Software Testing and Analysis: Fundamental Concepts

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Undecidability

- Basic Definitions
- Why and How
- Principles
- Some Facts
- Types of Testing
- Organization
- Test Process
- Issues
- Learning
- Psychology

- **Correctness** properties are undecidable

What Can We Do?

➢ **Basic Definitions**
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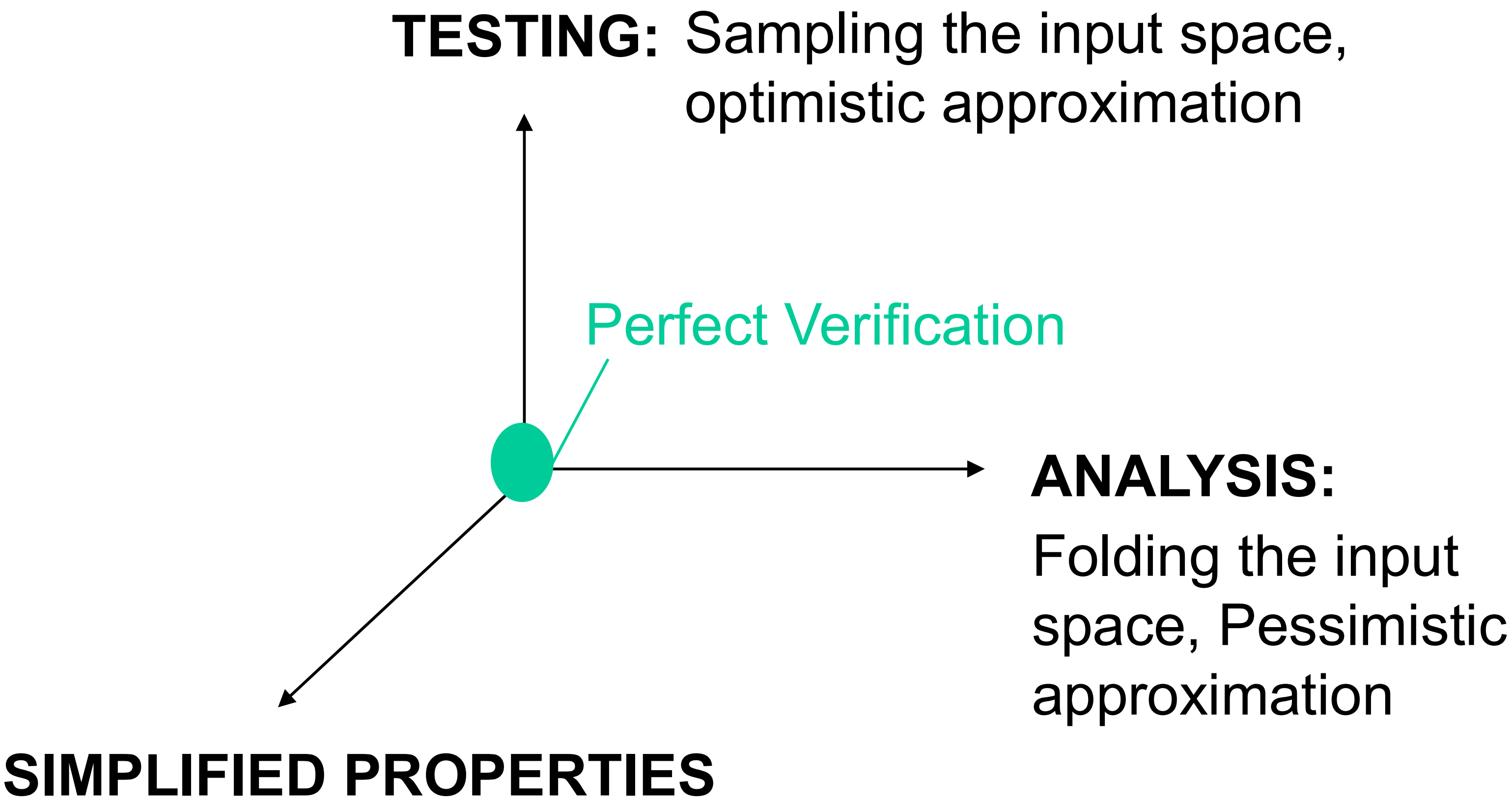
- We will need to allow for inaccuracy



Software Testing and Analysis Lifecycle: Phases and Outcomes

Basic Definitions
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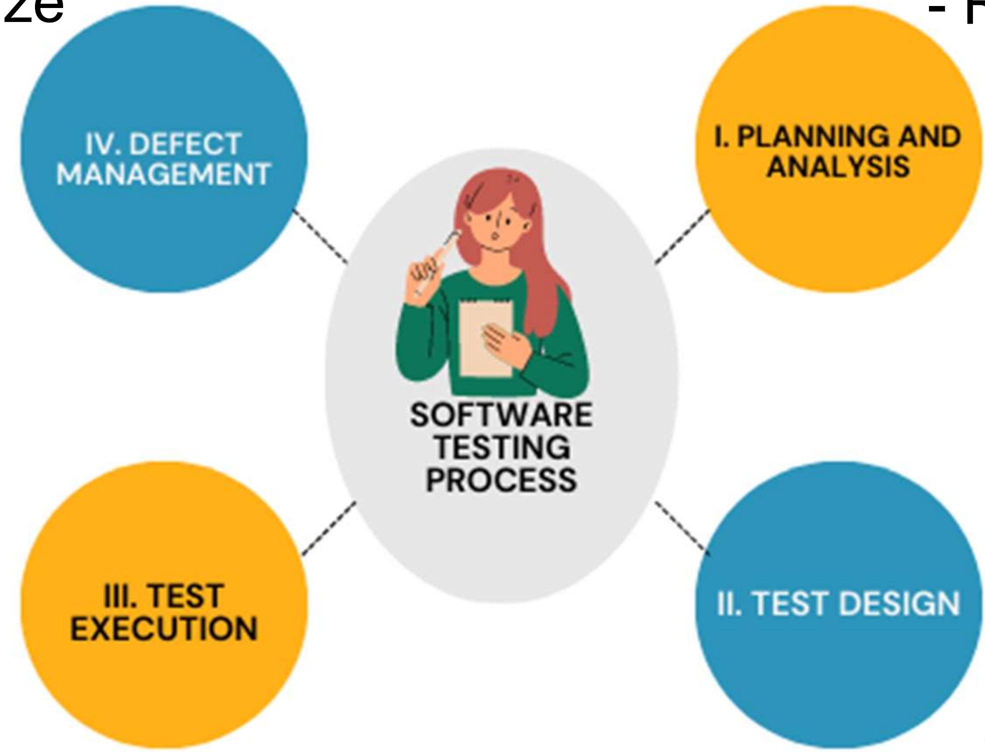
- Track
- Categorize
- Fix

- Buy Information
- Reduce Risk



- Report generation
- Identify bugs
- Behaves as expected

- Test Case
- Test Data
- Performance

- ➢ **Basic Definitions**
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- The process consisting of all life cycle activities concerned with planning, preparation, and evaluation of software products and related work products to determine if they satisfy specified requirements, to demonstrate that they are fit for purpose

- Testing and analysis are ways to
  - buy information
  - reduce risks

  like many more activities in software development

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- Dynamic technique
  - **requires execution of software code or artifacts**

- Optimistic inaccuracy: the program is executed on a (very small) subset on input data, the behavior of the program on every input is assumed to be consistent with the examined behaviors

Test Data vs. Test Cases

- **Basic Definitions**
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- Test data
  - inputs
  - generating them is relatively simple
    - they could be generated automatically
- Test case
  - (input, output)
  - generating them is much more complex
    - in general, they cannot be generated automatically

Software Analysis

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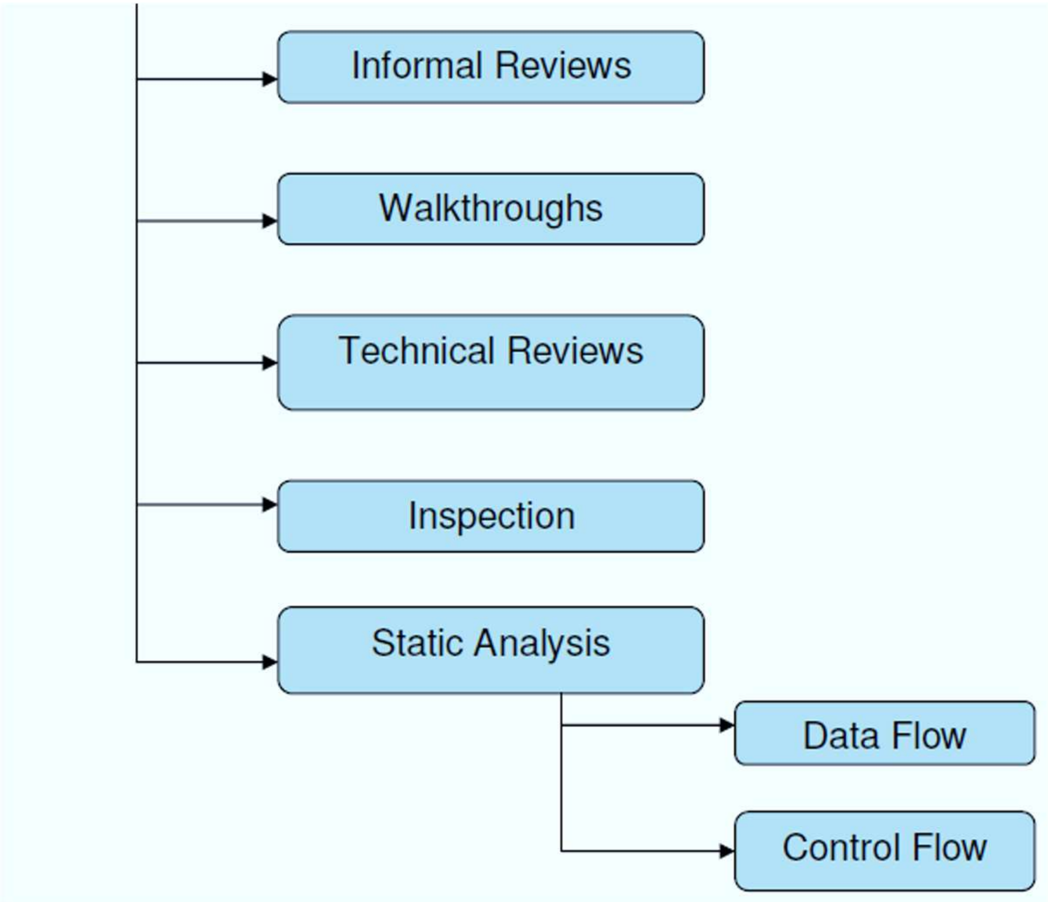

