

Software Testing and Validation

A.A. 2024/2025

Corso di Laurea in Informatica

Basic Notions

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General Info for This Class

- Software Testing and Verification is an elective course for the Informatica Bachelor Degree
- Lecturer: Igor Melatti
- Where to find these slides and more:
 - https://igormelatti.github.io/sw_test_val/20242025/index.html (Italian)
 - https://igormelatti.github.io/sw_test_val/20242025/index_eng.html (English)
 - also on MS Teams: “DT0758: Software Testing and Validation (2024/25)”, code **86obv1d**
- 2 classes every week, 2 hours per class



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Rules for Exams

- The exam consists of working on a project and discuss it
 - teams of at most 2 students are allowed for projects
- Project: perform testing and validation of a given software
 - each team may choose one among the ones selected by lecturer
 - or may propose one (but wait for lecturer approval!)
 - each team will have to discuss its project with slides
 - however, pre-evaluation is possible



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Verification Problem

- Dates back to computer science origins
 - of course, not only in computer science
- Generally speaking: we have built something, is it what we actually wanted to build? does it accomplishes its tasks?
 - I do not want to get tired standing up, I build a chair
 - am I actually not tired any more? or at least, less than before?
 - does the chair crash if I sit for too much time?
 - does it crash if I increase my weight?
 - could I have built the chair better (more comfortable, with less materials, ...)?
- The same holds for software
 - but also for hardware, or combinations hardware+software



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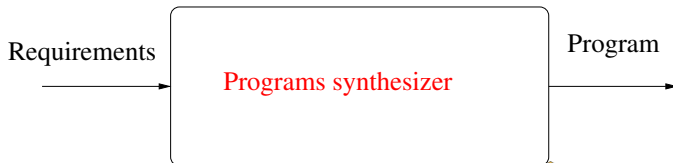
Utopia!

- ① Suppose you want to write a software fulfilling some given requirements
 - given an array A , sort A in a non-decreasing way
 - given a graph $G = (V, E)$ and two nodes $u, v \in V$, decide if there exists a path from u to v
 - build the data base for a library
 - manage an airport
 - etc.
- ② Let us try to write the corresponding requirements
 - $\forall 1 \leq i \leq n - 1 \ A[i] \leq A[i + 1]$
 - $\exists u_1, \dots, u_n$ s.t.
 $u_1 = u \wedge u_n = v \wedge \forall 1 \leq i \leq n - 1 \ (u_i, u_{i+1}) \in E?$
 - It is possible also for the remaining cases, though it is more complicated



Utopia!

- Suppose you have an **automatic program synthesizer (generator)**
 - a special program which takes *requirements* as input
 - must be described in some *formal* way, i.e., using an unambiguous mathematical language
 - ... and outputs a correct-by-construction program which fulfills the input requirements



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Utopia!

- All efforts are in making the program generator correct, efficient and effective
- It outputs correct-by-construction programs
 - if I say “give me a program sorting arrays”, then I obtain a program which *never* fails
 - i.e., given any array (input instance), it outputs always the correct sorted array (corresponding output)
- Verification problem does not exist
 - or it shifts on the requirements: did we write the requirements we actually wanted?
 - validation: we will be back on this

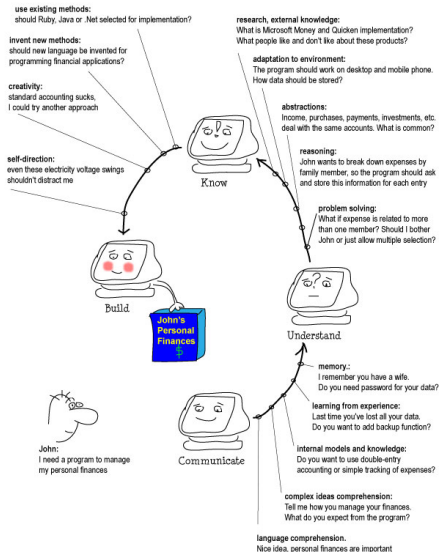


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Instead, the Reality



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Instead, the Reality

- Do you need to build a software? then, you will have to do it *ad hoc*
 - *totally* general approaches to build program generators cannot exist
 - it is easy to see that building a program generator is an undecidable problem
- Of course, you can rely on libraries, methodologies, etc, but...
- ... there is no guarantee that the starting requirements are met by the final software
 - e.g., if you implement an iterative program to sort arrays, but you forget to increment the index, the starting requirements will not be met
 - more subtle errors may be very difficult to find



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Software Verification

- So you need a *verification* phase
 - for simple cases like sorting, it is sufficient to perform it in the end
 - for more complex cases, verification must be performed also during developing phase
 - for very complex/important cases, verification must be performed also *before* developing the software
- **Verification goal is to find *errors*, if any**
 - for our purposes, an error is a violation of the requirements
 - some requirements are present since the beginning, some other may add up later



