

Practical Verification of Java

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The Java Modeling Language (JML)

- ✧ initiative of Gary Leavens [Iowa St.]
- ✧ Behavioral Interface Specification Language (BISL) for Java
 - ✧ annotations for Java programs expressing pre- and postconditions, invariants, etc.
- ✧ inspired by Eiffel's DBC and Larch
- ✧ Primary design goal: easy to learn
 - ✧ is a simple extension to Java's syntax

A JML Example

```
private int balance;  
final static int MAX_BALANCE;  
  
/*@ invariant 0 <= MAX_BALANCE &&  
           balance < MAX_BALANCE;  
   @*/
```

A JML Example

```

/*@ requires    0 <= amount;
   assignable balance;
   ensures     balance ==
                \old(balance) - amount;
   signals     (PurseException)
                balance == \old(balance);

```

@*/

```

public void debit(int amount) {

```

...

```

}

```


A JML Example

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/*@ requires      0 <= amount;
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   signals       (PurseException)
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public void debit(int amount);
  
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public void debit(int amount);
  
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A JML Example

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   signals      (PurseException)
                   balance == \old(balance);
/*@/

public void debit(int amount);

```

A Jml Example

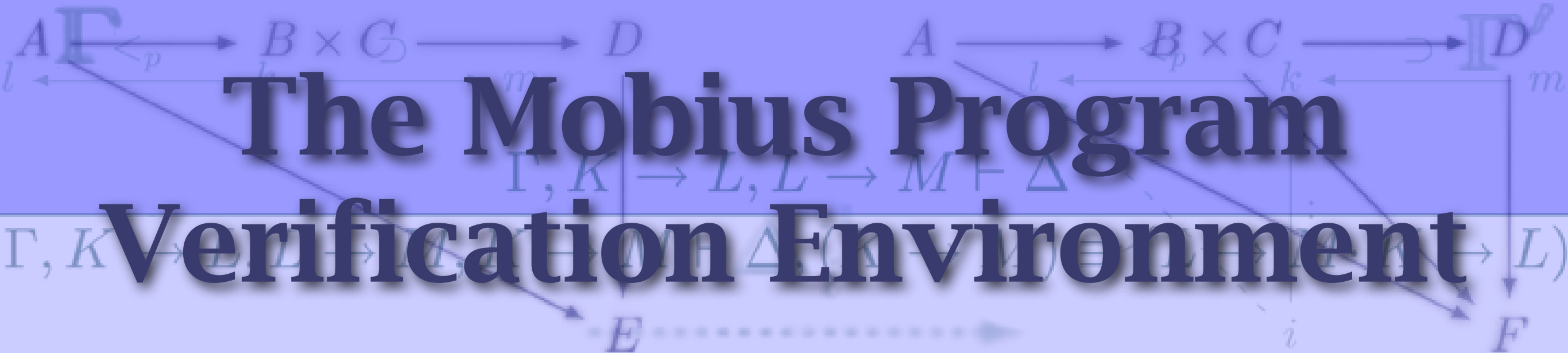
```
private byte[] pin;  
private byte  appletState;
```

```
/*@ invariant  
    appletState == PERSONALIZED  
    ==>  
    pin != null &&  
    pin.length == 4 &&  
    (\forallall int i; 0 <= i && i < 4;  
        0 <= pin[i] && pin[i] <= 9);  
@*/
```

A JML Example

