

Memory Consumption Analysis of Java Smart Cards

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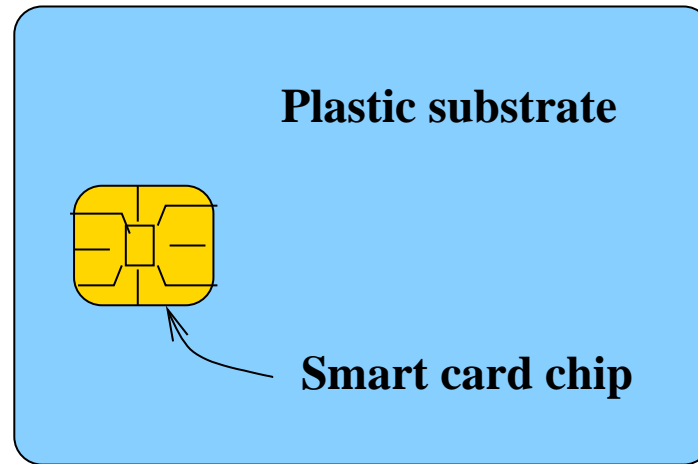
Overview

- Introduction and motivation
- Objective - Our approach
- Final discussion



Introduction and Motivation

Smart cards



- Small communicating devices with restricted resources
- Execute stand-alone applications specifically written for the hardware it runs on

New generation of Java smart cards

- High-level language for programming applets (JavaCard Language)
- Multi-application: various applets may be downloaded and interact in the same card
- Post-issuance: applets may be loaded on the card after issued by the manufacturer

Size (banking - high-tech cards): EEPROM (16K - 64K), ROM (16K - 200K), RAM (1K - 4K)

Applications: mobile phones, e-purse, e-identity, medical file management, etc

Security Issues

Downloaded applets may attack by leaking or modifying confidential information, causing malfunctioning, etc

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The “Sandbox” model relies on that applets are:

- Compiled to bytecode for a virtual machine
- Not given direct access to hardware resources
- Subject to a static analysis: **bytecode verification** (checks applets are well-typed)

Security Issues (cont.)

Extensions of the **bytecode verifier** are needed to guarantee (among others)

- Information flow (i.e. an applet does not “leak” confidential information)
- Reactiveness (bounding the running time of the applet between two interactions with the environment)
- Availability of services

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- Availability of services (**resource-awareness analysis - Memory**)

How to program in small devices?

Quoted from “Java Card Technology for Smart Cards - Sun Series” [Chen,2000; Chapter 13]

- “...neither persistent nor transient objects should be created willy-nilly.”
- “You should also limit nested method invocations...”
- “..applets should not use recursive calls.”
- “An applet should always check that an object is created only once.”

The problem

- Nothing in the standards prevents a(n) (intentionally) **badly written applet** to allocate **all** persistent memory on a card!
- State-of-the-art tools **do not** detect whether a given applet will make the card run out of memory

Example:

```
public class Example
    ...
    while(arg > 0)
        new Example();
    ...
```



Objectives - Our Approach

Objective

An **analyser** for estimating memory usage on Java smart cards, which

- Statically analyses the bytecode
- Does not assume any structure on the bytecode
- Comprises intra- and inter-procedural analysis
- Is as precise as possible
- Is compositional/extensible
- Has low complexity (on-card analyser)

