Memory Usage Estimation for Java Smart Cards

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Overview

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

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Introduction and Motivation

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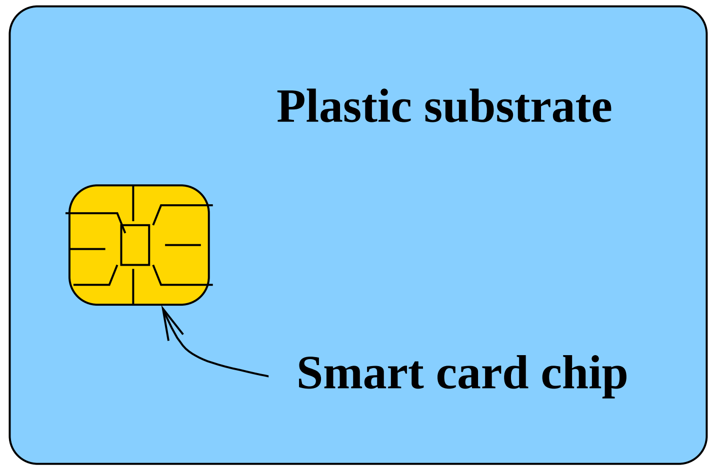
Smart cards



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

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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 - 200K), ROM (16K - 64K), 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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Downloaded applets may attack by leaking or modifying confidential information, causing malfunctioning, etc

The “Sandbox” model relies on that applets are:

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

Security Issues (cont.)

Extension 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

Security Issues (cont.)

