Software Verification and Validation

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Introduction to Software Testing

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Main Sources

- A. Mathur, Foundations of Software Testing, Pearson Education, 2008
- M. Pezze and M. Young, Software Analysis and Software Testing, Wiley, 2007
- P. Ammann and J Offutt, Introduction to Software Testing, Cambridge Press, 2007

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Examples of Software Failures

- Communications: Loss or corruption of communication media, non delivery of data.
- Space Applications: Lost lives, launch delays, e.g., European Ariane 5 shuttle, 1996:
  - From the official disaster report: “Due to a malfunction in the control software, the rocket veered off its flight path 37 seconds after launch.”
- Defense and Warfare: Misidentification of friend or foe.
- Transportation: Deaths, delays, sudden acceleration, inability to brake.
- Electric Power: Death, injuries, power outages, long-term health hazards (radiation).

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Examples of Software Failures (cont.)

- Money Management: Fraud, violation of privacy, shutdown of stock exchanges and banks, negative interest rates.
- Control of Elections: Wrong results (intentional or non-intentional).
- Control of Jails: Technology-aided escape attempts and successes, failures in software-controlled locks.
- Law Enforcement: False arrests and imprisonments.

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Ariane 5 – ESA

On June 4, 1996, the flight of the Ariane 5 launcher ended in a failure.

Only about 40 seconds after initiation of the flight sequence, at an altitude of about 3,700 m, the launcher veered off its flight path, broke up and exploded.

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Ariane 5 – Root Cause

- **Source: ARIANE 5 Flight 501 Failure, Report by the Inquiry Board**

  A program segment for converting a floating point number to a signed 16 bit integer was executed with an input data value outside the range representable by a signed 16-bit integer.

  This run time error (out of range, overflow), which arose in both the active and the backup computers at about the same time, was detected and both computers shut themselves down.

  This resulted in the total loss of attitude control. The Ariane 5 turned uncontrollably and aerodynamic forces broke the vehicle apart.

  This breakup was detected by an on-board monitor which ignited the explosive charges to destroy the vehicle in the air. Ironically, the result of this format conversion was no longer needed after lift off.

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Ariane 5 – Lessons Learned

- Adequate exception handling and redundancy strategies (real function of a backup system, degraded modes?)
- Clear, complete, documented specifications (e.g., preconditions, post-conditions)
- But perhaps more importantly: *usage-based testing (based on operational profiles), in this case actual Ariane 5 trajectories*
- Note this was not a complex, computing problem, but a deficiency of the software engineering practices in place …

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F-18 crash

- An F-18 crashed because of a missing exception condition:

  An if ... then ... block without the else clause that was thought could not possibly arise.
- In simulation, an F-16 program bug caused the virtual plane to flip over whenever it crossed the equator, as a result of a missing minus sign to indicate south latitude.

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Fatal Therac-25 Radiation

- In 1986, a man in Texas received between 16,500-25,000 radiations in less than 10 sec, over an area of about 1 cm.
- He lost his left arm, and died of complications 5 months later.

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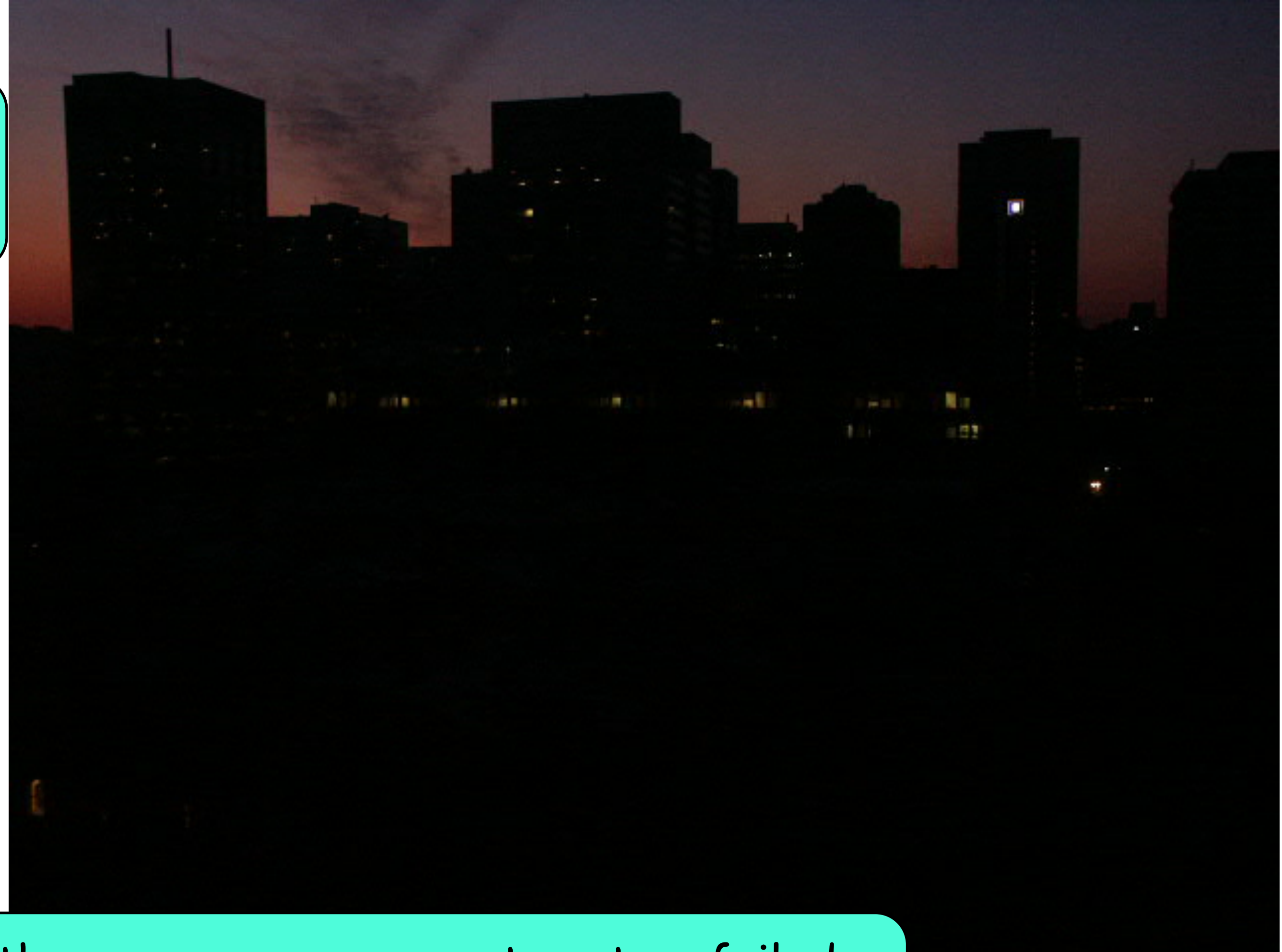
Power Shutdown in 2003



508 generating units and 256 power plants shut down

Affected 10 million people in Ontario, Canada

Affected 40 million people in 8 US states

Financial losses of $6 Billion USD

The alarm system in the energy management system failed due to a software error and operators were not informed of the power overload in the system

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Testing
Definitions & Objectives

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Basic Definitions

- Test case: A set of test data and test programs (test scripts) and their expected results. A test case validates one or more system requirements and generates a pass or fail.
- Test suite: A collection of test cases that are related or that cooperate with each other to achieve an objective.
- Test oracle / verdict: A source to determine expected results to compare with the actual result of the software under test.

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Test Stubs and Drivers

- Test Stub: Partial implementation of a component on which a unit under test depends.

- Test Driver: Partial implementation of a component that depends on a unit under test.

- Test stubs and drivers enable components to be isolated from the rest of the system for testing.

