Encoding Separation Logic in Coq and Its Application

Reynald Affeldt
AIST-RCIS

Nicolas Marti
University of Tokyo

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

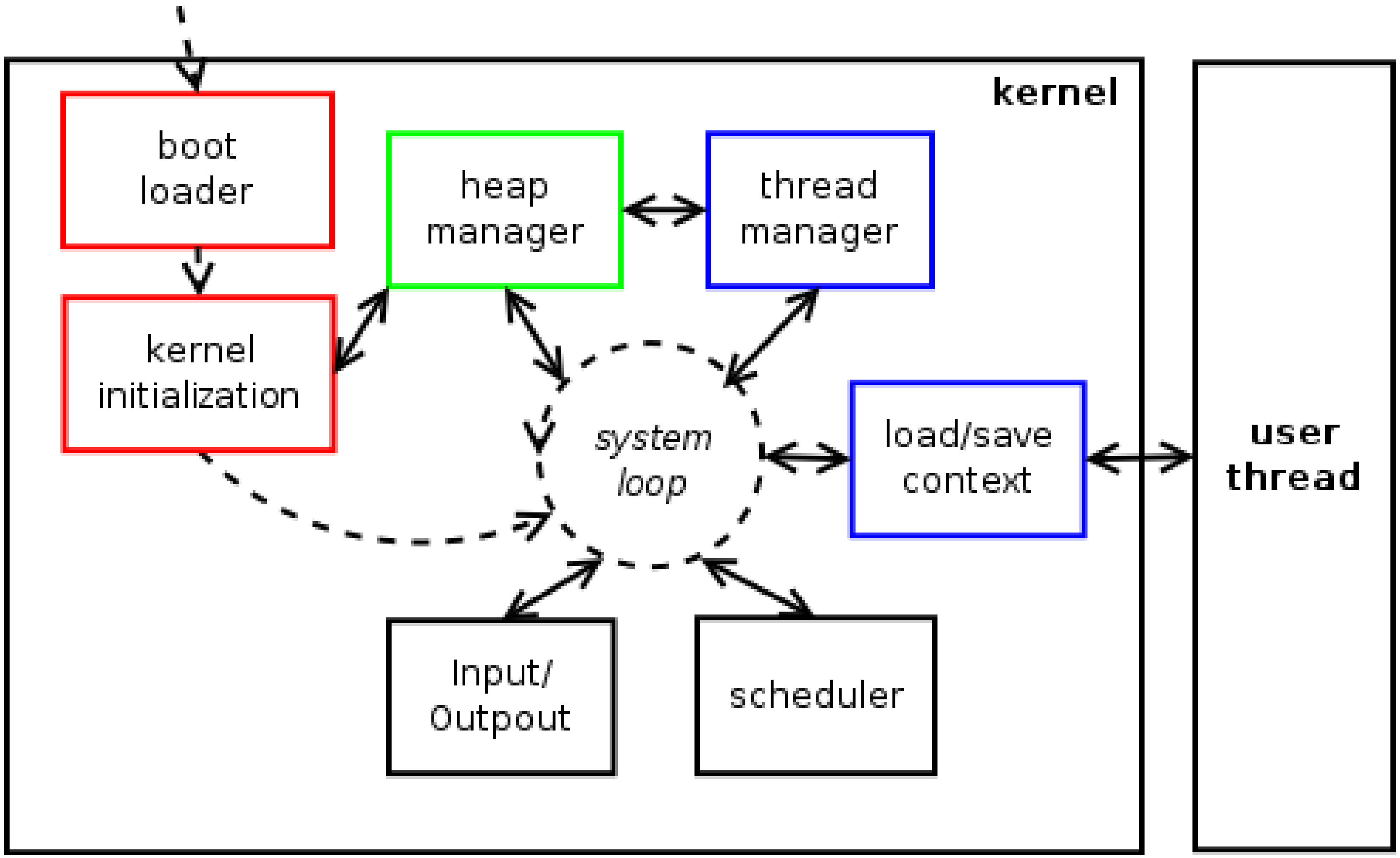
- Memory Isolation for Topsy
  - Specification Approach
  - Informal Specification
- Excerpt of Formal Verification
  - The Allocation Function
  - Formal Specification and Verification
- Coq Implementation
- Related and Future Work

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!

