Formal Methods for Software Development

Introduction to Model Checking

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April 8, 2024

[1]Acknowledgement: Based on material from Prof. Wolfgang Ahrendt.

Motivation: Software Defects cause BIG failures

Software is used widely in many applications where a bug in the system can cause large damage:

- Economically critical systems: e-commerce systems, Internet, microprocessors, etc.
- Safety critical systems: airplane control systems, medical care, train signalling systems, air traffic control, power plants, etc.

Price of software defects

Two very expensive software bugs:

- Intel Pentium FDIV bug (1994, approximately $500 million)
- Ariane 5 floating point overflow (1996, approximately $500 million)

Pentium FDIV — software bug in HW

Image © CPU-World.com

The floating point division algorithm uses an array of constants with 1066 elements. However, only 1061 elements of the array were correctly initialised.

Ariane 5

Exploded 37 seconds after takeoff - the reason was an overflow in a conversion of a 64 bit floating point number into a 16 bit integer.

Motivation:
Software Defects cause OMNIPRESENT Failures

Software is almost everywhere:

- Mobiles
- Smart devices
- Smart cards
- Cars
- ...

software/specification quality is a growing commercial and legal issue

Achieving Reliability in Engineering

Well-known strategies from mechanical and civil engineering

- Precise calculations/estimations of forces, stress, etc.
- Clear separation of subsystems
- Design follows patterns that are proven to work
- ...

Why This Does Not (Quite) Work For Software?

- Software systems compute non-continuous functions.
  Single bit-flip may change behaviour completely.
- Insufficient separation of subsystems.
  Seemingly correct sub-systems may together behave incorrectly.
- Software designs have very high logical complexity.
- Most SW engineers untrained to address correctness.
- Cost efficiency favoured over reliability.
- Design practise for reliable software in immature state for complex (e.g., distributed) systems.

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A central strategy: testing
(others: SW processes, reviews, . . .)

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Testing against external faults

- inject faults (memory, communication), e.g., by simulation
- trace fault propagation

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  How to test for the unexpected? Rare cases?
- Testing is labour intensive, hence expensive

What are Formal Methods

- Rigorous methods for system design/development/analysis
- Mathematics and symbolic logic $\Rightarrow$ formal
- Increase confidence in a system
- Two aspects:
  - System requirements
  - System implementation
- Make formal model of both
- Use tools for
  - exhaustive search for failing scenario, or
  - mechanical proof that implementation satisfies requirements

What are Formal Methods for

- Complement other analysis and design methods
- Increase confidence in system correctness
- Good at finding bugs
  (in code and specification)
- *Ensure* certain properties of the system (model)
- Should ideally be as automated as possible

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and

- Training in Formal Methods increases high quality development skills

Specification — What a System Should Do

- Simple properties
  - Safety properties
    Something bad will never happen (eg, mutual exclusion)
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    Something good will happen eventually
- General properties of concurrent/distributed systems
  - deadlock-free, no starvation, fairness
- Non-functional properties
  - Execution time, memory, usability, ...
- Full behavioural specification
  - Code functionality described by contracts (in particular for efficient, i.e., redundant, data representations)

The Main Point of Formal Methods is Not

- to show correctness of entire systems
- to replace testing
- to replace good design practises

No correct system w/o clear requirements & good design!

One can't formally verify messy code with unclear specs

But . . .

- Formal proof can replace (infinitely) many test cases
- Formal methods improve the quality of specs
  (even without formal verification)
- Formal methods guarantee specific properties of system model

A Fundamental Fact

Formalisation of system requirements is hard

Formalization Helps to Find Bugs in Specs

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Errors in specifications are as common as errors in code, but their discovery gives deep insights in (mis)conceptions of the system.

- Wellformedness and consistency of formal specs partly machine-checkable
- Declared signature (symbols) helps to spot incomplete specs
- Failed verification of implementation against spec gives feedback on erroneous formalization

Another Fundamental Fact

Proving properties of systems can be hard

Level of System (Implementation) Description

- Abstract level
  - Finitely many states (bounded size datatypes)
  - Automated proofs are (in principle) possible
  - Simplification, unfaithful modeling inevitable
- Concrete level
  - Unbounded size datatypes (pointer chains, dynamic containers, streams)
  - Complex datatypes and control structures
  - Realistic programming model (e.g., Java)
  - Automated proofs hard or impossible!

Expressiveness of Specification

- Simple
  - Simple or general properties
  - Finitely many case distinctions
  - Approximation, low precision
  - Automated proofs are (in principle) possible
- Complex
  - Full behavioural specification
  - Quantification over infinite or large domains
  - High precision, tight modeling
  - Automated proofs hard or impossible!

Main Approaches

Abstract programs, Simple properties	Abstract programs, Complex properties
Concrete programs, Simple properties	Concrete programs, Complex properties

Main Approaches

e.g., SPIN

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e.g., JML
+ KeY
Dafny..

