6SENG001W Reasoning about Programs

Lecture 1

Introduction to Formal Methods

&

the B-Method

Overview of Lecture 1: Introduction & B-Method

The aim of this lecture is to:

- Explain the need for *Formal Methods*:
  - describe the *"software crisis"*,
  - possible solutions, i.e. *"software engineering"*,
  - outline why formal methods (i.e. formal specification) is a *good or necessary* solution,
  - advantages of using the B-Method for formal specifications.
- Provide an overview of the *B-Method*:
  - outline the structure of a B specification – *Abstract Machines*,
  - present a simple example of an *Abstract Machine*.
- Introduce B-Method CASE tools:
  - **Atelier B** – supports all stages of B-Method, e.g. syntax & type checking.
  - **ProB** – a B specification "animator".

PART I

The Need for Formal Methods

Is there a “Lack of Confidence” in Software?

Consider:

A current “hot” topic of research is *“driver-less”* cars.

Question:

How do the public feel about getting into a *driver-less car*?

So lets look at some of the responses from a small sample of the public.

“Fake News” Fan

“I’ve never heard of any software ever going wrong.
Software bugs – fake news. Hilary loves software bugs.
Make Software Great Again!”

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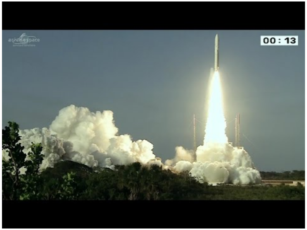

ESA’s Ariane 5 rocket exploded just after takeoff on its maiden flight!

Due to a **trivial software bug** – converting a 64-bit float to a 16-bit integer!

Unfortunately, its **not** “Fake News”.

The Microsoft Employee?

"No problem. I'm sure they'd have got rid of any bugs before they go on sale to the public. Just like when they release a new version of Windows."

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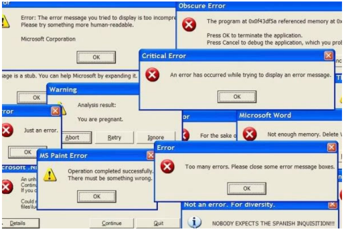

Is your name Bill Gates by any chance?

Extreme Sports Enthusiast

"I live near some cliffs & a railway crossing, but what's a few minor accidents between friends?"

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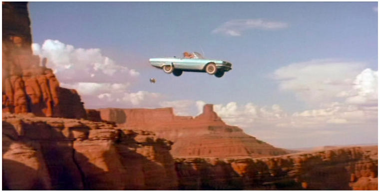


Ouch – that's got to hurt!

Clinically Insane?

“Playing Russian Roulette is my No. 1 hobby, so I just can’t wait!”

Clinically Insane?

“Playing Russian Roulette is my No. 1 hobby, so I just can’t wait!”

Safer to take up chainsaw juggling, unless you’re the world’s favourite rabbit.

Current Perception of Software & Computer Systems

The general perception of computer systems (software) is that it is — inherently unreliable & full of software bugs.

- In the past, this was mainly due to **hardware faults**.
- Now mainly/exclusively due to **unreliable software**.

Question:

So based on what you know about software would you use a driver-less car?

YES or NO

Impact of Poor Software

Today Software controls virtually all our systems & activities.

So if this software is not of a high quality, (e.g, correctness, robustness, etc) it can be a really BIG PROBLEM.

When the software is faulty, then a range of problems can arise:

- a simple nuisance, e.g. laptop crashes,
- financial loss, e.g. unauthorised financial transfers,
- safety of property, e.g. Ariane 5 rocket explosion 1996,
- loss of life, e.g. nuclear power plant accident, plane crashes, etc.

Cost($\pounds$) of Poor Software

Many (most?) large complex software systems:

- cost far more than initially budgeted for,
- are delivered late to the customer or are never delivered at all,
- faulty when declared finished & delivered.

Examples

- Most/all Government software systems, e.g. $\pounds 12.4^{+} bn$ NHS IT System.
- Microsoft OS's *bugs* & *viruses* – financial impact on huge number of individuals & companies.
- London Ambulance Service's Ambulance dispatcher system. (Cost in the 10's of millions of $\pounds$.)
- Cancellation of BBC's $\pounds 100m$ Digital Media Initiative (DMI) system.

“Software Crisis”

These problems of poor quality software, i.e. buggy & unreliable, with the associated problems of:

- a negative impact on our daily lives,
- the excessive cost of developing “working” systems,
- the total waste of money on NOT developing “working” systems,

are usually referred to as the – “Software Crisis”.

Conclusion

So anything that can improve the quality of the software we use will have a significant impact on all of our lives & bank balances.