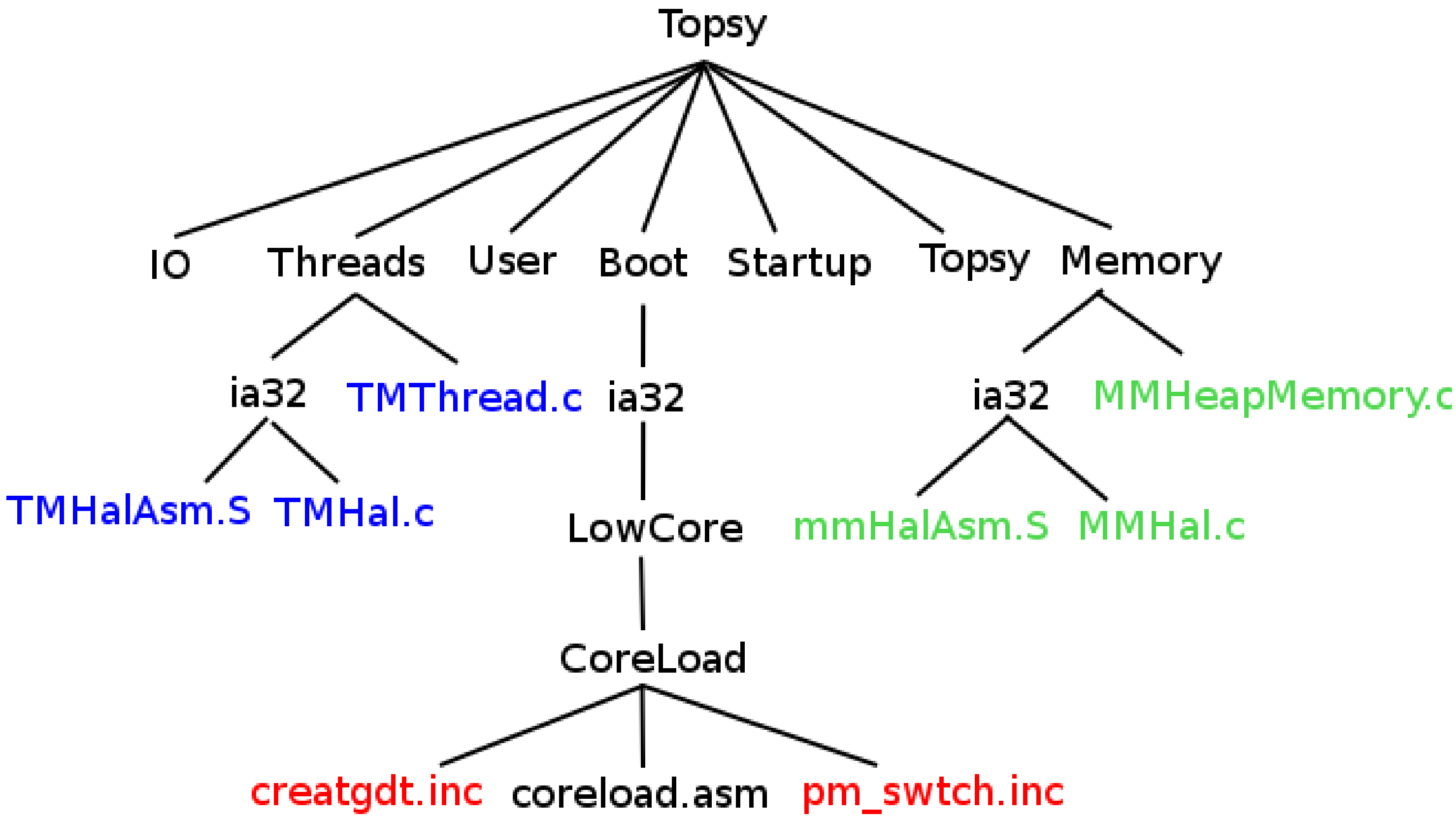
Where do We Need to Look?

