

Software Engineering using Formal Methods

Introduction

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Chalmers University of Technology
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1 September 2015

Teachers

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

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- ▶ 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 course portal

Google News Group

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

Passing Criteria

- ▶ Written exam 30 October 2015; re-exam 05 January 2016
- ▶ Two lab hand-ins
- ▶ Exam and labs can be passed separately

Course Structure

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Topic	# Lectures	# Exercises	Lab
Intro	1	✗	✗
Modeling & Model Checking with <i>PROMELA & SPIN</i>	6	3	✓
Specification & Verification with <i>JML & KeY</i>	7	3	✓

PROMELA & SPIN abstract programs, model checking, automated

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

... more on this later!

Lectures

- ▶ Please ask questions during lectures
- ▶ Please respond to my questions
- ▶ Slides appear online shortly *after* each lecture

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 interface working)

Labs

- ▶ 2 Lab handins: PROMELA/SPIN 2 Oct, JML/KeY 26 Oct
- ▶ 2 Lab FAQ Sessions
- ▶ Submission via **Fire**, linked from course home page
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- ▶ 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

^aOnly PhD students have to work alone.

Schedule

see course homepage

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

- ▶ **The Course Book:**

- Ben-Ari** Mordechai Ben-Ari: **Principles of the Spin Model Checker**, Springer, 2008.

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

- KeYbook** B. Beckert, R. Hähnle, and P. Schmitt, editors. **Verification of Object-Oriented Software: The KeY Approach**, vol 4334 of *LNCS*. Springer, 2006. *Chapters 1 and 10 only.* (Download via Chalmers library → E-books → Lecture Notes in Computer Science)

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Skills in object-oriented programming (like Java) assumed.

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- ▶ Finite Automata
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- ▶ Logic in Computer Science

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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
- ▶ Smart devices
- ▶ Smart cards
- ▶ Cars
- ▶ ...

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software/specification quality is a growing commercial and legal issue

Some well-known strategies from civil engineering

- ▶ Precise calculations/estimations of forces, stress, etc.

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- ▶ Design follows patterns that are proven to work

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- ▶ Cost efficiency favoured over reliability.
- ▶ Design practise for reliable software in **immature** state for complex, particularly distributed, systems.

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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 used in system design and development
- ▶ 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**

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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 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 ...

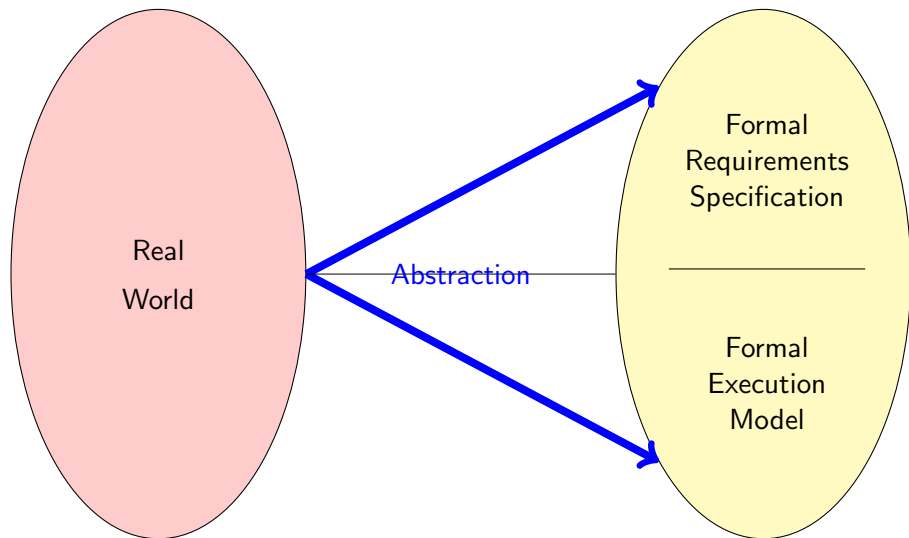
- ▶ Formal proof can replace (infinitely) many test cases
- ▶ Formal methods improve the quality of specs (even without formal verification)
- ▶ Formal methods guarantee specific properties of system model

