DATA 61

COMP4161: Advanced Topics in Software Verification

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Content

- Intro & motivation, getting started [1]
- Foundations & Principles
  - Lambda Calculus, natural deduction [1,2]
  - Higher Order Logic [3[a]]
  - Term rewriting [4]
- Proof & Specification Techniques
  - Inductively defined sets, rule induction [5]
  - Datatypes, recursion, induction [6, 7]
  - Hoare logic, proofs about programs, invariants [8[b],9]
  - (mid-semester break)
  - C verification [10]
  - CakeML, Isar [11[c]]
  - Concurrency [12]

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

Deep Embeddings

We used a **datatype** *com* to represent the **syntax** of IMP.

- ➜ We then defined its semantics over this datatype.

This is called a **deep embedding**:

- ➜ separate representation of language terms and their semantics.

Advantages:

- ➜ Prove general theorems about the **language**, not just of programs.
- ➜ e.g. expressiveness, correct compilation, inference completeness ...
- ➜ usually by structural induction over the syntax type.

Disadvantages:

- ➜ Semantically equivalent programs are not obviously equal.
- ➜ e.g. "IF True THEN SKIP ELSE SKIP = SKIP" is not a true theorem.
- ➜ Many concepts already present in the logic are reinvented in the language.

Shallow Embeddings

Shallow Embedding: represent only the semantics, directly in the logic.

- ➜ A definition for each language construct, giving its **semantics**.
- ➜ Programs are represented as instances of these definitions.

Example: program semantics as functions *state* ⇒ *state*

$$\begin{aligned} \text{SKIP} &\equiv \quad \lambda s.\ s \\ \text{IF b THEN c ELSE d} &\equiv \quad \lambda s.\ \text{if b s then c s else d s} \end{aligned}$$

- ➜ “IF True THEN SKIP ELSE SKIP = SKIP” is now a true statement.
- ➜ can use the simplifier to do semantics-preserving program rewriting.

Today: a shallow embedding for (interesting parts of) C semantics

Records in Isabelle

Records are a tuples with named components

Example:

$$\textbf{record}\ \mathsf{A} = \quad \mathsf{a} :: \mathsf{nat}$$
$$\mathsf{b} :: \mathsf{int}$$

- ➜ Selectors: $\mathsf{a} :: \mathsf{A} \Rightarrow \mathsf{nat}$, $\mathsf{b} :: \mathsf{A} \Rightarrow \mathsf{int}$, $\mathsf{a}\ r = \mathsf{Suc}\ 0$
- ➜ Constructors: $(\!|\ \mathsf{a} = \mathsf{Suc}\ 0,\ \mathsf{b} = -1\ |\!)$
- ➜ Update: $r(\!|\ \mathsf{a} := \mathsf{Suc}\ 0\ |\!)$, $\mathsf{b\_update}\ (\lambda b.\ b + 1)\ r$

Records are extensible:

$$\textbf{record}\ \mathsf{B} = \mathsf{A}\ +$$
$$\mathsf{c} :: \mathsf{nat}\ \mathsf{list}$$

$$(\!|\ \mathsf{a} = \mathsf{Suc}\ 0,\ \mathsf{b} = -1,\ \mathsf{c} = [0, 0]\ |\!)$$

Demo

Nondeterministic State Monad with Failure

Shallow embedding suitable for (a useful fragment of) C.

Can express lots of C ideas:

- ➜ Access to `volatile` variables, external APIs: **Nondeterminism**
- ➜ Undefined behaviour: **Failure**
- ➜ Early exit (`return`, `break`, `continue`): **Exceptional control flow**

Relatively straightforward Hoare logic

Used extensively in the seL4 verification work:

- ➜ Formalism for the seL4 abstract, design and *capDL* specifications
- ➜ Calculus for proving **refinement** between them and down to code.

AutoCorres: verified translation of C to monadic representation

- ➜ Specifically designed for humans to do proofs over.

State Monad: Motivation

Model the **semantics** of a (deterministic) computation as a function

$$'s \Rightarrow ('a \times \; 's)$$

The computation operates over a **state** of type *'s*:

- ➜ Includes all global variables, external devices, etc.

The computation also yields a **return value** of type *'a*:

- ➜ e.g. a program's exit status (in POSIX, *'a* would be 8-bit words)
- ➜ e.g. return-value of a C function

return – the computation that leaves the state unchanged and returns its argument:

$$\text{return } x \;\equiv\; \lambda s. \quad (x,s)$$

State Monad: Basic Operations

get – returns the entire state without modifying it:

$$\text{get} \equiv \lambda s.\ (s,s)$$

put – replaces the state and returns the unit value ():

$$\text{put}\ s \equiv \lambda\_.\ ((),s)$$

bind – sequences two computations; 2nd takes the first's result:

$$c \gg\!= d \equiv \lambda s.\ \textbf{let}\ (r,s') = c\ s\ \textbf{in}\ d\ r\ s'$$

gets – returns a projection of the state; leaves state unchanged:

$$\text{gets}\ f \equiv \text{get} \gg\!= (\lambda s.\ \text{return}\ (f\ s))$$

modify – applies its argument to modify the state; returns ():

$$\text{modify}\ f \equiv \text{get} \gg\!= (\lambda s.\ \text{put}\ (f\ s))$$

Monads, Laws

Formally: a monad **M** is a type constructor with two operations.

