PV260 - SOFTWARE QUALITY

[Spring 2024]

PRINCIPLES OF TESTING. SOFTWARE TESTING TECHNIQUES & TEST CASES RISK ANALYSIS

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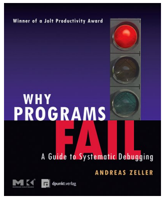
"Discovering the unexpected is more important than confirming the known."

George Box

Introduction

- In Eclipse and Mozilla, 30–40% of all changes are fixes (Sliverski et al., 2005)
- Fixes are 2–3 times smaller than other changes (Mockus + Votta, 2000)
- 4% of all one-line changes introduce new errors (Purushothaman + Perry, 2004)


Winner of a Jolt Productivity Award
WHY
PROGRAMS
FAIL
A Guide to Systematic Debugging
ANDREAS ZELLER

A. Zeller, Why Programs Fail, Second Edition: A Guide to Systematic Debugging,
2 edition. Amsterdam ; Boston: Morgan Kaufmann, 2009.

Motivational example: a Memory Leak (1/3)

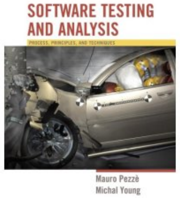
Apache web server, version 2.0.48

Response to normal page request on secure (HTTPS) port

```
Static void ssl_io_filter_disable(ap_filter_t *f)
{   bio_filter_in_ctx_t *inctx = f->ctx;

    inctx->ssl = NULL;
    inctx->filter ctx->pssl = NULL;
}
```

No obvious error, but Apache leaked memory slowly (in normal use) or quickly (if exploited for a DOS attack)



Motivational example: a Memory Leak (2/3)

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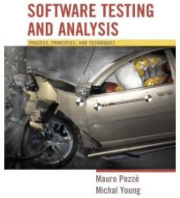
Response to normal page request on secure (HTTPS) port

```
Static void ssl_io_filter_disable(ap_filter_t *f)
{   bio_filter_in_ctx_t *inctx = f->ctx;
    SSL_free(inctx -> ssl);
    inctx->ssl = NULL;
    inctx->filter ctx->pssl = NULL;
}
```

The missing code is for a **structure defined and created elsewhere**, accessed through an opaque pointer.


SOFTWARE TESTING AND ANALYSIS
PROCESS, PRINCIPLES, AND TECHNIQUES
Mauro Pezzè
Michal Young

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{   bio_filter_in_ctx_t *inctx = f->ctx;
    SSL_free(inctx -> ssl);
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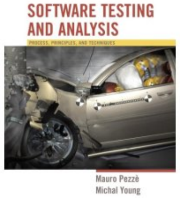
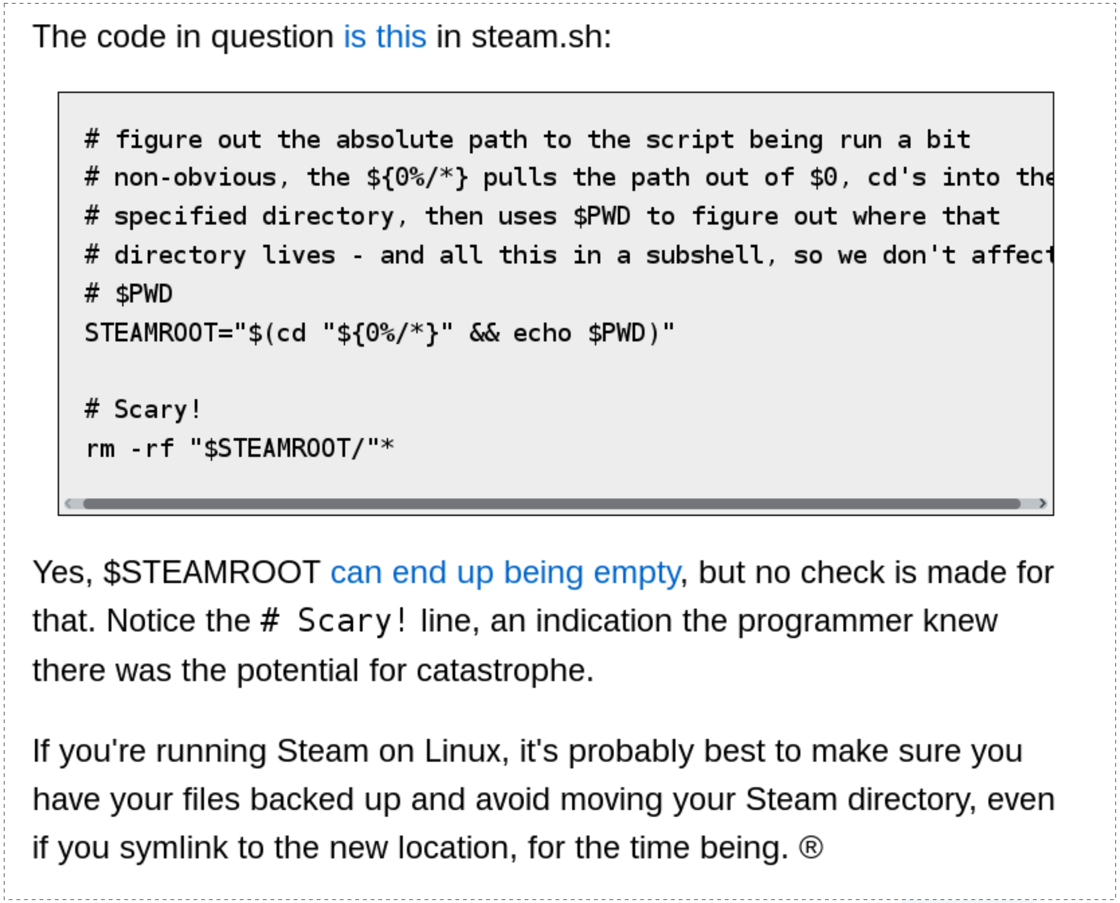
}
```

Almost impossible to find with unit testing.
 (Inspection and some dynamic techniques could have found it)



Defects are omnipresent



The code in question is this in steam.sh:

```
# figure out the absolute path to the script being run a bit
# non-obvious, the ${0%/*} pulls the path out of $0, cd's into the
# specified directory, then uses $PWD to figure out where that
# directory lives - and all this in a subshell, so we don't affect
# $PWD
STEAMROOT="$(cd "${0%/*}" && echo $PWD)"

# Scary!
rm -rf "$STEAMROOT/"*
```

Yes, $STEAMROOT can end up being empty, but no check is made for that. Notice the `# Scary!` line, an indication the programmer knew there was the potential for catastrophe.

If you're running Steam on Linux, it's probably best to make sure you have your files backed up and avoid moving your Steam directory, even if you symlink to the new location, for the time being. ®

https://en.wikipedia.org/wiki/List_of_software_bugs

What is Software Testing

“Testing is the ***process*** *of* ***exercising or evaluating*** *a system or system component by manual or automated means to verify that it* ***satisfies specified requirements****.”* IEEE standards definition

Test Oracle Problem: *the challenge of a mechanism to determine if the output is correct given a set of inputs*

"Program testing can be used to show the presence of bugs, but never to show their absence!" - Edsger W. Dijkstra

Software Testing – Important Terms

Failure: “*(A)* ***Termination*** *of the ability of a product to perform a required function or its inability to perform within previously specified limits. (B)* ***An event*** *in which a system or system component does not perform a required function within specified limits.*

→ *A failure may be produced when a fault is encountered*

Fault: “*A* ***manifestation*** *of an error in software.*”

Defect: “*An* ***imperfection*** *or* ***deficiency*** *in a work product where that work product* ***does not meet its requirements*** *or* ***specifications*** *and needs to be either repaired or replaced.*”

Error: “*A* ***human action*** *that produces an incorrect result*”

Definitions according to IEEE Std 1044-2009 “IEEE Standard Classification for Software Anomalies“

What about the term "Bug"?

- Very often a **synonymous of *"defect"*** so that ***"debugging"* is the activity related to removing defects in code**

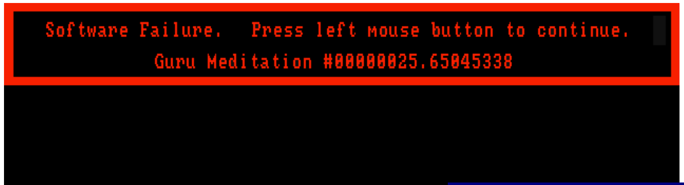
  However:

  → **it may lead to confusion**: it is not rare the case in which *"bug"* is used in natural language to refer to different levels:

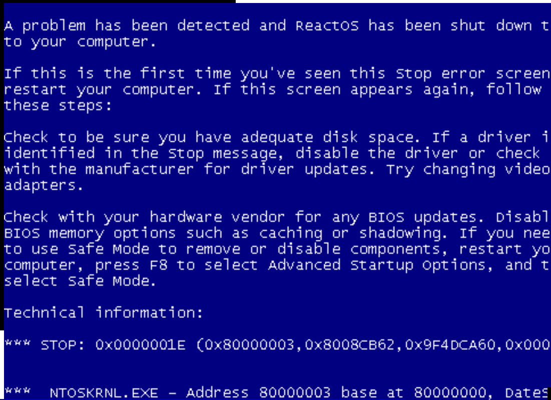
  "this line is buggy" - *"this pointer being null, is a bug"* - *"the program crashed: it's a bug"*

  → starting from Dijkstra, there was the search for terms that could **increase the responsibility of developers** – the term *"bug"* might give the impression of something that *magically* appears into software

Hopefully you have not seen many of these...



```
Software Failure.   Press left mouse button to continue.
        Guru Meditation #00000025.65045338
```



```
A problem has been detected and ReactOS has been shut down to prever
to your computer.

If this is the first time you've seen this Stop error screen,
restart your computer. If this screen appears again, follow
these steps:

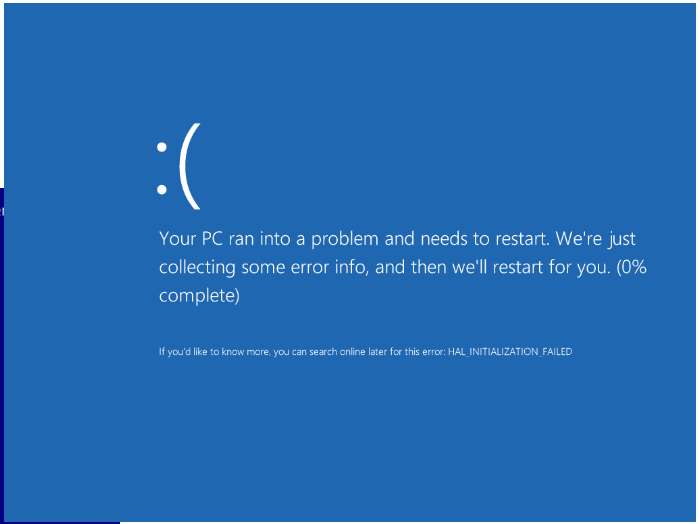
Check to be sure you have adequate disk space. If a driver is
identified in the Stop message, disable the driver or check
with the manufacturer for driver updates. Try changing video
adapters.

Check with your hardware vendor for any BIOS updates. Disable
BIOS memory options such as caching or shadowing. If you need
to use Safe Mode to remove or disable components, restart your
computer, press F8 to select Advanced Startup Options, and then
select Safe Mode.

Technical information:

*** STOP: 0x0000001E (0x80000003,0x8008CB62,0x9F4DCA60,0x00000000)

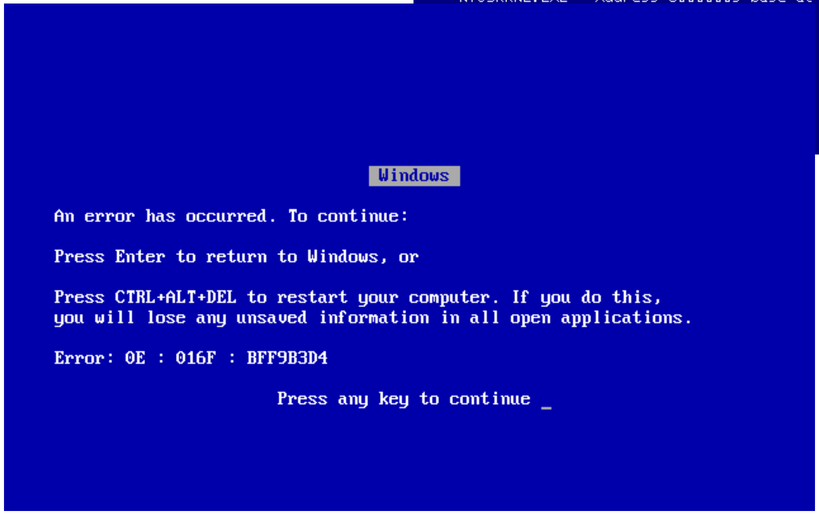
***  NTOSKRNL.EXE - Address 80000003 base at 80000000, DateS
                                             80000000, DateS
```



:(

Your PC ran into a problem and needs to restart. We're just collecting some error info, and then we'll restart for you. (0% complete)

If you'd like to know more, you can search online later for this error: HAL_INITIALIZATION_FAILED



```
                         Windows

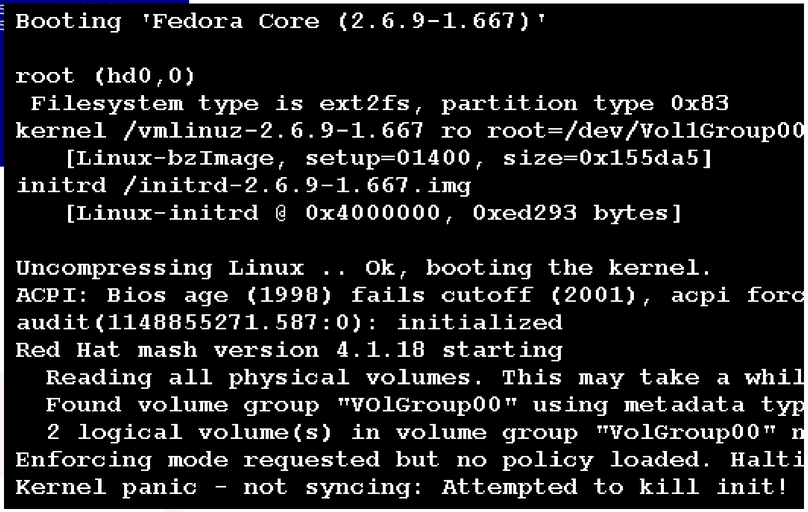
  An error has occurred. To continue:

  Press Enter to return to Windows, or

  Press CTRL+ALT+DEL to restart your computer. If you do this,
  you will lose any unsaved information in all open applications.