Software Analysis

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- Static technique
  - **it does not require execution of software code or artifacts**

- Why software analysis?
  - Because dynamic testing requires running code; analysis can be applied earlier in development
  - Because some kinds of defects are hard to find by testing (e.g., timing-dependent errors)
  - Because testing and analysis are complementary; each is best at finding different faults

Debugging

- ➢ **Basic Definitions**
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- Debugging is the development activity that
  - identifies the immediate causes (faults) of existing or possible failures
  - identifies the root causes of faults (errors)
  - fixes the defects
  - keeps all software artifacts consistent
- It is carried out by developers
  - not by testers

Evolution of Testing Definitions

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- 1979: the process of execution of a program or system with the intent of finding errors [Myers]
- 1983: any activity aimed at evaluating an attribute of a program or system. Testing is the measurement of software quality [Hetzel]
- 1990: the process of operating a system or component under specified conditions, observing or recording the results, and making an evaluation of some aspect of the system or component [IEEE]
- 2002: **a concurrent lifecycle process of engineering**, using, and maintaining testware in order to measure and improve the quality of the software being tested [Craing and Jaskiel]

Phases in a Tester's Mental Life [Beizer 1990]

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1. There's no difference between testing and debugging. Other than in support of debugging, testing has no purpose.
2. The purpose of testing is to show that the software works.
3. The purpose of testing is to show that the software does not work.
4. The purpose of testing is not to prove anything, but to reduce the perceived risk of not knowing to an acceptable value.
5. Testing is not an act. It is a mental discipline that results in low-risk software without much testing effort.

Last Phase Today [Actual]

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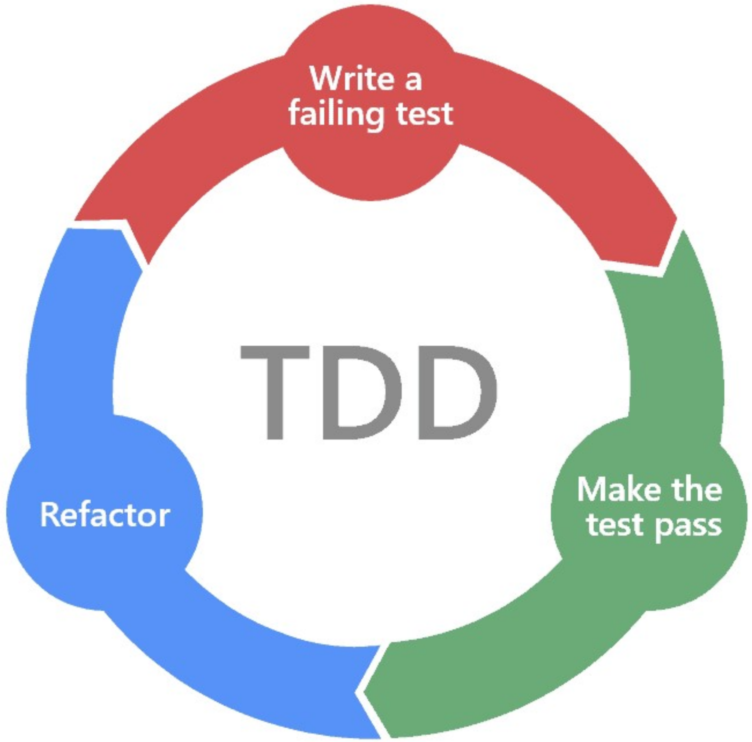
6. Probably we should try Test Driven Development!



Goals

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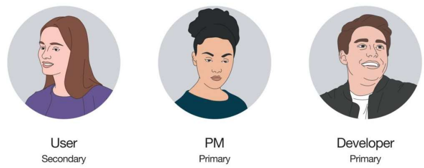
- "**Debug**" testing and analysis
  - find faults: a test is successful if it causes failures
  - support fault elimination
- "**Acceptance**" testing and analysis
  - estimate quality
  - increase confidence in software quality
    - correctness
    - reliability
    - …
  - increase confidence in the absence of certain faults
  - prevent errors

Stakeholders



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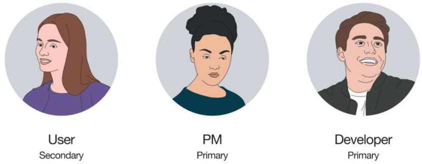
Developers

- list of errors and information to locate them
  - debugging
- feedback about common problems
  - prevention and improvement
- securing existing code by regression testing
  - spot side effects

Project and product managers

- open issues, test coverage
  - release decisions, progress monitoring
- issues and problems
  - risk estimation

Stakeholders



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- **Quality managers**
  - open issues, test coverage
    - quality assessment
  - common problems
    - prevention and process improvement
- **Customers and users**
  - open issues, test coverage
    - development progress monitoring
  - requirements-based tests
    - conformance to standards and specifications
  - …

Impact of the Type of Software on T & A

Basic
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➢ Why and How
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- **The type of software and its characteristics impact in different ways the testing and analysis activities**:
  - different emphasis may be given to the same properties
  - different (new) properties may be required
  - different (new) testing and analysis techniques may be needed

Impact of the Type of Software on T & A

Basic Definitions
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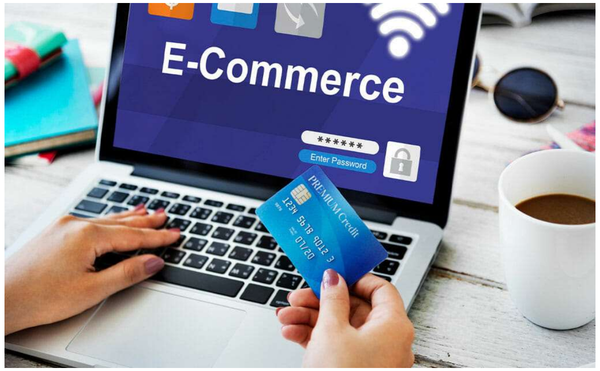
- **Dependability requirements differ radically between**
  - Safety-critical applications
    - flight control systems have strict safety requirements
    - telecommunication systems have strict robustness requirements
  - Mass-market products
    - dependability is less important than time to market

VS



Different Emphasis to the Same Properties

Basic Definitions
➢ Why and How
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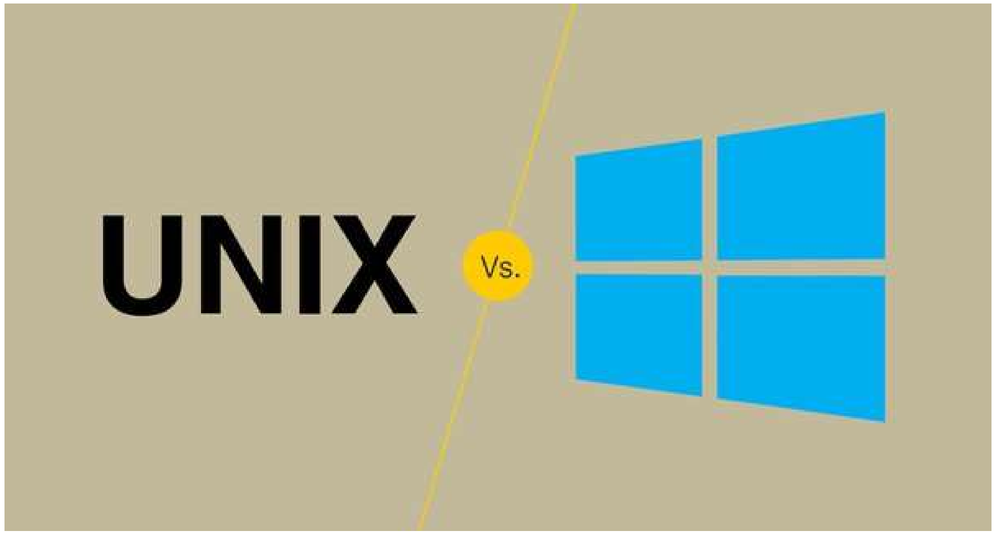
- **Dependability requirements can vary within the same class of products**:
  - reliability and robustness are key issues for multi-user operating systems (e.g., UNIX) less important for single users operating systems (e.g., Windows or MacOS)



Different Types of Software May Require Different Properties

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- **Timing properties**
  - deadline satisfaction is a key issue for real time systems, but can be irrelevant for other systems
  - performance is important for many applications, but not the main issue for hard-real-time systems
- **Synchronization properties**
  - absence of deadlock is important for concurrent or distributed systems, not an issue for other systems
- **External properties**
  - user friendliness is an issue for GUI, irrelevant for embedded controllers