Lessons from Developing Large Complex Software Projects

Experience shows that the majority of the cost of a developing a large complex software project is spent on fixing errors.

Most of these errors are:

- Introduced at the start of a software project, e.g. requirements, specification & design stages.
- Only found during *implementation*, *testing* or *maintenance*
  E.g. a system crash!
- **Never detected**.

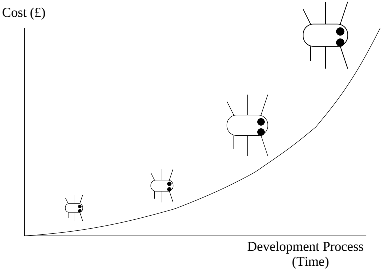
Errors are usually caused by:

- lack of precision at the requirements stage,
- incomplete or omitted specification stage,
- making poor design decisions & ignoring alternatives.

Outcome – We are Engaged in a Bug War!

Bugs are introduced at the *start of a project*, but are only detected *towards the end* or *not at all!*

Bugs tend to breed, so the longer they are around, i.e. earlier they appear, the more time they have to breed. (Consider your own software projects.)



Important implication — cost of fixing bugs grows very dramatically the later in the software project they are found & corrected, e.g. BBC DMI system.

This is the (hidden?) cost of the software crisis.

Attempted Solution I: Natural Language

The first software development techniques were pretty ad-hoc, very informal & did not use any Formal Methods.

Natural language approach or some structured subset is used to try to produce a:

> *“precise” description of the system.*

Does not work since natural language is ambiguous, *imprecise*, etc.

The use of natural language can **never** result in an unambiguous, precise & complete description of a system.

So it could never be good enough to use to as the starting point for developing good quality software.

Example: consider the variety of programs[1] students produce from the same coursework specification such as *input student marks & output a summary*.

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[1] Assuming no plagiarism of course!

Solution II: Software Engineering

Recognition of these problems has led to attempts to improve software development techniques, through the use of *software engineering*.

All very well to apply *”engineering principles”* approach, **BUT** compared to other engineering activities, e.g. building & manufacturing, engineering large software systems is very different:

- A large creative design phase, a trivial manufacturing phase, but requires a substantial testing phase.
- Software is far too easy to modify (i.e. *hackable*) & this contributes to many problems, aka. *“feature creep”*.
- Installed software is *“maintained”*, i.e. *“patches”*, *“updates”* & new features added.
- Eventually these changes result in a *loss of structure & understanding*, etc. of the original system.

Exercise: Compare this to building & maintaining a bridge or a plane.

Consider the “Standard” Software Development Life-Cycle Phases

Requirements Analysis	Identify, understand & define the system & problems that need to be solved.
System Specification	Write the *requirements* in an agreed form, e.g. functions, performance, reliability & usability.
Design	Alternative ways of satisfying the specification are investigated. *“Bridge”* from the start – *What is to be done?* to the finish – *How is it to be done?*
Prototyping & Implementation	Chosen *design* translated into *code*. Requires all details about functions & data to be sorted out.
Verification, Testing & Integration	Testing of individual components & the whole system.
Maintenance & Enhancement	Finished system delivered & from then on, bugs corrected & new features added.

Solution II.1: Software Engineering Methodology – UML

Currently, the most widely used Software Engineering methodology is *UML (+ Design Patterns)*.

Consider UML:

- based on "non-formal structured" diagrams,
- aimed at breaking down the problem into *sub-systems (objects)*,
- capturing the relationship between *data* & the *flow of information* through a system.
- etc. etc.

The way the software produced is shown to be correct relies *solely on extensive testing.*

It does not support any notion of *"mathematical proof"*, so can not *"prove"* that the software is correct.

Solution II.2: Software Testing

Software "bugs" are universally accepted & expected.

Encourages sloppy standards in software production, that would not be tolerated in other engineering disciplines, e.g. bridges, planes.

UK software suppliers are legally liable for the software they produce, under *Civil Liability* law & *Consumer Protection Act of 1987*.

A consequence of this is the reliance on *software testing*, but unfortunately the 1972 *Turing Award* winner Edsger Dijkstra pointed out that:

> *"... testing can **only** reveal errors but **never** demonstrate their absence ..."*

BUT – to function correctly a large software system has to make thousands or millions of: inputs, tests, decisions & calculations etc.

In order to *"prove"* such a system correct a *test plan* would have to consider every possible combination of these – **not feasible**.

Question: Does Software Testing Work?

Several years ago, Microsoft, as part of an attempt to improve the quality of their operating systems performed a *“formal analysis”* of *Windows XP*.

