Formal Methods for Software Development

Introduction

Wolfgang Ahrendt

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

04 September 2018

Course Team

Teachers

- Wolfgang Ahrendt (WA) examiner, lecturer
- Oskar Abrahamsson (OA) teaching assistant
- Andreas Lööw (AL) teaching assistant

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course assistant activities include:

- giving exercise classes
- correcting lab hand-ins
- student support via:
  - e-mail
  - meetings on e-mail request
    - Oskar, room 5461
    - Andreas, room 5461

Information Channels

Course Home Page

Linked from Chalmers and GU course portals

Google News Group

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

Course Structure

Course Structure

Topic	# Lectures	# Exercises	Lab
Intro	1	✘	✘
Modeling & Model Checking with PROMELA & SPIN	6	3	✔
Specification & Verification with JML & KeY	7	3	✔

PROMELA & SPIN abstract programs, model checking, automated

JML & KeY concrete Java, deductive verification, semi-automated

. . . more on this later!

Lectures

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- Please ask questions during lectures
- Please respond to my questions

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- Please respond to my questions; 'wrong' answers highly welcome

Lectures

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- Please respond to my questions
- Slides appear online shortly *after* each lecture

Exercises

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- 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)

Passing Criteria

- Oral examination in exam week
- Two lab hand-ins
- (No written end-exam)
- Oral exam and labs can be passed separately

Oral Exam

- individual, oral examination

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- slots between 29 October and 2 November

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- 2 Lab Questions Sessions
- Submission via Fire, linked from course home page
- If submission is returned, roughly one week for correction

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- 2 Lab Questions 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 Oskar by e-mail.

[a] Only PhD students have to work alone.

Schedule

see course homepage

Course Evaluation

1. course evaluation group:
    - student representatives
        - randomly selected (Chalmers)
        - volunteers (GU)
    - one meeting during the course, one after
2. web questionnaire after the course

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- John Lind
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GU students: please consider volunteering

Course Literature

- In part I, we partly use:

  Ben-Ari Mordechai Ben-Ari
  Principles of the Spin Model Checker
  Springer, 2008
  Ben-Ari received ACM award for outstanding contributions to CS education. Recommended by G. Holzmann. Excellent student text book.
  (E-book at `link.springer.com`)

- Relevant for part II:

  KeYbook *W. Ahrendt*, B. Beckert, R. Bubel, R. Hähnle, P. Schmitt, M. Ulbrich, editors.
  Deductive Software Verification - The KeY Book
  Vol 10001 of *LNCS*, Springer, 2016
  (E-book at `link.springer.com`)

Additional Literature

Holzmann Gerard J. Holzmann
The Spin Model Checker
Addison Wesley, 2004

BayerKatoen Christel Baier, Joost-Pieter Katoen
Principles of Model Checking
MIT Press, 2008

Connection to other Courses

Prerequisites

- Skills in first-order logic and temporal logic, e.g., from
  - Logic in Computer Science, or
  - Discrete Event Systems
- Skills in object-oriented programming (like Java)

Related courses (not assumed!)

- Concurrent Programming
- Finite Automata
- Testing, Debugging, and Verification

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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
- Clouds
- Smart cards
- Smart devices
- Cars
- ...

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software/specification quality is a growing commercial and legal issue

Achieving Reliability in Engineering

Well-known strategies from mechanical and civil engineering

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- Design follows patterns that are proven to work

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- Design practise for reliable software in immature state
  for complex (e.g., distributed) systems.

How to Ensure Software Correctness/Compliance?

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

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Testing against external faults

- inject faults (memory, communication) by simulation or radiation
- 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
- Formalise 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

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- Simple properties
  - Safety properties
    Something bad will never happen (e.g., green light mutual exclusion)
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  - Modularity, encapsulation
  - Refinement relation

The Main Point of Formal Methods is Not

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

There is no silver bullet!

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

But . . .

