Java Program Verification for Smart Cards

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Outline

I. Intro on smart cards and JavaCard
II. European IST-project VerifiCard (`www.verificard.org`)
III. LOOP project at Nijmegen: ***Java*** and ***JML*** to ***PVS***
IV. Java semantics using coalgebras
V. Hoare logic for JML
VI. Examples:
   - Decimal class for Purse applet
   - Phone card applet
VII. Conclusions & future work (scalability & security).

I. Smart Cards with Java

Smart Cards

Latest generation of cards has microprocessor plus memory (RAM, ROM, EEPROM) capable of:

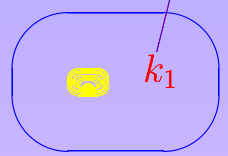
- storing information (tamper-resistant!)
- processing information, in paricular: ***encryption*** / ***decryption*** using private key on card.

Main applications:

Now:	bank cards, mobile phone SIMs, settop boxes
Future:	general identity cards, with PKI support

Cards and keys

Key pair of person A:
$\langle$ private key k_1, public key k_2 $\rangle$



Smart card of A

Name	Public key
...	...
A	k_2
...	...
⋮	⋮

PKI = Public Key Infrastructure

Old and New Cards

Traditional smart cards:

- Code in native, low-level assembly language, burned into ROM
- difficult to develop, and to re-use: inflexible

New generation of open cards:

- mini OS, providing a common basis: abstract machine, API, crypto
- abstraction from hardware & vendor-specific details
- multi-application: several applications (“applets”)
- post-issuance: new applets can be downloaded

JavaCard

JavaCard is a superset of a subset of Java, for programming the new generation of smart cards:

- It is a ***simplification*** of Java:

  No threads, floats, strings, multi-dim arrays, optional GC; because of hardware constraints

- It is an ***extension*** of Java:
  - Persistent and transient objects + transaction mechanism
  - Increased security: standard sandbox (cf. web-browsers) + firewall between applets

II. European Project VerifiCard

VerifiCard: background

- ***Multi-application*** + ***post-issuance downloading*** is both strength and weakness:
  Imagine a virus on your smart card!
- A malicious applet may do much damage, by:
  - exploiting a weakness of the platform
  - interfering with other applets
- Smart card industry is faced with higher certification demands, e.g. Common Criteria (CC) evaluations:
  - seven levels of evaluation
  - highest levels (6 + 7) require ***formal*** verifications
  - current card evaluations at levels 4 and 5.

VerifiCard: Relevance

JavaCard is an ideal target for use of formal methods:

- The systems involved are relatively small, and within reach of current verification technology + tools
- Correctness + security are essential for acceptance of new card-based services
- Cards are distributed in large numbers
- Smart card industry is open to formal methods (because of evaluations + security is their “product”)

Potential killer application for formal methods in software (both positively and negatively)

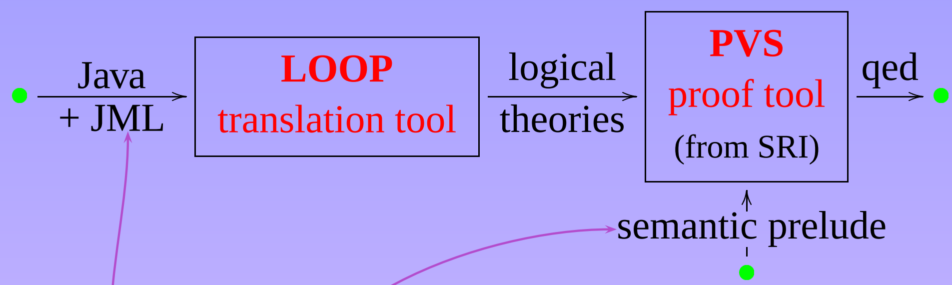
VerifiCard: Topics

Tool-assisted verification for JavaCard, along the lines:

JavaCard	platform	applets
byte code	JCVM, Verifier, CAP converter, compiler formalisation	abstract interpretation & model checking
source code	language semantics & logic, and API annotation	applet annotation in JML & Hoare-style verification

III. LOOP project at Nijmegen

LOOP project: overview



- JML annotations become PVS predicates, which should be proved for the (translated) Java code.
- The semantic prelude contains the semantics in PVS of Java language constructs like composition, if-then-else, while, try-catch-finally, ...