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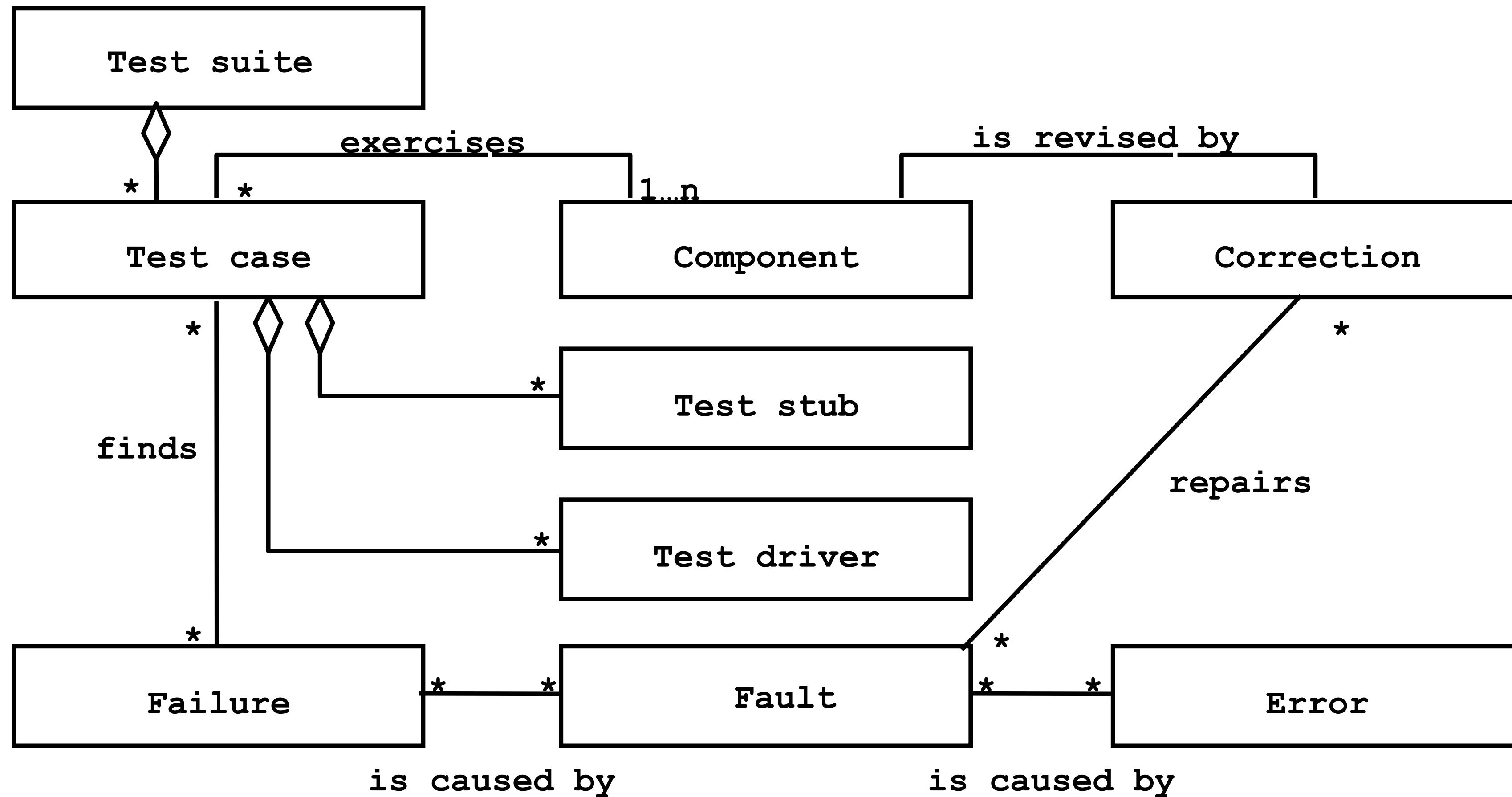
Summary of Definitions



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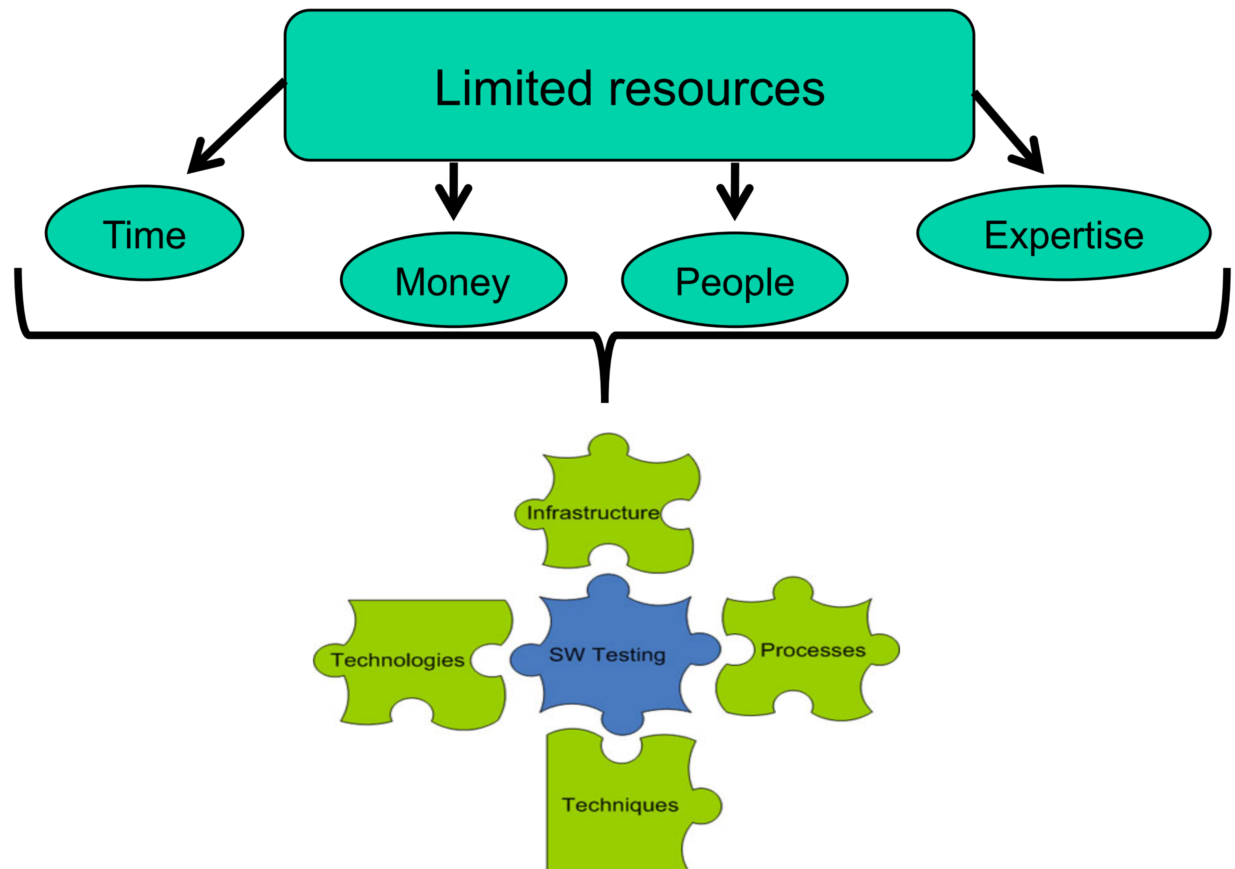
Motivations

- No matter how rigorous we are, software is going to be faulty
- Testing represent a substantial percentage of software development costs and time to market
- Impossible to test under all operating conditions – based on incomplete testing, we must gain confidence that the system has the desired behavior
- Testing large systems is complex – it requires strategy and technology- and is often done inefficiently in practice



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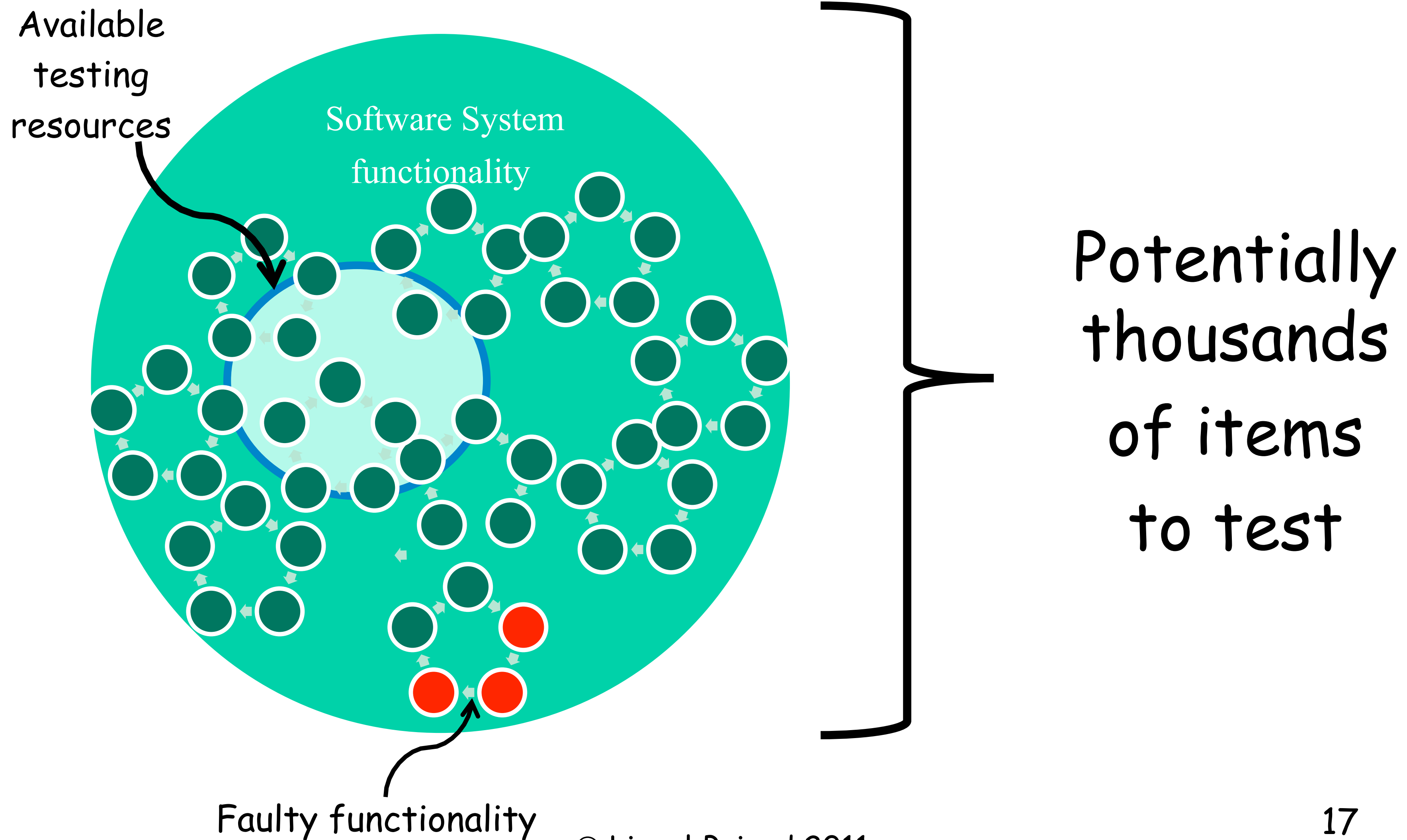
The Testing Dilemma