The JavaCard bytecode language

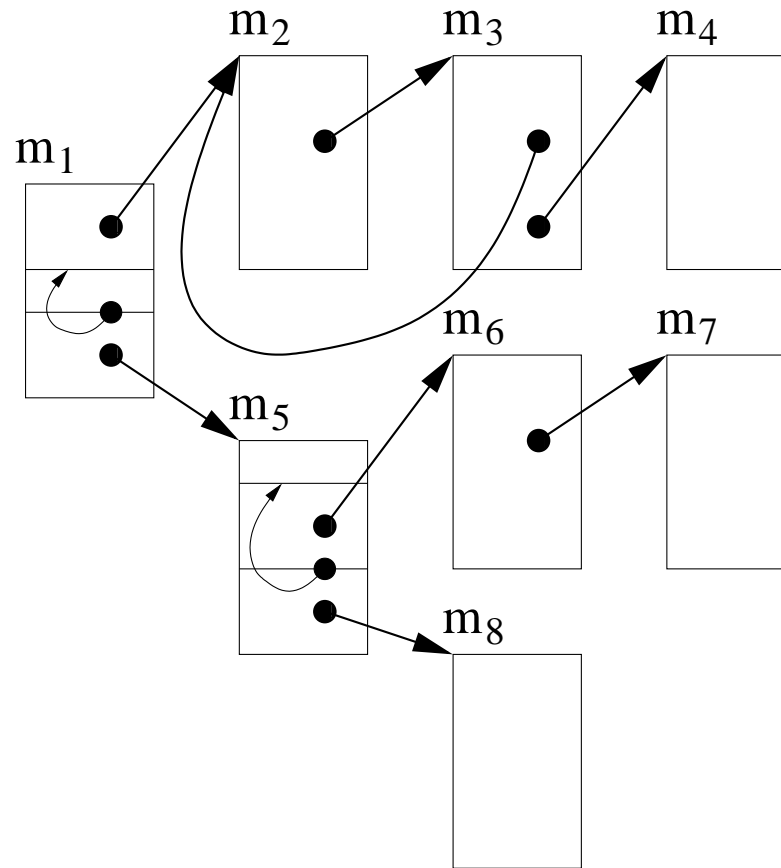
- Stack manipulation: `push`, `pop`, `dup`, `dup2`, `swap`, `numop`;
- Local variables manipulation: `load`, `store`;
- Jump instructions: `if`, `goto`;
- Heap manipulation: `new`, `putfield`, `getfield`;
- Array instructions: `arraystore`, `arrayload`;
- Method calls and return: `invokevirtual`, `invokedefinite`, `return`
- Exceptions and subroutines

Algorithm - Outline

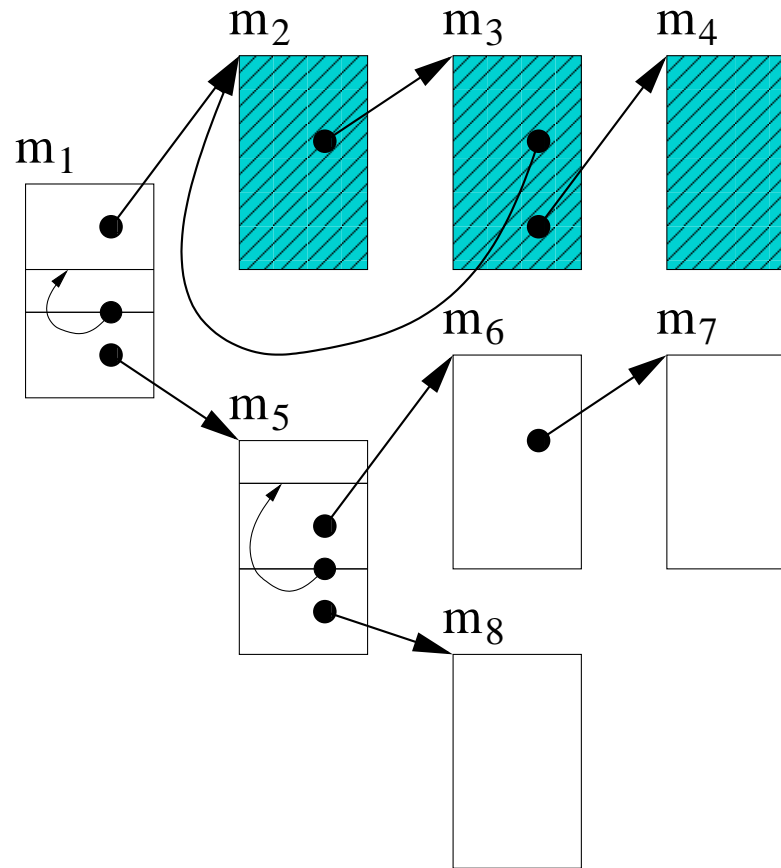
- Detection of (mutually) recursive methods and methods reachable from those (*Rec*)
- Detection of potential intra-method loops (*Loop*)
- Propagation of *Loop* inter-procedurally (*Loop'*)
- Identification of dynamic instantiation of classes (Γ)

Rec, *Loop* and *Loop'* are functions associating a set to pairs (m, pc)