```
private byte[] pin;  
private byte appletState;
```

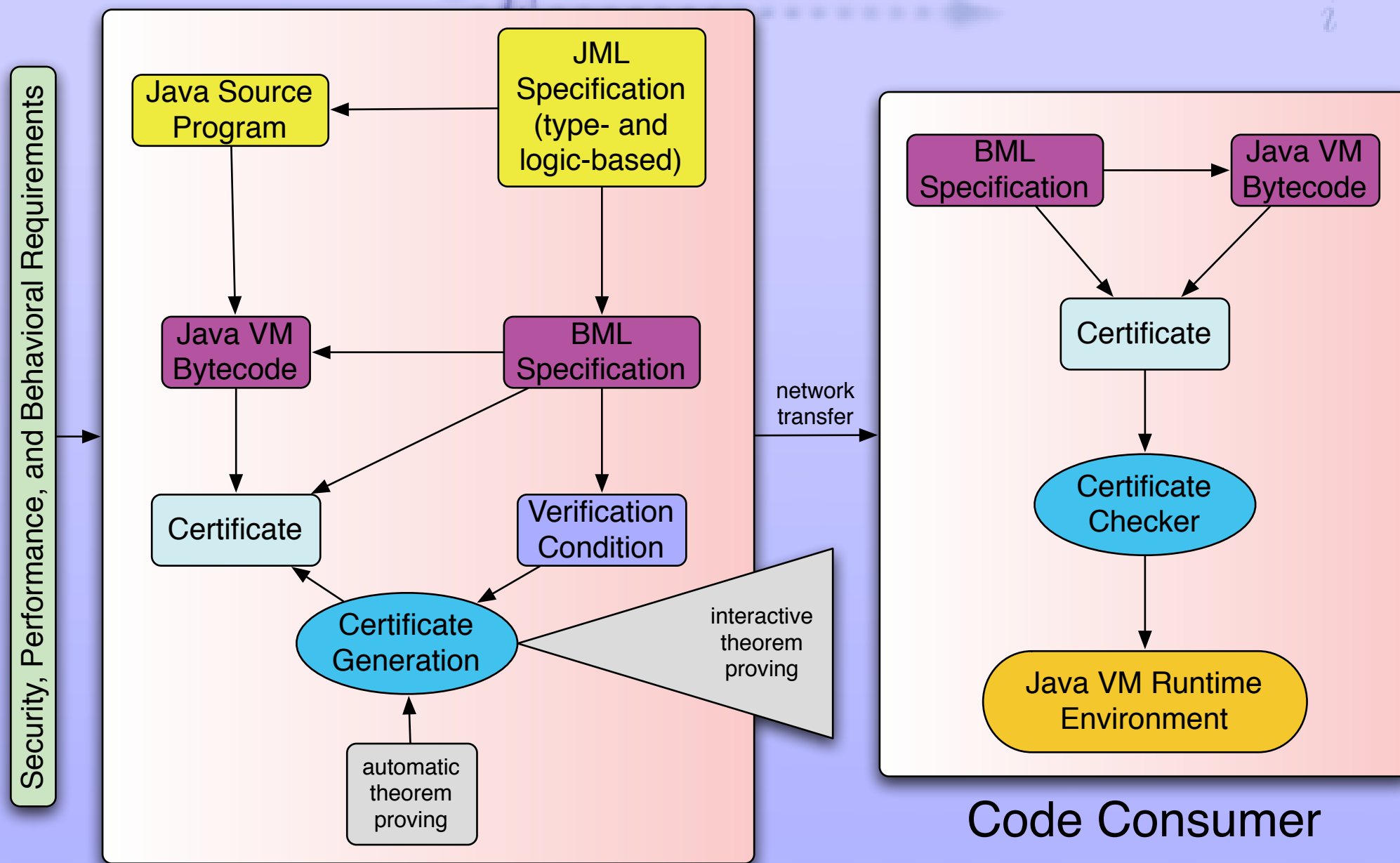
```
/*@ invariant  
    (appletState == PERSONALIZED)  
    ==>  
    (pin != null) &&  
    (pin.length == 4) &&  
    (\forallall int i; ((0 <= i) && (i < 4));  
        ((0 <= pin[i]) && (pin[i] <= 9)));  
@*/
```



The Mobius Program Verification Environment

- ✧ Mobius Program Verification Environment
[Mobius consortium, led by UCD]
 - ✧ combines existing best-of-breed tools
 - ✧ new, single semantic foundation
 - ✧ reasons about Java source and bytecode
 - ✧ produces proof-carrying code certificates
 - ✧ includes a PCC infrastructure for Java-like languages (i.e., OO + bytecode, Spec#-like)

Mobius Architecture



Code Producer

Code Consumer

Mobius PVE *User* Features

- ✧ Java program code features
 - ✧ writing new code
 - ✧ type-aware completion
 - ✧ compiling, debugging, refactoring, folding code
 - ✧ generate Javadoc documentation
 - ✧ analyze code complexity
 - ✧ analyze coding standard conformance
 - ✧ detecting common programming errors

Mobius PVE *User* Features

- ✧ Java Modeling Language features
 - ✧ writing new specifications
 - ✧ tracking refinement
 - ✧ compiling specifications to runtime tests
 - ✧ generate Javadoc documentation
- ✧ Bytecode Modeling Language features
 - ✧ display BML-annotated Java VM bytecode
 - ✧ edit BML
 - ✧ edit Java VM bytecode

Mobius PVE *User* Features

- ✧ JML-annotated programs features
 - ✧ unit test generation
 - ✧ specification generation
 - ✧ class and loop invariant generation, precondition propagation, requirement-driven generation
 - ✧ translation to guarded commands
 - ✧ indicate program parts that correspond to the current VC or proof fragment
 - ✧ annotation tracing
 - ✧ creation, justification, relationship to requirements, features, and bugs, etc.

Mobius PVE *User* Features

- ✧ theorem prover features
 - ✧ use in a natural way interactive provers
 - ✧ choose which automatic provers to use
- ✧ application requirements features
 - ✧ authoring new requirements
 - ✧ refine requirements into specifications
 - ✧ tracing requirements over time, through architecture, and into proof and certificate
- ✧ certificate features
 - ✧ generate Mobius PCC certificates

Verification Bus Features

- ✧ Java, JML, and BML lexer, parser, type checker, and transformation subsystem
 - ✧ generates, visualizes, and manipulates Java VM bytecode, JML annotations, Javadocs, BML-annotated bytecode, and DOT files
- ✧ FreeBoogie subsystem
 - ✧ FreeBoogiePL = structured and unstructured BoogiePL + explicit heap + separation logic
 - ✧ FreeBoogie VC generation targets Mobius VC back-end

Verification Bus Features

- ✧ Mobius VC back-end
 - ✧ unsorted and sorted VC representation
 - ✧ logic-aware syntax generation to several automatic and interactive theorem provers
 - ✧ generation of Mobius VCs in Base Logic in Coq
