Software Testing and Validation

A.A. 2023/2024

Corso di Laurea in Informatica

Basic Notions

Igor Melatti

Università degli Studi dell'Aquila

Dipartimento di Ingegneria e Scienze dell'Informazione e Matematica

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/20232024/index.html` (Italian)
  - `https://igormelatti.github.io/sw_test_val/20232024/index_eng.html` (English)
  - also on MS Teams: "DT0758: Software Testing and Validation (2023/24)", code **86obv1d**
- 2 classes every week, 2 hours per class

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Rules for Exams

- Each exam has a written part (50% of mark) and a project/paper (50% of mark)
  - each student may choose if making a project or reviewing a paper
  - teams of at most 2 students are allowed for projects
- Written exam will be a mix of open and closed questions on the whole exam program
- Project/paper may be discussed only after having passed the written exam
  - however, pre-evaluation is possible

Rules for Exams

- 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
- Paper: read a conference or journal paper and present it with slides
  - each student may choose one among the ones selected by lecturer
  - or may propose one (but wait for lecturer approval!)

Verification Problem

- Dates back to computer science origins
  - of course, not only in computer science
- Let us focus on software
- Only in some few cases it is possible to generate (synthesize) a correct-by-construction program starting from (formal) requirements
- Otherwise, the verification problem would not exist, at least not in its current form

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
   - write a program able to manage an airport
   - etc.
2. Let us try to write the corresponding requirements
   - $\forall 1 \leq i \leq n-1 \; A[i] \leq A[i+1]$
   - $\exists u_1, \ldots, u_n$ 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

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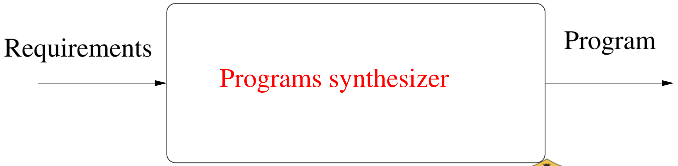
Utopia!

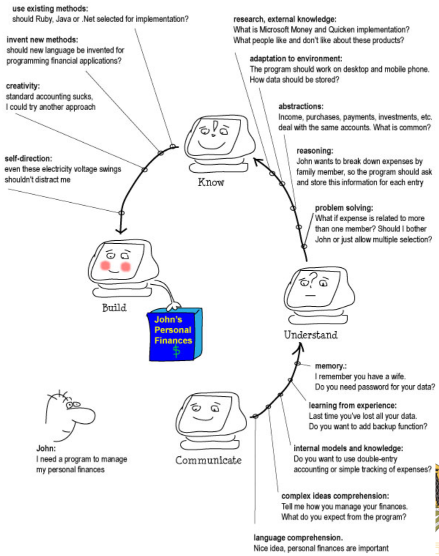
- Suppose you have an automatic program synthesizer (generator)
  - a special program which takes *requirements* as input
    - must be described in some *formal* way, i.e., using an unambiguous mathematical language
  - ... and outputs a correct-by-construction program which fulfills the input requirements



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)

Instead, the Reality


use existing methods:
should Ruby, Java or .Net selected for implementation?
invent new methods:
should new language be invented for programming financial applications?
creativity:
standard accounting sucks, I could try another approach
self-direction:
even these electricity voltage swings shouldn't distract me
research, external knowledge:
What is Microsoft Money and Quicken implementation? What people like and don't like about these products?
adaptation to environment:
The program should work on desktop and mobile phone. How data should be stored?
abstractions:
Income, purchases, payments, investments, etc. deal with the same accounts. What is common?
reasoning:
John wants to break down expenses by family member, so the program should ask and store this information for each entry
problem solving:
What if expense is related to more than one member? Should I bother John or just allow multiple selection?
Know
Build
John's Personal Finances $
Understand
memory.:
I remember you have a wife. Do you need password for your data?
learning from experience:
Last time you've lost all your data. Do you want to add backup function?
internal models and knowledge:
Do you want to use double-entry accounting or simple tracking of expenses?
complex ideas comprehension:
Tell me how you manage your finances. What do you expect from the program?
language comprehension.
Nice idea, personal finances are important
John:
I need a program to manage my personal finances
Communicate

