CS:5810

Formal Methods in Software Engineering

Course Introduction

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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

Some of it is critical

Failing software costs money and life!

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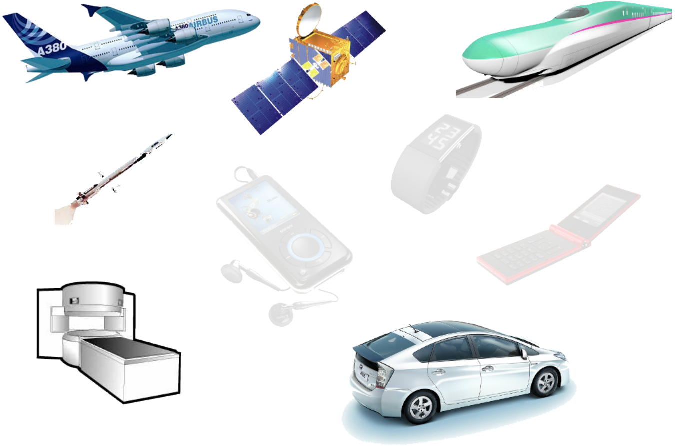

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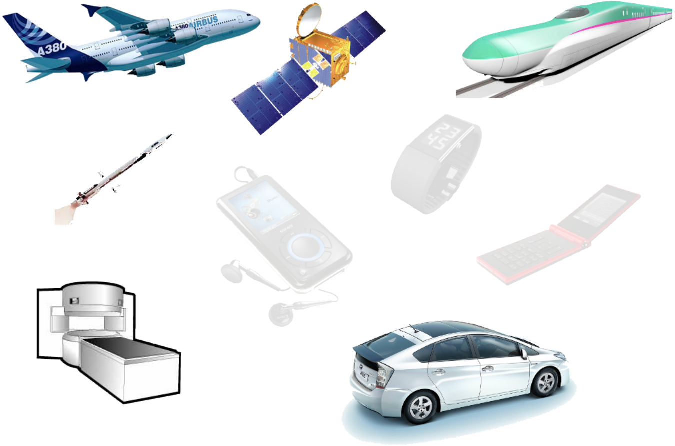

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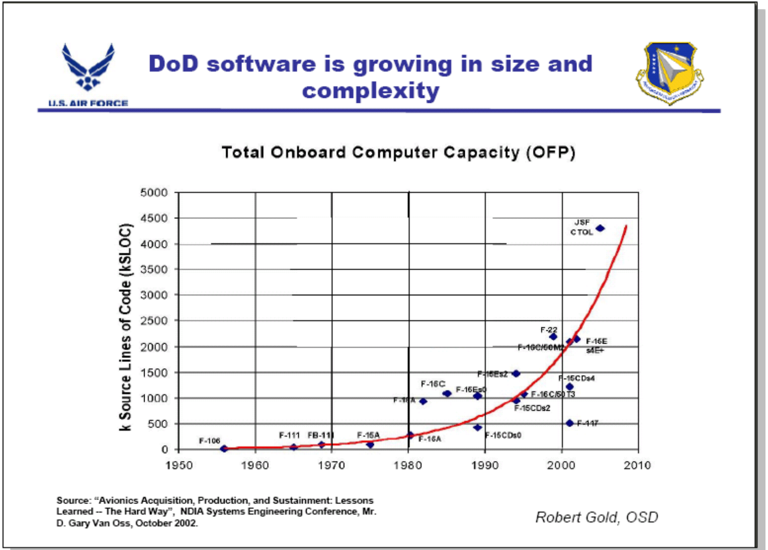
Software Systems Have Grown Very Large



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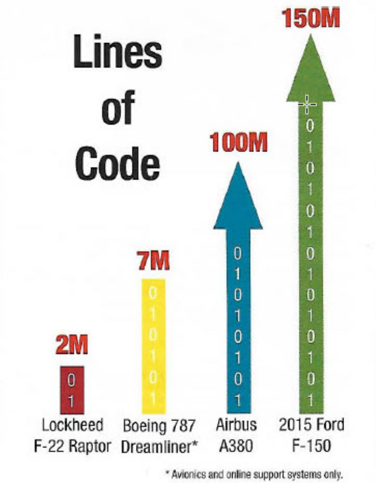

