

Contents

| | |
|---|--------------|
| List of Figures | xxv |
| List of Tables | xxix |
| List of Listings | xxxii |
| 1 Quo Vadis Formal Verification? | 1 |
| 1.1 What KeY Is | 1 |
| 1.2 Challenges To Formal Verification | 2 |
| 1.3 Roles of Deductive Verification | 4 |
| 1.3.1 Avoid the Need for Formal Specification | 4 |
| 1.3.2 Restricted Target Language | 5 |
| 1.3.3 Formal Verification in Teaching | 6 |
| 1.3.4 Avoid the Need for Fully Specified Formal Semantics | 8 |
| 1.3.5 Where Are We Now? | 8 |
| 1.4 The Architecture of KeY | 10 |
| 1.4.1 Prover Core | 10 |
| 1.4.2 Reasoning About Programs | 12 |
| 1.4.3 Proof Obligations | 14 |
| 1.4.4 The Frontends | 15 |
| 1.5 The Next Ten Years | 16 |
| 1.5.1 Modular Architecture | 16 |
| 1.5.2 Relational Properties Are Everywhere | 17 |
| 1.5.3 Learning from Others | 18 |
| 1.5.4 Code Reviews | 18 |
| 1.5.5 Integration | 18 |
| 2 First-Order Logic | 21 |
| 2.1 Introduction | 21 |
| 2.2 Basic First-Order Logic | 21 |
| 2.2.1 Syntax | 21 |

| | | |
|----------|---|-----------|
| 2.2.2 | Calculus | 25 |
| 2.2.3 | Semantics | 29 |
| 2.3 | Extended First-Order Logic | 33 |
| 2.3.1 | Variable Binders | 34 |
| 2.3.2 | Undefinedness | 35 |
| 2.4 | First-Order Logic for Java | 35 |
| 2.4.1 | Type Hierarchy and Signature | 36 |
| 2.4.2 | Axioms for Integers | 37 |
| 2.4.3 | Axioms for Heap | 38 |
| 2.4.4 | Axioms for Location Sets | 41 |
| 2.4.5 | Semantics | 42 |
| 3 | Dynamic Logic for Java | 47 |
| 3.1 | Introduction | 47 |
| 3.2 | Syntax of JavaDL | 48 |
| 3.2.1 | Type Hierarchies | 49 |
| 3.2.2 | Signatures | 49 |
| 3.2.3 | Syntax of JavaDL Program Fragments | 50 |
| 3.2.4 | Syntax of JavaDL Terms and Formulas | 52 |
| 3.3 | Semantics | 53 |
| 3.3.1 | Kripke Structures | 53 |
| 3.3.2 | Semantics of JavaDL Terms and Formulas | 54 |
| 3.4 | Describing Transitions between States: Updates | 55 |
| 3.4.1 | Syntax and Semantics of JavaDL Updates | 55 |
| 3.4.2 | Update Simplification Rules | 57 |
| 3.5 | The Calculus for JavaDL | 58 |
| 3.5.1 | JavaDL Rule Schemata and First-Order Rules | 58 |
| 3.5.2 | Nonprogram Rules for Modalities | 61 |
| 3.5.3 | Soundness and Completeness of the Calculus | 61 |
| 3.5.4 | Schema Variables for Program Constructs | 64 |
| 3.5.5 | The Active Statement in a Modality | 65 |
| 3.5.6 | The Essence of Symbolic Execution | 65 |
| 3.5.7 | Components of the Calculus | 66 |
| 3.6 | Rules for Symbolic Execution of Java Programs | 67 |
| 3.6.1 | The Basic Assignment Rule | 67 |
| 3.6.2 | Rules for Handling General Assignments | 68 |
| 3.6.3 | Rules for Conditionals | 73 |
| 3.6.4 | Unwinding Loops | 74 |
| 3.6.5 | Replacing Method Calls by their Implementation | 75 |
| 3.6.6 | Instance Creation and Initialization | 85 |
| 3.6.7 | Handling Abrupt Termination | 91 |
| 3.7 | Abstraction and Modularization Rules | 95 |
| 3.7.1 | Replacing Method Calls by Specifications: Contracts | 96 |
| 3.7.2 | Reasoning about Unbounded Loops: Loop Invariants | 99 |

