Memory Consumption Analysis of Java Smart Cards

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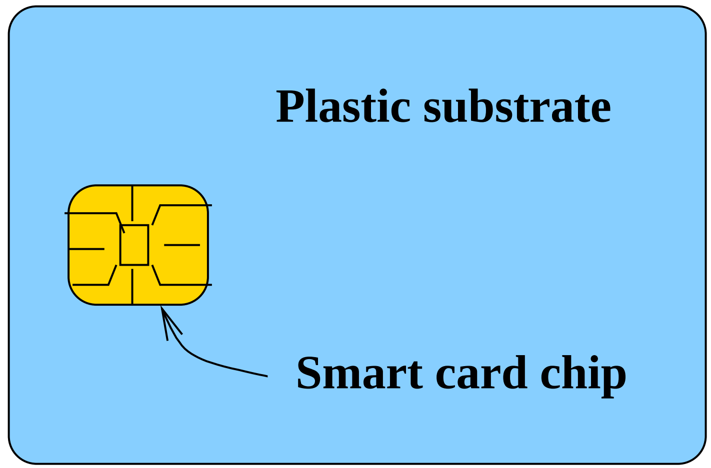
Overview

- 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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- Reactiveness (bounding the running time of the applet between two interactions with the environment)
- 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

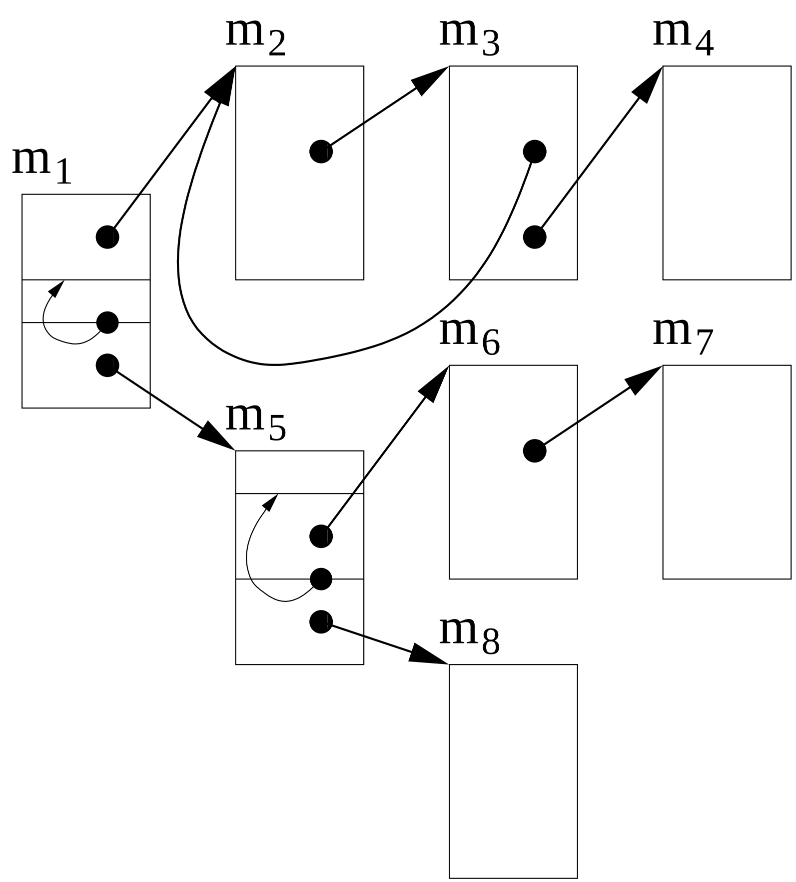
- Stack manipulation: `push`, `pop`, `dup`, `dup2`, `swap`, `numop`;
- Local variables manipulation: `load`, `store`;
- Jump instructions: `if`, `goto`;
- Heap manipulation: `new`, `putfield`, `getfield`;
- Array instructions: `arraystore`, `arrayload`;
- Method calls and return: `invokevirtual`, `invokedefinite`,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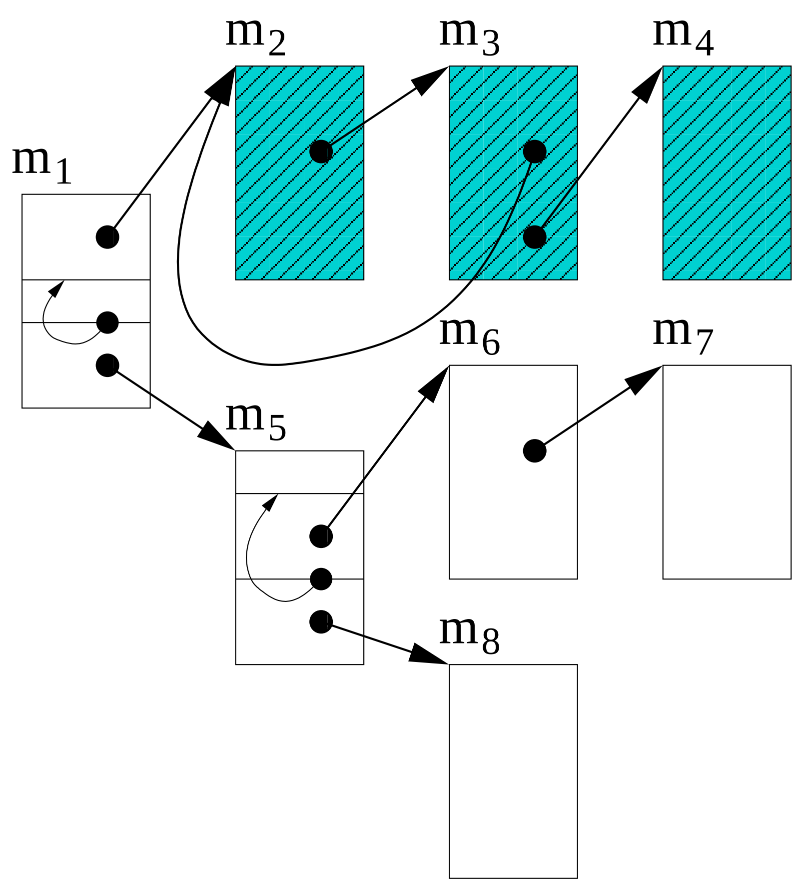