As expected, Windows XP was found to contain many different types of errors.

In particular, it contained more than **10,000** of a particular type of error known as *“null pointer exceptions”*!

The significance of this is that:

- these bugs had **not been detected**, let alone fixed before it reached the *end of its life*,
- even after being used by 100s of millions of users for many years & numerous “patches” & “updates”.

Answer: **NO**

The real *“Fake News”* is that software testing **“proves”** that software doesn’t contain any bugs!

What about the Highest Quality Software?

In the *"Safety or Security Critical" (SSC)* industries, e.g. nuclear, aviation, transport, health, finance & defence, the highest quality software is required.

For SSC software either errors/bugs are NOT acceptable, or errors are so rare that it is considered an *acceptable risk*.

Problem: most/all large complex software projects that use standard methods e.g. UML, usually end up:

- containing many errors, or
- way over budget, or
- delivered late, or
- never delivered at all, or
- take so long to be delivered they get cancelled, or
- a combination of the above.

UML etc. is okay for *"bog-standard"* software, but its **not** okay (or even legal) for *Safety or Security Critical* systems.

“Quality Standards” for Safety & Security Critical Systems

Within the *Safety & Security Critical Systems* sectors of the software industry there are several recognised *certification standards* for software quality:

- *Evaluation Assurance Level*: for the *security* of information systems, e.g. banking sector.
  “Levels of assurance”: EAL1 – EAL7, (7 is highest).

- *Safety Integrity Level*: for the *safety* of railway systems, automotive, chemical systems, etc.
  “Levels of Integrity”: SIL1 - SIL4, (4 is highest).
  SIL4 *“Mean Time to Failure”* is about **100,000 years**.

For systems to achieve the highest levels of certification, the use of *“formal methods”* is either essential or legally required.

Companies that produce this type of software (e.g. Siemens, Quinetic) have to use formal methods to *guarantee its quality*.

Problems with Solutions I & II

- Non-formal software development methods – *natural language*, *UML*, etc, **can not result in or guarantee** the production of high quality safety/security critical software.
- Since they all allow *errors to be introduced* far too easily, e.g. specification stage.
- Do **not** provide a satisfactory way to get rid of them, e.g. just *testing*.
- *None* has any notion of *"mathematical proof"*, which is the *ultimate bug killer*.
- So we need some other approach that is better.
- So the only thing that will do the job is *formal (mathematical) methods*.

Solution III: Software Development using *Formal Methods*

Definition

A *formal method* is a systematic mathematically based approach used to determine whether a program has certain desirable properties.

Formal Method Development Stages:

- Starts with the construction of an initial *"abstract model"* (mathematical specification) of the software system.
- It then concentrates on the construction of a *sequence of models* by successive *"refinements"* starting from the initial model.
- The *"desirable properties"* to be proved are parts of the models: *"invariants"* & *"refinements"*.
- At the end of the process, the *"most refined model"* (*"implementation"* model) is *automatically translated* into *program code*.

Overview of Formal Methods Refinement

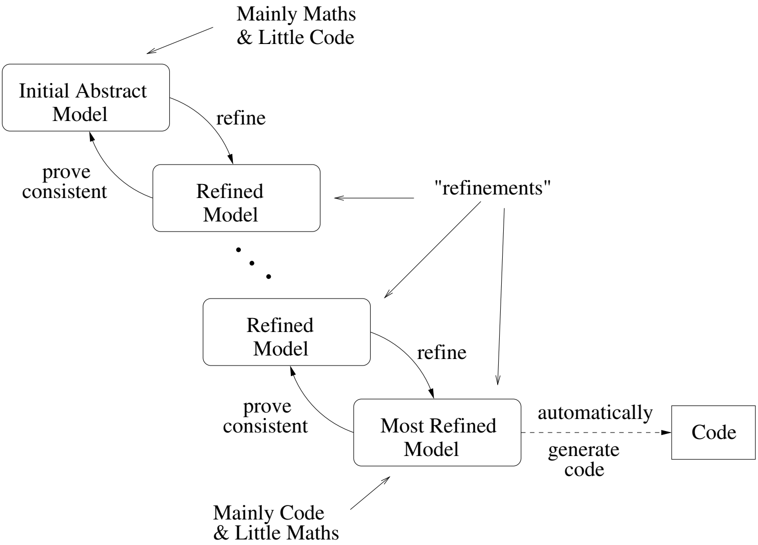


Figure : 1.1 Formal Methods Refinement

Solution III: Formal Specifications

We must use some kind of formal (i.e. mathematical) language to produce a *formal specification* of a system.