| | | |
|----------|---|------------|
| 4 | Proof Search with Taclets | 105 |
| 4.1 | Introduction | 105 |
| 4.1.1 | Purpose and Organization of this Chapter | 106 |
| 4.2 | A Taclet Tutorial | 107 |
| 4.2.1 | A Basic Theory of Lists | 107 |
| 4.2.2 | The List Theory in Concrete Syntax | 109 |
| 4.2.3 | Definitional Extension of the List Theory | 112 |
| 4.2.4 | Derivation of Lemmas | 115 |
| 4.3 | A Reference Manual of Taclets | 119 |
| 4.3.1 | The Taclet Language | 119 |
| 4.3.2 | Schema Variables | 128 |
| 4.3.3 | Application of Taclets | 134 |
| 4.4 | Reflection and Reasoning about Soundness of Taclets | 136 |
| 4.4.1 | Soundness in Sequent Calculi | 137 |
| 4.4.2 | Meaning Formulas of Sequent Taclets | 138 |
| 4.4.3 | Meaning Formulas for Rewriting Taclets | 140 |
| 4.4.4 | Elimination of Schema Variables | 141 |
| 5 | Theories | 147 |
| 5.1 | Introduction | 147 |
| 5.2 | Finite Sequences | 147 |
| 5.3 | Strings | 154 |
| 5.3.1 | Sequences of Characters | 154 |
| 5.3.2 | Regular Expressions for Sequences | 156 |
| 5.3.3 | Relating Java String Objects to Sequences of Characters | 157 |
| 5.3.4 | String Literals and the String Pool | 158 |
| 5.3.5 | Specification of the Java String API | 159 |
| 5.4 | Integers | 159 |
| 5.4.1 | Core Integer Theory | 160 |
| 5.4.2 | Variable Binding Integer Operations | 161 |
| 5.4.3 | Symbolic Execution of Integer Expressions in Programs | 162 |
| 6 | Abstract Interpretation | 165 |
| 6.1 | Introduction | 165 |
| 6.2 | Integrating Abstract Interpretation | 166 |
| 6.2.1 | Abstract Domains | 166 |
| 6.2.2 | Abstractions for Integers | 168 |
| 6.2.3 | Abstracting States | 168 |
| 6.3 | Loop Invariant Generation | 169 |
| 6.4 | Abstract Domains for Heaps | 172 |
| 6.5 | Abstract Domains for Objects | 176 |
| 6.5.1 | Null/Not-null Abstract Domain | 177 |
| 6.5.2 | Length Abstract Domain | 177 |
| 6.6 | Extensions | 182 |
| 6.6.1 | Abstractions for Arrays | 182 |

| | | |
|----------|--|------------|
| 6.6.2 | Loop Invariant Rule with Value and Array Abstraction . . . | 182 |
| 6.6.3 | Computation of the Abstract Update and Invariants | 184 |
| 6.6.4 | Symbolic Pivots | 185 |
| 6.7 | Conclusions | 187 |
| 7 | Formal Specification with the Java Modeling Language | 189 |
| 7.1 | Introduction to Method Contracts | 192 |
| 7.1.1 | Clauses of a Contract | 192 |
| 7.1.2 | Defensive Versus Offensive Method Implementations . . . | 195 |
| 7.1.3 | Specifications and Implementations | 196 |
| 7.2 | Expressions | 197 |
| 7.2.1 | Quantified Boolean Expressions | 197 |
| 7.2.2 | Numerical Comprehensions | 199 |
| 7.2.3 | Evaluation in the Prestate | 200 |
| 7.3 | Method Contracts in Detail | 201 |
| 7.3.1 | Visibility of Specifications | 201 |
| 7.3.2 | Specification Cases | 202 |
| 7.3.3 | Semantics of Normal Behavior Specification Cases | 204 |
| 7.3.4 | Specifications for Constructors | 205 |
| 7.3.5 | Notions of Purity | 205 |
| 7.4 | Class Level Specifications | 206 |
| 7.4.1 | Invariants | 207 |
| 7.4.2 | Initially Clauses | 212 |
| 7.4.3 | History Constraints | 213 |
| 7.4.4 | Initially Clauses and History Constraints: Static vs. Instance | 214 |
| 7.4.5 | Inheritance of Specifications | 214 |
| 7.5 | Nonnull Versus Nullable Object References | 216 |
| 7.6 | Exceptional Behavior | 218 |
| 7.7 | Specification-Only Class Members | 221 |
| 7.7.1 | Model Fields and Model Methods | 221 |
| 7.7.2 | Ghost Variables | 225 |
| 7.7.3 | Ghost Variables Versus Model Fields | 225 |
| 7.8 | Integer Semantics | 226 |
| 7.9 | Auxiliary Specification for Verification | 229 |
| 7.9.1 | Framing | 229 |
| 7.9.2 | Loop Invariants | 230 |
| 7.9.3 | Assertions and Block Contracts | 234 |
| 7.10 | Conclusion | 235 |
| 7.10.1 | Tool Support for JML | 235 |
| 7.10.2 | Comparison to Other Program Annotation Languages . . . | 236 |
| 8 | From Specification to Proof Obligations | 239 |
| 8.1 | Formal Semantics of JML Expressions | 240 |
| 8.1.1 | Types in JML | 241 |
| 8.1.2 | Translating JML Expressions to JavaDL | 242 |

