Software Testing and Validation

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Corso di Laurea in Informatica

Testing Preliminaries

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From Formal Verification to Testing

- Main analogies: both formal verification and testing are about checking some properties of a system
  - easiest property: does the system output the correct answer for a given input?
  - other properties: does it deadlock? does it run within given deadlines?
- Main difference: formal verification requires a formal *model* of the system and a specification of the properties in some temporal logic
  - in some cases, the model can be automatically built (e.g., for hardware verification or bounded software verification)
- Testing requires the current version (for part of) of the *actual* software
  - as for the property, no need that any temporal logic is used, though it may help
  - a simulator may be used for some physical components

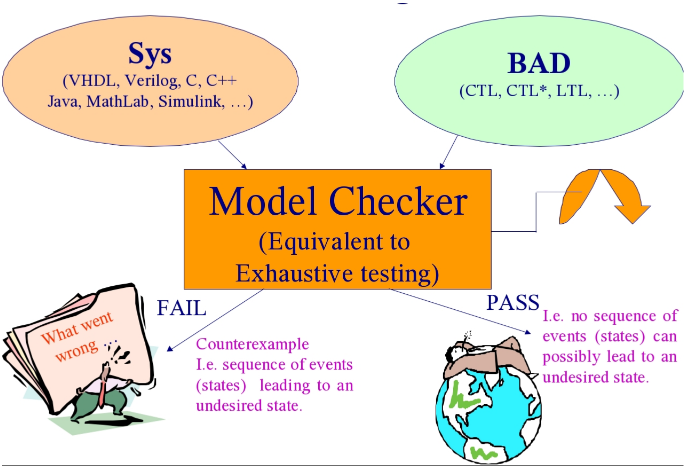
From Formal Verification to Testing

- Thus, testing is typically applied *late* in the design process
  - you need actual software, which is typically developed after architectural design and so on
  - at least for complex software projects
- However, if the software design process is well organized, testing may also be applied much early
  - e.g.: some components may be fully developed before others
  - as soon as they are developed, they may be tested
  - this is actually what it should be *always* done
  - the technique allowing this is called *scaffolding*

From Formal Verification to Testing

- So, no models in testing? NO!
  - you may not have a model of the system itself, but models however play an important role
  - in some cases, also a model of the system is available, why not to use it?
- Models in testing are typically used:
  - to generate inputs
  - to guide in generating inputs
  - to undestand if a testing phase is "adequate" or not
- What about algorithms?
  - no "real" algorithms are used in testing
  - forget μ-calculus or nested DFS or so on
  - though, as we will see, some algorithms may be helpful, exactly as for the models

From Model Checking...



… to Testing

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

Basic Notions on Testing

- No need of complex algorithms as in model checking: simply execute the system and see what happens
- Does this mean testing is easy? Obviously, NO!
- Main difficulties:
  - find a “good” subset of the possibly infinite inputs
  - which is the share of inputs you are using (*coverage*)?
  - running tests has a cost: consider project budget
  - integrate testing within software process
  - “execute the system”: not always straightforward (*scaffolding*)
  - “see what happens”: to be done automatically when possible (*oracles*)
  - no general tool is available

Basic Notions on Testing

- Model Checking is only performed for mission- or safety-critical systems with medium-high budget
- Testing is *always* performed on *any* software
  - from cli-based computer-science-first-year projects to airport management system
- Testing all features is typically impossible for complex projects
- For simpler projects, all features may be tested, but not at 100% coverage
  - actually, also 1% testing coverage is often too difficult to obtain
- Priorities must be defined
  - more risky and defect-likely parts of the software must be checked first
  - strictly followed by the parts which are executed more often
    - 80/20 rule: 80% of any daily business activity is provided by 20% of the business system functions, transactions, or workflow

Basic Notions on Testing

- Some authors distinguish between *positive* vs *negative* testing
  - positive testing: check that the software behaves as it should under “normal” conditions
  - negative testing: check that users cannot “break” the system
    - both if they are malicious: denial of service and similar issues
    - and if they are not: including apex by accident in a non-sanitized search...
- We will consider both these types of testing without further distinction