Instead, the Reality

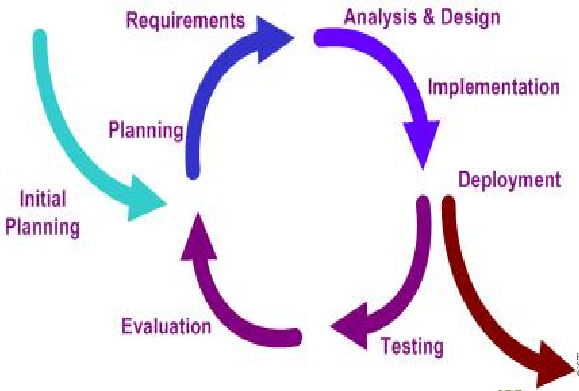
- Do you need to build a software? then, you will have to do it *ad hoc*
  - *totally* general approaches to build program generators cannot exist
  - it is easy to see that building a program generator is an undecidable problem
- Of course, you can rely on libraries, methodologies, etc, but...
- ... 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

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
- Verification goal is to find *errors*, if any
  - for our pruposes, an error is a violation of the requirements
  - some requirements are present since the beginning, some other may add up later

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*



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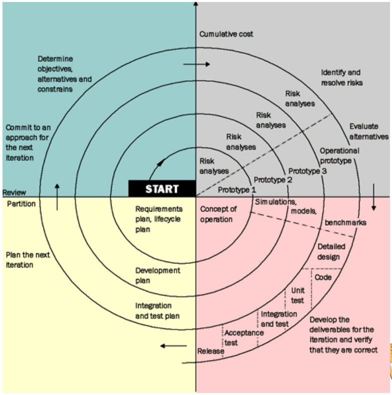

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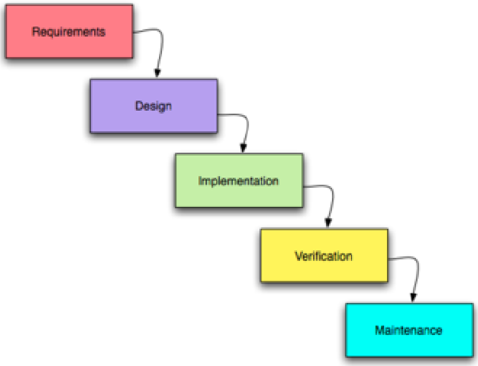

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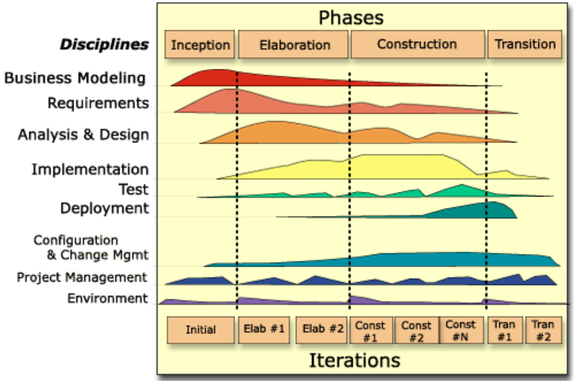

Systems Verification

- 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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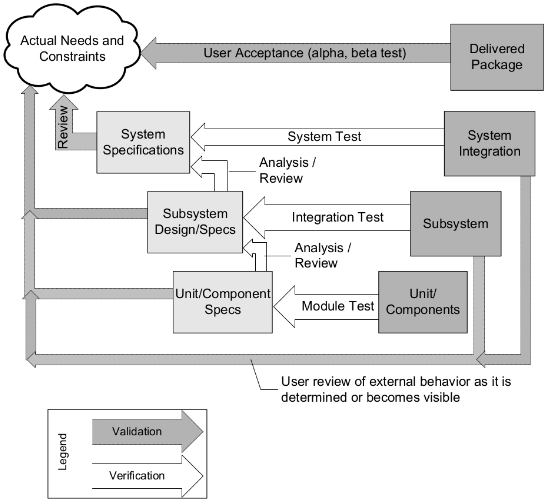
Validation

- 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?" $\rightarrow$ *useful* system
- Verification is "did we built the system right?" $\rightarrow$ *dependable* system

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 anaysis
    - 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

