COMP4161 Advanced Topics in Software Verification

C

Thomas Sewell, Miki Tanaka, Rob Sison

T3/2024

Last Time

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

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]
  - Proof automation, Isar (part 2) [8[b]]
  - 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

wp

apply (wp *extra_wp_rules*)

Tactic for automatic application of **weakest precondition rules**

- ➜ Developed for the seL4 verification proofs
- ➜ Knows about a huge collection of existing wp rules for monads
- ➜ Works best when precondition is a schematic variable
- ➜ related tool: **wpc** for Hoare reasoning over **case** statements

When used with **AutoCorres**, allows automated reasoning about C programs.

Today we will learn about AutoCorres and C verification.

Demo

Introduction to AutoCorres and wp

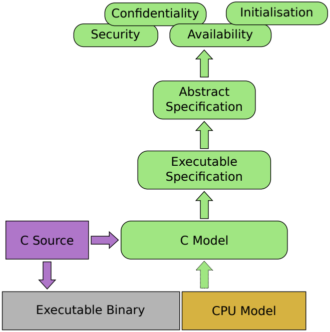
Some Context: The L4.verified Project

The seL4 microkernel was verified *functionally correct* using Isabelle/HOL.

- Project by “NICTA” @ UNSW.
- One of the largest proof projects, Isabelle projects, etc.

Initial proof (completed 2009).

- 3 encodings of seL4 in Isabelle.
- 2 proofs of simulation/refinement.
    - Involve `corres` & `ccorres`.

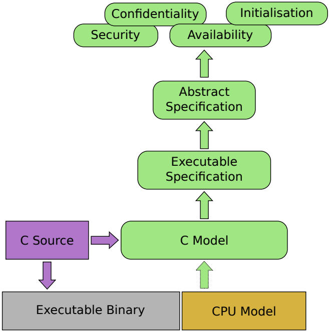


Relating L4.verified to Best Practice

The L4.verified project is a bit specialised, but some of these concepts are universal:

- *abstract spec*: describes the system as seen by an external party.
- *executable spec*: describes the algorithms of the system somewhat abstractly.
- *implementation*: ground model: encodes the semantics of the real system in detail.

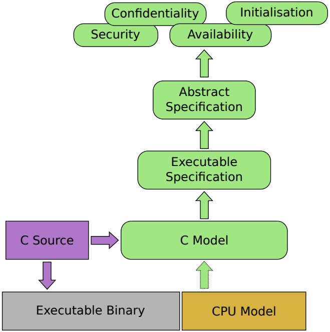
Think about a binary search tree. Where would its invariants go?



The AutoCorres Idea

The big idea of the AutoCorres project:

- Can we handle one layer *automatically*?



A Brief Overview of C and Simpl

C

Main new problems in verifying C programs:

- ➜ expressions with side effects
- ➜ more control flow (do/while, for, break, continue, return)
- ➜ local variables and blocks
- ➜ functions & procedures
- ➜ concrete C data types
- ➜ C memory model and C pointers

C is not a nice language for reasoning.

Things are going to get ugly.

AutoCorres will help.

C Parser: translates C into Simpl

Simpl: deeply embedded imperative language in Isabelle.

- ➜ generic imperative language by Norbert Schirmer, TU Munich
- ➜ state space and basic expressions/statements can be instantiated
- ➜ has operational semantics
- ➜ has its own Hoare logic with soundness and completeness proof, plus automated vcg

C Parser: parses C, produces Simpl definitions in Isabelle

- ➜ written by Michael Norrish, NICTA and ANU
- ➜ Handles a non-trivial subset of C
- ➜ Originally written to verify seL4's C implementation
- ➜ AutoCorres is built on top of the C Parser

Commands in Simpl

datatype ('s, 'p, 'f) com =
```
        Skip
      | Basic "'s ⇒ 's"
      | Spec "('s * 's) set"
      | Seq "('s, 'p, 'f) com" "('s, 'p, 'f) com"
      | Cond "'s set" "('s, 'p, 'f) com"  "('s, 'p, 'f) com"
      | While "'s set" "('s, 'p, 'f) com"
      | Call 'p
      | DynCom "'s ⇒ ('s, 'p, 'f) com"
      | Guard 'f "'s set" "('s, 'p, 'f) com"
      | Throw
      | Catch "('s, 'p, 'f) com" "('s, 'p, 'f) com"
```

