Verifying JAVA CARD Programs with KeY

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Overview

Goals

- Explain only really the necessary things, if hungry for more:
  - Reiner Hähnle's tutorial from COST Winter School 2009: http://www.key-project.org/costws09/
  - The KeY book

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Outline

- What is KeY?
- What is JAVA CARD?
- How does KeY deal with JAVA CARD?
- Tasks for the rest of the session

The KeY System

- First Order Java Dynamic Logic prover
  - $< p > \varphi$ – total correctness
  - $[\, p \,] \varphi$ – partial correctness
  - ($[\![p]\!] \varphi$ – strong invariant correctness)
  - Hoare triple in DL is $pre \rightarrow [\, p \,] post$

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- Rules can be fine tuned with taclet options
- Proofs can be guided by fiddling with prover options

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- Proofs can be guided by fiddling with prover options
- Verification paradigm: symbolic execution with state updates (implicit heap representation)

Symbolic Execution

```
\programVariables { int a, a@pre, b; }

\problem {

  b > 0 ->
  { a@pre := a }
    \<{ if(a == b) { a += 2; } }\>
  ( (a@pre != b & a = a@pre) | a = b + 2 )

}
```

Demo

example1.key

KeY Specification Languages

- The core of KeY is Java Dynamic Logic
- DL Proof Obligations (PO-s) can be generated from program contracts written in:
  - Object Constraint Language (OCL) – legacy
  - (Subset of) JML
  - Dynamic Logic itself
- The last option is most attractive:
  - (Almost) no translation overhead
  - JML semantics moving target, no need to worry about it
  - KeY semantics is different anyhow
  - Direct access to the logic enables more precise specifications
- KeY DL is easy!

Program Specifications – JML vs. KeY DL

JML

```
class MyClass {
  int i; //@invariant i > 0;

  //@requires o != null;
  //@ensures
      this.i == \old(o.i);
  //@assignable this.i;
  void setFrom(MyClass o) {
    this.i = o.i;
  }
}
```

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KeY DL

```
MyClass_setFrom {
  \programVariables {
      MyClass self, o; }
  o != null -> \<{
    self.setFrom(o)@MyClass;
  }\> (self.i = o@pre.i)

  \modifies { self.i }
};

\invariants (MyClass self) {
  MyClass_inv { self.i > 0 };
}
```

Program Specifications – JML vs. KeY DL

JML

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class MyClass {
  int i; //@invariant i > 0;

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  \modifies { self.i }
};

\invariants (MyClass self) {
  MyClass_inv { self.i > 0 };
}
```

Program Specifications

Exceptions

```
MyClass_setFrom {
  \programVariables { MyClass self, o; }

  true -> \<{
    #catchAll(java.lang.Exception e) {
      self.setFrom(o)@MyClass;
    }
  }\>(( e = null -> self.i = o@pre.i )
    & ( e != null ->
      java.lang.NullPointerException::instance(e) = TRUE ) )

  \modifies { self.i }
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    Each method ensures its postcondition.
    You are free to choose which invariants you need for that,
  - `RespectsModifies`
    Each method respects its modifies clause.
    Same w.r.t. invariant use,
  - `PreservesInv`
    On a per-contract application base, each method preserves invariants that were chosen during that contract application.

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    On a per-contract application base, each method preserves invariants that were chosen during that contract application.
- KeY will tell you what you need to prove to make it happy,
- Best explained with `example2.key`.

Example 2 – Code

```
public class MyClass {
  int i, j;

  void setIFrom(/*@ nullable @*/ MyClass other) {
    this.i = other.i;
  }

  void setJFrom(/*@ nullable @*/ MyClass other) {
    this.j = other.j;
  }

  void setFrom(/*@ nullable @*/ MyClass other) {
    setIFrom(other);
    setJFrom(other);
  }
}
```

Example 2 – Specification

```
MyClass_setIFrom { \programVariables { MyClass self, other; }
  other != null -> \<{ self.setIFrom(other)@MyClass; }\>
    (self.i = other@pre.i)
  \modifies { self.i } };

MyClass_setJFrom { \programVariables { MyClass self, other; }
  other != null -> \<{ self.setJFrom(other)@MyClass; }\>
    (self.j = other@pre.j)
  \modifies { self.j } };

MyClass_setFrom { \programVariables { MyClass self, other; }
  other != null -> \<{ self.setFrom(other)@MyClass; }\>
    (self.i = other@pre.i & self.j = other@pre.j)
  \modifies { self.i, self.j } };

\invariants (MyClass self) {
  inv_i { self.i >= 0 };
  inv_j { self.j >= 0 };
}
```

Let's Play!