  Error: 0E : 016F : BFF9B3D4

                   Press any key to continue _
```



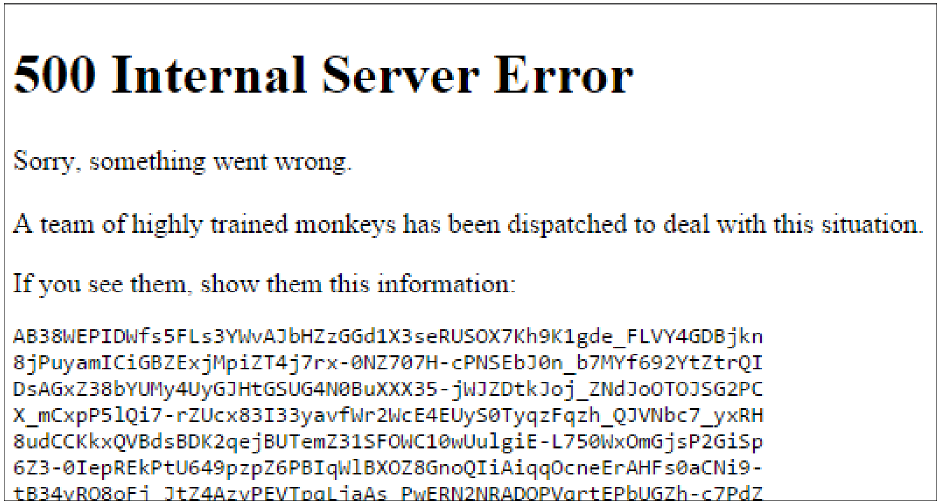
```
Booting 'Fedora Core (2.6.9-1.667)'

root (hd0,0)
 Filesystem type is ext2fs, partition type 0x83
kernel /vmlinuz-2.6.9-1.667 ro root=/dev/Vol1Group00
   [Linux-bzImage, setup=01400, size=0x155da5]
initrd /initrd-2.6.9-1.667.img
   [Linux-initrd @ 0x4000000, 0xed293 bytes]

Uncompressing Linux .. Ok, booting the kernel.
ACPI: Bios age (1998) fails cutoff (2001), acpi forc
audit(1148855271.587:0): initialized
Red Hat mash version 4.1.18 starting
  Reading all physical volumes. This may take a whil
  Found volume group "VOlGroup00" using metadata typ
  2 logical volume(s) in volume group "VolGroup00" n
Enforcing mode requested but no policy loaded. Halti
Kernel panic - not syncing: Attempted to kill init!
```

…or some of these

YouTube



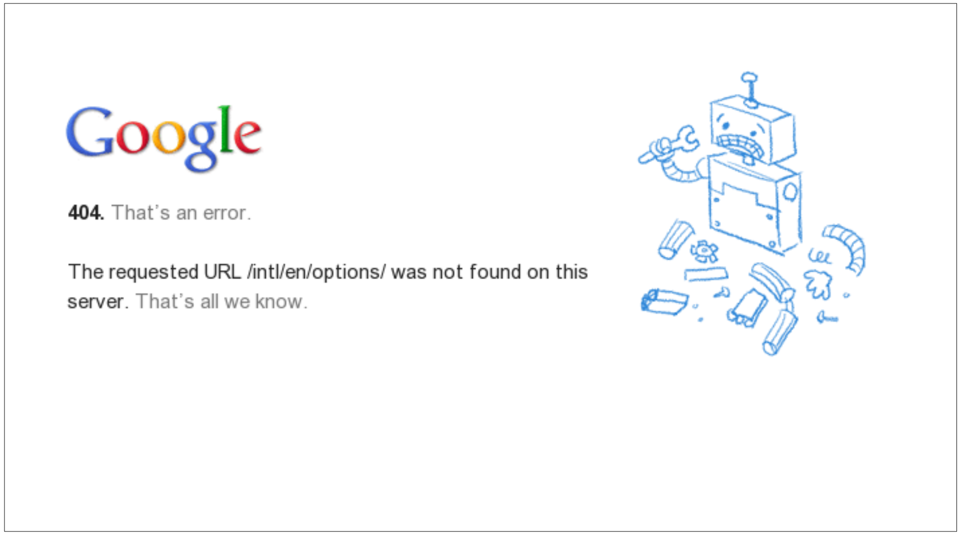
500 Internal Server Error

Sorry, something went wrong.

A team of highly trained monkeys has been dispatched to deal with this situation.

If you see them, show them this information:

```
AB38WEPIDWfs5FLs3YWvAJbHZzGGd1X3seRUSOX7Kh9K1gde_FLVY4GDBjkn
8jPuyamICiGBZExjMpiZT4j7rx-0NZ707H-cPNSEbJ0n_b7MYf692YtZtrQI
DsAGxZ38bYUMy4UyGJHtGSUG4N0BuXXX35-jWJZDtkJoj_ZNdJoOTOJSG2PC
X_mCxpP5lQi7-rZUcx83I33yavfWr2WcE4EUyS0TyqzFqzh_QJVNbc7_yxRH
8udCCKkxQVBdsBDK2qejBUTemZ31SFOWC10wUulgiE-L750WxOmGjsP2GiSp
6Z3-0IepREkPtU649pzpZ6PBIqWlBXOZ8GnoQIiAiqqOcneErAHFs0aCNi9-
tB34vRO8oFi_JtZ4AzvPEVTpqLjaAs_PwERN2NRADOPVartEPbUGZh-c7PdZ
```



Google

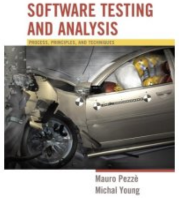
404. That's an error.

The requested URL /intl/en/options/ was not found on this server. That's all we know.

Basic Principles of Software Testing

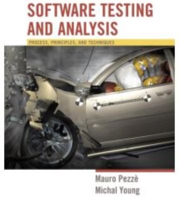
Basic Principles of Testing

- **Sensitivity:** better to fail every time than sometimes
- **Redundancy:** making intentions explicit
- **Restrictions:** making the problem easier
- **Partition:** divide and conquer
- **Visibility:** making information accessible
- **Feedback:** applying lessons from experience in process and techniques



Sensitivity: better to fail every time than sometimes

- Consistency helps:
  - a test selection criterion works better if every selected test provides the same result, i.e., **if the program fails with one of the selected tests, it fails with all of them (reliable criteria)**
  - run time deadlock analysis works better if it is machine independent, i.e., if the program deadlocks when analyzed on one machine, it deadlocks on every machine



Sensitivity: better to fail every time than sometimes

- Look at the following code fragment

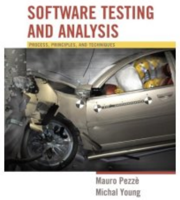
```
char before[] = “=Before=”;
char middle[] = “Middle”;
char after [] = “=After=”;

int main(int argc, char *argv){

   strcpy(middle, “Muddled”); /* fault, may not fail */
   strncpy(middle, “Muddled”, sizeof(middle)); /* fault, may not fail */


}
```

What's the problem?



Sensitivity Example

- Let's make the following adjustment

```
char before[] = “=Before=”;
char middle[] = “Middle”;
char after [] = “=After=”;

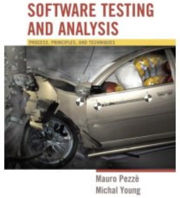
int main(int argc, char *argv){

   strcpy(middle, “Muddled”); /* fault, may not fail */
   strncpy(middle, “Muddled”, sizeof(middle)); /* fault, may not fail */
   stringcpy(middle, “Muddled”, sizeof(middle)); /* guaranteed to fail */

}

void stringcpy(char *target, const char *source, int size){
   assert(strlen(source) < size);
   strcpy(target, source);
}
```

This adds sensitivity to a non-sensitive solution



Sensitivity Example

- Let's look at the following Java code fragment. We use the ArrayList as a sort of queue and we remove one item after printing the results

```
public class TestIterator {

    public static void main(String args[]) {

        List<String> myList = new ArrayList<>();

        myList.add("PV260");
        myList.add("SW");
        myList.add("Quality");

        Iterator<String> it = myList.iterator();
        while (it.hasNext()) {
            String value = it.next();
            System.out.println(value);
            myList.remove(value);
        }
    }
}
```

Will this output
“PV260
SW
Quality” ?

Sensitivity Example

- Let's look at the following Java code fragment. We use the ArrayList as a sort of queue and we remove one item after printing the results

```
public class TestIterator {

    public static void main(String args[]) {

        List<String> myList = new ArrayList<>();

        myList.add("PV260");
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        myList.add("Quality");

        Iterator<String> it = myList.iterator();
        while (it.hasNext()) {
            String value = it.next();
            System.out.println(value);
            myList.remove(value);
        }
    }
}
```

Actually, this throws
java.util.ConcurrentModificationException

Sensitivity Example

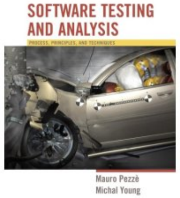
- From Java SE documentation:

Java SE Technical Documentation

- “[...] Some Iterator implementations (including those of all the general purpose collection implementations provided by the JRE) may choose to throw this exception if this behavior is detected. **Iterators that do this are known as *fail-fast* iterators, as they fail quickly and cleanly, rather that risking arbitrary, non-deterministic behavior at an undetermined time in the future.**”
- “Note that *fail-fast* behavior cannot be guaranteed as it is, generally speaking, impossible to make any hard guarantees in the presence of **unsynchronized concurrent modification**. *Fail-fast* operations throw *ConcurrentModificationException* on a best-effort basis. **Therefore, it would be wrong to write a program that depended on this exception for its correctness: *ConcurrentModificationException should be used only to detect bugs*.**”

Redundancy: making intentions explicit

- Redundant checks can increase the capabilities of catching specific faults early or more efficiently.
  - **Static type checking** is redundant with respect to **dynamic type checking**, but it can reveal many type mismatches earlier and more efficiently.
  - **Validation of requirement specifications** is redundant with respect to **validation of the final software**, but can reveal errors earlier and more efficiently.
  - **Testing and proof of properties are redundant**, but are often used together to increase confidence



Redundancy Example

- Adding redundancy by asserting that a condition must always be true for the correct execution of the program

```
void save(File *file, const char *dest){
   assert(this.isInitialized());
   ...
}
```

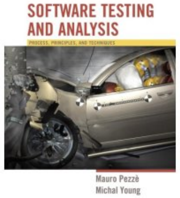
- From a language (e.g. Java) point of view, think about declarations of thrown exceptions from a method

```
    public void throwException() throws FileNotFoundException{
        throw new FileNotFoundException();
    }
```

Think if you could throw any exception from a method without declaration in the method signature

Restriction: making the problem easier

- Suitable restrictions can reduce hard (unsolvable) problems to simpler (solvable) problems
  - **A weaker spec may be easier to check**: it is impossible (in general) to show that pointers are used correctly, but the simple Java requirement that *pointers are initialized before use* is simple to enforce.
  - **A stronger spec may be easier to check**: it is impossible (in general) to show that type errors do not occur at run-time in a dynamically typed language, but statically typed languages impose stronger restrictions that are easily checkable.



Restriction Example

- Will the following compile in Java?

```
public static void questionable(){
    int k;
    for (int i=0; i<10;++i){
        if (someCondition(i)){
            k = 0;
        } else {
            k+=i;
        }
    }
}
```

Java ALWAYS enforces variable initialization before usage as the following example shows – this is a case of restriction

```
    int k;

    if (true == false){
        k+=i;
    }
```

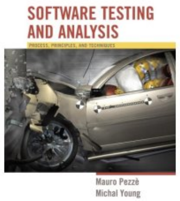
But restrictions can be applied at different levels, e.g. at the architectural level the decision of making the HTTP protocol stateless hugely simplified testing (and as such made the protocol more robust)

Partition: Divide & Conquer

- Hard testing and verification problems can be handled by **suitably partitioning the input space**:
  - both **structural** (**white box**) and **functional test** (**black box**) selection criteria identify suitable partitions of code or specifications (partitions drive the sampling of the input space)
  - **verification** techniques fold the input space according to specific characteristics, grouping homogeneous data together and determining partitions

→ Examples of **structural** (**white box**) techniques: ***unit testing***, ***integration testing***, ***performance testing***

→ Examples of **functional** (**black box**) techniques: ***system testing***, ***acceptance testing***



Partition Example

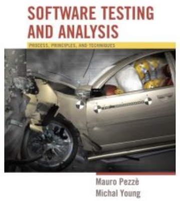
- Non-uniform distribution of faults
- Example: Java class “roots” applies quadratic equation $ax^2+bx+c=0$

$$x=\frac{-b\pm\sqrt{b^2-4ac}}{2a}$$

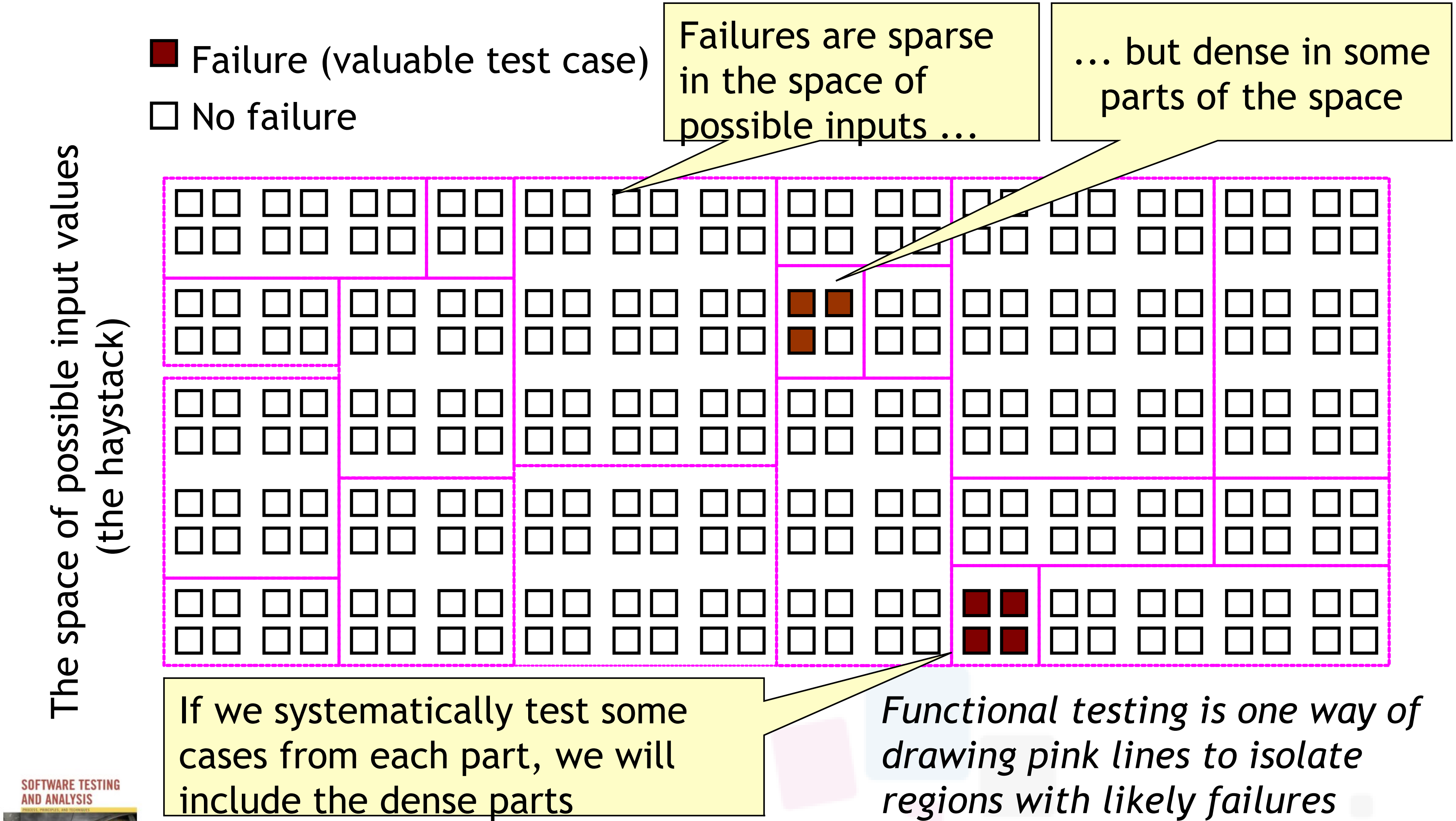
- Incomplete implementation logic: Program does not properly handle the case in which b^2 - 4ac = 0 and a = 0

These would make good input values for test cases

→ **Failing values are sparse in the input space** — needles in a very big haystack. **Random sampling** is unlikely to choose a=0.0 and b=0.0



Partition Example



■ Failure (valuable test case)

□ No failure

Failures are sparse in the space of possible inputs ...

... but dense in some parts of the space

The space of possible input values (the haystack)

If we systematically test some cases from each part, we will include the dense parts

Functional testing is one way of drawing pink lines to isolate regions with likely failures

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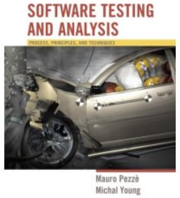
Visibility: Judging Status

- The ability to **measure progress** or **status against goals**
    - X visibility = ability to judge how we are doing on X, e.g., schedule visibility = *“Are we ahead or behind schedule”*, quality visibility = *“Does the quality meet our objectives?”*
  - Involves setting goals that can be assessed at each stage of development
    - The biggest challenge is early assessment, e.g., assessing specifications and design with respect to product quality
- Related to **observability**
  - Example: *Choosing a simple / standard internal data format to facilitate unit testing*



Visibility Example

- The HTTP Protocol