's = state, **'p** = procedure names, **'f** = faults

Expressions with side effects

```
a = a * b;   x = f(h);   i = ++i - i++;   x = f(h) + g(x);
```

- ➜ **a = a * b** — Fine: easy to translate into Isabelle
- ➜ **x = f(h)** — Fine: may have side effects, but can be translated sanely.
- ➜ **i = ++i - i++** — Seriously? What does that even mean? Make this an error, force programmer to write instead:
  i0 = i; i++; i = i - i0; (or just **i = 1**)
- ➜ **x = f(h) + g(x)** — Ok if **g** and **h** do not have any side effects
  $\Longrightarrow$ Prove all functions in expressions are side-effect free

Alternative:

Explicitly model nondeterministic order of execution in expressions.

Control flow

```
do { c } while (condition);
```

automatically translates into:

```
c; while (condition) { c }
```

Similarly:

```
for (init; condition; increment) { c }
```

becomes

```
init; while (condition) { c; increment; }
```


More control flow: break/continue

```
while (condition) {
    foo;
    if (Q) continue;
    bar;
    if (P) break;
}
```

Non-local control flow: **continue** goes to condition, **break** goes to end.
Can be modelled with exceptions:

- ➜ throw exception **'continue'**, catch at end of body.
- ➜ throw exception **'break'**, catch after loop.

Break/continue

Break/continue example becomes:

```
try {
    while (condition) {
        try {
            foo;
            if (Q) { exception = 'continue'; throw; }
            bar;
            if (P) { exception = 'break'; throw; }
        } catch { if (exception == 'continue') SKIP else throw; }
    }
} catch { if (exception == 'break') SKIP else throw; }
```

This is not C any more. But it models C behaviour!

Need to be careful that only the translation has access to exception state.

Return

```
if (P) return x;
foo;
return y;
```

Similar non-local control flow. **Similar solution:** use throw/try/catch

```
try {
    if (P) { return_val = x; exception = 'return'; throw; }
    foo;
    return_val = y; exception = 'return'; throw;
} catch {
    SKIP
}
```


AutoCorres

AutoCorres

AutoCorres: reduces the pain in reasoning about C code

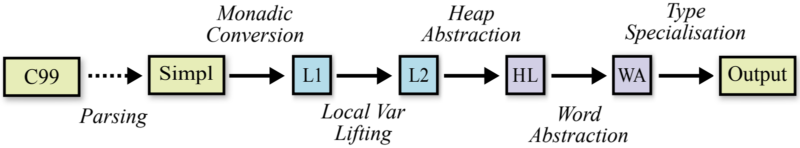
- Written by David Greenaway, NICTA and UNSW
- Converts C/Simpl into (monadic) shallow embedding in Isabelle
- Shallow embedding easier to reason about than Simpl

Is self-certifying: produces Isabelle theorems proving its own correctness

For each Simpl definition *C* and its generated shallow embedding *A*:

- AutoCorres proves an Isabelle theorem stating that *C* **refines** *A*
- Every behaviour of *C* has a corresponding behaviour of *A*
- Refinement guarantees that properties proved about *A* will also hold for *C*.
- (Provided that *A* never fails. c.f. Total Correctness)

AutoCorres Process



L1: initial monadic shallow embedding

L2: local variables introduced by λ-bindings

HL: heap state abstracted into a set of **typed heaps**

WA: machine words abstracted to idealised integers or nats

Output: human-readable output with **type strengthening**, polish

On-the-fly proof:
Simpl refines **L1** refines **L2** refines **HL** refines **WA** refines **Output**

Example: C99

We will use the following example program to illustrate each of the phases.

```
unsigned some_func(unsigned *a, unsigned *b, unsigned c) {
  unsigned *p = NULL;

  if (c > 10u){
    p = a;
  } else {
    p = b;
  }

  return *p;
}
```


Example: Simpl

```
some_func_body ≡
TRY
  ´p :== ptr_coerce (Ptr (scast 0));;
  IF 0xA < ´c THEN
    ´p :== ´a
  ELSE
    ´p :== ´b
  FI;;
  Guard C_Guard {|c_guard ´p|}
   (creturn global_exn_var_'_update ret__unsigned_'_update
     (λs. h_val (hrs_mem (t_hrs_' (globals s))) (p_' s)));;
  Guard DontReach {} SKIP
CATCH SKIP END
```

