Aliasing Issues: Call by reference, Pointer programs

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Reminder of the last lecture

- Additional feature of the programming language
  - *Exceptions*
  - Function contracts extended with *exceptional post-conditions*
- Additional features of the specification language
  - Product Types: *records* and such
  - Sum Types, e.g. *lists*
  - Abstract Types: e.g. sets, *maps*
- Programs on *Arrays*
- Computer Arithmetic: *bounded integers*, *floating-point numbers*

Exercise from Previous Lecture

- Implement and prove binary search using a immediate exit:

  $low = 0$; $high = n - 1$;
  while $low \leq high$:
  let m be the middle of low and $high$
  if $a[m] = v$ then return m
  if $a[m] < v$ then continue search between m and $high$
  if $a[m] > v$ then continue search between low and m

  See `bin_search.mlw`

Introducing Aliasing Issues

Compound data structures can be *modeled* using expressive specification languages

- Defined functions and predicates
- Product types (records)
- Sum types (lists, trees)
- Axiomatizations (arrays, sets)

Important points:

- *pure* types, no internal “in-place” assignment
- Mutable variables = *references to pure types*

Aliasing

Aliasing = two different "names" for the same mutable data

Two sub-topics:

- Call by reference
- Pointer programs

Outline

Need for call by reference

Example: stacks of integers

```
type stack = list int

val s:ref stack

let fun push(x:int):unit
  writes s
  ensures s = Cons(x,s@Old)
  body ...

let fun pop(): int
  requires s ≠ Nil
  writes s
  ensures result = head(s@Old) ∧ s = tail(s@Old)
```

Need for call by reference

If we need two stacks in the same program:

- We don't want to write the functions twice!

We want to write

```
type stack = list int

let fun push(s:ref stack,x:int): unit
  writes s
  ensures s = Cons(x,s@Old)
  ...

let fun pop(s:ref stack):int)
  ...
```

Call by Reference: example

```
val s1,s2: ref stack

let fun test():
  writes s1, s2
  ensures result = 13 ∧ head(s2) = 42
  body push(s1,13); push(s2,42); pop(s1)
```

- See file `stack1.mlw`

Aliasing problems

```
let fun test(s3,s4: ref stack) : unit
  writes s3, s4
  ensures { head(s3) = 42 ∧ head(s4) = 13 }
  body push(s3,42); push(s4,13)

let fun wrong(s5: ref stack) : int
  writes s5
  ensures { head(s5) = 42 ∧ head(s5) = 13 }
              something's wrong !?
  body test(s5,s5)
```

Aliasing is a major issue

Deductive Verification Methods like Hoare logic, Weakest Precondition Calculus implicitly require absence of aliasing

Syntax

- Declaration of functions: (references first for simplicity)

  let fun $f(y_1 : \text{ref } \tau_1, \ldots, y_k : \text{ref } \tau_k, x_1 : \tau'_1, \ldots, x_n : \tau'_n)$:
  ...

- Call:

  $f(z_1, \ldots, z_k, e_1, \ldots, e_n)$

  where each z_i must be a reference

Operational Semantics

Intuitive semantics, by substitution:

$$\frac{\Pi' = \{x_i \leftarrow [\![t_i]\!]_{\Sigma,\Pi}\} \quad \Sigma, \Pi' \models \mathit{Pre} \quad \mathit{Body}' = \mathit{Body}[y_j \leftarrow z_j]}{\Sigma, \Pi, f(z_1, \ldots, z_k, t_1, \ldots, t_n) \rightsquigarrow \Sigma, \Pi, (\mathit{Old} : \texttt{frame}(\Pi', \mathit{Body}', \mathit{Post}))}$$

- The body is executed, where each occurrence of reference parameters are replaced by the corresponding reference argument.
- Not a "practical" semantics, but that's not important...

