

# Separation Logic

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# Chapter 7

## The Frame Rule

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### Preservation of independent state

We have:

$$\{r \mapsto 2\} (\text{incr } r) \{\lambda_. r \mapsto 3\}$$

We also have:

$$\{r \mapsto 2 \star s \mapsto 7\} (\text{incr } r) \{\lambda_. r \mapsto 3 \star s \mapsto 7\}$$

More generally:

$$\{r \mapsto 2 \star H\} (\text{incr } r) \{\lambda_. r \mapsto 3 \star H\}$$

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### The frame rule

Principle: a triple remains valid when both the pre-condition and the post-condition are extended with a same heap predicate.

General form:

$$\frac{\{H_1\} t \{\lambda x. H'_1\}}{\{H_1 \star H_2\} t \{\lambda x. H'_1 \star H_2\}}$$

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## Frame rule and allocation

We have:

$$\{ [] \} (\text{ref } 3) \{ \lambda r. (r \mapsto 3) \}$$

By the frame rule, we have:

$$\{ s \mapsto 5 \} (\text{ref } 3) \{ \lambda r. (r \mapsto 3) \star (s \mapsto 5) \}$$

This post-condition ensures  $r \neq s$ .

The reference cell  $r$  is thus guaranteed to be distinct from any cell that might exist prior to the allocation of  $r$ .

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## Length of a mutable list, recursively

```
let rec mlength (p: 'a cell) =
  if p == null
  then 0
  else let n' = mlength p.tl in 1 + n'
```

Specification:

$$\forall pL. \{ p \rightsquigarrow \text{Mlist } L \} (\text{mlength } p) \{ \lambda n. [n = \text{length } L] \star p \rightsquigarrow \text{Mlist } L \}$$

We prove this specification by induction on  $L$ .

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## Verification of mlength: nil case

**Case  $p = \text{null}$ .** Goal is:

$$\{ p \rightsquigarrow \text{Mlist } L \} (0) \{ \lambda n. [n = \text{length } L] \star p \rightsquigarrow \text{Mlist } L \}$$

Exploit:

$$\text{null} \rightsquigarrow \text{Mlist } L \quad \triangleright \quad [L = \text{nil}] \star \text{null} \rightsquigarrow \text{Mlist } L$$

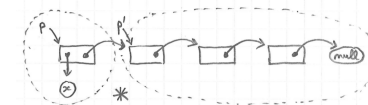
and:

$$0 = \text{length nil}$$

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## Verification of mlength: frame process

$$\forall pL. \{ p \rightsquigarrow \text{Mlist } L \} (\text{mlength } p) \{ \lambda n. [n = \text{length } L] \star p \rightsquigarrow \text{Mlist } L \}$$



Assume  $L = x :: L'$ .

$p \rightsquigarrow \text{Mlist } L$	pre-condition
$p \rightsquigarrow \{ \text{hd}=x; \text{tl}=p' \} \star p' \rightsquigarrow \text{Mlist } L'$	by unfolding
$p' \rightsquigarrow \text{Mlist } L'$	frame begins
$p' \rightsquigarrow \text{Mlist } L' \star [n' =  L' ]$	by induction
$p \rightsquigarrow \{ \text{hd}=x; \text{tl}=p' \} \star p' \rightsquigarrow \text{Mlist } L' \star [n' =  L' ]$	frame ends
$p \rightsquigarrow \text{Mlist } L \star [n' + 1 =  x :: L' ]$	by folding
$p \rightsquigarrow \text{Mlist } L \star [n =  L ]$	post-condition

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## Instantiation of the frame rule

Induction hypothesis:

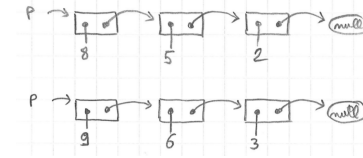
$$\begin{aligned} & \{p' \rightsquigarrow \text{Mlist } L'\} \\ & (\text{mlength } p') \\ & \{\lambda n'. [n = \text{length } L'] \star p' \rightsquigarrow \text{Mlist } L'\} \end{aligned}$$

By the frame rule:

$$\begin{aligned} & \{p' \rightsquigarrow \text{Mlist } L' \star p \rightsquigarrow \{\text{hd}=x; \text{tl}=p'\}\} \\ & (\text{mlength } p') \\ & \{\lambda n. [n = \text{length } L'] \star p' \rightsquigarrow \text{Mlist } L' \star p \rightsquigarrow \{\text{hd}=x; \text{tl}=p'\}\} \end{aligned}$$

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## Verification of in-place increment



```
let rec list_incr (p:'a cell) =
  if p != null then begin
    p.hd <- p.hd + 1;
    list_incr p.tl
  end
```

$$\forall pL. \{p \rightsquigarrow \text{Mlist } L\} (\text{list\_incr } p) \{\lambda_. p \rightsquigarrow \text{Mlist } (\text{map } (+1) L)\}$$

Exercise: describe the frame process for in-place increment.

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## Verification of in-place increment: frame process

$$\forall pL. \{p \rightsquigarrow \text{Mlist } L\} (\text{list\_incr } p) \{\lambda_. p \rightsquigarrow \text{Mlist } (\text{map } (+1) L)\}$$

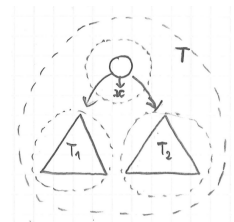
Assume  $L = x :: L'$ .

$p \rightsquigarrow \text{Mlist } L$	pre-condition
$p \rightsquigarrow \{\text{hd}=x; \text{tl}=p'\} \star p' \rightsquigarrow \text{Mlist } L'$	by unfolding
$p \rightsquigarrow \{\text{hd}=x+1; \text{tl}=p'\} \star p' \rightsquigarrow \text{Mlist } L'$	incrementing
$p' \rightsquigarrow \text{Mlist } L'$	frame begins
$p' \rightsquigarrow \text{Mlist } (\text{map } (+1) L')$	by induction
$p \rightsquigarrow \{\text{hd}=x+1; \text{tl}=p'\} \star p' \rightsquigarrow \text{Mlist } (\text{map } (+1) L')$	frame ends
$p \rightsquigarrow \text{Mlist } ((x+1) :: (\text{map } (+1) L'))$	by folding
$p \rightsquigarrow \text{Mlist } (\text{map } (+1) L)$	by rewriting
	post-condition

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## Specification of tree copy

```
let rec copy (p:node) : node =
  if p == null then null else
  let p1' = copy p.left in
  let p2' = copy p.right in
  { item = p.item;
    left = p1';
    right = p2' }
```



Exercise: specify the tree copy function.

$$\forall pT. \{p \rightsquigarrow \text{Mtree } T\} (\text{copy } p) \{\lambda p'. p \rightsquigarrow \text{Mtree } T \star p' \rightsquigarrow \text{Mtree } T\}$$

Exercise: describe the frame process for tree copy.