Validation and Verification



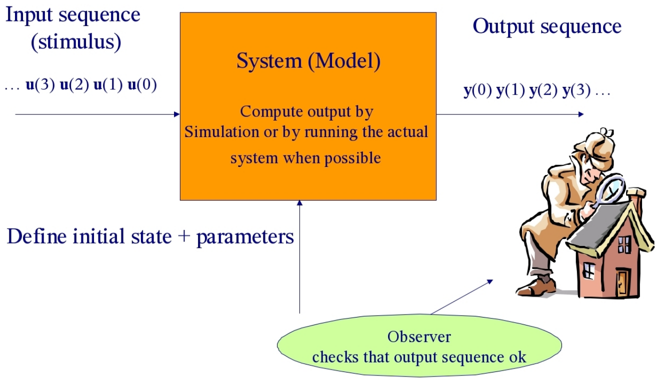
How Verification is Performed

- 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
- Method number 1 bis: *Simulation*
  - instead of using the actual system, you have a *(software) simulator*
  - especiall useful for hardware or for physical parts
  - if you want to do testing on hardware, you need to actually build it, which may be expensive

How Verification is Performed

An approximate answer

BUG HUNTING: Testing + Simulation


Input sequence (stimulus)
… u(3) u(2) u(1) u(0)
System (Model)
Compute output by Simulation or by running the actual system when possible
Output sequence
y(0) y(1) y(2) y(3) …
Define initial state + parameters
Observer checks that output sequence ok

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

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 late

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

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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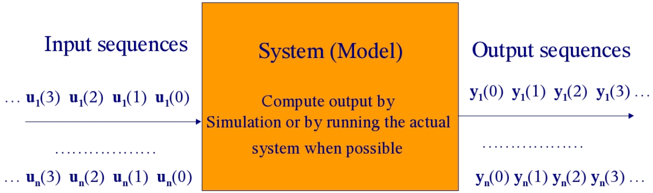
Testing and Simulation: Cons

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



Input sequences
... $\mathbf{u}_1(3)$ $\mathbf{u}_1(2)$ $\mathbf{u}_1(1)$ $\mathbf{u}_1(0)$
... $\mathbf{u}_n(3)$ $\mathbf{u}_n(2)$ $\mathbf{u}_n(1)$ $\mathbf{u}_n(0)$
System (Model)
Compute output by Simulation or by running the actual system when possible
Output sequences
$\mathbf{y}_1(0)$ $\mathbf{y}_1(1)$ $\mathbf{y}_1(2)$ $\mathbf{y}_1(3)$ ...
$\mathbf{y}_n(0)$ $\mathbf{y}_n(1)$ $\mathbf{y}_n(2)$ $\mathbf{y}_n(3)$ ...

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

Testing and Simulation: Cons

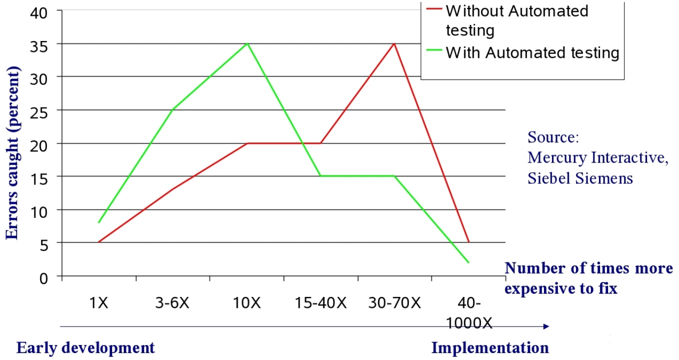
The coverage of the "input space" is low

- 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

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, al 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

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

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 researchers 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

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)

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 competitivity on the market
    - for both being late and for augemented costs

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Is Formal Verification Useful?

- Some famous errors in safety-critical systems
  - 20/7/1969: Apollo 11, during the final descent on the Moon, the driving computer fails multiple times
    - all ok because the large support team on Earth understands 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 rediations
    - 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 most expensive dash in history
    - that is, in the software, the dash sign for numbers is missing
    - resulting trajectory is completely wrong
    - the support team blows the probe to avoid it hits 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 ansers 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

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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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 methematical certification for the system correctness
    - only applied when budget allows it

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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  - only human intervention is to *model* the system

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- *Automatic methods*
  - only human intervention is to *model* the system
- There also exist hybridations among the two categories

