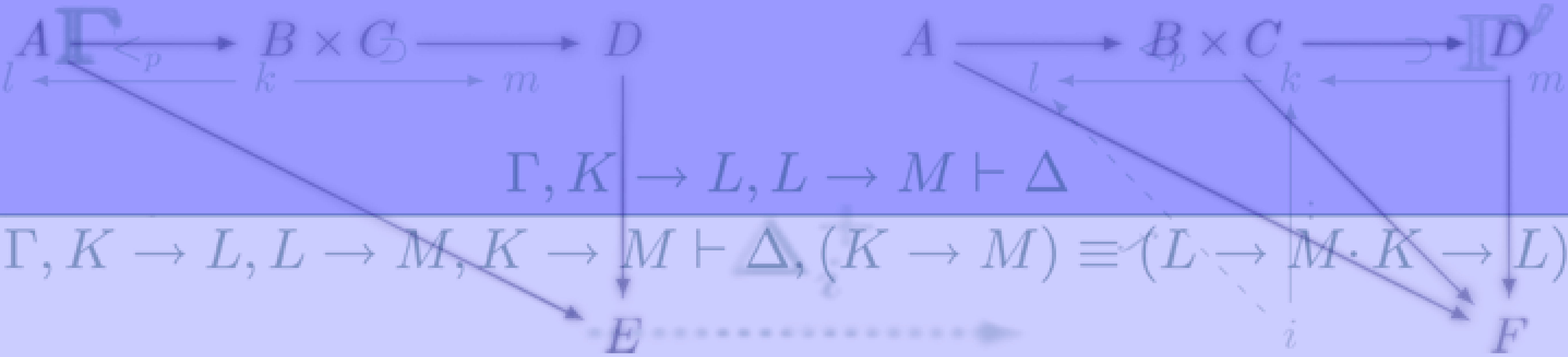

Practical Verification of Java

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Mobius

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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

```
/*@ requires   0 <= amount;
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                 \old(balance - amount);
    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 &&
      (\forall 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) &&
      (\forall 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)

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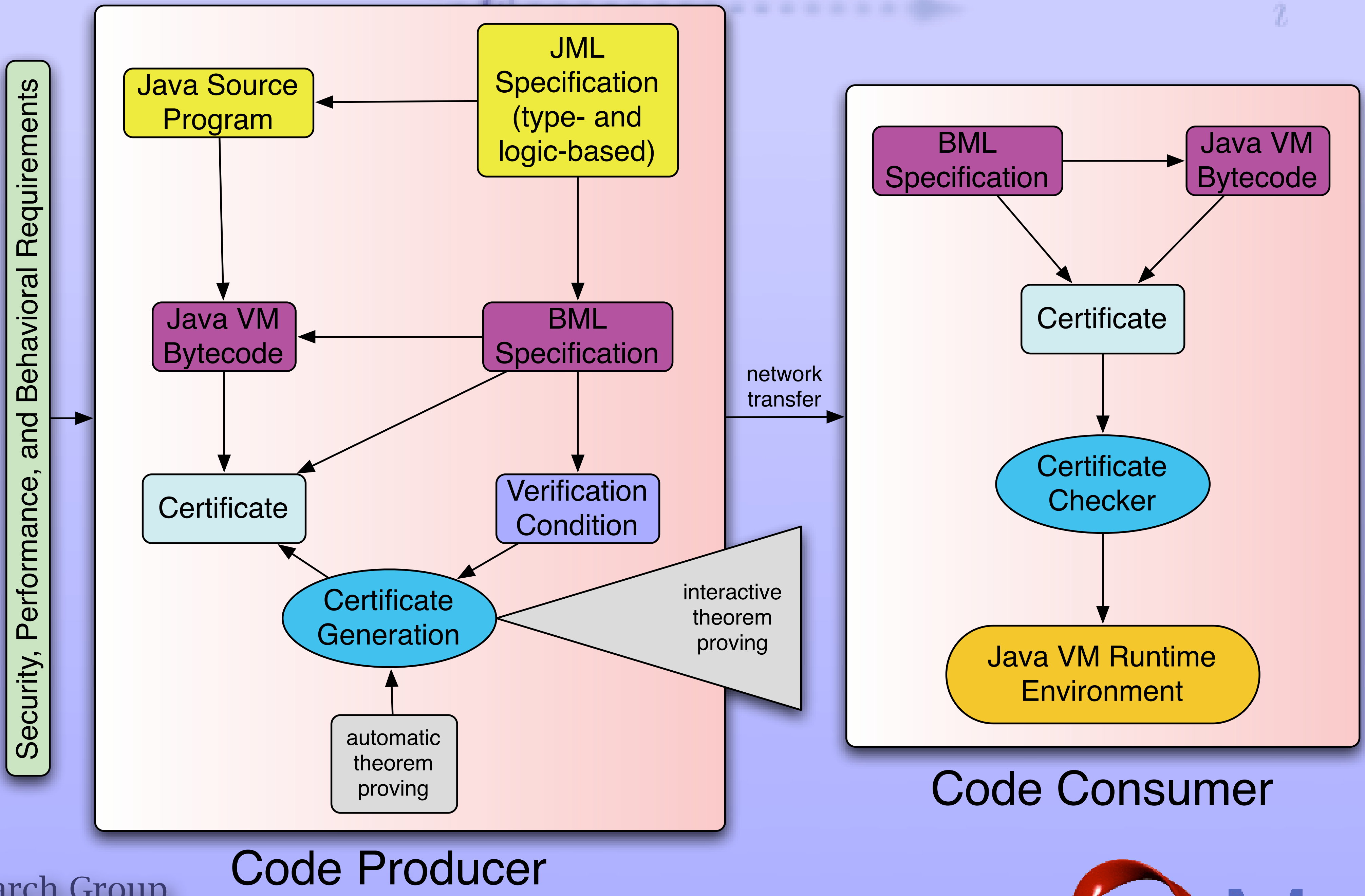