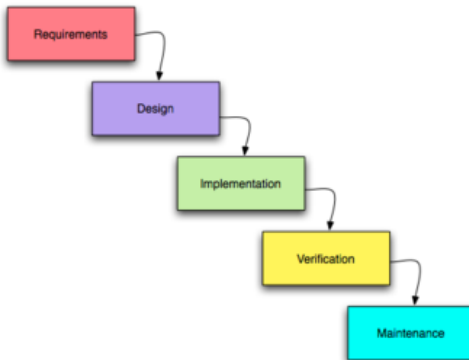
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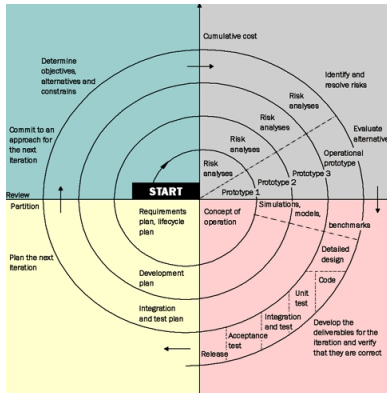
Software Verification

- Software Engineers are well aware of the problem
- All software design processes include one or more verification phases
 - though it may be simply called *test* o *testing*



Software Verification

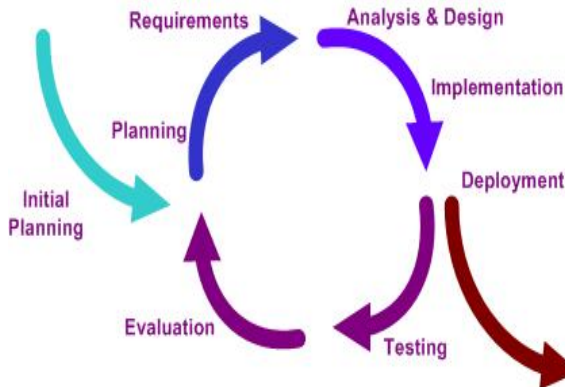
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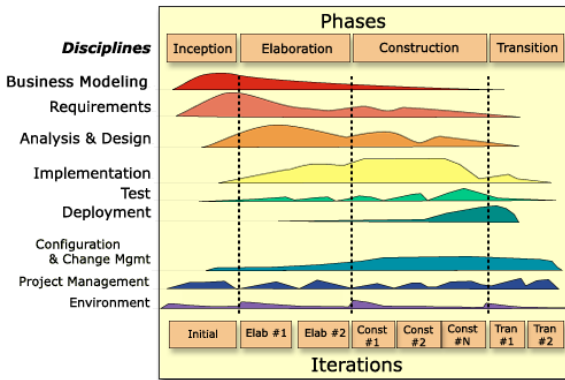
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Software Verification

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Systems Verification

- We have been speaking of software, but all we said holds for *any computer-based system*
- Hardware
 - digital circuits
 - microprocessors
- Embedded Systems
 - tiny *dedicated* computer inside bigger systems
 - typically, either *controllers* or *monitors*
 - cars (ABS, ESC/ESP...), generic means of transportation, domestic electrical appliances (fridges, TVs, ...)
 - errors could be in hardware, software, both, or in the “communication” (interface) between hardware and software



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Systems Verification

Summing up:

- ① start from requirements
- ② develop some (partial or final) solution
 - you may “complicate” such steps at wish
- ③ *verify* that the current solution fulfills the starting requirements
 - you may need to change the requirements (they could be wrong too, or they may have been changed)
 - recall that verification may also be done during the intermediate developing steps



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Validation

- Verification and validation are often used as synonyms
- However, there is an important distinction between the two terms
 - validation involves final users “expectations”
 - verification is performed only keeping in mind the software requirements already collected
 - verification does not care whether requirements are what users want or not
- Validation is “did we built the right system?” → *useful* system
- Verification is “did we built the system right?” → *dependable* system



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Validation and Verification

- Requirements analysis vs. requirements specifications
 - requirements analysis: what (we understood that) the users want
 - requirements specification: the solution we propose for the requirements analysis
- Validation is about checking requirements analysis
 - more focused on the overall requirements and the final code
- Verification is about checking requirements specifications
 - often with intermediate steps
- In this course, we will mainly focus on verification
 - though also validation will be treated

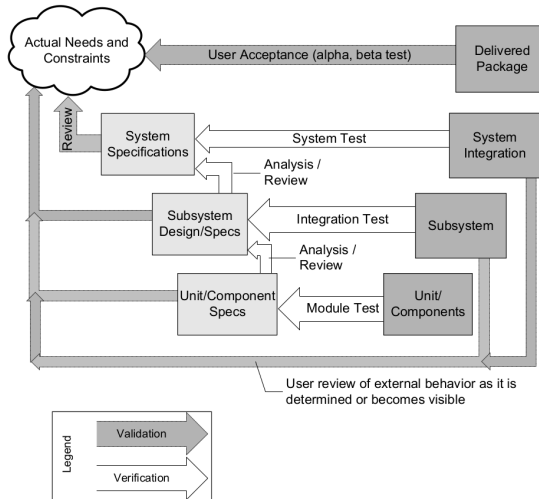


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Validation and Verification



How Verification is Performed

Method number 1: *Testing*

- ① you have the actual system (or a part of it)
- ② you feed it with predetermined *inputs*
- ③ you check if *outputs* are the expected ones
 - “expected” w.r.t. the requirements
- ④ if there is one output different from the expected one, then we have an error
- ⑤ you correct it and start over again
 - restarting from the “highest” point where you made the correction
 - requirements, design, code