- Preferred JDK is Sun/Oracle 1.6
- Install KeY 1.6
  `http://www.key-project.org/download/`
  - Permanent Installation
  - Java Webstart
- Switch off:
  - KiKi The Proof Assistant
  - Sound
- Load and prove `example1.key`
  - Change integer number semantics, try again & fix
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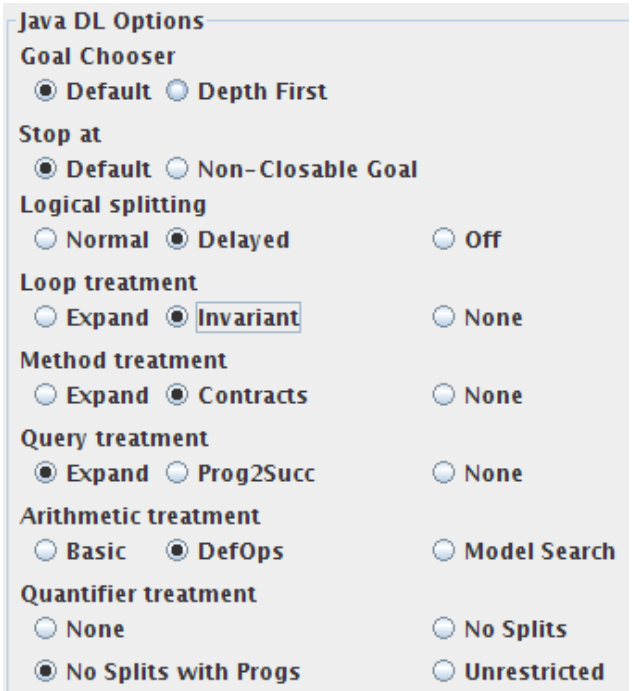

JAVA CARD

- A smart card running a cut-down JAVA VM
- Smart card specific cut-down JAVA API:
  - Smart card specific functionality
  - Cryptographic libraries
- No "disk" storage, only two types of memory:
  - RAM – session memory, fast, 0.5–4K
  - E^2PROM – storage memory, slow (write), 16–72K
  - Memory destination of a variable/field is determined by the declaration place and/or allocation method

JAVA CARD and Verification

Why important?

- Smart card applications highly security sensitive
- Roll-out and replacement expensive and time consuming:
  - Really need to be bug free
  - Patches and fixes are out of question

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  (4) Strings

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  (4) Strings (5) Large integers (6) Floats (7) I/O
  (8) External storage (9) Dynamic class loading
- Not much left really, seems to be an easy verification target for most tools...

JAVA CARD Verification Difficulties

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- Cryptography libraries
- Data is mostly byte arrays – reference aliasing issues
- Some API calls have very deep semantics:
  - Change the internal behaviour of the JAVA CARD VM
  - Hardly possible to model with a pre/-post contract
  - Most notably transaction mechanism calls

JAVA CARD Verification Difficulties

Applications

- Need to follow a few design and coding principles:
  - What is in RAM, what is in E^2PROM (session vs. stored data)
  - No (re-)allocation of memory after initialisation (prevent DOS)
  - Small code and memory footprint (limited resources)

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  - No (re-)allocation of memory after initialisation (prevent DOS)
  - Small code and memory footprint (limited resources)
- Applications can to be very complex at the same time:
  - Domains heavy on cryptography
  - The new JAVA CARD 3.0 technology – smart cards will run embedded web-servers and similar applications...