| | | |
|-----------|---|------------|
| 8.1.3 | Abstract Data Types in JML | 248 |
| 8.1.4 | Well-Definedness of Expressions | 249 |
| 8.2 | From JML Contract Annotations to JavaDL Contracts | 250 |
| 8.2.1 | Normalizing JML Contracts | 251 |
| 8.2.2 | Constructor Contracts | 260 |
| 8.2.3 | Model Methods and Model Fields | 261 |
| 8.2.4 | JavaDL Contracts | 264 |
| 8.2.5 | Loop Specifications | 267 |
| 8.3 | Proof Obligations for JavaDL Contracts | 268 |
| 8.3.1 | Proof Obligations for Functional Correctness | 268 |
| 8.3.2 | Dependency Proof Obligations | 274 |
| 8.3.3 | Well-Definedness Proof Obligations | 275 |
| 9 | Modular Specification and Verification | 285 |
| 9.1 | Modular Verification with Contracts | 287 |
| 9.1.1 | Historical and Conceptual Background | 287 |
| 9.1.2 | Example: Implementing a List | 290 |
| 9.1.3 | Modular Program Correctness | 292 |
| 9.1.4 | Verification of Recursive Methods | 294 |
| 9.2 | Abstract Specification | 296 |
| 9.2.1 | Model Fields | 298 |
| 9.2.2 | Model Methods | 307 |
| 9.3 | The Frame Problem | 315 |
| 9.3.1 | Motivation | 316 |
| 9.3.2 | Dynamic Frames | 318 |
| 9.3.3 | Proof Obligations for Dynamic Frames Specifications | 320 |
| 9.3.4 | Example Specification with Dynamic Frames | 321 |
| 9.4 | Calculus Rules for Modular Reasoning | 324 |
| 9.4.1 | Anonymizing Updates | 325 |
| 9.4.2 | An Improved Loop Invariant Rule | 326 |
| 9.4.3 | A Rule for Method Contracts | 332 |
| 9.4.4 | A Rule for Dependency Contracts | 335 |
| 9.4.5 | Rules for Class Invariants | 337 |
| 9.5 | Verifying the List Example | 339 |
| 9.6 | Related Methodologies for Modular Verification | 343 |
| 9.7 | Conclusion | 347 |
| 10 | Verifying Java Card Programs | 349 |
| 10.1 | Introduction | 349 |
| 10.2 | Java Card Technology | 350 |
| 10.3 | Java Card Transactions on Explicit Heaps | 353 |
| 10.3.1 | Basic Transaction Roll-Back | 354 |
| 10.3.2 | Transaction Marking and Balancing | 355 |
| 10.3.3 | Object Creation and Deletion | 356 |
| 10.3.4 | Persistent and Transient Arrays | 357 |

| | | |
|-----------|--|------------|
| 10.3.5 | Nonatomic Updates | 359 |
| 10.4 | Taclets for the New Rules | 360 |
| 10.5 | Modular Reasoning with Multiple Heaps | 363 |
| 10.6 | Java Card Verification Samples | 364 |
| 10.6.1 | Conditional Balance Updating | 365 |
| 10.6.2 | Reference Implementation of a Library Method | 366 |
| 10.6.3 | Transaction Resistant PIN Try Counter | 370 |
| 10.7 | Summary and Discussion | 372 |
| 10.7.1 | Related Work | 373 |
| 10.7.2 | On-going and Future Research | 373 |
| 10.7.3 | Multiple Heaps for Concurrent Reasoning | 373 |
| 11 | Debugging and Visualization | 377 |
| 11.1 | Introduction | 377 |
| 11.2 | Symbolic Execution | 379 |
| 11.3 | Symbolic Execution Debugger | 384 |
| 11.3.1 | Installation | 384 |
| 11.3.2 | Basic Usage | 385 |
| 11.3.3 | Debugging with Symbolic Execution Trees | 389 |
| 11.3.4 | Debugging with Memory Layouts | 391 |
| 11.3.5 | Help Program and Specification Understanding | 392 |
| 11.3.6 | Debugging Meets Verification | 393 |
| 11.3.7 | Architecture | 395 |
| 11.4 | A Symbolic Execution Engine based on KeY | 397 |
| 11.4.1 | Symbolic Execution Tree Generation | 397 |
| 11.4.2 | Branch and Path Conditions | 401 |
| 11.4.3 | Hiding the Execution of Query Methods | 402 |
| 11.4.4 | Symbolic Call Stack | 403 |
| 11.4.5 | Method Return Values | 403 |
| 11.4.6 | Current State | 404 |
| 11.4.7 | Controlled Execution | 405 |
| 11.4.8 | Memory Layouts | 405 |
| 11.5 | Conclusion And Future Work | 406 |
| 12 | Proof-based Test Case Generation | 409 |
| 12.1 | Introduction | 409 |
| 12.2 | A Quick Tutorial | 410 |
| 12.2.1 | Setup | 411 |
| 12.2.2 | Usage | 411 |
| 12.2.3 | Options and Settings | 413 |
| 12.3 | Test Cases, Test Suites, and Test Criteria | 415 |
| 12.4 | Application Scenarios and Variations of the Test Generator | 420 |
| 12.4.1 | KeYTestGen for Test Case Generation | 420 |
| 12.4.2 | KeYTestGen for Formal Verification | 421 |
| 12.5 | Architecture of KeYTestGen | 422 |