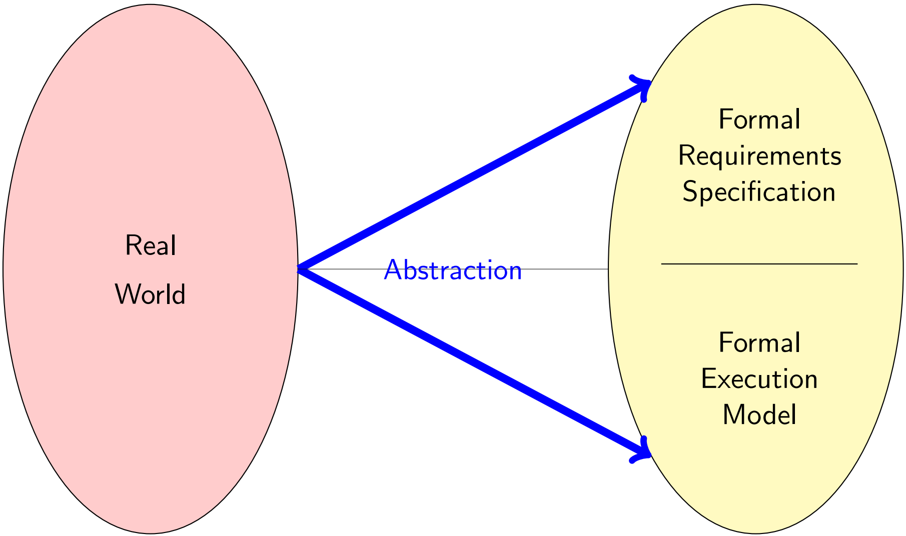
- Formal proof can replace (infinitely) many test cases
- Formal methods improve the quality of specs
  (even without formal verification)
- Formal methods guarantee specific properties of system (model)

A Fundamental Fact

Formalisation of system requirements is hard

Let's see why . . .

Difficulties in Creating Formal Models



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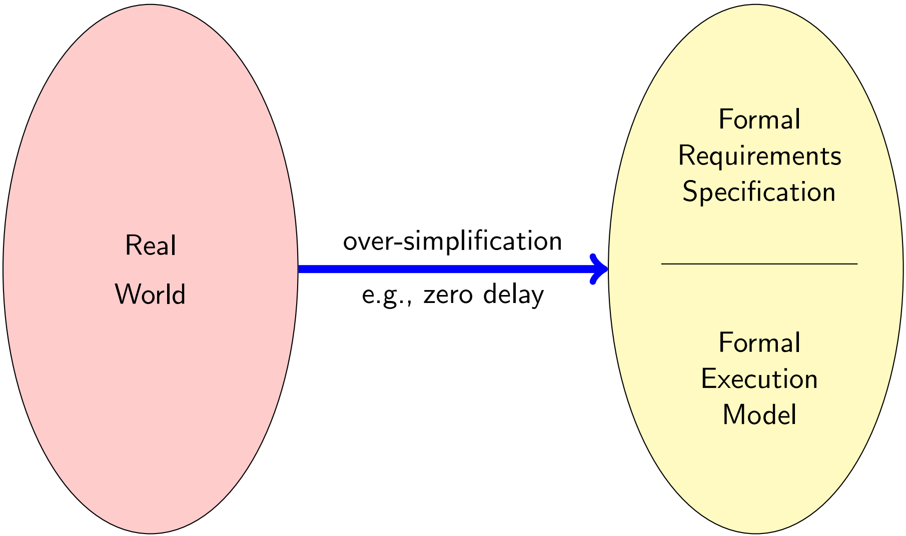