Different Properties Require Different T & A Techniques

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- **Performance** & **Reliability** can be analyzed using statistical techniques
- **Deadline** satisfaction requires exact computation of execution times
- **Correctness** can be checked with test selection criteria based on structural coverage (to reveal failures) or weakest precondition computation (to prove the absence of faults)

Different T&A for Checking the Same Properties for Different Software

Basic Definitions
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- **Test selection criteria based on structural coverage are different for**
  - procedural software (statement, branch, path,…)
  - functional software (tail recursion, stack management)
  - object-oriented software (coverage of combination of polymorphic calls and dynamic bindings,…)
  - concurrent software (coverage of concurrent execution sequences,…)

```
// *  Functional vs
// !  Object Oriented vs
// ?  Procedural programming
```

Principles

Basic Definitions
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- Principles underlying effective software testing and analysis techniques include:
  - **Sensitivity**: better to fail every time than sometimes
  - **Redundancy**: making intentions explicit
  - **Partitioning**: divide and conquer
  - **Restriction**: making the problem easier
  - **Feedback**: tuning the development process

Sensitivity: Better to Fail Every Time than Sometimes

Basic Definitions
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- **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

Redundancy: Making Intentions Explicit

Basic Definitions
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- **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

Partitioning: Divide and Conquer

Basic Definitions
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- **Hard testing and verification problems can be handled by suitably partitioning the input space**
  - both structural and functional test 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, thus grouping homogeneous data together and determining partitions

Restriction: Making the Problem Easier

Basic
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- **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

Feedback: Tuning the Development Process

Basic Definitions
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- **Learning from experience**:
  - checklists are built on the basis of errors revealed in the past
  - error taxonomies can help in building better test selection criteria

Exaustive Testing Is Impossible

Basic Definitions
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- **Testing everything**
  - all combinations of inputs and preconditions

  is not feasible
  - except for trivial cases
- **One should focus on**
  - goals
  - priorities
  - costs
  - risks

Testing Is No Proof of Correctness

Basic Definitions
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- **Testing can show that defects are present**
  - it cannot show that there are no defects
- **Testing reduces the degree of belief that there are undiscovered defects**
  - and increases the confidence in the correctness of a program
- **Testing does not prove that software is completely correct**

Test Early

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- **Testing activities should start as early as possible in the software development lifecycle**
  - be focused on specific objectives
- **Fixing late a defect introduced early may cost up to 200 times the cost of fixing it right away**

Defect Clustering

Basic Definitions
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- **A small set of modules contains most of the defects discovered during pre-release testing, or show the most operational failures**
  - about 80% of the defects come from 20% of the modules (Pareto rule)
  - about 50% of modules appear to be defect-free
  - about 90% of the downtime comes from at most 10% of the defects

Pesticide Paradox

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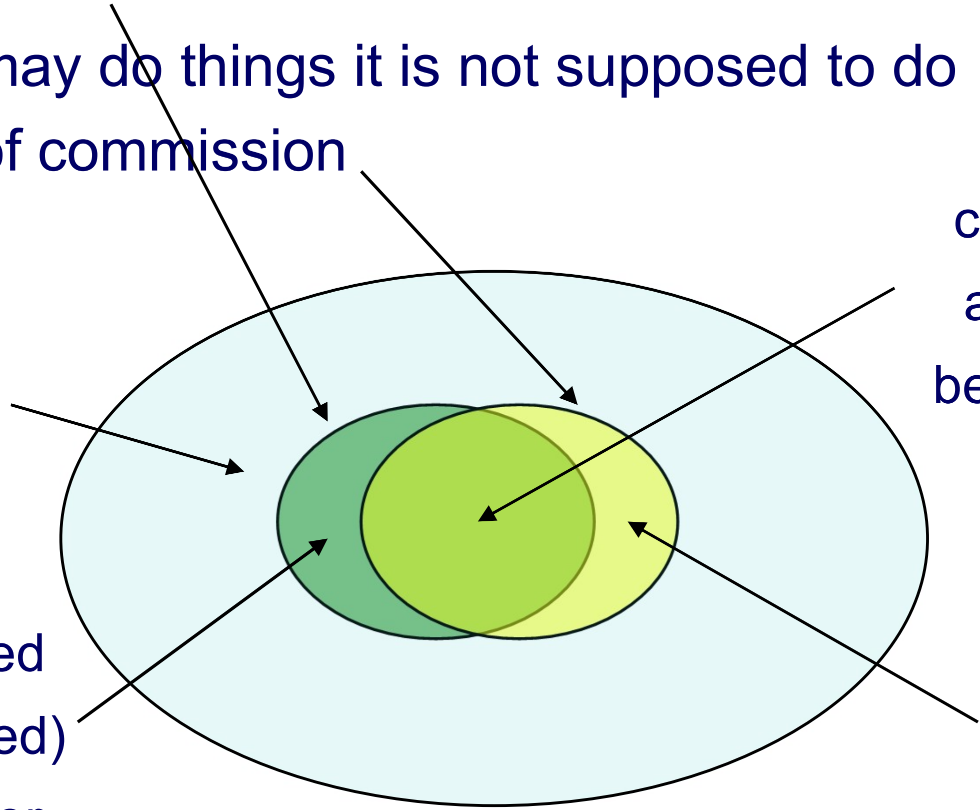
- Every method used to prevent or find bugs leaves a residue of subtler bugs against which those methods are ineffective
- The complexity of software and of bugs grows to the limits of our ability to master it

Faults of Omission and Commission

- Software may not do all that it is supposed to do
  - faults of omission
- Software may do things it is not supposed to do
  - faults of commission



V&V
(Verification & Validation)

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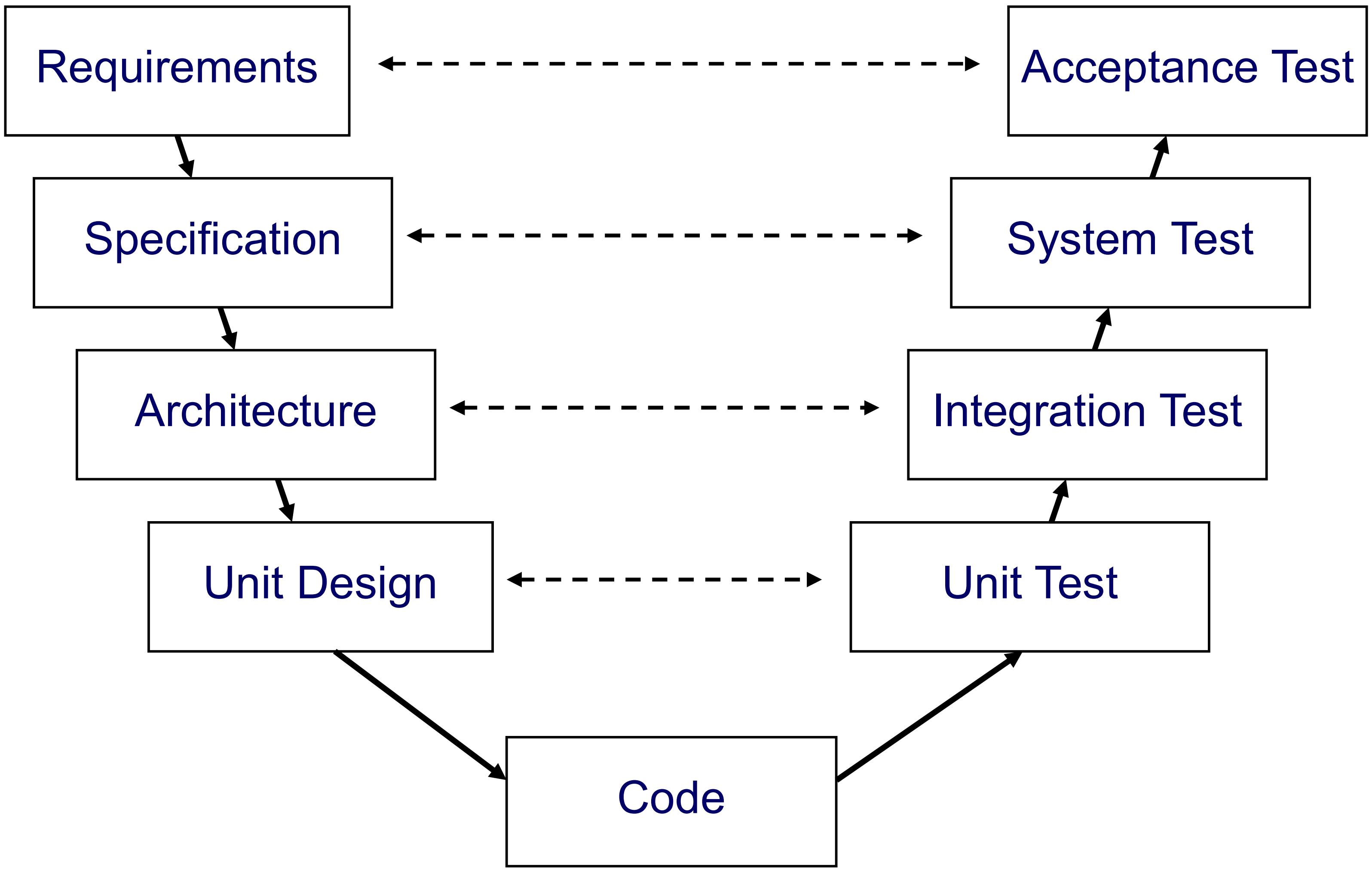

V&V (Verification & Validation)

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- **Verification**
  - confirmation that the artifacts (specification, design, models, code) properly reflect the requirements specified for them
  - building the product right
- **Validation**
  - confirmation that the product is fit or worth using for its operational mission
  - building the right product

