Introduction

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Software has become critical to modern life

- Process Control (oil, gas, water, . . .)
- Transportation (air traffic control, . . .)
- Health Care (patient monitoring, device control . . .)
- Finance (automatic trading, bank security . . .)
- Defense (intelligence, weapons control, . . .)
- Manufacturing (precision milling, assembly, . . .)
Embedded systems are everywhere.
Embedded software is everywhere. Some of them are critical.
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Failing software costs money and life!
SOFTWARE SYSTEMS ARE GROWING VERY LARGE

- Millions of LOCs in aircraft software

For cars:
- The GM Volt contains +10M lines of code: how do you verify that?
- Current cars admit hundreds of onboard functions: how do you cover their combination? E.g., does braking when changing the radio station and starting the windscreen wiper, affect air conditioning?
Failing Software Costs Money

- Thousands of dollars for each minute of factory down-time

- Huge losses of monetary and intellectual investment
  - Rocket boost failure (e.g., Ariane 5)

- Business failures associated with buggy software
  - (e.g., Ashton-Tate dBase)
Failing Software Costs Lives

- Potential problems are obvious:
  - Software used to control nuclear power plants
  - Air-traffic control systems
  - Spacecraft launch vehicle control
  - Embedded software in cars

- A well-known and tragic example: Therac-25 radiation machine failures
Tiny faults can have catastrophic consequences

Software seems particularly prone to faults:
- Ariane 5
- Mars Climate Orbiter, Mars Sojourner
- London Ambulance Dispatch System
- Denver Airport Luggage Handling System
- Pentium-Bug
- . . .

Rare bugs can happen

- Lifetime of a civil aircraft $\equiv$ 30 years
- Lifetime of a car $< 10$ years but . . . 1 billions cars in 2010
Building software is what most of you will do after graduation

- You’ll be developing systems in the context we just mentioned
- Given the increasing importance of software,
  - you may be liable for errors
  - your job may depend on your ability to produce reliable systems

What are the challenges in building reliable software?
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 (any airplane flies with dozens of known and minor defects)
- Design follows patterns that are proven to work
Why This Does Not 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
- No physical or modal **separation** of subsystems
  Local failures often affect whole system
- Software designs have very high logic **complexity**
- Most SW engineers **untrained** in correctness
- **Cost efficiency** more important than reliability
- Design practice for reliable software is **not yet mature**
HOW TO ENSURE SOFTWARE CORRECTNESS?

A Central Strategy: **Testing**
(others: SW processes, reviews, libraries, ...)

**Testing against inherent SW errors (“bugs”)**
- Design test configurations that hopefully are representative and
- ensure that the system behaves as intended on them

**Testing against external faults**
- Inject faults (memory, communication) by simulation or radiation
LIMITATIONS OF TESTING

