Chapter 1

Formal methods

Course “Model checking”
Volker Stolz, Martin Steffen
Autumn 2019

Chapter 1

Learning Targets of Chapter “Formal methods”.

The introductory chapter give some motivational insight into the field of “formal methods” (one cannot even call it an overview).

Chapter 1

Outline of Chapter “Formal methods”.

Motivating example

How to guarantee correctness

Software bugs

On formal methods

Formalisms for specification and verification

Summary

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Motivating example

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A simple computational problem

$$
\begin{aligned}
a_0 &= \frac{11}{2} \\
a_1 &= \frac{61}{11} \\
a_{n+2} &= 111 - \frac{1130 - \frac{3000}{a_n}}{a_{n+1}}
\end{aligned}
$$

A straightforward implementation

```
public class Mya {

    static double a(int n) {
      if (n==0)
         return 11/2.0;
      if (n==1)
         return 61/11.0;
      return 111 - (1130 - 3000/a(n-2))/a(n-1);
    }

    public static void main(String[] argv) {
      for (int i=0;i<=20;i++)
        System.out.println("a("+i+") = "+a(i));
    }
}
```

The solution (?)

```
$ java mya
a(0)  = 5.5
a(2)  = 5.5901639344262435
a(4)  = 5.674648620514802
a(6)  = 5.74912092113604
a(8)  = 5.81131466923334
a(10) = 5.861078484508624
a(12) = 5.935956716634138
a(14) = 15.413043180845833
a(16) = 97.13715118465481
a(18) = 99.98953968869486
a(20) = 99.99996275956511
```

Should we trust software?

a_n for any $n \geq 0$ may be computed by using the following expression:

$$a_n = \frac{6^{n+1} + 5^{n+1}}{6^n + 5^n}$$

Should we trust software?

a_n for any $n \geq 0$ may be computed by using the following expression:

$$a_n = \frac{6^{n+1} + 5^{n+1}}{6^n + 5^n}$$

Where

$$\lim_{n \to \infty} a_n = 6$$

We get then

$$a_{20} \approx 6 \tag{1}$$

Section

How to guarantee correctness

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Correctness

- A system is correct if it meets its “requirements” (or specification)

Examples:

- **System:** The previous program computing a_n
  Requirement: For any $n \geq 0$, the program should be conform with the previous equation

(incl. $\lim_{n \to \infty} a_n = 6$)

- **System:** A telephone system
- **Requirement:** If user A wants to call user B (and has credit), then *eventually* A will manage to establish a connection
- **System:** An operating system
  Requirement: A deadly embrace (nowaday’s aka *deadlock*) will never happen

How to guarantee correctness?

- not enough to show that it can meet its requirements
- show that a system cannot fail to meet its requirements

Dijkstra's dictum

"Program testing can be used to show the presence of bugs, but never to show their absence"

A lesser known dictum from Dijktra (1965)

On proving programs correct: "One can never guarantee that a proof is correct, the best one can say is: 'I have not discovered any mistakes'. "

- *automatic* proofs? (Halting problem, Rice's theorem)
- any *hope*?

Validation & verification

- In general, validation is the process of checking if something satisfies a certain criterion
- Do not confuse validation with *verification*

Validation

"Are we building the right product?", i.e., does the product do what the user really requires

Verification:

"Are we building the product right?", i.e., does the product conform to the specification

Approaches for validation

testing

- check the actual system rather than a model
- Focused on sampling executions according to some coverage criteria
- not exhaustive (“coverage”)
- often informal, formal approaches exist (MBT)

simulation

- A model of the system is written in a PL, which is run with different inputs
- not exhaustive

verification “[T]he process of applying a manual or automatic technique for establishing whether a given system satisfies a given property or behaves in accordance to some abstract description (specification) of the system”

Section

Software bugs

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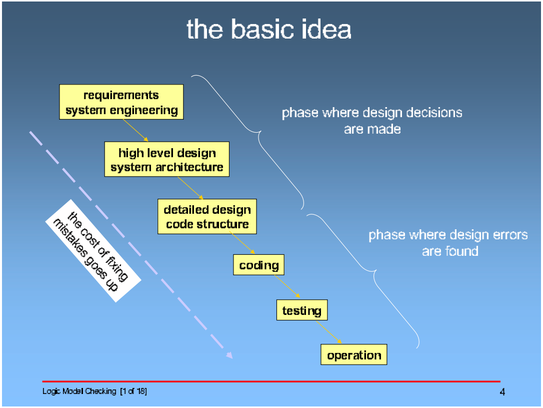
Sources of errors

- specification errors (incomplete or wrong specification)
- transcription from the informal to the formal specification
- modeling errors (abstraction, incompleteness, etc.)
- translation from the specification to the actual code
- handwritten proof errors
- programming errors
- errors in the implementation of (semi-)automatic tools/compilers
- wrong use of tools/programs
- ...

