Aliasing Issues: Call by reference, Pointer programs

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Reminder of the last lecture

- Additional features of the specification language
  - Sum Types, e.g. *lists*
- Programs on *lists*
- Additional feature of the programming language
  - *Exceptions*
  - Function contracts extended with *exceptional post-conditions*
- Computer Arithmetic: *bounded integers*, *floating-point numbers*
- A few home work to do

Home Work 1: McCarthy's 91 Function

$$f91(n) = \texttt{if } n \leq 100 \texttt{ then } f91(f91(n+11)) \texttt{ else } n - 10$$

Find adequate specifications

```
let f91(n:int): int
  requires ?
  variant ?
  writes ?
  ensures ?
body
  if n <= 100 then f91(f91(n + 11)) else n - 10
```

Use canvas file `mccarthy.mlw`

Home work 3

Prove the helper lemmas stated for the fast exponentiation algorithm

See `power_int_lemma_functions.mlw`

Home Work: Binary Search

$low = 0$; $high = a.length - 1$;
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 file `bin_search.mlw`

Home Work: Binary Search with an exception

$low = 0$; $high = a.length - 1$;
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 file `bin_search_exc.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, machine integers)
- Ghost code, lemma functions

Important points:

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

No Aliasing

Aliasing

Aliasing = two different “names” for the same mutable data

Two sub-topics of today’s lecture:

- Call by reference
- Pointer programs

Outline

Call by Reference

The Framing Issue

Pointer Programs

Need for call by reference

Example: stacks of integers

```
type stack = list int

val ref s: stack

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

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

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

Call by Reference: example

```
val ref s1,s2: stack

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

let wrong(ref s5: stack) : int
  writes s5
  ensures { head(s5) = 13 /\ head(s5) = 42 }
             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 $f(\text{ref } y_1 : \tau_1, \ldots, \text{ref } y_k : \tau_k, x_1 : \tau'_1, \ldots, x_n : \tau'_n)$:
  $\ldots$

- Call:

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

  where each z_i must be a (mutable) variable

Operational Semantics

Intuitive semantics, by substitution:

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

- 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:

$$\frac{\pi = \{y_j \mapsto \Sigma(z_j), x_i \mapsto [\![t_i]\!]_{\Sigma,\pi}\} \qquad \Sigma, \pi \models \mathit{Pre}}{\Sigma, \Pi, f(t_1, \ldots, t_n) \rightsquigarrow \Sigma, (\pi, \mathit{Post}) \cdot \Pi, (\mathit{Old} : \mathit{Body})}$$

$$\frac{\Sigma, \pi \models \mathit{Post}[\mathrm{result} \leftarrow v] \quad \Sigma' = \Sigma[z_j \leftarrow \pi(y_j)]}{\Sigma, (\pi, \mathit{Post}) \cdot \Pi, v \rightsquigarrow \Sigma', \Pi, v}$$

Operational Semantics

Variant: Semantics by copy/restore:

$$\frac{\pi = \{y_j \mapsto \Sigma(z_j), x_i \mapsto [\![t_i]\!]_{\Sigma,\pi}\} \qquad \Sigma, \pi \models \mathit{Pre}}{\Sigma, \Pi, f(t_1, \ldots, t_n) \rightsquigarrow \Sigma, (\pi, \mathit{Post}) \cdot \Pi, (\mathit{Old} : \mathit{Body})}$$

$$\frac{\Sigma, \pi \models \mathit{Post}[\mathrm{result} \leftarrow v] \quad \Sigma' = \Sigma[z_j \leftarrow \pi(y_j)]}{\Sigma, (\pi, \mathit{Post}) \cdot \Pi, v \rightsquigarrow \Sigma', \Pi, v}$$

Warning: not the same semantics !

Difference in the semantics

```
val ref g : int

let f(ref x: int):unit
  body x <- 1; x <- g+1

let 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 f(ref x: int, ref y: int):
  writes x, y
  ensures x = 1 /\ y = 2
  body x <- 1; y <- 2

val ref g : int

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

- Aliasing of reference parameters

Aliasing Issues (2)

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

let p(ref x: int):
  writes g1, x
  ensures g1 = 1 /\ x = 2
  body g1 <- 1; x <- 2

let 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 ref g : int

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

let 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 ref g : int

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

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

- See file `stack2.mlw`

Typing: Alias-Freedom Conditions

For a function of the form

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

Typing rule for a call to f:

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

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

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

More on aliasing control using static typing: *[Filliâtre, 2016]*

Outline

Introduction to Framing

(Example from exam 2017)

- Consider polynomials of the form $\sum_{i=0}^{n} c_i X^i$
- Representation: array of real numbers, len $n+1$, i-th cell is c_i

Example: $P_0 = X^3 + 4X - 7$ is represented as array $[-7; 4; 0; 1]$

Polynomial Evaluation

Function eval

Formally interprets an array of reals as a polynomial function