A Fundamental Fact

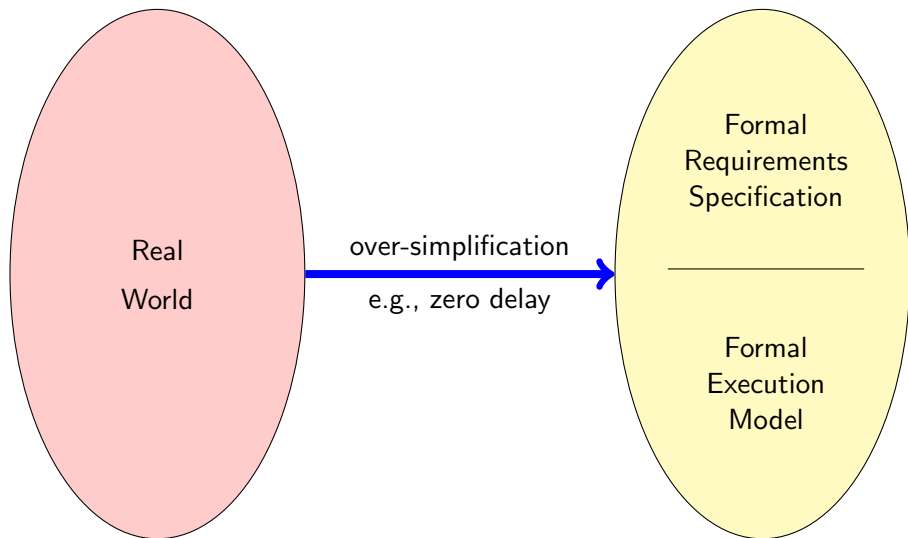
Formalisation of system requirements is hard

Let's see why ...

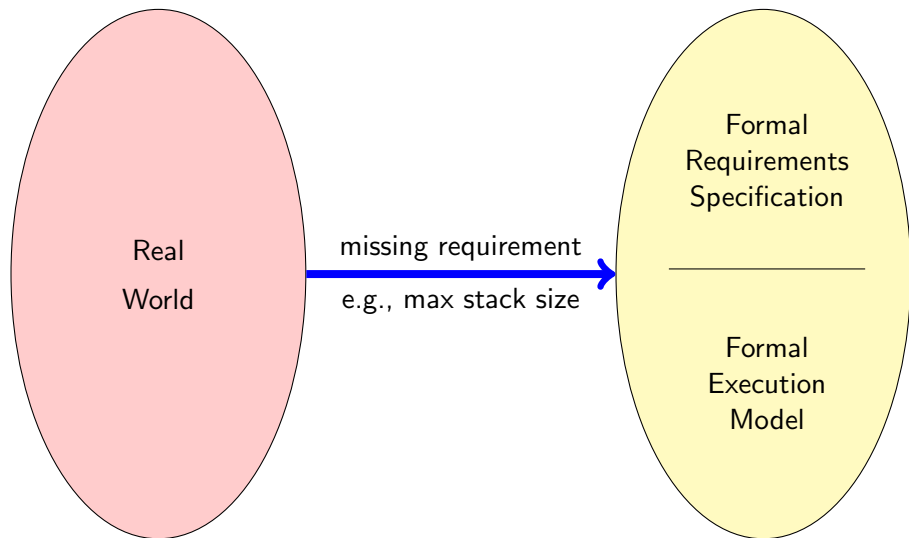
Difficulties in Creating Formal Models



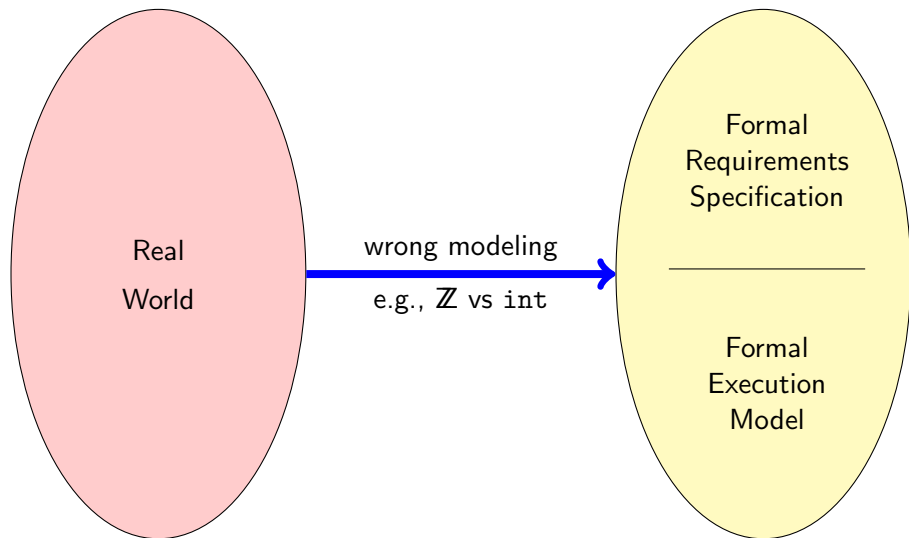
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Formalization Helps to Find Bugs in Specs

- ▶ 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

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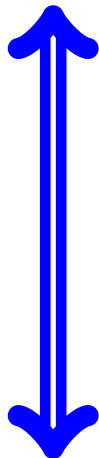
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Errors in specifications are at least as common as errors in code, but their discovery gives deep insights in (mis)conceptions of the system.