return :: $\alpha \Rightarrow \mathbf{M}\ \alpha$ bind :: $\mathbf{M}\ \alpha \Rightarrow (\alpha \Rightarrow \mathbf{M}\ \beta) \Rightarrow \mathbf{M}\ \beta$

Infix Notation: $a \gg= b$ is infix notation for bind a b

Do-Notation: $a \gg= (\lambda x.\ b\ x)$ is often written as **do** $\{\ x \leftarrow a;\ b\ x\ \}$

Monad Laws:

return-left:	$(\text{return}\ x \gg= f)$	$=$	$f\ x$
return-right:	$(m \gg= \text{return})$	$=$	m
bind-assoc:	$((a \gg= b) \gg= \text{c})$	$=$	$(\text{a} \gg= (\lambda x.\ b\ x \gg= \text{c}))$

State Monad: Example

A fragment of C:

```
void f(int *p) {
    int x = *p;
    if (x < 10)
{
        *p = x+1;
    }
}
```

record state =
    hp :: int ptr ⇒ int

f :: "int ptr ⇒ (state ⇒ (unit,state))"

f *p* ≡
do {
  x ← gets (λs. hp s p);
  if x < 10 **then**
    modify (hp_update (λh. (h(p := x + 1))))
  else
    return ()
}

State Monad with Failure

Computations can **fail**: $'s \Rightarrow (('a \times\ 's) \underline{\times \text{ bool}})$

bind – fails when either computation fails

bind a $b \equiv$ **let** $((r,s'),f) = \text{a } s$; $((r'',s''),f') = \text{b } r\ s'$ **in** $((r'',s''),\ f \vee f')$

fail – the computation that always fails:

fail $\equiv \lambda$s. (undefined, True)

assert – fails when given condition is False:

assert P $\equiv$ **if** P **then** return () **else** fail

guard – fails when given condition applied to the state is False:

guard P $\equiv$ get $\gg=$ (λs. assert (P s))

Guards

Used to assert the absence of **undefined behaviour** in C

➜ pointer validity, absence of divide by zero, signed overflow, etc.

f p $\equiv$
do {
  y ← guard (λs. valid s p);
  x ← gets (λs. hp s p);
  if x $<$ 10 **then**
    modify (hp_update (λh. (h(p := x + 1))))
  else
    return ()
}

Nondeterministic State Monad with Failure

Computations can be **nondeterministic:** $'s \Rightarrow (('a \times \ 's)\ \underline{\text{set}} \times \text{bool})$

Nondeterminism: computations return a **set** of possible results.

- ➜ Allows **underspecification:** e.g. malloc, external devices, etc.

bind – runs 2nd computation for all results returned by the first:

$$\text{bind}\ a\ b \equiv \quad \lambda\text{s}.\ (\{(r'',s'').\ \exists (r',s') \in \text{fst}\ (a\ s).\ (r'',s'') \in \text{fst}\ (b\ r'\ s')\},$$
$$\text{snd}\ (a\ s) \vee (\exists (r',\ s') \in \text{fst}\ (a\ s).\ \text{snd}\ (b\ r'\ s')))$$

All non-failing computations so far are **deterministic**:

- ➜ e.g. return $x \equiv \lambda\text{s}.\ (\{(x,s)\},\text{False})$
- ➜ Others are similar.

select – nondeterministic selection from a set:

$$\text{select}\ A \equiv \lambda\text{s}.\ \ ((A\ \times\{\text{s}\}),\text{False})$$

Demo

While Loops

Monadic while loop, defined **inductively**.

$$\begin{aligned}\text{whileLoop} :: \; & (\text{'}a \Rightarrow \text{'}s \Rightarrow \text{bool}) \Rightarrow \\ & (\text{'}a \Rightarrow (\text{'}s \Rightarrow (\text{'}a \times \text{'}s) \text{ set} \times \text{bool})) \Rightarrow \\ & (\text{'}a \Rightarrow (\text{'}s \Rightarrow (\text{'}a \times \text{'}s) \text{ set} \times \text{bool}))\end{aligned}$$

whileLoop C B

- ➜ **condition** C: takes **loop parameter** and **state** as arguments, returns **bool**
- ➜ **monadic body** B: takes **loop parameter** as argument, return-value is the **updated** loop paramter
- ➜ **fails** if the loop body ever fails or if the loop never terminates

Example: whileLoop $(\lambda p\ s.\ \text{hp}\ s\ p = 0)$ $(\lambda \text{p}.\ \text{return}\ (\text{ptrAdd}\ p\ 1))$ p