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## Verification of tree copy: frame process

$p \rightsquigarrow \text{Mtree } T$	by pre-condition
$p \mapsto \{x; p_1; p_2\} \star p_1 \rightsquigarrow \text{Mtree } T_1 \star p_2 \rightsquigarrow \text{Mtree } T_2$	by unfolding
$p_1 \rightsquigarrow \text{Mtree } T_1$	frame begins
$p_1 \rightsquigarrow \text{Mtree } T_1$ $\star p'_1 \rightsquigarrow \text{Mtree } T_1$	by induction
$p \mapsto \{x; p_1; p_2\} \star p_1 \rightsquigarrow \text{Mtree } T_1 \star p_2 \rightsquigarrow \text{Mtree } T_2$ $\star p'_1 \rightsquigarrow \text{Mtree } T_1$	frame ends
$p_2 \rightsquigarrow \text{Mtree } T_2$	frame begins
$p_2 \rightsquigarrow \text{Mtree } T_2$ $\star p'_2 \rightsquigarrow \text{Mtree } T_2$	by induction
$p \mapsto \{x; p_1; p_2\} \star p_1 \rightsquigarrow \text{Mtree } T_1 \star p_2 \rightsquigarrow \text{Mtree } T_2$ $\star p'_1 \rightsquigarrow \text{Mtree } T_1 \star p'_2 \rightsquigarrow \text{Mtree } T_2$	frame ends
$p \mapsto \{x; p_1; p_2\} \star p_1 \rightsquigarrow \text{Mtree } T_1 \star p_2 \rightsquigarrow \text{Mtree } T_2$ $\star p' \mapsto \{x; p'_1; p'_2\} \star p'_1 \rightsquigarrow \text{Mtree } T_1 \star p'_2 \rightsquigarrow \text{Mtree } T_2$	by allocation
$p \rightsquigarrow \text{Mtree } T$	
$\star p' \rightsquigarrow \text{Mtree } T$	by folding

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## Summary

$$\frac{\{H_1\} t \{\lambda x. H'_1\}}{\{H_1 \star H_2\} t \{\lambda x. H'_1 \star H_2\}} \text{FRAME}$$

In-place mutable list increment, when  $L = x :: L'$ .

$p \rightsquigarrow \text{Mlist } L$	
$p \rightsquigarrow \{\text{hd}=x; \text{tl}=p'\} \star p' \rightsquigarrow \text{Mlist } L'$	by unfolding
$p \rightsquigarrow \{\text{hd}=x+1; \text{tl}=p'\} \star p' \rightsquigarrow \text{Mlist } L'$	incrementing
$p' \rightsquigarrow \text{Mlist } L'$	frame begins
$p' \rightsquigarrow \text{Mlist } (\text{map } (+1) L')$	by induction
$p \rightsquigarrow \{\text{hd}=x+1; \text{tl}=p'\} \star p' \rightsquigarrow \text{Mlist } (\text{map } (+1) L')$	frame ends
$p \rightsquigarrow \text{Mlist } ((x+1) :: (\text{map } (+1) L'))$	by folding
$p \rightsquigarrow \text{Mlist } (\text{map } (+1) L)$	by rewriting

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## Chapter 8

### Small footprint specifications

### Small footprint access to records

$$p \rightsquigarrow \{\text{hd}=v; \text{tl}=q\} \equiv p.\text{hd} \mapsto v \star p.\text{tl} \mapsto q$$

Specification of a write on the head field:

$$\{p \rightsquigarrow \{\text{hd}=w; \text{tl}=q\}\} (p.\text{hd} \leftarrow v) \{\lambda_. p \rightsquigarrow \{\text{hd}=v; \text{tl}=q\}\}$$

Same, but with a smaller footprint:

$$\{p.\text{hd} \mapsto w\} (p.\text{hd} \leftarrow v) \{\lambda_. p.\text{hd} \mapsto v\}$$

or  $\{p.\text{hd} \mapsto -\} (p.\text{hd} \leftarrow v) \{\lambda_. p.\text{hd} \mapsto v\}$

From small to large footprint using frame:

$$\{p.\text{hd} \mapsto w \star p.\text{tl} \mapsto q\} (p.\text{hd} \leftarrow v) \{\lambda_. p.\text{hd} \mapsto v \star p.\text{tl} \mapsto q\}$$

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## Representation predicate for arrays

Representation predicate for C arrays:

$$p \rightsquigarrow \text{Array } L \equiv \bigotimes_{v \text{ at index } i \text{ in } L} p[i] \mapsto v$$

where:

$$p[i] \mapsto v \equiv (p + i) \mapsto v$$

Representation predicate for ML arrays:

$$p \rightsquigarrow \text{Array } L \equiv p.\text{length} \mapsto |L| \star \bigotimes_{v \text{ at index } i \text{ in } L} p[i] \mapsto v$$

where  $p.\text{length} \mapsto n$  and  $p[i] \mapsto v$  are abstract definitions for the user.

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## Small footprint specifications of array operations

$i \in \text{dom } L \Rightarrow$

$$\{p \rightsquigarrow \text{Array } L\} (\text{Array.get } i \text{ } p) \{ \lambda x. [x = L[i]] \star p \rightsquigarrow \text{Array } L \}$$

$$\{p \rightsquigarrow \text{Array } L\} (\text{Array.set } i \text{ } p \text{ } v) \{ \lambda \_. p \rightsquigarrow \text{Array } (L[i := v]) \}$$

$$\{p \rightsquigarrow \text{Array } L\} (\text{Array.length } p) \{ \lambda n. [n = |L|] \star p \rightsquigarrow \text{Array } L \}$$

Exercise: give small footprint specifications for array operations.