| | | |
|-----------|---|------------|
| 12.6 | Proof-based Constraint Construction for Test Input Data | 424 |
| 12.6.1 | Symbolic Execution for Test Constraint Generation | 424 |
| 12.6.2 | Implicit Case Distinctions | 425 |
| 12.6.3 | Infeasible Path Filtering | 426 |
| 12.6.4 | Using Loop Unwinding and Method Inlining | 427 |
| 12.6.5 | Using Loop Invariants and Method Contracts | 428 |
| 12.7 | From Constraints to Test Input Data | 431 |
| 12.7.1 | The Type System | 433 |
| 12.7.2 | Preserving the Semantics of Interpreted Functions | 434 |
| 12.7.3 | Preventing Integer Overflows | 435 |
| 12.7.4 | Model Extraction | 436 |
| 12.8 | Specification-based Test Oracle Generation | 436 |
| 12.8.1 | Generating a Test Oracle from the Postcondition | 436 |
| 12.8.2 | Using a Runtime Assertion Checker | 439 |
| 12.9 | Synthesizing Executable Test Cases | 439 |
| 12.10 | Perspectives and Related Work | 442 |
| 12.11 | Summary and Conclusion | 444 |
| 13 | Information Flow Analysis | 447 |
| 13.1 | Introduction | 447 |
| 13.2 | Specification and the Attacker Model | 449 |
| 13.3 | Formal Definition of Secure Information Flow | 451 |
| 13.4 | Specifying Information Flow in JML | 452 |
| 13.5 | Information Flow Verification with KeY | 454 |
| 13.5.1 | Efficient Double Symbolic Execution | 455 |
| 13.5.2 | Using Efficient Double Symbolic Execution in KeY | 463 |
| 13.6 | Summary and Conclusion | 464 |
| 14 | Program Transformation and Compilation | 467 |
| 14.1 | Interleaving Symbolic Execution and Partial Evaluation | 468 |
| 14.1.1 | General Idea | 468 |
| 14.1.2 | The Program Specialization Operator | 472 |
| 14.1.3 | Specific Specialization Actions | 473 |
| 14.1.4 | Example | 475 |
| 14.2 | Verified Correct Compilation | 476 |
| 14.3 | Implementation and Evaluation | 485 |
| 14.4 | Conclusion | 486 |
| 15 | Using the KeY Prover | 487 |
| 15.1 | Introduction | 487 |
| 15.2 | Exploring KeY Artifacts and Prover Simultaneously | 490 |
| 15.2.1 | Exploring Basic Notions And Usage | 491 |
| 15.2.2 | Exploring Terms, Quantification, and Instantiation | 503 |
| 15.2.3 | Exploring Programs in Formulas | 507 |
| 15.3 | Understanding Proof Situations | 524 |

