Towards Formal Verification of Memory Management Properties using Separation Logic

Nicolas Marti
University of Tokyo

Reynald Affeldt
AIST-RCIS

Akinori Yonezawa
University of Tokyo
AIST-RCIS

Research Project

- Verification of low-level software:
  - Specialized operating systems
  - Device drivers
- Difficulties:
  - Memory management
  - Hardware-dependent specifications
- Our approach:
  - Verification in the Coq proof assistant [INRIA, 1984-2005]
  - Using Separation Logic [Reynolds et al., 1999-2005]

This Presentation

- Use-case:
  - The Topsy operating system:
    - Specialized o.s. for network cards [Ruf, ANTA 2003]
    - Also used for educational purpose (in Swiss)
  - Verification of memory isolation:
    - Intuitively, "user-level threads cannot access kernel-level memory" [Bevier, IEEE Trans. 1988]
    - Obvious relation with security:
      - E.g., a user application replacing the process descriptor of an authentication server
- Coq implementation overview

Outline

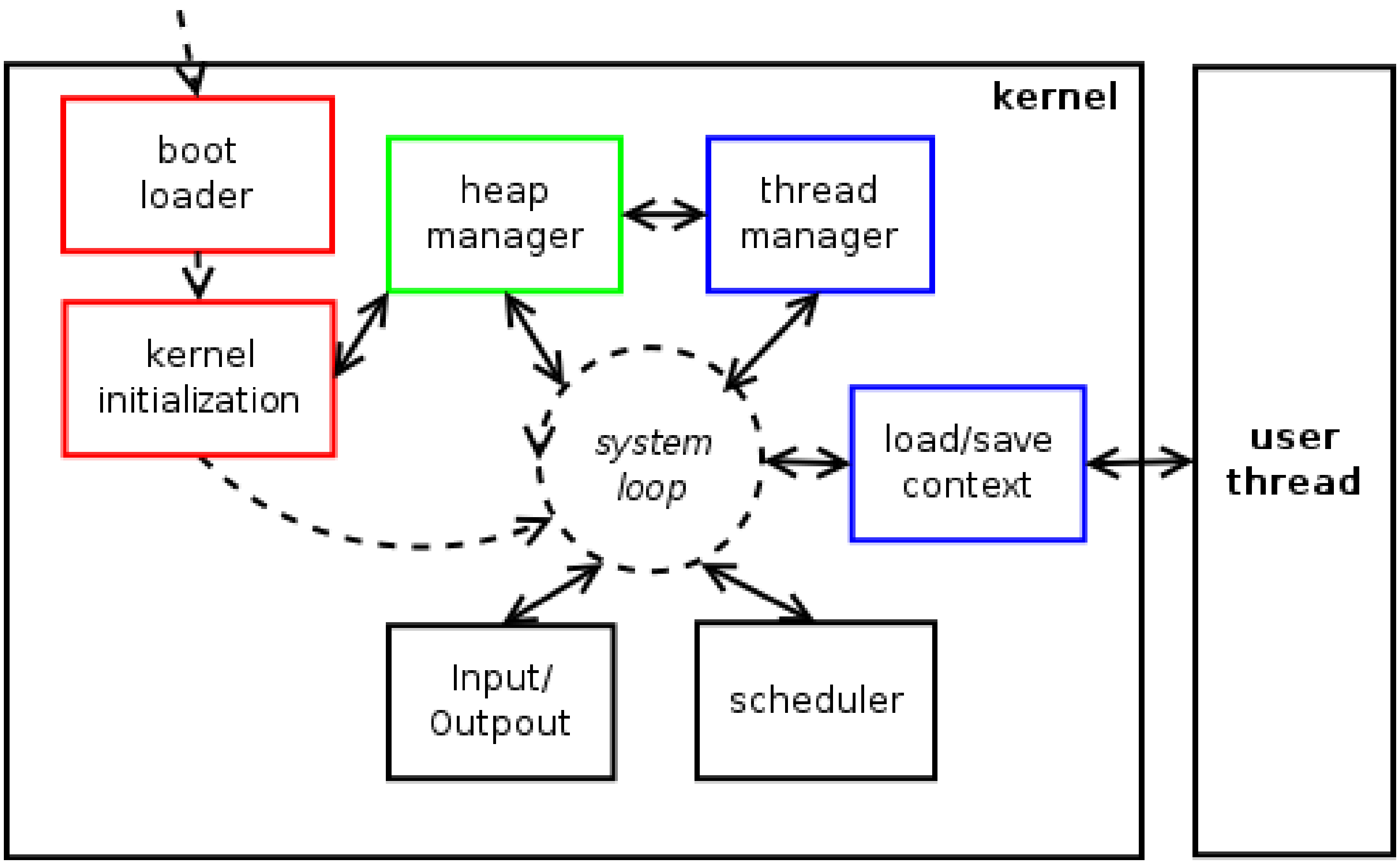
- Memory Isolation for Topsy
  - Specification Approach
  - Informal Specification
- Excerpt of Formal Verification
  - The Allocation Function
  - Formal Specification and Verification
- Coq Implementation
- Related and Future Work