Extension 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 (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();
    ...
```

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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
- Has low complexity (on-card analyser)

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)

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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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Our Solution

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`, `invokeinterface`, `return`

Algorithm - Outline

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

What is new about it?

Audience: But we know how to detect cycles in (assembly-like) programs!! (Compiler...)

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Answer: To write a constraint-based algorithm suitable to be formalised in Coq and to extract a certified analyser

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What is new about it?

Audience: But we know how to detect cycles in (assembly-like) programs!! (Compiler...)

Answer: Yes.

Audience: What is the challenge, then?

Answer: To write a constraint-based algorithm suitable to be formalised in Coq and to extract a certified analyser

Presented as a set of rules defining one (or more) constraint(s) for each bytecode instruction

Algorithm - Constraints

The constraints are 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
- Δ is the *context* being generated
- (m', pc') is the *next* instruction

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Detecting loops ($Loop$)

$$\frac{(m, pc) : \texttt{goto}\ pc'}{F_1(Loop(m, pc)) \sqsubseteq Loop(m, pc')}$$

$$\frac{(m, pc) : \texttt{if}\ t\ op\ \texttt{goto}\ pc'}{\begin{array}{c} F_1(Loop(m, pc)) \sqsubseteq Loop(m, pc') \\ F_3(Loop(m, pc)) \sqsubseteq Loop(m, pc+1) \end{array}}$$

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

$$\frac{(m, pc) : \texttt{return}}{\bot \sqsubseteq Loop(m, \mathrm{END}_m)} \qquad \frac{(m, pc) : \texttt{Instr}}{Loop(m, pc) \sqsubseteq Loop(m, pc+1)}$$

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Detecting recursive methods (Rec)

$$\frac{(m, pc) : \texttt{invokevirtual}\ m'}{\begin{array}{l} F(Rec(m, pc), m') \sqsubseteq Rec(m', 1) \\ Rec(m, pc) \sqsubseteq Rec(m, pc + 1) \end{array}}$$

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

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

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The algorithm - Γ

$$\frac{(m,pc) : \mathtt{new}(cl) \qquad Cycle(m,pc)}{\Gamma(m,pc) \cup \{<!>_{(m,pc)}\} \sqsubseteq \Gamma(m,pc+1)}$$

$$\frac{(m,pc) : \mathtt{new}(cl) \qquad \neg Cycle(m,pc)}{\Gamma(m,pc) \cup \{(m,pc)\} \sqsubseteq \Gamma(m,pc+1)}$$

$$\frac{(m,pc) : \mathtt{Instr}}{\Gamma(m,pc) \sqsubseteq \Gamma(m,pc+1)}$$

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Algorithm - How does it work?

- The abstract domains (lattices) chosen and the "form" of the constraints guarantees the existence of a *least fix-point*
- The well-foundedness of the lattices guarantees termination
- A constraint solver computes the least fix-point

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Final Discussion

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Achievements

- We have written a constraint-based algorithm for detecting possible memory overflow due to dynamic instantiation of classes inside cycles

Already done:

- Handwritten proof of
  - Termination
  - Soundness and completeness w.r.t. to an abstraction of the operational semantics

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Features of our algorithm

+ Written in a “good” way to be fed into Coq (certification)
+ Modular; $Loop$ and Rec reusable
+ Compositional
+ Static analysis

? Low computational complexity

– Over-approximation:
  - It detects (all the) syntactic cycles
  - An instruction in a method (not in a cycle) called more than once is counted once

Current Work

Currently adapting the algorithm slightly in order to reuse (in Coq):

- Lattice library
- Auxiliary lemmas
- Fix-point and constraint solver
- Proof strategies

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Current approach: We considered a maximal semantics (total runs of the program)

New approach: We have to consider a partial semantics (prefixes of runs of the program)

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Future Work

Still to be done:

- A more precise analysis: Exact amount of memory used if no `new` occurs in a cycle
- “Implement” the algorithm we have presented in Coq and extract the analyser
- Compare performance of both approaches: complexity Vs simplicity of proofs

Besides this work:

- Other techniques for resource-bounded analysis and other security properties

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Thank you very much!

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Rules for *Loop*

$$\frac{(m, pc) : \texttt{goto}\ pc' \qquad pc' \leq pc}{F_1(Loop(m, pc)) \sqsubseteq Loop(m, pc')}$$

$$\frac{(m, pc) : \texttt{goto}\ pc' \qquad pc' > pc}{F_2(Loop(m, pc)) \sqsubseteq Loop(m, pc')}$$

$$\frac{(m, pc) : \texttt{if}\ t\ op\ \texttt{goto}\ pc' \qquad pc' \leq pc}{\begin{array}{c} F_1(Loop(m, pc)) \sqsubseteq Loop(m, pc') \\ F_3(Loop(m, pc)) \sqsubseteq Loop(m, pc+1) \end{array}}$$

$$\frac{(m, pc) : \texttt{if}\ t\ op\ \texttt{goto}\ pc' \qquad pc' > pc}{\begin{array}{c} F_2(Loop(m, pc)) \sqsubseteq Loop(m, pc') \\ F_3(Loop(m, pc)) \sqsubseteq Loop(m, pc+1) \end{array}}$$

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Rules for *Loop* (cont.)

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

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

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

Definition of the functions

$$F_1(L_{m,pc}) = \begin{cases} L_{m,pc} \cup \{Yes_{pc}\} & \text{if } \{pc, pc'\} \subseteq L_{m,pc} \\ L_{m,pc} \cup \{pc, pc'\} & \text{otherwise} \end{cases}$$

$$F_2(L_{m,pc}) = \begin{cases} L_{m,pc} \setminus \mathbb{Y}_{<pc'} & \text{if } \{pc, pc'\} \subseteq L_{m,pc} \\ (L_{m,pc} \setminus \mathbb{Y}) \cup \{pc, pc'\} & \text{otherwise} \end{cases}$$

$$F_3(L_{m,pc}) = \begin{cases} L_{m,pc} \setminus \mathbb{Y}_{<pc+1} & \text{if } \{pc, pc+1\} \subseteq L_{m,pc} \\ (L_{m,pc} \setminus \mathbb{Y}) \cup \{pc, pc+1\} & \text{otherwise} \end{cases}$$

Where $\mathbb{Y}_{<pc'} \stackrel{\text{def}}{=} \{Yes_{pc} \mid pc < pc'\}$

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Rules for Rec

$$\frac{(m, pc) : \texttt{invokevirtual}\ m' \quad m = m'}{\begin{array}{l} Rec(m, pc) \cup \{m, Yes\} \sqsubseteq Rec(m', 1) \\ Rec(m, pc) \sqsubseteq Rec(m, pc+1) \end{array}}$$

$$\frac{(m, pc) : \texttt{invokevirtual}\ m' \quad m \neq m'}{\begin{array}{l} F(Rec(m, pc), m') \sqsubseteq Rec(m', 1) \\ Rec(m, pc) \sqsubseteq Rec(m, pc+1) \end{array}}$$

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

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

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Definition of F

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

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Example of *Loop*

```
20 ...             {30,50,31,41,40,70,20,Y70}
30 if goto 50      {30,50,31,41,40,70,20,Y70}
   ...             {30,31,50,41,40,51,70,20,Y70}
40 if goto 90      {30,31,50,41,40,51,70,20,Y70}
   ...             {30,31,41,40,50,51,70,20,Y70}
50 if goto 90      {30,31,41,40,50,51,70,20,Y70}
   ...             {30,31,41,40,50,51,70,20,Y70}
70 goto 20         {30,31,41,40,50,51,70,20,Y70}
   ...
90 ...             {30,31,40,90,41,50,51,70,20}
```

(b)

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Example of *Loop*

```
30 if goto 50
31 goto 49      {30,31}
   ...
40 goto 60      {30,50,31,49,40}
   ...
49 if goto 60   {30,31,49}
50 goto 40      {30,50,31,49}
   ...
60 ...          {30,31,49,60,40}
```

(a)

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