```
GET /index.html HTTP/1.1
Host: www.google.com
```

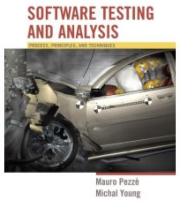
Why wasn't a more efficient binary format selected?

To note HTTP 2.0 **will** use a binary format (from https://http2.github.io/faq):
"Binary protocols are more efficient to parse, more compact "on the wire", and most importantly, they are much less error-prone, compared to textual protocols like HTTP/1.x, because they often have a number of affordances to "help" with things like whitespace handling, capitalization, line endings, blank links and so on."
In fact, reduction of visibility is confirmed by
"It's true that HTTP/2 isn't usable through telnet, but we already have some tool support, such as a Wireshark plugin."

Feedback: tuning the development process

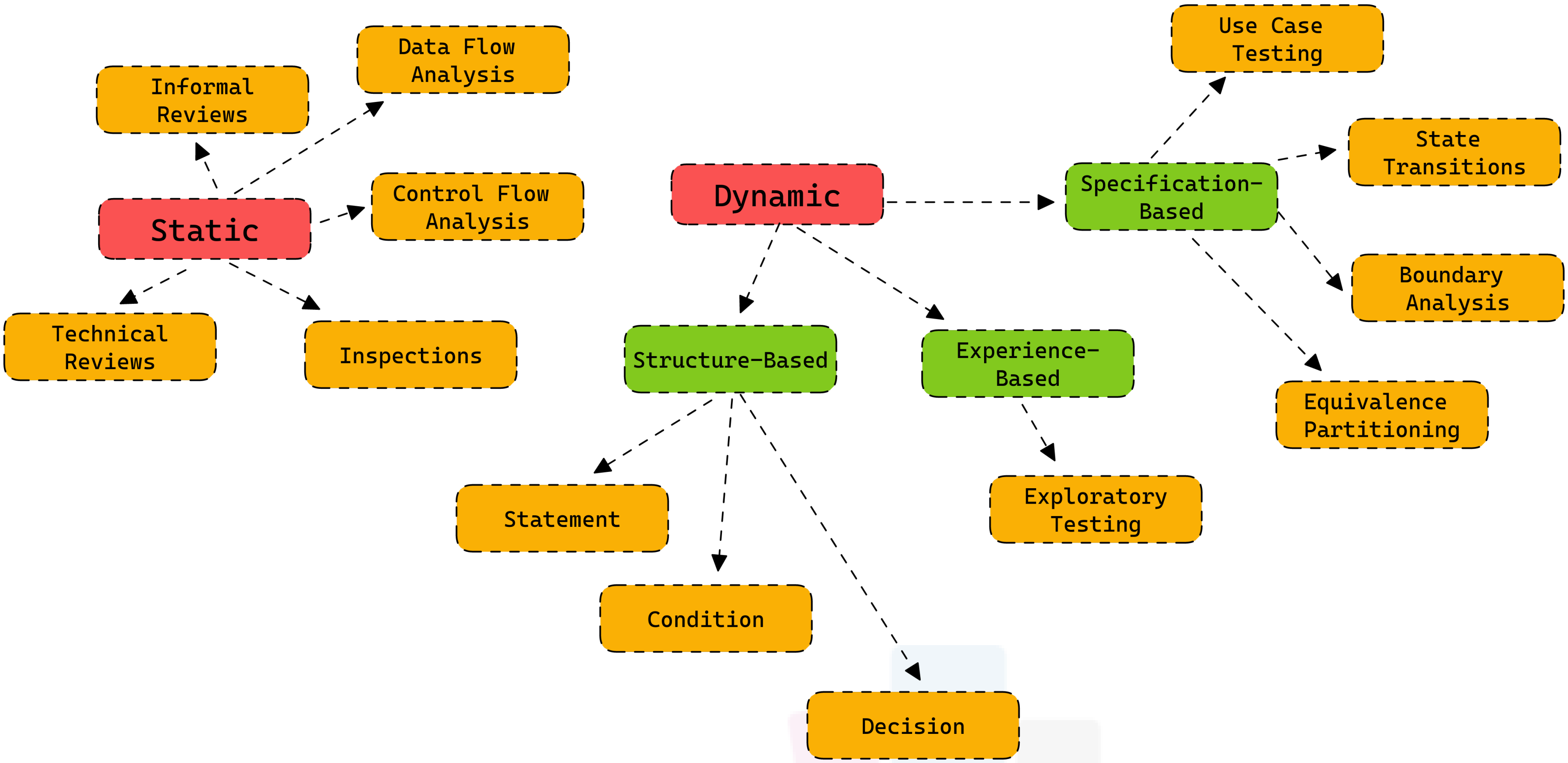
- **Learning from experience**: Each project provides information to improve the next project
- **Examples**

- Checklists are built on the basis of errors revealed in the past
- Error taxonomies can help in building better test selection criteria
- Design guidelines can avoid common pitfalls
- Using a software reliability model fitting past project data
- Looking for problematic modules based on prior knowledge

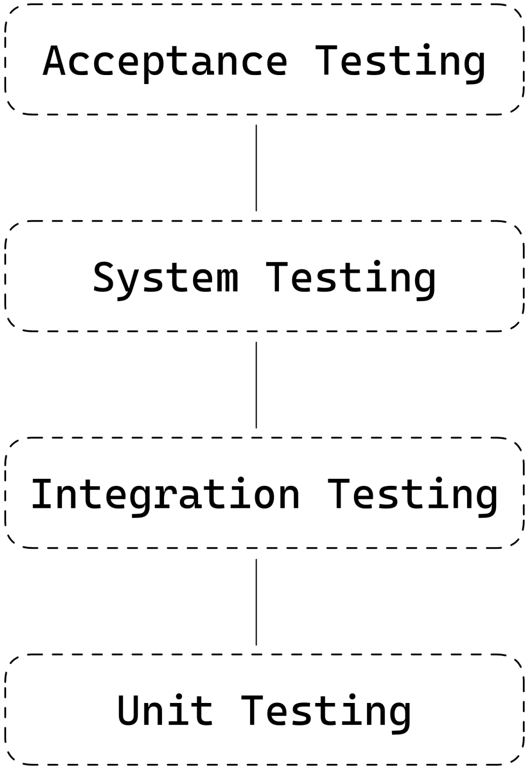


Testing Levels & Techniques

Testing Design Techniques



Testing Levels (1/2)



Acceptance Testing

A system is tested for acceptability. Aim: **evaluate the system's compliance with the business requirements and ready for delivery**.

System Testing

A complete, integrated system/software is tested. Aim: **evaluate the system's compliance with the specified requirements**

Integration Testing

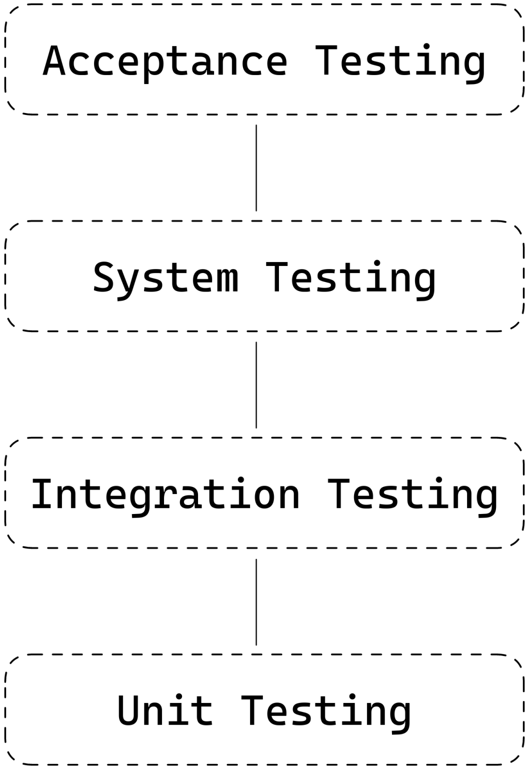
Individual units are combined and tested as a group. Aim: **expose faults in the interaction between integrated units**

Unit Testing

A level of the software testing process where individual units/components of a software/system are tested – **Validate that each unit performs as designed**

http://softwaretestingfundamentals.com/software-testing-levels/

Testing Levels (2/2)



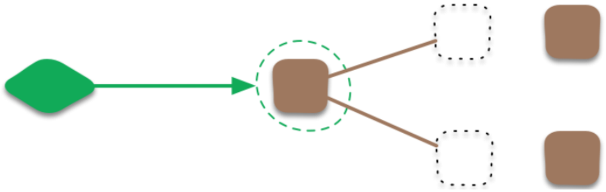
Acceptance Testing	BLACK BOX TESTING
System Testing	BLACK BOX TESTING
Integration Testing	BLACK BOX / WHITE BOX TESTING
Unit Testing	WHITE BOX TESTING

! Test Plans / Test cases are created *for each* level!

http://softwaretestingfundamentals.com/software-testing-levels/

Unit Testing

- **Unit Testing** is a process in which units (e.g., *classes*) are tested *independently* in *isolation* – tests must:
  - be **Fast**
  - be **Simple**
  - **not include duplication of implementation logic**
  - be **Readable**
  - be **Deterministic**
  - be **part of the build process**
  - use **Test Doubles** (e.g., mocks)
  - have **consistent naming conventions**



Img source: https://martinfowler.com/bliki/UnitTest.html

Unit Testing - Arrange, Act and Assert (AAA) Pattern

- **Arrange**: Set up the conditions for your test (e.g., create instances and set-up variables)
- **Act**: run the code under test
- **Assert**: verify the behaviour

```
# Arrange
MyStringUtils.init();