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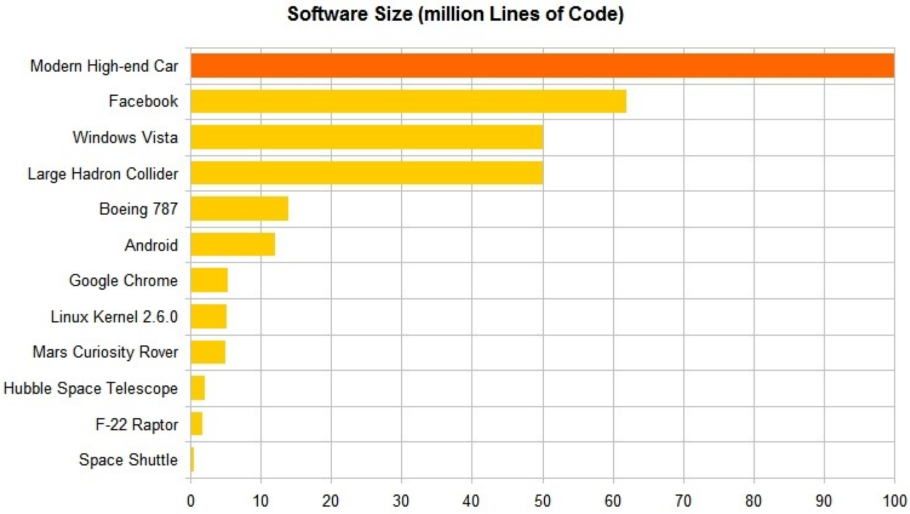

Software Systems are Growing Very Large

Automotive Software

A typical 2022 car model contains $>$100M lines of code

How do you verify that?

Current cars admit hundreds of onboard functions

How do you cover their combination?

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Failing Software Costs Money

Expensive recalls of 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)

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 > 1.4B cars in 2022

Logic and implementation errors represent security exploits

- (too many to mention)

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Observation

Building software is (still) 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?

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What are the challenges in building
reliable and secure software?

Achieving Reliability in Engineering

Some well-known strategies from civil/mechanical engineering:

- Precise calculations/estimations of forces, stress, etc.
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- Clear separation of subsystems (any airplane flies with dozens of known and minor defects)
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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 logical errors

  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 are untrained in correctness

- Cost efficiency more important than reliability

- Design practice for reliable software is not yet mature

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How to Ensure Software Correctness?

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

Testing against inherent SW errors ("bugs")

1. Design test configurations that hopefully are representative
2. Check that the system behaves as intended on them

Testing against external faults

1. Inject faults (memory, communication) by simulation, radiation, etc.
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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

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Complementing Testing: Formal Verification

A Sorting Program:

```
int[] sort(int[] a) {
  ...
}
```

Testing `sort`:

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

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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)` ☒

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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
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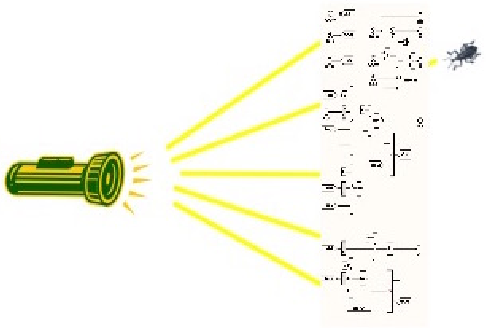
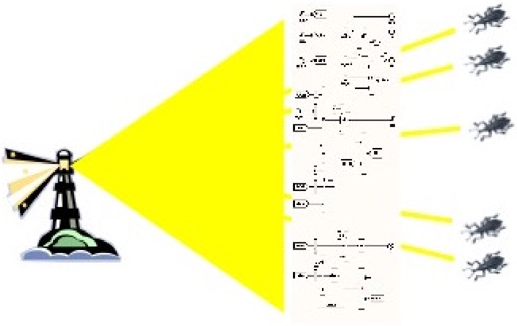
Contrasting Testing with Formal Verification

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

- 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)

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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)