Basic Notions on Testing

- Software related figures:
  - architects: general software "structure"
  - developers: write code
  - testers: plan, prepare and execute tests; furthermore, interpret test results
- For not-too-big projects, some or all of these figures could coincide
- For complex projects, testers should be separated from developers and/or architects
  - though they must know the corresponding skills
  - not influenced by having devised and/or implemented the system
  - the same programmer could be a developer in a project and a tester in another

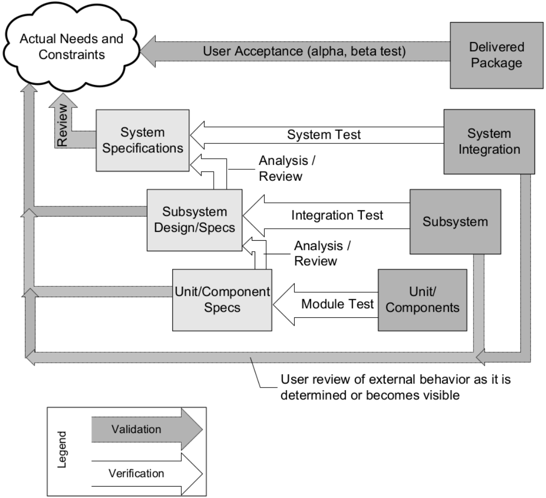
Basic Notions on Testing

- Skills of a software engineer specialized in testing:
  - planning tests: deciding priorities and dependencies
  - interpret test results, which could update the plan
  - from the plan, devise actual test cases
  - run the test cases and collect the results
- In a testing team, such capabilities could be properly mixed

Testing Timeline

- Let us consider complex projects: the following types of testing can be performed
  1. *unit testing*: test simple functions/classes/processes first
  2. *integration testing*: put some meaningful subsets of functions/classes/processes together and test them
  3. *system testing*: test the whole system
     - last step of integration...
  4. *acceptance testing (validation)*: test the whole system with the final users
  5. *regression testing*: how to re-test the system when new releases are issued
     - code (and possibly specifications) is modified

Testing Timeline



Testing Timeline

- Some of these steps may be deleted
  - for cli-based computer-science-first-year projects, unit testing is enough
  - for medium-size projects, integration testing and system testing may coincide
  - for a personal software, validation is straightforward as developers and final users coincide
- Not necessarily in cascade
  - errors discovered in later steps typically cause earlier steps to be re-run
  - sometimes not only re-running, but also devising new inputs could be required
- If errors are discovered, develpers have to fix them; then, re-run testing

Testing Main Techniques

- Two main overall methodologies:
  - *functional testing*: tester knows specs but not the code
    - also known as *black-box testing*
  - *structural testing*: tester exploits code knowledge
    - also known as *white-box testing*
    - includes *data-flow testing*
- Two other methodologies
  - *static testing*: code may not exist, look at documentation only
    - mainly done through model checking
    - but also prototyping may be used
  - *performance testing*: needs actual code
- Applicable to all types of testing, from unit to acceptance

Testing Main Techniques

- Orthogonal and/or auxiliary techniques:
  - *combinatorial testing*
    - given some values for single inputs, obtain a full input
  - *model-based testing*
    - extract inputs from models of software
    - special case: *fault-based testing*
  - *test execution*: not always straightforward
- Applicable to nearly all testing of the previous slide

Basic Notions on Testing

- Testing is not only for software: nearly all products must be tested before being sold
  - i.e., stressed in a controlled environment
- Typically, the testing phase is standardized for a given product
  - always repeated for some randomly chosen instance of the product
  - e.g., take a smartphone from a selling pack and drop it from 10m
- For products which are not built in series, testing must be individual
  - race cars, houses, etc.
- Of course, some guidelines may be available
  - e.g., testing of houses in a seismic environment

Basic Notions on Software Testing

- Software is among the most difficult things to be checked
  - it is virtually always "customized", thus each software needs its own testing phase
- There are guidelines, some of which will be covered in this course
- Some difficulties:
  - only errors presence can be proved
  - cost
    - it is easy to make some simple tests
    - it may be enough for very-non-critical software
    - for most software, a tradeoff is needed between testing cost and software criticality

- Some difficulties (continued):
  - non-linearity
    - if you successfully test an elevator to be able to carry 1000 kg, then it will be ok with 900 kg or less
    - if you successfully test a sorting procedure with 1000 elements, it may fail with 2 elements
    - if you make a small modification to a pair of glasses, you do not need to run full design test from scratch
    - if you make a small modification to a software (e.g., a security update), it may cause some failure in other previously tested parts of the software
    - recall the CrowdStrike vulnerability...