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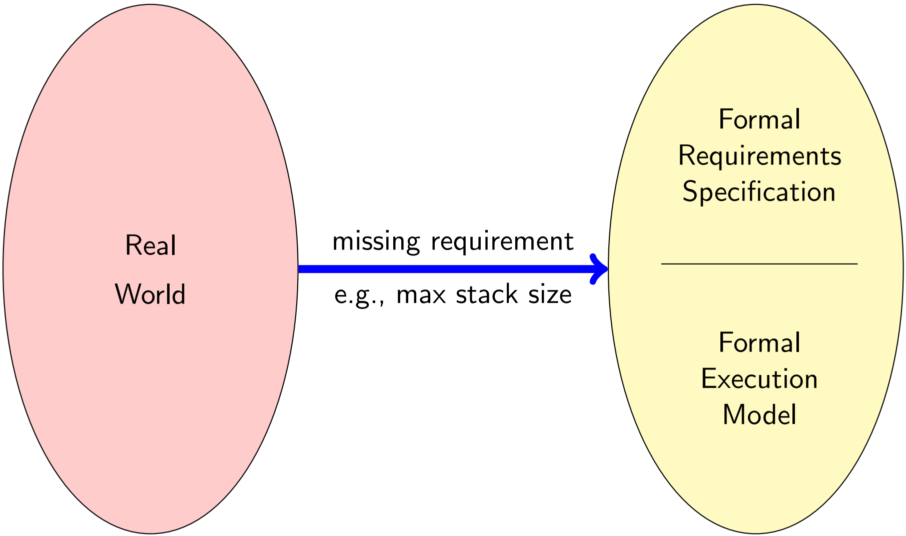

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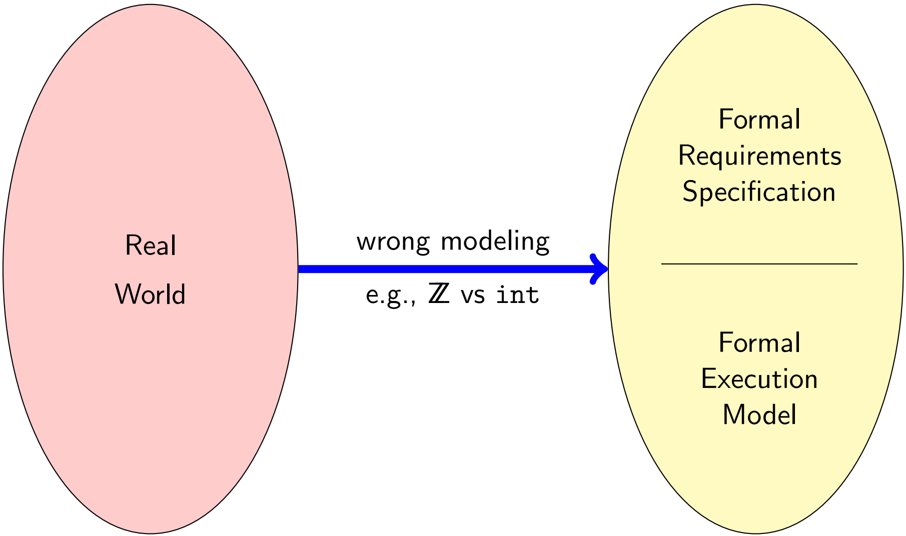

Formalization Helps to Find Bugs in Specs

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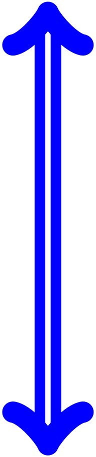
- Declared signature (symbols) helps to spot incomplete specs
- Failed verification of implementation against spec gives feedback on erroneous formalization

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

SPIN
1st part
of course

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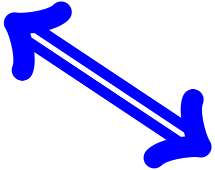
KeY
2nd part
of course

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

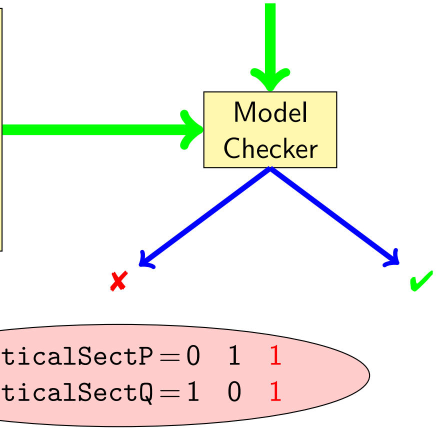
Model Checking with Spin

System Model

System Property

[] ! (criticalSectP && criticalSectQ)