Memory Isolation for Topsy

- Reminder:
  - “user-level threads cannot access kernel-level memory”
- In practice (for x86 processors):
  - Each thread and segment is given a privilege level
  - The hardware guarantees that user-level threads can only access user-level segments…
    …<u>under the hypothesis</u> that the operating system correctly manages privilege levels!

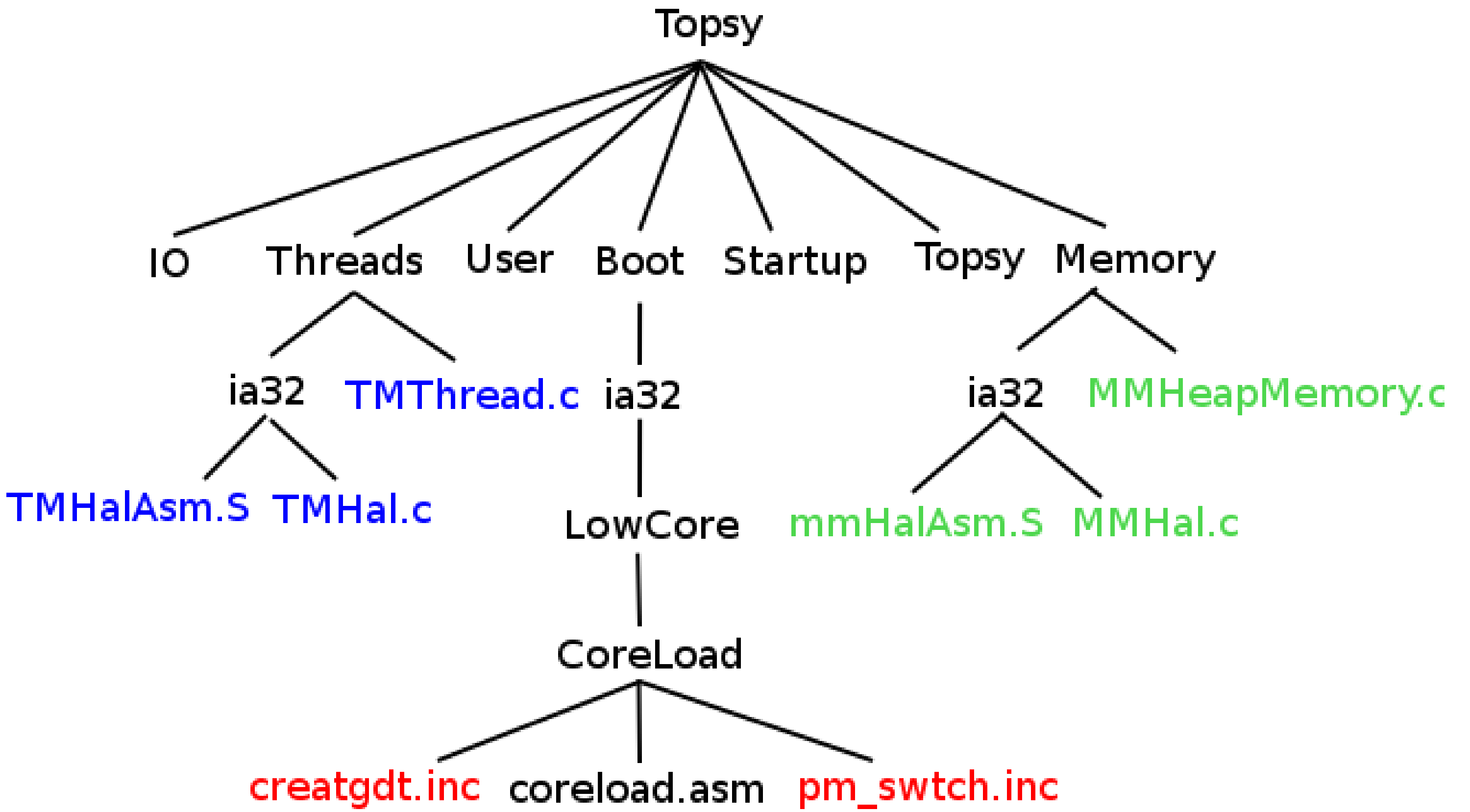
Where do We Need to Look?

