The University of Iowa **Fall 2013**

Formal Methods in Software Engineering

Introduction

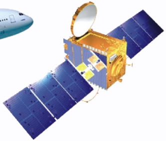
A Truism

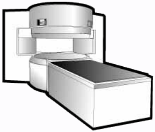
Software has become critical to modern life

- 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 Software

Embedded systems are everywhere.





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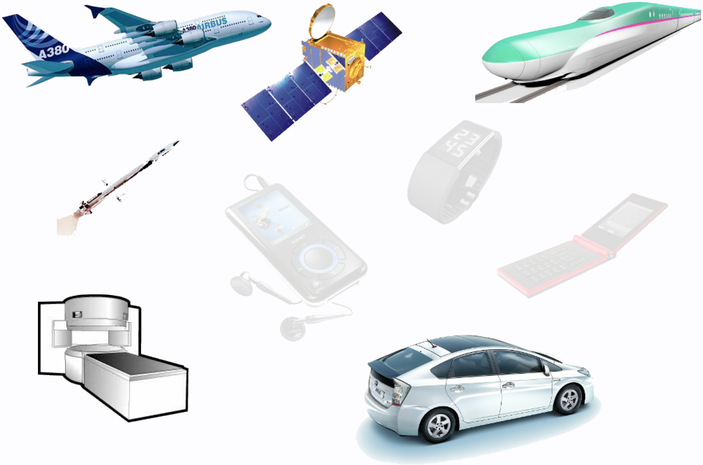

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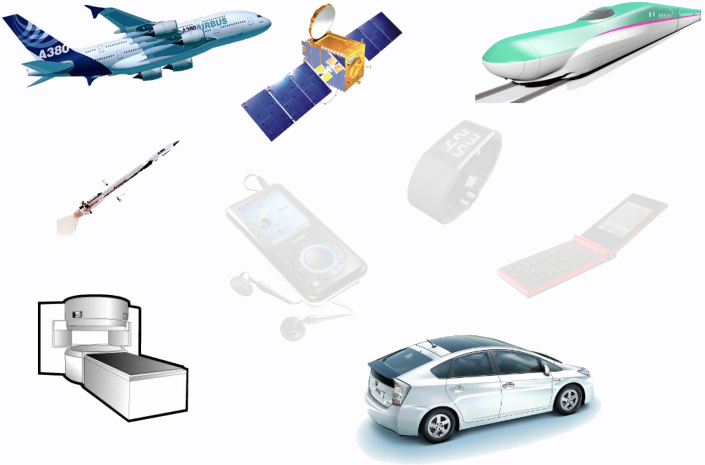
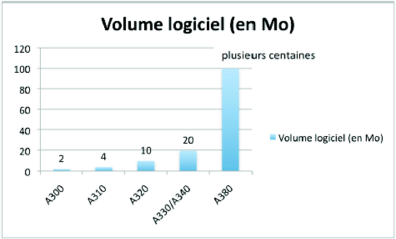


Failing software costs money and life!