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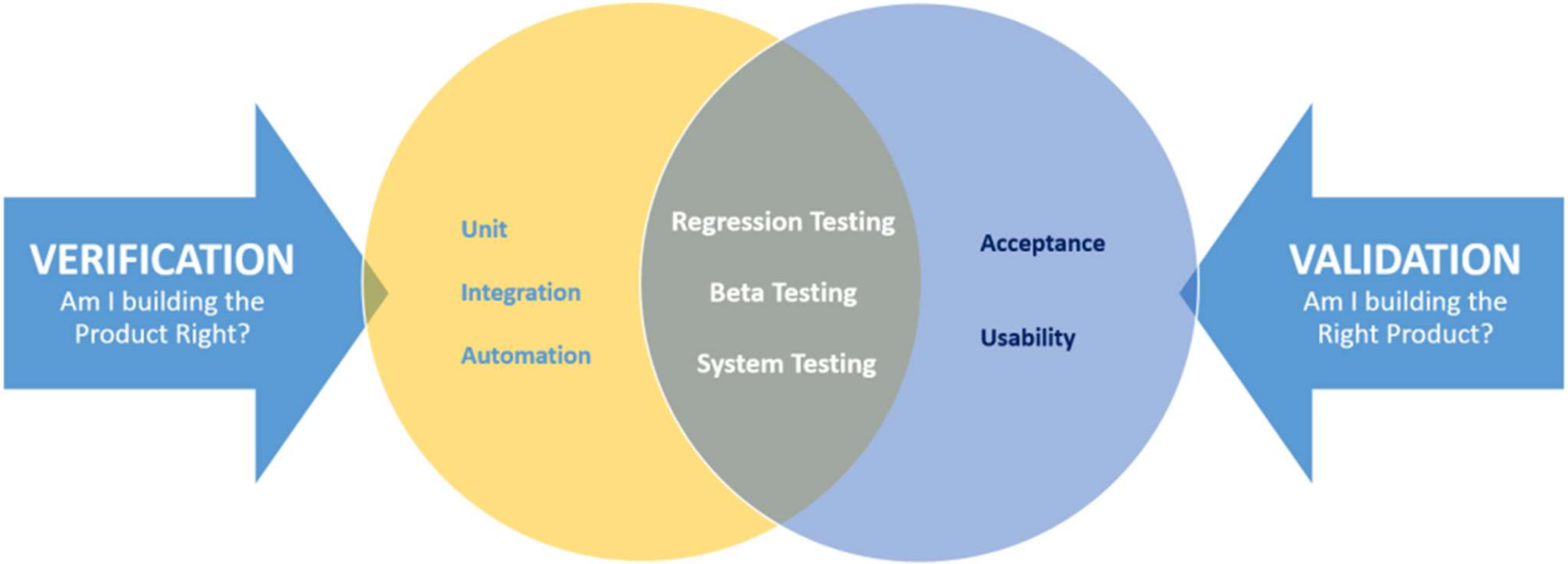

Unit Testing

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- **It is the process of testing the individual units of a program**
  - independently of the existence of the others
  - (also called component testing, module testing)
  - testers define the input domain for the units
  - it may require the construction of throwaway debugger code
  - it is often performed in a debugger

Unit Testing

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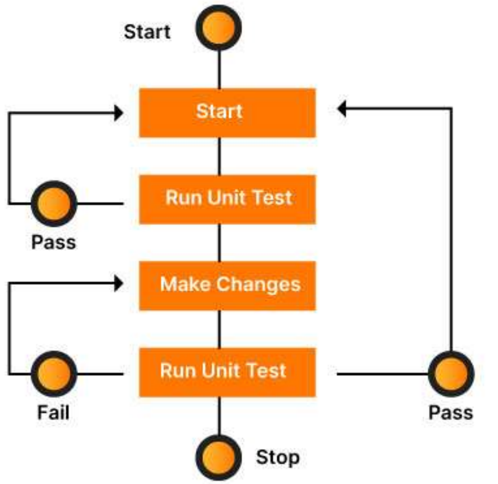
- **A unit is the smallest testable piece of software**
  - a class
  - a method
- **Unit testing is usually carried out by the programmer as part of coding**



Integration Testing

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- **It is the test process carried out to expose defects**
  - in the interfaces of units
  - in the interactions between units
  - the focus is on the subset of the domain that represents communication between the components
- **Carried out after unit testing**
  - it is somewhat assumed that units are “correct” in isolation
- **Some integration problems**
  - improper call or return sequences
  - inconsistent handling of data objects
- **Integration testing is usually carried out by**
  - tester, developer, or both

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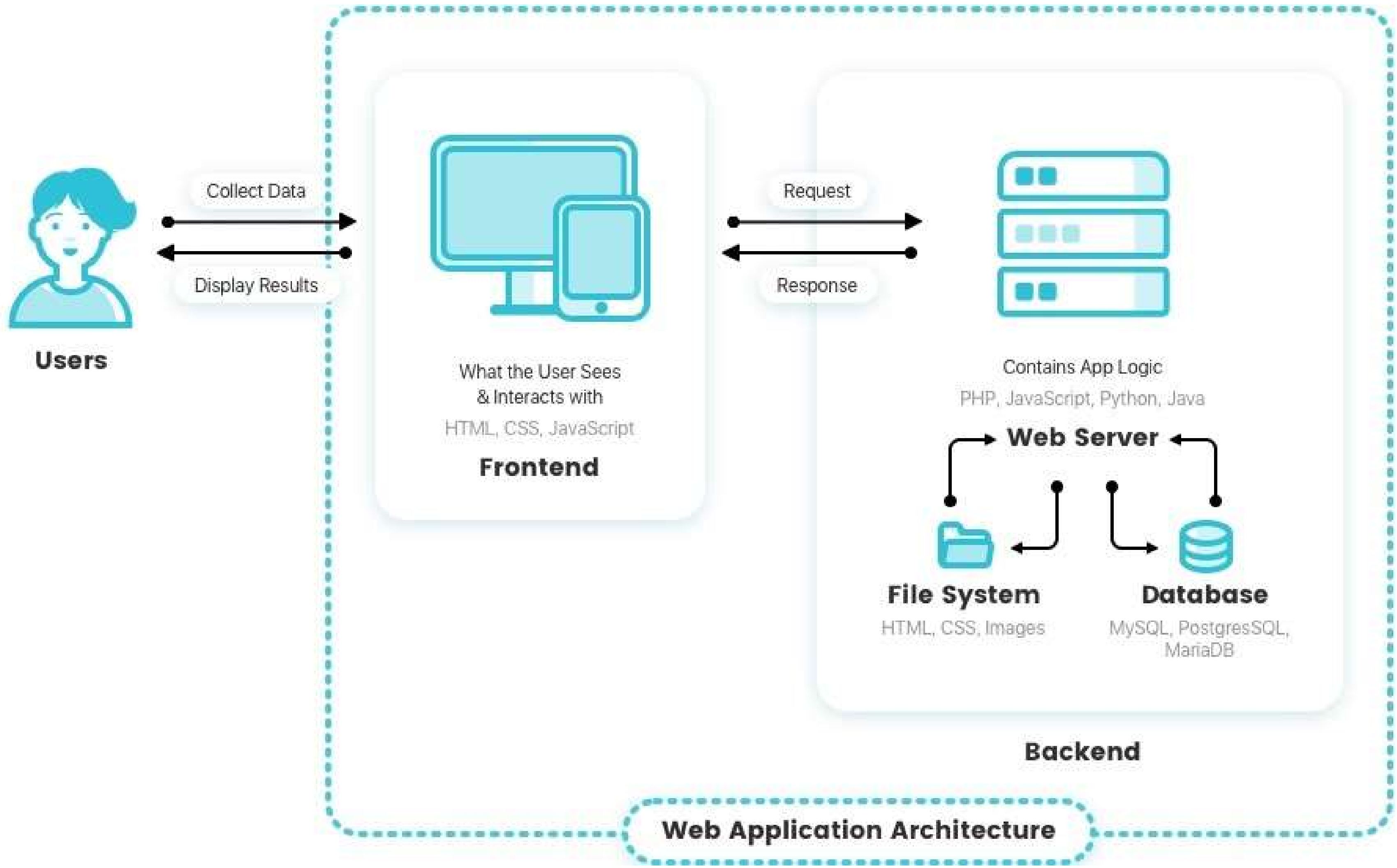

System Testing

Basic Definitions
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- It is the process of testing an integrated system to verify that it meets the requirements of the users/customers
- It concerns issues that can only be exposed by testing the entire integrated system or a major part of it
- The entire domain is taken into account
- **It usually includes testing for nonfunctional requirements**
  - performance, security, …