- Topsy control-flow:



What do We Need to Verify?

- Topsy source code:



Memory Isolation for Topsy

- Informal specification:

See paper and website for details

  - Boot loader and kernel initialization:
    - The boot loader builds the intended memory model and the processor runs in segmented mode

Next slides

  - Heap manager:
    - Newly allocated blocks do not override previously allocated blocks and only free blocks are marked as such

See paper and website for details

  - Thread manager:
    - Thread descriptors for user-level threads are initialized with user privilege and context switching preserves this privilege

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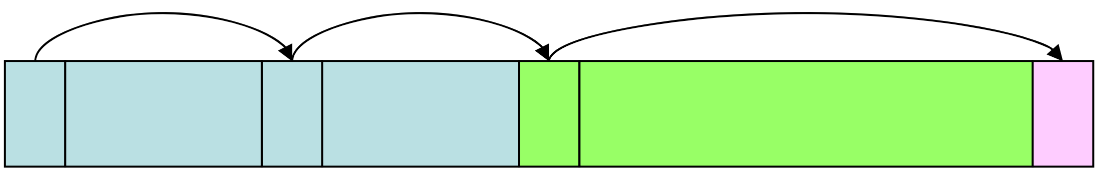
The Allocation Function

- Signature:

```
hmAlloc (y, sizey);
```

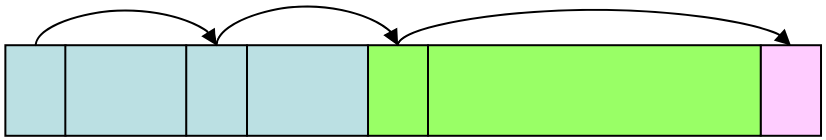
- The underlying data structure:
  - Blocks organized as a list
    - E.g., a heap-list with two free blocks and one allocated block:



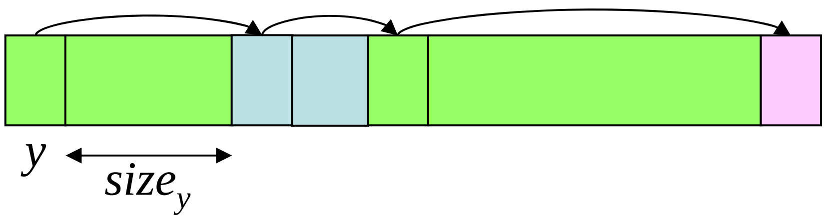
  - The “heap-list” covers a fixed region of memory reserved by the kernel

hmAlloc: Implementation

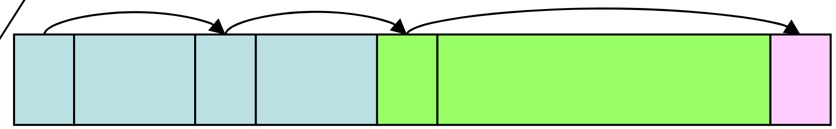
- Overall effect:



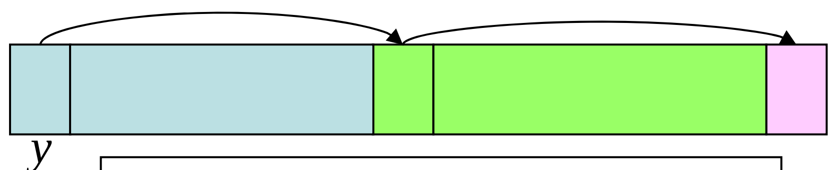
```
hmAlloc (y, sizey);
```




```
/* look for a large-enough block */
y = findFree (sizey);
```



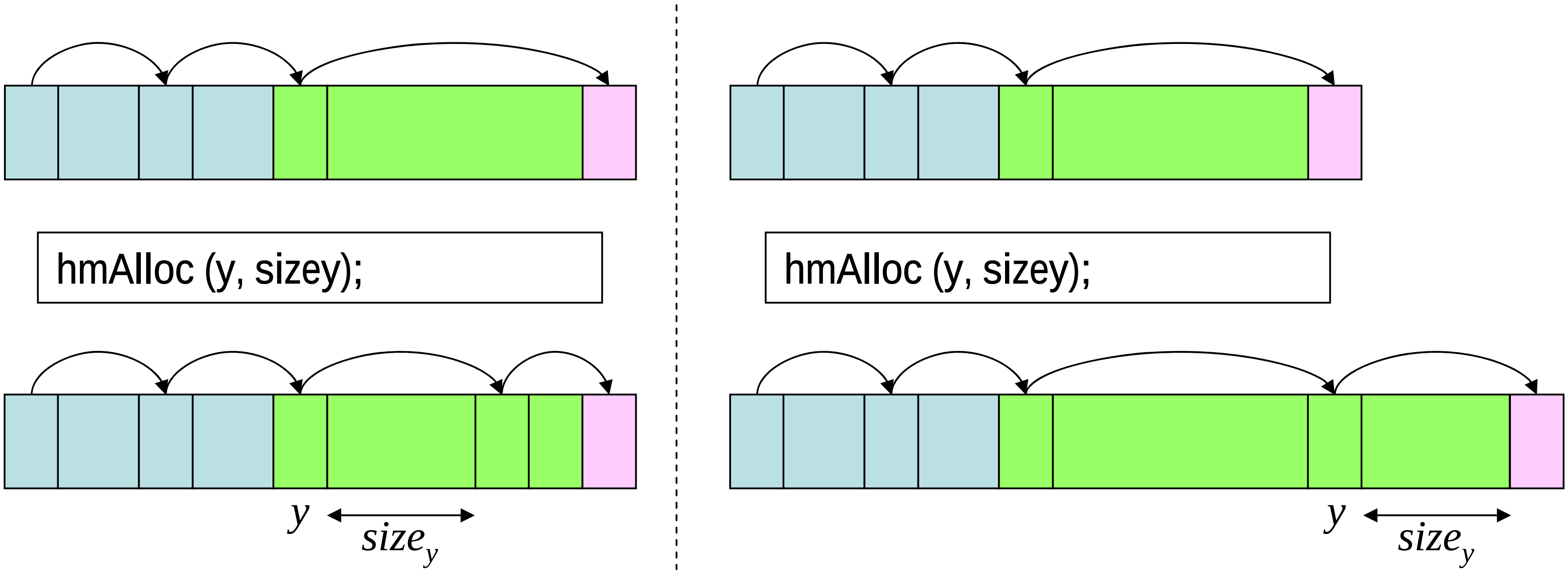
```
/* if not found, compact and
search again */
if (y == 0) {
  compact();
  y = findFree (sizey);
}
```




```
if (y == 0)
   return ERROR;
/* split the found block to the
appropriate size */
split (y, sizey);
```

Potential Problems Relevant to Memory Isolation

- Unexpected situations:



$\Rightarrow$Separation logic [Reynolds et al., 1999-2005] provides convenient formulas for such specifications