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

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Why Use Formal Methods

1. Contribute to the overall quality of the final product thanks to mathematical modeling and formal analysis

2. Increase confidence in the correctness/robustness/security of a system

3. Find more flaws and sooner (i.e., during specification and design vs. testing and maintenance)

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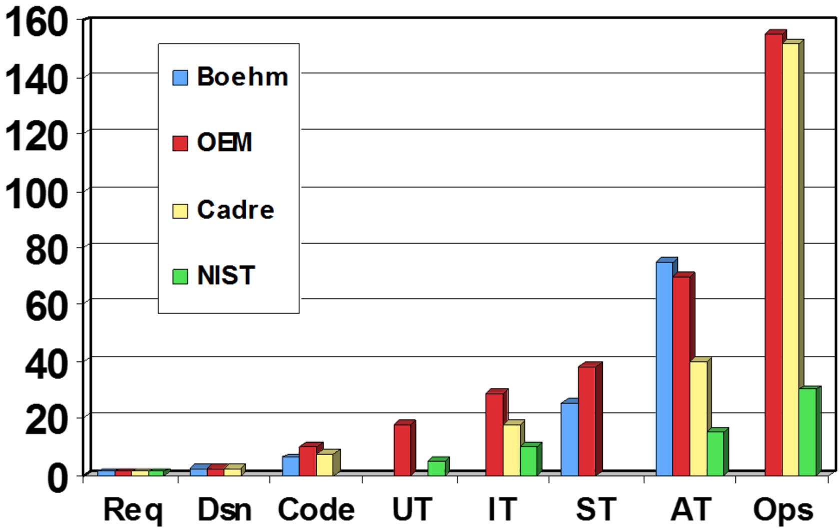
Relative cost to fix an error, by development phase



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 FMs in software engineering in general is still debated
- There are persistent myths about their practicality and cost
- FMs are not yet as widespread in industry as they could be
- They are mostly used in the development of safety-, business-, or mission-critical software (where the cost of faults is high)
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Beware: The Main Point of Formal Methods is Not

- To show “correctness” of entire systems
  - What is correctness? We can only (dis)prove specific properties!
- To replace testing entirely
  - FMs typically do not go below byte code level
  - Some properties are not formalizable
- To replace good design practices

There is no silver bullet!

But also, there is no correct system without clear requirements and good design

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4. Provides a precise reference to check requirements against
5. Provides rigorous documentation within a team of developers
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Specifications: What the system should do

Individual properties

- **Safety properties:** something bad will never happen
- **Liveness properties:** something good will happen eventually
- Non-functional properties: runtime, memory, usability, . . .

Complete behavior specification

- Equivalence requirements
- Refinement requirements
- Data consistency
- . . .

Formal Specification

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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:

- at or above the level of source code
- several levels possible

properties:

- expressed in some formal logic
- have a well-defined semantics

satisfaction:

- ideally (but not always) decided mechanically
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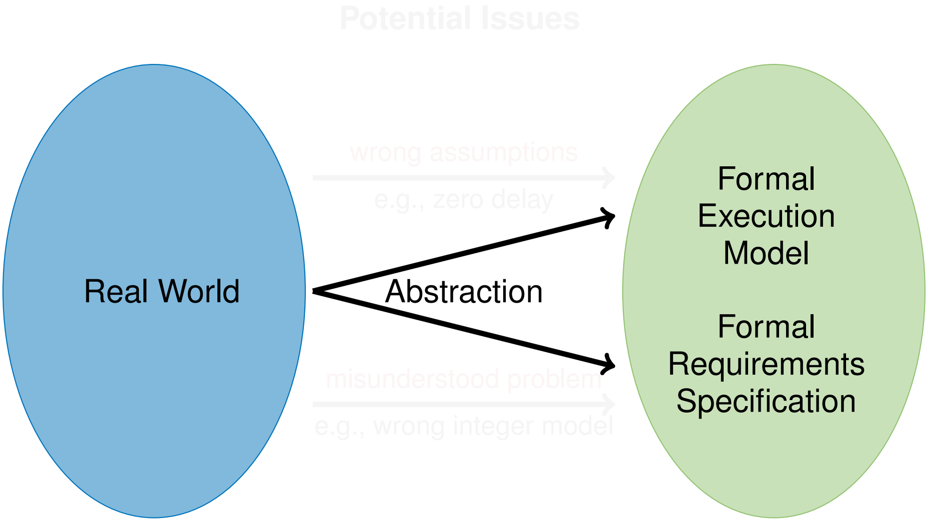
Formalization Helps Find Bugs in Specifications