Errors in the SE process



the basic idea

requirements system engineering

high level design system architecture

detailed design code structure

coding

testing

operation

phase where design decisions are made

phase where design errors are found

the cost of fixing mistakes goes up

Logic Model Checking [1 of 18]

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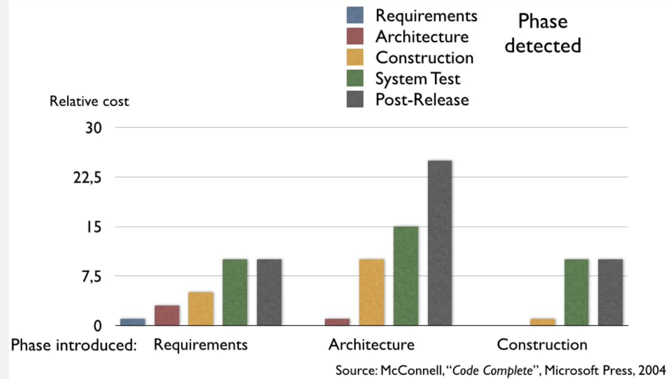
Costs of fixing defects



Source: McConnell, "*Code Complete*", Microsoft Press, 2004

Hall of shame

- July 28, 1962: Mariner I space probe
- 1985–1987: Therac-25 medical accelerator
- 1988: Buffer overflow in Berkeley Unix finger daemon
- 1993: Intel Pentium floating point divide
- June 4, 1996: Ariane 5 Flight 501
- November 2000: National Cancer Institute, Panama City
- 2016: Schiaparelli crash on Mars

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On formal methods

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What are formal methods?

FM

"Formal methods are a collection of notations and techniques for describing and analyzing systems" [2]

- Formal: based on "math" (logic, automata, graphs, type theory, set theory . . .)
- formal specification techniques: to unambiguously describe the system itself and/or its properties
- formal analysis/verification: techniques serve to verify that a system satisfies its specification (or to help finding out why it is not the case)

Terminology: Verification

The term *verification*: used in different ways

- Sometimes used only to refer the process of obtaining the formal correctness proof of a system (deductive verification)
- In other cases, used to describe any action taken for finding errors in a program (including *model checking* and maybe *testing*)

Formal verification (reminder)

Formal verification is the process of applying a manual or automatic *formal* technique for establishing whether a given system satisfies a given property or behaves in accordance to some abstract description (*formal* specification) of the system

Saying *'a program is correct'* is only meaningful w.r.t. a given spec.!

Limitations

- Software verification methods do not guarantee, in general, the correctness of the code itself but rather of an abstract model of it
- It cannot identify fabrication faults (e.g. in digital circuits)
- If the specification is incomplete or wrong, the verification result will also be wrong
- The implementation of verification tools may be faulty
- The bigger the system (number of possible states) more difficult is to analyze it (*state space explosion problem*)

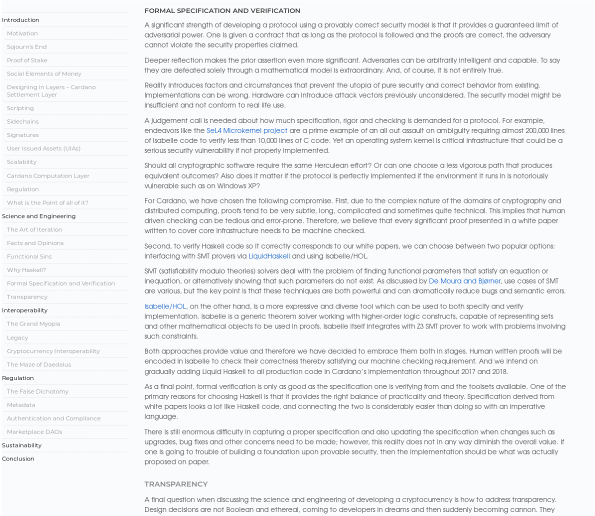
Any advantage?

be modest

Formal methods are not intended to guarantee absolute reliability but to *increase* the confidence on system reliability. They help minimizing the number of errors and in many cases allow to find errors impossible to find manually.

- remember the *VIPER* chip

Another netfind: “bitcoin” and formal methods :-)



FORMAL SPECIFICATION AND VERIFICATION

A significant strength of developing a protocol using a provably correct security model is that it provides a guaranteed limit of adversarial power. One is given a contract that as long as the protocol is followed and the proofs are correct, the adversary cannot violate the security properties claimed.

Deeper reflection makes the prior assertion even more significant. Adversaries can be arbitrarily intelligent and capable. To say they are defeated solely through a mathematical model is extraordinary. And, of course, it is not entirely true.