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How Verification is Performed

Method number 1 bis: *Simulation*

- two typical cases:
 - prototyping: you do not have the full code, but some simplified prototype may be built
 - feed inputs to the prototype instead of the actual software
 - especially useful to test designs (early testing)
 - you have the full code, but it is used to control/monitor of some physical system (*cyber-physical systems*)
 - the simulator is for such physical system: it accepts the same inputs and provides the same outputs of the physical system
 - connect the software to such simulator as it was the real system
 - proceed as in “normal” testing by feeding inputs and observing outputs
 - you might also use a prototype for the (control/monitor) software and a simulator for the physical system for early testing



How Verification is Performed

Cyber-physical systems: why this methodology?

- Must check if they work *before* connecting to the physical part
 - or, even worse, build it
 - at least, the most common/easy errors must be ruled out
- If you have a controller for a plane, you do not directly test it on an actual plane, a simulator of the plane is used
 - only when tests on the simulator are ok you move to test on the actual plane
 - if the simulator says the plane is crashed, it is less severe than an actual plane crashing
- It is not a matter of safety only: it might also be an economical problem
 - e.g., testing on microprocessors must use some simulator before, as “writing” on silicon is expensive
 - e.g., if you are building a new airplane also basing on its controller, you must know if there are problem in the design



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How Verification is Performed: Errors Correction

- This might not be easy: testing typically only *triggers* errors
- Then, you might have to reproduce the error in some smaller scale
- Then, you have to understand where the problem is and what causes it
 - requirements? architecture? design? single point in the code? an intricate flow in the code?
- Then, design and implement the actual correction
- In this course, we only deal with error triggering



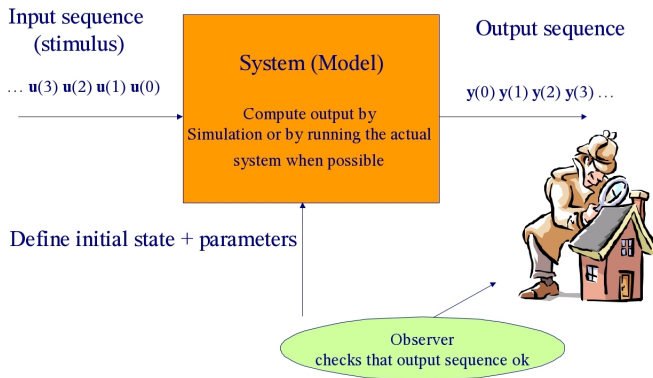
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How Verification is Performed

An approximate answer BUG HUNTING: Testing + Simulation



How Verification is Performed

- Both testing and simulation may be performed in refined ways
- In fact, the *testing plan* (the predetermined sequence of inputs) may be computed using dedicated algorithms so that *coverage* is maximized
 - we will get back soon on this concept
- This is the most challenging and important step for such techniques



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Testing and Simulation: Pro and Cons

Pro

- (Relatively) easy to implement
 - easier than the other methods we will consider here
- Largely used in industry
 - in most cases, testing and/or simulation are the *only* verification methods used

Cons

- They can prove that a system *has* errors, but cannot prove that a system *does not have* errors
- Cannot be used to prove generic formal properties
- The coverage of the “input space” is low
- Errors are frequently detected when it is too



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Testing and Simulation: Cons

They can prove that a system *has* errors, but cannot prove that a system *does not have* errors

- If an error is detected, then the system must be corrected, happy to have discovered it
- Otherwise, *we cannot conclude anything*
- That is, **we cannot say that the system is error-free**
- In fact, having not be able to spot errors does not imply that there are no errors



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Testing and Simulation: Cons

Cannot be used to prove generic formal properties

- This is a consequence of the previous slide
- As an example: in an operating system, is it true that mutual exclusion is enforced for 2 given processes?
- In order to test such a property you would have to modify the system itself
 - so that the output contains something like “propriety violated” or “property ok”
- But even in this case, we cannot draw a formal statement on the validity of the property
- Again, not finding a violation does not imply there are no violations



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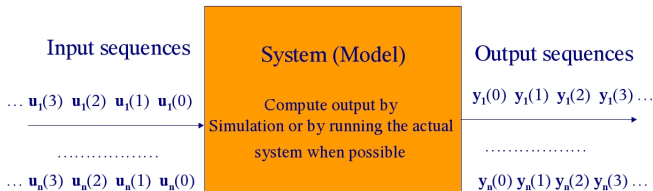


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Testing and Simulation: Cons

The coverage of the “input space” is low

- A successful testing phase should consider “all what may happen” to the system in a real-world environment
- This would need too much tests or simulations