Proof Automation

- "Automated" Proof
  ("batch-mode")
  - No interaction (or lemmas) necessary
  - Proof may fail or result inconclusive
    Tuning of tool parameters necessary
  - Formal specification still "by hand"

- "Semi-Automated" Proof
  ("interactive")
  - Interaction (or lemmas) may be required
  - Need certain knowledge of tool internals
    Intermediate inspection can help
  - User steps are checked by tool

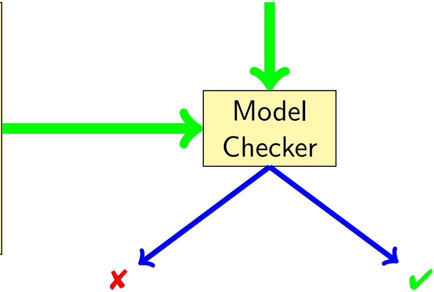
Model Checking (with SPIN)

System Model

```
byte n = 0;
active proctype P() {
   ...
}
active proctype Q() {
   ...
}
```

System Property

`[] ! (criticalSectP && criticalSectQ`



criticalSectP =	0	1	1
criticalSectQ =	1	0	1

Model Checking in Industry—Examples

- Hardware verification
  - Good match between limitations of technology and application
  - Intel, Motorola, AMD, ...
- Software verification
  - Specialized software: control systems, protocols
  - Typically no direct checking of executable system, but of abstractions
  - Bell Labs, Microsoft

A Major Case Study with SPIN

Checking feature interaction for telephone call processing software

- Software for PathStar© server from Lucent Technologies
- Automated abstraction of unchanged C code into PROMELA
- Web interface, with SPIN as back-end, to:
  - determine properties (ca. 20 temporal formulas)
  - invoke verification runs
  - report error traces
- Finds error trace, reported as C execution trace
- Work farmed out to 16 computers, daily, overnight runs
- 18 months, 300 versions of system model, 75 bugs found
- Strength: detection of undesired feature interactions (difficult with traditional testing)
- Main challenge: defining meaningful properties

Deductive Verification with KeY

Java Code

Formal specification

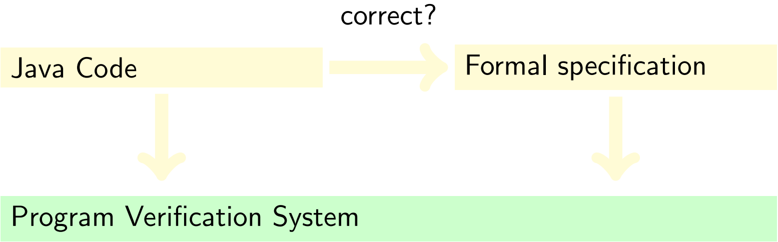
Deductive Verification with KeY

correct?

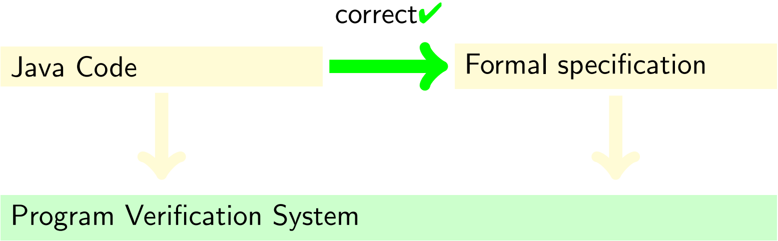
Java Code

Formal specification

Deductive Verification with KeY



Deductive Verification with KeY



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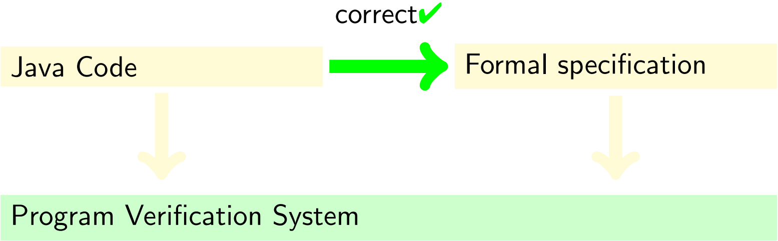

Proof rules establish relation “implementation conforms to specs”

Deductive Verification in Industry—Examples

- Hardware verification
  - For complex systems, mostly floating-point processors
  - Intel, Motorola, AMD, ...
- Software verification
  - Safety critical systems:
    - Paris driver-less metro (Meteor)
    - Emergency closing system in North Sea
  - Libraries
  - Implementations of Protocols

Major Case Studies with KeY

Java Card 2.2.1 API Reference Implementation

- Reference implementation and full functional specification
- All Java Card 2.2.1 API classes and methods
  - 60 classes; ca. 5,000 LoC (250kB) source code
  - specification ca. 10,000 LoC
- Conformant to implementation on actual smart cards
- All methods fully verified against their spec
  - 293 proofs; 5–85,000 nodes
- Total effort several person months
- Most proofs fully automatic
- Main challenge: getting specs right

Main topics of the module

The rest of the module will concentrate especially on:

- modelling of systems,
- specifying properties, and
- using model checkers to verify them,

Theoretical background of model checking (anyone interested can contact me).

Additional Literature

BaierKatoen	Christel Baier, Joost-Pieter Katoen Principles of Model Checking MIT Press, 2008
HuthRyan	Michael Huth, Mark Ryan Logic in Computer Science
Holzmann	Gerard J. Holzmann The Spin Model Checker Addison Wesley, 2004
Ben-Ari	Mordechai Ben-Ari Principles of the Spin Model Checker Springer, 2008