System Testing

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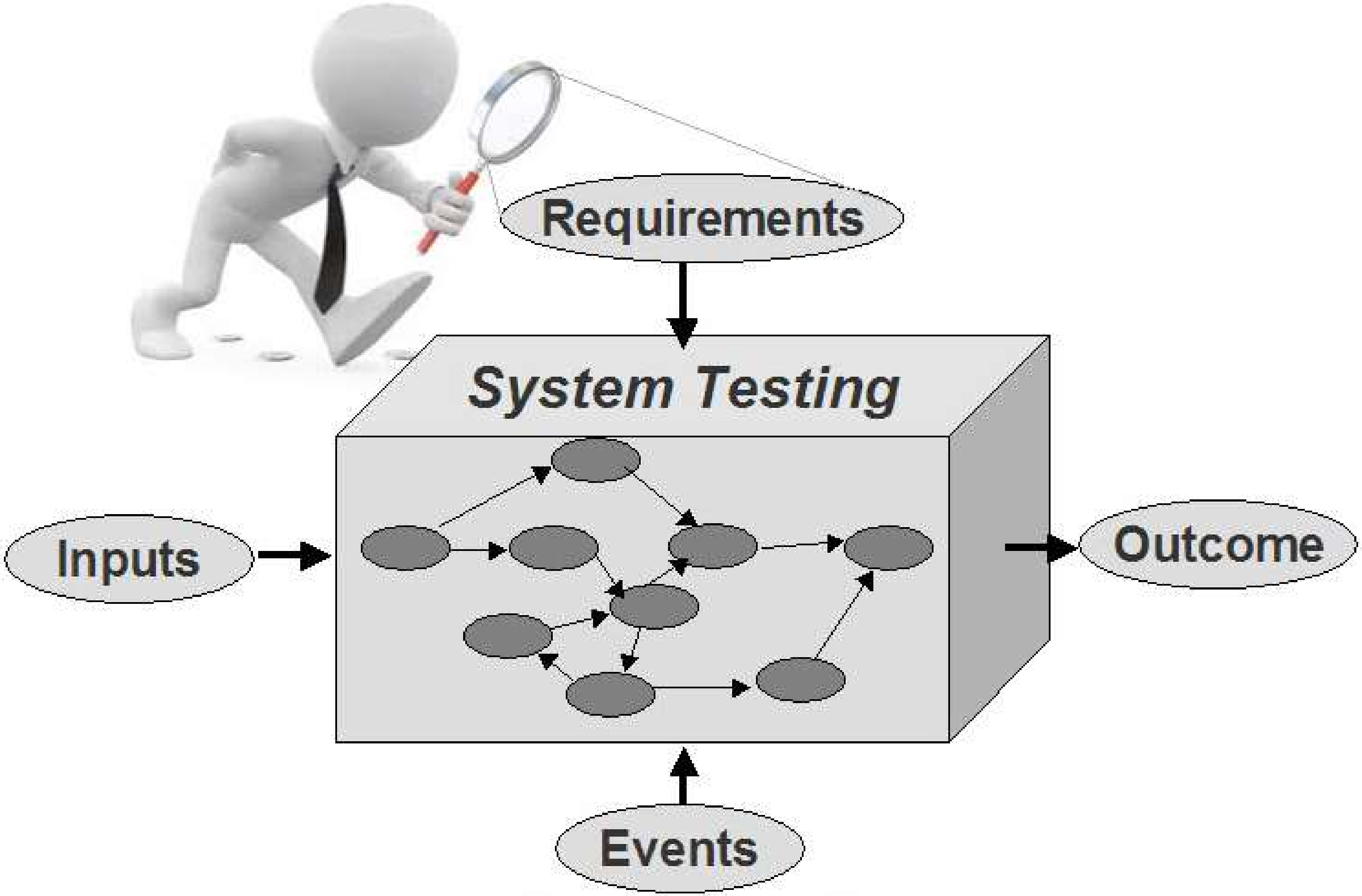

Acceptance Testing

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- Testing carried out to determine whether a system satisfies the requirements, to enable the customers or their consultants to determine whether the system is acceptable
- Acceptance testing is
  - **carried out with the customers**
  - in an environment that closely resembles the production environment
    - HW, SW, configurations, real data, following the organizations business processes
  - often defined in the contract as for
    - procedures, responsibilities, tests, and test data

Acceptance Testing

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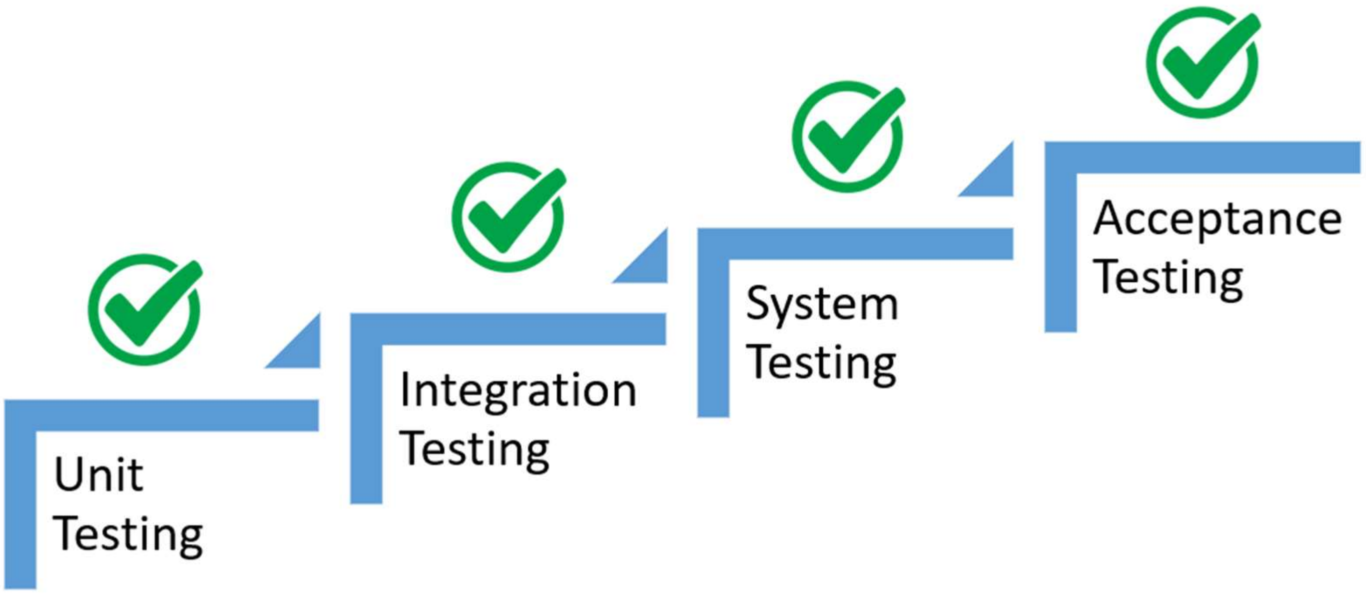

Beta Testing

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- Operational testing carried out by potential and/or existing users/customers at an external site to determine whether a system satisfies the user/customer needs and fits within the business processes
- Beta testing is
  - often carried out as a form of external acceptance testing for off-the-shelf software to acquire feedback from the market, so …
    - with the customers
    - **in an environment that closely resembles the production environment**
      - HW, SW, configurations, real data, following the organizations business processes
    - without any contractual obligations

Regression Testing

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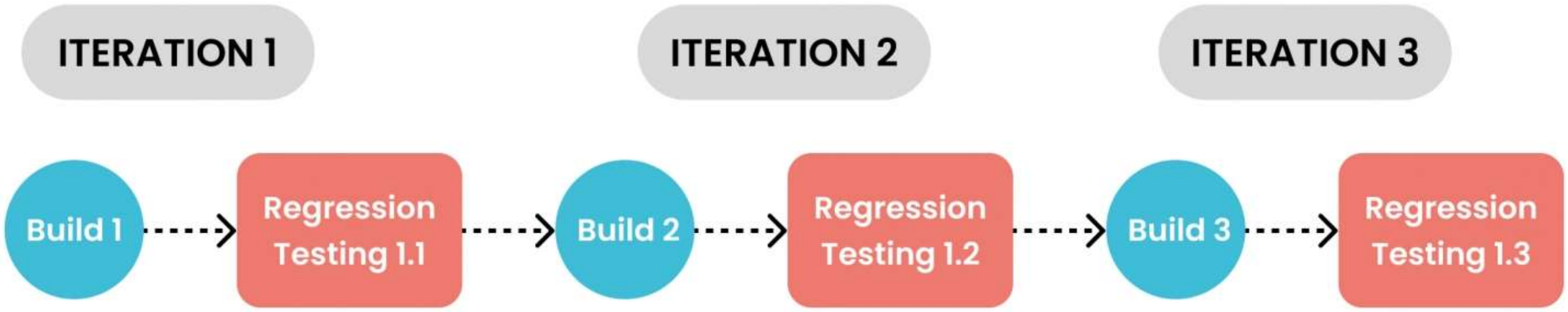
- Regression testing is used to check the behavior of new releases
- **Old test suites are used to check the correct functioning of new releases**
- Old test suites need to be maintained



Goals and Constraints

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Organization goals & priorities differ

- time-to-market, feature list vs. reliability, robustness; priorities for a pacemaker will not be the same as for a spreadsheet

Process constrains quality measures

- Example: Reliability is measurable only late in the process, so we may measure an earlier indicator (e.g., fault density)

Organizational Issues

Basic Definitions
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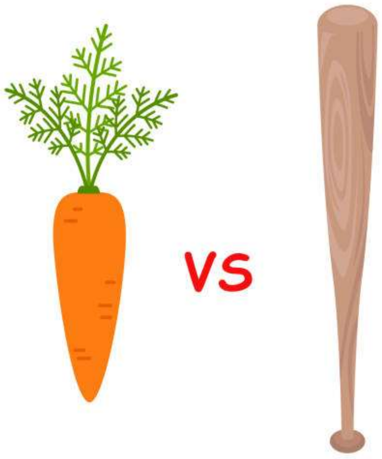
- **Risk and reward system must avoid "perverse incentive"**
  - example: reporting fault avoidance and identification must not be risky
- **Lines of responsibility influence behavior**
  - developer responsibility vs. independent test
  - who is the boss of the tester?
  - can problems be "thrown over the wall"?