- The n in the figure may easily be 10^6 and more; outputs must also be checked



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Testing and Simulation: Cons

The coverage of the “input space” is low

- This also has another bad consequence
- Testing and simulation find the “easy” errors
 - the most frequent ones
 - i.e., those that are caused by many (different) input sequences
- Instead, *corner cases* usually go undetected
 - i.e., errors that are caused by a few (or even single) input sequences are usually not found



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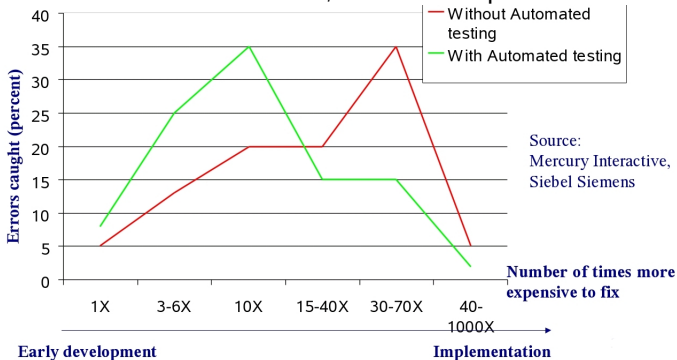


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Testing and Simulation: Cons

Errors are frequently detected when it is too late

- This is a consequence of the previous point: you need many tests to get a reasonable coverage and discover possible corner cases
- The later an error is found, the more expensive the correction



Formal Verification

- To solve the above underlined problems, we should consider *all* inputs
- That is, all possible system *evolutions*
 - of course, testing and simulation only consider *some* evolutions: those “activated” by inputs chosen by the testing plan in use
- A possible way to do this is to prove a dedicated theorem, stating that the system is correct for all inputs
- For sorting, this could be done (and it is actually done in Algorithms textbooks...)
- For other cases (e.g., microprocessor design), it would be too difficult or time consuming
- Thus, techniques of *formal verification* have been developed



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Formal Verification Methods

- A set of (heterogeneous) techniques which make possible the impossible
- That is, algorithms able to generate and analyze *all* system evolutions
 - so, they provide a *mathematical certification* of correctness (not achievable with testing/simulation)
 - also for generic properties, like mutual exclusion
- Actually, the problem of verifying a given system w.r.t. a given property is *undecidable*
 - the property to be verified may be: is this system always terminating?
- So, there will be some (acceptable in many cases) limitations



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Is Formal Verification Useful?

- There are many techniques available for formal verification
- Applying any of these techniques is usually much more difficult than testing/simulation
 - both in terms of personnel and notions required
- So, why to do this?
- Because there are many cases in which testing/simulation simply *are not enough*
 - for both economic and safety reasons



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Is Formal Verification Useful?

- **Safety-critical** systems: failures may affect humans
 - public transport software controllers (if an automatic pilot of an airplane has a failure...)
 - trains crossing
 - ABS for cars
 - ...
- For most of such systems, formal verification is **mandatory** by law
 - ESA (European Space Agency)
 - IEC (International Electrotechnical Commission)



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Is Formal Verification Useful?

- **Mission-critical** systems: failures cause huge economic losses
 - automatic space probes
 - logistics
 - communication networks
 - microprocessors
 - ...
- Internal company regulations often make formal verification **mandatory** as well



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Is Formal Verification Useful?

- Also for systems which are neither safety nor mission critical: there are economic motivations to use formal verification
- Using testing/simulations, errors are eventually discovered
- The problem is that they may be found *late*
 - this is a consequence of the low coverage issue
- So late, that often errors are found *after* the system has been deployed, i.e., when it is already used by its final users
 - for, e.g., a *word processor*, it is annoying, but we are somewhat used to software updates to fix bugs
 - this is not always possible or easy
 - e.g., a legacy software out of support



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Is Formal Verification Useful?

- Hardware circuits: to “write” a circuit on silicon is the most expensive part of the developing process
- So, finding an error after having written the circuit entails a huge economic loss
- This also holds for other systems, when the developing process is lengthy
- In fact, finding a late error may cause going again through preceding developing phases
 - less competitiveness on the market
 - for both being late and for augmented costs



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Is Formal Verification Useful?

- Some famous errors in safety-critical systems
 - 20/7/1969: on the Apollo 11, the driving computer fails multiple times during the final descent on the Moon
 - all ok because the large support team on Earth finds out that the error may be ignored
 - 26/9/1983, URSS believes USA have launched 5 nuclear weapons
 - no 3rd WW only because a Russian official finds it strange there are only 5 missiles
 - all due to a software bug in recognizing false negatives
 - 1985-1987: Therac-25, computer system to treat cancer through radiations
 - many patients due to too high radiations
 - the error was afterwards tracked to a “race condition” among concurrent processes



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Is Formal Verification Useful?

