Developing Software Rigorously: Introduction and Motivation[1]

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[1] Many slides borrowed from J. R. Abrial and M. Butler

Take notes

TECHNOLOGY

To Remember a Lecture Better, Take Notes by Hand

Students do worse on quizzes when they use keyboards in class.

Picture & headline © *The Atlantic*

https://www.theatlantic.com/technology/archive/2014/05/to-remember-a-lecture-better-take-notes-by-hand/361478/

I will make notes / slides available *after* the lectures

I will ask you to work during the lectures

Plan

- Three-hour lectures.
  - Three 50-minute sections with ten-minute breaks.
  - Worked well in previous years.
- Homework + term project (with presentation).
- Final exam for those who **choose not** to do HW + project.
- Hands-on lectures when possible.

Purpose of the course

- To give you some insights about modelling and formal reasoning
- To show how programs can be *correct by construction*
- To show that modelling can be made practical
- To illustrate this approach with many examples

Requirements

No formal requirements.
But I expect you to be familiar with a series of topics:

- You should have a fairly ample base in programming.
- You should have a working knowledge of first order logic.
- You should feel comfortable with rigorous / math reasoning.

What you will learn

By the end of the course you should be comfortable with:

- Modelling (versus programming).
- Abstraction and refinement.
- Some mathematical techniques used to reason about programs.
- Proving as a means to construct (provably) correct programs.
- Using tools to help in the above.

Software is omnipresent

Today's car: typically 100+ microprocessors, 100 M. lines of code, 20.000 programmer years.

Software is omnipresent

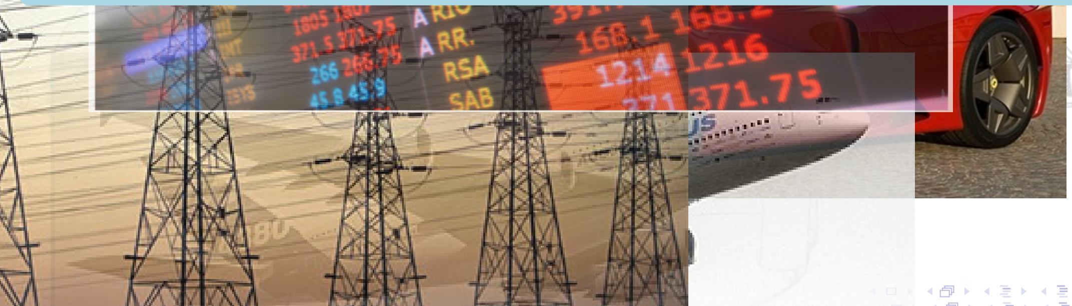
Plane: computers manage controls, calculate routes, ...

Software is omnipresent

Large interconnected systems: independent, isolated, automatic decision making (which must be globally correct).

Software is omnipresent

- Cell phones (from O.S. to compression algorithms to user interfaces).
- HDTV (routing, encoding and decoding), Netflix, . . .
- Buying and selling on the Internet (web interfaces, databases, encryption).
- Stock market (algorithmic trading, high frequency trading).
- Skype, Whatsapp, AirBnB, idealista, GroupOn, FB, Steam, Spotify, E-Banking, Google Maps / Waze, Uber / Lyft, Tesla, . . .



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- All of them *critical* to a certain degree.
- Some **extremely** critical

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Overall challenge:

How to develop complex software, with resources that are **always limited**, ensuring that it will work correctly?

Growth in complexity and expectations

- Processes managed by computing systems increasingly complex.
- Same software is to run in several platforms.
- Computing systems interact more and more with each other.
- They should be increasingly autonomous.
- Reactive.

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(Only showing some types of problems)

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July 16, 2012: Skype bug sends messages to unintended recipients.

July 13, 2012: Apple's "in-app purchase" service for iOS bypassed by Russian hacker.

July 13, 2012: German security experts find major flaw in credit card terminals.

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July 12, 2012: Hackers expose 453,000 credentials allegedly taken from Yahoo service.

July 12, 2012: Mountain Lion (Mac OS X version) sends some 64-bit Macs to sleep (related to graphics drivers).

July 7, 2012: Still infected, 300,000 PCs to lose Internet access.

July 6, 2012: Apple fixes App Store DRM error, crash-free downloads resume.

July 5, 2012: "Find and Call" app becomes first trojan to appear on iOS App Store.

July 5, 2012: iOS, Mac app crashes linked to botched FairPlay DRM.

Just two weeks

The Ariane 5 incident

Example: effect of a *single* integer overflow

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- June 4, 1996: After launch, the Ariane 5 rocket exploded.
- This was its maiden voyage.
- It flew for about 37 Sec only in Kourou's sky.
- No injury in the disaster.

The story

- Normal behavior of the launcher for 36 Sec after lift-off
- Failure of both Inertial Reference Systems almost simultaneously
- Strong pivoting of the nozzles of the boosters and Vulcan engine
- Self-destruction at an altitude of 4000 m (1000 m from the pad)

More details

- Both inertial computers failed because of the overflow of one variable
- This caused a software exception that stopped these computers
- These computers sent post-mortem info through the bus
- Normally, main computer receives velocity info through the bus
- The main computer was confused and pivoted the nozzles

More details

- The faulty program was working correctly on Ariane 4
- The faulty program was not tested for A5 (since it worked for A4)
- But the velocity of Ariane 5 was far greater than that of Ariane 4
- That caused the overflow in one variable
- The faulty program happened to be useless for Ariane 5

Messages

- Clear, up to date, realistic requirements
- Relationship requirements / programs
- Proof that programs were built according to requirements

> *Note: we will not deal with* requirement engineering, *which is related and very interesting in itself.*

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3. How do we prove that the program performs according to specifications?