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

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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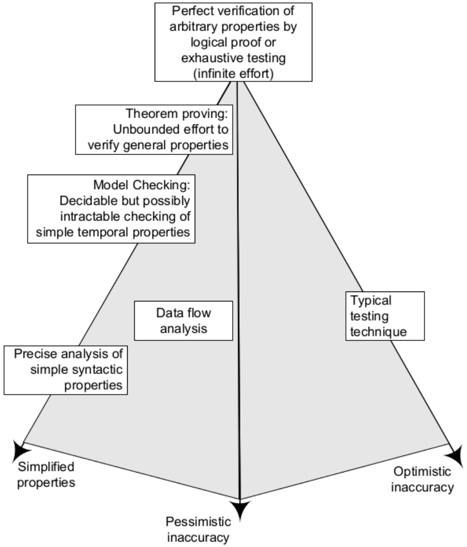
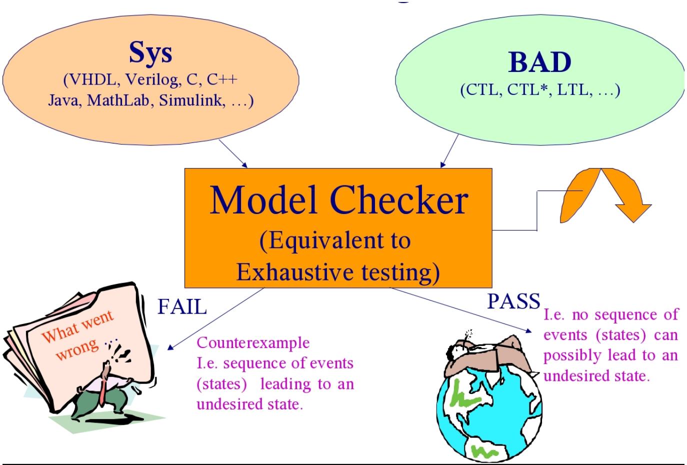
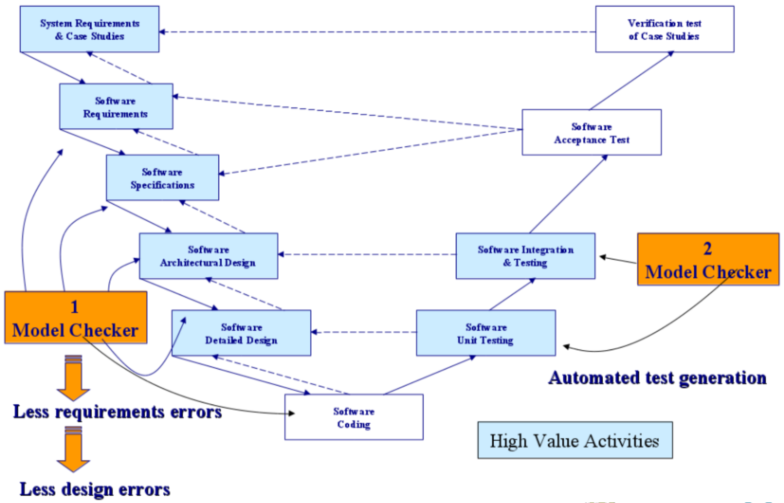
Verification Tradeoffs


Perfect verification of arbitrary properties by logical proof or exhaustive testing (infinite effort)
Theorem proving: Unbounded effort to verify general properties
Model Checking: Decidable but possibly intractable checking of simple temporal properties
Data flow analysis
Typical testing technique
Precise analysis of simple syntactic properties
Simplified properties
Optimistic inaccuracy
Pessimistic inaccuracy

The Model Checking Dream


Sys
(VHDL, Verilog, C, C++
Java, MathLab, Simulink, …)
BAD
(CTL, CTL*, LTL, …)
Model Checker
(Equivalent to
Exhaustive testing)
FAIL
What went wrong …
Counterexample
I.e. sequence of events (states) leading to an undesired state.
PASS
I.e. no sequence of events (states) can possibly lead to an undesired state.

The Model Checking Dream



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

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 $D_1, \ldots, D_n$ as our n variables domains, then a state is $s \in \times_{i=1}^{n} D_i$

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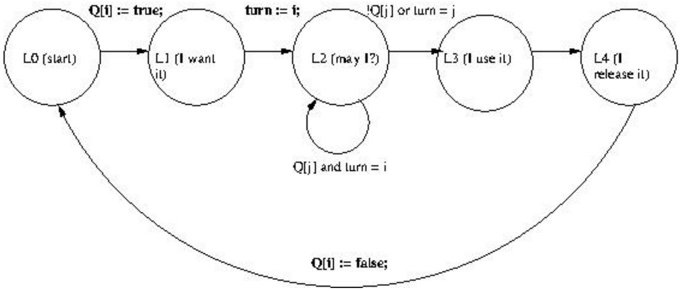
What Is a *State*: Example