# Act
result = MyStringUtils.reverse(“Anna”);

# Assert
assertEquals(result, "annA"),
```

About Test Doubles

- **Test Double**[1]: a replacement for a dependent component or module that is used in a unit test
  - **Dummy objects”:** items passed around but never used (e.g., to fill parameter lists)
  - **Fake objects**: have working implementations but not suitable for production (e.g., an in-memory database)
  - **Stubs** provide constrained answers to calls made during the test, not responding to anything outside of the tests
  - **Spies:** stubs that also record information based on how they were called (e.g., stub email service that logs # emails sent)
  - **Mocks**: *“objects pre-programmed with expectations which form a specification of the calls they are expected to receive”*[2]

[1] Defined by Gerard Meszaros in the book "xUnit Test Patterns" (2007)

[2] For more details see: https://martinfowler.com/articles/mocksArentStubs.html

Integration Testing

- The goal of **Integration Testing** is to test *“whether many separately developed modules work together as expected”*
  - Differently than Unit tests, integration tests use external dependencies
  - Integration Tests verify several modules at once
  - Slower and more complex than Unit tests

See https://martinfowler.com/bliki/IntegrationTest.html

System Testing

- **Tests** that deal with the validation of the *complete* and *integrated* software system. The main categories:
  - **Usability Testing:** test the usability / UI of the system so that they meet the requirements
  - **Load/Stress Testing:** verify the system under heavy loads
  - **Performance**: verify the performance of the system, if complies to the requirements
  - **Functional Testing:** focuses more on the requirements side: checking for functionality that might be missing
  - **Security Testing:** identify vulnerabilities of the system (security should be embedded from the beginning, see *Security by Design*)

There can be more sub-categories: *installation/deployment* testing, *documentation* testing, *migration* testing, etc...

Acceptance Tests (1/2)

Acceptance Tests ensure that a software system meets the requirements from the customer

Example: using Fitnesse (http://fitnesse.org) to write acceptance tests so that the customer can actually write the acceptance conditions for the software

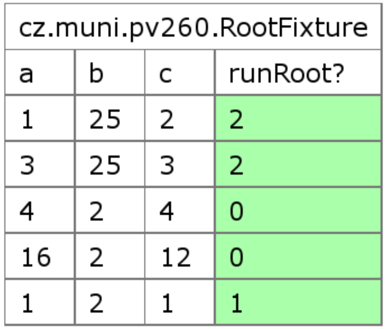
Looking at our previous example the “root” case

$$ax^2+bx+c=0$$

That we solve by means of

$$x=\frac{-b\pm\sqrt{b^2-4ac}}{2a}$$

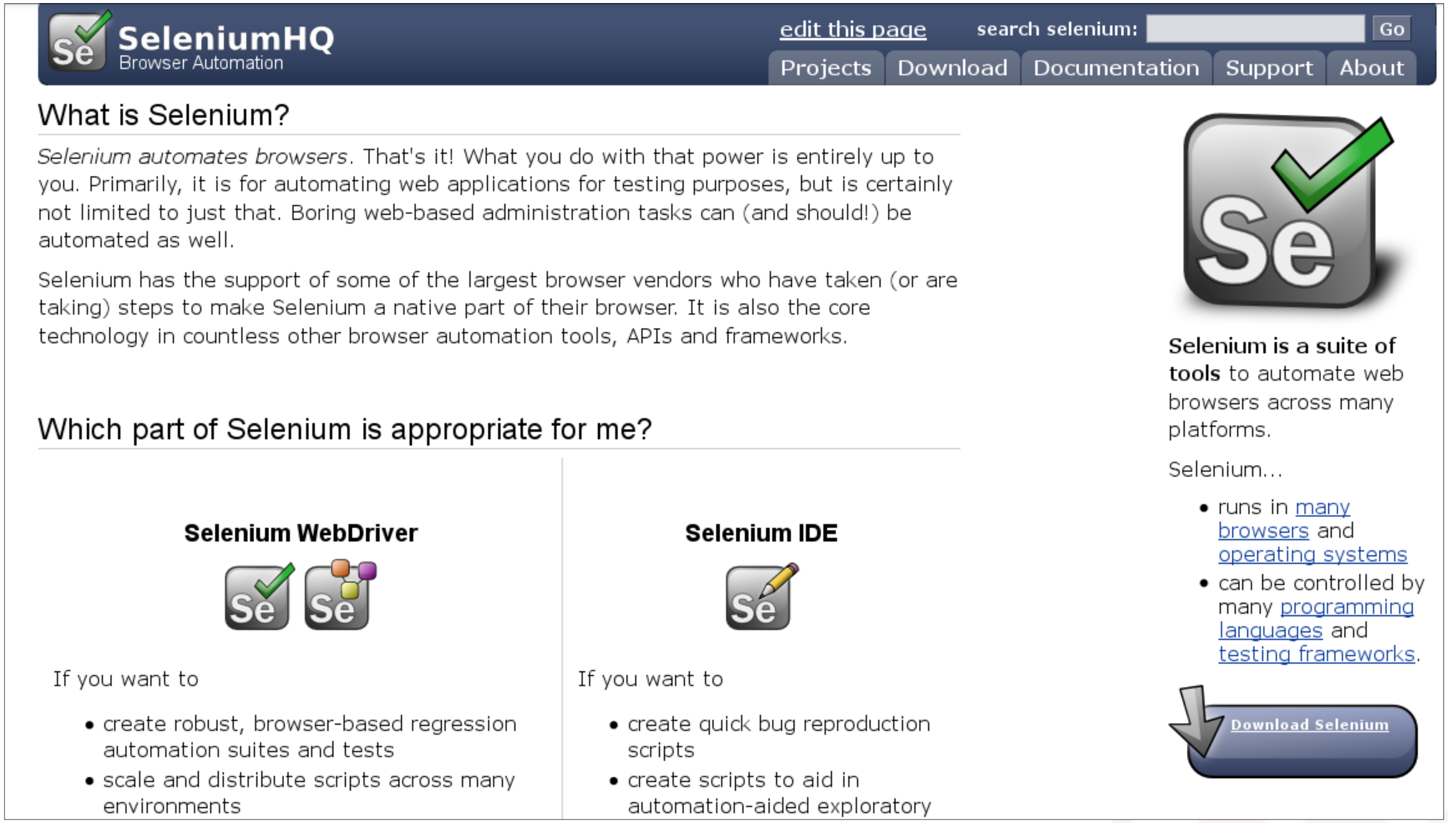
The **customer** can write what he expects from the implementation



cz.muni.pv260.RootFixture			
a	b	c	runRoot?
1	25	2	2
3	25	3	2
4	2	4	0
16	2	12	0
1	2	1	1

Acceptance Tests (2/2)

Other frameworks are available for **automation** of acceptance testing, like Selenium (https://www.seleniumhq.org) for web-based acceptance testing



What is Selenium?

Selenium automates browsers. That's it! What you do with that power is entirely up to you. Primarily, it is for automating web applications for testing purposes, but is certainly not limited to just that. Boring web-based administration tasks can (and should!) be automated as well.

Selenium has the support of some of the largest browser vendors who have taken (or are taking) steps to make Selenium a native part of their browser. It is also the core technology in countless other browser automation tools, APIs and frameworks.

Which part of Selenium is appropriate for me?

Selenium WebDriver

If you want to

- create robust, browser-based regression automation suites and tests
- scale and distribute scripts across many environments

Selenium IDE

If you want to

- create quick bug reproduction scripts
- create scripts to aid in automation-aided exploratory

Selenium is a suite of tools to automate web browsers across many platforms.

Selenium...

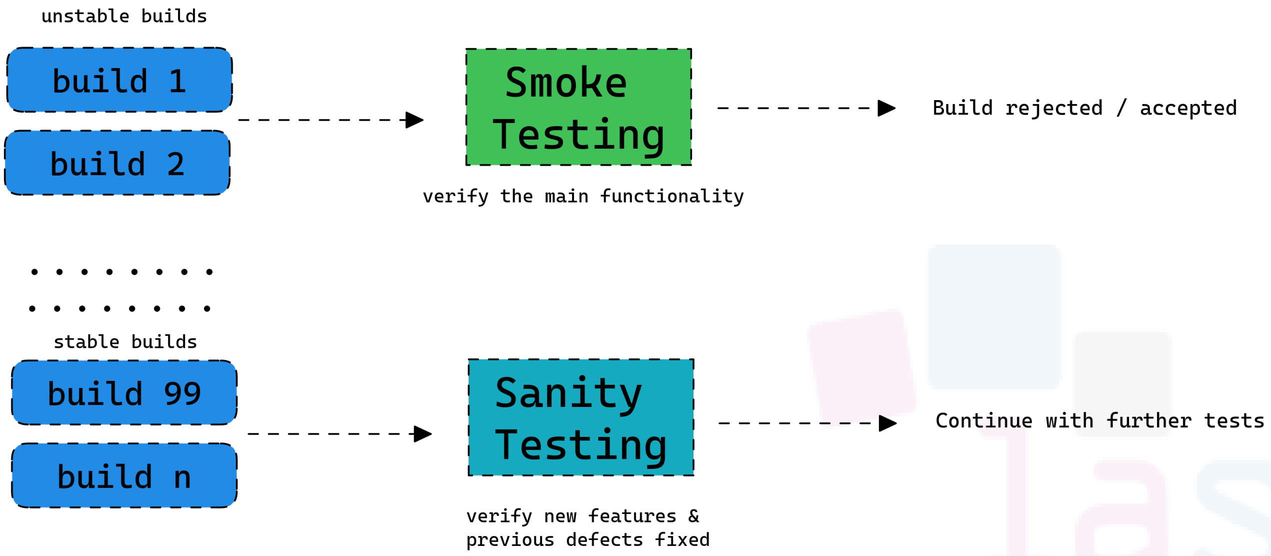
- runs in many browsers and operating systems
- can be controlled by many programming languages and testing frameworks.

Regression Testing

- **Regression Testing:** verify that no changes made during the development have caused new defects (or *old defects re-appearing*)
- This is a **cross-cutting** concept in relation to different test levels

Smoke Testing / Sanity Testing

- **Software Smoke Testing:** carried out to check whether the critical functionalities of a software application **in a new unstable build** are working properly
  - *If the smoke test fails, the build is rejected and not deployed*
- **Software Sanity Testing:** done to verify that a software application in **a new stable build** is working as expected and to go for further testing at other levels
  - *the goal is to catch issues as soon as possible*


unstable builds
build 1
build 2
Smoke Testing
verify the main functionality
Build rejected / accepted
stable builds
build 99
build n
Sanity Testing
verify new features & previous defects fixed
Continue with further tests

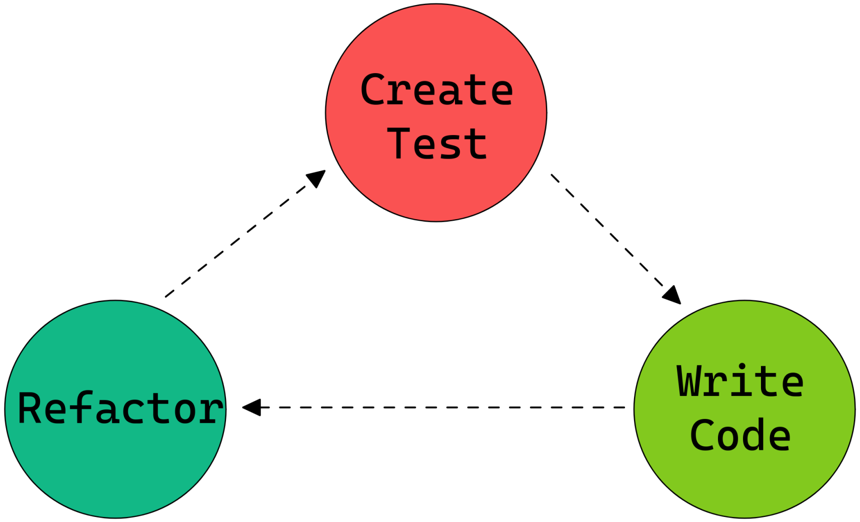
Exploratory Testing

- It is about learning, design tests and executing the tests
- Might trigger failures that systematic testing misses
- This is a kind a semi-manual test
  - **Completely freestyle**: no rules, just the judgment of the tester
  - **Strategy-based**: use common techniques (like *boundary checks*) together with the instinct of the tester
  - **Scenario-based**: start from the requirements and try to play those with variations

- This explains why there are videogame companies *paying* players to test their games – e.g., *“do the craziest things you will think about when playing the game”*

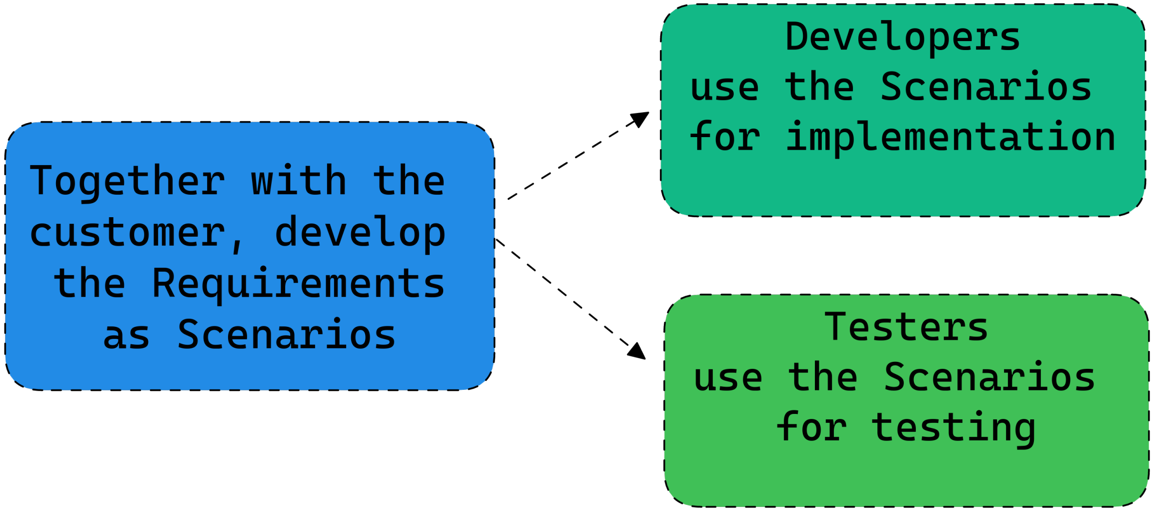
Test Driven Development (TDD)

1) Create a *failing* Test
2) Code it to make it pass
3) Refactor other code and tests



- Tests have to be:
  - **Fast**: short time to run
  - **Independent**: never depend on other tests, components, db, etc...
  - **Repeatable**: they must be deterministic
  - **Self-checking**: a test must be able to check its own state
  - **Timely**: test **must** come first than the implementation

Behaviour Driven Development (BDD) (1/2)



Together with the customer, develop the Requirements as Scenarios

Developers use the Scenarios for implementation

Testers use the Scenarios for testing

Behaviour Driven Development (BDD) (2/2)

- Run tests based on scenarios according to **Given**, **When**, **Then** constructs

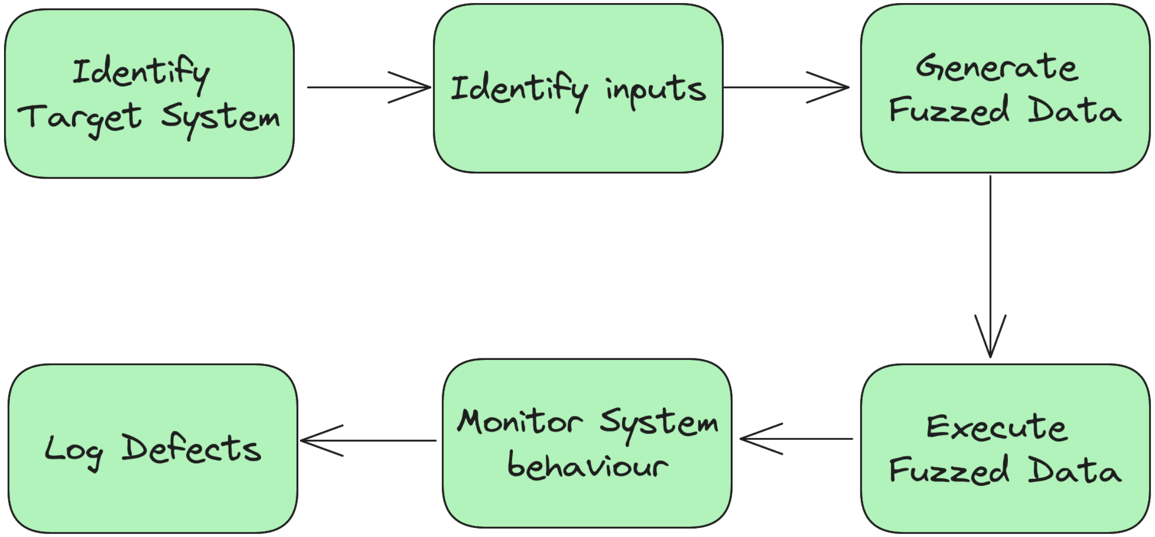
```
Scenario: When a user adds a product to the shopping cart, the product should be
included in the user's shopping cart.
Given a user
Given a shopping cart
Given a product
When the user adds the product to the shopping cart
Then the product must be included in the list of the shoppingcart's entries
```