Potentially thousands of items to test

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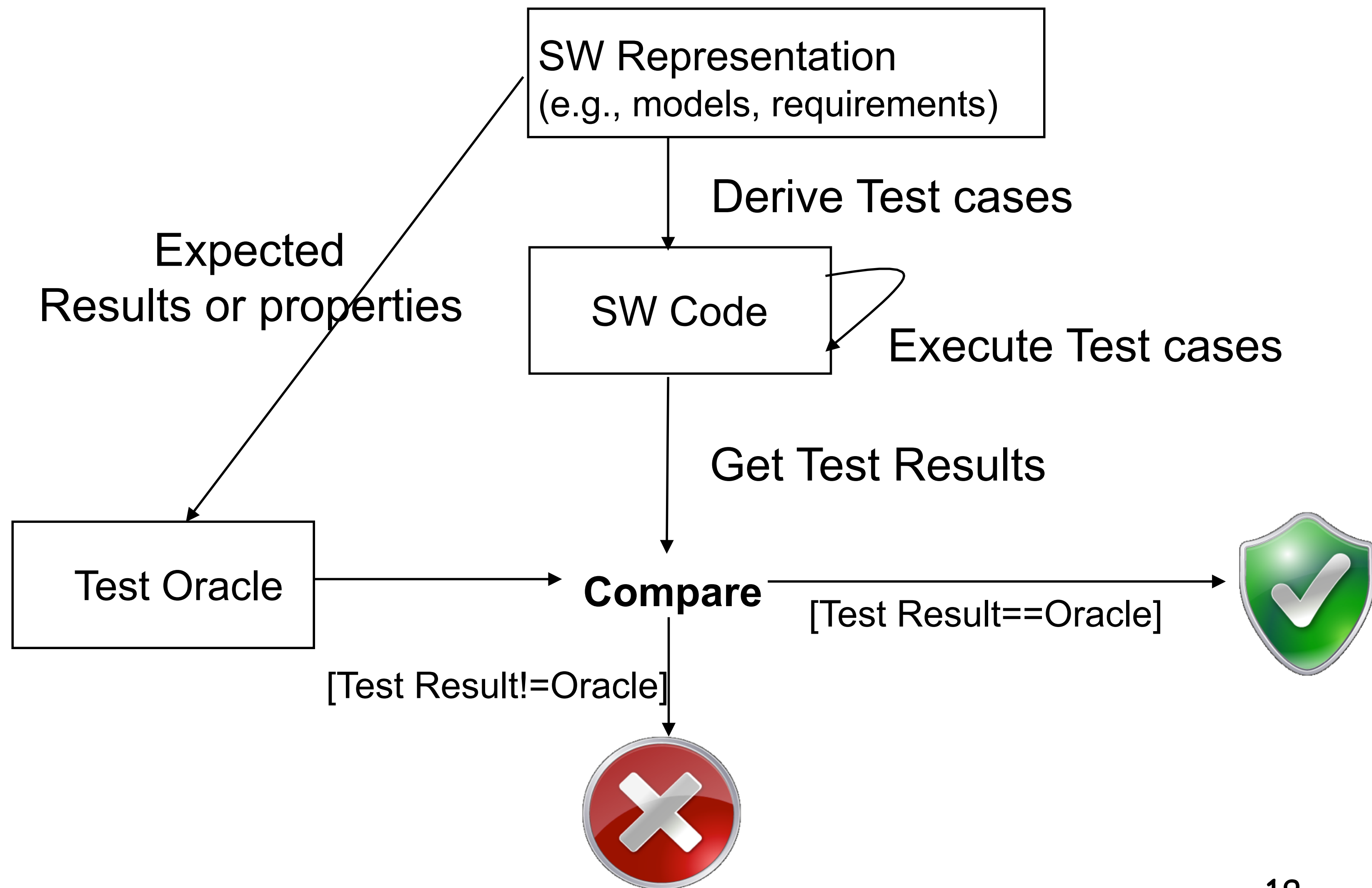
Testing Process Overview



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Types of Testing

- Functional Testing: testing functional requirements.
  - Functional requirements specify specific behavior or functions of a software.
  - Functional testing is thus checking the correct functionality of a system.
- Non-functional Testing: testing non-functional requirements.
  - Non-functional requirements:
    - Specify criteria that can be used to judge the operation of a system, rather than specific behaviors.
    - Typical non-functional requirements are performance, reliability, scalability, and cost.
    - Non-functional requirements are often called the -*ilities* of a system.
    - Examples next…

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Non-functional SW Requirements

- Accessibility
- Availability
- Efficiency (resource consumption for given load)
- Effectiveness (resulting performance in relation to effort)
- Extensibility
- Maintainability
- Performance / Response time
- Resource constraints (required processor speed, memory, disk space, network bandwidth, etc.)
- Reliability (e.g. Mean Time Between Failures - MTBF)
- Robustness
- Safety
- Scalability
- Security

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Qualities of Testing

- *Effective* at uncovering faults
- Help *locate* faults for debugging
- *Repeatable* so that a precise understanding of the fault can be gained and the correction can be verified
- *Automated* so as to lower the cost and timescale
- *Systematic* so as to be predictable in terms of its effect on dependability

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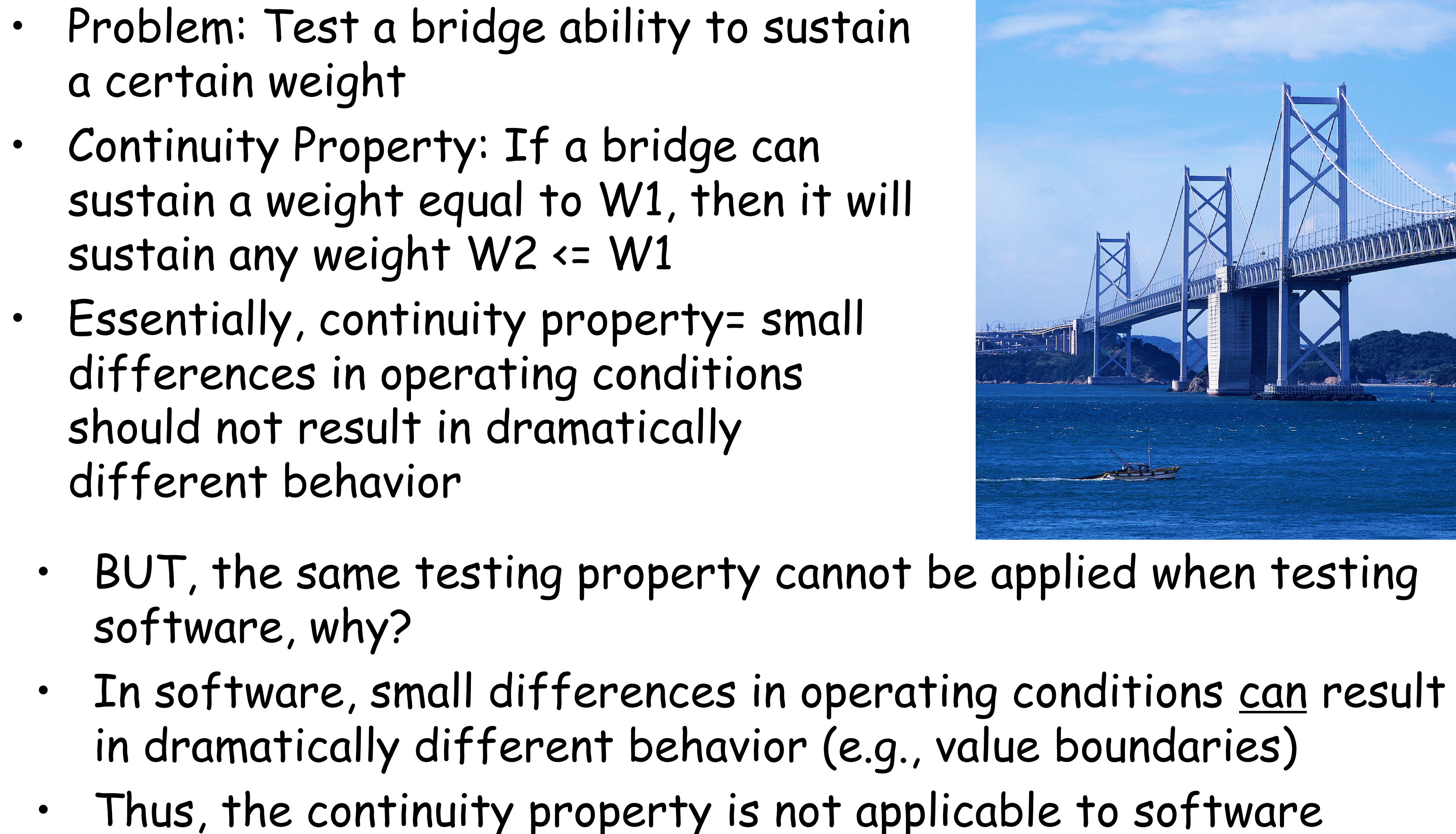
Continuity Property

- Problem: Test a bridge ability to sustain a certain weight
- Continuity Property: If a bridge can sustain a weight equal to W1, then it will sustain any weight W2 <= W1
- Essentially, continuity property= small differences in operating conditions should not result in dramatically different behavior



- BUT, the same testing property cannot be applied when testing software, why?
- In software, small differences in operating conditions <u>can</u> result in dramatically different behavior (e.g., value boundaries)
- Thus, the continuity property is not applicable to software

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Subtleties of Software Dependability

- *Dependability:* Correctness, reliability, safety, robustness
- A program is correct if it obeys its specification.
- Reliability is a way of statistically approximating correctness.
- Safety implies that the software must always display a safe behavior, under any condition.
- A system is robust if it acts reasonably in severe, unusual or illegal conditions.