Example: L1 (monadic shallow embedding)

```
l1_some_func  ≡  L1_seq (L1_init ret__unsigned_'_update)
 (L1_seq (L1_modify (p_'_update (λ_. ptr_coerce (Ptr (scast 0)))))
   (L1_seq (L1_condition (λs. 0xA < c_' s)
                         (L1_modify (λs. s(|p_' := a_' s|)))
                         (L1_modify (λs. s(|p_' := b_' s|))))
     (L1_seq (L1_guard (λs. c_guard (p_' s)))
       (L1_seq (L1_modify (λs. s(|ret__unsigned_' :=
                   h_val (hrs_mem (t_hrs_' (globals s))) (p_' s)|)))
         (L1_modify (global_exn_var_'_update (λ_. Return)))))))
```

State type is the same as Simpl, namely a record with fields:

- ➜ **globals**: heap and type information
- ➜ **a_'**, **b_'**, **c_'**, **p_'** (parameters and local variables)
- ➜ **ret__unsigned_'**, **global_exn_var_'** (return value, exception type)

Example: L2 (local variables lifted)

```
l2_some_func a b c ≡
L2_seq (L2_condition (λs. 0xA < c)
                     (L2_gets (λs. a) [''p''])
                     (L2_gets (λs. b) [''p'']))
  (λp. L2_seq (L2_guard (λs. c_guard p))
     (λ_. L2_gets (λs. h_val (hrs_mem (t_hrs_' s)) p) [''ret'']))
```

State is a record with just the **globals** field

- ➜ function now takes its parameters as arguments
- ➜ local variable **p** now passed via λ-binding
- ➜ **L2_gets** annotated with local variable names
- ➜ This ensures preservation by later AutoCorres phases

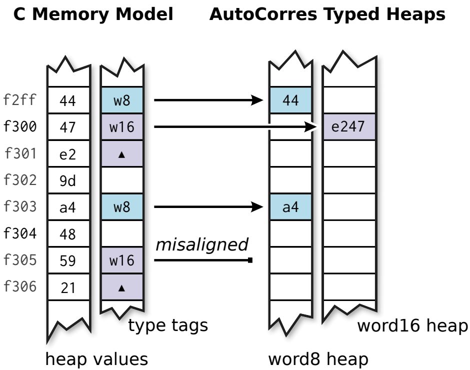
Example: HL (heap abstracted into typed heaps)

```
hl_some_func a b c ≡
L2_seq (L2_condition (λs. 0xA < c)
                     (L2_gets (λs. a) [''p''])
                     (L2_gets (λs. b) [''p'']))
  (λr. L2_seq (L2_guard (λs. is_valid_w32 s r))
    (λ_. L2_gets (λs. heap_w32 s r) [''ret'']))
```

State is a record with a set of **is_valid_** and **heap_** fields:

- ➜ These store **pointer validity** and **heap contents** respectively, per type
- ➜ above example has only 32-bit word pointers

Heap Abstraction



C Memory Model: by Harvey Tuch

- ➜ **Heap** is a mapping from 32-bit addresses to bytes: 32 word ⇒ 8 word
- ➜ **Heap Type Description** stores type information for each heap location

Example: WA (words abstracted to ints and nats)

```
wa_some_func a b c ≡
L2_seq (L2_condition (λs. 10 < c)
                     (L2_gets (λs. a) [''p''])
                     (L2_gets (λs. b) [''p'']))
 (λr. L2_seq (L2_guard (λs. is_valid_w32 s r))
      (λ_. L2_gets (λs. unat (heap_w32 s r)) [''ret'']))
```

Word abstraction: C **int** → Isabelle int, C **unsigned** → Isabelle nat

- ➜ Guards inserted to ensure absence of unsigned underflow and overflow
- ➜ Signed under/overflow already has guards (it has undefined behaviour)

In the example, the **unsigned** argument **c** is now of type **nat**

- ➜ The function also returns a nat result
- ➜ The heap is not abstracted, hence the call to **unat**

Example: Output (type strengthening and polish)

```
some_func' a b c ≡
DO p ← oreturn (if 10 < c then a else b);
   oguard (λs. is_valid_w32 s p);
   ogets (λs. unat (heap_w32 s p))
OD
```