- 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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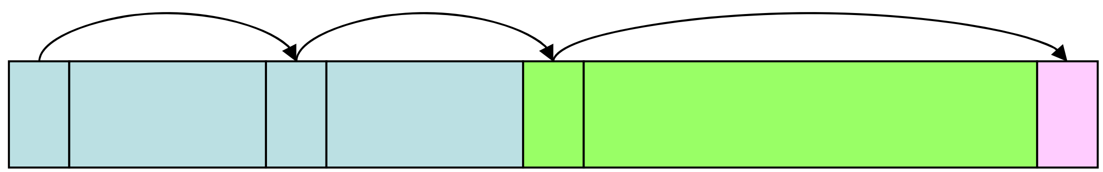
The Allocation Function

- Signature:

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

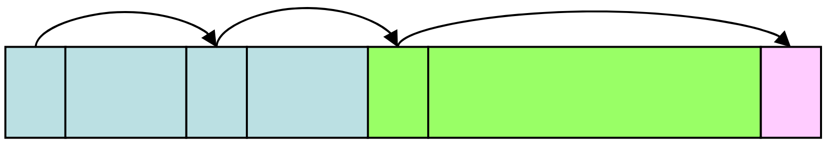
- The underlying data structure:
  - Blocks organized as a list
    - E.g., a heap-list with two free blocks and one allocated block:



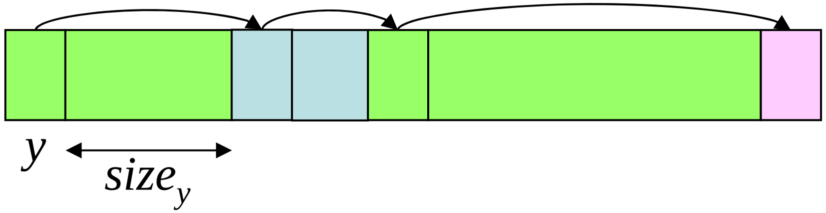
  - The “heap-list” covers a fixed region of memory reserved by the kernel

hmAlloc: Implementation

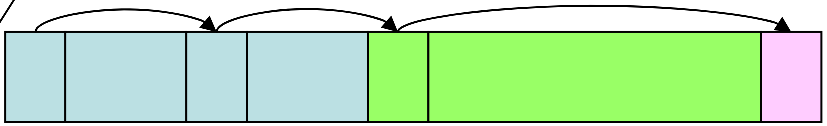
- Overall effect:



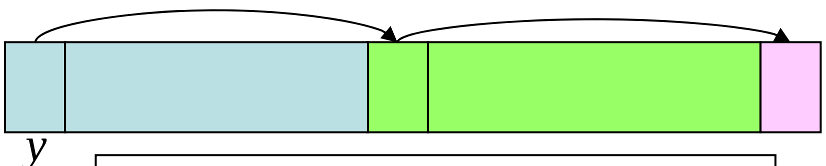
```
hmAlloc (y, sizey);
```




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



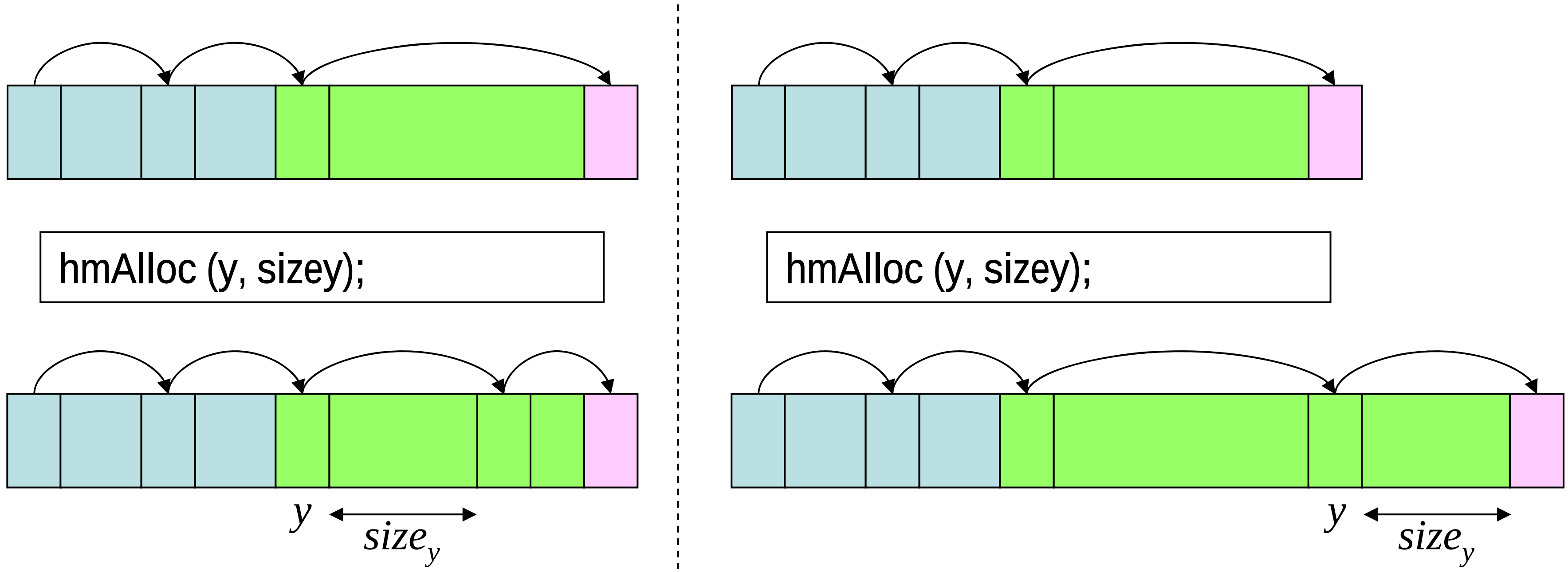
```
/* if not found, compact and
search again */
if (y == 0) {
  compact();
  y = findFree (sizey);
}
```