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Subtleties of Software Dependability II

- *Correct but not safe or robust:* the specification is inadequate
- *Reliable but not correct:* failures rarely happen
- *Safe but not correct:* annoying failures may happen
- *Reliable and robust but not safe:* catastrophic failures are possible

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Traffic Light Controller

- *Correctness, Reliability:*

The system should let traffic pass according to the correct pattern and central scheduling on a continuous basis.

- *Robustness:*

The system should provide degraded functionality in the presence of abnormalities: default traffic pattern

- *Safety:*

It should never signal conflicting greens.

An example degraded function: the line to central controlling is cut-off and a default pattern is then used by local controller.

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Dependability Needs Vary

- Safety-critical applications
  - flight control systems have strict safety requirements
  - telecommunication systems have strict robustness requirements
- Mass-market products
  - dependability is less important than time to market
- Can vary within the same class of products:
  - reliability and robustness are key issues for multi-user operating systems (e.g., UNIX) less important for single users operating systems (e.g., Windows or MacOS)

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Fundamental Principles

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Exhaustive Testing

- Exhaustive testing, i.e., testing a software system using all the possible inputs, is most of the time impossible.
- Examples:
  - A program that computes the factorial function (n!=n.(n-1).(n-2)…1)
    - Exhaustive testing = running the program with 0, 1, 2, …, 100, … as an input!
  - A compiler (e.g., javac)
    - Exhaustive testing = running the (Java) compiler with any possible (Java) program (i.e., source code)

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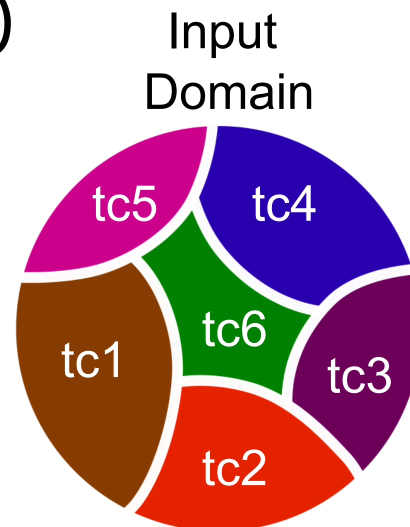
Input Equivalence Classes

- General principle to reduce the number of inputs
  - Testing criteria group input elements into (equivalence) classes
  - One input in selected in each class (notion of test coverage)

Input Domain



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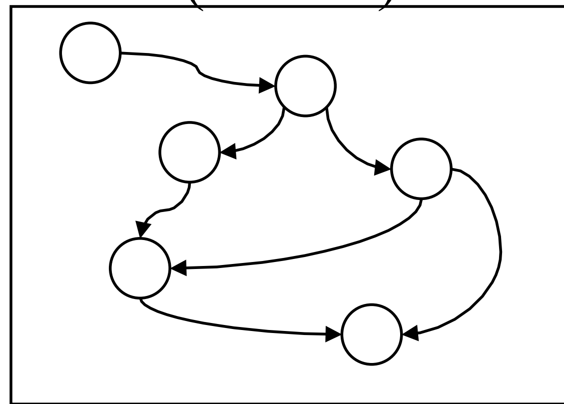
Test Coverage

Software Representation (Model)



Associated Criteria

Test cases must cover all the … in the model

Test Data

Representation of

- the specification ⇒ Black-Box Testing
- the implementation ⇒ White-Box Testing

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Complete Coverage: White-Box

```
if x > y then
   Max := x;
else
   Max :=x ;  // fault!
end if;
```

{x=3, y=2; x=2, y=3} can detect the error, more "coverage"
{x=3, y=2; x=4, y=3; x=5, y=1} is larger but cannot detect it

- **Testing criteria group input domain elements into (equivalence) classes (control flow paths here)**
- **Complete coverage attempts to run test cases from each class**

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Complete Coverage: Black-Box

- **Specification of Compute Factorial Number:** If the input value n is < 0, then an appropriate error message must be printed. If 0 <= n < 20, then the exact value of n! must be printed. If 20 <= n < 200, then an approximate value of n! must be printed in floating point format, e.g., using some approximate method of numerical calculus. The admissible error is 0.1% of the exact value. Finally, if n>=200, the input can be rejected by printing an appropriate error message.

- Because of expected variations in behavior, it is quite natural to divide the input domain into the classes {n<0}, {0<= n <20}, {20 <= n < 200}, {n >= 200}. We can use one or more test cases from each class in each test set. Correct results from one such test set support the assertion that the program will behave correctly for any other class value, but there is no guarantee!

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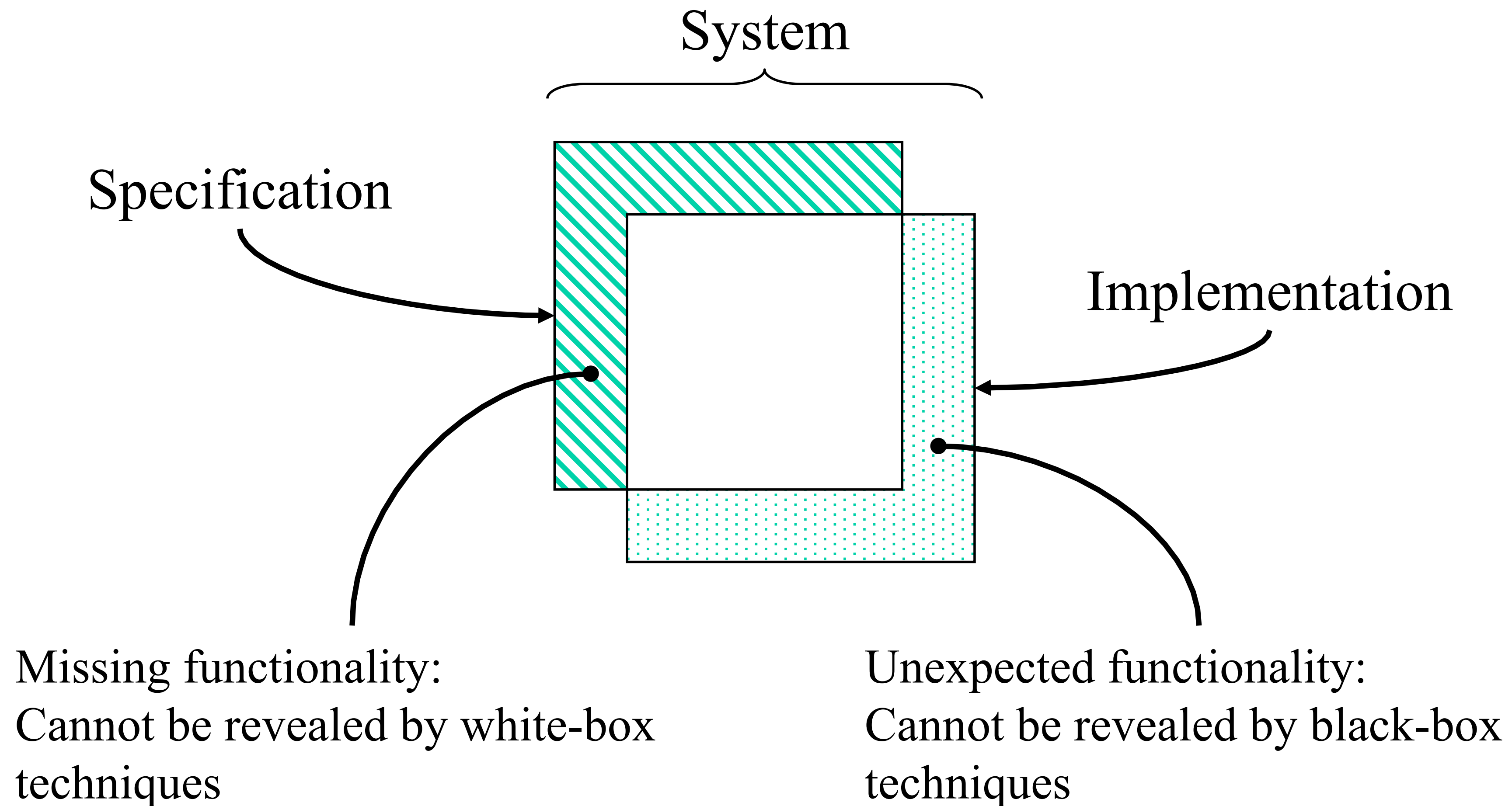
Black vs. White Box Testing



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White-box vs. Black-box Testing: Pro's and Con's