- Testing can show the presence of errors, but not their absence
  (exhaustive testing viable only for trivial systems)
- Representativeness of test cases/injected faults is subjective
  How to test for the unexpected? Rare cases?
- Testing is labor intensive, hence expensive
A Sorting Program:

```c
int* sort(int* a) {
    ...
}
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Testing `sort()`:

- `sort({3, 2, 5}) == {2, 3, 5}  √`
- `sort({}) == {}  √`
- `sort({17}) == {17}  √`
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Testing `sort()`:
- `sort({3, 2, 5}) == {2, 3, 5}` ✓
- `sort({}) == {}` ✓
- `sort({17}) == {17}` ✓

Missed Test Cases!
- `sort({2, 1, 2}) == {1, 2, 2}` ✗
- `sort(NULL) == exception` ✗
**Theorem.** The program `sort()` is correct: For any given non-null integer array `a`, calling the program `sort(a)` returns an integer array that is sorted wrt \(\leq\) and is a permutation of `a`.

However, methodology differs from Mathematics:

1. **Formalize** the claim in a logical representation
2. **Prove** the claim with the help of an automated reasoner
Formal Methods

- Rigorous design and development methods for computational (hardware/software) systems
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  2. system implementation
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a. a formal specification of (1)
b. a formal execution model of (2)
**FORMAL METHODS**

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- Consider two main artifacts:
  1. system requirements
  2. system implementation

- Are based on
  a. a formal specification of (1)
  b. a formal execution model of (2)

- Use tools to verify mechanically that (b) satisfies (a)
Complement other analysis and design methods

Are good at finding bugs (in code and specification)

Reduce development (and testing) time

Can ensure certain properties of the formal system model

Should ideally be automatic
Run the system at chosen inputs and observe its behavior

- Randomly chosen
- Intelligently chosen (by hand: expensive!)
- Automatically chosen (need formalized spec)

What about other inputs? (test coverage)

What about the observation? (test oracle)

Challenges can be addressed by/require formal methods
SPECIFICATIONS: WHAT THE SYSTEM SHOULD DO

- Simple properties
  - Safety properties
    Something bad will never happen
  - Liveness properties
    Something good will happen eventually
  - Non-functional properties
    Runtime, memory, usability, ...

- “Complete” behaviour specification
  - Equivalence check
  - Refinement
  - Data consistency
  - ...

The expression in some formal language and at some level of abstraction of a collection of properties that some system should satisfy [van Lamsweerde]

- **Formal language:**
  - Syntax can be mechanically processed and checked
  - Semantics is defined rigorously by mathematical means

- **Abstraction:**
  - Above the level of source code
  - Several levels possible
FORMAL SPECIFICATIONS

The expression in some **formal language** and at some level of **abstraction** of a collection of **properties** that some system should **satisfy** [van Lamsweerde]

- **Properties:**
  - Expressed in some formal logic
  - Have a well-defined semantics

- **Satisfaction:**
  - Ideally (but not always) decided mechanically
**A Warning**

- The notion of “formality” is often misunderstood (formal vs. rigorous)
- The effectiveness of formal methods is still debated
- There are still persistent myths about FM’s practicality and cost
- FM’s are not yet widespread in industry
The Main Point of Formal Methods is **Not**

- To show “correctness” of entire systems
  (What is correctness? Always go for specific properties!)
- To replace testing entirely
  (Formal methods work on source code or, at most, bytecode)
  (Some properties are not formalizable)
- To replace good design practices

There is no silver bullet!

No correct system w/o clear requirements & good design

This holds for Formal Methods as well
**Benefits of Using Formal Methods**

- Forces developers to think about issues in a systematic way
- Improves the quality of specifications, even without formal verification
- Leads to better design and earlier detection of inconsistencies and flaws
- Provides a precise reference to check requirements against
- Provides documentation within a team of developers
- Gives direction to latter development phases (leading to coding)
- Provides a basis for reuse via specification matching
- Can replace (infinitely) many test cases
- Facilitates automatic test case generation
SUCCESSFUL FORMAL METHODS...

- are integrated into the development process, in particular at early design stages
- avoid unreasonable new demands or skills from the user (FMs should be learnable as part of Masters in CS)
- work at large scale
- save time or money in getting a good quality product out
- increase the feasible complexity of products
Typical Areas

- **Saving time**
  - Time to market

- **Saving money**
  - Intel Pentium bug
  - Smart cards in banking

- **More complex products**
  - Modern processors, fault tolerant software

- **Saving human lives**
  - Avionics, X-by-wire
FORMALIZATION HELPS TO FIND BUGS IN Specs

- Wellformedness and consistency of formal specs checkable with tools
- Fixed signature (symbols) helps to spot incomplete specs
- Failed verification of implementation against spec gives feedback on erroneous formalization
Formalisation of system requirements is hard
DIFFICULTIES IN CREATING FORMAL MODELS

Real World

<table>
<thead>
<tr>
<th>Formal Execution Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Formal Requirements Specification</td>
</tr>
</tbody>
</table>

Abstraction

- Wrong assumption (e.g., zero delay)
- Missing requirement (e.g., stack overflow)
- Misunderstood problem (e.g., wrong integer model)
DIFFICULTIES IN CREATING FORMAL MODELS

Real World

wrong assumption
eg. zero delay

Formal Execution Model

Formal Requirements Specification
DIFFICULTIES IN CREATING FORMAL MODELS

Real World

- wrong assumption
  - eg. zero delay
- missing requirement
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Formal Execution Model
Formal Requirements Specification
DIFFICULTIES IN CREATING FORMAL MODELS

Real World

- wrong assumption
  - eg. zero delay
- missing requirement
  - eg, stack overflow
- misunderstood problem
  - eg, wrong integer model

Formal Execution Model
Formal Requirements Specification
Proving properties of systems can be hard
LEVEL OF SYSTEM DESCRIPTION

- Low level (machine level)
  - Finitely many states
  - Tedious to program, worse to maintain
  - Automatic proofs are (in principle) possible

- High level (programming language level)
  - Complex datatypes and control structures, general programs
  - Easier to program
  - Automatic proofs (in general) impossible!
EXPRESSIVENESS OF SPECIFICATION

- Simple
  - Finitely many cases
  - Approximation, low precision
  - Automatic proofs are (in principle) possible

- Complex
  - General properties
  - High precision, tight modeling
  - Automatic proofs (in general) impossible!
CURRENT AND FUTURE TRENDS

Slowly but surely formal methods are more than ever used in (serious) industries.

- Design for formal verification
- Combining semi-automatic methods with SAT, theorem provers
- Combining static analysis of programs with automatic methods and with theorem provers
- Combining test and formal verification
- Integration of formal methods into SW development process
Software is becoming pervasive and very complex

Current development techniques are inadequate

Formal methods . . .
- are not a panacea, but will be increasingly necessary
- are (more and more) used in practice
- can shorten development time
- can push the limits of feasible complexity
- can increase product quality

We will learn to use several different formal methods, for different development stages