```
@Given("a user")
public void aUser() {
     user = new User();
}
@Given("a shopping cart")
public void aShoppingCart() {
     shoppingCart = new ShoppingCart();
}
@Given("a product")
public void aProduct() {
     product = new Product("Coffee");
}
@When("the user adds the product to the shopping cart")
public void userAddsProductToTheShoppingCart() {
     ShoppingCart.add(user, product);
}
@Then("the product must be included in the list of the shoppingcart's entries")
public void productMustBeListed() {
     List<Product> entries = shoppingCart.getProductsByUser(user);
     Assert.assertTrue(entries.contains(product));
}
```

Fuzzing & Metamorphic Testing

Software Fuzzing or Fuzz Testing (1/3)

- A testing technique to inject **invalid**, **malformed**, or **unexpected inputs** into a system to **reveal software failures and crashes**

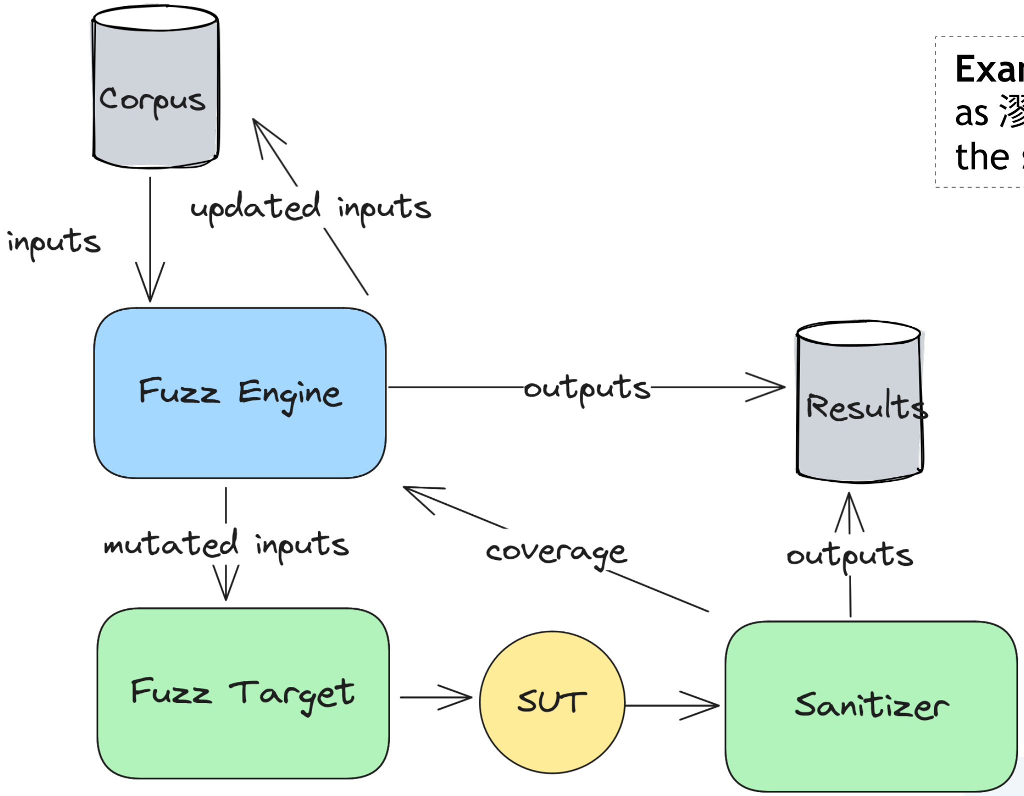


> If you are developing a software of a certain importance, somebody is (likely) fuzzing your system to try to discover vulnerabilities (e.g., buffer overflows) that can be exploited

See https://www.fuzzingbook.org/html/Fuzzer.html

Software Fuzzing or Fuzz Testing (2/3)

- Typical structure of a fuzzer:



SUT = System Under Test

Example: testing the output for inputs such as 漻猴揩秇甄奥轼 \u0dcc\udb87 胮 → will the system crash?

Software Fuzzing or Fuzz Testing (3/3)

- Suggested video to watch - at home :)

https://www.youtube.com/watch?v=eg7SiXr31Qk

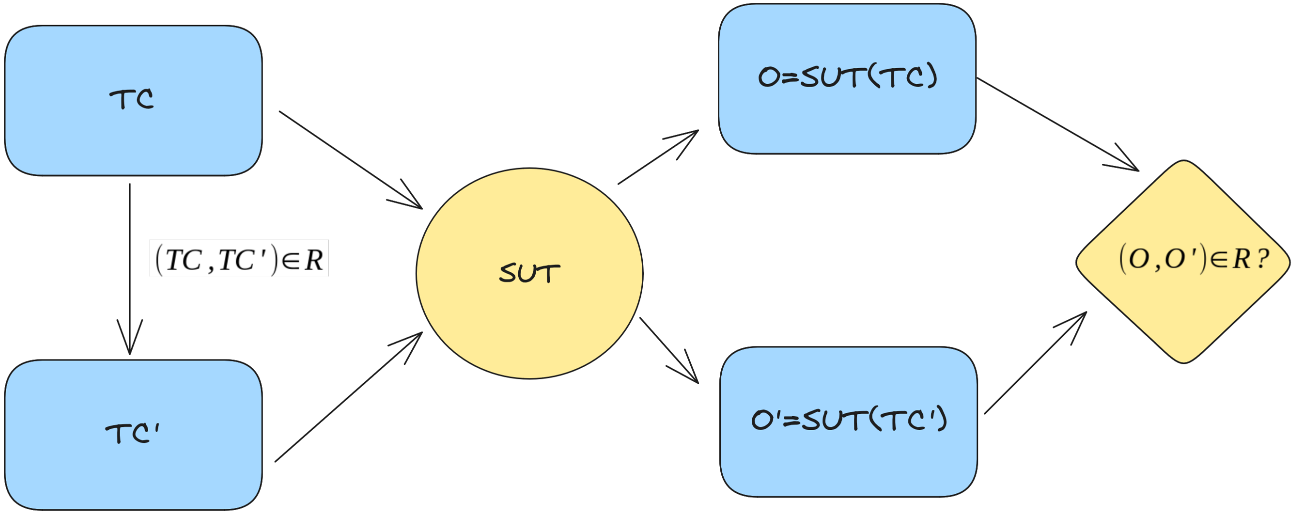
Metamorphic Testing (1/3)

- **Metamorphic testing:** test cases are designed based on the **relationships** between the input and output of the system under test rather than on specific input-output pairs
- Check whether the expected relationships or properties still hold after applying the transformations to the inputs
- The **test oracle problem** becomes more like to check if the *metamorphic relations* hold

For a very interesting discussion about testing ML models with metamorphic testing, see:
https://towardsdatascience.com/metamorphic-testing-of-machine-learning-based-systems-e1fe13baf048

Metamorphic Testing (2/3)

- In summarized form:



SUT = System Under Test
TC = Test Case

Metamorphic Testing (3/3)

- Example: Suppose we have a program `P` that computes the shortest path between two edges (`a,b`) in an undirected graph (`G`)

  `P(G,a,b)`

- It is generally **unfeasible** to test whether the output of P is really the shortest path
- A metamorphic relation can be derived as follows: if we *swap* a,b the output has to be the same
- We can test for `|P(G,b,a)| = |P(G,a,b)|`

  `e.g., {c,f,h,l,j} ≠ {c,d,e,f,h,l,j}`

See Chen, Tsong Yueh, et al. "Metamorphic testing: A review of challenges and opportunities." ACM Computing Surveys (CSUR) 51.1 (2018): 1-27.

Question Time

- Can Fuzzing and Metamorphic Testing be combined?
- What would be the advantages?

Quality of Software Tests – Mutation Testing

Estimating Software Test Suite Quality

- What if we could judge the effectiveness of a test suite in finding real faults, by measuring how well it finds **seeded fake faults**?
- How can **seeded faults** be representative of real defects?

Example: I add **100 new defects** to my application

- they are exactly like real defects in every way
- I make **100 copies** of my program, **each** with one of my **100 new defects**

I run my test suite on the programs with seeded defects ...

- ... and the tests reveal 20 of the defects
- (the other 80 program copies do not fail)

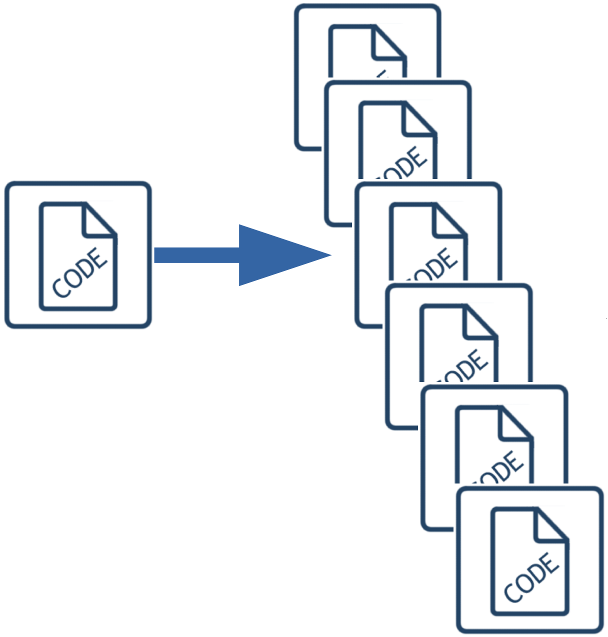
→ **What can I infer about my test suite?**

Mutation Testing Assumptions

- Competent programmer hypothesis:
  - Programs are “nearly” correct
    - Real faults are **small variations from the correct program**
    - → Mutants are reasonable models of real buggy programs
- Coupling effect hypothesis:
  - Tests that find **simple faults also find more complex faults**
    - Even if mutants are not perfect representatives of real faults, a test suite that kills mutants is good at finding real faults too

How Mutation Testing works (1/3)

- Create many **modified copies** of the original program called **mutants** Each mutant with a single variation from the original program.



- Mutation Process: application of **mutation operators**, such as statement deletions, statement modifications (e.g. != instead of ==)

Algorithm 1: Original Code

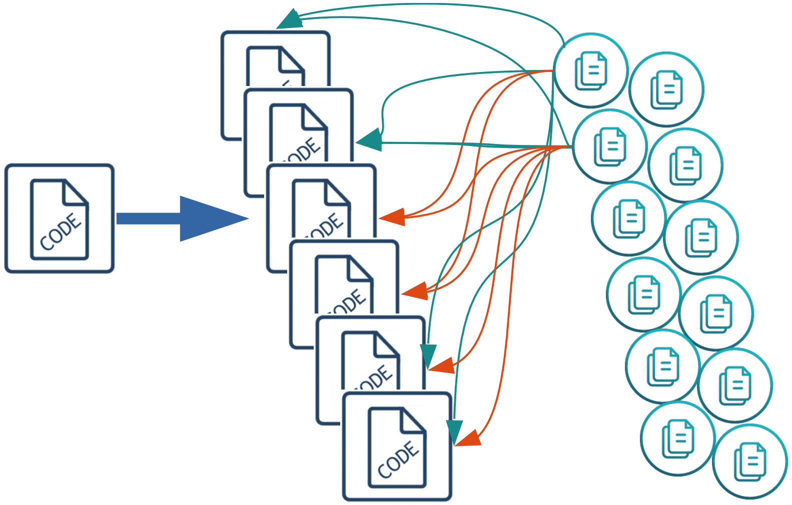
```
if $(a == b)$ then
    // do something
else
    // do something
```

Algorithm 2: Mutated Code

```
if $(a != b)$ then
    // do something
else
    // do something
```

How Mutation Testing works (2/3)

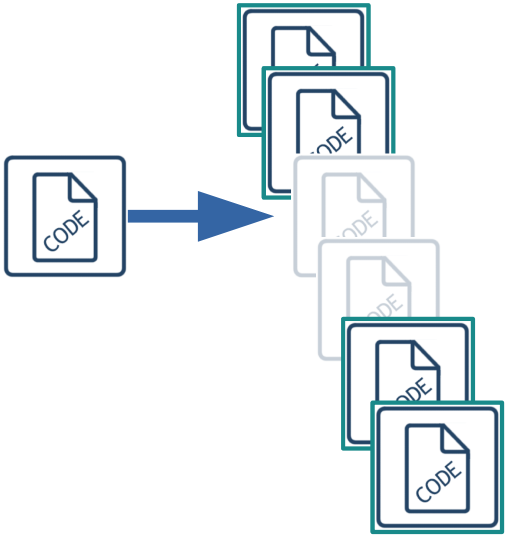
- All **mutants** are then tested by test suites to get the percentage of mutants failing the tests



- The failure of mutants is expected!
- If mutants do not cause tests to fail, they are considered **live mutants**

How Mutation Testing works (3/3)

- All **mutants** are then tested by test suites to get the percentage of mutants failing the tests



- The number of **live mutants** can be a sign of:
  - i) **tests are not sensitive enough** to catch the modified code
  - ii) there are **equivalent mutants**

e.g. original program