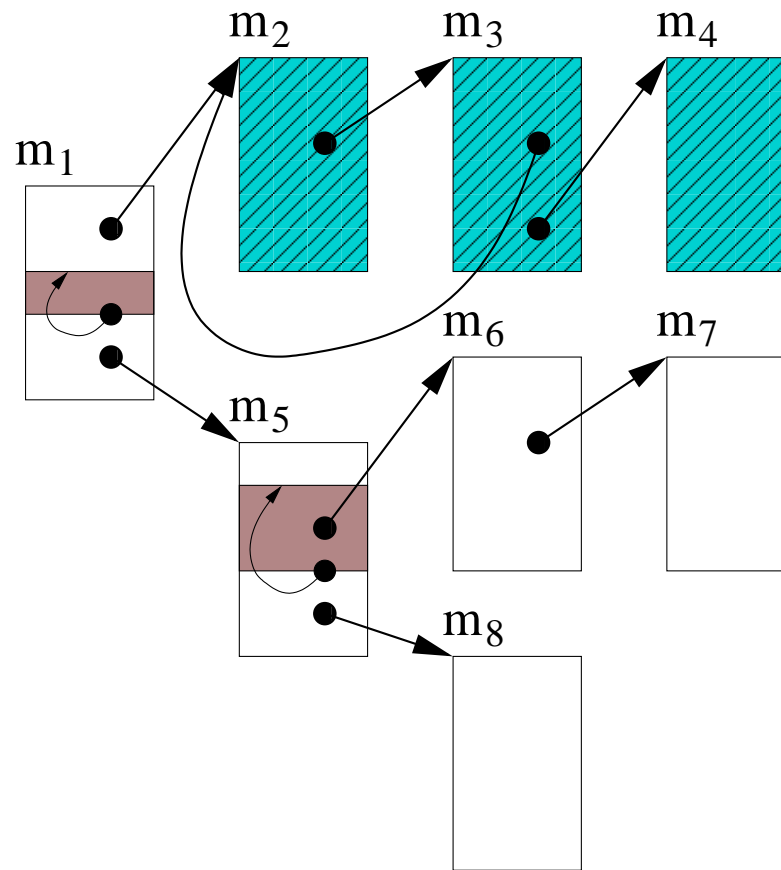
Example: *Rec, Loop and Loop'*



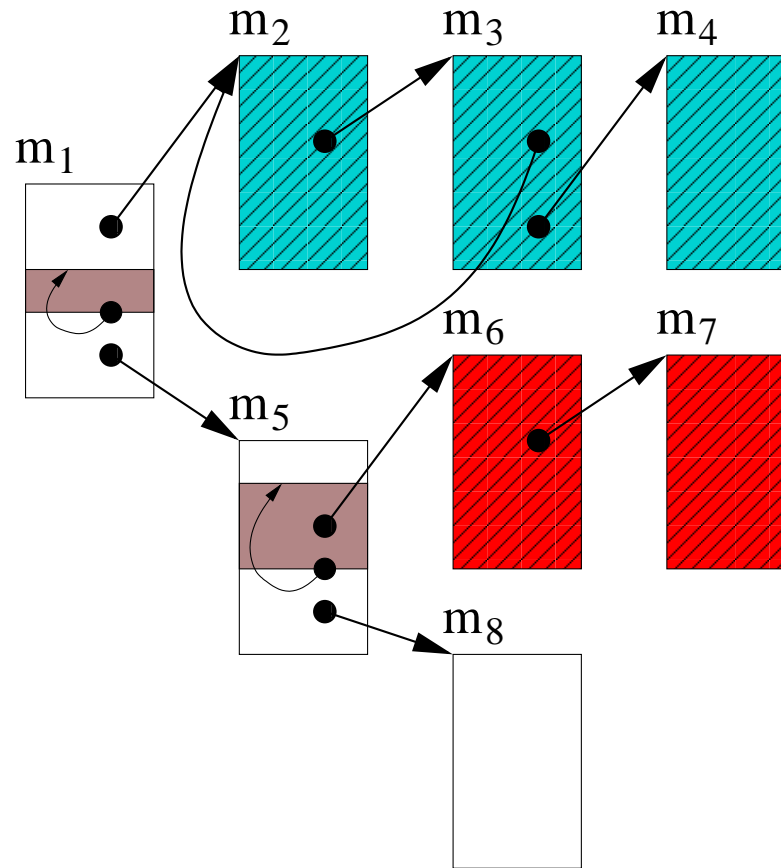
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Example - Detecting loops (*Loop*)

method m

1 goto 4

2 ...

3 goto 2

4 return

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method m

1 goto 4 $Loop(m,1) = \{1\}$

2 ... $Loop(m,2) = \{\}$

3 goto 2 $Loop(m,3) = \{\}$

4 return $Loop(m,4) = \{\}$

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A reasonable complex applet may have hundreds of LoC and around 50 jumps!