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

Potential Problems Relevant to Memory Isolation

- Unexpected situations:



⇒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

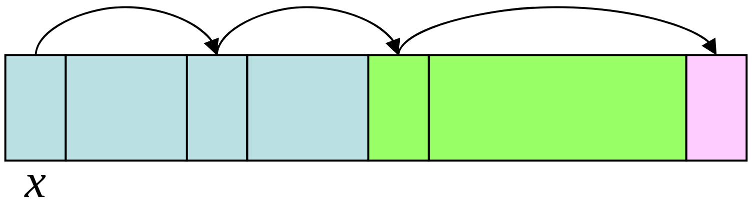
<u>Formal predicates:</u>

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

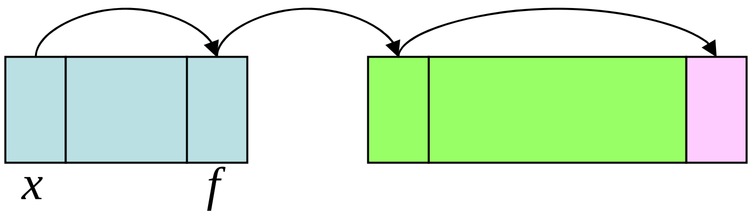
$$\text{Heap-list } l =$$
$$\exists st. (l \mapsto st, nil) \vee$$
$$\exists next. (next \neq nil) \wedge (l \mapsto free, next) *$$
$$(\text{Array } (l+2)\ (next - l - 2)) * (\text{Heap-list } next) \vee$$
$$\exists next. (next \neq nil) \wedge (l \mapsto allocated, next) *$$
$$(\text{Array } (l+2)\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

The Heap-List Predicate (cont'd)

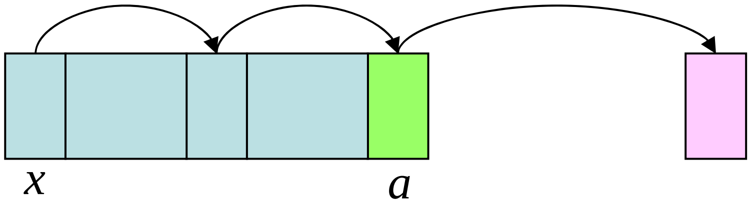
- Heap-lists "with holes":
  - Heap-List $A\ F\ x$ holds for a heap-list without the blocks in A or F
  - E.g.:
    - Heap-List $\{\}\ \{\}\ x$ holds for



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



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



Formal Specification of hmAlloc

$$\left\{\text{Heap-List}\,\{x\}\,\{\}\;hm\_base * \text{Array}\;x\;size_x\right\}$$

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

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

Proof Overview (1/2)

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

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

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

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

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

$$\}$$

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

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

Commands

Assignments pointer dereferences, destructive updates, loops, etc.

Operational semantics
st —*c*→ *st'*

Soundness

Hoare triples
{P}c{Q}

States

Variables and heap

Satisfaction relation
|=

Formulas

$\wedge$, $\rightarrow$, $*$,
$\exists$, $\neg$, $=$, etc.

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)