LOOP project: results

- Translation covers essentially all of sequential Java
- Translation of JML is still under construction, but covers the basics: class invariants & constraints, method specifications including modifiable clauses, but not yet model variables
- Major case studies:
  - non-trivial invariant for Java's Vector class
  - functional specification & verification of JavaCard's AID class
  - applet case studies
  - ESC/Java + JML JavaCard API specs (on web).

JML: Java Modeling Language

In ***JML*** [Leavens et al.] one may add specifications as special comments in Java code, for:

- Class invariants and constraints
- Method specifications:

```
/*@ behavior
  @ requires   <precondition>
  @ modifiable <items that may be modified>
  @ diverges   <precondition for non-termination>
  @ ensures    <postcond for normal termination>
  @ signals    <postcond for exceptional
  @            termination>
  @*/
void method() { ...  }
```

- Model variables (specification only)

JML: example

JML method specifications may clarify the behaviour of Java methods:

```
/*@ normal_behavior
  @ requires     x >= 1;
  @ modifiable   \nothing;
  @ ensures      \result * \result <= x &&
  @              x < (\result + 1) * (\result +
  @*/
int square(int x) {
  int count = 0, sum = 1;
  while (sum <= x) {
    count++;
    sum += 2 * count + 1;
  }
  return count;
}
```

JML: difference with javadoc

- Javadoc also uses special comments `/**...*/` to annotate programs, with special tags like **`@param`** and **`@return`**.
- A special compiler recognises these comments and produces html pages for uniform documentation.
- But: JML has a formal semantics and its assertions can be ***formally verified***.
- For this purpose, its language is richer (eg. has class invariants).

JML: Tool support

Especially appealing: range of options for JML:

runtime checking — static checking — interactive verification

- Iowa (Leavens et al.): JML parser, typechecker, inserter of run-time checks
- Compaq (Leino et al): extended static checking: automatic verification of ***simple*** assertions
- MIT (Ernst): ***Daikon*** invariant detection tool
- Nijmegen theorem proving, via LOOP tool: interactive verification of arbitrary assertions.

JML with its tools is also great in (formal) Java courses!

IV. Java Semantics

General Semantics

- Statements and expressions are standardly modeled as state transformer functions acting on a suitable (global) state space
- Before looking at the situation in Java, we first look at statements with possible non-termination
- One can distinguish two representations:

Option 1: Modify the state space:

$$(\{\mathrm{hang}\} + \mathrm{State}) \xrightarrow{\mathrm{stat}} (\{\mathrm{hang}\} + \mathrm{State})$$

with requirement:

$$\mathrm{stat}(\mathrm{hang}) = \mathrm{hang}$$

- The state space gets more complicated, but statement composition is simply function composition.
- However, side-conditions have to be kept in mind.

Option 2: Modify the output type:

$$\mathrm{State} \xrightarrow{\mathrm{stat}} (\{\mathrm{hang}\} + \mathrm{State})$$

- State space remains simple, and there are no side-conditions.
- But statement composition must deal with non-termination:

$$\begin{aligned}(s_1 \, ; \, s_2) \cdot x \quad = \quad & \mathrm{CASES}\ s_1 \cdot x\ \mathrm{OF}\ \{ \\ & \mid \mathrm{hang} \longmapsto \mathrm{hang} \\ & \mid y \longmapsto s_2 \cdot y\ \}\end{aligned}$$

Modeling exceptions: Two ways:

- **In the state space**
  - Most common, e.g. used by ***Alves-Foss & Lam*** (with continuations), or ***von Oheimb & Nipkow***.
  - ***Disadvantage***: complicates the state space; not so transparent; non-trivial side-conditions.
- **In the output type of the state transformers**

  Coalgebraic way, with statements and expressions:

$$\mathrm{State} \xrightarrow{\mathrm{stat}} \{\mathrm{hang}\} + \mathrm{State} + (\mathrm{State} \times \mathrm{Excp})$$

$$\mathrm{State} \xrightarrow{\mathrm{expr}} \{\mathrm{hang}\} + (\mathrm{State} \times \mathrm{Out}) + (\mathrm{State} \times \mathrm{Excp})$$

Coalgebras

- General form: functions with ***structured*** output type:

$$\mathrm{State} \longrightarrow \boxed{\cdots \quad \mathrm{State} \quad \cdots}$$

- No clutter in state space, nor complicated side conditions
- The type system forces explicit handling of all termination modes via pattern matching.

