Software Engineering using Formal Methods

Introduction

Wolfgang Ahrendt

Department of Computer Science and Engineering
Chalmers University of Technology
and
University of Gothenburg

30 August 2016
Course Team

Teachers

- Wolfgang Ahrendt (WA) examiner, lecturer
- Mauricio Chimento (MC) teaching assistant
- Raúl Pardo (RP) teaching assistant

Course assistant activities include:

- Giving exercise classes
- Correcting lab hand-ins
- Student support via:
  - E-mail
  - Meetings on e-mail request
    - Mauricio, room 5446
    - Raúl, room 5447
Organisational Stuff

Course Home Page

www.cse.chalmers.se/edu/course/TDA293/
Also linked from Chalmers and GU course portals

Google News Group

- Sign up via course home page (see News)
- Changes, updates, questions, discussions (don't post solutions)

Passing Criteria

- Written exam 28 October 2016; re-exam 21 December 2016
- Two lab hand-ins
- Exam and labs can be passed separately
## Course Structure

<table>
<thead>
<tr>
<th>Topic</th>
<th># Lectures</th>
<th># Exercises</th>
<th>Lab</th>
</tr>
</thead>
<tbody>
<tr>
<td>Intro</td>
<td>1</td>
<td>✗</td>
<td>✗</td>
</tr>
<tr>
<td>Modeling &amp; Model Checking with <strong>Promela &amp; Spin</strong></td>
<td>6</td>
<td>3</td>
<td>✓</td>
</tr>
<tr>
<td>Specification &amp; Verification with <strong>JML &amp; KeY</strong></td>
<td>7</td>
<td>3</td>
<td>✓</td>
</tr>
</tbody>
</table>

**Promela & Spin** abstract programs, model checking, automated  
**JML & KeY** concrete Java, deductive verification, semi-automated  

...more on this later!
<table>
<thead>
<tr>
<th>Lectures</th>
</tr>
</thead>
<tbody>
<tr>
<td>▶ Please ask questions during lectures</td>
</tr>
<tr>
<td>▶ Please respond to my questions; ‘wrong’ answers highly welcome</td>
</tr>
<tr>
<td>▶ Slides appear online shortly after each lecture</td>
</tr>
</tbody>
</table>
Exercises

- One exercise web page (almost) each week (6 in total)
- Discussed in next exercise class
- Play around with the exercises before coming to the class
- Exercises highly recommended
- Bring laptops if you have
  (ideally w. installed tools or browser interfaces working)
Labs

- 2 Lab handins: PROMELA/SPIN 30 Sep, JML/KeY 28 Oct
- 2 Lab FAQ Sessions
- Submission via Fire, linked from course home page
- If submission is returned, roughly one week for correction
- You work in groups of two. No exception!\(^a\)

You pair up by either:
1. talk to people
2. post to the Google group
3. participate in pairing at first exercise session

In case all that is not sufficient, contact Mauricio by e-mail.

\(^a\)Only PhD students have to work alone.
see course homepage
Course Evaluation

1. course evaluation group:
   ▶ randomly selected student representatives + teacher
   ▶ one meeting during the course, one after

2. web questionnaire after the course
Course Literature

- **The Course Book:**
  
  **Ben-Ari**  
  *Authored by receiver of ACM award for outstanding contributions to CS education. Recommended by G. Holzmann. Excellent student text book.*  
  (E-book at link.springer.com)

- **further reading:**
  
  **Holzmann**  

  **KeYbook**  
  (Download via Chalmers library → E-books → Lecture Notes in Computer Science)
Skills in object-oriented programming (like Java) assumed.

Knowledge corresponding to the following courses can further help:

- Concurrent Programming
- Finite Automata
- Testing, Debugging, and Verification
- Logic in Computer Science

if you took any of those: nice
if not: don't worry, we introduce everything we use here
Motivation: Software Defects cause BIG Failures

Tiny faults in technical systems can have catastrophic consequences

In particular, this goes for software systems

- Ariane 5
- Mars Climate Orbiter
- London Ambulance Dispatch System
- NEDAP Voting Computer Attack
Motivation:
Software Defects cause OMNIPRESENT Failures

Ubiquitous Computing results in Ubiquitous 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

Some well-known strategies from civil engineering

- Precise calculations/estimations of forces, stress, etc.
- Hardware redundancy ("make it a bit stronger than necessary")
- Robust design (single fault not catastrophic)
- 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.
- Redundancy as replication doesn’t help against **bugs**. Redundant SW development only viable in extreme cases.
- 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, particularly distributed, systems.
A central strategy: testing
(others: SW processes, reviews, libraries, ...)

Testing against internal SW errors ("bugs")
- find (hopefully) representative test configurations
- check intentional system behaviour on those

Testing against external faults
- inject faults (memory, communication) by simulation or radiation
- trace fault propagation
Limitations of Testing

- Testing shows presence of errors, not their absence (exhaustive testing viable only for trivial systems)
- Representativeness of test cases/injected faults subjective
  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 ⇒ 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

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)
  - Liveness properties
    - *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**
  - Data consistency, system **invariants**
    - (in particular for efficient, i.e., redundant, data representations)
  - Modularity, encapsulation
  - Refinement relation
The Main Point of Formal Methods is **Not**

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

There is no silver bullet!

