# Model Checking of Multi-Applet JavaCards

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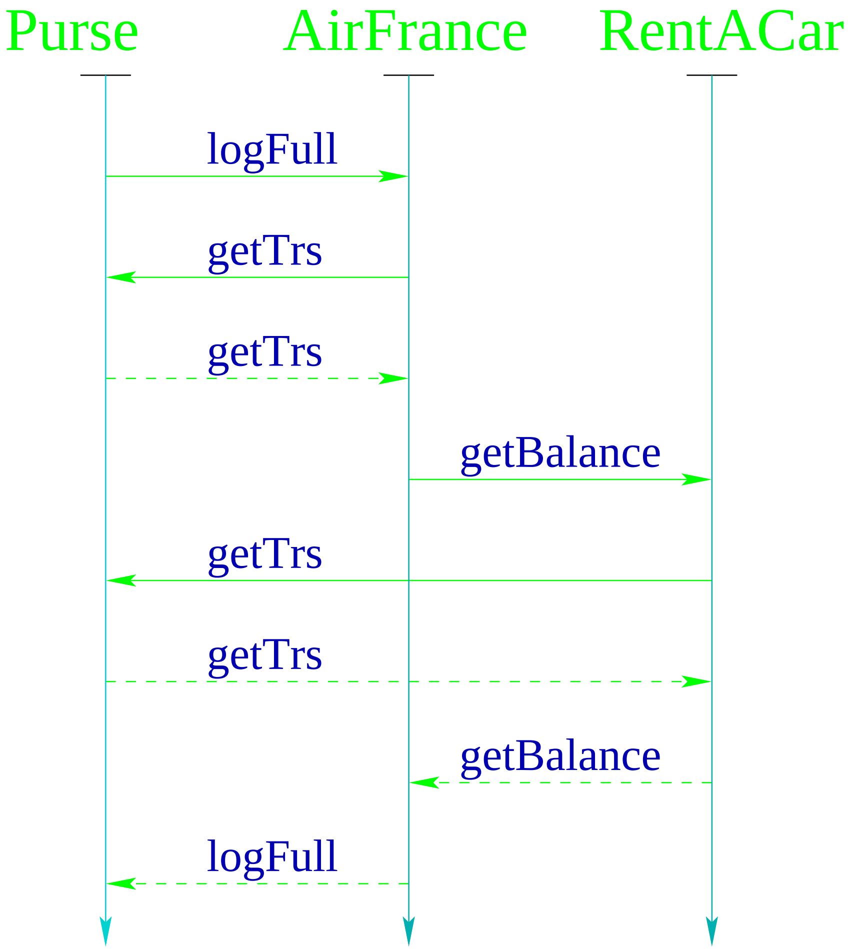
# Problem Statement

- Analyse inter-applet method call patterns
- Motivating example due to Lanet et al:



# VerifiCard Context

WP4: Analysis of Applet properties on the byte code level
INRIA Sophia-Antipolis & SICS

A common card model:

- A set of applets consisting of methods with program points
- Execution steps are:
  - Methods calls and returns
  - Intra method control flow
- Data is completely abstracted away

# VerifiCard Context II

Barthe, Gurov and Huisman (FASE'02): a compositional program model

- Each applet has its own control stack of program points: $\langle A, P_0 \cdot \ldots \cdot P_n \rangle$
- A compositional operational semantics for deriving global transitions $A_1 \parallel \ldots \parallel A_n \rightarrow$ from local ones $A_i \rightarrow$
- A compositional proof system (Gentzen style, logic the modal $\mu$-calculus)

$$(1)\ \mathsf{AirFrance} : \phi_A$$

$$(2)\ \mathsf{Purse} : \phi_P$$

$$(3)\ \mathsf{RentACar} : \phi_R$$

$$\frac{(4)\ X_A : \phi_A,\ X_P : \phi_P,\ X_R : \phi_R \vdash\ X_A \parallel X_P \parallel X_R : \phi}{\mathsf{AirFrance} \parallel \mathsf{Purse} \parallel \mathsf{RentACar} : \phi}$$

# Our Verification Approach

- Application of model checking techniques by combining existing tools to achieve “push-button” verification
- Useful for checking individual applets