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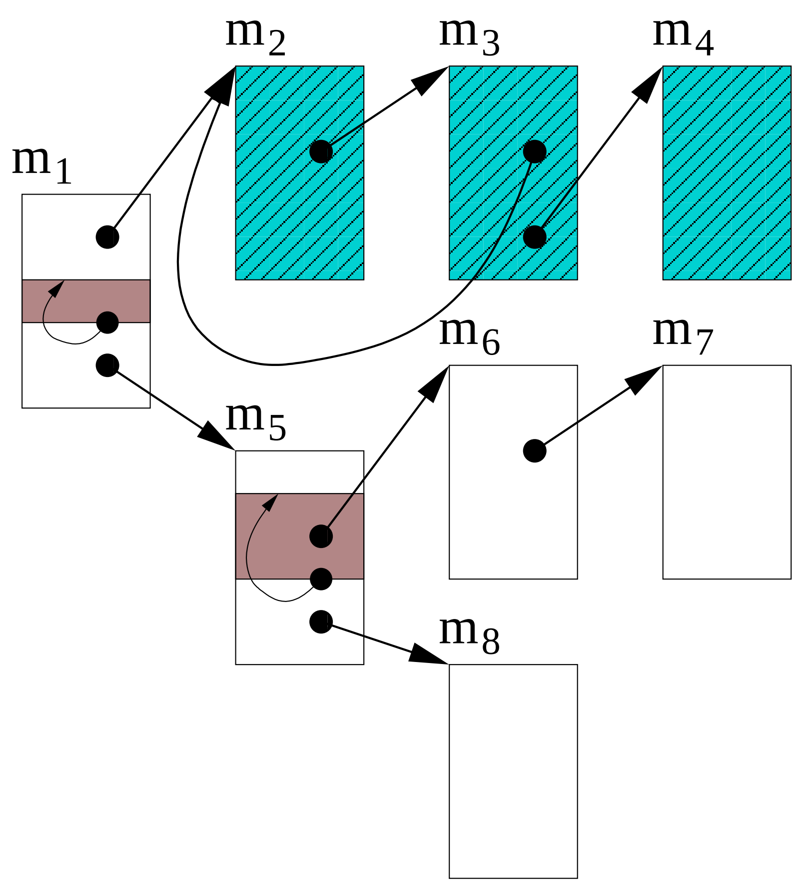