Separation Logic Formulas

- Provides a symbolic representation of memory storage:
  - Atoms:
    - E.g., $(l_0 \mapsto e_0)$
  - Separating conjunction:
    - P $*$ Q holds when the storage can be split into two parts that respectively satisfy P and Q
    - E.g., $(l_0 \mapsto e_0) * (l_1 \mapsto e_1)$ does not hold if $l_o = l_1$
  - Neutral: emp

The Heap-list Predicate

- The Array predicate:
  - An array is a set of contiguous locations
- The Heap-list predicate:
  - Inductively, a heap-list is either:
    - An empty list, or
    - A free block followed by a heap-list, or
    - An allocated block followed by a heap-list

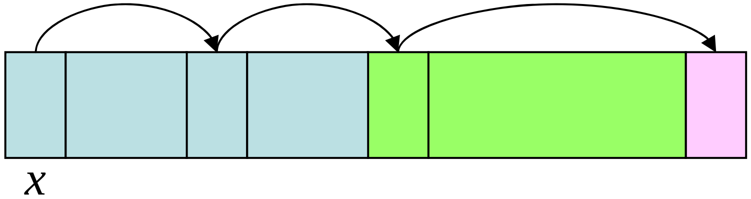
<u>Formal predicates:</u>

$$\text{Array } l\ sz =$$
$$(sz = 0 \wedge \text{emp}) \vee$$
$$(sz > 0 \wedge ((\exists e.l \mapsto e) * (\text{Array } (l+1)\ (sz-1))))$$

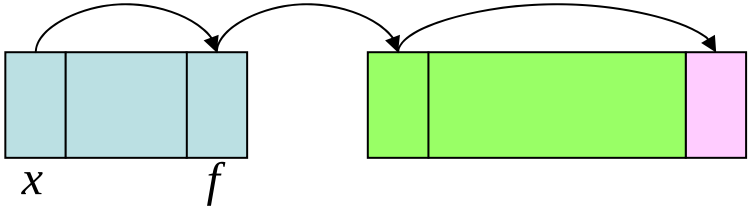
$$\text{Heap-list } l =$$
$$\exists st.(l \mapsto st, nil) \vee$$
$$\exists next.(next \neq nil) \wedge (l \mapsto free, next) *$$
$$(\text{Array } (l+2)\ (next-l-2)) * (\text{Heap-list } next) \vee$$
$$\exists next.(next \neq nil) \wedge (l \mapsto allocated, next) *$$
$$(\text{Array } (l+2)\ (next-l-2)) * (\text{Heap-list } next)$$

The Heap-List Predicate (cont'd)

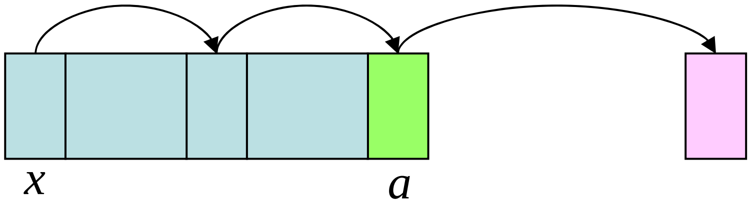
- Heap-lists "with holes":
  - Heap-List $A\ F\ x$ holds for a heap-list without the blocks in A or F
  - E.g.:
    - Heap-List $\{\}\ \{\}\ x$ holds for



    - Heap-List $\{\}\ \{f\}\ x$ holds for



    - Heap-List $\{a\}\ \{\}\ x$ holds for



Formal Specification of hmAlloc

$$\{\text{Heap-List}\ \{x\}\{\}\ hm\_base * \text{Array}\ x\ size_x\}$$

$$\text{hmAlloc}\ (y, size_y);$$

$$\left\{\begin{array}{l} \exists size.size \geq size_y \wedge \\ \text{Heap-List}\ \{x, y\}\{\}\ hm\_base * \text{Array}\ x\ size_x * \text{Array}\ y\ size \\ \qquad\qquad\qquad\qquad \vee \\ y = 0 \wedge \text{Heap-List}\ \{x\}\{\}\ hm\_base * \text{Array}\ x\ size_x \end{array}\right\}$$