```
let rec function eval_aux (p:array real) (x:real)
                          (i j:int) : real
= if j <= i then 0.0 else
  p[i] + x * eval_aux p x (i+1) j

function eval (p:array real) (x:real) : real =
    eval_aux p x 0 p.length
```

Example

$$
\begin{aligned}
& \texttt{eval}\ P_0\ 0.5 \\
& = \texttt{eval\_aux}\ [-7; 4; 0; 1]\ 0.5\ 0\ 4 \\
& = (-7) + 0.5 * \texttt{eval\_aux}\ [-7; 4; 0; 1]\ 0.5\ 1\ 4 \\
& = \vdots \\
& = (-7) + 0.5 * (4 + 0.5 * (0 + 0.5 * 1))
\end{aligned}
$$

Adding a constant to a polynomial

Function add_const

Adds a constant to a polynomial

```
let add_const (p:array real) (c:real) : unit
  requires { p.length >= 1 }
  writes { p }
  ensures { forall x. eval p x = eval (old p) x + c }
= p[0] <- p[0] + c
```

As such, this function is not proved automatically, why?

Need for a framing property

Let p' denote the array after assignment. Proving the post-condition requires to establish:

```
eval p' x = eval p x + c
```

that is, after unfolding `eval`:

```
eval_aux p' x 0 l = eval_aux p x 0 l + c
```

By expanding using the definition of `eval_aux`:

```
p'[0] + eval_aux p' x 1 l = p[0] + eval_aux p x 1 l + c
```

After simplification:

```
eval_aux p' x 1 l = eval_aux p x 1 l
```

Framing

To prove that p' is equal to p on the range $1 \ldots l$, a *frame property* is needed

Frame property

Frame property for `eval_aux`

For any arrays p and q, if

$$\forall k. i \leq k < j \rightarrow p[k] = q[k]$$

then

$$\texttt{eval\_aux}\ p\ x\ i\ j = \texttt{eval\_aux}\ q\ x\ i\ j$$

A lemma function can be stated as follows to enforce a proof by induction on $j - i$:

```
let rec lemma eval_aux_frame (p q:array real) (x:real) (i j:int)
  requires { forall k. i <= k < j -> p[k] = q[k] }
  variant { j - i }
  ensures { eval_aux p x i j = eval_aux q x i j }
= if j > i then eval_frame p q x (i+1) j
```

Property needed very often, e.g. for addition of polynomials

Frame properties in general

For a predicate P, the *frame* of P is the set of memory locations $fr(P)$ that P depends on.

Frame property

P is invariant under mutations outside $fr(P)$

$$\frac{H \vdash P \qquad H \cap fr(P) = H' \cap fr(P)}{H' \vdash P}$$

See also *[Kassios, 2006]*

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; linked_list next; }
  *linked_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
  [See lecture next week]

Component-as-array trick

[Bornat, 2000]

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 our previous programming language:

- Use maps indexed by locs (instead of integers for arrays)

Component-as-array model

```
type loc
constant null : loc

val acc(ref field: loc -> 'a, l:loc) : 'a
  requires l <> null
  reads field
  ensures result = select(field,l)

val upd(ref field: loc -> 'a, l:loc, v:'a):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; linked_list next; }
  *linked_list;

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

- Encoded as

```
val ref data: loc -> int
val ref next: loc -> loc
val ref p : loc

while p <> null do
   upd(data,p,acc(data,p)+1);
   p <- acc(next,p)
```

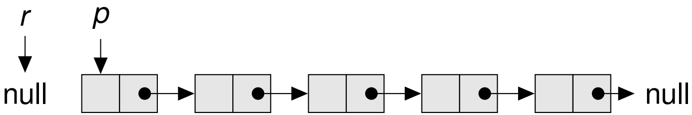
In-place List Reversal

A la C/Java:

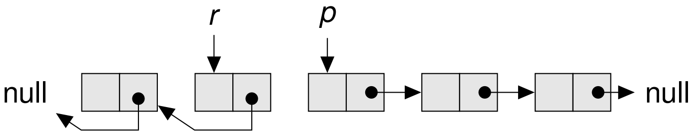
```
linked_list reverse(linked_list l) {
   linked_list p = l;
   linked_list r = null;
   while (p != null) {
     linked_list n = p->next;
     p->next = r;
     r = p;
     p = n
  }
  return r;
}
```