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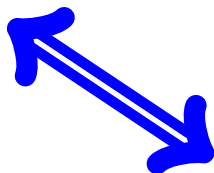
Abstract programs, Simple properties	Abstract programs, Complex properties
Concrete programs, Simple properties	Concrete programs, Complex properties

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
 - ▶ Proof is checked by tool



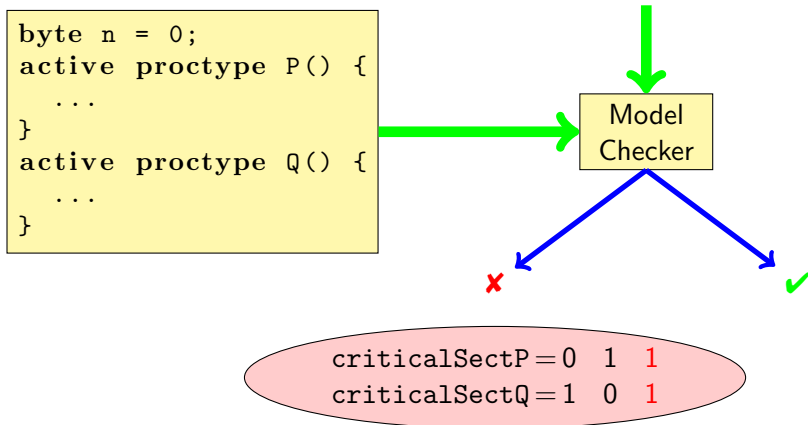
Model Checking with SPIN

System Model

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

System Property

$[\] ! (\text{criticalSectP} \ \&\& \ \text{criticalSectQ})$



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 checking of executable source code, 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

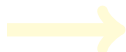
Java Code

Formal specification

Deductive Verification with KeY

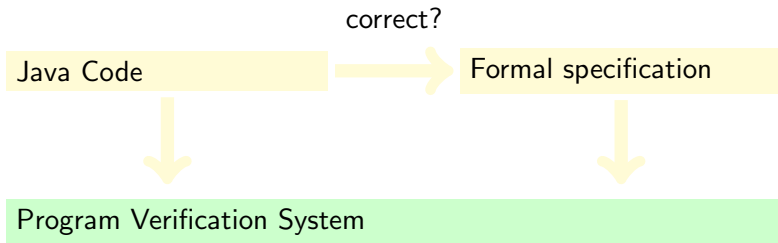
correct?

Java Code



Formal specification

Deductive Verification with KeY



Deductive Verification with KeY

correct ✓

Java Code

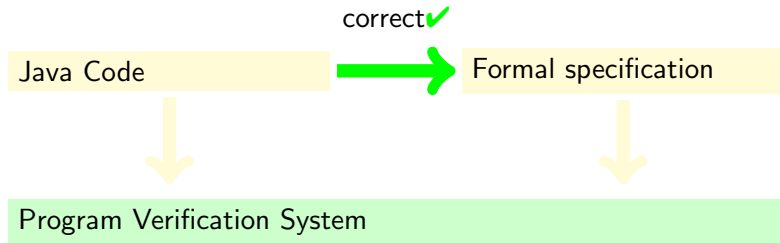


Formal specification



Program Verification System

Deductive Verification with KeY



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](#)

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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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



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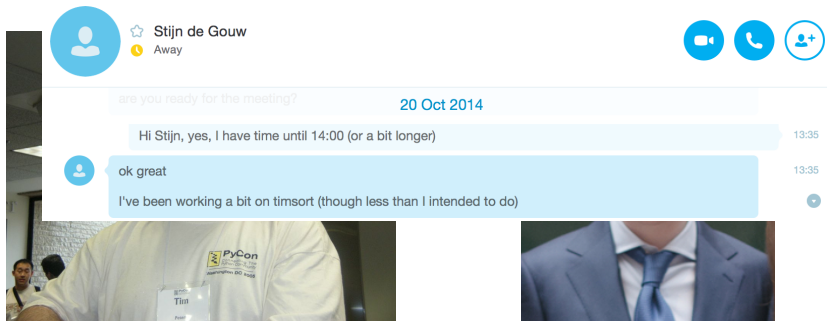


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Timsort: People

The screenshot shows a WhatsApp chat interface. At the top left is a profile card for 'Stijn de Gouw' with a star icon and a yellow 'Away' status. To the right are icons for video call, voice call, and a group of people. The chat history shows a message from Stijn: 'are you ready for the meeting?' dated '20 Oct 2014'. A reply from the other person says: 'Hi Stijn, yes, I have time until 14:00 (or a bit longer)' at 13:35. Another reply says: 'ok great' at 13:35. A final message from Stijn says: 'I've been working a bit on timsort (though less than I intended to do)'. A date separator '27 Oct 2014' is shown. A message from the other person says: 'morning richard' at 08:52. A long message follows: '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 soring algorithm used in the jdk)'. Below this is another long message: '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 😊'. A reply says: 'Cool 😊' at 09:07. The final message says: 'Good morning!'. On the left side of the chat, there are three blue arrow icons pointing right. At the bottom right, there is a blue arrow icon pointing right followed by the text 'PhD in Computer Science'.