Six Principles for Testing (and Verification)

- The following principles characterize the Testing and Validation as an activity of its own:
  - partition, visibility, feedback
    - nothing new: also other engineering activities may use this
  - sensitivity, redundancy, restriction
    - specific for testing and validation

Six Principles for Testing (and Verification)

- *Sensitivity*
  - problem: many errors may not be "observable"
  - e.g., a buffer overflow in C/C++ may or may not cause a failure in the running process
  - sensitivity asks that errors or faults in the software always result in observable failures
  - especially hits in code design/implementation: add assertions or similar code fragments
    - or use languages with dynamic checks such that Java, Python or Rust
  - as for verification, model checking is actually more suited for sensitivity
  - also manual code inspection may be used

Sensitivity Example

```c
/**
 * Worse than broken: Are you feeling lucky?
 */

#include <assert.h>

   char before[ ] = "=Before=";
   char middle[ ] = "Middle";
   char after[ ] = "=After=";

void show() {
   printf("%s\n%s\n%s\n", before, middle, after);
}

void stringCopy(char *target, const char *source, int howBig);

int main(int argc, char *argv) {
   show();
   strcpy(middle, "Muddled");       /* Fault, but may not fail */
   show();
   strncpy(middle, "Muddled", sizeof(middle)); /* Fault, may not fail */
   show();
   stringCopy(middle, "Muddled",sizeof(middle)); /* Guaranteed to fail */
   show();
}

/* Sensitive version of strncpy; can be counted on to fail
 * in an observable way EVERY time the source is too large
 * for the target, unlike the standard strncpy or strcpy.
 */
void stringCopy(char *target, const char *source, int howBig) {
   assert(strlen(source) < howBig);
   strcpy(target, source);
}
```

Six Principles for Testing (and Verification)

- *Redundancy*
  - in a broad sense: having some behavior that depend on something other
  - you declare an 'intent", so we can test if the intent is fulfilled
  - typed languages are a type of redundancy by intent
    - e.g., you declare something to be integer and you can raise an error if instead there is a float
  - as for actual testing: check if an implementation is ok w.r.t. its specification is actually a type of redundancy
  - specifications should be written so as to ease automatic testing or manual inspection

Six Principles for Testing (and Verification)

- *Restriction*
  - your desired property is too difficult to attain?
  - restrict it, i.e., try with something easier
    - but however meaningful
  - e.g.: too difficult to check that a variable is always initialized, then check if there exist the possibility that it may uninitialized

Restriction Example

```java
    /** A trivial method with a potentially uninitialized variable.
     * Maybe someCondition(0) is always true, and therefore k is
     * always initialized before use ... but it's impossible, in
     * general, to know for sure. Java rejects the method.
     */
    static void questionable() {
        int k;
        for (int i=0; i < 10; ++i) {
            if (someCondition(i)) {
                k = 0;
            } else {
                k += i;
            }
        }
        System.out.println(k);
    }
}
```

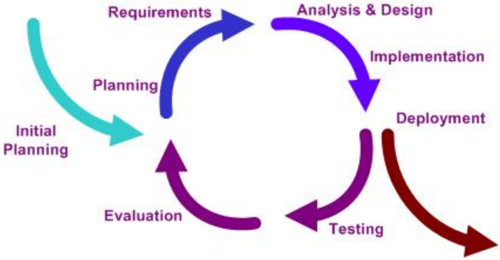
- *Partition*
  - divide and conquer (divide et impera)
  - decompose the problem to be tested
  - the very fact that many different testing techniques exists, and may be employed on the same software, it is a matter of partition
    - unit testing, functional testing, structural testing...
  - also making a model of the system is a partitioning technique
    - from “does this software satisfy my property?”...
    - to “does this model satisfy my property?” and “does this model faithfully represent the software?”

