The University of Iowa

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Formal Methods in Software Engineering

Introduction

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(Thanks to Cesare Tinelli, Pierre-Loïc Garoche, Reiner Hänle, Steven Miller, Haniel Barbosa)

A Truism

Software has become critical to modern life

- Communication (internet, voice, video, . . .)
- Transportation (air traffic control, avionics, cars, . . .)
- Health Care (patient monitoring, device control, . . .)
- Finance (automatic trading, banking, . . .)
- Defense (intelligence, weapons control, . . .)
- Manufacturing (precision milling, assembly, . . .)
- Process Control (oil, gas, water, . . .)
- . . .

Embedded Software

Software is now embedded everywhere

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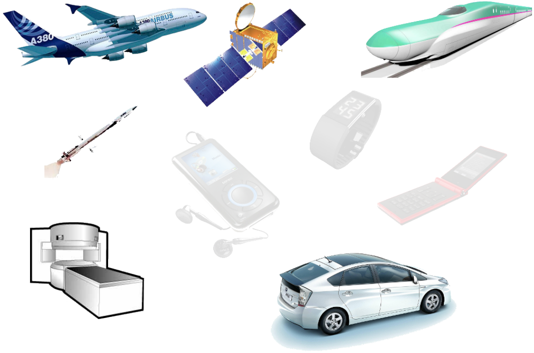
Some of it is critical



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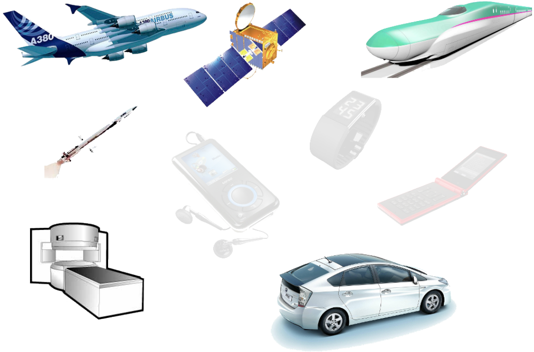
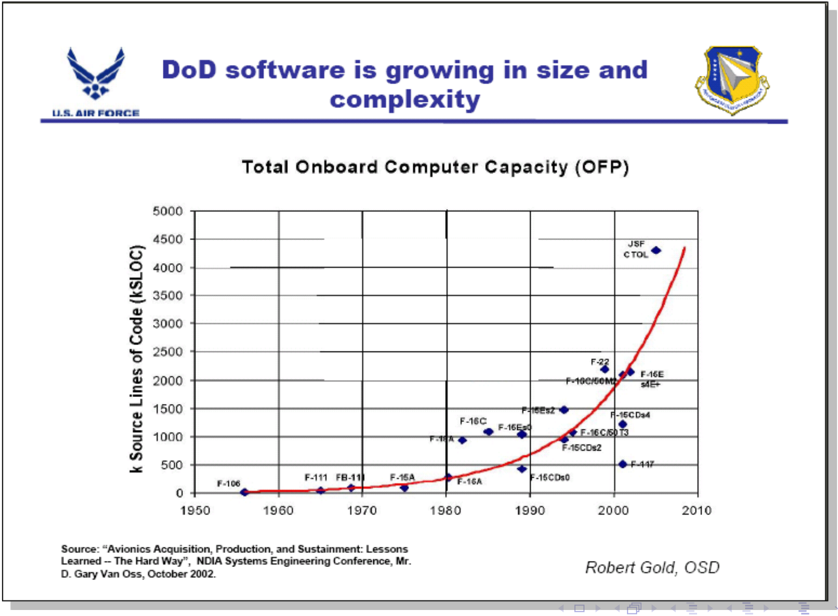


Failing software costs money and life!

Software Systems are Growing Very Large



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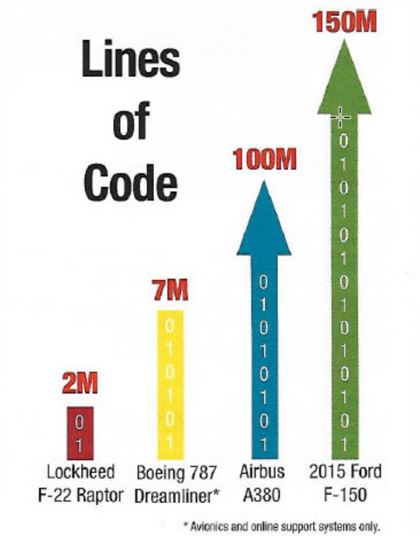

Software Systems are Growing Very Large

Automotive Software

- A typical 2017 car model contains $\sim$100M 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

- Expensive recalls products with embedded software
- Lawsuits for loss of life or property damage
  - Car crashes (e.g., Toyota Camry 2005)
- Thousands of dollars for each minute of down-time
  - (e.g., Denver Airport Luggage Handling System)
- 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, Knight Capital)

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

Software seems particularly prone to faults

Tiny faults can have catastrophic consequences

- Ariane 5
- Mars Climate Orbiter, Mars Sojourner
- Pentium-Bug
- ...