Stijn de Gouw
☆
🟡 Away

are you ready for the meeting?
20 Oct 2014

Hi Stijn, yes, I have time until 14:00 (or a bit longer) 13:35

ok great 13:35

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

27 Oct 2014

morning richard 08:52

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Cool 😊 09:07

Good morning!

▶ PhD in Computer Science

Timsort: People

The screenshot shows a WhatsApp chat interface. At the top left is a profile card for 'Stijn de Gouw' with a yellow 'Away' status. On the right are icons for video call, voice call, and a group of people. The chat history shows a message from Stijn: 'are you ready for the meeting?' dated '20 Oct 2014'. A reply from the other person says: 'Hi Stijn, yes, I have time until 14:00 (or a bit longer)' at 13:35. Another reply says: 'ok great' at 13:35. A third message says: 'I've been working a bit on timsort (though less than I intended to do)'. A date separator '27 Oct 2014' is shown. A new message from the other person says: 'morning richard' at 08:52. The main message follows: '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 soring algorithm used in the jdk)'. The next line says: '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 😊'. The phrase 'but I actually discovered a bug' is highlighted with a red box. A final reply says: 'Cool 😊' at 09:07, followed by 'Good morning!'.

Stijn de Gouw
Away

are you ready for the meeting?
20 Oct 2014

Hi Stijn, yes, I have time until 14:00 (or a bit longer) 13:35

ok great 13:35

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

27 Oct 2014

morning richard 08:52

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 soring 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 😊 09:07

Good morning!

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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

Major Case Studies with KeY

Found Bug in Java Libraries' main Sorting Method using KeY

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- ▶ **Same bug** present in **Android** SDK, **Oracle's** JDK, **Phyton** library, **Haskell** library

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` and `java.util.Arrays.sort` implement **Timsort**
- ▶ KeY verification of `Arrays.sort` revealed *bug*.
- ▶ **Same bug** previously reported in `Python` library, `Haskell` `mergeSort` and with corrected code shown in

Verified

- ▶ Fixing
- ▶ Verified

Some researchers found an error in the logic of `mergeSort`, explained here, and with corrected code shown in `Python`. It should be fixed anyway, and their suggested fix looks good to me.

Tim Peters via Python-Bugtracker

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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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.

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

Literature for this Lecture

- FM in SE** B. Beckert, R. Hähnle, T. Hoare, D. Smith, C. Green, S. Ranise, C. Tinelli, T. Ball, and S. K. Rajamani: Intelligent Systems and Formal Methods in Software Engineering. *IEEE Intelligent Systems*, 21(6):71–81, 2006.
(Access to e-version via Chalmers Library)
- KeY** R. Hähnle: A New Look at Formal Methods for Software Construction. In: B. Beckert, R. Hähnle, and P. Schmitt, editors. *Verification of Object-Oriented Software: The KeY Approach*, pp 1–18, vol 4334 of *LNCS*. Springer, 2006.
(Access to e-version via Chalmers Library)
- SPIN** Gerard J. Holzmann: A Verification Model of a Telephone Switch. In: *The Spin Model Checker*, pp 299–324, Chapter 14, Addison Wesley, 2004.

You will gain experience in ...

- ▶ Modelling, and modelling languages

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- ▶ Specification, and specification languages

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- ▶ ...

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

Q: What should be preserved for 2015?

Some answers (shortened):

- ▶ Exercises
- ▶ Lab assignments
- ▶ Overall structure
- ▶ Not publishing Lab assignments before content appeared in lectures

Q: What should be preserved for 2015?

Some answers (shortened):

- ▶ Exercises
- ▶ Lab assignments
- ▶ Overall structure
- ▶ Not publishing Lab assignments before content appeared in lectures
- ▶ Showing this kind of slide

Q: What should be changed for 2015?

Some answers (shortened):

- ▶ More opportunities for lab supervision (avoiding queues at assistants' offices)
- ▶ More links to literature (e.g. Büchi automata)
- ▶ Lab 2 deadline not in exam week
- ▶ Clarify how long lab grading shall take (A: Three working days after the *deadline*, no after your hand-in)
- ▶ Highlight connection to industrial applications