Six Principles for Testing (and Verification)

- *Visibility*
  - very similar to observability
  - again, mainly a design issue to ease testing
  - typical example: base program information on textual files rather than binary files
    - low performance degradation, but much better readability and capability of testing
  - e.g., HTTP exchange information as text
  - e.g., Unix-based OSs use text files for configuration
- *Feedback*
  - learn to build better testing phase from previous testing phase

Software Process

- Not “process” in the sense of operating systems: “software process” is the whole set of activities needed to develop a high-quality software for some specific problem
  - software process contains: requirement analysis and specification, software design, implementation, validation and verification
  - organized in many ways
- Testing (and verification in general) cannot be simply done at the end



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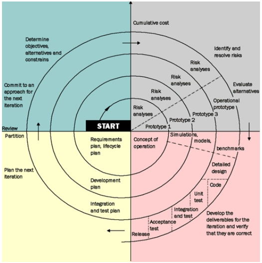

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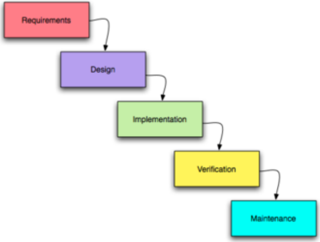

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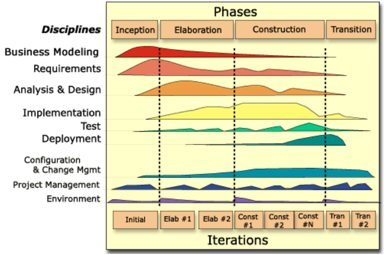

Software Process: Testing

Completeness important class of faults are suitably targeted

- "important" depends on what you are building
- e.g., if C/C++ is used, beware of memory leaks

Timeliness discover errors as soon as possible

- error in coding revealed at unit testing OK
- error in coding revealed at system integration BAD
- error in coding discovered by final user VERY BAD
- error in the system specifications discovered in system acceptance test CATASTROPHE

Cost effectiveness achieve completeness and timeliness within budget

- on the whole process: do not repeat heavy tasks because of errors

Software Quality Through Testing

- Process visibility: progress must be easily detectable
- This entails that quality goals must be clearly stated and refined
- Goals are measured on software product qualities, which may be:
  - *internal*: only visible to the software developers and designers
    - e.g.: maintainability, reusability, traceability
  - *external*: also visible to final users
    - e.g.: throughput, latency, usability
    - summing up, either dependability or usefulness goals
    - dependability: does it have (functional) faults?
    - usefulness: provided it is dependable, does it have other (typically non-functional) faults?
    - e.g.: bad user interface, software is too slow, etc

Software Dependability

- Simplest dependability property: correctness
  - all behaviors of the software are as specified
- Reliability: statistical approximation of correctness
  - if not all behaviors are ok, then at least, e.g., 90% of them are
  - often specified w.r.t. a particular usage profile
  - the same program can be more or less reliable depending on how it is used
  - a possible formal definition: percentage of successful operations in a given period $\frac{100|S|}{|S|+|F|}$
    - S is the set of all operations which succeed in the given period

Software Reliability: Other Possibile Definitions

- Availability: reliability when failures duration is important
  - may be defined as $100\frac{u}{u+d}$
  - u: software is up and accepting requests
  - d: software is down and not accepting requests
  - typically, $u + d = 1$ day, or 1 week
- MTBF: Mean Time Between Failures
  - may be defined as $\frac{1}{|F|}\sum_{f \in F} |f|$
  - F is the set of all failures in the given period (1 day, 1 week...)
  - for a failure $f \in F$, $|f|$ is the duration, i.e., time required for fixing f
  - more detailed than availability: e.g., it distinguishes from 30 failures of 1 minute and 1 failure of 30 minutes

Software Dependability

- Robustness: correct and reliable only within some defined operational limits
  - if there is a failure only because of a 100x load, the system is however robust
- Safety: nothing bad occurs
  - of course, must be defined w.r.t. some property
  - e.g.: there is never more than one process in the critical section
  - broader sense than what we have defined in model checking
  - essentially, it is any property you can specify, so also liveness and neither liveness nor safety