Operational Semantics

Variant: Semantics by copy/restore:

$$\frac{\Sigma' = \Sigma[y_j \leftarrow \Sigma(z_j)] \quad \Pi' = \{x_i \leftarrow [\![t_i]\!]_{\Sigma,\Pi}\} \quad \Sigma, \Pi' \models Pre}{\Sigma, \Pi, f(z_1, \ldots, z_k, t_1, \ldots, t_n) \rightsquigarrow \Sigma', \Pi, (Old : \texttt{frame}(\Pi', Body, Post))}$$

$$\frac{\Sigma, \Pi' \models P[\text{result} \leftarrow v] \quad \Sigma' = \Sigma[z_j \leftarrow \Sigma(y_j)]}{\Sigma, \Pi, (\texttt{frame}(\Pi', v, P)) \rightsquigarrow \Sigma', \Pi, v}$$

Warning: not the same semantics !

Difference in the semantics

```
val g : ref int

let fun f(x:ref int):unit
  body x := 1; x := g+1

let fun test():unit
  body g:=0; f(g)
```

After executing test:

- Semantics by substitution: `g = 2`
- Semantics by copy/restore: `g = 1`

Aliasing Issues (1)

```
let fun f(x:ref int, y:ref int):
  writes x, y
  ensures x = 1 ∧ y = 2
  body x := 1; y := 2

val g : ref int

let fun test():
  body
    f(g,g);
    assert g = 1 ∧ g = 2 (* ???? *)
```

- Aliasing of reference parameters

Aliasing Issues (2)

```
val g1 : ref int
val g2 : ref int

let fun p(x:ref int):
  writes g1, x
  ensures g1 = 1 ∧ x = 2
  body g1 := 1; x := 2

let fun test():
  body
    p(g2); assert g1 = 1 ∧ g2 = 2; (* OK *)
    p(g1); assert g1 = 1 ∧ g1 = 2; (* ??? *)
```

- Aliasing of a global variable and reference parameter

Aliasing Issues (3)

```
val g : ref int

val fun f(x:ref int):unit
  writes x
  ensures x = g + 1
  (* body x := 1; x := g+1 *)

let fun test():unit
  ensures { g = 1 or 2 ? }
  body g := 0; f(g)
```

- Aliasing of a read reference and a written reference

Aliasing Issues (3)

New need in specifications

Need to *specify read references in contracts*

```
val g : ref int

val f(x:ref int):unit
  reads g          (* new clause in contract *)
  writes x
  ensures x = g + 1
  (* body x := 1; x := g+1 *)

let fun test():unit
  ensures { g = ? }
  body g := 0; f(g)
```

- See file `stack2.mlw`

Typing: Alias-Freedom Conditions

For a function of the form

$f(y_1 : \tau_1, ..., y_k : \tau_k, ...) : \tau$:
writes $\vec{w}$
reads $\vec{r}$

Typing rule for a call to f:

$$\frac{\ldots \quad \forall ij, i \neq j \rightarrow z_i \neq z_j \quad \forall i, j, z_i \neq w_j \quad \forall i, j, z_i \neq r_j}{\ldots \vdash f(z_1, \ldots, z_k, \ldots) : \tau}$$

- effective arguments z_j must be distinct
- effective arguments z_j must not be read nor written by f

Proof Rules

Thanks to restricted typing:

- Semantics by substitution and by copy/restore coincide
- Hoare rules remain correct
- WP rules remain correct

New references

- Need to return newly created references
- Example: stack continued

```
let fun create():ref stack
  ensures result = Nil
  body (ref Nil)
```

- Typing should require that a returned reference is always *fresh*

Outline

Example: Sorting Algorithms

```
let fun sort (a:array int)
  writes a
  ensures ?
```

How to formalize postconditions:

- array in increasing order between 0 and $a.length - 1$
- array at exit is a permutation of the array at entrance

Inductive Predicates

- Definition à la Prolog, also in Coq, PVS, etc.
- An inductive definition of a predicate has the form

  inductive $p(\tau_1, \ldots, \tau_n)$:
  | id_1: $clause_1$
  ...
  | id_k: $clause_k$

  where clauses have the form

  forall $\vec{x}$. $hyp \Rightarrow p(e_1, \ldots, e_n)$

  and p occurs only positively in hyp (Horn clause).
- Always one smallest fix-point:
  predicate satisfying the clauses that is true the less often.