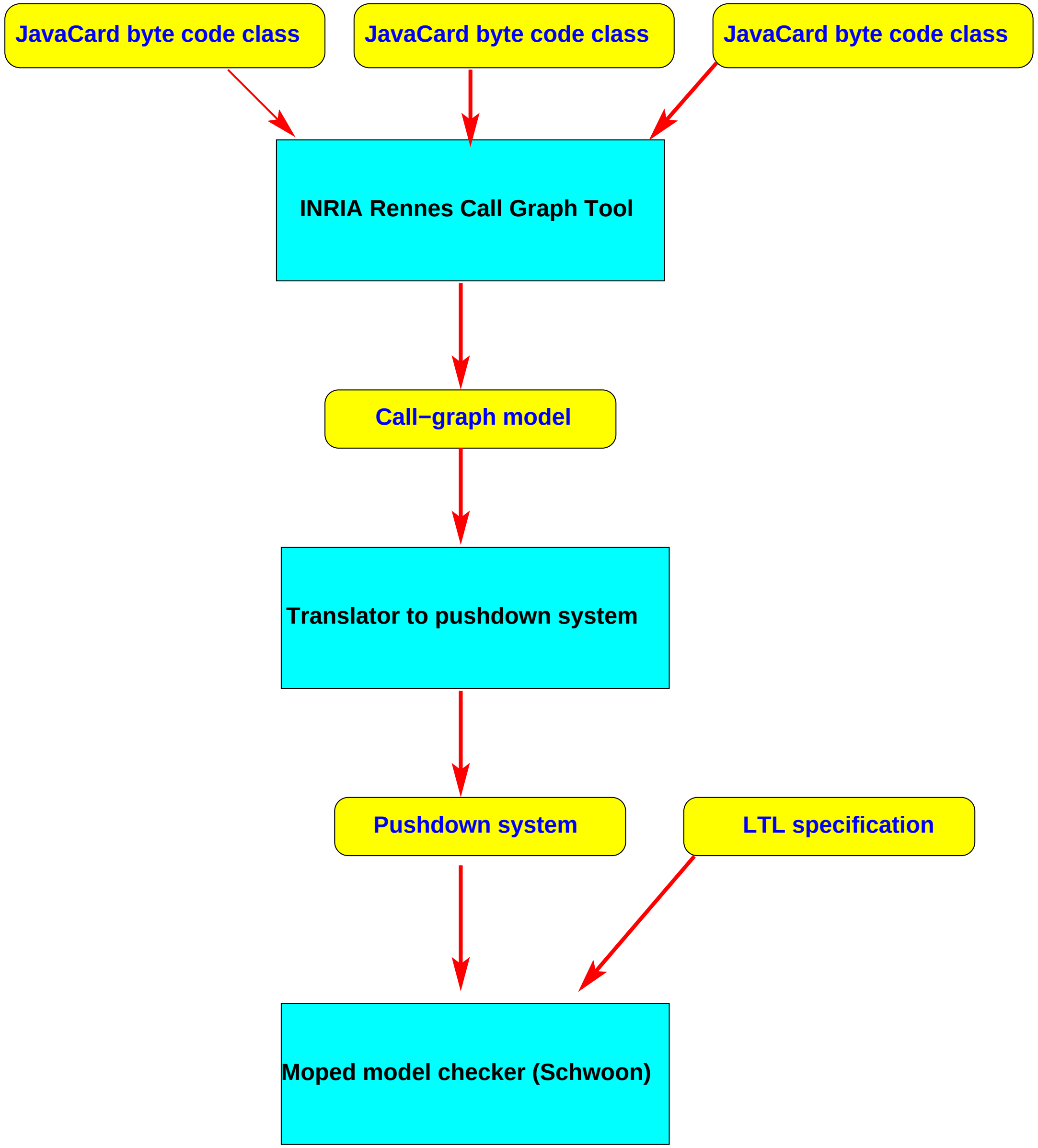
$$\mathsf{AirFrance} : \phi_A$$

- Generally for checking closed systems

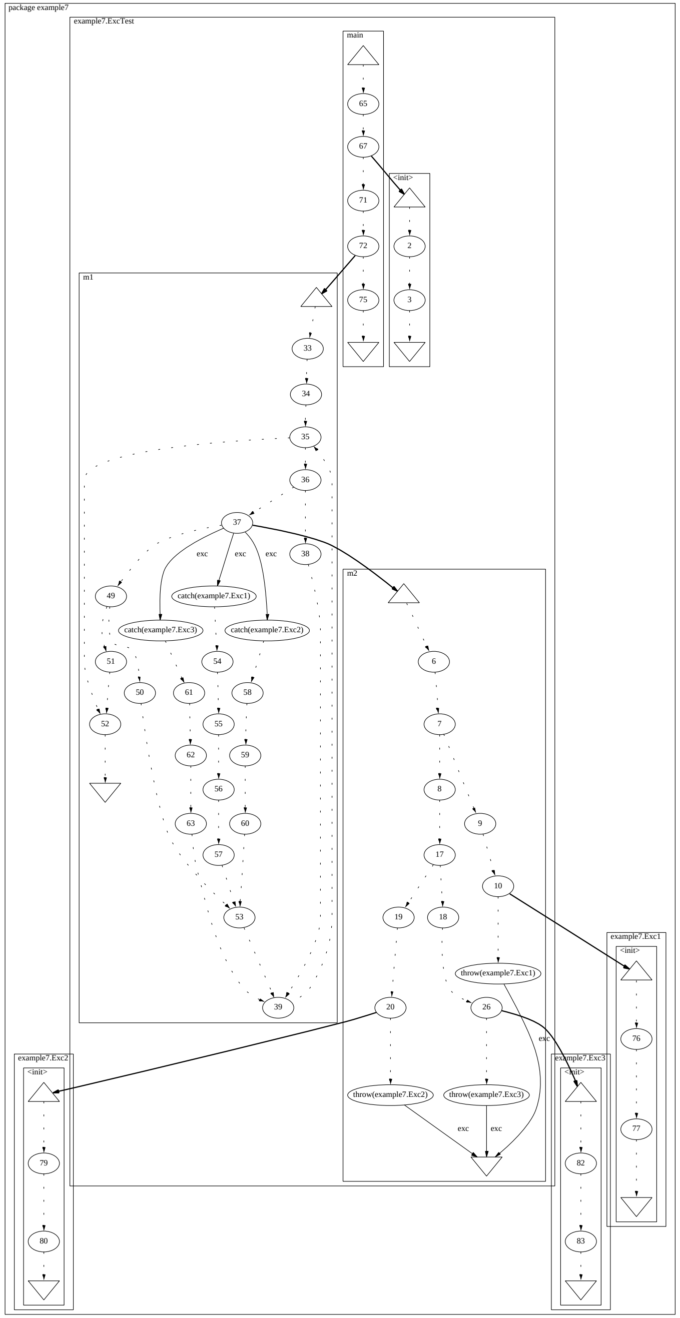
$$\mathsf{AirFrance} \parallel \mathsf{Purse} \parallel \mathsf{RentACar} : \phi$$

but not for open ones

# Overview of Method



# Call Graph Example




test of graph reduction procedures

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# Call Graph Construction

- Method call graphs produced by INRIA Rennes JVM analysis tool (Jenset et al) based on *Soot*
- Call graphs abstract away from data dependencies
  Branching constructs introduce graph nondeterminism
- Construction is class based
  Applet instances cannot be distinguished
- Class based (package based) analysis is a good fit with the JavaCard firewall mechanism

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# Generating Call-Graphs for JavaCard

The adaptation of the call-graph construction tool for JavaCard mostly concerns information collection

- For each applet class (inherits from `Applet` class) the call graphs for methods `install`, `select`, `deselect`, `process` and `getShareableInterfaceObject` are generated