Proof Overview (1/2)

$$\{\text{Heap-List}\ \{x\}\{\}\ hm\_base * \text{Array}\ x\ size_x\}$$

$$y = \text{findFree}(size_y);$$

$$\text{if}\ (y == 0)\ \{$$

$$\quad \text{compact}();$$

$$\quad y = \text{findFree}(size_y);$$

$$\}$$

$$\left\{\begin{array}{l} \exists size. size \geq size_y \wedge \\ \text{Heap-List}\ \{x\}\{y\} hm\_base * \text{Array}\ x\ size_x * \text{Array}\ y\ size \\ \vee \\ y = 0 \wedge \text{Heap-List}\ \{x\}\{\} hm\_base * \text{Array}\ x\ size_x \end{array}\right\}$$

Proof Overview (2/2)

$$\left\{\begin{array}{c}\exists size.size \geq size_y \wedge \\ \text{Heap-List}\,\{x\}\{y\} hm\_base * \text{Array}\ x\ size_x * \text{Array}\ y\ size \\ \vee \\ y = 0 \wedge \text{Heap-List}\,\{x\}\{\} hm\_base * \text{Array}\ x\ size_x \end{array}\right\}$$

if ($y == 0$) {
  return ERROR;
}
split (y, $size_y$);

$$\left\{\begin{array}{c}\exists size.size \geq size_y \wedge \\ \text{Heap-List}\,\{x, y\}\{\}\ hm\_base * \text{Array}\ x\ size_x * \text{Array}\ y\ size \\ \vee \\ y = 0 \wedge \text{Heap-List}\,\{x\}\{\}\ hm\_base * \text{Array}\ x\ size_x \end{array}\right\}$$

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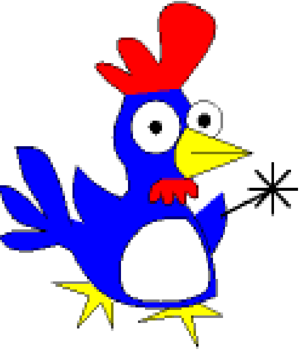
Coq Implementation

Next slide

- Reusable part (around 6500 lines):
  - Core separation logic
    [Reynolds, LICS 2002]
  - Additional facilities
    - Data structures, lemmas, etc.