Visibility

Basic Definitions
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- **How is status measured against goals, throughout development**
  - a general process issue, applies also to schedule, cost, etc.
- **Challenge is early visibility**
  - progress against QA plans
  - early assurances and predictors (e.g., of testability)

Testing Activities before Coding

Basic Definitions
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Planning

- acceptance test planning (requirements elicitation)
- system test planning (requirements specification)
- integration & unit test planning (architectural design)

Generation

- generate acceptance tests (requirements specification)
- create functional system tests (requirements specification)
- generate integration tests (high-level design)
- generate test oracles (detailed design)
- generate black box unit tests (detailed design)

Example Process

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Requirements Elicitation	Requirements Specification	Architectural Design	Detail Design	◊ ◊ ◊
• Identify qualities • Acceptance test planning	• Validate specifications • System test planning • Create functional tests	• Architectural design inspection • Integration & unit test planning • Automated architectural design analysis	• Design inspections • Generate oracles • Generate black-box test cases • Automated design analyses	

Testing Activities after Coding

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- **Generation**
  - create scaffoldings (unit coding)
- **Execution**
  - unit test execution (unit coding)
  - integration test execution (integration and delivery)
  - system test execution (integration and delivery)
  - acceptance test execution (integration and delivery)
  - regression test execution (maintenance)
- **Measuring**
  - coverage analysis (unit coding)
- **Generation**
  - delivery regression test suites (integration and delivery)
  - revise regression tests (maintenance)

Example Process

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Detail Design	Unit Coding	Integration & Delivery	Maintenance
Design inspections	Code inspections	Integration test execution	Regression test execution
Generate oracles	Create scaffolding	System test execution	Revise regression test suite
Generate black-box test cases	Unit test execution	Acceptance test execution	
Automated design analyses	Automated code analyses	Deliver regression test suite	
	Coverage analysis		

Test Process

Basic Definitions
Why and How
Principles
Some Facts
Types of Testing
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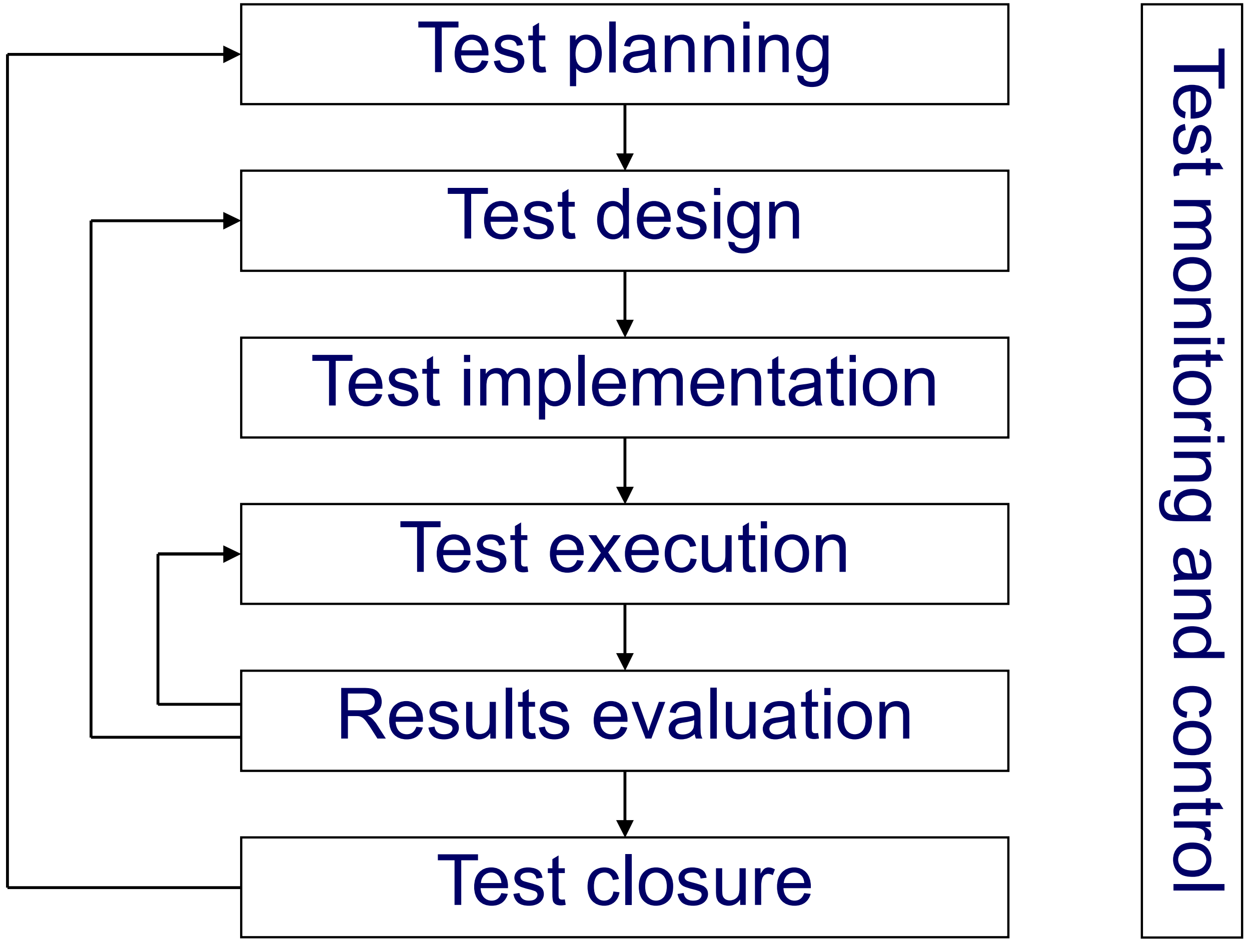

Overview of Testing Activities

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- **Test planning**
  - defining the objectives of testing and the specification of test activities in order to meet the objectives
- **Test control**
  - continuous comparison of actual progress against the plan and reporting the status
  - involves taking actions necessary to meet the objectives
- **Test analysis and design**
  - general testing objectives are transformed into tangible test designs

Overview of Testing Activities

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- **Test implementation**
  - test conditions are transformed into test cases and testware
- **Test execution**
  - running the test cases according to the planned sequence
  - comparing actual results with expected results
  - reporting of any discrepancies
- **Evaluating exit criteria**
  - test execution is assessed against the defined objectives
- **Test closure activities**
  - collection and archival of data from completed test activities to consolidate experience, testware, facts, and data

Test Planning

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- Determining the scope of testing, identifying the objectives
- Determining the test approach
  - techniques, test items, coverage, identifying and interfacing the teams involved in testing, etc.
- Determining the required test resources
  - e.g., people, hardware
- Scheduling the test activities
  - analysis and design, test implementation, execution and evaluation, etc.
- Determining the exit criteria

Test Control

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- Measuring and analyzing results
- Monitoring and documenting
  - progress, test coverage, and exit criteria
- Initiation of corrective actions

Test Analysis and Design

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- Reviewing the test basis
  - requirements, architecture, design, interfaces, etc.
- Identifying test requirements and required test data based on
  - analysis of test items, specification, behavior and structure
- Designing the test
- Evaluating testability of the system
- Designing the test environment set-up and identifying any required infrastructure and tools

Test Implementation and Execution

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- Developing and prioritizing test cases, creating test data, writing test procedures
- Creating test suites from the test cases
- Verifying that the test environment has been set up correctly
- Executing test cases
  - manually or by using test execution tools
- Logging the outcome of test execution
- Comparing actual results with expected results
- Reporting discrepancies as incidents and analyzing them in order to establish their cause
  - a defect in the code, in specified test data, in the test document, or a mistake in the way the test was executed

Evaluating Exit Criteria and Reporting

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- Checking test logs against the exit criteria specified in test planning
- Assessing if more tests are needed or if the exit criteria specified should be changed
- Writing a test summary report

Test Closure Activities

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- Archiving
  - testware
  - the test environment
  - the test infrastructure

  for later reuse
- Handover of testware to the maintenance team
- Analyzing lessons learned for future projects

The Scaffolding Problem

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- **How to provide the environment for executing the tests**
  - scaffolding is extremely important for unit and integration testing
  - scaffolding may require a conceivable coding effort
  - good scaffolding is an important step toward efficient regression testing