How to derive the large footprint specifications from them?

$$\{p[i] \mapsto v\} (\text{Array.get } i \text{ } p) \{ \lambda x. [x = v] \star p[i] \mapsto v \}$$

$$\{p[i] \mapsto -\} (\text{Array.set } i \text{ } p) \{ \lambda \_. p[i] \mapsto v \}$$

$$\{p.\text{length} \mapsto n\} (\text{Array.length } p) \{ \lambda x. [x = n] \star p.\text{length} \mapsto n \}$$

$$\begin{aligned} p \rightsquigarrow \text{Array } L &= p[i] \mapsto L[i] \\ &\star p.\text{length} \mapsto |L| \\ &\star \bigotimes_{v \text{ at index } j \text{ in } L} p[j] \mapsto v \\ &\quad \text{with } j \neq i \end{aligned}$$

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## Access to a memory cell

In C, record and array accesses are treated uniformly:

$$p.\text{hd} = v \quad \text{compiles to} \quad *(p+\text{hd})=v$$

$$p[i] = v \quad \text{compiles to} \quad *(p+i)=v$$

Common small footprint specification for accessing a memory cell:

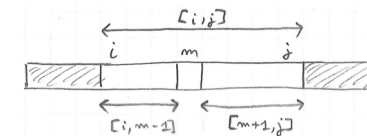
$$\{p \mapsto -\} (*p = v) \{ \lambda \_. p \mapsto v \}$$

$$\{p \mapsto v\} (*p) \{ \lambda x. [x = v] \star p \mapsto v \}$$

All other specifications for read and write operations are derivable.

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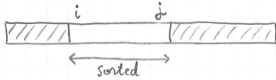
## Quicksort code



```
let rec qsort i j t =
  if j - i > 1 then begin
    let m = pivot i j t in
    qsort i (m-1) t;
    qsort (m+1) j t;
  end
```

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## Large-footprint specification of quicksort



$$\forall p L i j. \quad 0 \leq i \leq j < |L| \Rightarrow$$

$$\left\{ \begin{array}{l} p \rightsquigarrow \text{Array } L \\ (\text{qsort } i \ j \ p) \\ \{\lambda \dots \exists L'. \quad (p \rightsquigarrow \text{Array } L') \\ \quad \star [\text{sortedSeg } i \ j \ L'] \\ \quad \star [\text{permut } L \ L'] \\ \quad \star [\forall a \in [0, i) \cup (j, |L|). \ L'[a] = L[a]] \end{array} \right\}$$

where:  $\text{sortedSeg } i \ j \ L' \equiv \forall a, b \in [i, j]. \ a \leq b \Rightarrow L'[a] \leq L'[b]$ .

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## Group of array cells

Definition  $p \rightsquigarrow \text{Cells } M \equiv \bigotimes_{(i,v) \in M} p[i] \mapsto v$

where  $M$  has type "map int  $A$ ", for some  $A$ .

Conversions:

$$p \rightsquigarrow \text{Array } L = p.\text{length} \mapsto |L| \star p \rightsquigarrow \text{Cells } (\text{mapOfList } L)$$

$$p \rightsquigarrow \text{Cells } \emptyset = []$$

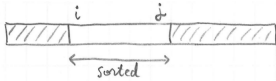
$$p \rightsquigarrow \text{Cells } \{(i, v)\} = p[i] \mapsto v$$

$$p \rightsquigarrow \text{Cells } (M_1 \uplus M_2) = p \rightsquigarrow \text{Cells } M_1 \star p \rightsquigarrow \text{Cells } M_2 \quad (\text{when } M_1 \perp M_2)$$

where:  $\text{mapOfList } L \equiv \{(i, v) \mid v \text{ at index } i \text{ in } L\}$ .

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## Small-footprint specification of quicksort



Exercise: give a small-footprint specification for quicksort.

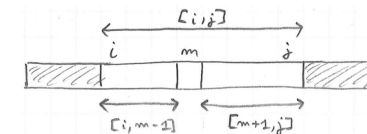
- ▶ use  $p \rightsquigarrow \text{Cells } M$  with some constraints to describe a segment,
- ▶ use  $\text{sortedSeg } i \ j \ M$  to assert that a segment is sorted,
- ▶ use  $\text{permut } M \ M'$  to assert that values in a segment are permuted.

$$\forall p M i j. \quad \text{dom } M = [i, j] \Rightarrow$$

$$\left\{ \begin{array}{l} p \rightsquigarrow \text{Cells } M \\ (\text{qsort } i \ j \ p) \\ \{\lambda \dots \exists M'. \quad p \rightsquigarrow \text{Cells } M' \\ \quad \star [\text{sortedSeg } i \ j \ M'] \\ \quad \star [\text{permut } M \ M'] \end{array} \right\}$$

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## Segment splitting in Quicksort



Assume  $\text{dom } M = [i, j]$  with  $j - i > 1$ . Then:

$$p \rightsquigarrow \text{Cells } M = p \rightsquigarrow \text{Cells } (M_{|[i, m-1]})$$

$$\star p \rightsquigarrow \text{Cells } (M_{|[m, m]})$$

$$\star p \rightsquigarrow \text{Cells } (M_{|[m+1, j]})$$

Note that:

$$p \rightsquigarrow \text{Cells } (M_{|[m, m]}) = p[m] \mapsto M[m]$$

In recursive calls, we frame over the cells that are not involved.

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## Operations on groups of cells

Convenient specifications for operating directly on groups of cells:

$i \in \text{dom } M \Rightarrow$

$\{p \rightsquigarrow \text{Cells } M\} (\text{Array.get } i \text{ } p) \{\lambda x. [x = M[i]] \star p \rightsquigarrow \text{Cells } M\}$

$\{p \rightsquigarrow \text{Cells } M\} (\text{Array.set } i \text{ } p \text{ } v) \{\lambda \_. p \rightsquigarrow \text{Cells } (M[i := v])\}$

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## Summary

Representation of a full array using a list:

$$p \rightsquigarrow \text{Array } L \equiv p.\text{length} \mapsto |L| \star \bigotimes_{v \text{ at index } i \text{ in } L} p[i] \mapsto v$$

Small footprint accesses:

$\{p[i] \mapsto -\} (\text{Array.get } i \text{ } p) \{\lambda \_. p[i] \mapsto v\}$

$\{p[i] \mapsto v\} (\text{Array.set } i \text{ } p \text{ } v) \{\lambda x. [x = v] \star p[i] \mapsto v\}$

$\{p.\text{length} \mapsto n\} (\text{Array.length } p) \{\lambda x. [x = n] \star p.\text{length} \mapsto n\}$