- Black-box
  - (+) Check conformance with specifications
  - (+) It scales up (different techniques at different granularity levels)
  - (−) It depends on the specification notation and degree of detail
  - (−) Do not 'exactly' know how much of the system is being tested
  - (−) Do not detect unspecified task.
- White-box
  - (+) It allows you to be confident about test coverage
  - (+) It is based on control or data flow coverage
  - (−) It does not scale up (mostly applicable at unit and integration testing levels)
  - (−) Unlike black-box techniques, it cannot reveal missing functionalities (part of the specification that is not implemented)

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Theoretical Foundations of Testing: Formal definitions

- Let P be a program
- Let D and R denote its input domain and range
  - P is a function: D→R
- Let OR denote the expected output values (ORacle)
- P is said to be *correct* for all d ∈ D if P(d) satisfies OR; if not, we have a *failure*
- A test case is an element d of D and the expected value of P in OR given d
- A test set (a.k.a. suite) T is a finite set of test cases

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Theoretical Foundations of Testing: Test Adequacy Criterion

- A *test adequacy criterion* C how "much" of D we should target by our test set.
- Example: Defining a criterion C for a program model M
  - **M: the Control Flow Graph (CFG) of a function**
  - **C: the set of all the edges in the CFG**
- Formally: A *test adequacy criterion* C is a subset of P_D, where P_D is the set of all finite subsets of D that we could target when devising test sets (note the two levels of subsets). (Recall: D denotes the input domain of P).
- The *coverage ratio* of a test set T is the proportion of the elements in M defined by C covered by the given test set T.
- A test set T is said to be adequate for C, or simply C-adequate, when the coverage ratio achieves 100% for criterion C.
- We will have examples soon…

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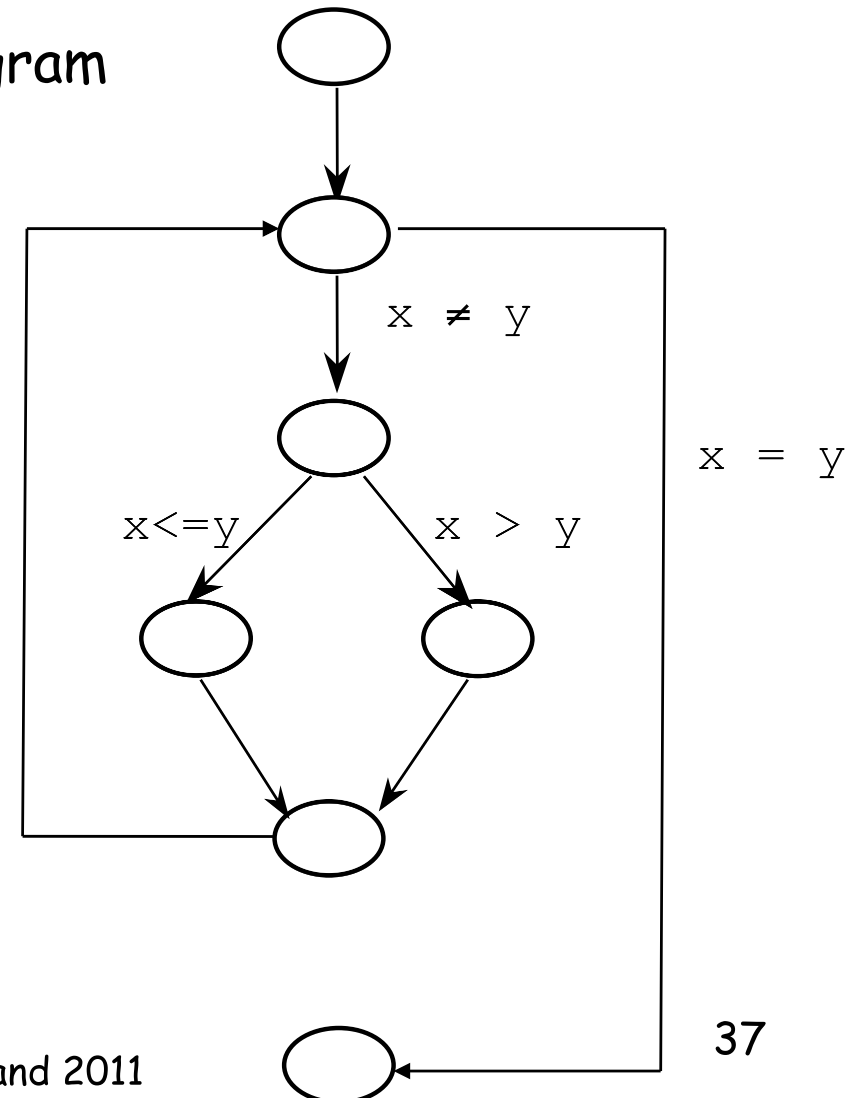
Control Flow Graph (CFG) Example

Greatest common divisor (GCD) program

```
read(x);
read(y);
while x ≠ y loop
   if x>y then
    x := x - y;
   else
    y := y - x;
   end if;
end loop;
gcd := x;
```



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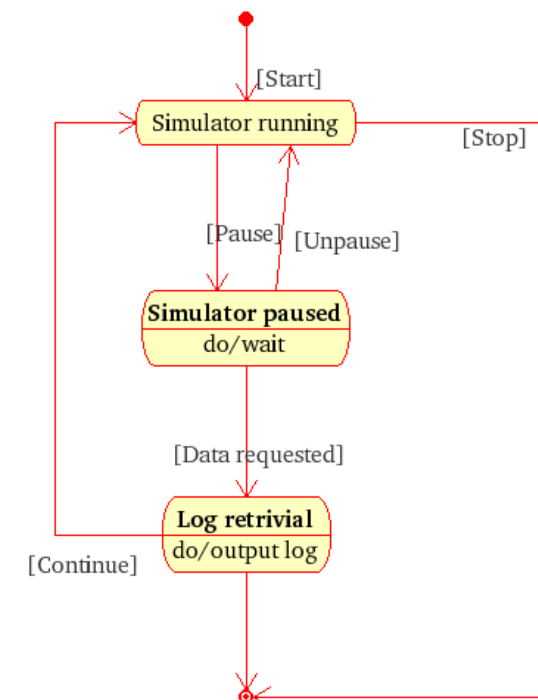
Theoretical Foundations of Testing: Hierarchy of Adequacy Criteria

- Let us define a subsumption relationship between different test criteria associated with a program model
- Given a model M, and two criteria C1 and C2 for that model:

  C1 subsumes C2 if any C1-adequate test set is also C2-adequate.

- Example: Consider criteria all-transitions and all-paths for finite state machines:
  - all-paths subsumes all-transitions

- If C1 subsumes C2, we assume:
  - Satisfying C1 is more "expensive" (e.g., # of test cases) than satisfying C2
  - C1 allows the detection of more faults (on average) than C2



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Theoretical Foundations of Testing
Ideal Test Set

- A test set T is said to be *ideal* if, whenever P is incorrect, there exists a d ∈ T such that P is incorrect for d, i.e., P(d) does not satisfy OR.
- If T is an ideal test set and T is successful for P, then P is *correct*
- T satisfies a test adequacy criterion C if its input values belong to C.

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Theoretical Foundations of Testing: Test Consistency and Completeness

- A *test adequacy criterion* C is *consistent* if, for any pair of test sets T1 and T2, both satisfying C, T1 is successful if and only T2 is.
- A *test adequacy criterion* C is *complete* if, whenever P is incorrect, there is an unsuccessful test set that satisfies C.
- If C is consistent *and* complete, any test set T satisfying C is *ideal* and could be used to decide P's correctness.
- The problem is that it is not possible in general to derive algorithms that helps determine whether a criterion, a test set, or a program has any of the above mentioned properties … they are undecidable problems ☹

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Theoretical Foundations of Testing: Empirical Testing Principle

- As we discussed, it is impossible to determine (find) consistent and complete test criteria from the theoretical standpoint
- Also, exhaustive testing cannot be performed in practice
- Therefore, we need test *strategies* that have been *empirically* investigated
- A *significant* test case is a test case with high error detection probability – its execution increases our confidence in the program correctness
- The goal is to run a *sufficient* number of significant test cases – and that number should be as small as possible (to save time and $$)

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Practical Aspects

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Many Causes of Failures

- The specification may be wrong or incomplete
- The specification may contain a requirement that is impossible to implement given the prescribed software and hardware
- The system design may contain a fault
- The program code may be wrong

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Test Organization

- Many different potential causes of failure, Large systems -> testing involves several stages
- Module, component, or unit testing
- Integration testing
- Function test
- Performance test
- Acceptance test
- Installation test