- 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

Let’s see why …
Difficulties in Creating Formal Models

- Real World
- Formal Requirements Specification
- Formal Execution Model
- Abstraction
Difficulties in Creating Formal Models

Real World

over-simplification

e.g., zero delay

Formal Requirements Specification

Formal Execution Model
Difficulties in Creating Formal Models

Real World

Formal Requirements Specification

Formal Execution Model

missing requirement
e.g., max stack size
Difficulties in Creating Formal Models

Real World

wrong modeling

e.g., \( \mathbb{Z} \) vs \text{int}
Errors in specifications are at least 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

<table>
<thead>
<tr>
<th>SPIN</th>
<th>KeY</th>
</tr>
</thead>
<tbody>
<tr>
<td>1st part</td>
<td>2nd part</td>
</tr>
<tr>
<td>of course</td>
<td>of course</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Abstract programs, Simple properties</th>
<th>Abstract programs, Complex properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concrete programs, Simple properties</td>
<td>Concrete programs, Complex properties</td>
</tr>
</tbody>
</table>
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)
```

Model Checker

```
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 shortest possible *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 $\rightarrow$ Formal specification

Program Verification System

Proof rules establish relation “implementation conforms to specs”

Computer support essential for verification of real programs

synchronized StringBuffer append(char c)

- ca. 15.000 proof steps
- ca. 200 case distinctions
- Two human interactions, ca. 1 minute computing time
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
## 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**
**Timsort**

Hybrid sorting algorithm (insertion sort + merge sort) optimized for partially sorted arrays (typical for real-world data).

**Facts**

- Designed by Tim Peters (for Python)
- Since Java 1.7 default algorithm for non-primitive arrays/collections

**Timsort is used in**

- Java (standard library), used by Oracle
- Python (standard library), used by Google
- Android (standard library), used by Google
- ... and many more languages / frameworks!
Timsort: People

- Tim Peters
  - Sorting Algorithm Designer
  - Python Guru

- Stijn de Gouw
  - Postman in the NL
  - Interested in sorting for professional reasons
  - PhD in Computer Science
Stijn de Gouw: 20 Oct 2014

Hi Stijn, yes, I have time until 14:00 (or a bit longer)

Ok great

I've been working a bit on timsort (though less than I intended to do)

Stijn de Gouw: 27 Oct 2014

Morning Richard

don't want to keep this from you, but please keep it to yourself for now... as you know I was working on proving correctness of timsort (the sorting algorithm used in the jdk)

I figured that the jdk was probably pretty thoroughly tested so went right ahead with specifying rather than debugging the algorithm ... but I actually discovered a bug 😁

Cool 😊

Good morning!
Found Bug in Java Libraries’ main Sorting Method using KeY

- `java.util.Collections.sort` and `java.util.Arrays.sort` implement Timsort
- KeY verification of OpenJDK implementation revealed bug.
- Same bug present in Android SDK, Oracle’s JDK, Python library, Haskell library

Verified Fix using KeY

- Fixing the implementation
- Verified new version with KeY
Found Bug in Java Libraries’ main Sorting Method using KeY

- `java.util.Collections.sort` and `java.util.Arrays.sort` implement Timsort
- KeY verification of OpenJDK implementation revealed bug.
- Same bug present in Android SDK, Oracle’s JDK, Python library, Haskell library.

Some researchers found an error in the logic of merge-collapse, explained here, and with corrected code shown in...

It should be fixed anyway, and their suggested fix looks good to me.

Tim Peters via Python-Bugtracker
Found Bug in Java Libraries’ main Sorting Method using KeY

- java.util.Collections.sort and java.util.Arrays.sort implement Timsort
- KeY verification of OpenJDK implementation revealed bug.
- Same bug present in Android SDK, Oracle’s JDK, Python library, Haskell.

Some researchers found an error in the logic of merge collapse, explained here, and with corrected code shown in Python-Bugtracker.

It should be fixed anyway, and their suggested fix looks good to me.

Tim Peters via Twitter

Verified Fix using KeY

- Fixing the implementation
- Verified with KeY

Congratulations to Stijn de Gouw et al. for finding and fixing a bug in TimSort using formal methods!

Joshua Bloch via Twitter
Tool Support is Essential

Some Reasons for Using Tools

- Automate repetitive tasks
- Avoid typos, etc.
- Cope with large/complex programs
- Make verification certifiable

Tools used in this course:

**Spin** to verify **PROMELA** programs against Temporal Logic specs

**Spin** web interface Developed by Bart van Delft for this course!

**JSpin** A Java interface for **Spin**

**KeY** to verify Java programs against contracts in JML

All are free and run on Windows/Unixes/Mac.

**Install first Spin and JSpin on your computer, or make sure the Spin web interface works.**
**Literature for this Lecture**

**FM in SE**  
(Access to e-version via Chalmers Library)

**KeY**  
(Access to e-version via Chalmers Library)

**Spin**  
You will gain experience in ...

- Modelling, and modelling languages
- Specification, and specification languages
- In depth analysis of possible system behaviour
- Typical types of errors
- Reasoning about system (mis)behaviour
- ...

Learning Outcomes—Knowledge and Understanding

- judge the potential and limitations of using logic based verification methods for assessing and improving software correctness,
- judge what can and what cannot be expressed by certain specification/modelling formalisms,
- judge what can and cannot be analysed with certain logics and proof methods,
- differentiate between syntax, semantics, and proof methods in connection with logic-based systems for verification.
Learning Outcomes—Skills and Abilities

▶ express safety properties of (concurrent) programs in a formal way,
▶ describe the basics of verifying safety properties via model checking,
▶ use tools which integrate and automate the model checking of safety properties,
▶ write formal specifications of object-oriented system units, using the concepts of method contracts and class invariants,
▶ describe how the connection between programs and formal specifications can be represented in a program logic,
▶ verify functional properties of simple Java programs with a verification tool,
Learning Outcomes—Judgement and Approach

- acknowledge the socio-economical costs caused by faulty software,
- judge and communicate the significance of correctness for software development,
- approach the issue of correctly functioning software by means of abstraction, modeling, and rigorous reasoning.