```
 if (x==2 && y==2){
      int z = x+y;
  }
```

equiv mutant

```
if (x==2 && y==2){
   int z = x*y;
  }
```

Mutation Score as indication of the tests quality:

$$M_{Score} = \frac{M_{killed}}{M_{tot} - M_{eq}}$$

Mutation Operators

- Syntactic change from legal program to legal program
  - Specific to each programming language. C++ mutations don't work for Java, Java mutations don't work for Python
- Examples:
  - crp: constant for constant replacement
    - for instance: from (x < 5) to (x < 12)
    - select from constants found somewhere in program text
  - ror: relational operator replacement
    - for instance: from (x <= 5) to (x < 5)
  - vie: variable initialization elimination
    - change int x =5; to int x;

Problems of Mutation Testing

- Mutation testing has not yet widely adopted for a series of reasons, mainly:
  - **Performance** reasons
  - The **equivalent mutants** problem
  - Missing **integration tools**
  - **Benefits** might not be immediately clear

$$M_{Score} = \frac{M_{killed}}{M_{tot} - M_{eq}}$$

Equivalent mutants problem: determining **syntactically different** but **semantically equal** mutant is **undecidable**

Weak Mutation

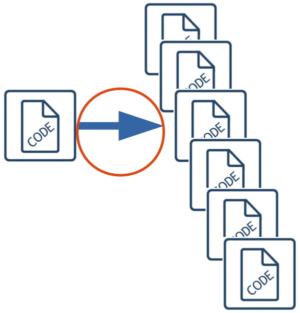
- Problem: *There are lots of mutants. Running each test case to completion on every mutant is expensive*
    - Number of mutants grows with the square of program size
- Approach:
    - Execute **meta-mutant** (with many seeded faults) together with original program
    - Mark a seeded fault as “killed” as soon as a difference in intermediate state is found
        - Without waiting for program completion
        - Restart with new mutant selection after each “kill”

Statistical Mutation

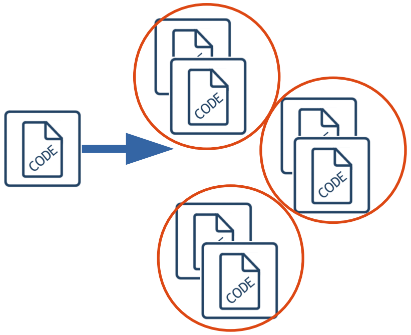
- Problem: *There are lots of mutants. Running each test case on every mutant is expensive*
    - It's just too expensive to create N^2 mutants for a program of N lines (even if we don't run each test case separately to completion)
- Approach: Just create a **random sample** of mutants
    - May be just as good for *assessing* a test suite
        - Provided we don't design test cases to kill particular mutants

Other Optimization Approaches

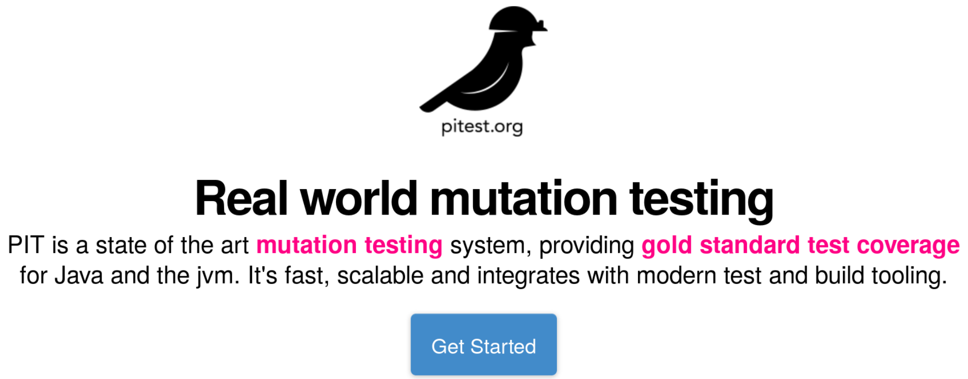
- **Selective mutation:** reduce the number of active operators selecting only the most efficient operators → produce mutants not easy-to-kill



- **Second Order Strategies:** combining more than a single mutation, putting together First Order Mutants (different sub-strategies to combine them)



Sample Demo with PiTest



Real world mutation testing

PIT is a state of the art **mutation testing** system, providing **gold standard test coverage** for Java and the jvm. It's fast, scalable and integrates with modern test and build tooling.

Risk-based Testing

Test Case Definition

According to ISO/IEC/IEEE 29119 Testing Standard:

Test Case Specification: “(A) A set of **test inputs**, **execution conditions**, and **expected results** developed for a particular objective, such as to **exercise a particular program path** or to **verify compliance with a specific requirement**. (B) A document specifying **inputs**, **predicted results**, and a **set of execution conditions** for a **test item**”

Example:

1. Open the browser

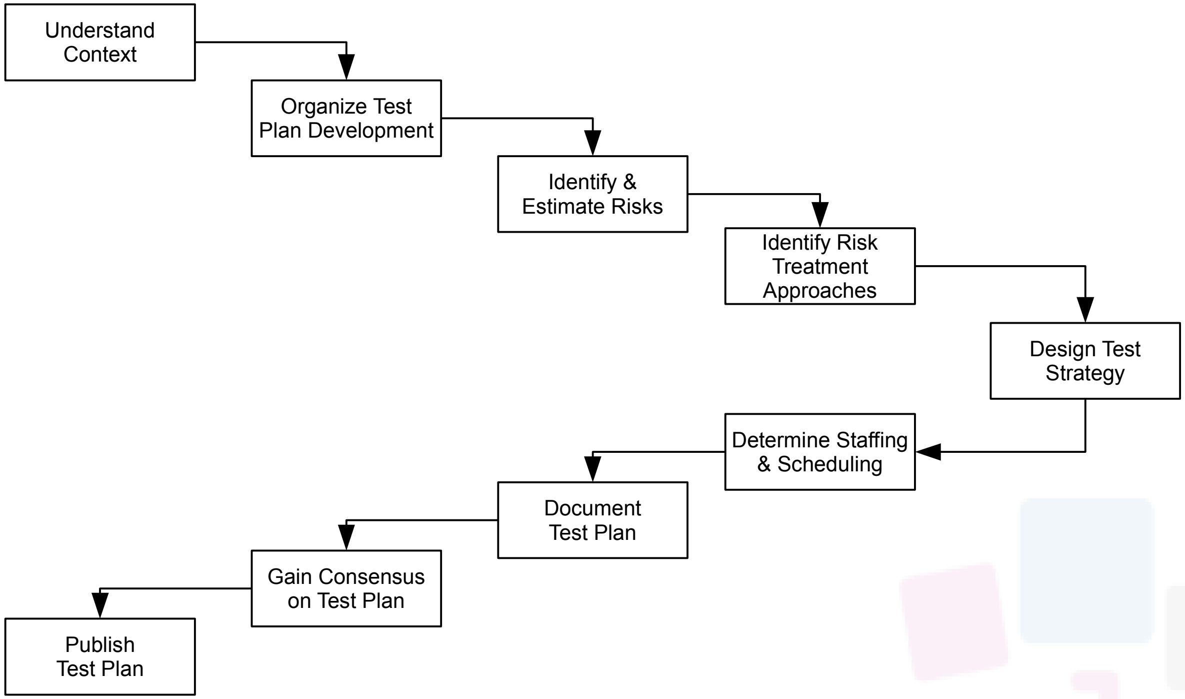
2. Go to shopping cart page (pre-conditions: user is logged-in, no items are in the shopping cart, the check-out button is not available)

3. Add item “x” → exp result: i) the page is updated with the new item, ii) the check-out button becomes available

4. Remove item “x” → exp result: i) no items are listed, ii) the check-out button is not available

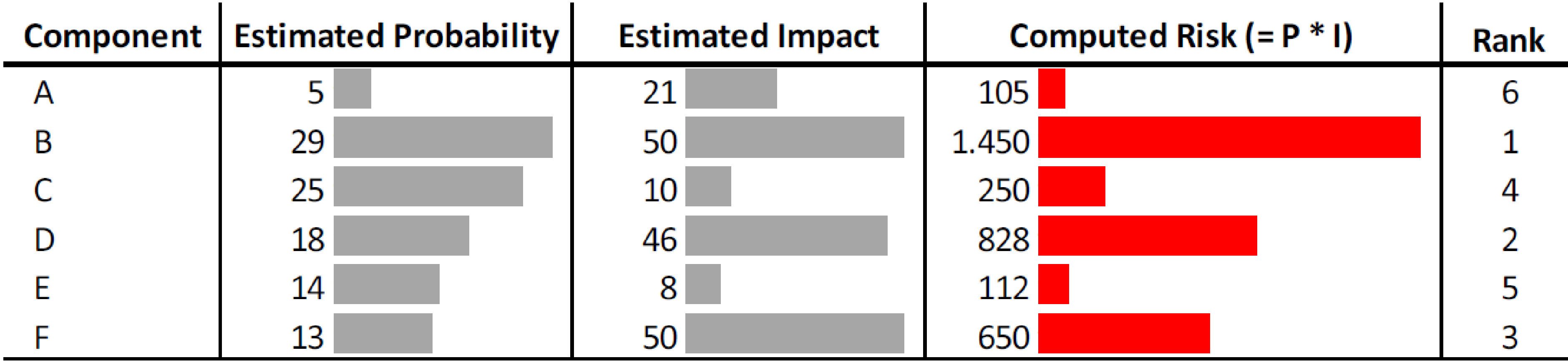
Tests Prioritization - Risk Analysis

- **Risk analysis** deals with the **identification of the risks** (*damage* and *probabilities*) in the software testing process and in the prioritization of the test cases
- ISO/IEC/IEEE 29119 Testing Standard from 2022 suggests to adopt Risk-based testing


Understand Context
Organize Test Plan Development
Identify & Estimate Risks
Identify Risk Treatment Approaches
Design Test Strategy
Determine Staffing & Scheduling
Document Test Plan
Gain Consensus on Test Plan
Publish Test Plan

Steps for Risk Analysis (1/3)

1. Define the risk items (e.g. type of failures for components)
2. Define probability of occurrence
3. Estimate impact
4. Compute Risk Values

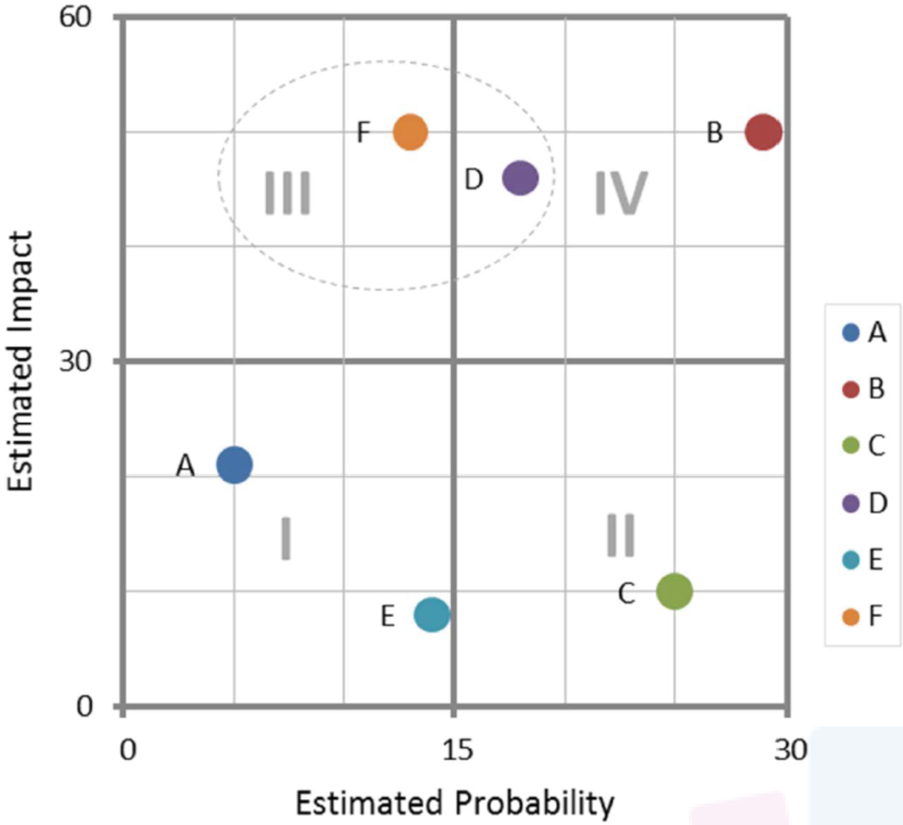


Component	Estimated Probability	Estimated Impact	Computed Risk (= P * I)	Rank
A	5	21	105	6
B	29	50	1.450	1
C	25	10	250	4
D	18	46	828	2
E	14	8	112	5
F	13	50	650	3

M. Felderer, “Development of a Risk-Based Test Strategy and its Evaluation in Industry”, PV226 Lasaris Seminar, 3rd Nov 2016.

Steps for Risk Analysis (2/3)

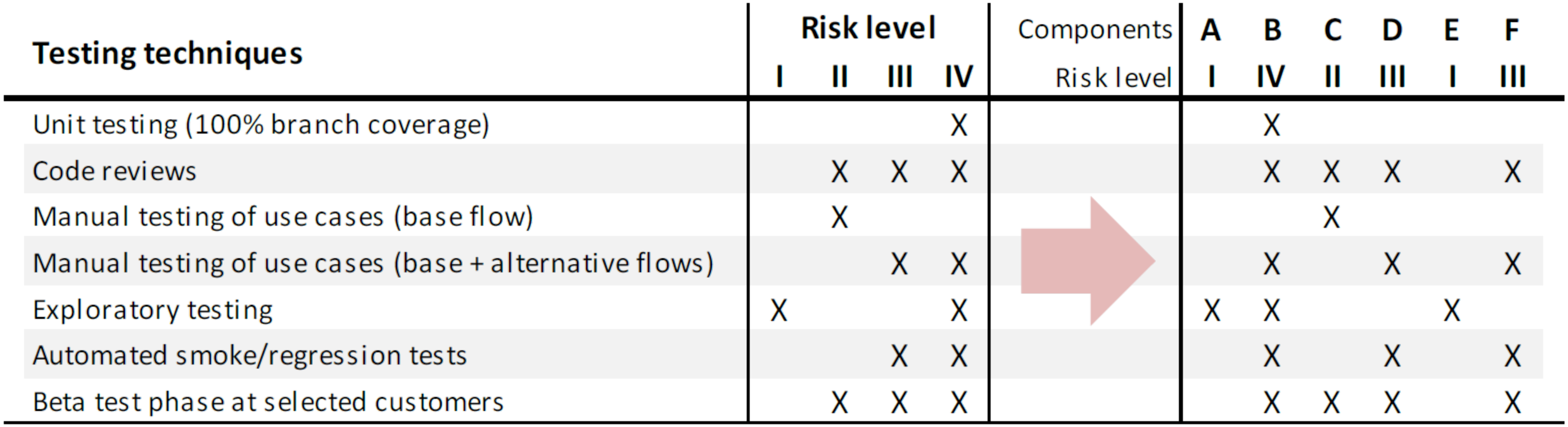
5. Determine Risk levels



M. Felderer, “Development of a Risk-Based Test Strategy and its Evaluation in Industry”, PV226 Lasaris Seminar, 3rd Nov 2016.

Steps for Risk Analysis (3/3)

6. Definition and Refinement of Test Strategy



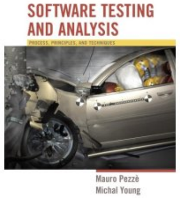
Testing techniques	Risk level				Components	A	B	C	D	E	F
	I	II	III	IV	Risk level	I	IV	II	III	I	III
Unit testing (100% branch coverage)				X			X				
Code reviews		X	X	X			X	X	X		X
Manual testing of use cases (base flow)		X						X			
Manual testing of use cases (base + alternative flows)			X	X			X		X		X
Exploratory testing	X			X		X	X			X	
Automated smoke/regression tests			X	X			X		X		X
Beta test phase at selected customers		X	X	X			X	X	X		X

M. Felderer, “Development of a Risk-Based Test Strategy and its Evaluation in Industry”, PV226 Lasaris Seminar, 3rd Nov 2016.

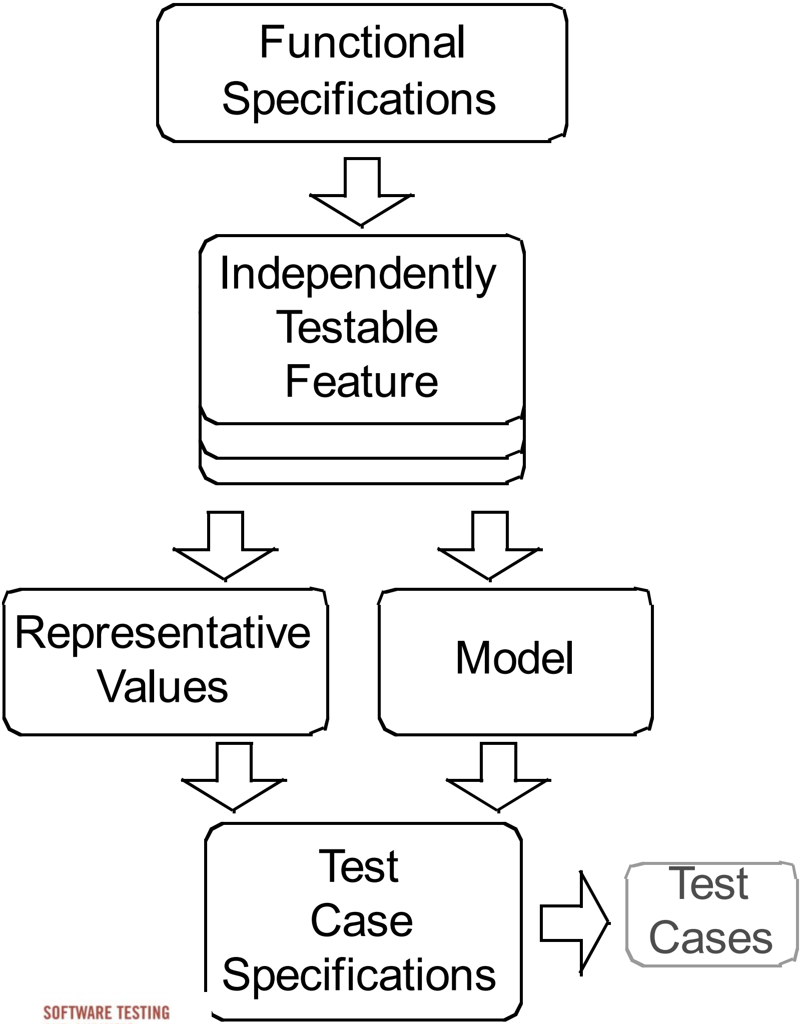
Functional (Black Box) Testing

Specification-based / Functional Testing

- **Functional testing:** Deriving test cases from program specifications (Functional specification = description of intended program behavior)
  - *Program code is* ***not*** *necessary*
  - *Functional* **refers to the source of information** used in test case design, not to what is tested