- Some famous errors in mission-critical systems
 - 1962: Mariner 1 automatic space probe (80 M\$)
 - the dash sign for negative numbers is missing (“the most expensive dash in history”)
 - resulting trajectory is completely wrong
 - the support team blows the probe to avoid it hitting something on ground
 - 1990: AT&T network failure
 - just one code line wrong in one telephone exchange
 - for hours, 60000 users are unable to make calls
 - 1990: another space probe, Ariane 5 (500 M€)
 - overflow in converting numbers from 64 to 16 bits (!)
 - due to reuse of Ariane 4 software



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Is Formal Verification Useful?

- Some famous errors in mission-critical systems (continued)
 - 1994: Intel Pentium computes wrong answers on some floating point errors (450 M\$)
 - 2006: Airbus A380 internal wires
 - errors in the software controlling wiring
 - all design process have to be restarted from scratch
 - extremely huge economic losses
 - 2010: Toyota Prius ABS
 - error “glitch” in the ABS controller
 - 185,000 cars recalled for updating
 - also bad publicity



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Is Formal Verification Useful?

- A should-be-famous error in mission-critical systems: Needham-Schroeder protocol
 - public-key authentication protocol, designed in 1978
 - widespread use in many systems for decades
 - initiated a large body of work on the design and analysis of cryptographic protocols
- After 17 years of usage, an error was (manually) discovered in 1995 by Lowe
- In 1996, Lowe showed that, using formal verification, it would have been easy to immediately detect the error
 - more in detail, by using model checking
- Other examples are in <https://spinroot.com/spin/success.html>



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Is Formal Verification Useful?

The most recent case: CrowdStrike vulnerability

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MONDO

Crash CrowdStrike, verso la normalità. Microsoft: 8,5 milioni di dispositivi coinvolti

20 lug 2024 - 19:14



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Is Formal Verification Useful?

The most recent case: CrowdStrike vulnerability

La “schermata blu della morte” che ha bloccato i computer in tutto il mondo: ecco cosa è successo. “Più pesante del Millennium Bug”

di Diego Longhin



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Is Formal Verification Useful?

The most recent case: CrowdStrike vulnerability *The New York Times*

Global Tech Outage | What We Know | When Tech Fails | More Flights Canceled | Passengers Still Struggling | Guard Against Scams

Chaos and Confusion: Tech Outage Causes Disruptions Worldwide

Airlines, hospitals and people's computers were affected after CrowdStrike, a cybersecurity company, sent out a flawed software update.

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Summing Up

- Testing and simulation are the most used verification tools
 - most companies (especially for software) use *only* these tools
 - easier and cheaper to use
 - at least one between testing and simulation are *always* performed
- For mission critical or safety critical systems, formal verification methods must be used
 - more difficult to be applied
 - may provide a mathematical certification for the system correctness
 - only applied when budget allows it



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Formal Verification Methodologies: a Classification

There are two macro-categories:

- *Interactive methods*
- *Automatic methods*



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Formal Verification Methodologies: a Classification

There are two macro-categories:

- *Interactive methods*
 - as the name suggests, not (fully) automatic
 - human intervention is typically required
 - in this course, we do not deal with such techniques
- *Automatic methods*



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Formal Verification Methodologies: a Classification

There are two macro-categories:

- *Interactive methods*
 - as the name suggests, not (fully) automatic
 - human intervention is typically required
 - in this course, we do not deal with such techniques
- *Automatic methods*
 - only human intervention is to *model* the system



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- There also exist hybridations among the two categories



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Interactive Methods

- Also called *proof checkers*, *proof assistants* or *high-order theorem provers*
- Tools which helps in building a mathematical proof of correctness for the given system and property
- **Pros**
 - virtually no limitation to the type of system and property to be verified
- **Cons**
 - highly skilled personnel is needed
 - both in mathematical logic and in deductive reasoning
 - needed to “help” tools in building the proof



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Interactive Methods

- Used for projects with high budgets
- For which the automatic methods limitations are not acceptable
 - used, e.g., to prove correctness of microprocessor circuits or OS microkernels
- Some tools in this category (see https://en.wikipedia.org/wiki/Proof_assistant):
 - HOL
 - PVS
 - Coq



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Automatic Methods

- Commonly dubbed *Model Checking*
- Model Checking software tools are called *model checkers*
- There are some tens model checkers developed; the most important ones are listed in https://en.wikipedia.org/wiki/List_of_model_checking_tools
- Many are freely downloadable and modifiable for research and study purposes
- Research area with many achievements in over 30 years