- ✧ Mobius ESC VC back-end
 - ✧ generation of ESC VCs in ESC Logics
 - ✧ generate ESC VCs for several automatic and interactive theorem provers
 - ✧ extended static checking of ESC VCs with rich in-editor feedback

Verification Bus Features

- * Mobius Prover back-end
 - * generic interaction with a variety of automatic and interactive theorem provers
 - * automatic provers supported
 - * Simplify, SMT, CVC3, Yices, Fx7
 - * interactive provers supported
 - * Coq and PVS
 - * proof status maintenance
 - * proof unit/smoke testing
 - * automatic and seamless proof sharing amongst distributed collaborators

Verification Bus Features

- ✧ Mobius proof-transforming compiler
 - ✧ VC generation from Java source
 - ✧ compilation of source code-level proofs to bytecode-level proofs
- ✧ integration of several support tools
 - ✧ e.g., CheckStyle and FindBugs
 - ✧ the Race Condition Checker (RCC)
- ✧ help system and process management
 - ✧ task and feature tracking
 - ✧ online hypertext architecture docs and help

Mobius PVE: Status

- ✧ full support available for:
 - ✧ all Java and nearly all JML features
 - ✧ editing, compilation, doc generation, etc.
 - ✧ code complexity and style checking
 - ✧ partial BML support
 - ✧ no editing of BML or bytecode
 - ✧ Mobius VC back-end
 - ✧ Mobius Prover back-end
 - ✧ interactive proof support for Coq

Mobius PVE: Next Steps

✧ next version to integrate the subsystems:

- ✧ full BML support
- ✧ Universe type inference
- ✧ FreeBoogie and the Race Condition Checker
- ✧ user feedback of proof state in JML/Java
- ✧ proof status and unit/smoke testing
- ✧ Mobius VC generator (in Coq)
- ✧ interactive proof support for PVS
- ✧ Coq PCC certificate generation
- ✧ basic help system and process management

Use in Industry

- ✧ JavaCard

- ✧ subset of a superset of Java for programming smart cards
 - ✧ the subset: no floats, no threads, limited API, optional GC
 - ✧ the superset: support for allocation in EEPROM or RAM, transactions
- ✧ ideal target for formal methods



Use in Industry

- ✧ MIDP (Mobile Information Device Profile)
 - ✧ subset of a superset of Java for programming small devices
 - ✧ primarily mobiles and PDAs
 - ✧ includes networking capability, limited concurrency, small API, persistent store
 - ✧ is the primary target of the Mobius PVE

Use in Industry

- * isolated cases in specific settings
- * mostly independent from JML team
- * sometimes the result of interactions with members of the JML team (e.g., consulting)
- * most popular uses:
 - * runtime checking of preconditions
 - * static checking to eliminate NPEs

Use in Academia

- ✧ JML's use in undergraduate and graduate instruction
 - ✧ dozens of universities use JML and these tools for many different kinds of courses
 - ✧ introductory programming, programming languages, software engineering, problem- and project-based learning, applied formal methods, semantics, etc.
