COMP4161
Advanced Topics in Software Verification

Gerwin Klein, June Andronick, Miki Tanaka, Johannes Åman Pohjola

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Last Time

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

Content

➜ Foundations & Principles

- Intro, Lambda, natural deduction [1,2]
- Higher Order Logic (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

wp

apply (wp *extra_wp_rules*)

Tactic for automati  on of **weakest precondition rules**

- ➜ Originally developed by Thomas Sewell, NICTA, for the seL4 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

A Brief Overview of C and Simpl

C

Main new problems in verifying C programs:

- ➜ expressions with s
- ➜ more control flow for, break, continue, return)
- ➜ local variables and
- ➜ 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 [illegible] by Norbert Schirmer, TU Munich
- ➜ state space and bl[illegible]sions/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

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

automatically transla

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


Similarly:


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


becomes


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

More control flow: break/continue


```
while (                    on) {
    foo;
    if (                   inue;
    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 (condit
        try {
            foo;
            if (Q) { exception = 'continue'; throw; }
            bar;
            if (P) { exception = 'break'; throw; }
        } catch { if (exception == 'continue') SKIP else th
    }
} 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) retu
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: reduces the pain in reasoning about C code

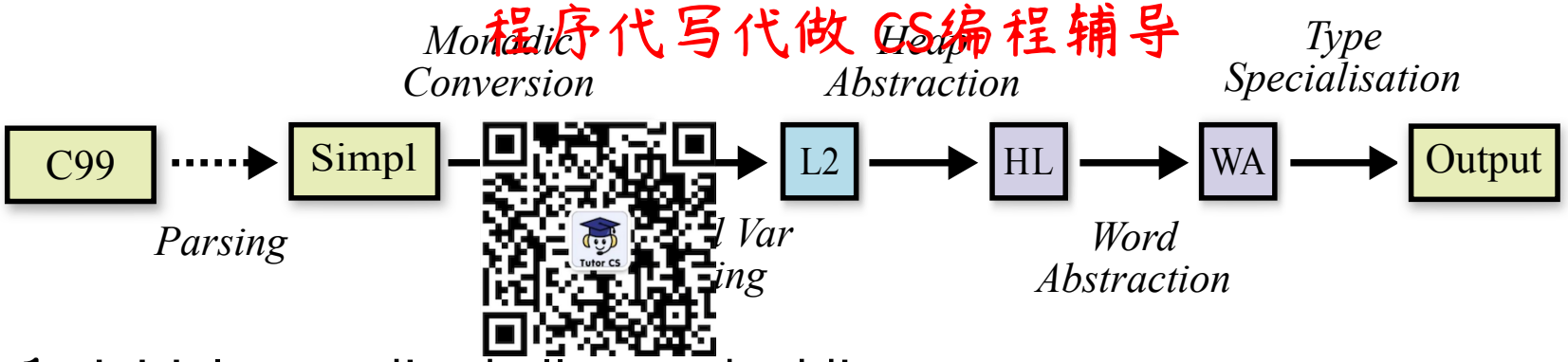
- ➜ Written by David [illegible], NICTA and UNSW
- ➜ Converts C/Simpl [illegible]adic) shallow embedding in Isabelle
- ➜ Shallow embeddi[illegible] reason about than Simpl

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_f                igned *a, unsigned *b, unsigned
  unsigned *p = NULL;

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

  return *p;
}
```

Example: Simpl

```
some_func_body ≡
TRY
   ´p :== ptr_coerce                    ast 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_init ret__unsigned_'_update)
 (L1_seq (L1_modify (_'_update (λ_. ptr_coerce (Ptr (scast 0)))))
   (L1_seq (L1_con                    s. 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
L2_seq (L2_condit                    0xA < c)
                                  _gets (λs. a) [''p'']
                                  _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

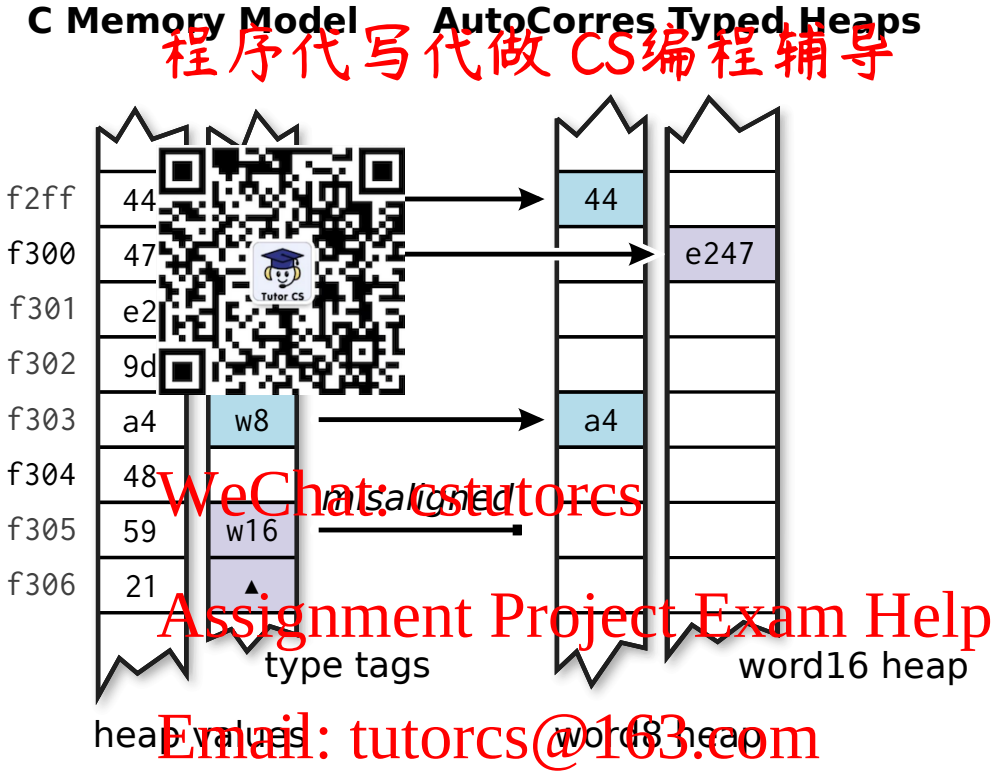
Example: HL (heap abstracted into typed heaps)


```
hl_some_func a
L2_seq (L2_conc                    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. ...d_w32 s p);
   ogets (λs. u...ap_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 $\mathbf{10} < \mathbf{c}$ doesn't depend on the state

Type Strengthening

Example:


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

Monad Type	Kind	Type	Example
pure	Pure function	*'a*	0
gets	Read-only, non-failing	*'s* ⇒ *'a*	λs. 0
option	Read-only function	*'s* ⇒ *'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:

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

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:

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

$$\text{ovalid}\ (P\ x)\ (\text{oreturn}\ x)\ P$$

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

Exception Monad

Exceptions used to model early return, break and continue.

Exception Monad: $('s \Rightarrow ('e + 'a) \times 's)$ set $\times$ 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 $e \mid$ Inr $r \Rightarrow b\ r)$

bindE: $a >>=$E $b \equiv a >>= ($lift b$)$ **Do notation:** doE ... odE

Hoare Rules for Exceptions

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

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

Weakest Precondition Rules:

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

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

(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