Formal Specification is seen as a "real" solution to the software crisis.

Since it allows the requirements of a software system to be described:

- *succinctly*,
- *precisely*,
- *unambiguously*
- allows essential & desirable properties to be *proved*,
- allows checking of *consistency* of the specification.

The consequences of **NOT** using *Formal Specifications* & using an *"informal specification or set of requirements"* (i.e. non-mathematical), is that we do not have a sound way of checking:

> *"If the final software system does what it was actually required to do".*

Essential Role of "Proofs" about Specifications (Models)

Mathematical Proofs about a *formal specification* of a software system play an *essential* role in developing quality software.

Proof that a *"desirable property"* holds about the system specification, can mean that the same property holds about the *implemented system*.

Example

To be able to prove that:

> *"Thermostat control software does not crash if it inputs unexpected temperature readings, but closes the system down safely."*

This is obviously a **VERY** desirable property to prove for a thermostat in a nuclear power plant!

Note: the proof of desirable properties about a system at the *specification stage* can also *eradicate errors* that could continue in the system until it was *delivered* or more likely *never found*.

Which Formal Method?

So, what we need is a *Formal Method* & *Specification Language* which offers:

Precision:
- be as *precise as necessary*,
- so as to *remove any ambiguity* about what is required.
- Similar to precision of a programming language.

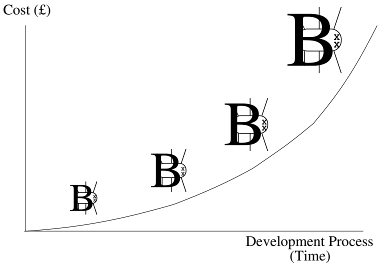
Abstraction:
- allows us to *abstract away from unnecessary detail*, e.g. algorithms & data structures,
- until we are *ready to deal with it*.

Proof:
- ability to *"prove" desirable properties* about our specifications.
- *"proofs"* are best way to eliminate errors & bugs.

Answer: *B-Method*

Killing Bugs with B

For the reasons outlined above, B can be seen as an effective *bug killer*!



There is an additional cost when using B to eradicate bugs, & that is, that much more effort is spent on the specification stage of a project.

It also usually requires either an investment in staff development, i.e. teaching them B; or employing trained B practitioners.

For this reason companies are often not willing to make this “up front” investment, but usually end up having to *spend much more on the testing stages* of a project getting rid of bugs.

PART II

Introduction to the B-Method

So what is the *B-Method?*

- History: created by Jean-Raymond Abrial (80's & 90's).
  Successor to Abrial's Z Specification Language.
- Its a *formal software development method* that supports *all* stages of the *software life-cycle* in a uniform and formal way.
- Incorporates & combines many ideas from a range of formal methods.
- The main elements are: *B models* (specifications) & *proofs*.
- A *B model* is a collection of *"components"*, called *"machines"*.
- B specifications are written in its formal specification language: *Abstract Machine Notation (AMN)*.
- AMN is a "wide spectrum" pseudo-programming language that covers both *abstract specifications* & *implementation level code*.
- Supported by CASE tools, we shall use two B-Method tools:
  - **Atelier B** – syntax & type checking, theorem prover. (ClearSy, France).
  - **ProB** – animator, (Heinrich-Heine-University, Germany).

Overview of B-Method Software Development

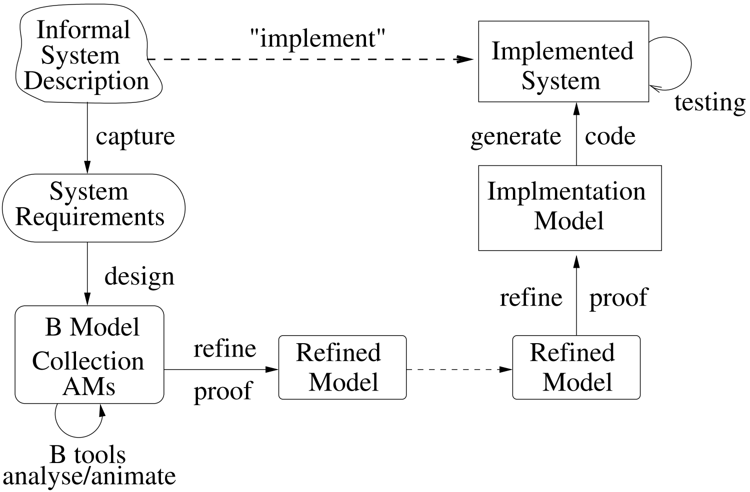


Figure : 1.2 B-Method Software Development

B-Method Software Development Stages

The B-Method's formal software development process can be broken down into several "phases" or "stages":

- *Capture the System Requirements*

  — Initial *"vague system description"* turned into a list of *requirements*. (Pre B-Method.)