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



Model Checking in Industry—Examples

- Hardware verification
  - Good match between limitations of methods 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

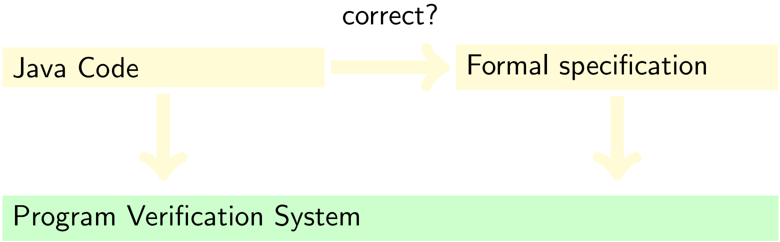
Formal specification

Deductive Verification with KeY

correct?

Java Code → Formal specification

Deductive Verification with KeY



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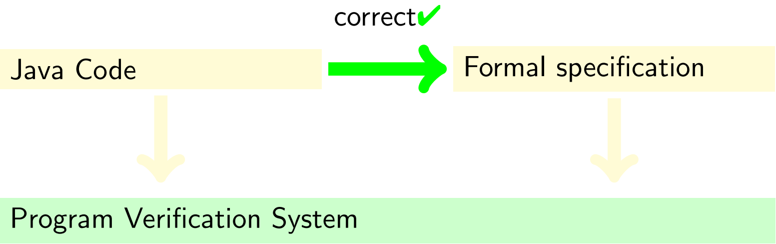

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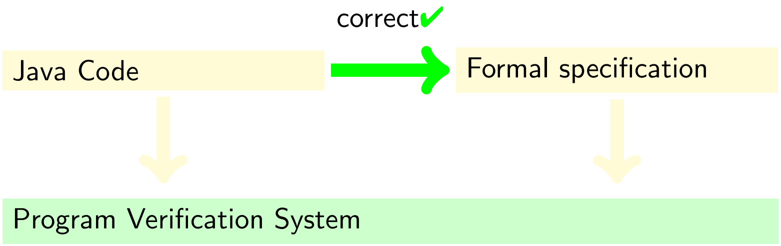

Proof rules establish relation "implementation conforms to specs"

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

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

Major Case Studies with KeY: Timsort

Timsort

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

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Facts

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Timsort is used in

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

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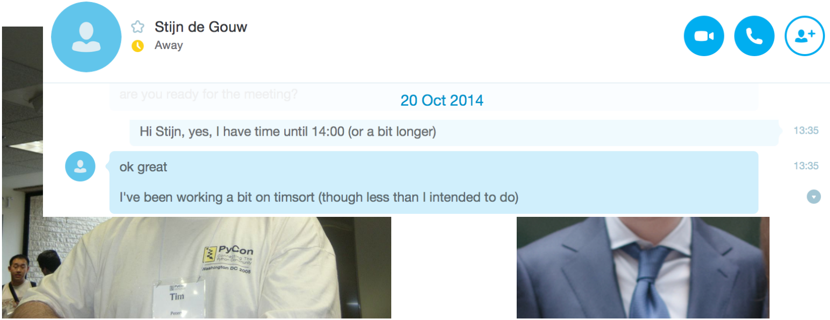