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

The Peculiarity of Software Systems

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

OBSERVATION

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

Complementing Testing: Formal Verification

A Sorting Program:

```
int* sort(int* a) {
  ...
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- sort({}) == {} $\surd$
- sort({17}) == {17} $\surd$

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- sort({17}) == {17} √

Missed Test Cases!

- sort({2,1,2}) == {1,2,2} ☒
- sort(NULL) == exception ☒
-

Formal Verification as Theorem Proving

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

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- 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)

Formal Methods: The Vision

- 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

FORMAL METHODS AND TESTING

- 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
  - . . .

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]

- 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 as 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

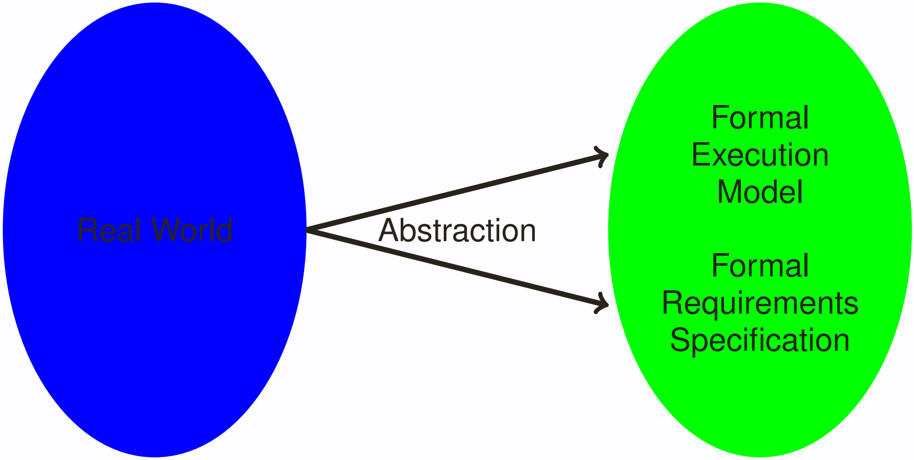
Formalization Helps to Find Bugs in Specs

- 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

A Fundamental Fact

Formalisation of system requirements is hard

Difficulties in Creating Formal Models



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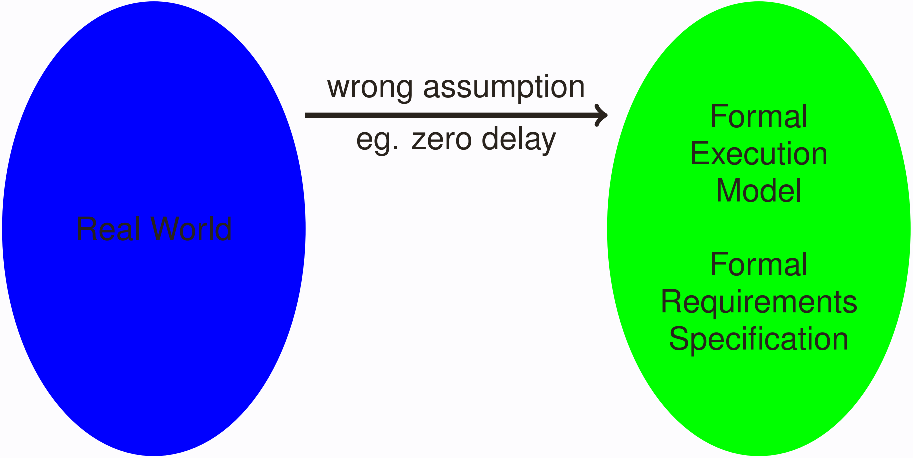

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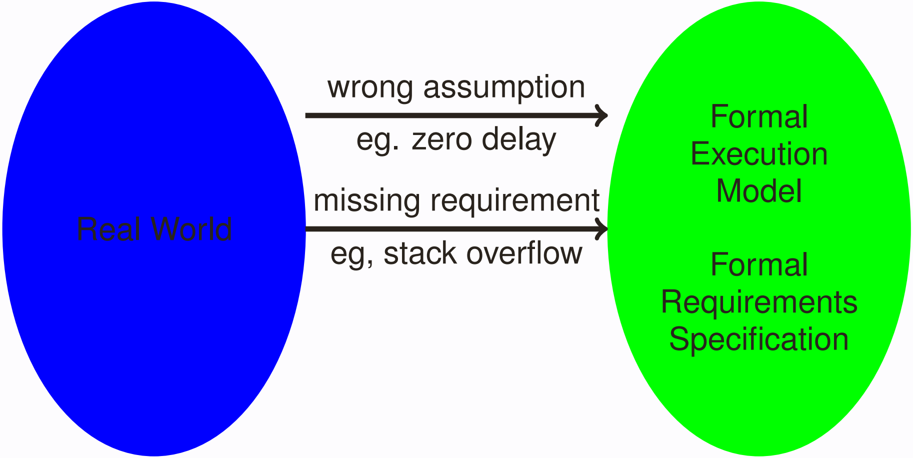

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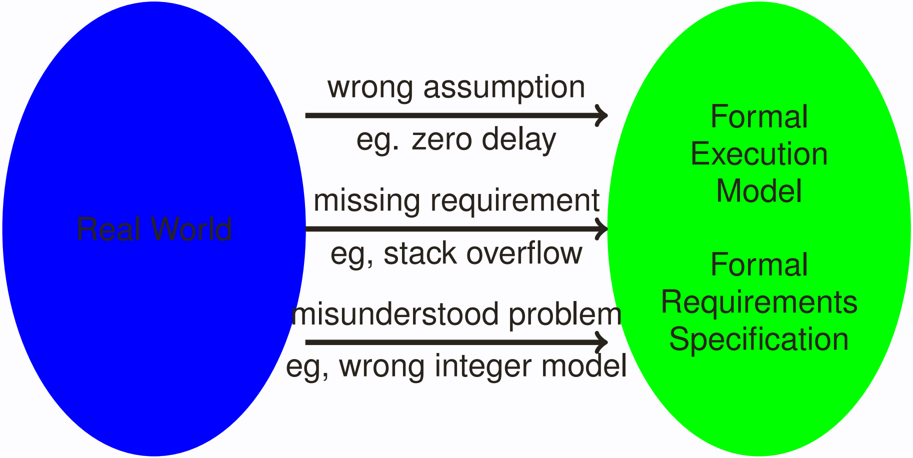

Another Fundamental Fact

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

SUMMARY

- 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