Form of the constraint rules

For each function Δ (*Rec*, *Loop* and *Loop'*), the specification is given by a set of **constraint** rules of the form:

$$\frac{(m, pc) : \text{Instr} \quad \text{Cond}}{f(\Delta(m, pc)) \sqsubseteq \Delta(m', pc')}$$

- *Instr* is the current instruction
- *Cond* is a set of conditions (predicate)
- f is a monotonic function
- (m', pc') is the *next* instruction

Detecting loops (*Loop*)

$$\frac{}{\{1\} \sqsubseteq \text{Loop}(m, 1)}$$

$$\frac{(m, pc) : \text{goto } pc'}{F(\text{Loop}(m, pc), pc') \sqsubseteq \text{Loop}(m, pc')}$$

$$\frac{(m, pc) : \text{if } t \text{ op goto } pc'}{F(\text{Loop}(m, pc), pc') \sqsubseteq \text{Loop}(m, pc') \\ F(\text{Loop}(m, pc), pc + 1) \sqsubseteq \text{Loop}(m, pc + 1)}$$

$$\frac{(m, pc) : \text{invokevirtual } m'}{\text{Loop}(m, pc) \sqsubseteq \text{Loop}(m, pc + 1)}$$

$$\frac{(m, pc) : \text{return}}{\perp \sqsubseteq \text{Loop}(m, \text{END}_m)}$$

$$\frac{(m, pc) : \text{Instr}}{\text{Loop}(m, pc) \sqsubseteq \text{Loop}(m, pc + 1)}$$

Instr is any instruction different from the ones appearing in the rules and also from throw and jsr

Spec. of the main algorithm - Γ

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Let $Cycle_{m,pc} \equiv Loop_{m,pc} \vee Loop'_{m,pc} \vee Rec_{m,pc}$

$$\Gamma(m, pc) = \begin{cases} \infty & \text{if } (m, pc) : \text{new}(cl) \wedge Cycle_{m,pc} \\ 1 & \text{if } (m, pc) : \text{new}(cl) \wedge \neg Cycle_{m,pc} \\ 0 & \text{otherwise} \end{cases}$$

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Fix-point computations: Rec , $Loop$ and $Loop'$!

Algorithm - How does it work?

- The domains (lattices) used and the “form” of the constraints guarantee the existence of a *least fix-point*
- The well-foundedness of the lattices guarantees termination
- A **constraint solver** computes the least fix-point

Exceptions and Subroutines

- The `finally` block of a `try...finally` Java construct is compiled into a subroutine, a fragment of code called with the `jsr` bytecode instruction
- In Java, exceptions are thrown using the `throw` instruction, compiled into `throw`
- Other forms of exceptions (`try...catch`) are compiled into `invokevirtual` method calls (accessing the Exception Table)

Exceptions and Subroutines (cont.)

We have extended the above algorithm to handle subroutines and throw exceptions by adding rules to *Loop* and *Rec*

- Added rules for handling subroutines

$$\frac{(m, pc) : \text{jsr } pc'}{F(\text{Loop}(m, pc)) \sqsubseteq \text{Loop}(m, pc')}$$
$$F(\text{Loop}(m, pc)) \sqsubseteq \text{Loop}(m, pc + 1)$$

$$\frac{(m, pc) : \text{ret } i}{\perp \sqsubseteq \text{Loop}(m, \text{END}_{ret})}$$

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- Similar rules for treating exceptions

We don't need to change the previous defined rules!



Final Discussion

Achievements

- We have written a **constraint-based algorithm** for detecting possible memory overflow due to dynamic instantiation of classes inside cycles
- Handwritten proof of
 - Termination
 - Soundness and completeness w.r.t. to an abstraction of the operational semantics

Features of our algorithm

- + Written in a “good” way to be fed into Coq (certification)
- + *Rec*, *Loop* and *Loop'* reusable/extensible
- + Static analysis
- +/- Low space and time complexity
- +/- Compositional
- Over-approximation:
 - It detects (all the) syntactic cycles
 - An instruction in a method (not in a cycle) called more than once is counted once

Related Work

- In [CJPS05]: a certified analyser for Java card bytecode
 - Constraint-based
 - Formalisation based on abstract interpretation
 - A proof of the algorithm soundness in Coq
 - Extraction of OCAML code from its Coq's proof

[CJPS05] D. Cachera, T. Jensen, D. Pichardie and G. Schneider. Certified Memory Usage Analysis. In: Formal Methods. LNCS 3582, p.91-106. July 2005

Contributions (comparison)

- Improved the algorithm presented in [CJPS05]
 - Our algorithm performs better in terms of space-complexity (for a method with 200 lines and 50 basic blocks *Loop* uses 10 KB vs 40 KB)
 - We treat exceptions (partially)
 - We treat subroutines
- Time complexity is similar (computation of fix-points converges at most in 4 iterations)
- No Coq proof in our work (paper-proof of its correctness and completeness)

Improvements to be done

- Implementation would improve efficiency
- Treat all the cases of exceptions (not difficult!)
- Propagate the *pc*-numbers of basic blocks only to relevant points (not difficult!)
 - For analysing an applet with methods containing 50 basic blocks (independently of the Nr of LoC) *Loop* would need only 2.5 KB!
- Extend the analysis for “open” composite applets (a bit more difficult!)