- For each applet class the call-graphs for methods callable using sharable interfaces are generated

```
package purse.Loyalty;

...

public interface LoyaltyPurseInterface

extends Shareable { void grantPoints (byte[] buffer); }
```

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# Pushdown System

- Pushdown systems are a natural execution model for programs with recursion
- A *pushdown system (PDS)* is a tuple

$$\mathcal{P} \triangleq \langle P, \Gamma, \Delta \rangle$$

  (i) $P$ is a finite set of *control locations*

  (ii) $\Gamma$ is a finite set of *stack symbols*

  (iii) $\Delta \subseteq (P \times \Gamma) \times (P \times \Gamma^\star)$ is a finite set of *rewrite rules* of the shape $\langle p, \gamma \rangle \longrightarrow \langle q, \sigma \rangle$

- A *run* of $\mathcal{P}$ is a sequence $\rho = \langle p_0, \sigma_0 \rangle \langle p_1, \sigma_1 \rangle \langle p_2, \sigma_2 \rangle \cdots$ such that for all $i$, there is a rule $\langle p_i, \gamma \rangle \longrightarrow \langle p_{i+1}, \sigma \rangle$ and $\omega \in \Gamma^\star$ such that $\sigma_i \equiv \gamma \cdot \omega$ and $\sigma_{i+1} \equiv \sigma \cdot \omega$