Reality introduces factors and circumstances that prevent the utopia of pure security and correct behavior from existing. Implementations can be wrong. Hardware can introduce attack vectors previously unconsidered. The security model might be insufficient and not conform to real life use.

A judgement call is needed about how much specification, rigor and checking is demanded for a protocol. For example, endeavors like the SeL4 Microkernel project are a prime example of an all out assault on ambiguity requiring almost 200,000 lines of Isabelle code to verify less than 10,000 lines of C code. Yet an operating system kernel is critical infrastructure that could be a serious security vulnerability if not properly implemented.

Should all cryptographic software require the same Herculean effort? Or can one choose a less vigorous path that produces equivalent outcomes? Also does it matter if the protocol is perfectly implemented if the environment it runs in is notoriously vulnerable such as on Windows XP?

For Cardano, we have chosen the following compromise. First, due to the complex nature of the domains of cryptography and distributed computing, proofs tend to be very subtle, long, complicated and sometimes quite technical. This implies that human driven checking can be tedious and error-prone. Therefore, we believe that every significant proof presented in a white paper written to cover core infrastructure needs to be machine checked.

Second, to verify Haskell code so it correctly corresponds to our white papers, we can choose between two popular options: interfacing with SMT provers via LiquidHaskell and using Isabelle/HOL.

SMT (satisfiability modulo theories) solvers deal with the problem of finding functional parameters that satisfy an equation or inequation, or alternatively showing that such parameters do not exist. As discussed by De Moura and Bjørner, use cases of SMT are various, but the key point is that these techniques are both powerful and can dramatically reduce bugs and semantic errors.

Isabelle/HOL, on the other hand, is a more expressive and diverse tool which can be used to both specify and verify implementation. Isabelle is a generic theorem solver working with higher-order logic constructs, capable of representing sets and other mathematical objects to be used in proofs. Isabelle itself integrates with Z3 SMT prover to work with problems involving such constraints.

Both approaches provide value and therefore we have decided to embrace them both in stages. Human written proofs will be encoded in Isabelle to check their correctness thereby satisfying our machine checking requirement. And we intend on gradually adding Liquid Haskell to all production code in Cardano’s implementation throughout 2017 and 2018.

As a final point, formal verification is only as good as the specification one is verifying from and the toolsets available. One of the primary reasons for choosing Haskell is that it provides the right balance of practicality and theory. Specification derived from white papers looks a lot like Haskell code, and connecting the two is considerably easier than doing so with an imperative language.

There is still enormous difficulty in capturing a proper specification and also updating the specification when changes such as upgrades, bug fixes and other concerns need to be made; however, this reality does not in any way diminish the overall value. If one is going to trouble of building a foundation upon provable security, then the implementation should be what was actually proposed on paper.

TRANSPARENCY

A final question when discussing the science and engineering of developing a cryptocurrency is how to address transparency. Design decisions are not Boolean and ethereal, coming to developers in dreams and then suddenly becoming cannon. They

Using formal methods

Used in different stages of the development process, giving a classification of formal methods

1. We describe the system giving a *formal specification*
2. We can then *prove some properties* about the specification
3. We can proceed by:
   - Deriving a program from its specification (formal synthesis)
   - *Verifying* the specification wrt. implementation

Formal specification

- A specification formalism must be unambiguous: it should have a *precise syntax and semantics*
  - Natural languages are not suitable
- A trade-off must be found between expressiveness and analysis feasibility
  - More expressive the specification formalism more difficult its analysis

Do not confuse the specification of the system itself with the specification of some of its properties

- Both kinds of specifications may use the same formalism but not necessarily. For example:
  - the system specification can be given as a program or as a state machine
  - system properties can be formalized using some logic

Proving properties about the specification

To gain confidence about the correctness of a specification it is useful to:

- Prove some properties of the specification to check that it really means what it is supposed to
- Prove the equivalence of different specifications

Example

a should be true for the first two points of time, and then oscillate.