Rare bugs can occur

- avg. lifetime of a passenger plane: 30 years
- avg. lifetime of a car: $<$ 10 years, but already $>$ 1.2B cars in 2014

Logic and implementation errors represent security exploits

- (too many to mention)

OBSERVATION

Building software is what most of you will do after graduation

- You'll be developing systems in the context above
- 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 and secure 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) {
   ...
}
```

COMPLEMENTING TESTING: FORMAL VERIFICATION

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Testing `sort`:

- `sort({3,2,5}) == {2,3,5}` $\surd$
- `sort({}) == {}` $\surd$
- `sort({17}) == {17}` $\surd$

Complementing Testing: Formal Verification

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Testing sort:

- sort({3,2,5}) == {2,3,5} √
- sort({}) == {} √
- sort({17}) == {17} √

Typically missed test cases

- sort({2,1,2}) == {1,2,2} ☒
- sort(null) == exception ☒
- isPermutation(sort(a),a) ☒

Formal Verification as Theorem Proving

Consider program with an array access:

```
int foo(int d[10], int x, int y){
  int i = getIndex(x,y);
  return d[i];
}
int getIndex(int x, int y){
  if( x<y ) { return 0; }
  while ( (x+y) % 7!=3 ){
    x = x+2;
    y = y+1;
  }
  int z = x-y;
  while( z>=10 ){ z = z-10; }
  return z;
}
```

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- Ensures x>y
- z > 0
- 0 <= z < 10

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- Safe
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  Overflow?
- z > 0
- 0 <= z < 10

Formal Verification as Theorem Proving

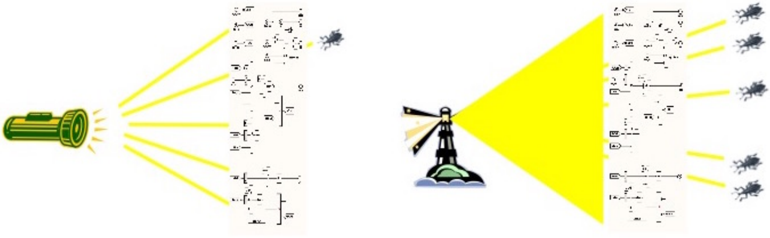
Theorem (Correctness of `sort()`) For any given non-null int array `a`, calling the program `sort(a)` returns an int array that is sorted wrt $\leq$ *and is a permutation of* `a`.

However, methodology differs from mathematics:

1. Formalize the expected property in a logical language
2. Prove the property with the help of an (semi-)automated tool

CONTRASTING TESTING WITH FORMAL VERIFICATION

Testing Checks Only the Values We Select **_Formal Verification Checks Every Possible Value!_**



Even Small Systems Have Trillions (of Trillions) of Possible Tests!

Finds every exception to the property being checked!

Formal Methods

Rigorous techniques and tools for the development and analysis of computational (hardware/software) systems

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Rigorous techniques and tools for the development and analysis of computational (hardware/software) systems