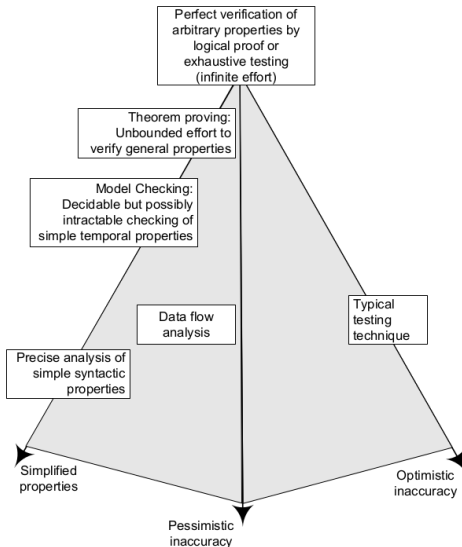


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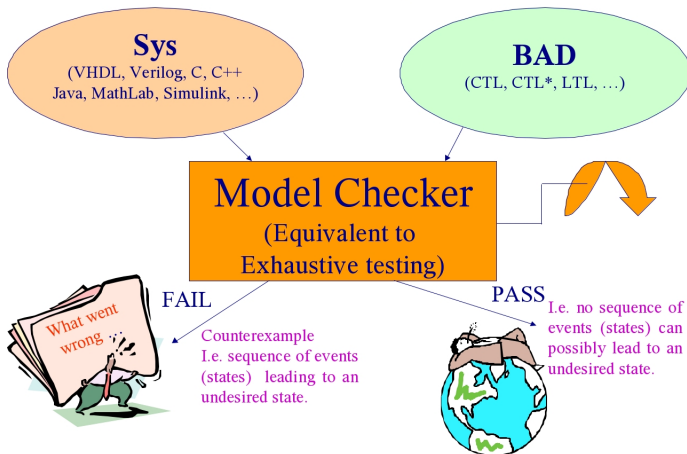


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Verification Tradeoffs



The Model Checking Dream

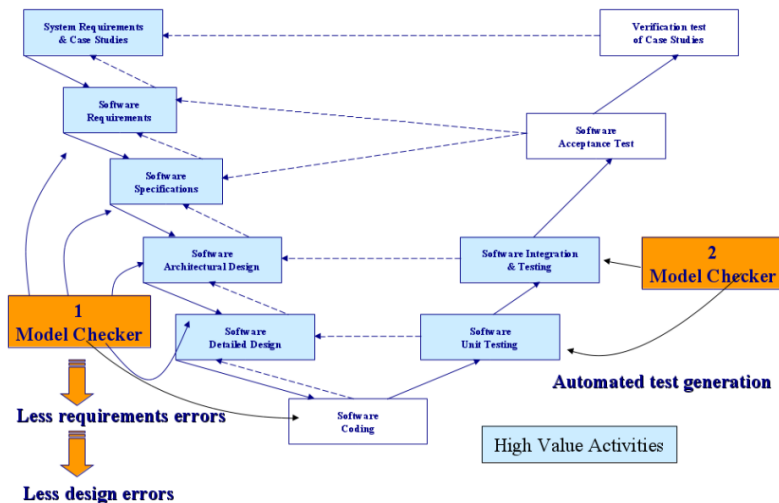


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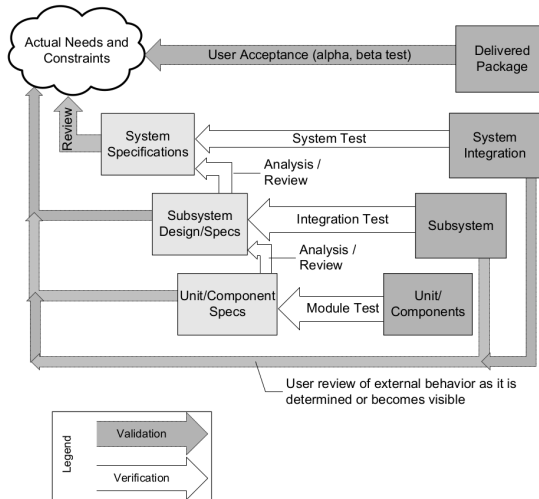


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The Model Checking Dream



Also Keep This in Mind



Actual Model Checking

- In order to have this computationally feasible, we need a strong assumption on the system under verification (SUV)
- I.e., it must have a *finite number of states*
 - *Finite State System* (FSS)
- In this way, model checkers “simply” have to implement reachability-related algorithms on graphs
- Such finite state assumption, though strong, is applicable to many interesting systems
 - that is: many systems are actually FSSs
 - or they may be approximated as such
 - or a part of them may be approximated as such



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What Is a *State*?

- There are many notions of “state” in computer science
- Model checking states are *not* the ones in UML-like state diagrams
- Model checking states are similar to operational semantics states
- That is: suppose that a system is “described” by n variables
- Then, a state is an assignment to all n variables
 - given D_1, \dots, D_n as our n variables domains, a state is $s \in \times_{i=1}^n D_i$



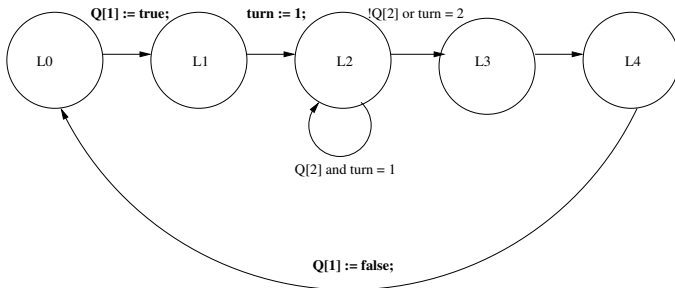
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What Is a *State*: Example