- some attempt attempt:

$$a(0) \wedge a(1) \wedge \forall t.\ a(t+1) = \neg a(t)$$

Formal synthesis

- It would be helpful to automatically obtain an implementation from the specification of a system
- Difficult since most specifications are *declarative* and not *constructive*
    - They usually describe what the system should do; not how it can be achieved

Example: program extraction

- specify the operational semantics of a programming language in a constructive logic (calculus of constructions)
- prove the correctness of a given property wrt. the operational semantics (e.g. in Coq)
- extract (*ocaml*) code from the correctness proof (using Coq's extraction mechanism)

Verifying specifications w.r.t. implementations

Mainly two approaches:

- Deductive approach ((automated) theorem proving)
    - Describe the specification φ_{spec} in a formal model (logic)
    - Describe the system's model φ_{imp} in the same formal model
    - Prove that $\varphi_{imp} \implies \varphi_{spec}$
- Algorithmic approach
    - Describe the specification φ_{spec} as a formula of a logic
    - Describe the system as an interpretation M_{imp} of the given logic (e.g. as a finite automaton)
    - Prove that M_{imp} is a "model" (in the logical sense) of φ_{spec}

A few success stories

- Esterel Technologies (synchronous languages – Airbus, Avionics, Semiconductor & Telecom, . . .)
  - Scade/Lustre
  - Esterel
- Astrée (Abstract interpretation – used in Airbus)
- Java PathFinder (model checking – find deadlocks on multi-threaded Java programs)
- verification of circuits design (model checking)
- verification of different protocols (model checking and verification of infinite-state systems)

. . .

Classification of systems

Before discussing how to choose an appropriate formal method we need a classification of systems

- Different kind of systems and not all methodologies/techniques may be applied to all kind of systems
- Systems may be classified depending on
  - architecture
  - type of interaction

Classification of systems: architecture

- Asynchronous vs. synchronous hardware
- Analog vs. digital hardware
- Mono- vs. multi-processor systems
- Imperative vs. functional vs. logical vs. object-oriented software
- Concurrent vs. sequential software
- Conventional vs. real-time operating systems
- Embedded vs. local vs. distributed systems

Classification of systems: type of interaction

- Transformational systems: Read inputs and produce outputs – These systems should always terminate
- Interactive systems: Idem previous, but they are not assumed to terminate (unless explicitly required) – Environment has to wait till the system is ready
- Reactive systems: Non-terminating systems. The environment decides when to interact with the system – These systems must be fast enough to react to an environment action (real-time systems)

Taxonomy of properties

Functional correctness The program for computing the square root really computes it

Temporal behavior The answer arrives in less than 40 seconds

Safety properties (*"something bad never happens"*): Traffic lights of crossing streets are never green simultaneously

Liveness properties (*"something good eventually happens"*): process A will eventually be executed

Persistence properties (stabilization): For all computations there is a point where process A is always enabled

Fairness properties (some property will hold infinitely often): No process is ignored infinitely often by an OS/scheduler

When and which formal method to use?

Examples:

- Digital circuits . . . (BDDs, model checking)
- Communication protocol with unbounded number of processes. . . . (verification of infinite-state systems)
- Overflow in programs (static analysis and abstract interpretation)
- . . .

Open distributed, concurrent systems ⇒ Very difficult!!
Need the combination of different techniques

Section

Formalisms for specification and verification

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Some formalisms for specification

- Logic-based formalisms
  - Modal and temporal logics (E.g. LTL, CTL)
  - Real-time temporal logics (E.g. Duration calculus, TCTL)
  - Rewriting logic
- Automata-based formalisms
  - Finite-state automata
  - Timed and hybrid automata
- Process algebra/process calculi
  - CCS (LOTOS, CSP, ..)
  - π-calculus . . .
- Visual formalisms
  - MSC (Message Sequence Chart)
  - Statecharts (e.g. in UML)
  - Petri nets

Some techniques and methodologies for verification

- algorithmic verification
    - Finite-state systems (model checking)
    - Infinite-state systems
    - Hybrid systems
    - Real-time systems
- deductive verification (theorem proving)
- abstract interpretation
- formal testing (black box, white box, structural, . . .)
- static analysis
- constraint solving

Section

Summary

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Summary

- Formal methods are useful and needed
- which FM to use depends on the problem, the underlying system and the property we want to prove
- un real complex systems, only part of the system may be formally proved and no single FM can make the task
- our course will concentrate on
    - temporal logic as a specification formalism
    - safety, liveness and (maybe) fairness properties
    - SPIN (LTL Model Checking)
    - few other techniques from student presentation (e.g., abstract interpretation, CTL model checking, timed automata)

Ten Commandments of formal methods

From “Ten commandments revisited” [1]

1. Choose an appropriate notation
2. Formalize but not over-formalize
3. Estimate costs
4. Have a formal method guru on call
5. Do not abandon your traditional methods
6. Document sufficiently
7. Do not compromise your quality standards
8. Do not be dogmatic
9. Test, test, and test again
10. Do reuse

References I

Bibliography

[1] Bowen, J. P. and Hinchey, M. G. (2005). Ten commandments revisited: a ten-year perspective on the industrial application of formal methods. In *FMICS '05: Proceedings of the 10th international workshop on Formal methods for industrial critical systems*, pages 8–16, New York, NY, USA. ACM Press.

[2] Peled, D. (2001). *Software Reliability Methods*. Springer Verlag.