# Translation of Call-Graphs to PDSs

- Translation of call-graphs to pushdown systems is easy. A single control location $c$ is used and the stack symbols encode JavaCard program points
- A common abstraction is to collapse API calls
- A method call from program point $p$ to method $m$ becomes the PDS rule

$$\langle c, p \rangle \rightarrow \langle c, m \cdot p \rangle$$

- A method return from program point $p$ becomes

$$\langle c, p \rangle \rightarrow \langle c, \epsilon \rangle$$

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# Correctness Properties

- Linear Temporal Logic used to specify properties for model checking:
  $\neg\phi$, $\phi \wedge \psi$, $\phi \vee \psi$, true, false
  $\mathcal{X}\ \phi$ ($\phi$ holds in the next configuration)
  $\phi\ \mathcal{U}\ \psi$ ($\phi$ holds until $\psi$ eventually holds)
  $\phi\ \mathcal{W}\ \psi$ ($\phi$ holds until $\psi$ holds)
- The basic predicates are program points ($p$), classes (class $c$) and packages (package $p$)
- The satisfaction relation of a formula $\phi$ is defined relative to a run, $r \models \phi$
  Example: $\langle c_0, p \cdot \sigma \rangle \langle c_1, \sigma_1 \rangle \ldots \models p'$ iff $p \equiv p'$
- The judgment $m \vdash \phi$ expresses the claim that every run $r$ of the PDS from the configuration $\langle c, m \rangle$ satisfies $\phi$

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# Specification Patterns

- Specification patterns are used to write more readable properties and to provide the link to compositional verification ($\mu$-calculus)
- Examples:

$$\begin{aligned}
\text{Eventually } \phi &\triangleq \text{true } \mathcal{U} \ \phi \\
\text{Always } \phi &\triangleq \neg\,(\text{true } \mathcal{U} \ \neg\phi) \\
\text{Never } \phi &\triangleq \text{Always } \neg\phi
\end{aligned}$$

$$\begin{aligned}
\text{Within } m\ \phi &\triangleq m \vdash \phi \\
a \text{ CannotCall } m &\triangleq \text{Always}\,(\textbf{package } a \Rightarrow \neg\,(\mathcal{X}\ m)) \\
m_1 \text{ NeverTriggers } m_2 &\triangleq \text{Within } m_1 \ (\text{Never } m_2) \\
m_2 \text{ After } m_1 &\triangleq (\text{Never } m_2) \ \mathcal{W} \ m_1 \\
m_1 \text{ Excludes } m_2 &\triangleq \text{Eventually } m_1 \ \Rightarrow \ \text{Never } m_2
\end{aligned}$$

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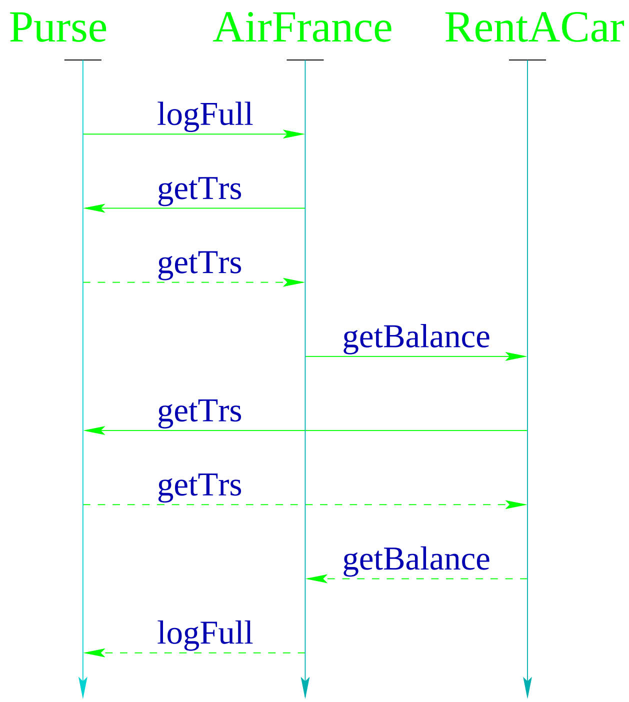
# Example Revisited