- We have two identical processes accessing a shared resource
 - in the figure below, i, j denote the two processes
 - the well-known Peterson algorithm is used



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What Is a *State*: Example

- The 5 “states” in the preceding figure are actually *modalities*
- From a model checking point of view, they correspond to *multiple* (i.e., sets of) states
- To see which are the actual states, let us model this system with the following variables:
 - m_i , with $i = 1, 2$: the modality for process i
 - Q_i , with $i = 1, 2$: Q_i is a boolean which holds iff process i wants to access the shared resource
 - turn : shared variable



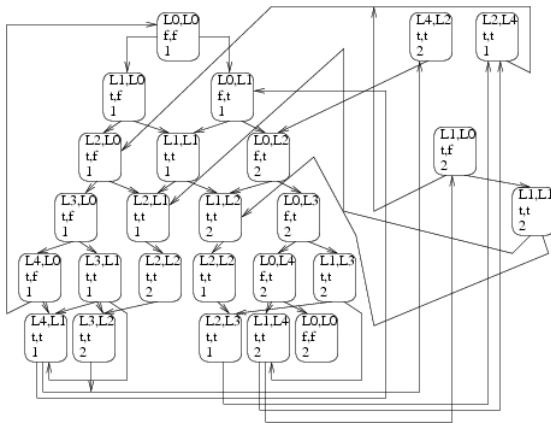
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What Is a *State*: Example

- Thus, the resulting model checking states are the following:



What Is a *State*: Example

- There are 25 *reachable states*
 - assuming state $\langle L0, L0, f, f, 1 \rangle$ as the starting one
- All *possible* states are 200
 - there are 3 variables with two possible values (the 2 variables Q, plus the turn variable) and 2 variables (P) with 5 possible values, thus $2^3 \times 5^2$ overall assignments
- The L0 modality for the first process encloses 6 (reachable) states

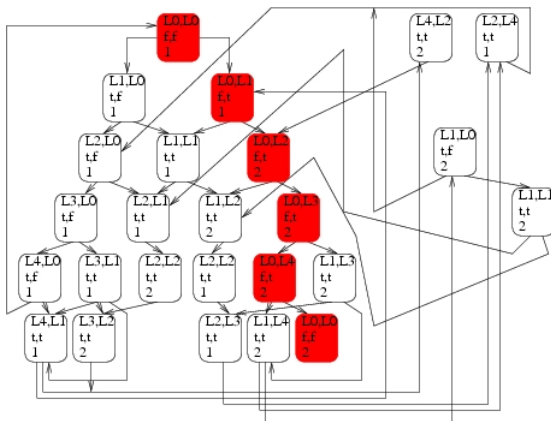


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What Is a *State*: Example



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- The L0 modality for the first process encloses 6 (reachable) states
- No need of guards on transitions!



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From State Diagrams to Model Checking

- The UML-like state diagram is often useful to write the model
 - as we will see, this will depend on the model checker *input language*
- It is the model checker task to extract the global (reachable) graph as seen before
- And then analyze it



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Is Model Checking Important?

- ESA, NASA e IEC require most of their project to be model checked
- Important companies have dedicated laboratories for Model Checking
 - hardware: Intel, IBM, SUN, NVIDIA
 - software: IBM, SUN, Microsoft
- Many universities have research groups
 - USA: MIT, CMU, Austin, Stanford...
 - very close collaboration with companies
- The 3 “inventors” of Model Checking received Touring Award in 2007:
 - E. A. Emerson, E. M. Clarke, J. Sifakis

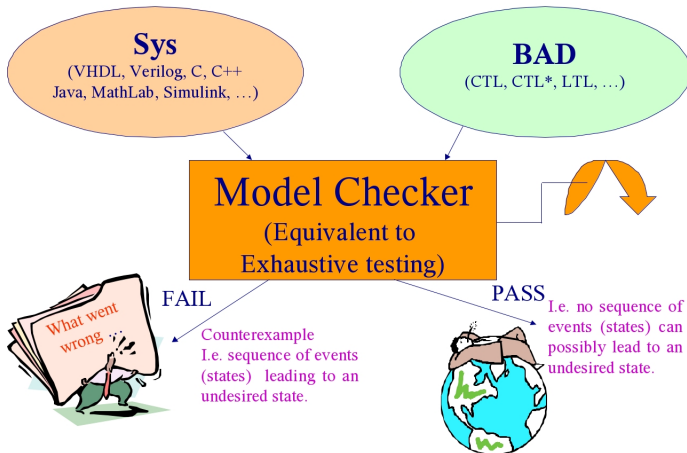


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Model Checking Usage



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Model Checking Usage

3 steps:

- 0 Choose the model checker M which is most suitable to the SUV \mathcal{S} (and the property φ)
- 1 Describe \mathcal{S} in the input language of M
- 2 Describe the property φ
- 3 Invoke the model checker and wait for the answer
 - OK $\Rightarrow \mathcal{S} \models \varphi$
 - FAIL \Rightarrow counterexample
 - correct the error (it may happen that \mathcal{S} or φ must be corrected instead...) and go back to step 3
 - OutOfMem or OutOfTime
 - adjust system parameters (or the description of \mathcal{S})