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

A Fundamental Fact

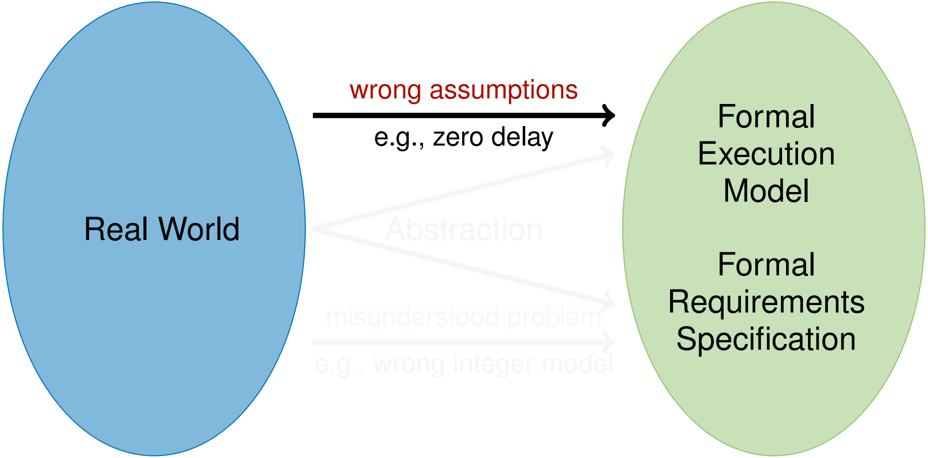
Formalizing system requirements is hard

Difficulties in Creating Formal Models



Difficulties in Creating Formal Models

Potential Issues



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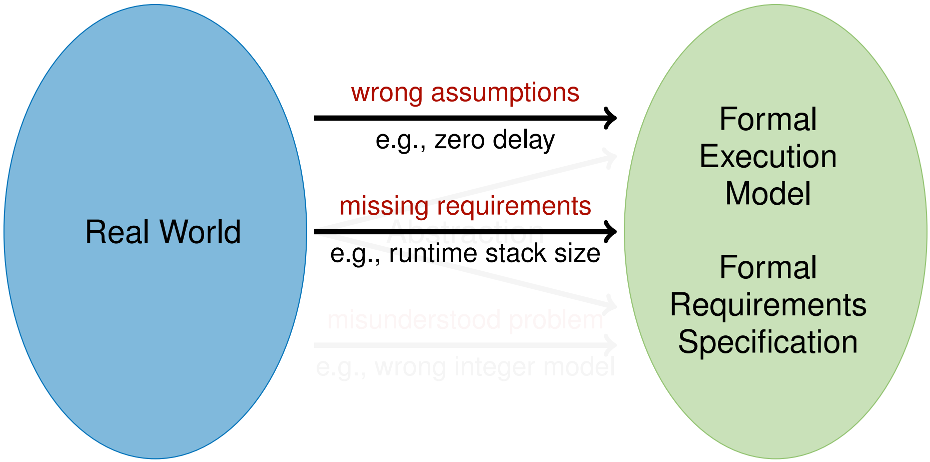

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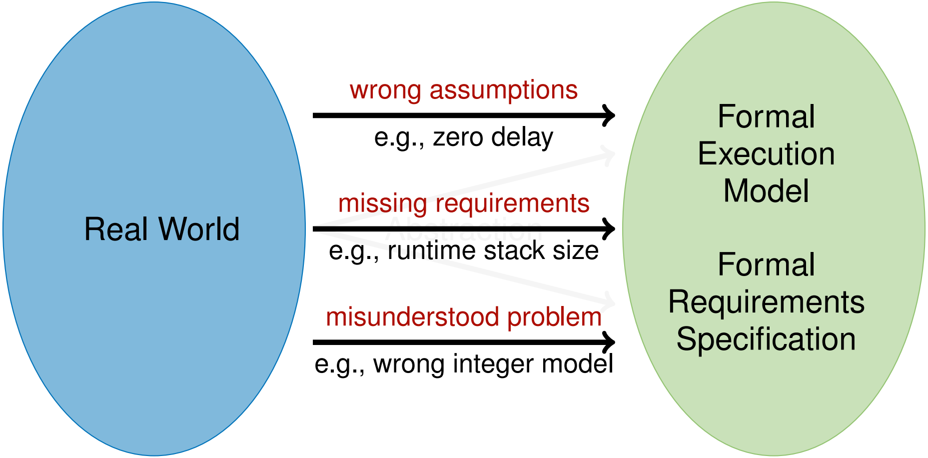

Another Fundamental Fact

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

⋮

Low level (machine level)

- Finitely many states
- Tedious to program, worse to maintain

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

Formal methods are finding increased use 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 testing and formal verification
- Integration of formal methods into software development process

Current and Future Trends

Need for secure systems is a big incentive to using FMs

- Security is intrinsically hard
- 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 reliability
- can improve system security

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