In-place List Reversal

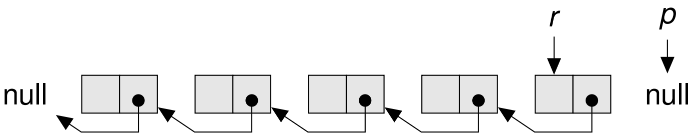
initial step:



intermediate step:



final state:



In-place Reversal in our Model

```
let reverse (l:loc) : loc =
   let ref p = l in
   let ref r = null in
   while p <> null do
     let n = acc(next,p) in
     upd(next,p,r);
     r <- p;
     p <- n
  done;
  r
```

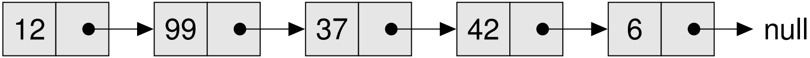
Goals:

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

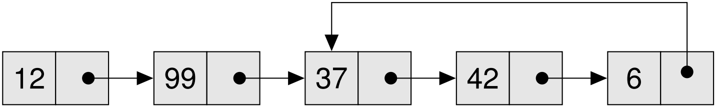
Specifying `reverse`

Three possibilities for a shape of a linked list:

- null terminated, e.g.:



- cyclic, e.g.:



- or…infinite ! (not forbidden in our model)

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

```
predicate list_seg (p:loc, next: loc -> loc,
                    pM:list loc, q:loc) =
  match pM with
  | Nil -> p = q
  | Cons h t ->
    p <> null /\ h=p /\ list_seg((next p),next,t,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

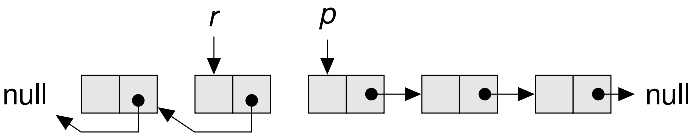
Annotated In-place Reversal

```
let 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 ref p = l in
   let ref r = null in
   while p <> null do
     let n = acc(next,p) in
     upd(next,p,r);
     r <- p;
     p <- n
  done;
  r
```

See file `linked_list_rev.mlw`

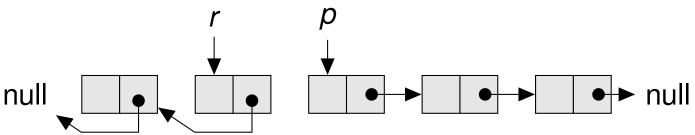
In-place Reversal: loop invariant

```
while (p <> null) do
  let n = acc(next,p) in
  upd(next,p,r);
  r <- p;
  p <- n
```



In-place Reversal: loop invariant

```
while (p <> null) do
  let n = acc(next,p) in
  upd(next,p,r);
  r <- p;
  p <- n
```



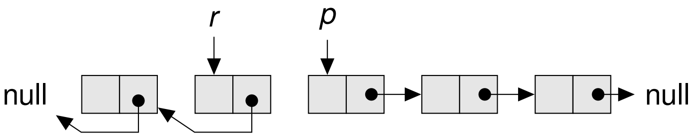
Local ghost variables p_M, r_M

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

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

In-place Reversal: loop invariant

```
while (p <> null) do
  let n = acc(next,p) in
  upd(next,p,r);
  r <- p;
  p <- n
```



Local ghost variables p_M, r_M

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

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

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

Needed lemmas

To prove invariant `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 r v: loc, pM:list loc.
  list_seg(p,next1,pM,q) /\
  next2 = store(next1,r,v) /\
  not mem(r,pM) -> list_seg(p,next2,pM,q)
```

This is again an instance of the general *frame property*

Needed lemmas

- To prove invariant `list_seg`$(p, next, p_M, null)$, we need to show that `list_seg` remains true when `next` is updated:
- But to apply the frame lemma, we need to show that a path going to `null` cannot contain repeated 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)
```

Needed lemmas

- To prove invariant $\texttt{list\_seg}(r, next, r_M, null)$, we need the frame property

Needed lemmas

- To prove invariant $\texttt{list\_seg}(r, \mathit{next}, r_M, \mathit{null})$, we need the frame property
- Again, to apply the frame lemma, 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`

Bibliography

Aliasing control using static typing

[Filliâtre, 2016] J.-C. Filliâtre, L. Gondelman, A. Paskevich. A Pragmatic Type System for Deductive Verification, 2016. (see also Gondelman's PhD thesis)

Component-as-array modeling

[Bornat, 2000] Richard Bornat, Proving Pointer Programs in Hoare Logic, *Mathematics of Program Construction*, 102–126, 2000

[Kassios, 2006] I. Kassios. Dynamic frames: Support for framing, dependencies and sharing without restrictions, *International Symposium on Formal Methods*.

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