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Model Checking Usage

- Most used for *reactive systems*
 - always executing systems:
 - monitors: warns if something bad happens
 - controllers: avoids that something bad happens
 - services: wait for requests and serve it
 - more in general, concurrent execution of processes/threads with shared memory/messages exchange
 - errors may occur because of interactions/interleaving between different processes/threads
- Not good for standalone (1-process) programs
 - e.g., sorting an array or perform BFS of a graph
 - for such systems, testing can be complemented with theorem proving (or with manual proof derivation)
 - of course, budget must be taken into account



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Model Checking: Pro and Cons

Pro

- Same guarantees of proof checking
- But requiring less “mathematics” and “computer science” knowledge

Cons

- Computational Complexity
 - causing “OutOfMem” and “OutOfTime”: *State Explosion Problem*
- You check a model of the system, not the actual system
 - though in some cases models can be automatically extracted from the system
- Useful only for multi-process/thread software



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State Explosion Problem: Why?

- With some simplification, all Model Checking algorithms are essentially like this:
 - 1 Extract, from the description of the SUV \mathcal{S} , the *transition relation* of \mathcal{S}
 - 2 Compute the *reachable states* (*reachability*)
 - 3 Check if φ holds in all reachable states
- All steps may be computationally heavy, but let us focus on the reachability
 - see mutual exclusion example
- If \mathcal{S} is described by n (binary) variables, then the number of reachable states is $O(2^n)$



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State Explosion Problem: Why?

- Such complexity cannot be avoided in the most general case
- Theoretically speaking, (LTL) Model Checking is P-SPACE complete
 - CTL Model Checking is in P, but as we will see this does not make things better
- There are different model checking algorithms, depending on the “type” of \mathcal{S}
 - each checker has its “preferred” SUVs



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Model Checking Algorithms

There are 3 categories:

- Explicit
- Implicit (symbolic)
- SAT-based



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Model Checking Algorithms

There are 3 categories:

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 - each reachable state is separately stored
 - very good for communication protocols
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- SAT-based
 - many problems may be theoretically rewritten as SAT, but in model checking this works pretty well also in practice
 - software model checking



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- SAT-based
 - many problems may be theoretically rewritten as SAT, but in model checking this works pretty well also in practice
 - software model checking
- Proof checker ibridations
 - not completely automatic, but better than proof checkers



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Model Checking-Related Problems

- Controllers generators
 - particular case for the program synthesizer seen in the beginning
 - controllers are software modules which sends digital commands to some physical device
 - in some cases, they may be built automatically, using algorithms similar to those of Model Checking
- Probabilistic Model Checking
 - verification of stochastic processes
- Stochastic Model Checking
 - verification outcome is correct with high probability



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From Model Checking to Testing

- Not all software is mission- or safety-critical
 - actually, most software do not fall in such categories
- Moreover, testing is required also for such systems
 - not all features may be checked through formal verification
- Hence, testing is at least as important as model checking and similar techniques
 - early 2000s estimate: software failures cost US economy nearly \$ 60 billion per year
 - early 2000s estimate: at least \$ 22 billion per year could be saved by applying proper software testing
- No general frameworks exist, but we have some general “best practises”
 - we will cover them in this course



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What If We Use AI?

- Most recent version of, e.g., ChatGPT, are very powerful and may directly address both code and designs
 - may be employed in both ways: given specifications, generate code...
 - ... and given code, generate tests
 - also model checking models
- Problem for generation: no guarantee of correctness!
 - code generated may be flawed exactly as that generated by a human
 - but it would be more difficult to track errors, if they are found
 - time must be used to also understand the generated code
- Problem for verification: no guarantee that coverage is better than human-made one
- May be used to give a starting point, to be refined



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We Will See Theory...

- A Kripke structure is a 4-tuple: $\langle S, I, R, L \rangle$
- Formulas satisfiability: $\pi \models \varphi \mathbf{U} \psi$ iff
 $\exists j \in \mathbb{N} \forall 0 \leq i < j \pi(i) \models \varphi \wedge \pi(j) \models \psi$
- μ -calculus, e.g.: $R(x) = \mu Z [I(x) \vee \exists x' [N(x', x) \wedge Z(x')]]$
- Algorithms on graphs, hash tables, OBDDs...



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...and Practice

- We will examine the most important model checkers, also considering the source code
 - often very well written
 - in order to delay state explosion as much as possible
 - good way to learn how to code
- SUVs modeling examples
- Software testing best practices, with examples



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Roadmap

- 1 Modeling systems with the Murphi model checker
- 2 Kripke structures and algorithms inside Murphi: Model Checking of invariants
- 3 LTL and CTL properties
 - safety and liveness
- 4 CTL Model Checking algorithms
- 5 LTL Model Checking with SPIN
- 6 CTL Model Checking with NuSMV
- 7 Bounded Model Checking with NuSMV
- 8 Testing (starting from November)
 - granularity
 - techniques
 - best practises



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