Representation of a set of array cells using a finite map:

$$p \rightsquigarrow \text{Cells } M \equiv \bigotimes_{(i,v) \in M} p[i] \mapsto v$$

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## Chapter 9

### Heap entailment

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## Definition of Hprop

Let:

$$\text{Hprop} \equiv \text{Heap} \rightarrow \text{Prop}$$

For example:

$$[] : \text{Hprop}$$

$$l \mapsto v : \text{Hprop}$$

$$H_1 \star H_2 : \text{Hprop}$$

In particular:

$$(\star) : \text{Hprop} \rightarrow \text{Hprop} \rightarrow \text{Hprop}$$

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## The separation algebra

Associativity:  $(H_1 \star H_2) \star H_3 = H_1 \star (H_2 \star H_3)$

Commutativity:  $H_1 \star H_2 = H_2 \star H_1$

Neutral element:  $H \star [] = H$

Extrusion of existentials:  $(\exists x. H_1) \star H_2 = \exists x. (H_1 \star H_2)$  (if  $x \notin H_2$ )

Extrusion of pure facts:  $([P] \star H) m = P \wedge (H m)$

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## Extensionality

Functional extensionality:

$$(\forall x. f x = g x) \Rightarrow (f = g) \quad (\text{if } f, g: A \rightarrow B)$$

Propositional extensionality:

$$(P \Leftrightarrow Q) \Rightarrow (P = Q) \quad (\text{if } P, Q: \text{Prop})$$

Predicate extensionality:

$$(\forall x. P x \Leftrightarrow Q x) \Rightarrow (P = Q) \quad (\text{if } P, Q: A \rightarrow \text{Prop})$$

Heap predicate extensionality:

$$(\forall m. H m \Leftrightarrow H' m) \Leftrightarrow (H = H') \quad (\text{if } H, H': \text{Hprop})$$

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## Heap entailment

Definition:

$$H_1 \triangleright H_2 \equiv \forall m. H_1 m \Rightarrow H_2 m$$

For example:

$$(r \mapsto 6) \triangleright \exists n. (r \mapsto n) \star [\text{even } n]$$

Thanks to ( $\triangleright$ ), we never need to manipulate heaps explicitly.

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## Heap entailment as a partial order

$$H_1 \triangleright H_2 \equiv \forall m. H_1 m \Rightarrow H_2 m$$

The relation ( $\triangleright$ ) defines a partial order on the type Hprop:

REFLEXIVITY

$$\frac{}{H \triangleright H}$$

TRANSITIVITY

$$\frac{H_1 \triangleright H_2 \quad H_2 \triangleright H_3}{H_1 \triangleright H_3}$$

ANTISYMMETRY

$$\frac{H_1 \triangleright H_2 \quad H_2 \triangleright H_1}{H_1 = H_2}$$

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## Frame property for heap entailment

$$\frac{H_1 \triangleright H'_1}{H_1 \star H_2 \triangleright H'_1 \star H_2} \text{ENTAIL-FRAME}$$

For example, to prove:

$$(r \mapsto 2) \star (s \mapsto 3) \triangleright (r \mapsto 2) \star (t \mapsto n)$$

it suffices and prove:

$$(s \mapsto 3) \triangleright (t \mapsto n).$$

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## Heap implications: true or false?

1.  $(r \mapsto 3) \star (s \mapsto 4) \triangleright (s \mapsto 4) \star (r \mapsto 3)$  true
2.  $(r \mapsto 3) \triangleright (s \mapsto 4) \star (r \mapsto 3)$  false
3.  $(s \mapsto 4) \star (r \mapsto 3) \triangleright (r \mapsto 4)$  false
4.  $(s \mapsto 4) \star (r \mapsto 3) \triangleright (r \mapsto 3)$  false
5.  $[\text{False}] \star (r \mapsto 3) \triangleright (s \mapsto 4) \star (r \mapsto 4)$  true
6.  $(r \mapsto 4) \star (s \mapsto 3) \triangleright [\text{False}]$  false
7.  $(r \mapsto 4) \star (r \mapsto 3) \triangleright [\text{False}]$  true
8.  $(r \mapsto 3) \star (r \mapsto 3) \triangleright [\text{False}]$  true

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## Instantiation of existentials and propositions

$$(r \mapsto 6) \triangleright (\exists n. (r \mapsto n) \star [\text{even } n])$$

To prove the above, we exhibit an even number  $n$  for which  $r \mapsto n$ .

Rules:

$$\frac{H_1 \triangleright ([x \rightarrow v] H_2)}{H_1 \triangleright (\exists x. H_2)} \text{EXISTS-R} \quad \frac{(H_1 \triangleright H_2) \quad P}{H_1 \triangleright (H_2 \star [P])} \text{PROP-R}$$

Example:

$$\frac{\frac{\frac{\overline{(r \mapsto 6) \triangleright (r \mapsto 6)} \text{REFL} \quad \overline{\text{even } 6} \text{MATH}}{(r \mapsto 6) \triangleright (r \mapsto 6) \star [\text{even } 6]} \text{PROP-R}}{(r \mapsto 6) \triangleright [n \rightarrow 6] ((r \mapsto n) \star [\text{even } n])} \text{SUBST}}{(r \mapsto 6) \triangleright \exists n. (r \mapsto n) \star [\text{even } n]} \text{EXISTS-R}$$

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## Extraction of existentials and propositions

$$(\exists n. [\text{even } n] \star (r \mapsto n)) \triangleright (\exists m. [\text{even } m] \star (r \mapsto m + 2))$$

To prove the above, we show that for any even number  $n$ , we have:

$$(r \mapsto n) \triangleright \exists m. [\text{even } m] \star (r \mapsto m + 2)$$

Reasoning rules:

$$\frac{\forall x. (H_1 \triangleright H_2)}{(\exists x. H_1) \triangleright H_2} \text{EXISTS-L} \quad \frac{P \Rightarrow (H_1 \triangleright H_2)}{([P] \star H_1) \triangleright H_2} \text{PROP-L}$$

Same with explicit proof contexts:

$$\frac{\Gamma, x : A \vdash H_1 \triangleright H_2}{\Gamma \vdash (\exists(x : A). H_1) \triangleright H_2} \text{(} x \neq H_2 \text{)} \quad \frac{\Gamma, h : P \vdash H_1 \triangleright H_2}{\Gamma \vdash ([P] \star H_1) \triangleright H_2}$$

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## Heap implications: true or false?