Defining While Loops Inductively

Two-part definition: results and termination

Results: while_results :: $('a \Rightarrow 's \Rightarrow \text{bool}) \Rightarrow$
$('a \Rightarrow ('s \Rightarrow ('a \times 's)\ \text{set} \times \text{bool})) \Rightarrow$
$((('a \times 's)\ \text{option}) \times (('a \times 's)\ \text{option}))\ \text{set}$

$$\frac{\neg\ C\ r\ s}{(\text{Some}\ (r,s),\ \text{Some}\ (r,s)) \in \text{while\_results}\ C\ B}\ (\text{terminate})$$

$$\frac{C\ r\ s \quad \text{snd}\ (B\ r\ s)}{(\text{Some}\ (r,s),\ \text{None}) \in \text{while\_results}\ C\ B}\ (\text{fail})$$

$$\frac{C\ r\ s \quad (r',s') \in \text{fst}\ (B\ r\ s) \quad (\text{Some}\ (r',\ s'),\ z) \in \text{while\_results}\ C\ B}{(\text{Some}\ (r,s),\ z) \in \text{while\_results}\ C\ B}\ (\text{loop})$$

Defining While Loops Inductively

Termination:

$$\text{while\_terminates} :: ('a \Rightarrow 's \Rightarrow \text{bool}) \Rightarrow ('a \Rightarrow ('s \Rightarrow ('a \times 's)\ \text{set} \times \text{bool})) \Rightarrow 'a \Rightarrow 's \Rightarrow \text{bool}$$

$$\frac{\neg\ C\ r\ s}{\text{while\_terminates}\ C\ B\ r\ s}\ \text{(terminate)}$$

$$\frac{C\ r\ s \quad \forall (r',s') \in \text{fst}\ (B\ r\ s).\ \text{while\_terminates}\ C\ B\ r'\ s'}{\text{while\_terminates}\ C\ B\ r\ s}\ \text{(loop)}$$

$$\begin{aligned} &\text{whileLoop}\ C\ B \equiv \\ &\quad (\lambda r\ s.\ (\{(r',s').\ (\text{Some}\ (r,\ s),\ \text{Some}\ (r',\ s')) \in \text{while\_results}\ C\ B\}, \\ &\qquad (\text{Some}\ (r,\ s),\ \text{None}) \in \text{while\_results} \lor \\ &\qquad \neg\text{while\_terminates}\ C\ B\ r\ s)) \end{aligned}$$

Hoare Logic over Nondeterministic State Monads

Partial correctness:

$$\{\!|P|\!\}\ m\ \{\!|Q|\!\} \equiv \forall s.\ P\ s \longrightarrow \forall (r,s') \in \text{fst}\ (m\ s).\ Q\ r\ s'$$

➜ Post-condition Q is a predicate of return-value and result state.

Weakest Precondition Rules

$\{\!|\lambda s.\ P\ x\ s|\!\}$ return x $\{\!|\lambda r\ s.\ P\ r\ s|\!\}$ $\{\!|\lambda s.\ P\ s\ s|\!\}$ get $\{\!|P|\!\}$ $\{\!|\lambda s.\ P\ ()\ x|\!\}$ put x $\{\!|P|\!\}$

$\{\!|\lambda s.\ P\ (f\ s)\ s|\!\}$ gets f $\{\!|P|\!\}$ $\{\!|\lambda s.\ P\ ()\ (f\ s)|\!\}$ modify f $\{\!|P|\!\}$

$\{\!|\lambda s.\ P \longrightarrow Q\ ()\ s|\!\}$ assert P $\{\!|Q|\!\}$ $\{\!|\lambda\_.\ \text{True}|\!\}$ fail $\{\!|Q|\!\}$

More Hoare Logic Rules

$$\frac{P \Longrightarrow \{\!|Q|\!\}\ f\ \{\!|S|\!\} \quad \neg\ P \Longrightarrow \{\!|R|\!\}\ g\ \{\!|S|\!\}}{\{\!|\lambda s.(P \longrightarrow Q\ s) \wedge (\neg P \longrightarrow R\ s)|\!\}\ \textbf{if}\ P\ \textbf{then}\ f\ \textbf{else}\ g\ \{\!|S|\!\}}$$

$$\frac{\bigwedge x.\ \{\!|B\ x|\!\}\ g\ x\ \{\!|C|\!\} \quad \{\!|A|\!\}\ f\ \{\!|B|\!\}}{\{\!|A|\!\}\ \textbf{do}\{\ x \leftarrow f;\ g\ x\ \}\ \{\!|C|\!\}}$$

$$\frac{\{\!|R|\!\}\ m\ \{\!|Q|\!\} \quad \bigwedge s.\ P\ s \Longrightarrow R\ s}{\{\!|P|\!\}\ m\ \{\!|Q|\!\}}$$

$$\frac{\bigwedge r.\ \{\!|\lambda s.\ I\ r\ s \wedge C\ r\ s|\!\}\ B\ \{\!|I|\!\} \quad \bigwedge r\ s.\ [\![I\ r\ s;\ \neg\ C\ r\ s]\!] \Longrightarrow Q\ r\ s}{\{\!|I\ r|\!\}\ \text{whileLoop}\ C\ B\ r\ \{\!|Q|\!\}}$$

Demo

We have seen today

- ➜ Deep and shallow embeddings
- ➜ Isabelle records
- ➜ Nondeterministic State Monad with Failure
- ➜ Monadic Weakest Precondition Rules