Thank you very much!
Questions?

Research on this topic?

- **Fortunately**, there are many interesting M.Sc. (Ph.D.) research possibilities related to the topic of this talk

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- **Fortunately**, there are many interesting M.Sc. (Ph.D.) research possibilities related to the topic of this talk
- **Unfortunately**, I don't have money for scholarships

Some M.Sc. (Ph.D.) subjects

- Implement the O.S. of the JCVM, and the (optimised) analysis in Maude
- Prove correctness of the algorithm in Coq (using a prefix semantics) and extract the program
- Specify and implement a modular analysis in order to minimise global fix-point computations

Objective (Cont.)

The technique used should allow us to:

- Develop a **certified analyser**
- **Extract** a correct analyser

Moreover, we want the formalism to be compatible with previous work (certified Data Flow Analyser developed at IRISA)

Detecting recursive methods (*Rec*)

$(m, pc) : \text{invokevirtual } m' \quad m = m'$

$\text{Rec}(m, pc) \cup \{m, \bullet\} \sqsubseteq \text{Rec}(m', 1)$

$\text{Rec}(m, pc) \sqsubseteq \text{Rec}(m, pc + 1)$

$(m, pc) : \text{invokevirtual } m' \quad m \neq m'$

$G(\text{Rec}(m, pc), m') \sqsubseteq \text{Rec}(m', 1)$

$\text{Rec}(m, pc) \sqsubseteq \text{Rec}(m, pc + 1)$

$(m, pc) : \text{return}$

$\text{Rec}(m, pc) \sqsubseteq \text{Rec}(m, \text{END}_m)$

$(m, pc) : \text{Instr}$

$\text{Rec}(m, pc) \sqsubseteq \text{Rec}(m, pc + 1)$

Rules for *Loop'*

$$\frac{(m, pc) : \text{invokevirtual } m' \quad \text{Loop}_{m,pc}}{\quad}$$

- $\sqsubseteq \text{Loop}'(m', 1)$

$$\text{Loop}'(m, pc) \sqsubseteq \text{Loop}'(m, pc + 1)$$
$$\frac{(m, pc) : \text{invokevirtual } m' \quad \neg \text{Loop}_{m,pc}}{\quad}$$
$$\text{Loop}'(m, pc) \sqsubseteq \text{Loop}'(m', 1)$$
$$\text{Loop}'(m, pc) \sqsubseteq \text{Loop}'(m, pc + 1)$$
$$\frac{(m, pc) : \text{Instr}}{\quad}$$
$$\text{Loop}'(m, pc) \sqsubseteq \text{Loop}'(m, pc + 1)$$
$$\frac{(m, pc) : \text{return}}{\quad}$$
$$\perp \sqsubseteq \text{Loop}'(m, \text{END}_m)$$

Definition of the functions F and G

$$F(L_{m,pc}, pc') = \begin{cases} L_{m,pc} \cup \{\bullet\} & \text{if } pc' \in L_{m,pc} \\ L_{m,pc} \setminus \{\bullet\} \cup \{pc'\} & \text{otherwise} \end{cases}$$

$$G(R_{m,pc}, m') = \begin{cases} R_{m,pc} \cup \{m, \bullet\} & \text{if } m' \in R_{m,pc} \\ R_{m,pc} \cup \{m\} & \text{if } m' \notin R_{m,pc} \end{cases}$$

Rules for Handling Exceptions

$$\frac{(m, pc) : \text{throw } e \quad (m, pc') \in \text{findHandler}(m, pc, e)}{}$$
$$F(\text{Loop}(m, pc)) \sqsubseteq \text{Loop}(m, pc')$$
$$\frac{(m, pc) : \text{throw } e \quad (m', pc') \in \text{findHandler}(m, pc, e) \quad m' \neq m}{}$$
$$G(\text{Rec}(m, pc), m') \sqsubseteq \text{Rec}(m', pc')$$

How to obtain a certified analyser?

- Formalise the operational semantics of the language in a Proof Assistant (**Coq**)
- Define the abstract domains (lattices)
- Prove well-foundedness of the lattices
- Code the algorithm into Coq (as a **constraint-based** algorithm)
- Prove the correctness of the algorithm w.r.t. (an abstraction of) the operational semantics
- Extract a program (proof-as-program paradigm) using Coq's extraction mechanism

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