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

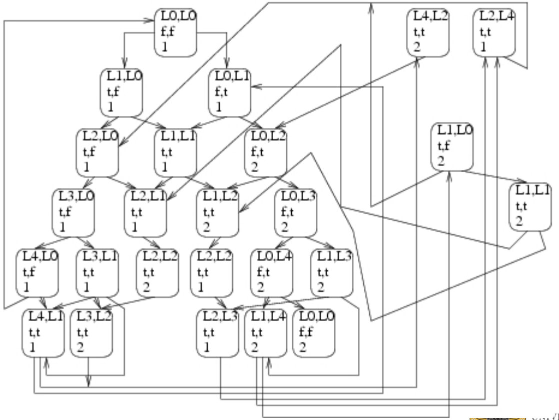


What Is a *State*: Example

- The 5 “states” in the preceding figure are actually *modalities*
- From a model checking point of view, they correspond to *multiple* 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

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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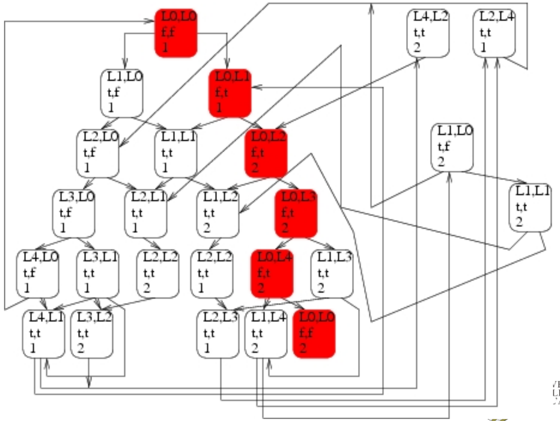
What Is a *State*: Example



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- The `L0` modality for the first process encloses 6 (reachable) states
- No need of guards on transitions!
  - guards will be needed for systems with external inputs

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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

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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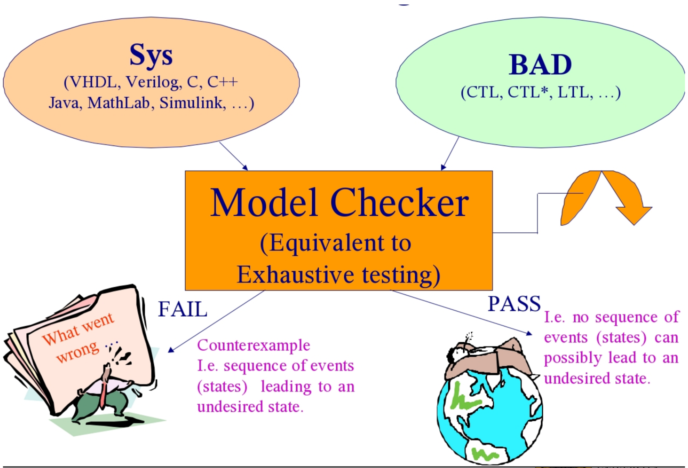
Model Checking Usage


Sys
(VHDL, Verilog, C, C++
Java, MathLab, Simulink, …)
BAD
(CTL, CTL*, LTL, …)
Model Checker
(Equivalent to
Exhaustive testing)
FAIL
What went wrong …
Counterexample
I.e. sequence of events (states) leading to an undesired state.
PASS
I.e. no sequence of events (states) can possibly lead to an undesired state.

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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

- Not actually to verify programs with “standard” input and outputs
  - input is known in advance, e.g. in sorting; standalone computation
  - for such systems, testing can be complemented with theorem proving (or with manual proof derivation)
  - of course, budget must be taken into account
- Most used for *reactive systems*
  - always executing: monitoring (warns if something bad happens) or controlling (avoids that something bad happens)

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

State Explosion Problem: Why?

- With some semplification, 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 $O(2^n)$

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

Model Checking Algorithms

There are 3 categories:

- Explicit
- Implicit (symbolic)
- SAT-based

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    - software model checking
- Proof checker ibridations
    - not completely automatic, but better than proof checkers

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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We Will See Theory...

- A Kriepke 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-calcolus, e.g.: $R(x) = \mu Z[I(x) \vee \exists x'[N(x', x) \wedge Z(x')]]$
- Algorithms on graphs, hash tables, OBDDs...

...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

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 April)