- |  |       |
|--|-------|
| 1. $(r \mapsto 3) \triangleright \exists n. (r \mapsto n)$   | true  |
| 2. $\exists n. (r \mapsto n) \triangleright (r \mapsto 3)$   | false |
| 3. $\exists n. (r \mapsto n) \star [n > 0] \triangleright \exists n. [n > 1] \star (r \mapsto (n - 1))$    | true  |
| 4. $(r \mapsto 3) \star (s \mapsto 3) \triangleright \exists n. (r \mapsto n) \star (s \mapsto n)$         | true  |
| 5. $\exists n. (r \mapsto n) \star [n > 0] \star [n < 0] \triangleright (r \mapsto n) \star (r \mapsto n)$ | true  |

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## Proving heap entailment relations

Systematic approach to dealing with heap entailment:

1. extract from left hand side,
2. instantiate in right hand side,
3. cancel equal predicates on both sides.

Example:

$$\frac{}{a : \text{int}, a > 5 \vdash (r \mapsto 3) \star (s \mapsto a) \triangleright (r \mapsto 3) \star (s \mapsto a)}$$

$$\frac{}{a : \text{int}, a > 5 \vdash (r \mapsto 3) \star (s \mapsto a) \triangleright (r \mapsto 3) \star (s \mapsto 3 + (a - 3))}$$

$$\frac{}{a : \text{int}, a > 5 \vdash (r \mapsto 3) \star (s \mapsto a) \triangleright \exists m. (r \mapsto 3) \star (s \mapsto 3 + m)}$$

$$\frac{}{a : \text{int}, a > 5 \vdash (r \mapsto 3) \star (s \mapsto a) \triangleright \exists nm. (r \mapsto n) \star (s \mapsto n + m)}$$

$$\frac{}{\emptyset \vdash \exists a. [a > 5] \star (r \mapsto 3) \star (s \mapsto a) \triangleright \exists nm. (r \mapsto n) \star (s \mapsto n + m)}$$

$$\frac{}{\emptyset \vdash (r \mapsto 3) \star \exists a. [a > 5] \star (s \mapsto a) \triangleright \exists nm. (s \mapsto n + m) \star (r \mapsto n)}$$

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## Summary

( $\star$ ) is associative, commutative, and has  $[\ ]$  as neutral element.

Existentials and pure facts may be extruded from stars.

( $\triangleright$ ) is a partial order, satisfying the frame property.

" $[\text{False}] \triangleright H$ " is always true.

" $(r \mapsto n) \star (r \mapsto m)$ " is equivalent to " $[\text{False}]$ ".

Strategy: extract from the right, instantiate on the left, then cancel out.

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## Chapter 10

### Structural rules

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## Frame rule

$$\frac{\{H_1\} t \{\lambda x. H'_1\}}{\{H_1 \star H_2\} t \{\lambda x. H'_1 \star H_2\}}$$

Reformulation:

$$\frac{\{H_1\} t \{Q_1\}}{\{H_1 \star H_2\} t \{Q_1 \star H_2\}} \text{ FRAME}$$

with the overloading:

$$Q \star H \equiv \lambda x. (Q x \star H)$$

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## Consequence rule

$$\frac{H \triangleright H' \quad \{H'\} t \{Q'\} \quad Q' \triangleright Q}{\{H\} t \{Q\}} \text{ CONSEQUENCE}$$

with the overloading:

$$Q' \triangleright Q \equiv \forall x. (Q' x \triangleright Q x)$$

Note that  $H$  and  $H'$  must cover the same set of memory cells, that is, no garbage collection is allowed here. Similarly for  $Q$  and  $Q'$ .

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## Recall the need for garbage collection

```
let myref x =
  let r = ref x in
  let s = ref r in
  r
```

From:

$$\{\{\}\} (\text{myref } x) \{\lambda r. r \mapsto x \star \exists s. s \mapsto r\}$$

To:

$$\{\{\}\} (\text{myref } x) \{\lambda r. r \mapsto x\}$$

Can the following rule be used?

$$\frac{\{H\} t \{Q \star H'\}}{\{H\} t \{Q\}} \text{ GC-POST'}$$

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## Garbage collection rule

$$\frac{\{H\} t \{Q \star \text{GC}\}}{\{H\} t \{Q\}} \text{ GC-POST} \quad \text{where: } \text{GC} \equiv \exists H'. H'$$

Same as:

$$\frac{\{H\} t \{\lambda x. (Q x \star \exists H'. H')\}}{\{H\} t \{Q\}}$$

Observe that  $H'$  may depend on the return value  $x$ :

For  $(\lambda r. r \mapsto x \star \exists s. s \mapsto r)$ , we may instantiate  $H'$  as  $(\exists s. s \mapsto r)$ .

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## Garbage collection in the pre-condition

$$\frac{\{H\} t \{Q\}}{\{H \star GC\} t \{Q\}} \text{GC-PRE} \quad \frac{\{H\} t \{Q\}}{\{H \star H'\} t \{Q\}} \text{GC-PRE}'$$

Exercise: show that GC-PRE is derivable from GC-POST and FRAME.

$$\frac{\{H\} t \{Q \star GC\}}{\{H\} t \{Q\}} \text{GC-POST} \quad \frac{\{H_1\} t \{Q_1\}}{\{H_1 \star H_2\} t \{Q_1 \star H_2\}} \text{FRAME}$$

Proof:

$$\frac{\frac{\{H\} t \{Q\}}{\{H \star GC\} t \{Q \star GC\}} \text{FRAME}}{\{H \star GC\} t \{Q\}} \text{GC-POST}$$

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## Combined structural rule

$$\frac{H \triangleright H' \quad \{H'\} t \{Q'\} \quad Q' \triangleright Q}{\{H\} t \{Q\}} \text{CONSEQUENCE}$$

$$\frac{\{H\} t \{Q \star GC\}}{\{H\} t \{Q\}} \text{GC-POST} \quad \frac{\{H_1\} t \{Q_1\}}{\{H_1 \star H_2\} t \{Q_1 \star H_2\}} \text{FRAME}$$

$$\frac{H = H_1 \star H_2 \quad \{H_1\} t \{Q_1\} \quad Q_1 \star H_2 = Q}{\{H\} t \{Q\}} \text{FRAME}'$$

$$\frac{H \triangleright H_1 \star H_2 \quad \{H_1\} t \{Q_1\} \quad Q_1 \star H_2 \triangleright Q \star GC}{\{H\} t \{Q\}} \text{COMBINED}$$