  This works very naturally, both in specification and verification. See exception mechanism paper at [ESOP'01].

Java Expressions

- $\text{State} \xrightarrow{\text{expr}} \{\text{hang}\} + (\text{State} \times \text{Out}) + (\text{State} \times \text{Excp})$
- with ***constructors***

$$\text{expr} \cdot x \;=\; \begin{cases} \text{hang} \\ \text{norm}(y, r) \\ \text{excp}(z, e) \end{cases}$$

  allowing ***pattern matching***

- Possible in a simple type theory with products $\times$ and coproduct $+$ types.

Java Statements I

- First version

$$\text{State} \xrightarrow{\text{stat}} \{\text{hang}\} + \text{State} + (\text{State} \times \text{Excp})$$

  is too simple: ***expressions*** in Java can only terminate abruptly because of an exception, but ***statements*** also because of a ***return***, ***break***, or ***continue***. Instead:

- $\text{State} \xrightarrow{\text{stat}} \{\text{hang}\} + \text{State} + \text{Abrupt}$

  where Abrupt is:

$$(\text{State} \times \text{Excp}) + \text{State} + (\text{State} \times \text{Lift}(\text{string})) + (\text{State} \times \text{Lift}(\text{string}$$

Java Statements II

This representation involves nested pattern matching:

$$\text{stat} \cdot x \;=\; \begin{cases} \text{hang} \\ \text{norm}(y) \\ \text{abnorm}(\text{a}) \end{cases}$$

where:

$$\text{a} \;=\; \begin{cases} \text{excp}(z, e) \\ \text{rtrn}(z) \\ \text{break}(z, \ell) \\ \text{cont}(z, \ell) \end{cases}$$

Example: Composition

- For two statements

$$\text{State} \overset{s_1}{\underset{s_2}{\rightrightarrows}} \{\text{hang}\} + \text{State} + \text{Abrupt}$$

- Define the composite statement as:

$$\begin{aligned}(s_1 \,;\, s_2) \cdot x \;=\; & \text{CASES } s_1 \cdot x \text{ OF } \{ \\ & \quad \mid \text{hang} \longmapsto \text{hang} \\ & \quad \mid \text{norm}(y) \longmapsto s_2 \cdot y \\ & \quad \mid \text{abnorm}(a) \longmapsto \text{abnorm}(a) \; \}\end{aligned}$$

In this way all Java constructs are translated into PVS.

V. Hoare Logic for JML

Hoare logic for JML 1 [FASE'01]

- This Hoare logic not at ***syntactic***, but ***semantic*** level:

  I.e. ***not*** $\{\,P\,\}\,m\,\{\,Q\,\}$, ***but*** $\{\,P\,\}\,[\![\,m\,]\!]\,\{\,Q\,\}$,

  Since $[\![\,s_1\,;\,s_2\,]\!] = [\![\,s_1\,]\!]\,;\,[\![\,s_2\,]\!]$ proofs are still "syntax driven"

- Complications in Hoare logic for Java:
  - exceptions and other abrupt control flow
  - expressions may have side effects

  Thus:
  - not Hoare ***triples*** but Hoare ***n-tuples***,
  - both for statements & expressions

Hoare Logic for JML 2

For $\{\,Pre\,\}\,m\,\{\,Post\,\}$ write $\left(\begin{array}{rcl}\text{requires} & = & Pre\\ \text{statement} & = & m\\ \text{ensures} & = & Post\end{array}\right)$

For JML one needs: $\left(\begin{array}{rcl}\text{diverges} & = & D\\ \text{requires} & = & Pre\\ \text{statement} & = & m\\ \text{ensures} & = & Post\\ \text{signals} & = & P_{exc}\\ \text{return} & = & P_{ret}\\ \text{break} & = & P_{brk}\\ \text{continue} & = & P_{cnt}\end{array}\right)$