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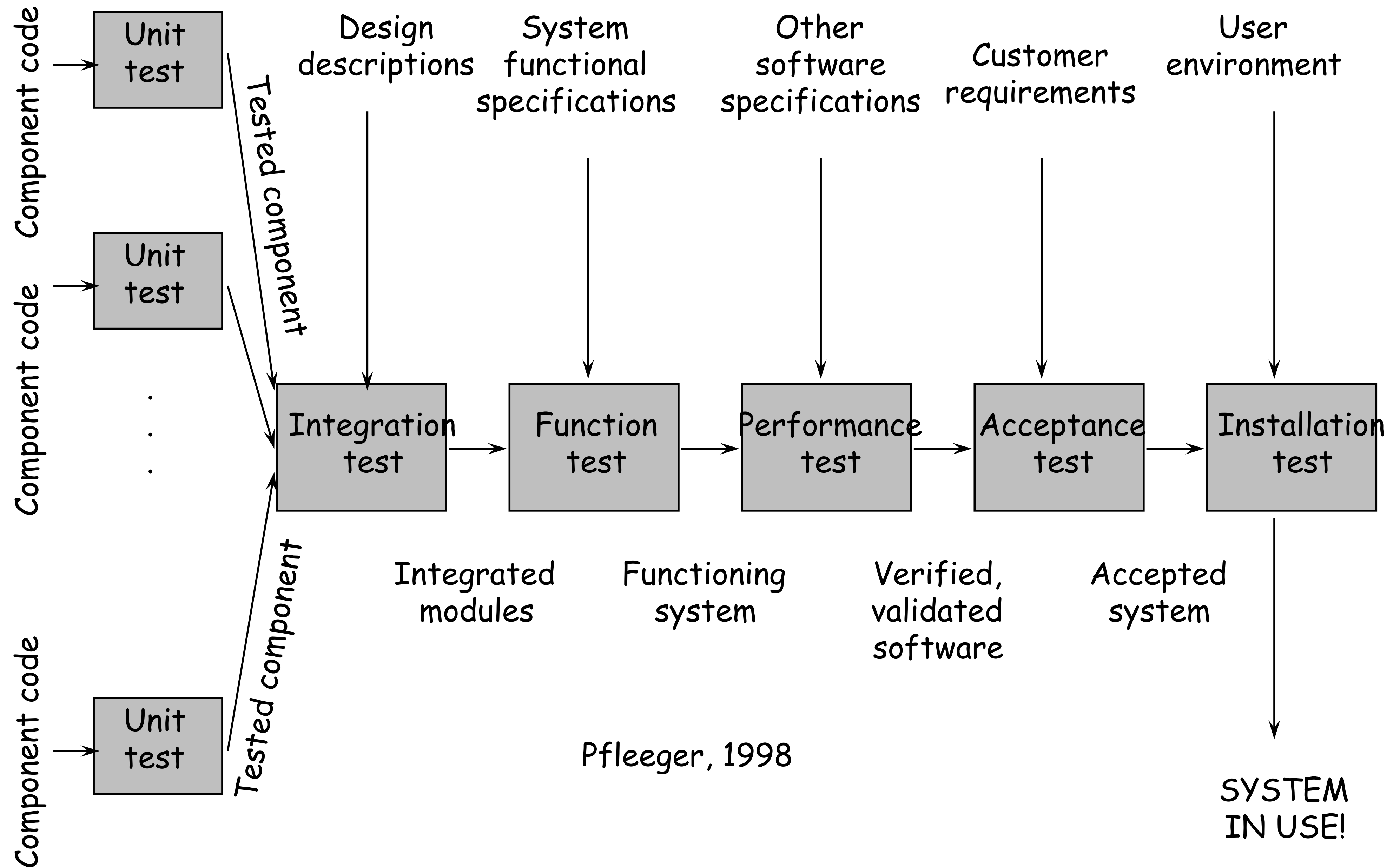

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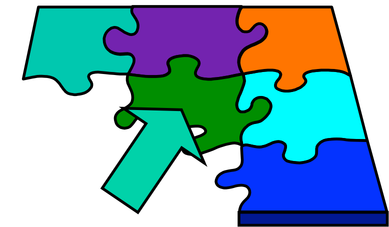
Unit Testing

- (Usually) performed by each developer.
- Scope: Ensure that each module (i.e., class, subprogram) has been implemented correctly.
- Often based on White-box testing.



Test

- A unit is the smallest testable part of an application.
- In procedural programming, a unit may be an individual subprogram, function, procedure, etc.
- In object-oriented programming, the smallest unit is a method; which may belong to a base/super class, abstract class or derived/child class.

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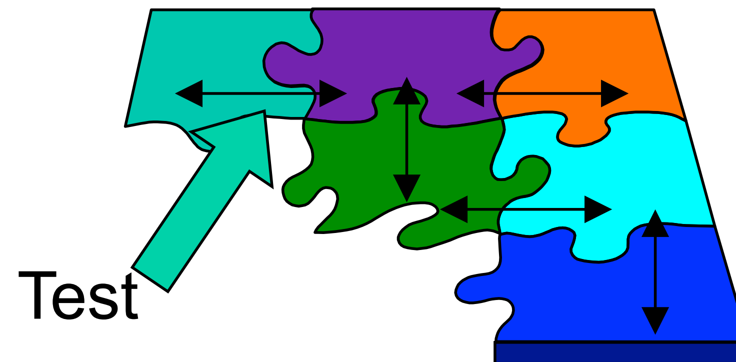
Integration/Interface Testing

- Performed by a small team.
- *Scope*: Ensure that the interfaces between components (which individual developers could not test) have been implemented correctly, e.g., consistency of parameters, file format



- Test cases have to be planned, documented, and reviewed.
- Performed in a relatively small time-frame

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Integration Testing Failures

Integration of well tested components may lead to failure due to:

- Bad use of the interfaces (bad interface specifications / implementation)
- Wrong hypothesis on the behavior/state of related modules (bad functional specification / implementation), e.g., wrong assumption about return value
- Use of poor drivers/stubs: a module may behave correctly with (simple) drivers/stubs, but result in failures when integrated with actual (complex) modules.

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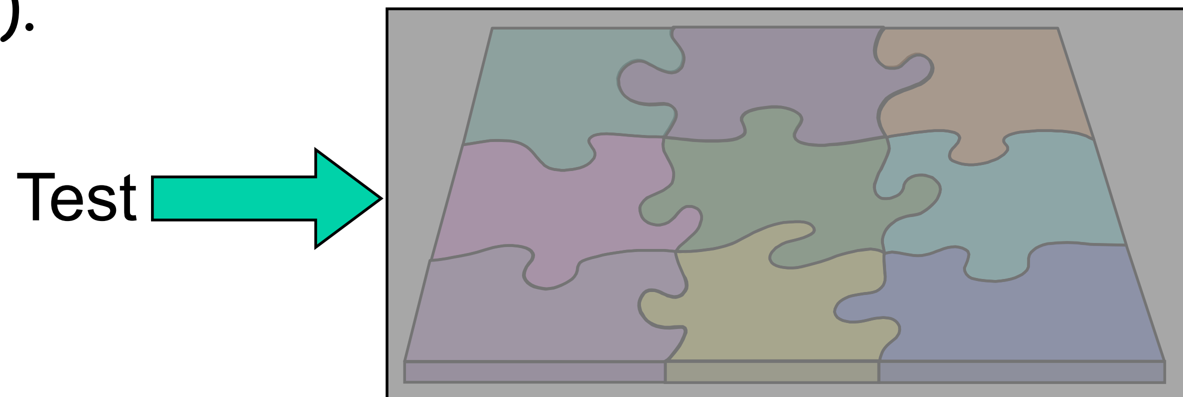
System Testing

- Performed by a separate group within the organization (Most of the times).
- *Scope*: Pretend *we* are the end-users of the product.
- Focus is on functionality, but may also perform many other types of non-functional tests (e.g., recovery, performance).



- Black-box form of testing, but code coverage can be monitored.
- Test case specification driven by system's use-cases.

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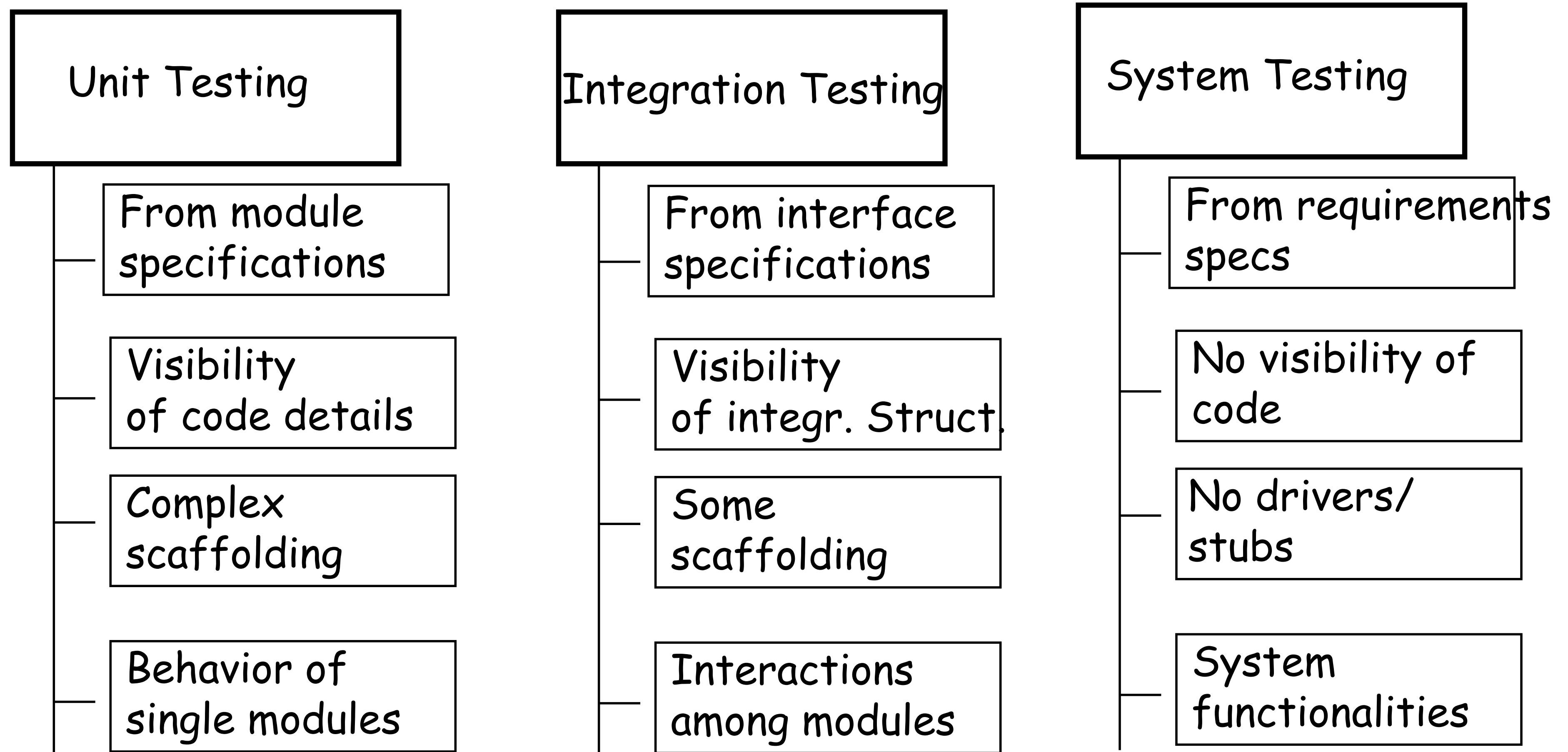
Differences among Testing Activities