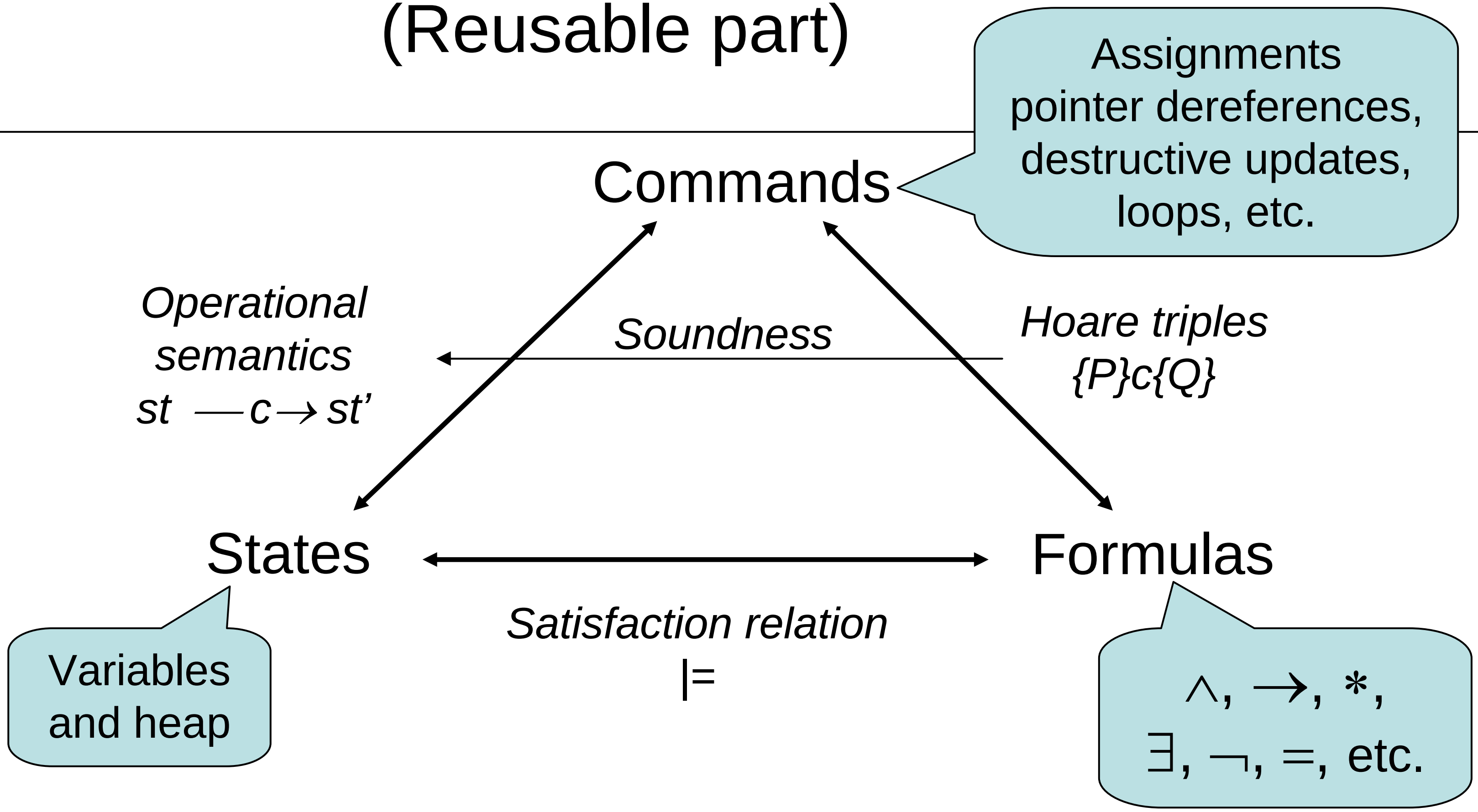
Overview in previous slides

- Use-case part (around 4500 lines):
  - Translation of Topsy functions
    - C and assembly code (around 300 lines)
  - Specification and verification
    - In progress (some elementary steps left out for lack of time)



Coq Implementation
(Reusable part)

Core separation logic



Additional facilities

Data structures (arrays, lists),
lemmas (split, concatenation, insertion, etc.),
weakest preconditions generator (triples for backward reasoning),
frame rule (for compositional reasoning),
tactics for heap partitions

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Related Work

- Proof assistant-based verification:
  - Verification of micro-kernels:
    - Delta-core [Zhu et al., O.S.Review 2001]
      - Commercial o.s. verified in PowerEpsilon
      - Verification of error-recovery of system calls
    - VFiasco [Hohmuth and Tews, ECOOP-PLOS 2005]
      - C++ translation into PVS
  - Verification of C programs:
    - Schorr-Waite algorithm in Coq [Hubert and Marche, SEFM 2005]
  - Separation logic encoding:
    - In Isabelle [Weber, CSL 2004]
- Verification using separation logic:
  - Decidable fragment [Berdine et al., FSTTCS 2004]
  - Symbolic evaluator [Berdine et al., APLAS 2005]

Future Work

- Implementation in progress:
  - Complete libraries of lemmas for data structures
  - Polish verification of memory isolation for Topsy
- Automate verification:
  - Interface with the symbolic evaluator of [Berdine et al., APLAS 2005]:
    - Verification of their implementation as a side-effect
  - Semi-automatic generation of loop invariants
  - Interface with theorem provers for BI logic?

Conclusion

- We have presented:
  - A reusable implementation of separation logic in the Coq proof assistant
  - A real-world use-case: memory isolation for the Topsy operating system
    - Overview of memory allocation, see the paper and the website for the rest of the verification (boot loader, memory and thread management)