Corresponding to coalgebra +-options

Filled in only during proofs

Logic for JML 3: Composition Rule

$$\frac{\left(\begin{array}{rcl}\text{requires} & = & Pre\\ \text{statement} & = & s_1\\ \text{ensures} & = & Q\\ \text{signals} & = & P_{exc}\\ \text{return} & = & P_{ret}\\ \text{break} & = & P_{brk}\\ \text{continue} & = & P_{cnt}\end{array}\right) \qquad \left(\begin{array}{rcl}\text{requires} & = & Q\\ \text{statement} & = & s_2\\ \text{ensures} & = & Post\\ \text{signals} & = & P_{exc}\\ \text{return} & = & P_{ret}\\ \text{break} & = & P_{brk}\\ \text{continue} & = & P_{cnt}\end{array}\right)}{\left(\begin{array}{rcl}\text{requires} & = & Pre\\ \text{statement} & = & s_1\,;\,s_2\\ \text{ensures} & = & Post\\ \text{signals} & = & P_{exc}\\ \text{return} & = & P_{ret}\\ \text{break} & = & P_{brk}\\ \text{continue} & = & P_{cnt}\end{array}\right)}$$

Weak Precondition Calculus (WPC)

- Most recent addition: WPC, integrated within Hoare logic for JML.
- Implemented as (provable) rules in PVS, used for automatic rewriting in special command **(WP-ASSERT)**, using dedicated PVS strategies.
- Automatically computes WPs for all Java constructs, excepts loops—which need (in)variant annotations.
- Requires much computational power
- Failure traces, if any, are hard to interpret—like with model checking.

WP-rule for plus

$$\dfrac{\forall i_1, i_2.\ \left(\begin{array}{rcl} \textsf{requires} & = & Pre \\ \textsf{statexprs} & = & \ell\,;\,(e_1 \Rightarrow i_1)\,;\,(e_2 \Rightarrow i_2) \\ \textsf{ensures} & = & \lambda x.\, i = i_1 + i_2 \Rightarrow Post(x) \\ \textsf{signals} & = & P_{exc} \\ \textsf{return} & = & P_{ret} \\ \textsf{break} & = & P_{brk} \\ \textsf{continue} & = & P_{cnt} \end{array}\right)}{\left(\begin{array}{rcl} \textsf{requires} & = & Pre \\ \textsf{statexprs} & = & \ell\,;\,((e_1 + e_2) \Rightarrow i) \\ \textsf{ensures} & = & Post \\ \textsf{signals} & = & P_{exc} \\ \textsf{return} & = & P_{ret} \\ \textsf{break} & = & P_{brk} \\ \textsf{continue} & = & P_{cnt} \end{array}\right)}$$

VI. Applet Case Studies:

- **Purse applet**
- **Phone applet**

Purse example [AMAST'02]

- Electronic purse applet case study provided by smart card manufacturer ***Gemplus***.

  (debit, credit, currency conversion, communication with loyalty applets)
- About 65 K of Java code, check in ESC/Java (Cataño & Huisman): numerous small bugs.
- Utility class Decimal verified with the LOOP tool: Several obvious bugs; complicated methods verified.

Purse example: Decimal class 1

- There are no floats in JavaCard, so a currency amount is a pair of ***shorts***

  (`intPart`, `decPart`)

  with fixed `PRECISION = 1000`.

- Decimal class invariant:
```
/*@ invariant -PRECISION < decPart
        && decPart < PRECISION; @*/
```


Purse example: Decimal class 2

- €1.35 can be
  - `(intPart = 1, decPart = 350)`
  - `(intPart = 2, decPart = -650)`
- Relevant value:

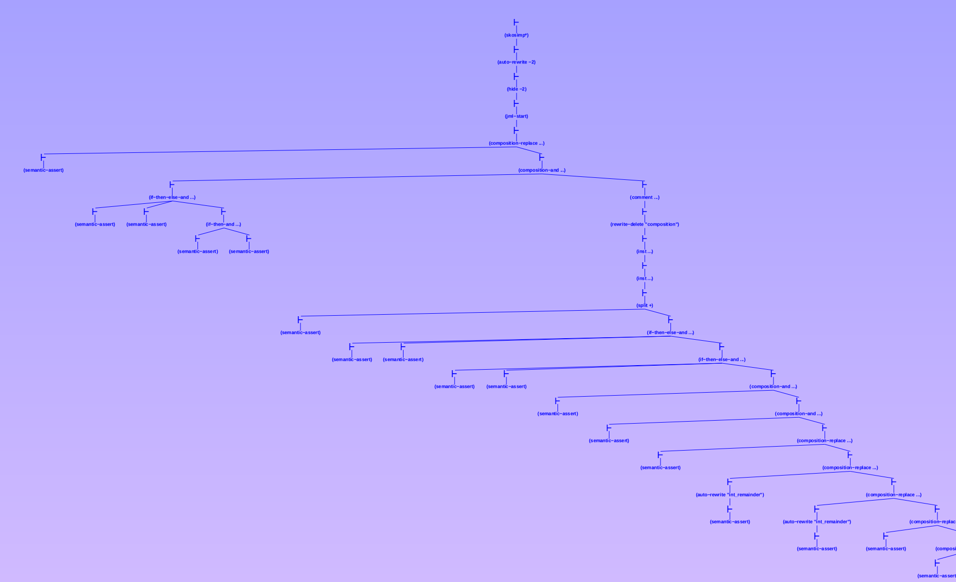
  `intPart * PRECISION + decPart`

  should be used as ***model variable***.
- Hence we use 1350 *milli-€*, to prove correctness of addition, multiplication, subtraction, etc.

Purse example: add method

```
/*@ normal_behavior
  @ requires -PRECISION < f && f < PRECISION;
  @ modifiable intPart, decPart;
  @ ensures intPart * PRECISION + decPart ==
  @ (\old(intPart)+e)*PRECISION+\old(decPart)+f;
  @*/
private void add(short e, short f) {
   intPart += e;
   if ( intPart > 0 && decPart < 0 ) {
      intPart--; decPart = (short) (decPart + PRECISION); }
   else if ( intPart < 0 && decPart > 0 ) {
         intPart++; decPart = (short) (decPart - PRECISION); }
   decPart += f;
   if ( intPart > 0 && decPart < 0 ) {
      intPart--; decPart = (short) (decPart + PRECISION); }
   else if ( intPart < 0 && decPart > 0 ) {
      intPart++; decPart = (short) (decPart - PRECISION); }
   else { short retenue = (short) 0; short signe = 1;
         if ( decPart < 0 ) { signe = (short) -1;
                              decPart = (short) -decPart; }
         retenue = (short) (decPart / PRECISION);
         decPart = (short) (decPart % PRECISION);
         retenue *= signe; decPart *= signe; intPart += retenue; }
}
```


Hoare logic proof tree in PVS



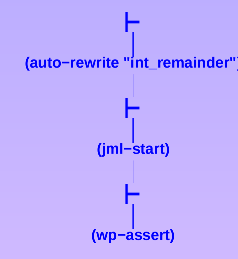
Weak Precondition proof

- Add example involves too many case distinctions:
  PVS becomes too big and crashes after handling > 66.
- Two solutions . . .

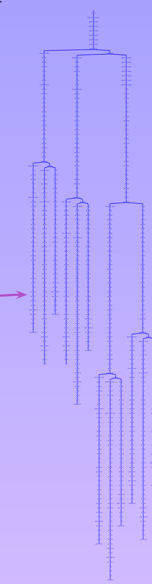
WP solution 1: cheat

Simplification:
replace **&&** by **&**,
to avoid many splits.

Resulting prooftree:



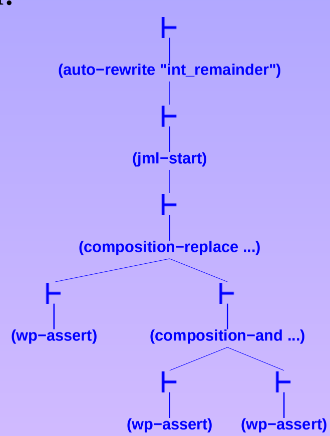
Expanded version:



WP solution 2: combine Hoare + WP

Use Hoare logic rules to break up the proof goal into manageable parts, to be handled by `(WP-ASSERT)`.

For the add method:



Example: simple phone card applet

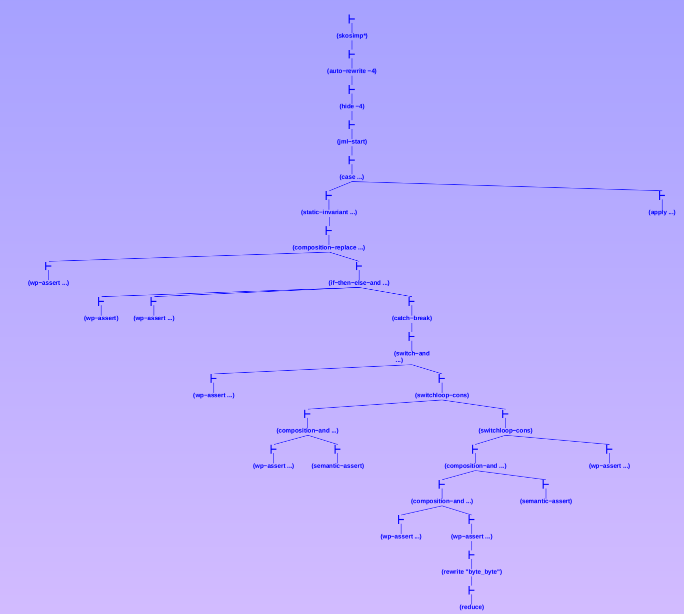
- 3 operations: decrement-value, show-value, set-value
- set-value may only be used once before the card is 'issued'
- Communication with card proceeds (in two directions) via special byte sequences, called ***apdu***'s.
  Apdu's are handled by a method **`process`**.
- The applet uses two instance variables:
  ```
  private byte value;
  private boolean issued;
  ```

Process specification + implementation

```
/*@ behavior
  @ requires apdu != null;
  @ modifiable value, issued, apdu.buffer[*];
  @ ensures \old(issued) ==> (issued &&
  @                  value <= \old(value));
  @ signals (ISOException e) \old(issued) &&
  @    (value <= 0 || apdu.buffer[1] == 0x73)
  @    && issued && value == \old(value);
  @*/
public void process(APDU apdu) {
   byte[] buffer = apdu.getBuffer();
   if (value <= 0 && issued) { ISOException.throwIt((short)0x6982); }
   else { switch( buffer[1] ) {
           case 0x71:  value--; break;
           case 0x72:  apdu.setOutgoing();
                       apdu.setOutgoingLength((short)1);
                       buffer[0] = value;
                       apdu.sendBytes((short)0,(short)1); break
           case 0x73:  if (issued) { ISOException.throwIt(
                                    (short)0x6982); }
                       else { value = buffer[2]; issued = true; }
                       break; } }

}
```


Hoare & WP proof of process



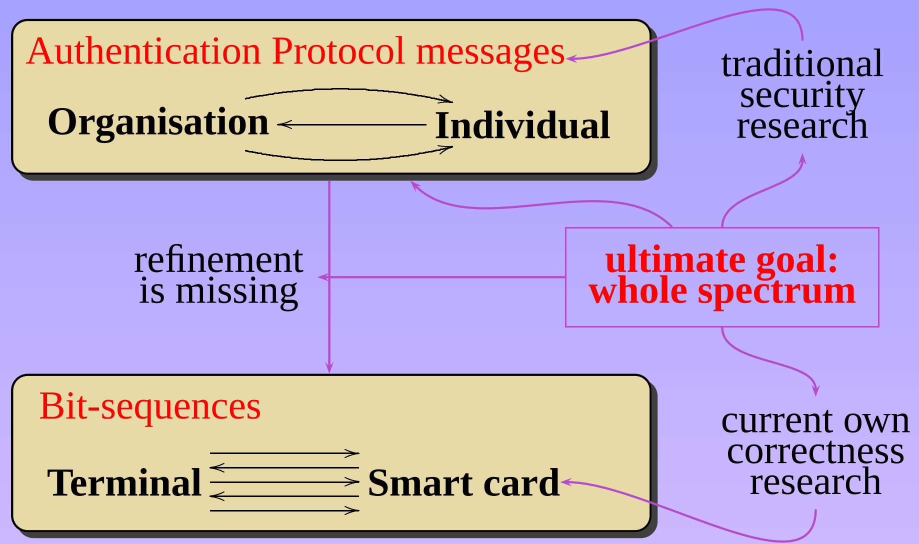
VII. Future work

Scalability

The LOOP verification technology for Java + JML works.
Now we have to scale it further, via:

- Just waiting for faster hardware!
- Reducing the user-interaction:
  - even better PVS strategies
  - Weak precondition reasoning, integrated with
  - annotated programs (proof outlines)

Extension to Security



Conclusions

- JavaCard presents a real challenge and opportunity for formal methods to deliver in the software area.
- The tool-based verification technology for Java(Card) is there, but scaling it up to larger programs is still a challenge.
- Standard approaches (Hoare, WP) work, after non-trivial extensions.
- Transfer to industry is happening: Gemplus, Schlumberger, Ericsson, IBM, France Telecom, TNO, . . .

More info at: `www.cs.kun.nl/~bart/LOOP`