Mobius Architecture



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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, programing 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.

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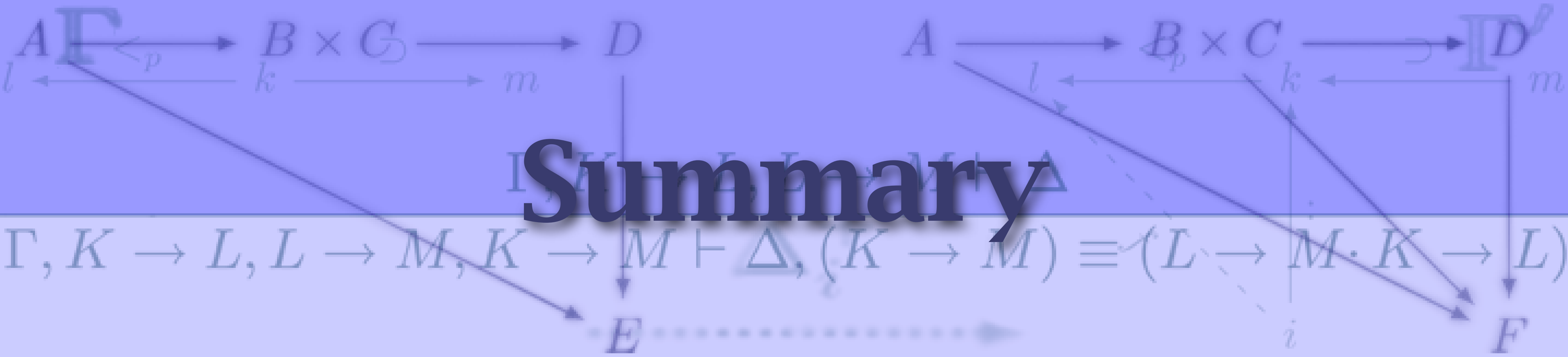
Opportunities

- 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

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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

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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

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