



COMP4161: Advanced Topics in Software Verification



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Last Time



- Weakest preconditions
- Verification conditions
- Example program proofs
- Arrays, pointers

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, C verification [8^b,9]
 - (mid-semester break)
 - Writing Automated Proof Methods [10]
 - Isar, codegen, typeclasses, locales [11^c,12]

^aa1 due; ^ba2 due; ^ca3 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 that we already have 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 of type $state \Rightarrow state$

$SKIP \equiv \lambda s. s$

$IF\ b\ THEN\ c\ ELSE\ d \equiv \lambda s. \text{if } b\ s\ \text{then } c\ s\ \text{else } d\ s$

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

Today we learn about a formalism suitable for shallowly embedding C semantics.

Records in Isabelle



Records are a tuples with named components

Example:

```
record A =  a :: nat
           b :: int
```

- Selectors: $a :: A \Rightarrow \text{nat}$, $b :: A \Rightarrow \text{int}$, $a\ r = \text{Suc } 0$
- Constructors: $(\mid a = \text{Suc } 0, b = -1 \mid)$
- Update: $r(\mid a := \text{Suc } 0 \mid)$, $b_update\ (\lambda b. b + 1)\ r$

Records are extensible:

```
record B = A +
           c :: nat list
```

```
(\mid a = \text{Suc } 0, b = -1, c = [0, 0] \mid)
```

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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
- Refinement 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 of type

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

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:

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

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:

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

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 \mathbf{M} is a type constructor with two associated operations.

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

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

→ $\gg=$ binds to the left: $(a \gg= b \gg= c) = ((a \gg= b) \gg= c)$

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

Monad Laws:

return-left: $(\text{return } x \gg= f) = f \ x$

return-right: $(m \gg= \text{return}) = m$

bind-assoc: $((a \gg= b) \gg= c) = (a \gg= (\lambda x. b \ x \gg= c))$

State Monad: Example



A fragment of C:

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

```
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 ()  
od
```

State Monad with Failure



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

bind – fails when either computation fails

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

fail – the computation that always fails:

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

assert – fails when given condition is False:

$\text{assert } P \equiv \text{if } P \text{ then return } () \text{ else fail}$

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

$\text{guard } P \equiv \text{get } \gg= (\lambda s. \text{assert } (P \ s))$

Guards



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

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

```
f p ≡  
  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 ()  
  od
```

Nondeterministic State Monad with Failure



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

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:

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

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

→ e.g. $\text{return } x \equiv \lambda s. (\{(x, s)\}, \text{False})$

→ Others are similar.

select – nondeterministic selection from a set:

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

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While Loops



Monadic while loop, defined **inductively**.

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

`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 parameter
- **fails** if the loop body ever fails or if the loop never terminates

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

Defining While Loops Inductively



Two-part definition: results and termination

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

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

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

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

Defining While Loops Inductively



Termination:

$$\text{while_terminates} :: ('a \Rightarrow 's \Rightarrow \text{bool}) \Rightarrow$$
$$('a \Rightarrow ('s \Rightarrow ('a \times 's) \text{ set} \times \text{bool})) \Rightarrow$$
$$'a \Rightarrow 's \Rightarrow \text{bool}$$
$$\frac{\neg C r s}{\text{while_terminates } C B r s} \text{ (terminate)}$$
$$\frac{C r s \quad \forall (r', s') \in \text{fst } (B r s). \text{ while_terminates } C B r' s'}{\text{while_terminates } C B r s} \text{ (loop)}$$

$\text{whileLoop } C B \equiv$

$$(\lambda r s. (\{(r', s'). (\text{Some } (r, s), \text{Some } (r', s')) \in \text{while_results } C B\},$$
$$(\text{Some } (r, s), \text{None}) \in \text{while_results} \vee$$
$$\neg \text{while_terminates } C B r s))$$

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

$$\{\lambda s. P x s\} \text{ return } x \{ \lambda r s. P r s \} \quad \{\lambda s. P s s\} \text{ get } \{P\} \quad \{\lambda s. P () x\} \text{ put } x \{P\}$$

$$\{\lambda s. P (f s) s\} \text{ gets } f \{P\} \quad \{\lambda s. P () (f s)\} \text{ modify } f \{P\}$$

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

More Hoare Logic Rules



$$\frac{P \implies \{Q\} f \{S\} \quad \neg P \implies \{R\} g \{S\}}{\{\lambda s. (P \longrightarrow Q s) \wedge (\neg P \longrightarrow R s)\} \text{ if } P \text{ then } f \text{ else } g \{S\}}$$

$$\frac{\bigwedge x. \{B x\} g x \{C\} \quad \{A\} f \{B\}}{\{A\} \text{ do } x \leftarrow f; g x \text{ od } \{C\}}$$

$$\frac{\{R\} m \{Q\} \quad \bigwedge s. P s \implies R s}{\{P\} m \{Q\}}$$

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



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Demo

We have seen today



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