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## Extraction of existentials and propositions

$$\{\exists n. (r \mapsto n) \star [\text{even } n]\} (!r) \{\lambda x. \dots\}$$

To prove the above, we need to show that:

$$\forall n. \text{even } n \Rightarrow \{r \mapsto n\} (!r) \{\lambda x. \dots\}$$

Rules:

$$\frac{\forall x. \{H\} t \{Q\}}{\{\exists x. H\} t \{Q\}} \text{EXISTS} \quad \frac{P \Rightarrow \{H\} t \{Q\}}{\{[P] \star H\} t \{Q\}} \text{PROP}$$

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## Application: copying a tree with invariants

Specification of copy for binary trees:

$$\{p \rightsquigarrow \text{Mtree } T\} (\text{copy } p) \{\lambda p'. p \rightsquigarrow \text{Mtree } T \star p' \rightsquigarrow \text{Mtree } T\}$$

Description of complete binary trees:

$$p \rightsquigarrow \text{MtreeComplete } T \equiv \exists n. (p \rightsquigarrow \text{Mtree } T) \star [\text{depth } n T]$$

Exercise: give a specification of copy in terms of MtreeComplete; which rules are used to derive this specification?

$$\{p \rightsquigarrow \text{MtreeComplete } T\} (\text{copy } p) \{\lambda p'. p \rightsquigarrow \text{MtreeComplete } T \star p' \rightsquigarrow \text{MtreeComplete } T\}$$

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## Proof of the derived specification

(1) By unfolding of MtreeComplete:

$$\begin{aligned} & \{\exists n. (p \rightsquigarrow \text{Mtree } T) \star [\text{depth } n T]\} \\ & \text{(copy p)} \\ & \{\lambda p'. \exists n. (p \rightsquigarrow \text{Mtree } T) \star [\text{depth } n T] \} \\ & \star \{\exists n. (p' \rightsquigarrow \text{Mtree } T) \star [\text{depth } n T]\} \end{aligned}$$

(2) By the EXISTS and PROP rules:

$$\begin{aligned} & \forall n. \text{depth } n T \Rightarrow \{p \rightsquigarrow \text{Mtree } T\} \\ & \text{(copy p)} \\ & \{\lambda p'. \exists n. (p \rightsquigarrow \text{Mtree } T) \star [\text{depth } n T] \} \\ & \star \{\exists n. (p' \rightsquigarrow \text{Mtree } T) \star [\text{depth } n T]\} \end{aligned}$$

(3) By the CONSEQUENCE rule:

$$p \rightsquigarrow \text{Mtree } T \star p' \rightsquigarrow \text{Mtree } T \triangleright \begin{aligned} & \exists n. (p \rightsquigarrow \text{Mtree } T) \star [\text{depth } n T] \\ & \star \exists n. (p' \rightsquigarrow \text{Mtree } T) \star [\text{depth } n T] \end{aligned}$$

(4) Conclude using comm., assoc., extrusion, and EXISTS-R and PROP-R.

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## Summary

Structural rules:

$$\frac{H \triangleright H_1 \star H_2 \quad \{H_1\} t \{Q_1\} \quad Q_1 \star H_2 \triangleright Q \star GC}{\{H\} t \{Q\}} \text{ COMBINED}$$

$$\frac{\forall x. \{H\} t \{Q\}}{\{\exists x. H\} t \{Q\}} \text{ EXISTS} \quad \frac{P \Rightarrow \{H\} t \{Q\}}{\{\{P\} \star H\} t \{Q\}} \text{ PROP}$$

Other structural rules are derivable.

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## Chapter 11

### Reasoning rules for terms

## Reasoning rule for sequences

Example:

$$\frac{\{r \mapsto n\} (\text{incr } r) \{\lambda_. r \mapsto n + 1\}}{\{r \mapsto n + 1\} (!r) \{\lambda x. [x = n + 1] \star r \mapsto n + 1\}} \quad \frac{\{r \mapsto n\} (\text{incr } r; !r) \{\lambda x. [x = n + 1] \star r \mapsto n + 1\}}{\{r \mapsto n\} (\text{incr } r; !r) \{\lambda x. [x = n + 1] \star r \mapsto n + 1\}}$$

Exercise: complete the rule for sequences.

$$\frac{\{\dots\} t_1 \{\dots\} \quad \{\dots\} t_2 \{\dots\}}{\{H\} (t_1; t_2) \{Q\}}$$

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## Reasoning rule for sequences

Solution 1:

$$\frac{\{H\} t_1 \{\lambda.. H'\} \quad \{H'\} t_2 \{Q\}}{\{H\} (t_1 ; t_2) \{Q\}}$$

Solution 2:

$$\frac{\{H\} t_1 \{Q'\} \quad \{Q' ()\} t_2 \{Q\}}{\{H\} (t_1 ; t_2) \{Q\}} \text{ SEQ}$$

Remark:  $Q' = \lambda.. H'$  is equivalent to  $Q' () = H'$ .

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## Reasoning rule for let-bindings

Exercise: complete the reasoning rule for let-bindings.

$$\frac{\{\dots\} t_1 \{\dots\} \quad \forall x. (\{\dots\} t_2 \{\dots\})}{\{H\} (\text{let } x = t_1 \text{ in } t_2) \{Q\}}$$

Solution:

$$\frac{\{H\} t_1 \{Q'\} \quad \forall x. \{Q' x\} t_2 \{Q\}}{\{H\} (\text{let } x = t_1 \text{ in } t_2) \{Q\}} \text{ LET}$$

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## Example of let-binding

$$\frac{\{H\} t_1 \{Q'\} \quad \forall x. \{Q' x\} t_2 \{Q\}}{\{H\} (\text{let } x = t_1 \text{ in } t_2) \{Q\}}$$

Exercise: instantiate the rule for let-bindings on the following code.

$$\{r \mapsto 3\} (\text{let } a = !r \text{ in } a+1) \{Q\}$$

Solution:

$$\begin{aligned} H &\equiv (r \mapsto 3) \\ Q &\equiv \lambda x. [x = 4] \star (r \mapsto 3) \\ Q' &\equiv \lambda y. [y = 3] \star (r \mapsto 3) \end{aligned}$$

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## Reasoning rule for values