- With these specification patterns the example




violates the correctness property

Within AirFrance.logFull

CannotCall RentACar Purse.getTrs

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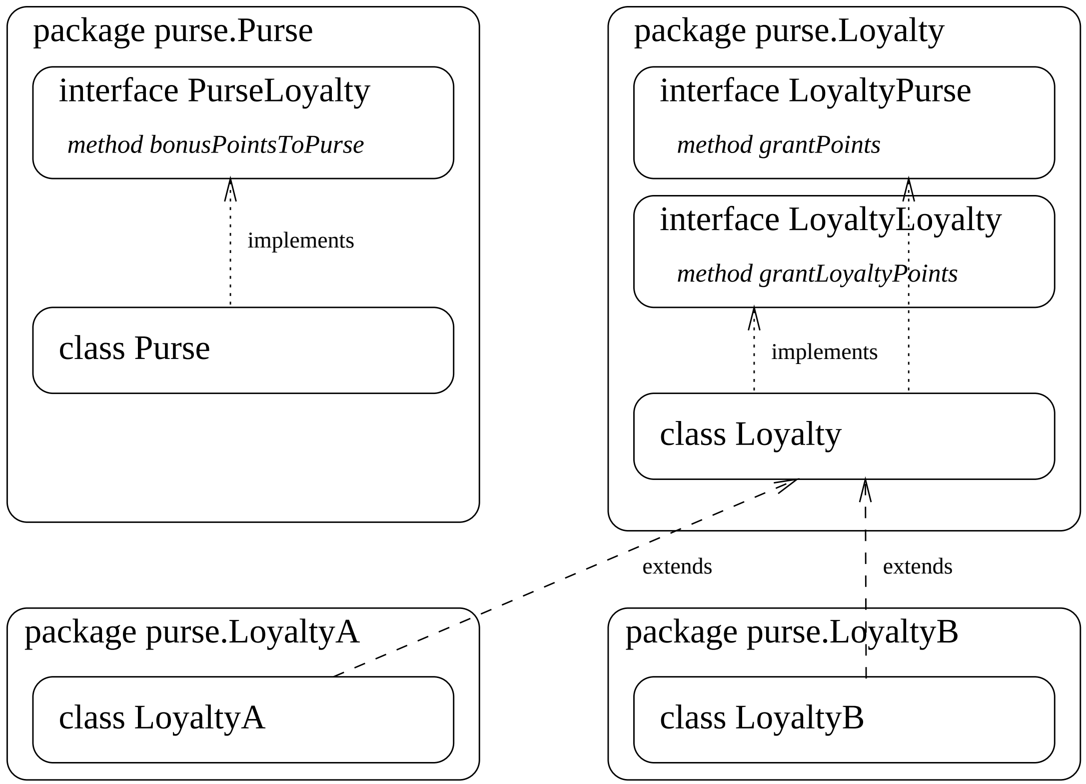
# Model Checking of PDSs

- Could not find an efficient $\mu$-calculus based model checker
- Instead: Moped for LTL (Schwoon)
- Approach: a Büchi automaton is built for the negation of the formula and combined with the original PDS into a “Büchi” PDS; check if there is an accepting run
- Time complexity $O(p^2b^3)$ where $p$ is the size of the pushdown system and $b$ is the size of the Büchi automaton; space complexity is $O(p^2b^2)$.
- Diagnostics: reduced PDS exhibiting the error
- Encoding of basic properties via regular expressions

# In Practice

- A concrete example (a modified purse from the SUN JavaCard development toolkit):



# Example Properties

- Property A: *Calls to* `grantPoints` *are not transitive*

  For all loyalty applets $L$ and $L'$, a call to $L$.`grantPoints` never triggers a call to $L'$.`grantPoints`

  `loyaltyA.grantPoints` NeverTriggers `loyaltyB.grantPoints`

- Property B: *An object constructor is not called from the* `process` *method*

  Any constructor invocation is recognized by the regular expression Constructor $\triangleq$ `.*\..*\.<init>_.*`
  Checking:

  Within `purse.Purse.process` Never Constructor

# Example Results

- Example size approx. 1400 lines of Java code
- About the same number of rewrite rules with API abstracted away
- Call graph generation approx. 15 seconds
- Model checking each property takes less than a second

# Conclusions

- Automatic and light-weight verification techniques attractive to end users
- Possible to implement on-card in the near future?
- Is abstracting away all data dependencies too coarse an abstraction?
- Work in progress; first polished prototype to be delivered during autumn
- Paper describing initial experiments and results will be presented at CARDIS'02

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