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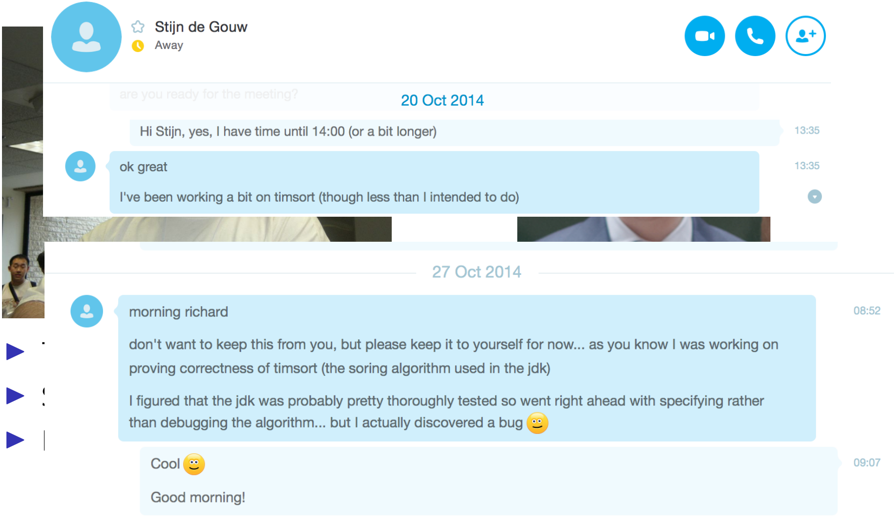

professional reasons

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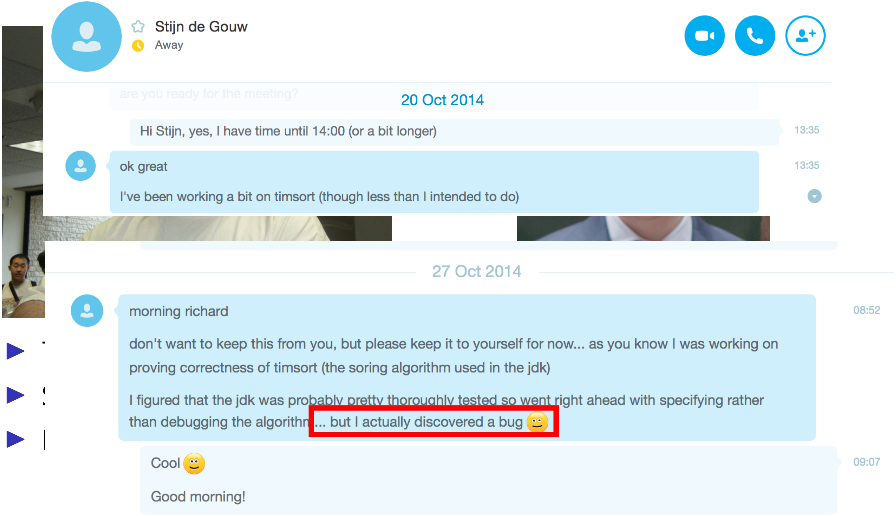

professional reasons

Major Case Studies 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, Phyton library, Haskell library

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Verified Fix using KeY

- Fixing the implementation
- Verified new version with KeY

Major Case Studies with KeY

Found Bug in Java Libraries' main Sorting Method using KeY

- `java.util.Collections.sort` an… `util.Arrays.sort` implement Timsort
- KeY verification of O… revealed *bug*.
- Same bug pr… K, Phyton library, Haskell …

Verified …

- Fixing …
- Verified … with KeY

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

Major Case Studies with KeY

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It should be fixed ... gested fix looks goo...

Tim Peters via ...**acker**

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

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SPIN to verify PROMELA programs against Temporal Logic specs

SPIN **web interface** developed for this course!

JSPIN front-end for SPIN

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

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Install first SPIN and JSPIN on your computer,
or make sure the SPIN web interface works.

You will gain experience in ...

- Modelling, and modelling languages

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- Modelling, and modelling languages
- Specification, and specification languages

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- ...

Learning Outcomes—Knowledge and Understanding

- Explain the potential and limitations of using logic based verification methods for assessing and improving software correctness
- Identify what can and what cannot be expressed by certain specification/modeling formalisms
- Identify what can and cannot be analyzed with certain logics and proof methods

Learning Outcomes—Skills and Abilities

- Express safety and liveness properties of (concurrent) programs in a formal way
- Describe the basics of verifying safety and liveness properties via model checking
- Successfully employ tools which prove or disprove temporal 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—Judgment and Approach

- Judge and communicate the significance of correctness for software development
- Employ abstraction, modelling, and rigorous reasoning when approaching the development of correctly functioning software

Literature for this Lecture

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