Example:

$$\{\{\}\} 3 \{\lambda x. [x = 3]\}$$

Rule:

$$\frac{}{\{\{\}\} v \{\lambda x. [x = v]\}} \text{ VAL}$$

Exercise: state a reasoning rule for values using a heap implication.

$$\frac{\dots \triangleright \dots}{\{H\} v \{Q\}}$$

Solution:

$$\frac{H \triangleright Q v}{\{H\} v \{Q\}} \text{ VAL-FRAME}$$

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## Derivability of the val-frame rule

$$\frac{H \triangleright Q v}{\{H\} v \{Q\}} \text{ VAL-FRAME}$$

Proof:

$$\frac{\frac{\frac{\overline{\{[]\} v \{\lambda x. [x = v]\}} \text{ VAL}}{\{H\} v \{\lambda x. [x = v] \star H\}} \text{ FRAME}}{\{H\} v \{Q\}} \text{ CONSEQ}}{\frac{\frac{\overline{H \triangleright Q v} \text{ HYPOTHESIS}}{\forall x. x = v \Rightarrow (H \triangleright Q x)} \text{ SUBST}}{\forall x. ([x = v] \star H) \triangleright (Q x)} \text{ PROP-L}}{(\lambda x. [x = v] \star H) \triangleright Q} \text{ DEF OF } \triangleright}$$

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## Reasoning rule for conditionals

Rule:

$$\frac{(v = \text{true} \Rightarrow \{H\} t_1 \{Q\}) \quad (v = \text{false} \Rightarrow \{H\} t_2 \{Q\})}{\{H\} (\text{if } v \text{ then } t_1 \text{ else } t_2) \{Q\}}$$

Transformation to A-normal form:

$$(\text{if } t_0 \text{ then } t_1 \text{ else } t_2) = (\text{let } v = t_0 \text{ in } (\text{if } v \text{ then } t_1 \text{ else } t_2))$$

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## Reasoning rule for top-level functions

Rule:

$$\frac{v_1 = \lambda x. t \quad \{H\} ([x \rightarrow v_2] t) \{Q\}}{\{H\} (v_1 v_2) \{Q\}}$$

Transformation to A-normal form:

$$(t_1 t_2) = (\text{let } f = t_1 \text{ in let } v = t_2 \text{ in } (f v))$$

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## Verification of a simple function

```
let incr r =
  let a = !r in
  r := a+1
```

Specification:

$$\forall r n. \{r \mapsto n\} (\text{incr } r) \{\lambda \_. r \mapsto n + 1\}$$

Verification:

Fix  $r$  and  $n$ . We need to prove that the body satisfies the specification:

$$\{r \mapsto n\} (\text{let } a = !r \text{ in } r := a+1) \{\lambda \_. r \mapsto n + 1\}$$

We conclude using the let-binding rule:  $Q' \equiv \lambda x. [x = n] \star (r \mapsto n)$ .

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## Reasoning rule for top-level recursive functions

Rule:

$$\frac{v_1 = \mu f. \lambda x. t \quad \{H\} ([f \rightarrow v_1] [x \rightarrow v_2] t) \{Q\}}{\{H\} (v_1 v_2) \{Q\}}$$

Specification of recursive functions may be established by induction.

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## Verification of a recursive function

```
let rec mlength (p:'a cell) =
  if p == null
  then 0
  else let p' = p.tl in
        let n' = mlength p' in
        1 + n'
```

Specification:

$$\forall pL. \{p \rightsquigarrow \text{Mlist } L\} (\text{mlength } p) \{\lambda n. [n = |L|] \star p \rightsquigarrow \text{Mlist } L\}$$

We prove this specification by induction on  $L$ .

Consider  $p$  and  $L$ . Apply the “if” rule.

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## Verification of mlength: nil case

**Case  $p = \text{null}$ .** Goal is:

$$\{p \rightsquigarrow \text{Mlist } L\} (0) \{\lambda n. [n = |L|] \star p \rightsquigarrow \text{Mlist } L\}$$

- Replace  $p$  with  $\text{null}$ .
- Rewrite  $\text{null} \rightsquigarrow \text{Mlist } L$  to  $[L = \text{nil}]$  in the pre and the post.
- By the PROP rule:

$$L = \text{nil} \Rightarrow \{[]\} (0) \{\lambda n. [n = |L|] \star [L = \text{nil}]\}$$

- Replace  $L$  with  $\text{nil}$ .

$$\{[]\} (0) \{\lambda n. [n = |\text{nil}|] \star [\text{nil} = \text{nil}]\}$$

- Apply the VAL-FRAME rule.

$$[] \triangleright [0 = 0] \star [\text{nil} = \text{nil}]$$

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## Verification of mlength: cons case (1/2)

**Case  $p \neq \text{null}$ .** Goal is:

$$\begin{aligned} &\{p \rightsquigarrow \text{Mlist } L\} \\ &(\text{let } p' = p.\text{tl} \text{ in let } n' = \text{mlength } p' \text{ in } 1 + n') \\ &\{\lambda n. [n = |L|] \star p \rightsquigarrow \text{Mlist } L\} \end{aligned}$$

- Unfold Mlist in pre and post, and decompose  $L$  as  $x :: L'$ :

$$p' \rightsquigarrow \text{Mlist } L' \star p \rightsquigarrow \{\text{hd}=x; \text{tl}=p'\}$$

- Apply the let-binding rule, and the read axiom. Remains:

$$\begin{aligned} &\{p' \rightsquigarrow \text{Mlist } L' \star p \rightsquigarrow \{\text{hd}=x; \text{tl}=p'\}\} \\ &(\text{let } n' = \text{mlength } p' \text{ in } 1 + n') \\ &\{\lambda n. [n = |L|] \star p' \rightsquigarrow \text{Mlist } L' \star p \rightsquigarrow \{\text{hd}=x; \text{tl}=p'\}\} \end{aligned}$$

- Apply the frame rule to remove:  $p \rightsquigarrow \{\text{hd}=x; \text{tl}=p'\}$ .
- Apply the let-binding rule with :  $Q \equiv \lambda n'. [n' = |L'|] \star p' \rightsquigarrow \text{Mlist } L'$ .

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## Verification of mlength: cons case (2/2)

There remains to prove the two premises of the let-rule.