The Scaffolding Problem

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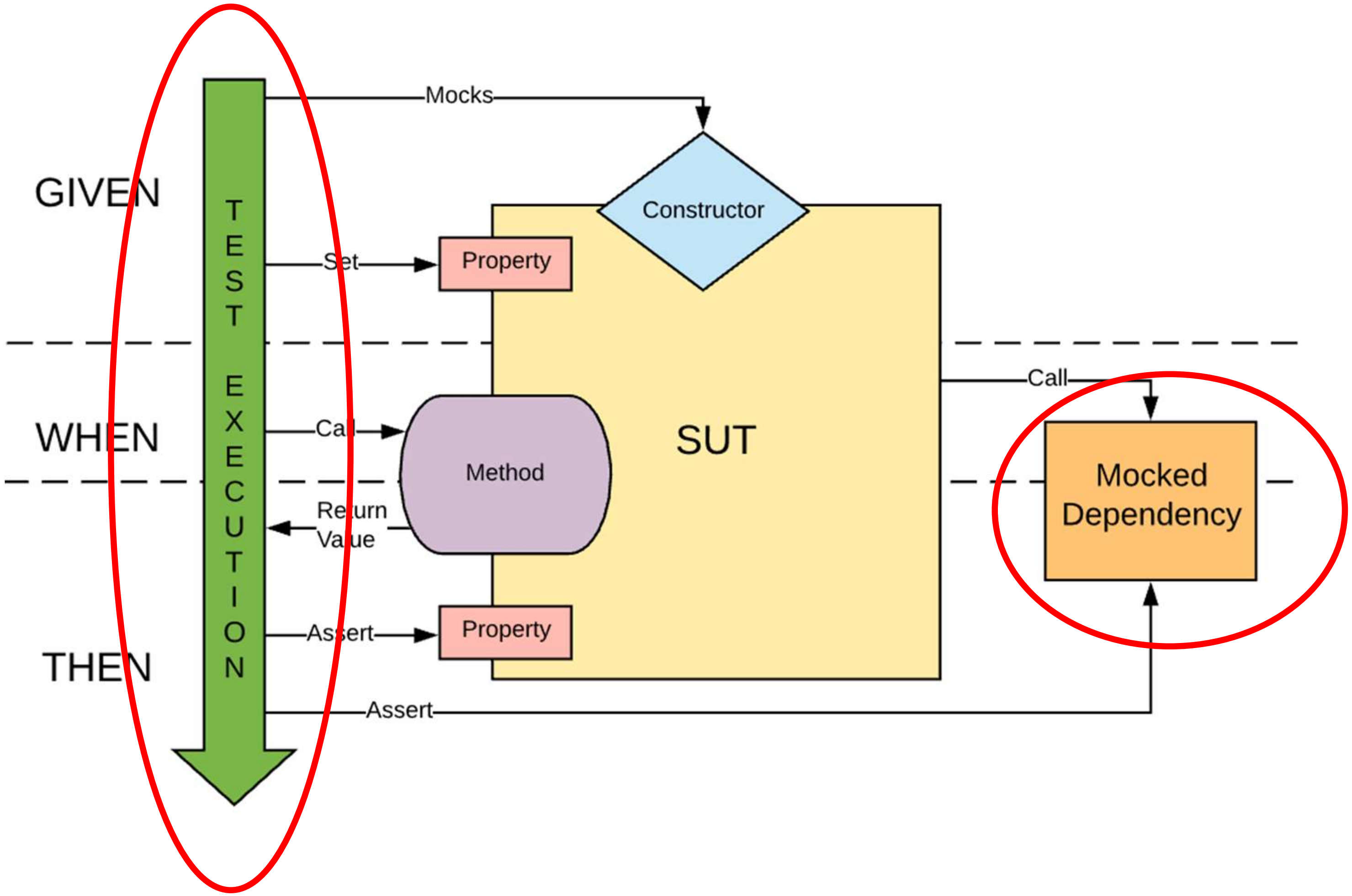
Learning Psychology



The Oracle Problem

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- **How to inspect the results of executing test and reveal failures**
  - Oracles are required at each stage of testing
  - Automated test oracles are required for running large amounts of tests
  - Oracles are difficult to design - no universal recipe
  - Oracles may be designed with different techniques

The Oracle Problem

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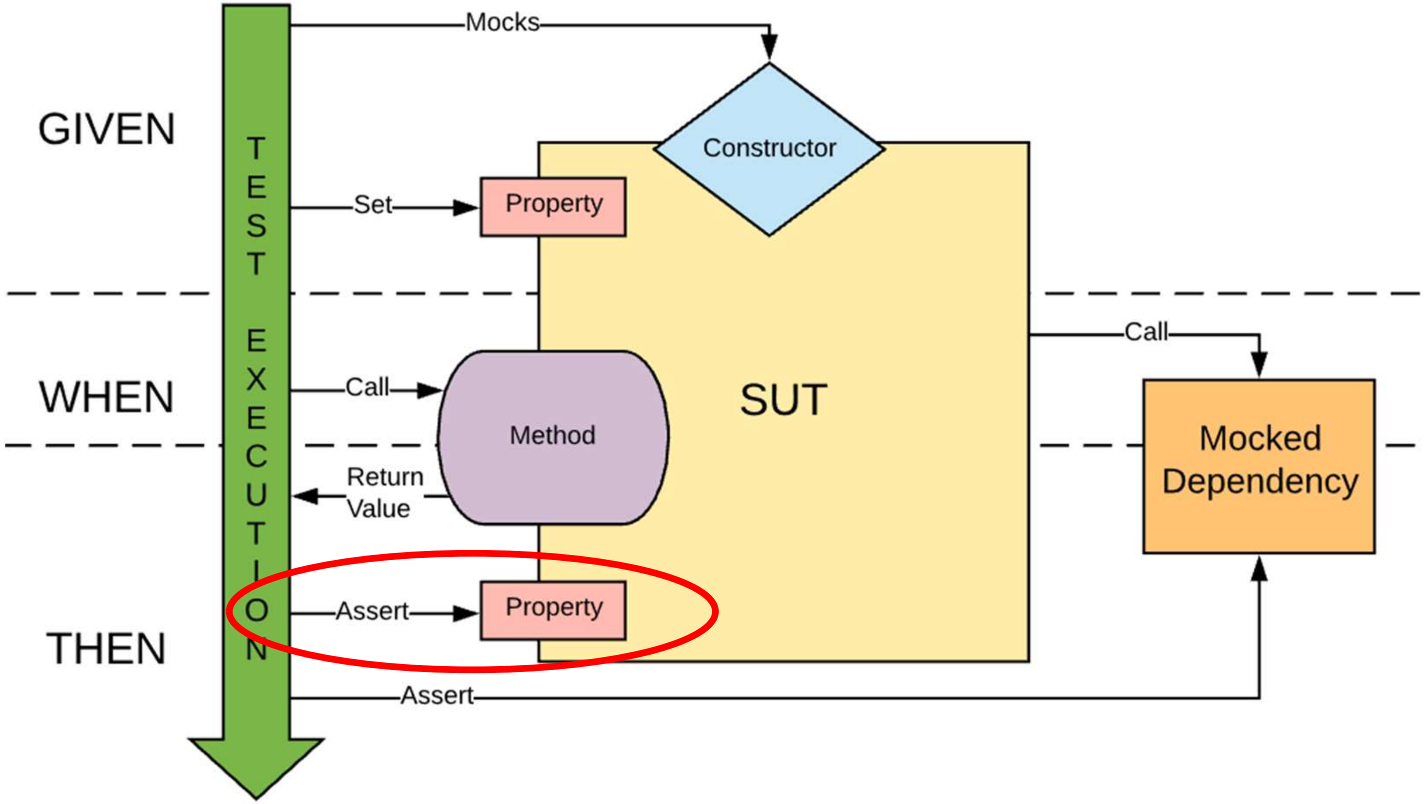

The Test Case Generation Problem

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- **How to generate test data**
- Partition testing: divide program in (quasi-) equivalence classes
  - random
  - functional (black box)
    - based on specifications
  - structural (white box)
    - based on code
  - fault based
    - based on classes of faults

Test Case Generation

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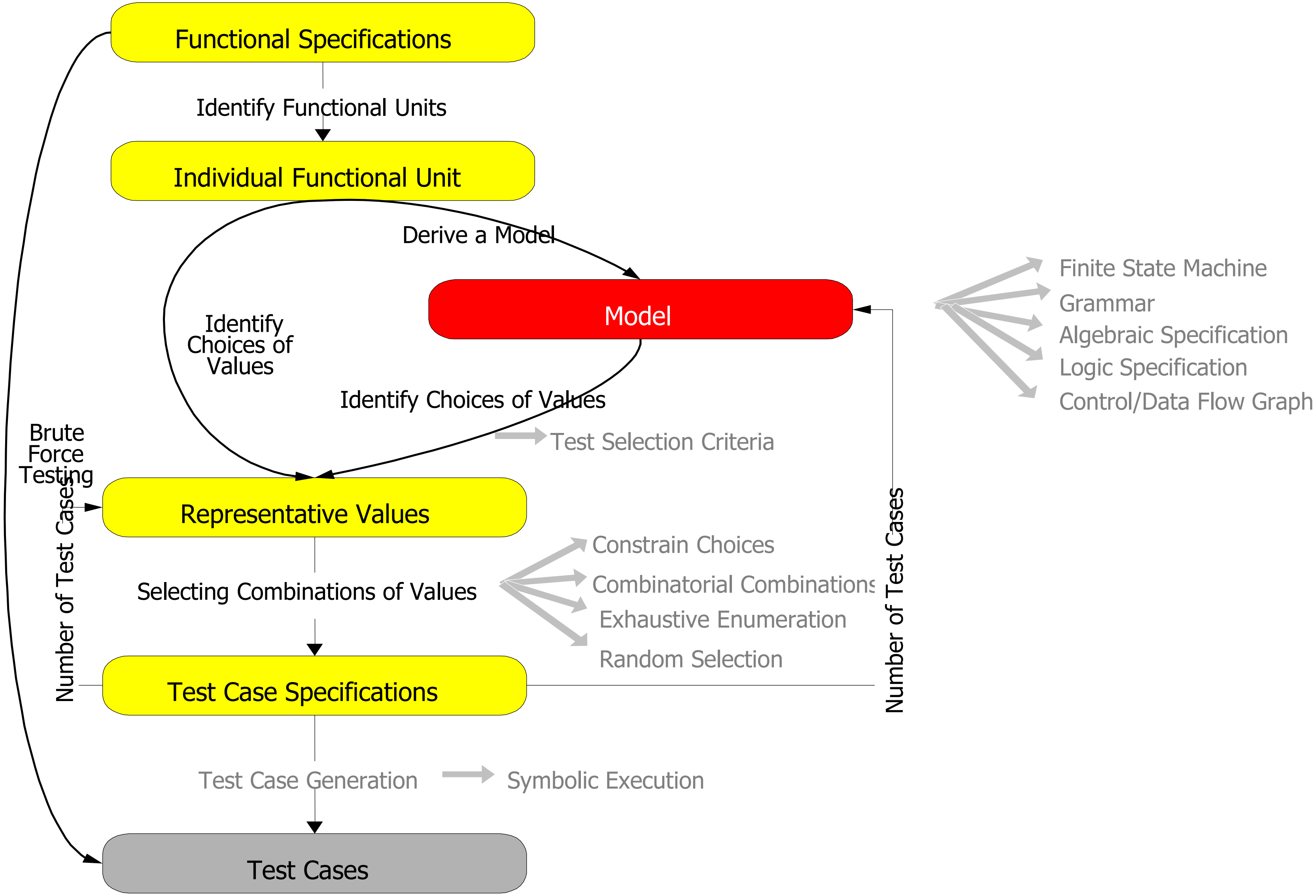