 - ✧ primary tools in use are the core JML tool suite and ESC/Java2

Use in The Netherlands

- ✧ OOTI course at Eindhoven
[jointly with Oostdijk, Hubbers, and Poll]
- ✧ graduate course for mature international students, some with industry experience
- ✧ focused on applied use of JML and its tools and model checking of protocols
- ✧ students focused one of a set of JavaCard applets (e.g., electronic purse)
- ✧ applets installed and run on real cards

Use in Ireland

- ✧ all of my courses include the use of JML
 - ✧ first year students learn to *read* (basic) JML and work in independent small teams on a small project, identical across all teams
 - ✧ second year students learn to *write* (basic) JML and work on a full-class project in medium-sized teams
 - ✧ third year students use JML and other techniques and tools as necessary on projects of their own design

Research Challenges

- * challenges of OO program verification
 - * aliasing, callbacks, open systems, concurrency, modular & sound reasoning
- * (deeper) theoretical and tool integration
 - * several semantics of VM, Java, and JML
- * incorporation of leading languages, frameworks, tools, and theory
 - * e.g., B, VDM, Z, CSP, etc.

Opportunities

- ✧ large, friendly, open community
 - ✧ finding collaborators is easy
- ✧ wide use in academia and growing use in industry
 - ✧ course materials available for reuse
 - ✧ if you build a good tool, they will come
 - ✧ many open and interesting problems

Summary

- * assertion-based languages are a promising way to leverage applied formal methods
 - * familiar syntax and semantics
 - * no need for a formal model for users
 - * easy to introduce and use incrementally
 - * JML as a de facto standard and a vehicle for research
 - * join us! <http://www.jmlspecs.org/>

Tools for JML

- ✧ tools for reading and writing specifications
- ✧ tools for generating specifications
- ✧ tools for checking an implementation against specifications

Tools for Reading and Writing Specifications

- ✧ parsing and typechecking (primarily as a part of other tools)
 - ✧ two best tools for these purposes are ESC/Java2 and the JML typechecker (“jml”)
- ✧ jmldoc: **javadoc** for JML
 - ✧ extends Javadoc to include specs in generated documentation

Tools for Reading and Writing Specifications

- ✧ the JML Eclipse plugin
[KSU, David Cok, Nijmegen, UCD]
- ✧ the ESC/Java2 Eclipse plugin
[Cok, Nijmegen, Warsaw, UCD]
- ✧ the ESC/Java2 specification consistency checker [Kiniry et al, UCD]
 - ✧ detect when specifications are unsound and identify problematic specs

Tools for Generating Specifications

- ✧ invariant detection using Daikon
[Michael Ernst, MIT]
 - ✧ Daikon observes execution of code to detect likely invariants
- ✧ specification guessing using Houdini
[Rustan Leino, DEC SRC then Poll et al, Nijmegen]
 - ✧ Houdini statically analyzes program structure to guess likely specifications