JAVA CARD Example

```
public class CountersApplet extends Applet implements ISO7816 {

  private final static byte GET_COUNTS = 0x10;

  private short selectCounter = 0;

  private short[] commandCounter = JCSystem.makeTransientShortArray(
        (short)1, JCSystem.CLEAR_ON_RESET);

  protected CountersApplet() {
    register();
  }

  public static void install(byte[] data, short off, short len) {
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  if(selectingApplet()) { selectCounter++; return; }
  commandCounter[0]++;
  byte[] buffer = apdu.getBuffer();
  switch(buffer[OFFSET_INS]) {
    case GET_COUNTS:
      Util.setShort(buffer, (short)0, selectCounter);
      Util.setShort(buffer, (short)2, commandCounter[0]);
      apdu.setOutgoingAndSend((short)0, (short)4);
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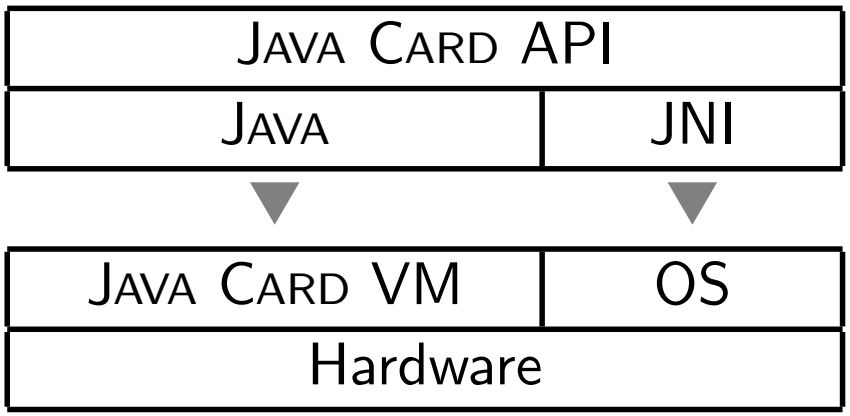
KeY and JAVA CARD

KeY's JAVA CARD VM Model

- Different kinds of memory:
  - Implicit field `<transient>` for objects (like `length` for arrays)
- Semantics of transactions, rather heavyweight inside KeY
- Relies on dedicated (built-in) API methods and tailored logic rules, rather than contracts
  I.e. built-in contracts for `KeYJCSystem.jvm*`
- Exactly as real API relies on the underlying OS through JNI

KeY and JAVA CARD



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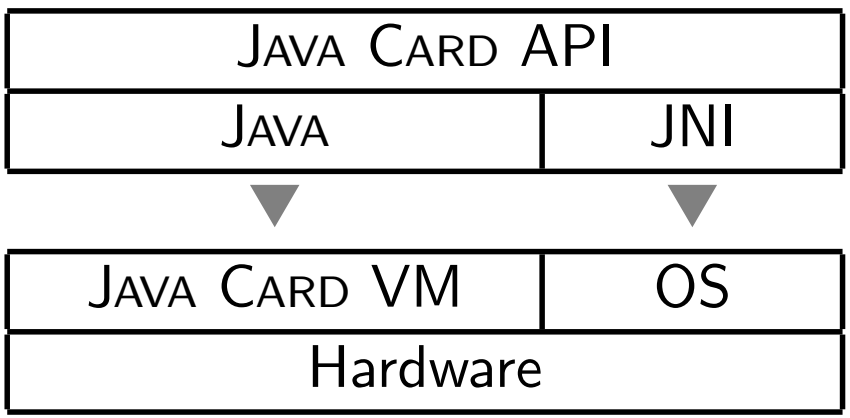

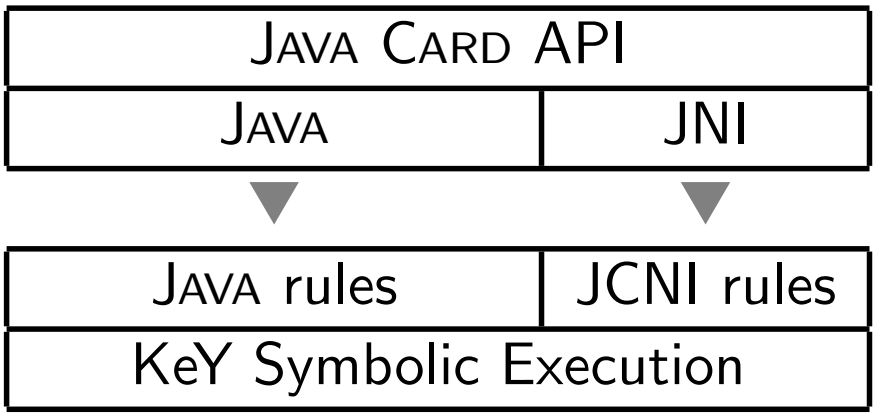

KeY and JAVA CARD

In Practice

- KeY JAVA CARD mode – taclet options
- For modular verification best use DL specified contracts
- Be aware that some API methods have a built-in meaning
  No contracts provided

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JAVA CARD API

- Specified reference implementation
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- DL method contracts & class invariants

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Electronic Driving License JAVA CARD Implementation

- Proper JAVA CARD code (actually deployed in NL)
- Only partly specified

KeY Setup for Today

- All JAVA CARD features on
- Overflow control on
- Taclet options:

```
intRules:
  arithmeticSemanticsCheckingOF
javacard:jcOn
transactions:transactionsOn
transactionAbort:abortOn
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- KeY project files
  http://limerick.cost-ic0701.org/home/verifying-java-card-programs-with-key

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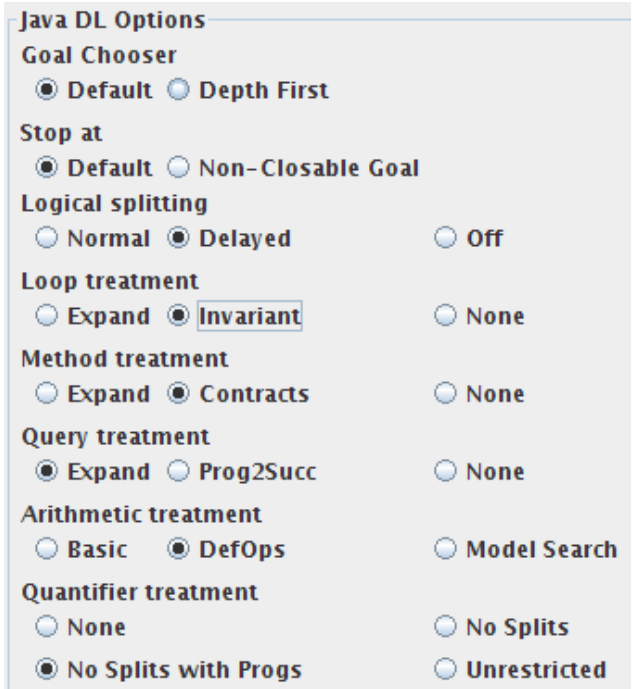

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  - More difficult (small interactions & proof guiding):
    `APDU.setOutgoingAndSend`
    Ask me for Proof Strategy Settings
  - Even more difficult (careful invariant choice):
    `JCSystem.lookupAID`
  - Load file `javacardapi.key` into KeY

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  - Load file `javacardapi.key` into KeY
- For experts: specify and verify `FileSystem.getFileIndex`
  - Consult with me first
  - Look for hints in `FileSystem.key`
  - Load file `edl.key` into KeY

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  - `Normal` Branch the proof "at will"
  - `Delayed` Analyse the program code first, only then branch

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- Logical splitting:
  - `Normal` Branch the proof "at will"
  - `Delayed` Analyse the program code first, only then branch
- Arithmetic treatment:
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- Leave the rest as suggested

Resources

- Tutorial page & material
  http://limerick.cost-ic0701.org/home/verifying-java-card-programs-with-key
- KeY download / webstart
  http://www.key-project.org/download/
- JAVA CARD API Documentation
  http://www.cs.ru.nl/~woj/javacardapi221/index.html
- ISO18013 Electronic Driving License project
  http://sourceforge.net/projects/isodl/
- More top quality material on KeY
  http://www.key-project.org/costws09/

APDUs

Application Protocol Data Units

- Half-duplex communication channel
- Essentially byte arrays

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ISO18013 Implementation

Electronic Driving License Card

- Files, called Data Groups (DGs), with driver's data:
  - Name, Date of Birth, . . . , License Categories
  - Picture and signature, both JPEG(2000)
  - Biometric information, e.g. fingerprints
- Document Security Object: special DG with hashes of the data and issuer's digital signature
- DGs are read with APDUs:
  - `INS_SELECT_FILE`, instruction byte `0xA4`
  - `INS_READ_BINARY`, instruction byte `0xB0`
- Access to data subject to access control: BAP and EAP. . .

ISO18013 Implementation

Basic Access Protection (BAP)

- Protects all read outs from the card
- Secure messaging channel based on a static DES key (card#)
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Extended Access Protection (EAP)

- Requires BAP, protects sensitive data, e.g. biometrics
- Proves the card authenticity to the terminal (Diffie-Hellman) and terminal access rights to the card (certificate verification)
- Several APDUs