- *Design a "B Model" (Abstract Model) from the System Requirements*

  — B model is a *"high level"*, *"abstract" specification*.

- *Refine the"Abstract Model" into an "Implementation Model"*

  — Translate the *"maths"* descriptions into *"program code"*.

- *Generate "Program Code" from Implementation Model*

  — **Atelier B** tool generates: C, C++, Ada code.

Industrial Use of the B-Method

The B-Method's approach to formal software development has been applied in large industrial projects by the following companies:

- Qinetic – very high quality s/w systems, e.g. defence, avionics
- Siemens (Transportation Systems) – train control systems, e.g. Paris METRO Line 14.
- Volvo, Peugeot, Renault – electronics in cars
- Nokia – microelectronics
- France Telecom – electronics
- Gemplus – smart card security, e.g banking sector
- BOSCH – electronics
- EDF – nuclear control system design

Possible current & future areas – Google driver-less cars, Apple iCar??

PART III

Introduction to the B-Method's Abstract Machines

B-Method's Abstract Machines (AM)

The building block of the B-method is the concept of an *Abstract Machine (AM)*.

It is a concept similar to the programming concepts of: *modules*, *class definition* (e.g. Java) or *abstract data types*.

An *abstract machine (model)* is a *specification* of:

- **what** a system should be like, or
- **how** it should behave (*operations*);
- but **not how** a system is to be built, i.e. no implementation details.

An *abstract machine* has a:

- **name**,
- **local state**, represented by *"encapsulated" variables*,
- **interface**, i.e. a collection of operations, that can access & update the state variables.

Example: `PaperRound` Abstract Machine

A *paper round manager* keeps track of houses that receive deliveries, it uses a state variable $houseset$ & has two operations: add & $number$.

MACHINE $PaperRound$

  VARIABLES $houseset$

  INVARIANT $houseset \subseteq \mathbb{N}_1$

  INITIALISATION $houseset := \{\}$

  OPERATIONS

    $add(new) =$

      PRE $new \in \mathbb{N}_1 \ \wedge \ new \notin houseset$

      THEN $houseset := houseset \cup \{ \ new \ \}$

      END ;

    $ans \leftarrow number =$

      BEGIN

        $ans := card(houseset)$

      END

END

Abstract Machine Notation (AMN): B Symbols & Machine Readable ASCII

The B tools require machine readable ASCII versions of the various B symbols & AMN notation.

B symbols & AMN used in `PaperRound`:

Symbol	ASCII	Description
$\mathbb{N}_1$	`NAT1`	Set of natural numbers from 1
$x \in A$	`x : A`	x is an element of A
$x \notin A$	`x /: A`	x is not an element of A
$A \subseteq B$	`A <: B`	A is a subset or equal to B
$\varnothing$, $\{\ \}$	`{}`	Empty set
$A \cup B$	`A \/ B`	Union of A and B
$\mathrm{card}(A)$	`card(A)`	Number of elements in set A
$P \wedge Q$	`P & Q`	Logical Conjunction (“P and Q”)
$var := exp$	`var := exp`	Assignment: `var` set to `exp`
$out \leftarrow op$	`out <-- op`	Operation `op` with output `out`
`BEGIN` .. `END`	`BEGIN` .. `END`	Statement Block
`PRE` .. `THEN` .. `END`	`PRE` .. `THEN` .. `END`	Operation Pre-Condition

Atelier B & ProB Machine Readable PaperRound

PaperRound

```
MACHINE PaperRound

  VARIABLES
    houseset

  INVARIANT
    houseset <: NAT1

  INITIALISATION
    houseset := {}

  OPERATIONS

    add(new) =
      PRE  new : NAT1  &  new /: houseset
      THEN
           houseset := houseset \/ { new }
      END ;

    ans <-- number =
        BEGIN
             ans := card( houseset )
        END
END
```

B-Method Tools: **Atelier B** & **ProB**

In the tutorials you will use the two B-Method CASE tools to develop B specifications:

- **Atelier B** – supports all stages of B-Method:
  syntax & *type checking*, *theorem proving*, *refinement* &
  code generation into C, C++ & Ada.

- **ProB** – is an *"animator"*.
  It allows you to animate (i.e. execute) the operations defined in a B specification.

First Tutorial

The first tutorial is intended to introduce you to the B tools & *AMN*.

You will be required to type in the `PaperRound` machine into **Atelier B**, then syntax & type check it using **Atelier B**.

Finally, animate it using **ProB**.