Inductive Predicates: Example

Classical example: transitive closure.

```
predicate r(x:t,y:t) = ...

inductive r_star(t,t) =
  | refl: forall x:t. r_star(x,x)
  | single: forall x y:t. r(x,y) → r_star(x,y)
  | trans: forall x y z:t.
    r_star(x,y) ∧ r_star(y,z) → r_star(x,z)
```

Exercise: Selection Sort

```
let fun swap (a : array int) (i: int) (j: int) : unit
  writes a ensures ?

let fun index_min (a : array int) (i: int) : int ...

let fun sel_sort (a: array int) ...
```

1. Formalize postconditions:
   - array in increasing order between 0 and $a.length - 1$,
   - array at exit is a permutation of the array at entrance.
2. Implement and prove selection sort algorithm:

   for each i from 0 to $a.length - 1$:
   find index idx of the min element between i and $a.length - 1$
   swap elements at indexes i and idx

See `sel_sort.mlw`

Outline

Pointer programs

- We drop the hypothesis "no reference to reference"
- Allows to program on *linked data structures*. Example (in the C language):

```
struct List { int data; list next; } *list;
while (p <> NULL) { p->data++; p = p->next }
```

- "In-place" assignment
- References are now *values* of the language: "pointers" or "memory addresses"

We need to handle aliasing problems differently

Syntax

- For simplicity, we assume a language with pointers to records
- Access to record field: `e→f`
- Update of a record field: `e→f := e'`

Operational Semantics

- New kind of values: *loc* = the type of pointers
- A special value *null* of type loc is given
- A program state is now a pair of
  - a *store* which maps variables identifiers to values
  - a *heap* which maps pairs (loc, field name) to values
- Memory access and updates should be proved safe (no "null pointer dereferencing")
- For the moment we forbid allocation/deallocation

Component-as-array trick

If:

- a program is *well-typed*
- The set of *all field names are known*

then the heap can be also seen as *a finite collection of maps*, one for each field name

- map for a field of type τ maps loc to values of type τ

This "trick" allows to *encode pointer programs* into Why3 programs

- Use maps indexed by locs instead of integers

Component-as-array model

```
type loc
constant null : loc

val acc(field: ref (map loc α),l:loc) : α
  requires l ≠ null
  reads field
  ensures result = select(field,l)

val upd(field: ref (map loc α),l:loc,v:α):unit
  requires l ≠ null
  writes field
  ensures field = store(field@Old,l,v)
```

Encoding:

- Access to record field: `e→f` becomes `acc(f,e)`
- Update of a record field:
  `e→f := e'` becomes `upd(f,e,e')`

Example

- In C

```
struct List { int data; list next; } *list;

while (p <> NULL) { p->data++; p = p->next }
```

- In Why3

```
val data: ref (map loc int)
val next: ref (map loc loc)

while p ≠ null do
   upd(data,p,acc(data,p)+1);
   p := acc(next,p)
```

In-place List Reversal

A la C/Java:

```
list reverse(list l) {
   list p = l;
   list r = null;
   while (p != null) {
     list n = p->next;
     p->next = r;
     r = p;
     p = n
  }
  return r;
}
```

In-place Reversal in our Model

```
let fun reverse (l:loc) : loc =
   let p = ref l in
   let r = ref null in
   while (p ≠ null) do
     let n = acc(next,p) in
     store(next,p,r);
     r := p;
     p := n
  done;
  r
```

Goals:

- Specify the expected behavior of `reverse`
- Prove the implementation

Specifying the function

Predicate `list_seg`$(p, next, p_M, q)$: p points to a list of nodes p_M that ends at q.

$$p = p_0 \overset{next}{\mapsto} p_1 \cdots \overset{next}{\mapsto} p_k \overset{next}{\mapsto} \mathrm{q}$$

$$p_M = Cons(p_0, Cons(p_1, \cdots Cons(p_k, Nil) \cdots))$$

p_M is the *model list* of p

```
inductive list_seg(loc,map loc loc,list loc,loc) =
| list_seg_nil:
  forall p:loc, next:map loc loc. list_seg(p,next,Nil,p)
| list_seg_cons:
  forall p q:loc, next:map loc loc, pM:list loc.
    p ≠ null ∧ list_seg(select(next,p),next,pM,q) →
      list_seg(p,next,Cons(p,pM),q)
```

Specification

- pre: input l well-formed:

$$\exists l_M.\texttt{list\_seg}(l, next, l_M, null)$$

- post: output well-formed:

$$\exists r_M.\texttt{list\_seg}(result, next, r_M, null)$$

  and

$$r_M = rev(l_M)$$

Issue: quantification on l_M is global to the function

- Use *ghost* variables

Annotated In-place Reversal

```
let fun reverse (l:loc) (ghost lM:list loc) : loc =
  requires list_seg(l,next,lM,null)
  writes next
  ensures list_seg(result,next,rev(lM),null)
  body
   let p = ref l in
   let r = ref null in
   while (p ≠ null) do
     let n = acc(next,p) in
     store(next,p,r);
     r := p;
     p := n
  done;
  r
```

In-place Reversal: loop invariant

```
while (p ≠ null) do
  let n = acc(next,p) in
  store(next,p,r);
  r := p;
  p := n
```

Local ghost variables p_M, r_M

$$\texttt{list\_seg}(p, next, p_M, null)$$

$$\texttt{list\_seg}(r, next, r_M, null)$$

$$append(rev(p_M), r_M) = rev(l_M)$$

See file `linked_list_rev.mlw`

Needed lemmas

- To prove invariant $\texttt{list\_seg}(p, next, p_M, null)$, we need to show that `list_seg` remains true when `next` is updated:

```
lemma list_seg_frame: forall next1 next2:map loc loc,
  p q v: loc, pM:list loc.
  list_seg(p,next1,pM,null) ∧
  next2 = store(next1,q,v) ∧
  ¬ mem(q,pM) → list_seg(p,next2,pM,null)
```

- For that, we need to show that a path going to `null` cannot contain repeted elements

```
lemma list_seg_no_repet:
  forall next:map loc loc, p: loc, pM:list loc.
    list_seg(p,next,pM,null) → no_repet(pM)
```

- To prove invariant $\texttt{list\_seg}(r, next, r_M, null)$, we need the frame lemma, again, and for that, we need to show that p_M, r_M remain *disjoint* : it is an additional invariant

Exercise

The algorithm that appends two lists *in place* follows this pseudo-code:

```
append(l1,l2 : loc) : loc
  if l1 is empty then return l2;
  let ref p = l1 in
  while p→next is not null do p := p→ next;
  p → next := l2;
  return l1
```

1. Specify a post-condition giving the list models of both `result` and `l2` (add any ghost variable needed)
2. Which pre-conditions and loop invariants are needed to prove this function?

See `linked_list_app.mlw`

Advertising next lectures

- Reasoning on pointer programs using the component-as-array trick is complex
  - need to state and prove *frame* lemmas
  - need to specify many *disjointness* properties
  - even harder is the handling of *memory allocation*
- *Separation Logic* is another approach to reason on heap memory
  - memory resources *explicit* in formulas
  - frame lemmas and disjointness properties are internalized

Schedule:

- Lectures on January 29th, February 5th
- February 12th: Lab session, help for solving the project
- Lectures on February 19th, February 26th
- Written exam on March 12th