Black Box

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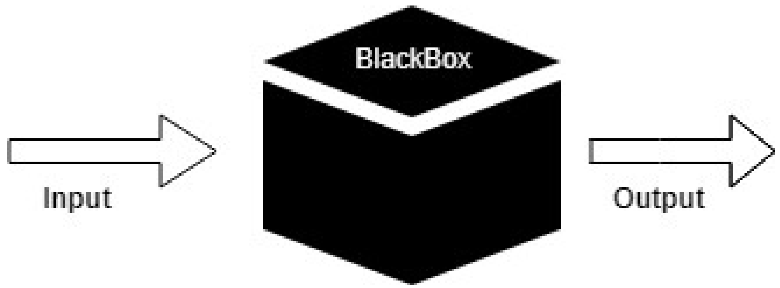
- **It depends on the specification notation**
- It scales up
  - different techniques at different granularity levels
- It may not reveal the presence of code-specific faults
  - same specification implemented with different modules



White Box

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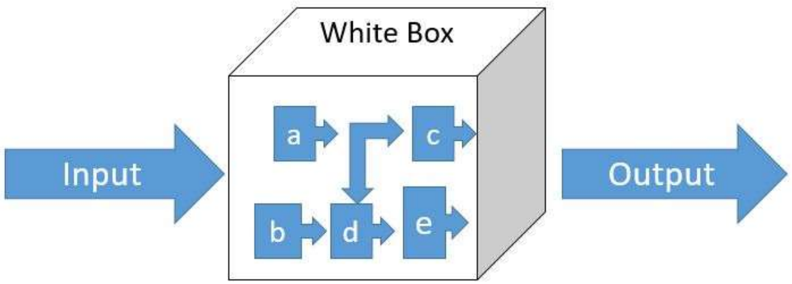
Psychology

- **It is based on control or data flow coverage**
- It does not scale up
  - mostly applicable at unit and integration testing level
- It cannot reveal missing path errors
  - part of the specification that is not implemented



The Termination Problem

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- **The main problems for managers**
- **When resources (time and budget) are over**
  - no information about the efficacy of the test
  - BUT… resource constraints must be taken into account
- **When some coverage is reached**
  - no assurance of software quality
  - it can be a reasonable and objective criterion
  - it can be (partially) automated
- **Rules of thumb**
  - 25% to 50% (and more) of project costs

Too Much Testing

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- Waste of resources
- Delayed time to market
- Increased costs
- Delayed schedules
- Defects remain

Too Little Testing

Basic Definitions
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- Defects remain and cause loss of or damage to lives and property
- Customer dissatisfaction
- High costs to repair
- Costs of post-sale support

Quality Monitoring Activities

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- **Sequential models (waterfall)**
  - Risk assessment, robust specifications
  - Specify and design for testability
  - Acceptance test plan and earlier measures
- **Risk-based models (spiral)**
  - All of the above (for each wind), plus choosing incremental builds for early assessment

Designing a Feedback Mechanism

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- **We lack good data about the nature and sources of faults**
  - Information for fault avoidance, early removal, and better measurement

- **Feedback can be built into the process**

Product vs. Process Improvement

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- Product improvement
  - Fault is detected (by inspection, testing, user report, ...)
  - **Fault is diagnosed and repaired**

- Process improvement
  - Faults are detected (and maybe repaired)
  - **Fault record is analyzed to tune process**

Steps in Fault Analysis

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- **What are the faults?**
  - Categorize by kind (Memory leak, interface error, mis-feature, etc.)
  - And by severity
- **When did they occur? And when were they found?**
  - Coding? Design? Requirements?
- **Why did they occur?**
  - Look for "root causes"
- **How could they be prevented?**

Root Cause Analysis

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- **One rule of thumb: “Ask why six times”**
  - Example: Memory leak because ...
    - failed to release memory in exception handler, because
    - didn’t know what needed to be cleaned up there, because
    - resource management scheme assumes normal flow of control, because
    - exceptional conditions were an afterthought dealt with late in design

Prevention Measures

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- Prevent fault insertion or make earlier detection likely *(these may not be different)*
- Sometimes: Tweaking an existing step
  - Example: Revising checklists for inspection
- Other times: New practices
  - Example: Exception handling in all resource managers

Aim is cost-effectiveness, not perfection

Tester's Description

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- [McConnell] Job interview: How would you describe your approach to software development? … such as carpenter, firefighter, architect, artist, author, explorer, scientist …My favorite answer: "During software design, I'm an architect. When I'm designing the user interface, I'm an artist. During construction, I'm a craftsman. And during testing, I'm one mean son of a bitch!"

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- **Testing is a destructive activity**
  - a successful test is a test that causes a failure
- **Testing is an extremely creative and intellectual challenging activity**
  - if a program is tricky to write, it is usually even trickier to test …
- **Testing and development need to work together to improve software quality**
  - testers cause failures
  - developers fix defects
- **The best tester is not the one who embarasses the most developers, but the one who gets the most bugs fixed.**

Should Developers Test Their Own Code?

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- **Advantages**
  - detailed knowledge of the program to be tested
  - instant feedback about defects
  - guidance for debugging
  - no communication overhead
  - more confidence in one's own code
  - double-checking the specifications
  - learning from mistakes

Should Developers Test Their Own Code?

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- **Disadvantages**
  - “blindness” for one’s own mistakes
  - overly optimistic, biased view
  - no critical mindset to break one’s own program
  - problems due to misunderstood specifications cannot be found
  - “changing hat” problem
  - unwillingness to report problems
  - insufficient knowledge of test methods and tools

Levels of Independence

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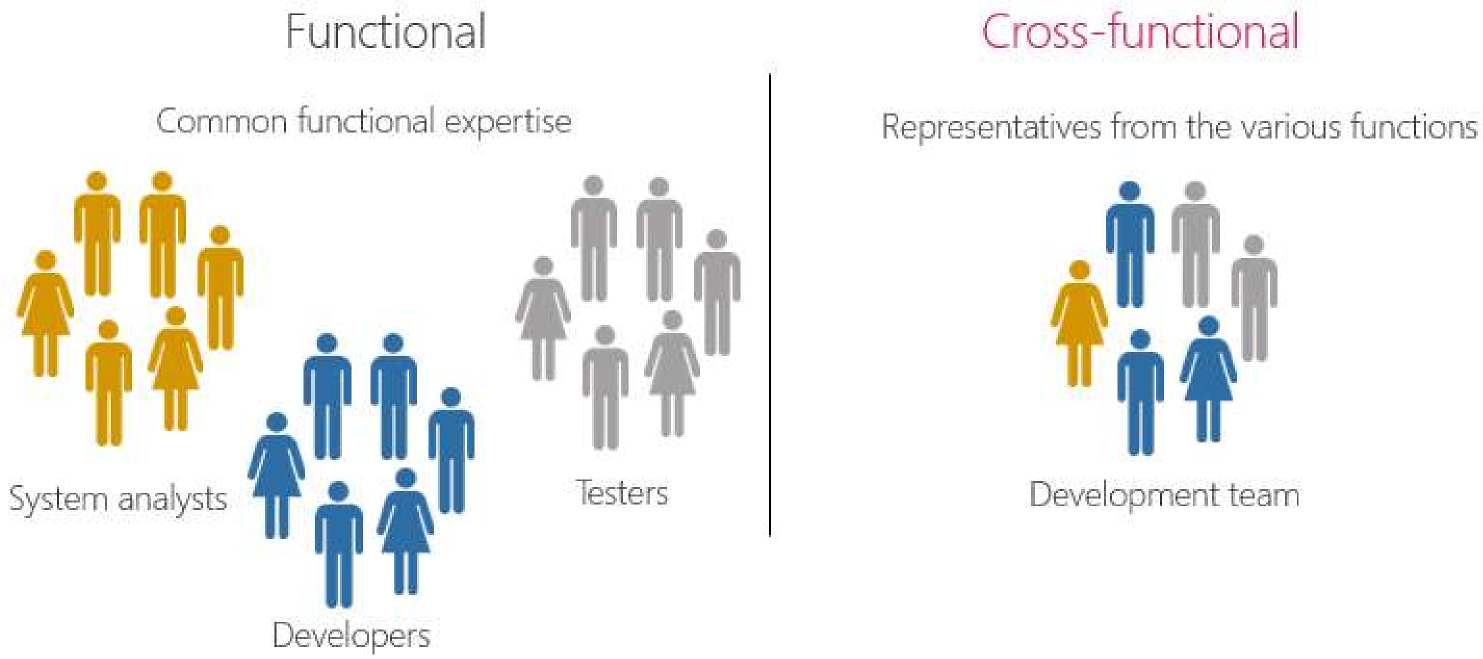

Levels of Independence

Basic Definitions
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➢ Psychology

- In increasing order of independence
  - **developer testing**: testing by the person(s) who wrote the software
  - **pair testing**: testing by another person from the development team too
  - **test team**: testing by a person from a different organizational group
  - **test lab/external assessor**: testing by persons coming from a different organization
    - outsourcing
    - certification body