| | | |
|-----------|---|------------|
| 15.4 | Further Features | 529 |
| 15.5 | What Next? | 531 |
| 16 | Formal Verification with KeY: A Tutorial | 533 |
| 16.1 | Introduction | 533 |
| 16.2 | A Program without Loops | 535 |
| 16.3 | A Brief Primer on Loop Invariants | 538 |
| 16.3.1 | Introduction | 538 |
| 16.3.2 | Why Are Loop Invariants Needed? | 539 |
| 16.3.3 | What Is A Loop Invariant? | 539 |
| 16.3.4 | Goal-Oriented Derivation of Loop Invariants | 541 |
| 16.3.5 | Generalization | 542 |
| 16.3.6 | Recovering the Context | 543 |
| 16.3.7 | Proving Termination | 545 |
| 16.3.8 | A More Complex Example | 547 |
| 16.3.9 | Invariants: Concluding Remarks | 549 |
| 16.4 | A Program with Loops | 550 |
| 16.5 | Data Type Properties of Programs | 554 |
| 16.6 | KeY and Eclipse | 557 |
| 16.6.1 | Installation | 558 |
| 16.6.2 | Proof Management with KeY Projects | 558 |
| 16.6.3 | Proof Results via Marker | 559 |
| 16.6.4 | The Overall Verification Status | 560 |
| 17 | KeY-Hoare | 563 |
| 17.1 | Introduction | 563 |
| 17.2 | The Programming Language | 564 |
| 17.3 | Background | 565 |
| 17.3.1 | First-Order Logic | 565 |
| 17.3.2 | Hoare Calculus | 566 |
| 17.4 | Hoare Logic with Updates | 567 |
| 17.4.1 | State Updates | 568 |
| 17.4.2 | Hoare Triples with Update | 569 |
| 17.4.3 | Hoare Style Calculus with Updates | 569 |
| 17.4.4 | Rules for Updates | 571 |
| 17.5 | Using KeY-Hoare | 572 |
| 17.6 | Variants of the Hoare Logic with Updates | 574 |
| 17.6.1 | Total Correctness | 574 |
| 17.6.2 | Worst-Case Execution Time | 574 |
| 17.7 | A Brief Reference Manual for KeY-Hoare | 576 |
| 17.7.1 | Installation | 576 |
| 17.7.2 | Formula Syntax | 577 |
| 17.7.3 | Input File Format | 577 |
| 17.7.4 | Loading and Saving Problems and Proofs | 579 |
| 17.7.5 | Proving | 580 |

| | | |
|-----------|--|------------|
| 17.7.6 | Automation | 581 |
| 18 | Verification of an Electronic Voting System | 583 |
| 18.1 | Electronic Voting | 583 |
| 18.2 | Overview | 584 |
| 18.2.1 | Verification of Cryptographic Software | 585 |
| 18.2.2 | Verification Approach | 585 |
| 18.2.3 | System Description | 586 |
| 18.3 | Specification and Verification | 589 |
| 18.3.1 | Specification | 589 |
| 18.3.2 | Verification | 593 |
| 18.4 | Discussion | 595 |
| 18.4.1 | A Hybrid Approach to Information Flow Analysis | 595 |
| 18.4.2 | Related Work | 596 |
| 18.4.3 | Conclusion | 597 |
| 19 | Verification of Counting Sort and Radix Sort | 599 |
| 19.1 | Counting Sort and Radix Sort Implementation | 599 |
| 19.2 | High-Level Correctness Proof | 602 |
| 19.2.1 | General Auxiliary Functions | 603 |
| 19.2.2 | Counting Sort Proof | 604 |
| 19.2.3 | Radix Sort Proof | 605 |
| 19.3 | Experience Report | 607 |
| 20 | Java Modeling Language Reference | 609 |
| 20.1 | JML Syntax | 609 |
| 20.2 | JML Expression Semantics | 613 |
| 20.3 | JML Expression Well-Definedness | 616 |
| 21 | KeY File Reference | 619 |
| 21.1 | Predefined Operators in JavaDL | 619 |
| 21.1.1 | Arithmetic Functions | 619 |
| 21.1.2 | Arithmetic Functions with Modulo Semantics | 620 |
| 21.1.3 | Predicates for Arithmetics and Equality | 622 |
| 21.1.4 | Integer Semantics Dependent Functions | 622 |
| 21.1.5 | Integer Semantics Dependent Predicate Symbols | 624 |
| 21.1.6 | Heap Related Function and Predicate Symbols | 624 |
| 21.1.7 | Location Sets Related Function and Predicate Symbols | 625 |
| 21.1.8 | Finite Sequence Related Function and Predicate Symbols | 626 |
| 21.1.9 | Map Related Function and Predicate Symbols | 627 |
| 21.2 | The KeY Syntax | 628 |
| 21.2.1 | Notation, Keywords, Identifiers, Numbers, Strings | 629 |
| 21.2.2 | Terms and Formulas | 631 |
| 21.2.3 | Rule Files | 639 |
| 21.2.4 | User Problem and Proof Files | 647 |
| 21.2.5 | Schematic Java Syntax | 650 |

xxiv

References

Index

Contents

655

679