- Applied at various stages of the development cycle
- Also used in reverse engineering to model and analyze existing systems
- Based on mathematics and symbolic logic (formal)

Main Artifacts in Formal Methods

1. System requirements
2. System implementation

MAIN ARTIFACTS IN FORMAL METHODS

1. System requirements
2. System implementation

Formal methods rely on

a. some formal specification of (1)
b. some formal execution model of (2)

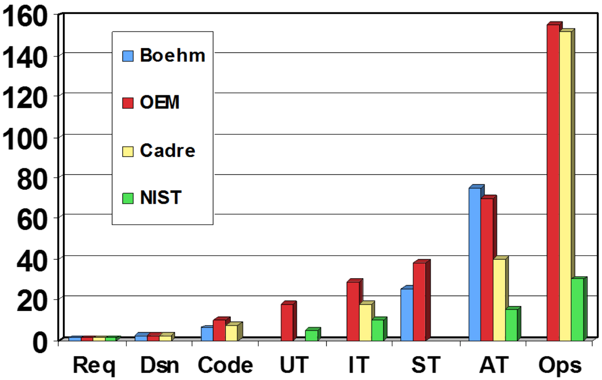
Use tools to verify mechanically that implementation satisfies (a) according to (b)

Why Use Formal Methods

- Mathematical modeling and analysis contribute to the overall quality of the final product
- Increase confidence in the correctness/robustness/security of a system
- Find more flaws and earlier (i.e., during specification and design vs. testing and maintenance)

WHY USE FORMAL METHODS

Relative cost to fix an error, by development phase



Finding errors earlier reduces development costs

Formal Methods: The Vision

- Complement other analysis and design methods
- Help find bugs in code and specification
- Reduce development, and testing, cost
- Ensure certain properties of the formal system model
- Should be highly automated

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

A WARNING

- The notion of “formality” is often misunderstood (formal vs. rigorous)
- The effectiveness of formal methods is still debated
- There are persistent myths about their practicality and cost
- Formal methods are not yet widespread in industry
- They are mostly used in the development of safety, business, or mission critical software, where the cost of faults is high

THE MAIN POINT OF FORMAL METHODS IS NOT

- To show “correctness” of entire systems
  - What is correctness? Go for specific properties!
- To replace testing entirely
  - Formal methods do not go below byte code level
  - Some properties are not formalizable
- To replace good design practices

There is no silver bullet!

No correct system w/o clear requirements & good design

Overall Benefits of Using Formal Methods

- Forces developers to think systematically about issues
- Improves the quality of specifications, even without formal verification
- Leads to better design
- Provides a precise reference to check requirements against
- Provides documentation within a team of developers
- Gives direction to latter development phases
- Provides a basis for reuse via specification matching
- Can replace (infinitely) many test cases
- Facilitates automatic test case generation