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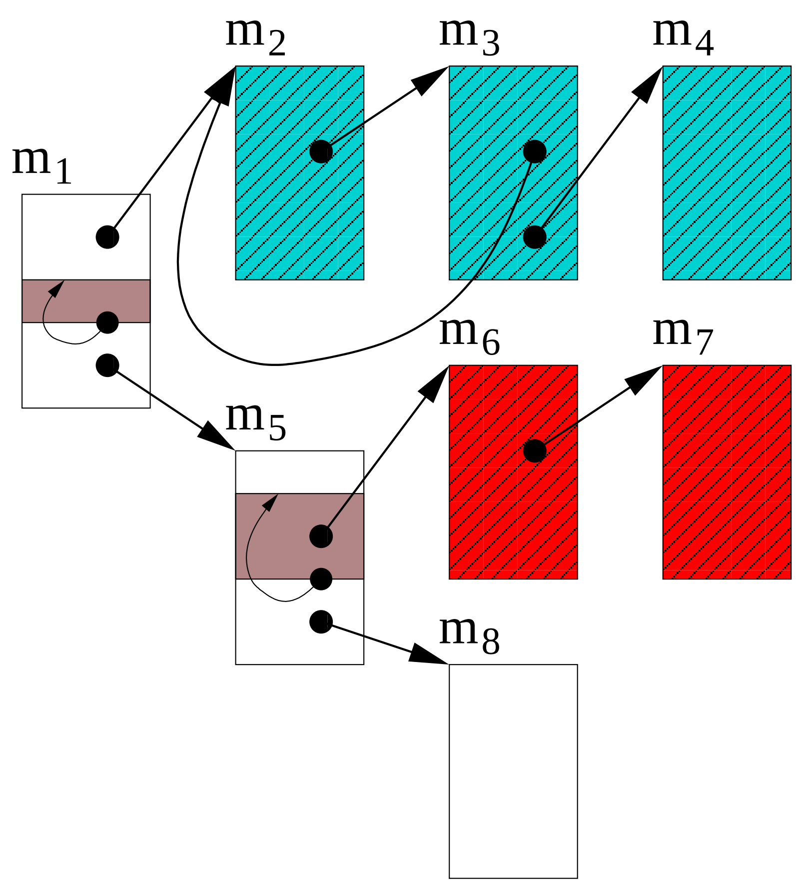

Example - Detecting loops ($Loop$)

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:

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

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

Detecting loops ($Loop$)

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

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

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

$$\frac{(m, pc) : \texttt{return}}{\bot \sqsubseteq Loop(m, \mathrm{END}_m)}$$

$$\frac{(m, pc) : \texttt{if}\ t\ op\ \texttt{goto}\ pc'}{\begin{array}{l} F(Loop(m, pc), pc') \sqsubseteq Loop(m, pc') \\ F(Loop(m, pc), pc+1) \sqsubseteq Loop(m, pc+1) \end{array}}$$

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

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

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

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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

$$\frac{(m, pc) : \texttt{jsr}\ pc'}{\begin{array}{l} F(Loop(m,pc)) \sqsubseteq Loop(m, pc') \\ F(Loop(m,pc)) \sqsubseteq Loop(m, pc+1) \end{array}} \qquad \frac{(m, pc) : \texttt{ret}\ i}{\bot \sqsubseteq Loop(m, \mathrm{END}_{ret})}$$

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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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- Unfortunately, I don't have money for scholarships

Detecting recursive methods (Rec)

$$\frac{(m, pc) : \texttt{invokevirtual}\ m' \qquad m = m'}{\begin{array}{c} Rec(m, pc) \cup \{m, \bullet\} \sqsubseteq Rec(m', 1) \\ Rec(m, pc) \sqsubseteq Rec(m, pc+1) \end{array}}$$

$$\frac{(m, pc) : \texttt{return}}{Rec(m, pc) \sqsubseteq Rec(m, \mathrm{END}_m)}$$

$$\frac{(m, pc) : \texttt{invokevirtual}\ m' \qquad m \neq m'}{\begin{array}{c} G(Rec(m, pc), m') \sqsubseteq Rec(m', 1) \\ Rec(m, pc) \sqsubseteq Rec(m, pc+1) \end{array}}$$

$$\frac{(m, pc) : \texttt{Instr}}{Rec(m, pc) \sqsubseteq Rec(m, pc+1)}$$

Rules for *Loop*'

$$\frac{(m, pc) : \texttt{invokevirtual}\ m' \quad Loop_{m,pc}}{\begin{array}{l}\bullet \sqsubseteq Loop'(m', 1) \\ Loop'(m, pc) \sqsubseteq Loop'(m, pc+1)\end{array}}$$

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

$$\frac{(m, pc) : \texttt{invokevirtual}\ m' \quad \neg Loop_{m,pc}}{\begin{array}{l}Loop'(m, pc) \sqsubseteq Loop'(m', 1) \\ Loop'(m, pc) \sqsubseteq Loop'(m, pc+1)\end{array}}$$

$$\frac{(m, pc) : \texttt{return}}{\bot \sqsubseteq Loop'(m, \mathrm{END}_m)}$$

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

$$\frac{(m, pc) : \texttt{throw}\ e \qquad (m, pc') \in \mathit{findHandler}(m, pc, e)}{F(\mathit{Loop}(m, pc)) \sqsubseteq \mathit{Loop}(m, pc')}$$

$$\frac{(m, pc) : \texttt{throw}\ e \qquad (m', pc') \in \mathit{findHandler}(m, pc, e) \qquad m' \neq m}{G(\mathit{Rec}(m, pc), m') \sqsubseteq \mathit{Rec}(m', pc')}$$

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 an 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)

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)
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