 1) \\
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$$

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- ➜ A wide field of its own

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

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Demo: The Definitions in Isabelle

Proofs about Programs

Now we know:

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

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

$$\textbf{lemma}\ \langle \text{factorial}, \sigma \rangle \rightarrow \sigma' \Longrightarrow \sigma' B = \text{fac}\ (\sigma A)$$
$$(\text{where} \quad \text{fac}\ 0 = 1, \quad \text{fac}\ (\text{Suc}\ n) = (\text{Suc}\ n) * \text{fac}\ n)$$

Demo: Example Proof

Too tedious

Induction needed for each loop

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Is there something easier?

Floyd/Hoare

Idea: describe meaning of program by pre/post conditions

Examples:

Floyd/Hoare

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

Floyd/Hoare

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

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

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Proofs: have rules that directly work on such triples

Meaning of a Hoare-Triple

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

What are the assertions P and Q?

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

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Total Correctness:

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$$(\forall \sigma.\ P\ \sigma \longrightarrow \exists \sigma'.\ \langle c, \sigma\rangle \rightarrow \sigma')$$

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This lecture: partial correctness only (easier)

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

Hoare Rules

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

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

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Are the Rules Correct?

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Demo: Hoare Logic in Isabelle