- *Also known as*:
  - specification-based testing (from specifications)
  - black-box testing (no view of the code)
- Functional testing is best for **missing logic faults**
  - A common problem: Some program logic was simply **forgotten**
  - Structural (code-based) testing will **not** focus on code that is not there!

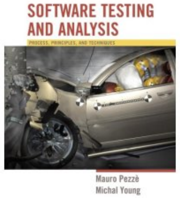


Steps: from specifications to test cases



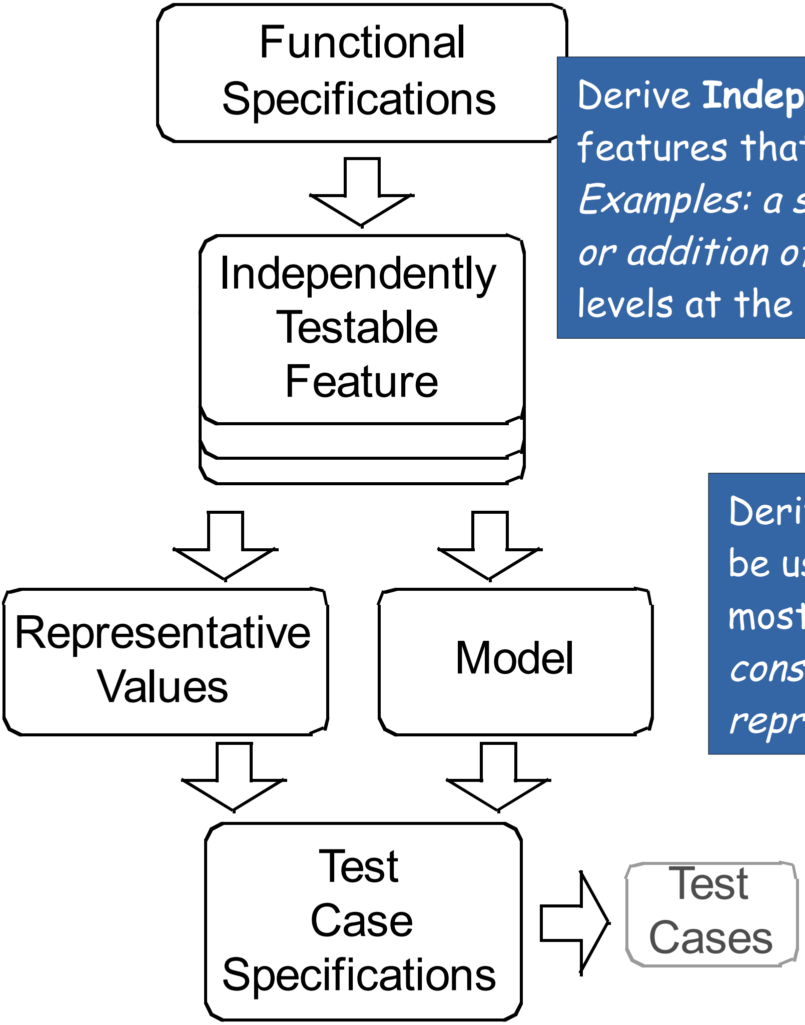
1. Decompose the specification
   - If the specification is large, break it into ***independently testable features*** to be considered in testing
2. Select representatives
   - Representative values of each input, or

     Representative behaviors of a *model*
     - Often simple input/output transformations don't describe a system. We use models in program specification, in program design, and in test design
3. Form test specifications
   - Typically: combinations of input values, or model behaviors
4. Produce and execute actual tests



(c) 2007 Mauro Pezzè & Michal Young

Steps: from specifications to test cases



Functional Specifications

Independently Testable Feature

Representative Values

Model

Test Case Specifications

Test Cases

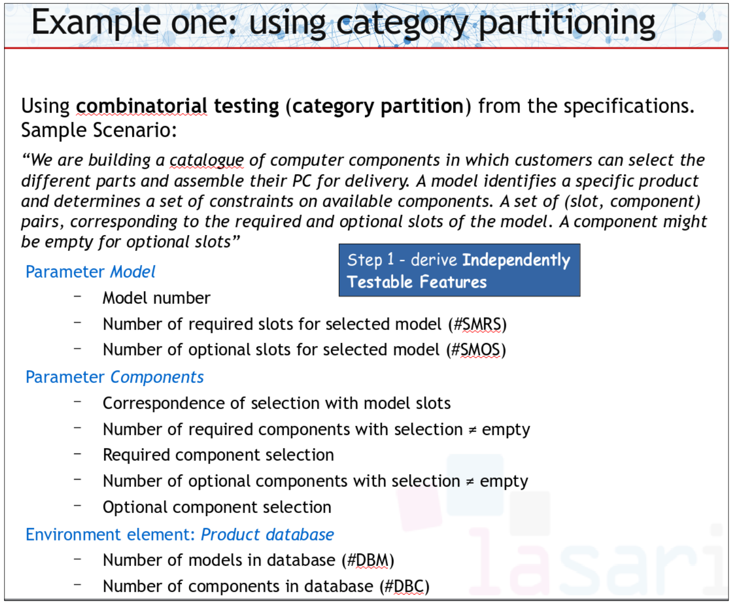
Derive **Independently Testable Features**: identify features that can be tested separately *Examples: a search functionality on a web application or addition of new users* → this may map to different levels at the design and code level

NOTE: this helps also in determining if there are requirements that are not testable or need to be rewritten or clarified!

Derive **Representative values OR a model** that can be used to derive test cases. Note that this phase is mostly enumeration of values in isolation. *Example: considering empty list or a one element list as representative cases*

Generation of test case specification based on the previous step, usually based on the Cartesian product from the enumeration values (considering feasible cases). *Example: the search functionality, representative values might be 0,1, many characters and 0,1, many special characters, but the case {0,many} is clearly impossible*

Example: using category partitioning (1/2)



Example one: using category partitioning

Using **combinatorial testing** (**category partition**) from the specifications.
Sample Scenario:

"We are building a catalogue of computer components in which customers can select the different parts and assemble their PC for delivery. A model identifies a specific product and determines a set of constraints on available components. A set of (slot, component) pairs, corresponding to the required and optional slots of the model. A component might be empty for optional slots"

Step 1 - derive **Independently Testable Features**

Parameter *Model*

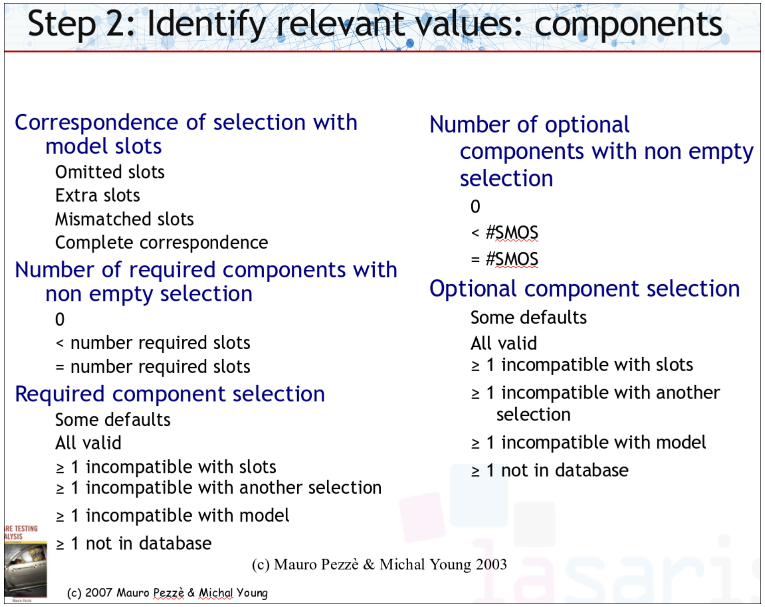
- Model number
- Number of required slots for selected model (#SMRS)
- Number of optional slots for selected model (#SMOS)

Parameter *Components*

- Correspondence of selection with model slots
- Number of required components with selection ≠ empty
- Required component selection
- Number of optional components with selection ≠ empty
- Optional component selection

Environment element: *Product database*

- Number of models in database (#DBM)
- Number of components in database (#DBC)



Step 2: Identify relevant values: components

Correspondence of selection with model slots

- Omitted slots
- Extra slots
- Mismatched slots
- Complete correspondence

Number of required components with non empty selection

- 0
- < number required slots
- = number required slots

Required component selection

- Some defaults
- All valid
- ≥ 1 incompatible with slots
- ≥ 1 incompatible with another selection
- ≥ 1 incompatible with model
- ≥ 1 not in database

Number of optional components with non empty selection

- 0
- < #SMOS
- = #SMOS

Optional component selection

- Some defaults
- All valid
- ≥ 1 incompatible with slots
- ≥ 1 incompatible with another selection
- ≥ 1 incompatible with model
- ≥ 1 not in database

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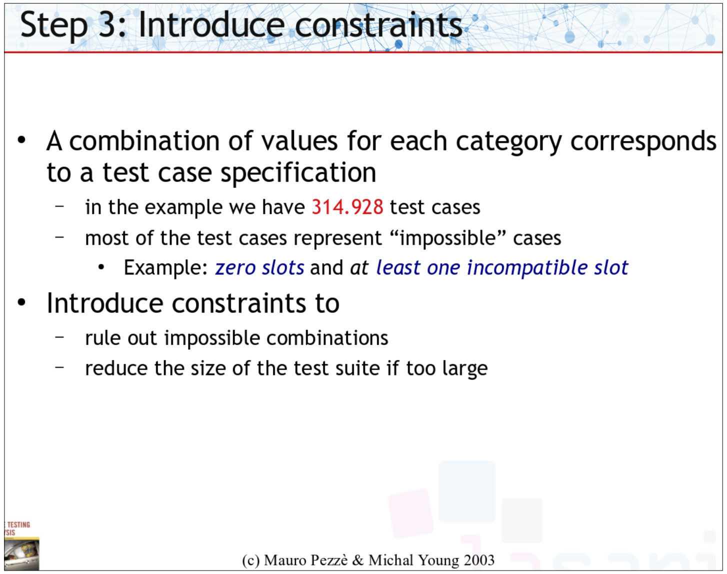

Step 3: Introduce constraints

- A combination of values for each category corresponds to a test case specification
  - in the example we have 314.928 test cases
  - most of the test cases represent "impossible" cases
    - Example: *zero slots* and *at least one incompatible slot*
- Introduce constraints to
  - rule out impossible combinations
  - reduce the size of the test suite if too large

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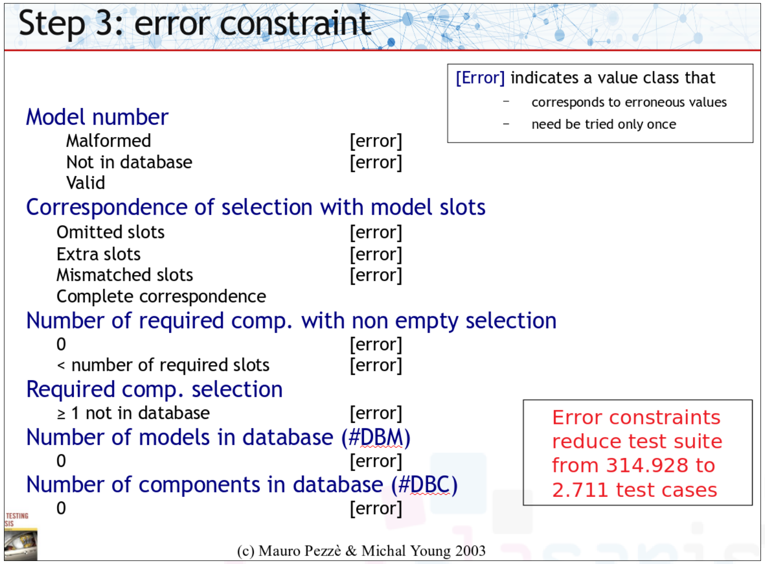

Step 3: error constraint

[Error] indicates a value class that

- corresponds to erroneous values
- need be tried only once

Model number	
Malformed	[error]
Not in database	[error]
Valid	
Correspondence of selection with model slots	
Omitted slots	[error]
Extra slots	[error]
Mismatched slots	[error]
Complete correspondence	
Number of required comp. with non empty selection	
0	[error]
< number of required slots	[error]
Required comp. selection	
≥ 1 not in database	[error]
Number of models in database (#DBM)	
0	[error]
Number of components in database (#DBC)	
0	[error]

Error constraints reduce test suite from 314.928 to 2.711 test cases

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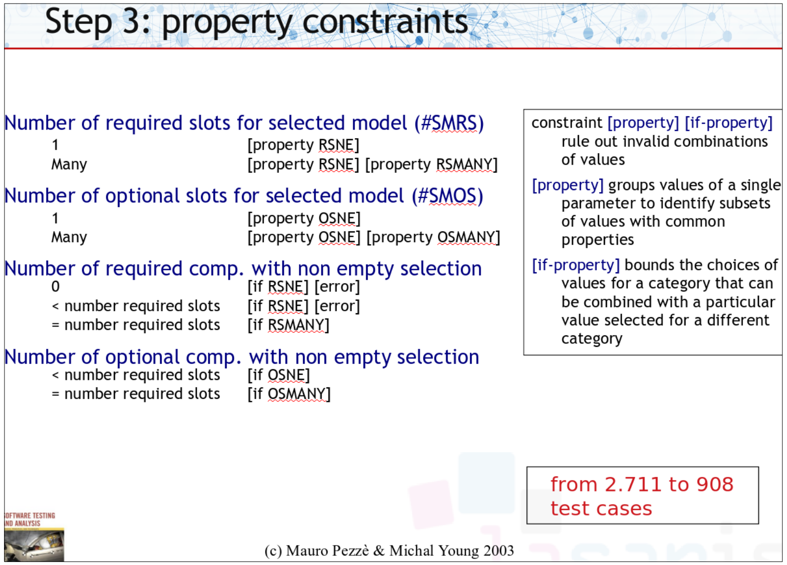
Example: using category partitioning (2/2)



Step 3: property constraints

Number of required slots for selected model (#SMRS)

1	[property RSNE]
Many	[property RSNE] [property RSMANY]

Number of optional slots for selected model (#SMOS)

1	[property OSNE]
Many	[property OSNE] [property OSMANY]

Number of required comp. with non empty selection

0	[if RSNE] [error]
< number required slots	[if RSNE] [error]
= number required slots	[if RSMANY]

Number of optional comp. with non empty selection

< number required slots	[if OSNE]
= number required slots	[if OSMANY]

constraint [property] [if-property] rule out invalid combinations of values