– First branch, exploit the induction hypothesis:

$$\{p' \rightsquigarrow \text{Mlist } L'\} \{ \text{mlength } p' \} \{ \lambda n'. [n = |L'|] \star p' \rightsquigarrow \text{Mlist } L' \}$$

– Second branch:

$$\{p' \rightsquigarrow \text{Mlist } L' \star [n' = |L'|]\} (1 + n') \{ \lambda n. [n = |L|] \star p' \rightsquigarrow \text{Mlist } L' \}$$

– Apply the PROP rule and the VAL-FRAME rule.

$$n' = |L'| \Rightarrow p' \rightsquigarrow \text{Mlist } L' \triangleright [1 + n' = |L|] \star p' \rightsquigarrow \text{Mlist } L'$$

– Cancel equal parts, conclude using  $|L| = |x :: L'| = 1 + |L'| = 1 + n'$ .

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## Reasoning rule for local functions

Rule template:

$$\frac{\forall f. (...) \Rightarrow \{H\} t_2 \{Q\}}{\{H\} (\text{let rec } f x = t_1 \text{ in } t_2) \{Q\}}$$

Hypothesis about  $f$ :

$$\forall x H' Q'. \{H'\} t_1 \{Q'\} \Rightarrow \{H'\} (f x) \{Q'\}$$

Rule:

$$\frac{\forall f. (\forall x H' Q'. \{H'\} t_1 \{Q'\} \Rightarrow \{H'\} (f x) \{Q'\}) \Rightarrow \{H\} t_2 \{Q\}}{\{H\} (\text{let rec } f x = t_1 \text{ in } t_2) \{Q\}}$$

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## Summary

$$\overline{\{ [] \} v \{ \lambda x. [x = v] \}}$$

$$\frac{\{H\} t_1 \{Q'\} \quad \forall x. \{Q' x\} t_2 \{Q\}}{\{H\} (\text{let } x = t_1 \text{ in } t_2) \{Q\}}$$

$$\frac{v = \text{true} \Rightarrow \{H\} t_1 \{Q\} \quad v = \text{false} \Rightarrow \{H\} t_2 \{Q\}}{\{H\} (\text{if } v \text{ then } t_1 \text{ else } t_2) \{Q\}}$$

$$\frac{\forall f. (\forall x H' Q'. \{H'\} t_1 \{Q'\} \Rightarrow \{H'\} (f x) \{Q'\}) \Rightarrow \{H\} t_2 \{Q\}}{\{H\} (\text{let rec } f x = t_1 \text{ in } t_2) \{Q\}}$$

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## Summary of Course 2

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## Summary of chapter 7

$$\frac{\{H_1\} t \{\lambda x. H'_1\}}{\{H_1 \star H_2\} t \{\lambda x. H'_1 \star H_2\}} \text{FRAME}$$

In-place mutable list increment, when  $L = x :: L'$ .

$p \rightsquigarrow \text{Mlist } L$	
$p \rightsquigarrow \{\text{hd}=x; \text{tl}=p'\}$	$\star p' \rightsquigarrow \text{Mlist } L'$ by unfolding
$p \rightsquigarrow \{\text{hd}=x+1; \text{tl}=p'\}$	$\star p' \rightsquigarrow \text{Mlist } L'$ incrementing
	$p' \rightsquigarrow \text{Mlist } L'$ frame begins
	$p' \rightsquigarrow \text{Mlist } (\text{map } (+1) L')$ by induction
$p \rightsquigarrow \{\text{hd}=x+1; \text{tl}=p'\}$	$\star p' \rightsquigarrow \text{Mlist } (\text{map } (+1) L')$ frame ends
$p \rightsquigarrow \text{Mlist } ((x+1) :: (\text{map } (+1) L'))$	by folding
$p \rightsquigarrow \text{Mlist } (\text{map } (+1) L)$	by rewriting

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## Summary of chapter 8

Small footprint specification for C-style memory accesses:

$$\begin{aligned} \{p \mapsto w\} (*p = v) &\{ \lambda \_. p \mapsto v \} \\ \{p \mapsto v\} (*p) &\{ \lambda x. [x = v] \star p \mapsto v \} \end{aligned}$$

Representation of a full array using a list:

$$p \rightsquigarrow \text{Array } L \equiv p.\text{length} \mapsto |L| \star \bigotimes_{v \text{ at index } i \text{ in } L} p[i] \mapsto v$$

Representation of a set of array cells using a finite map:

$$p \rightsquigarrow \text{Cells } M \equiv \bigotimes_{(i,v) \in M} p[i] \mapsto v$$

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## Summary of chapter 9

$(\star)$  is associative, commutative, and has  $[\ ]$  as neutral element.

$(\triangleright)$  is a partial order, regular w.r.t.  $(\star)$ .

" $[\text{False}] \triangleright H$ " is always true.

" $(r \mapsto n) \star (r \mapsto m)$ " is equivalent to " $[\text{False}]$ ".

Strategy: extract from the right, instantiate on the left, then cancel out.

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## Summary of chapter 10

Structural rules:

$$\frac{H \triangleright H_1 \star H_2 \quad \{H_1\} t \{Q_1\} \quad Q_1 \star H_2 \triangleright Q \star \text{GC}}{\{H\} t \{Q\}} \text{COMBINED}$$

$$\frac{\forall x. \{H\} t \{Q\}}{\{\exists x. H\} t \{Q\}} \text{EXISTS} \quad \frac{P \Rightarrow \{H\} t \{Q\}}{\{\{P\} \star H\} t \{Q\}} \text{PROP}$$

Other structural rules are derivable.

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## Summary of chapter 11

$$\overline{\{\ [] \} v \{ \lambda x. [x = v] \}}$$

$$\frac{\{H\} t_1 \{Q'\} \quad \forall x. \{Q' x\} t_2 \{Q\}}{\{H\} (\text{let } x = t_1 \text{ in } t_2) \{Q\}}$$

$$\frac{v = \text{true} \Rightarrow \{H\} t_1 \{Q\} \quad v = \text{false} \Rightarrow \{H\} t_2 \{Q\}}{\{H\} (\text{if } v \text{ then } t_1 \text{ else } t_2) \{Q\}}$$

$$\frac{\forall f. (\forall x H' Q'. \{H'\} t_1 \{Q'\} \Rightarrow \{H'\} (f x) \{Q'\}) \Rightarrow \{H\} t_2 \{Q\}}{\{H\} (\text{let rec } f x = t_1 \text{ in } t_2) \{Q\}}$$

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## Exercises

- Exam from 2015, Exercise 2: Operations on binary search trees.

Available from the webpage of the course.

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The end!

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