Type Strengthening:

- ➜ Tries to convert output to a more restricted monad
- ➜ The above is in the **option** monad because it doesn't modify the state, but might fail
- ➜ The **type** of the option monad implies it cannot modify state

Polish:

- ➜ Simplify output as much as possible
- ➜ The **condition** has been rewritten to a **return** because the condition **10** $<$ **c** doesn't depend on the state

Type Strengthening

Example:

```
unsigned zero(void){ return 0u; }
```

Monad Type	**Kind**	**Type**	**Example**
pure	Pure function	*'a*	0
gets	Read-only, non-failing	*'s* $\Rightarrow$ *'a*	λs. 0
option	Read-only function	*'s* $\Rightarrow$ *'a* option	oreturn 0

Effect information now encoded in function **types**

Later proofs get this information for free!

Can be controlled by the **ts_force** option of AutoCorres

(Reader) Option Monad

Another standard monad, familiar from e.g. Haskell

Return:

$$\text{oreturn } x \equiv \lambda s.\ \text{Some } x$$

Bind:

$$\text{obind } a\ b \equiv \lambda s.\ \text{case } a\ s \text{ of None} \Rightarrow \text{None} \mid \text{Some } r \Rightarrow b\ r\ s$$

- **Infix notation:** $|\gg$
- **Do notation:** DO ... OD

Hoare Logic:

$$\text{ovalid } P\ f\ Q \equiv \forall s\ r.\ P\ s \wedge f\ s = \text{Some } r \longrightarrow Q\ r\ s$$

$$\text{ovalid } (P\ x)\ (\text{oreturn } x)\ P \qquad \frac{\bigwedge r.\ \text{ovalid } (R\ r)\ (g\ r)\ Q \quad \text{ovalid } P\ f\ R}{\text{ovalid } P\ (f\ |\gg g)\ Q}$$

Exception Monad

Exceptions used to model early return, break and continue.

Exception Monad: $'s \Rightarrow ((\underline{'e + 'a}) \times 's)\ \text{set} \times \text{bool}$

- ➜ Instance of the nondeterministic state monad: return-value type is **sum type** $'e + 'a$
- ➜ Sum Type Constructors: **Inl** $:: 'e \Rightarrow 'e + 'a$ **Inr** $:: 'a \Rightarrow 'e + 'a$
- ➜ **Convention:** Inl used for exceptions, Inr used for ordinary return-values

Basic Monadic Operations

returnOk $x \equiv$ return (Inr x) throwError $e \equiv$ return (Inl e)

lift $b \equiv (\lambda x.$ case x of Inl $e \Rightarrow$ throwError e | Inr $r \Rightarrow b\ r)$

bindE: $a \gg\!=\!\text{E}\ b \equiv a \gg\!= (\text{lift b})$ **Do notation:** doE ... odE

Hoare Rules for Exceptions

New kind of Hoare triples to model normal and exceptional cases:

$$\{\!|P|\!\}\ f\ \{\!|Q|\!\},\ \{\!|E|\!\}$$
$$\equiv$$
$$\{\!|P|\!\}\ f\ \{\!|\lambda x\ s.\ \text{case}\ x\ \text{of Inl}\ e\ \Rightarrow E\ e\ s\ |\ \text{Inr}\ r\ \Rightarrow Q\ r\ s\,|\!\}$$

Weakest Precondition Rules:

$$\frac{}{\{\!|P\ x|\!\}\ \text{returnOk}\ x\ \{\!|P|\!\},\{\!|E|\!\}} \qquad \frac{}{\{\!|E\ e|\!\}\ \text{throwError}\ e\ \{\!|P|\!\},\{\!|E|\!\}}$$

$$\frac{\bigwedge x.\ \{\!|R\ x|\!\}\ b\ x\ \{\!|Q|\!\},\{\!|E|\!\} \qquad \{\!|P|\!\}\ a\ \{\!|R|\!\},\{\!|E|\!\}}{\{\!|P|\!\}\ a\ \gg\!=\!\text{E}\ b\ \{\!|Q|\!\},\{\!|E|\!\}}$$

(other rules analogous)

Today we have seen

- ➜ The automated proof method **wp**
- ➜ The C Parser and translating C into Simpl
- ➜ AutoCorres and translating Simpl into monadic form
- ➜ The option and exception monads