[property] groups values of a single parameter to identify subsets of values with common properties

[if-property] bounds the choices of values for a category that can be combined with a particular value selected for a different category

from 2.711 to 908 test cases

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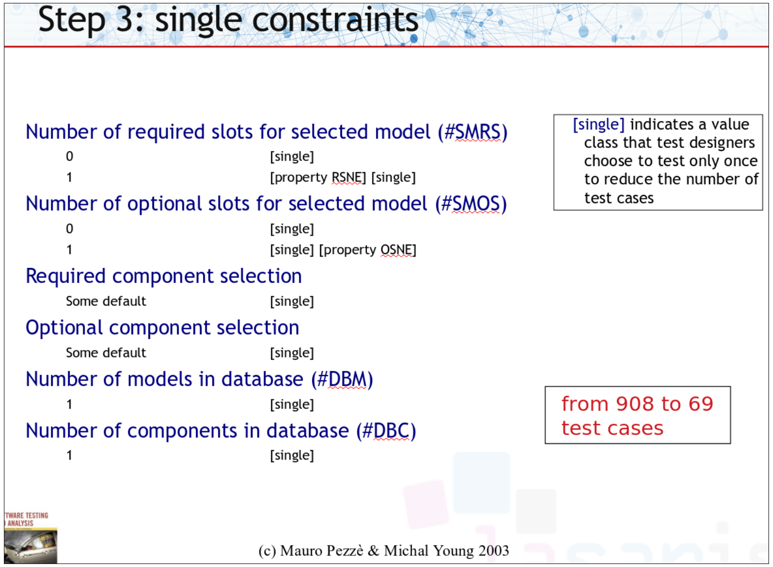

Step 3: single constraints

Number of required slots for selected model (#SMRS)

0	[single]
1	[property RSNE] [single]

Number of optional slots for selected model (#SMOS)

0	[single]
1	[single] [property OSNE]

Required component selection

Some default	[single]

Optional component selection

Some default	[single]

Number of models in database (#DBM)

1	[single]

Number of components in database (#DBC)

1	[single]

[single] indicates a value class that test designers choose to test only once to reduce the number of test cases

from 908 to 69 test cases

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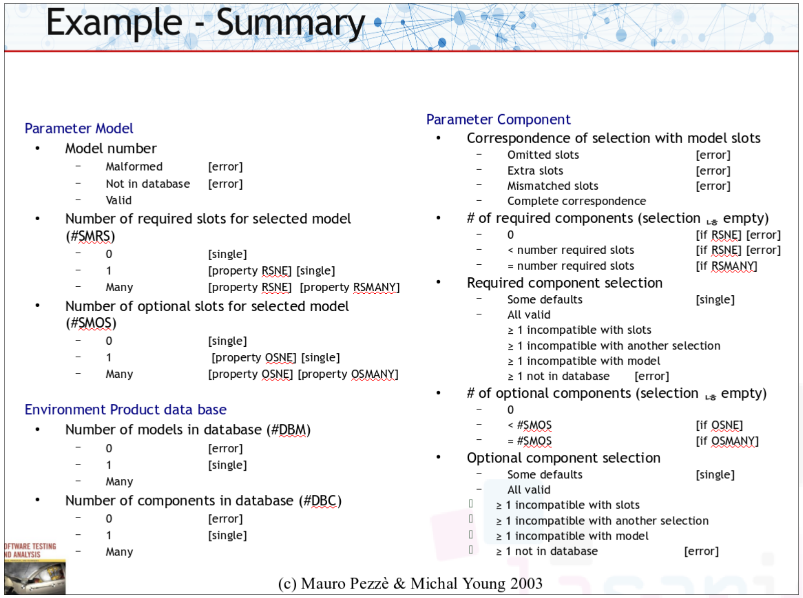

Example - Summary

Parameter Model

- Model number

– Malformed	[error]
– Not in database	[error]
– Valid	

- Number of required slots for selected model (#SMRS)

– 0	[single]
– 1	[property RSNE] [single]
– Many	[property RSNE] [property RSMANY]

- Number of optional slots for selected model (#SMOS)

– 0	[single]
– 1	[property OSNE] [single]
– Many	[property OSNE] [property OSMANY]

Environment Product data base

- Number of models in database (#DBM)

– 0	[error]
– 1	[single]
– Many	

- Number of components in database (#DBC)

– 0	[error]
– 1	[single]
– Many	

Parameter Component

- Correspondence of selection with model slots

– Omitted slots	[error]
– Extra slots	[error]
– Mismatched slots	[error]
– Complete correspondence	

- # of required components (selection ㄴ홍 empty)

– 0	[if RSNE] [error]
– < number required slots	[if RSNE] [error]
– = number required slots	[if RSMANY]

- Required component selection

– Some defaults	[single]
– All valid	
≥ 1 incompatible with slots	
≥ 1 incompatible with another selection	
≥ 1 incompatible with model	
≥ 1 not in database	[error]

- # of optional components (selection ㄴ홍 empty)

– 0	
– < #SMOS	[if OSNE]
– = #SMOS	[if OSMANY]

- Optional component selection

– Some defaults	[single]
– All valid	
▯ ≥ 1 incompatible with slots	
▯ ≥ 1 incompatible with another selection	
▯ ≥ 1 incompatible with model	
▯ ≥ 1 not in database	[error]

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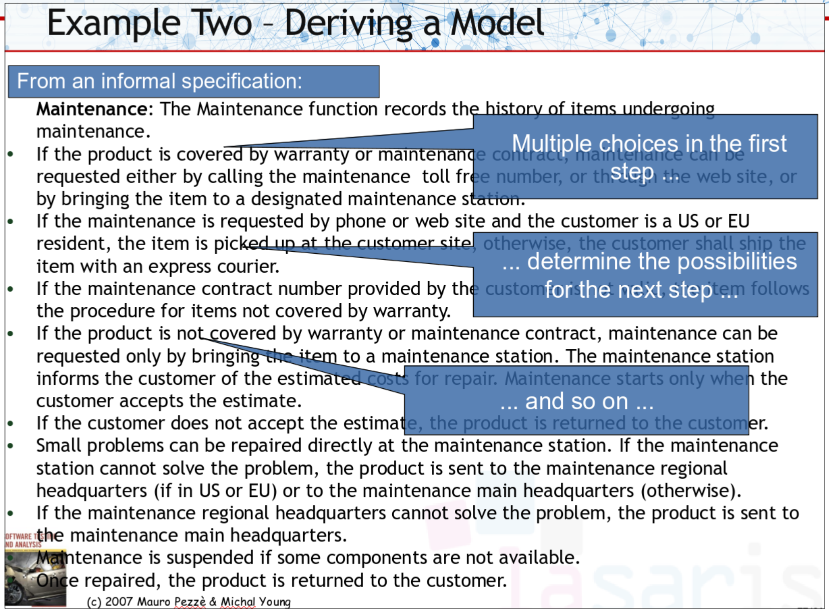
Example: Deriving a Model & Transition Coverage



Example Two – Deriving a Model

From an informal specification:

Maintenance: The Maintenance function records the history of items undergoing maintenance.

- If the product is covered by warranty or maintenance contract, maintenance can be requested either by calling the maintenance toll free number, or through the web site, or by bringing the item to a designated maintenance station.
- If the maintenance is requested by phone or web site and the customer is a US or EU resident, the item is picked up at the customer site, otherwise, the customer shall ship the item with an express courier.
- If the maintenance contract number provided by the customer is not valid, the item follows the procedure for items not covered by warranty.
- If the product is not covered by warranty or maintenance contract, maintenance can be requested only by bringing the item to a maintenance station. The maintenance station informs the customer of the estimated costs for repair. Maintenance starts only when the customer accepts the estimate.
- If the customer does not accept the estimate, the product is returned to the customer.
- Small problems can be repaired directly at the maintenance station. If the maintenance station cannot solve the problem, the product is sent to the maintenance regional headquarters (if in US or EU) or to the maintenance main headquarters (otherwise).
- If the maintenance regional headquarters cannot solve the problem, the product is sent to the maintenance main headquarters.

Maintenance is suspended if some components are not available.

Once repaired, the product is returned to the customer.

Multiple choices in the first step ...

... determine the possibilities for the next step ...

... and so on ...

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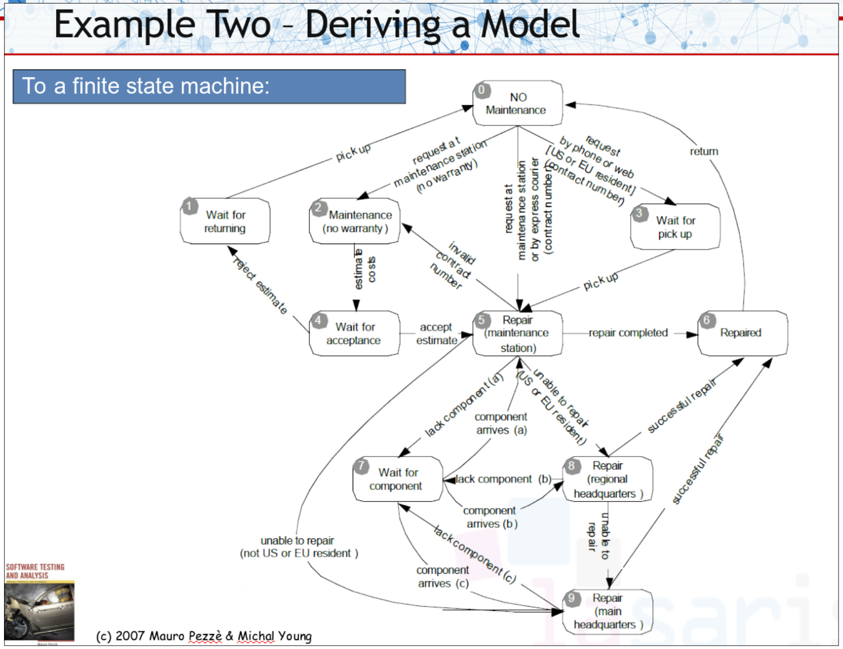

Example Two – Deriving a Model

To a finite state machine:

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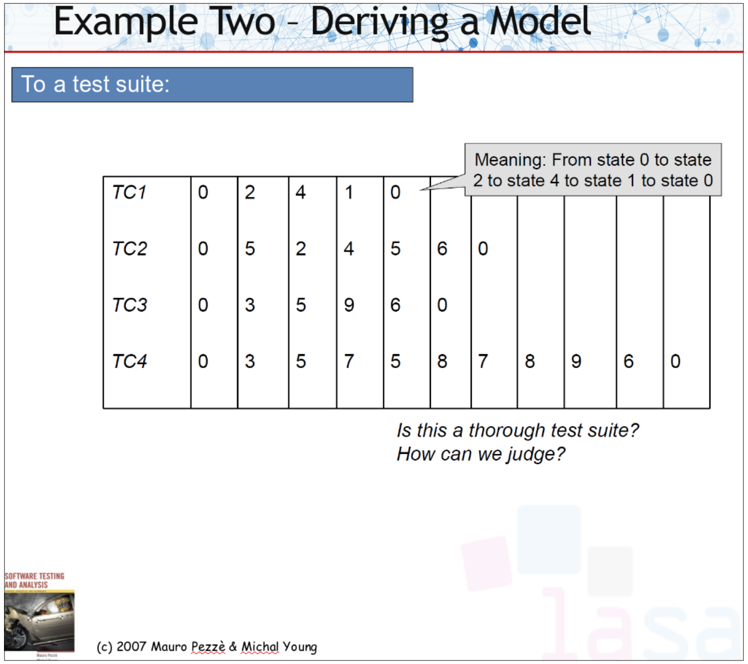

Example Two – Deriving a Model

To a test suite:

TC1	0	2	4	1	0						
TC2	0	5	2	4	5	6	0				
TC3	0	3	5	9	6	0					
TC4	0	3	5	7	5	8	7	8	9	6	0

Meaning: From state 0 to state 2 to state 4 to state 1 to state 0

Is this a thorough test suite?
How can we judge?

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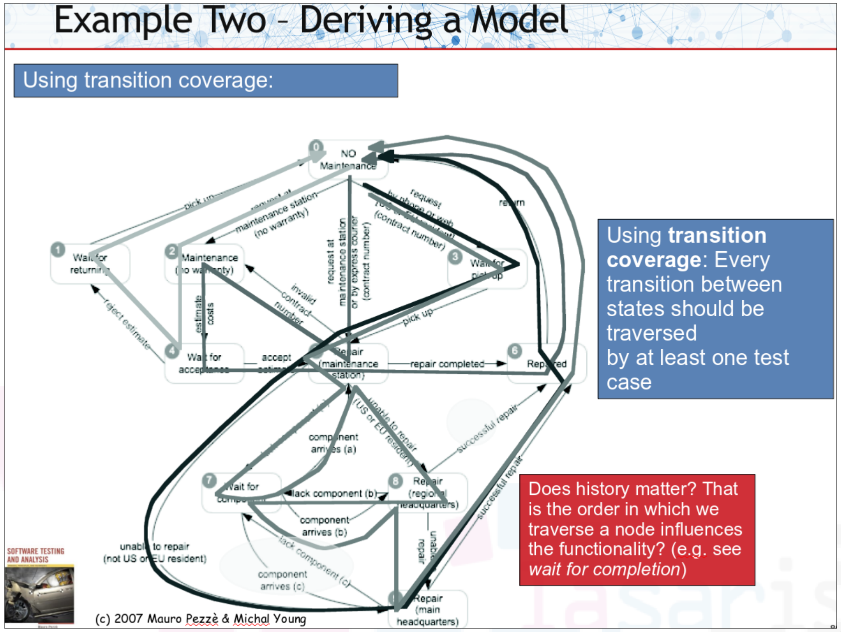

Example Two – Deriving a Model

Using transition coverage:

Using **transition coverage**: Every transition between states should be traversed by at least one test case

Does history matter? That is the order in which we traverse a node influences the functionality? (e.g. see *wait for completion*)

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References

Most of the source code examples, class diagrams, etc... from [2] if not differently stated

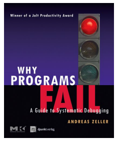
[1] A. Zeller, *Why Programs Fail, Second Edition: A Guide to Systematic Debugging*, 2 edition. Amsterdam ; Boston: Morgan Kaufmann, 2009.

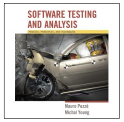
[2] M. Pezzè and M. Young, *Software Testing And Analysis: Process, Principles And Techniques*. Hoboken, N.J.: John Wiley & Sons Inc, 2007.

[3] Michel Felderer, “Development of a Risk-Based Test Strategy and its Evaluation in Industry”, PV226 Lasaris Seminar, 3rd Nov 2016.

[4] ISO/IEC/IEEE 29119 Software Testing Standard, downloadable from:

https://standards.iso.org/ittf/PubliclyAvailableStandards/index.html





Acceptance Testing example using Fitnesse (www.fitnesse.org)

Mutation Testing example using PiTest (www.pitest.org)