Pezze and Young, 2007

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System vs. Acceptance Testing

- System testing
  - The software is compared with the requirements specifications (verification)
  - Usually performed by the developers, who know the system
- Acceptance testing
  - The software is compared with the end-user requirements (validation)
  - Usually performed by the customer (buyer), who knows the environment where the system is to be used
  - Sometime distinguished between α - β-testing for general purpose products

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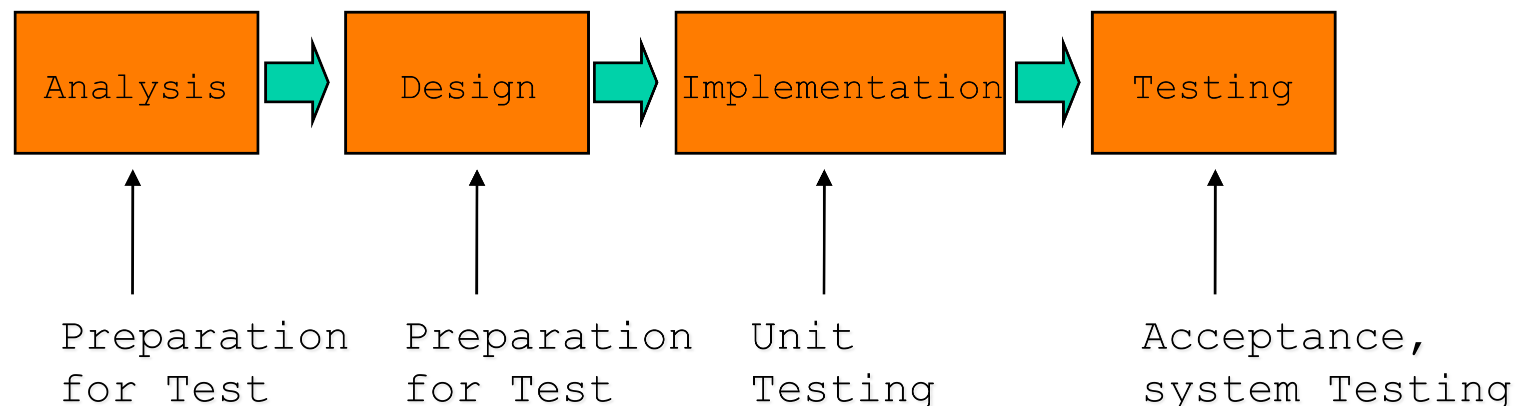
Testing throughout the Lifecycle

- Much of the life-cycle development artifacts provides a rich source of test data
- Identifying test requirements and test cases early helps shorten the development time
- They may help reveal faults
- It may also help identify early low testability specifications or design



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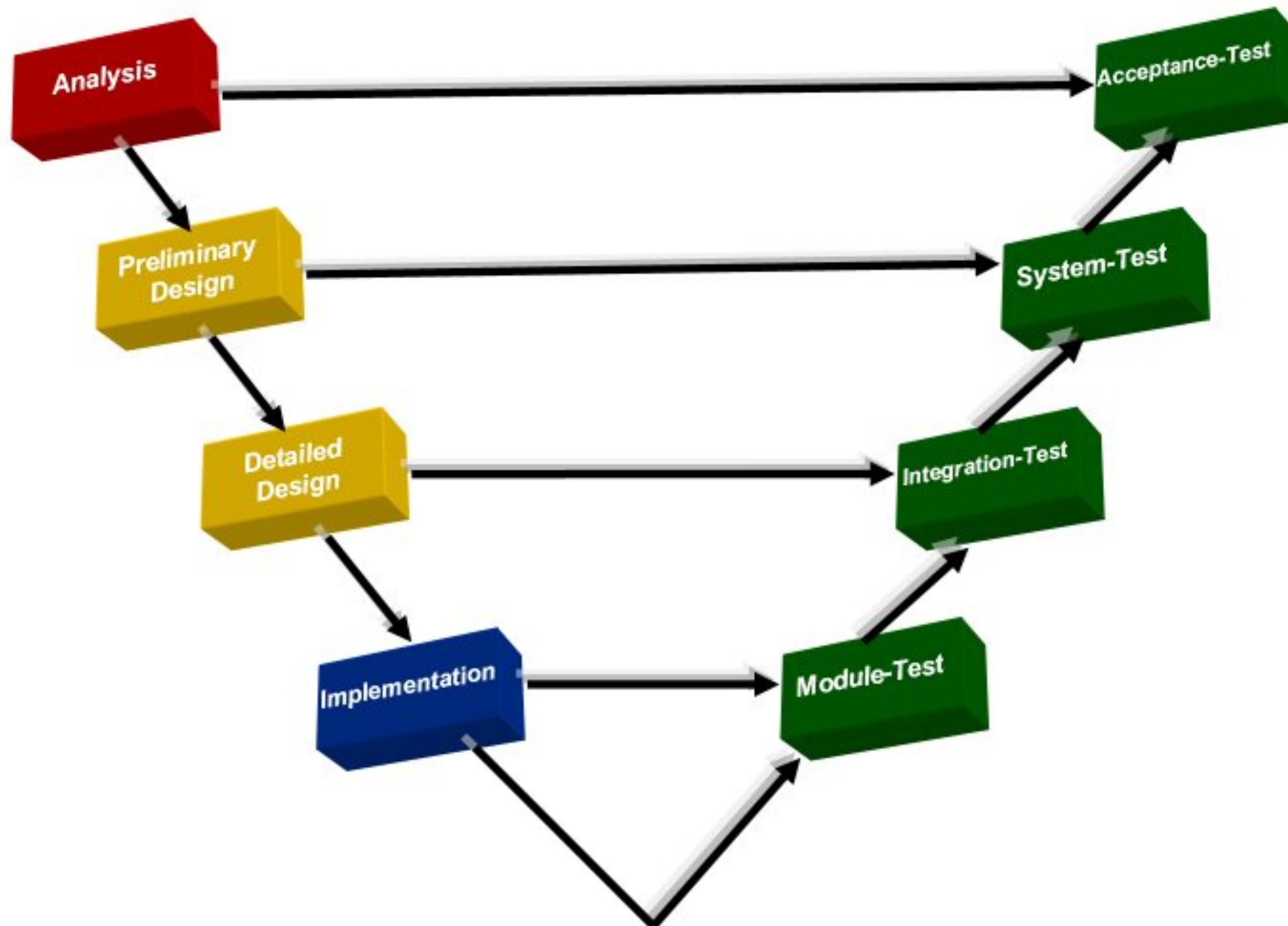
Testing throughout the Lifecycle – in the "V" model (half of this is about testing!)