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 Specification

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 unambiguously by mathematical means
- abstraction:
  - above the level of source code
  - several levels possible

Formal Specification

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
  - based on automated deduction and/or model checking techniques

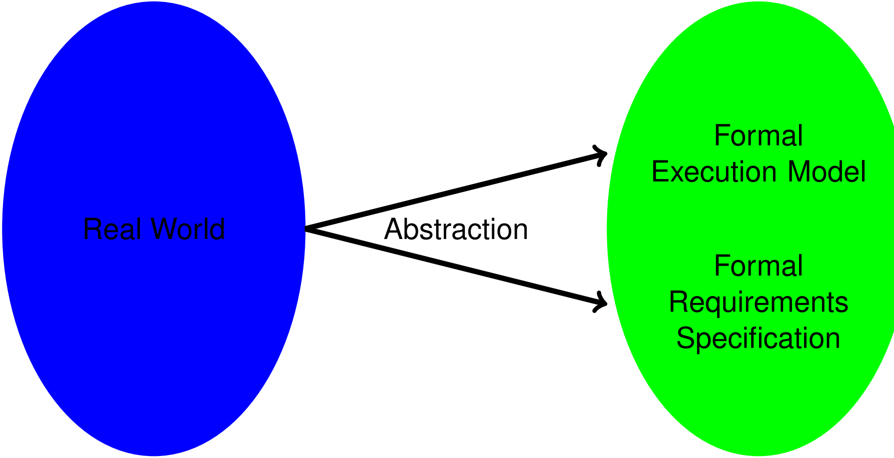
Formalization Helps to Find Bugs in Specs

- Well-formedness and consistency of formal specs are checkable with tools
- Fixed signature (set of symbols) helps spot incomplete specs
- Failed verification of implementation against spec gives feedback on errors
  - in the implementation or
  - in the (formalization of the) spec

A Fundamental Fact

Formalisation of system requirements is hard

Difficulties in Creating Formal Models



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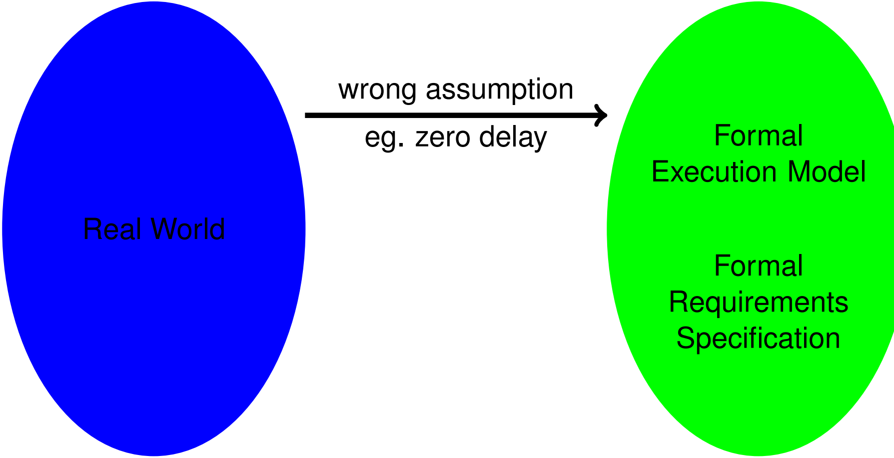

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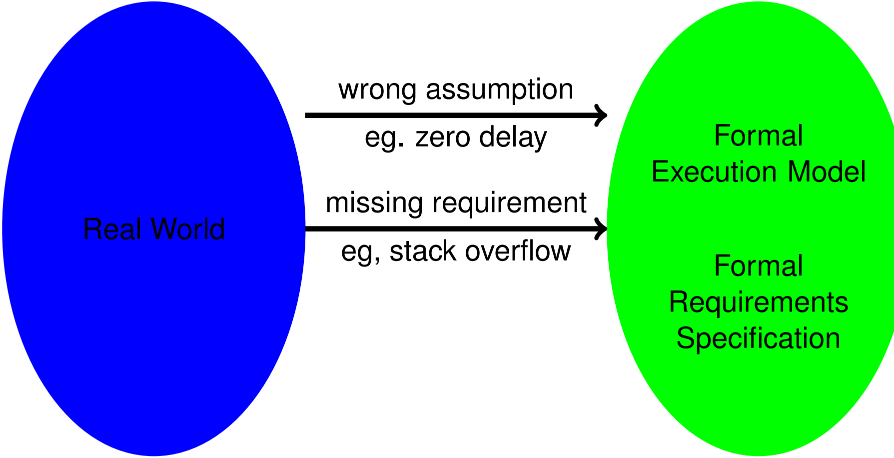

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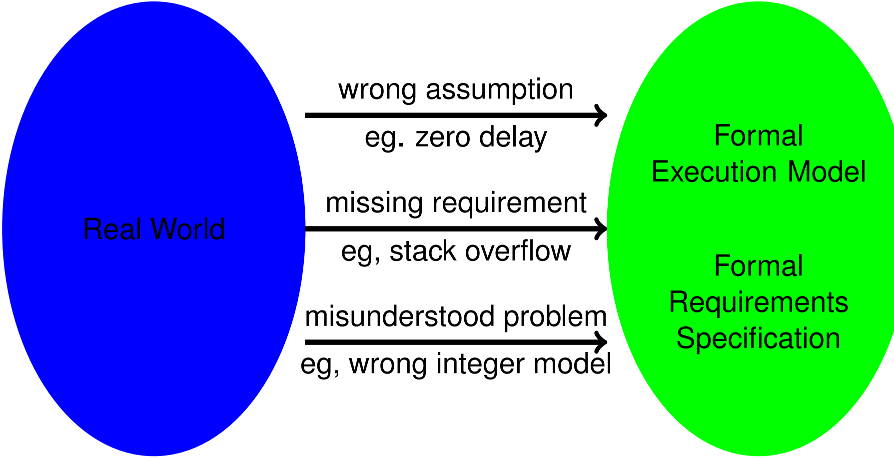

Another Fundamental Fact

Proving properties of systems can be hard

Level of System Description

High level (modeling/programming language level)

- Complex datatypes and control structures, general programs
- Easier to program
- Automatic proofs (in general) impossible!

⋮

Low level (machine level)

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

Expressiveness of Specification

High

- General properties
- High precision, tight modeling
- Automatic proofs (in general) impossible!

⋮

Low

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

Current and Future Trends

Slowly but surely formal methods are finding increased used in industry.

- Designing for formal verification
- Combining semi-automatic methods with SAT/SMT solvers, 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

Current and Future Trends

Need for secure systems is increasing the use of FMs

- Security is intrinsically hard
- "Security is to safety as Lucifer is to Murphy"
- Redundant fault-tolerant systems are often used to meet safety requirements
- Fault-tolerance depends on the independence of component failures
- Security attacks are intelligent, coordinated and malicious
- Formal methods provides a systematic way to meet stringent security requirements

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
  - can improve system security
- We will learn to use several different formal methods, for different development stages