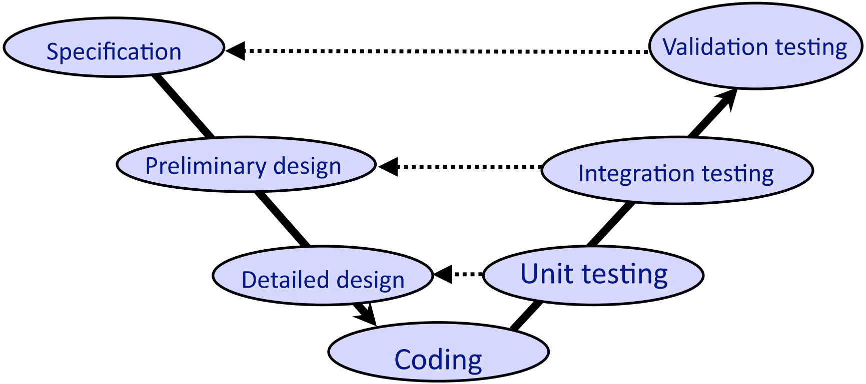
...in a way that is (a) dependable and (b) cost-effective?

Rate of error discovery

Cost of error fixes

The V model

When are errors discovered in the V Model?



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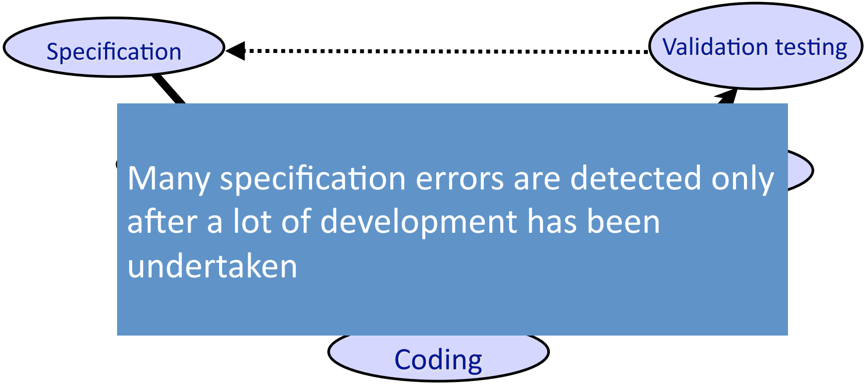

Many specification errors are detected only after a lot of development has been undertaken

Some sources of errors

- Lack of precision
  - Ambiguities
  - Inconsistencies
- Too much complexity
  - Complexity of requirements
  - Complexity of operating environment
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Some preventive measures

- Early stage analysis
  - Precise descriptions of intent
  - Amenable to analysis by tools
  - Identify and fix ambiguities and inconsistencies as early as possible
- Mastering complexity
  - Encourage abstraction
  - Focus on what a system does
  - Early focus on key / critical features
  - Incremental analysis and design

Formal methods

- Rigorous techniques for formulation and analysis of systems
- They facilitate:
  - Clear specifications (contract)
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Formal methods

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> *there is little chance that we can decide whether it actually does it*

Deciding whether it does that it ought to do

Validation: Did we specify the right system?

- Answered informally: *did we build the right system?*

Verification: Does the finished product satisfy the specification?

- Can be answered formally: *did we build the system right?*

Specifications and the real world?

How can specifications be used?

- Use specifications to build tests (generation of tests based on specifications).
- Use specifications to check that a program computes what it should (static analysis, verification, model checking).
- Use specifications to compute (functional / logic / equational programming).
- Use specifications to drive the generation of a program (correctness by construction, automatic code generation).

How can guarantees be given?

- Enlightened management: of little help.
- Convincing arguments beyond any reasonable doubt:
  - Formal basis.
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- Carefully prove that programs will behave as expected.

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- Carefully prove that programs will behave as expected.
- For **every** single program?

It's too difficult for humans to do!

- Mechanization, automation
- Computer-assisted software development
  - Correctness by construction
  - Automatic analysis
  - Verification (model checking, deductive verification)
  - Automated testing

  ...to ensure relevant properties hold.
- Many properties generic (e.g., termination, if necessary).
- Others specific (e.g., what some program is expected to do).
- Difficult!

“Simple” properties and “simple” code

- How easy is it to decide whether a program terminates or not?

```
input n;

while n > 1 do
    if n mod 2 = 0 then
        n:= n / 2
    else
        n:= 3*n + 1
    end if
end while
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- Will it finish for **any** input value `n`?

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- Will it finish for **any** input value `n`?
- Sometimes we cannot prove a property because:
  - It is difficult to prove.
  - It is false.
  - It is undecidable.

A specification example

```
procedure WhatDoIDo(A: Array)
  repeat
    swapped := false
    for i := 1 to length(A) - 1 do
      if A[i-1] > A[i] then
        swap(A[i-1], A[i])
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- What does this program do?

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- What does this program do?
- Can you specify (using FOL) the property that characterizes a sorted array?
- Can we prove that, after executing the code above, array A is sorted?
- Can we use specifications to derive a correct sorting program?

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