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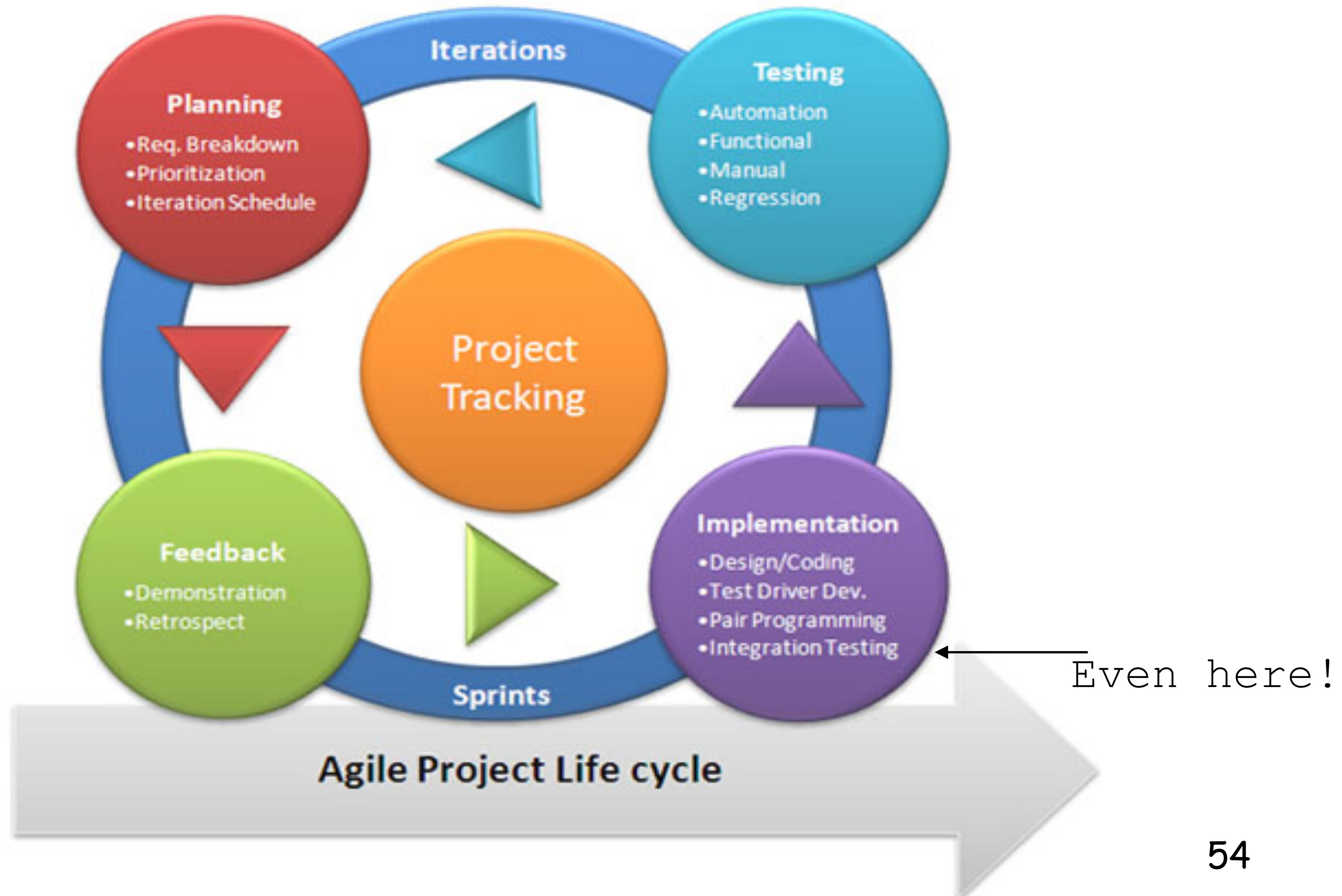
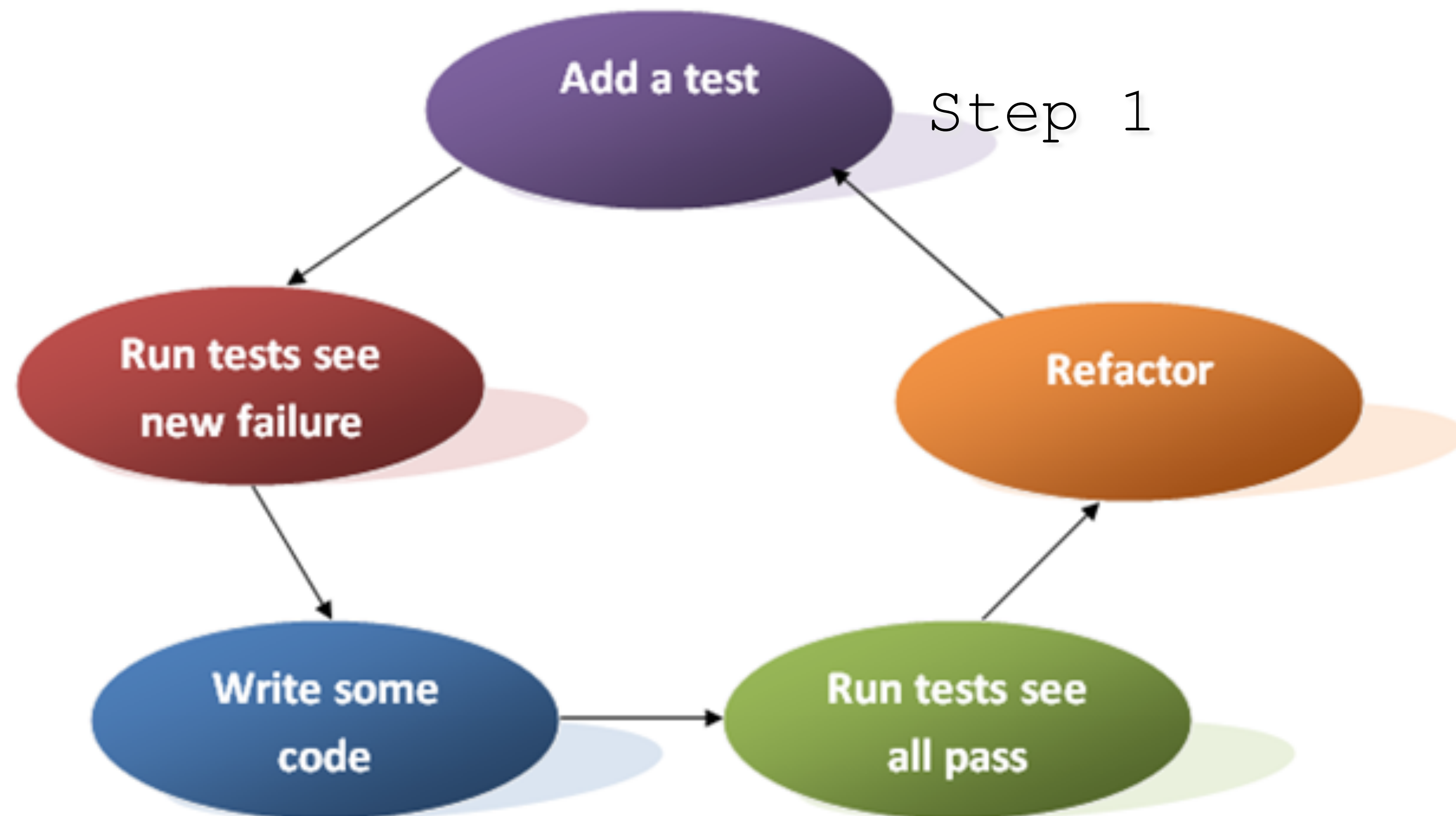
Testing throughout the Lifecycle – in Agile Development



Testing throughout the Lifecycle – in TDD
(Test-Driven Development)



In TDD, test cases are actually the requirements of the system.

Types of testing

One possible classification is based on the following four classifiers:

C1: Source of test case generation.

C2: Lifecycle phase in which testing takes place

C3: Goal of a specific testing activity

C4: Characteristics of the artifact under test

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C1: Source of test generation

Artifact	Technique	Example
Requirements (informal)	Black-box	Ad-hoc testing Boundary value analysis Category partition Classification trees Cause-effect graphs Equivalence partitioning Partition testing Predicate testing Random testing
Code	White-box	Adequacy assessment Coverage testing Data-flow testing Domain testing Mutation testing Path testing Structural testing Test minimization using coverage
Requirements and code	Black-box and White-box	
Formal model: Graphical or mathematical specification	Model-based Specification	Statechart testing FSM testing Pairwise testing Syntax testing
Component interface	Interface testing	Interface mutation Pairwise testing

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C2: Lifecycle phase in which testing takes place

Phase	Technique
Coding	Unit testing
Integration	Integration testing
System integration	System testing
Maintenance	Regression testing
Post system, pre-release	Beta-testing

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C3: Goal of specific testing activity

Goal	Technique	Example
Advertised features	Functional testing	
Security	Security testing	
Invalid inputs	Robustness testing	
Vulnerabilities	Vulnerability testing	
Errors in GUI	GUI testing	Capture/plaback
		Event sequence graphs
		Complete Interaction Sequence
Operational correctness	Operational testing	Transactional-flow
Reliability assessment	Reliability testing	
Resistance to penetration	Penetration testing	
System performance	Performance testing	Stress testing
Customer acceptability	Acceptance testing	
Business compatibility	Compatibility testing	Interface testing
		Installation testing
Peripherals compatibility	Configuration testing	

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C4: Artifact under test

Characteristics	Technique
Application component	Component testing
Client and server	Client-server testing
Compiler	Compiler testing
Design	Design testing
Code	Code testing
Database system	Transaction-flow testing
OO software	OO testing
Operating system	Operating system testing
Real-time software	Real-time testing
Requirements	Requirement testing
Software	Software testing
Web service	Web service testing

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Testing Activities BEFORE Coding

- Testing is a time consuming activity
- Devising a test strategy and identify the test requirements represent a substantial part of it
- Planning is essential
- Testing activities undergo huge pressure as it is is run towards the end of the project
- In order to shorten time-to-market and ensure a certain level of quality, a lot of QA-related activities (including testing) must take place early in the development life cycle

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Testing takes creativity

- Many jobs out there in test automation
- To develop an effective test, one must have:
  - Detailed understanding of the system
  - Knowledge of testing techniques
  - Skill to apply these techniques in an effective and efficient manner (e.g., tools)
- Testing is done best by independent testers
- Programmer often stick to the data set that makes the program work
- A program often does not work when tried by somebody else.

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