Tools for Generating Specifications

- ✱ loop invariant derivation using ESC/Java
[Cormac Flanagan et al, SRC then
Kiniry et al, UCD]

ESC/Java2 uses heuristics, abstract interpretations, and wp calculi to guess then check loop invariants and variants

Tools for Checking Specifications

- ✧ the Runtime Assertion Checker (RAC)
[Gary Leavens et al, Iowa St. and many others]

tests if specs are violated at runtime

- ✧ not terrifically exciting to academia, but very appealing to industry
- ✧ well-specified code is easy to test
 - ✧ RAC handles `\old`, `\forall`, `\exists`, etc.

Tools for Checking Specifications

- ✧ jmlunit (JML and jUnit combined)
[Gary Leavens et al, Iowa St.
and many others]

use specifications as test oracles

- ✧ automatically generate and compose a large number of unit tests into a test suite
- ✧ again, useful for students and industry
- ✧ no more hand-written unit tests

Tools for Checking Specifications

- ✧ the Extended Static Checker for Java (ESC/Java) [Rustan Leino et al, SRC]

automatic verification of simple properties

- ✧ not sound or complete, but finds many bugs quickly
- ✧ e.g., can statically “prove” the absence of many kinds of runtime exceptions

Tools for Checking Specifications

- ✧ the Chase tool [Nestor Cataño, INRIA]

frame condition checker

- ✧ remedies one important source of unsoundness in static checking
- ✧ the Race-Condition Checker (RCC)
[Flanagan et al, SRC then Kiniry et al, UCD]

statically detects field race conditions in concurrent Java programs

Tools for Checking Specifications

- ✧ ESC/Java2

[Cok and Kiniry et al, Nijmegen then UCD]
builds upon ESC/Java in *many* ways to
improve static checking capabilities

- ✧ reasons about all of core JML
- ✧ frame condition checking
- ✧ soundness and completeness warnings
- ✧ specification-aware dead code detection
- ✧ support for new provers and logics

Tools for Checking Specifications

- ✧ “real” program verification
 - ✧ JACK tool [Lilian Burdy, Gemplus then many others at INRIA]
 - ✧ inspired by ESC/Java, integrated in Eclipse
 - ✧ targets several provers, but mainly supports the B prover and Simplify
 - ✧ LOOP tool [Bart Jacobs et al, Nijmegen]
 - ✧ automatic and interactive (A&I) program verification in PVS

Tools for Checking Specifications

- ✧ the KeY tool [Chalmers and Karlsruhe]
 - ✧ A&I program verification using a CASE tool and a dynamic logic prover
- ✧ Krakatoa tool [INRIA/Orsay]
 - ✧ A&I program verification in Coq using Why
- ✧ the Bandera, Bogor, and Kiasan tools [John Hatcliff and Robby, KSU]
 - ✧ model checking and symbolic execution

Tools for Checking Specifications

- ✧ there is a large range of tools offering differing levels of assurance at different costs (i.e., time and effort)
- ✧ runtime assertion checking
- ✧ specification-based unit testing
- ✧ extended static checking
- ✧ automated and interactive full program verification