Testing & Test-cases

http://d3s.mff.cuni.cz

Department of Distributed and Dependable Systems

D3S

Software Engineering for Dependable Systems

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faculty of mathematics and physics

Testing

Validation and Verification (V&V)

- Validation: Building the right product.
  - Does the software meet the expectations of the customer?
- Verification: Building the product right.
  - Does the software conform to its specification?
- When to check quality:
  - In some software development processes, V&V is done as early as possible (e.g., prototyping, agile).
- It is understood that problems discovered early are easier and less expensive to fix.
- However, there are parts of the specification that can be checked only when the system is ready to be deployed.

Functional and Nonfunctional Properties

- Functional properties are related to what a system (or a part of it) is supposed to do.
  - Use cases, use-case diagrams (UML)
- Nonfunctional (or extrafunctional) properties are related to how the system carries out an operation.
  - Performance; e.g., response time or throughput.
  - Security.
  - Availability; e.g., uptime 99.999%.
  - Some nonfunctional properties are more difficult to check during early stages of the development process.

Product Qualities

- Internal qualities
  - Maintainability, extensibility, portability, testability, ...

- External qualities
  - usefulness qualities:
    - usability, performance, security, interoperability
  - dependability
    - correctness, reliability, safety, robustness

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Dependability Qualities

- Correctness:
  - A program is correct if it is consistent with its specification
    - seldom practical for non-trivial systems
- Reliability:
  - likelihood of correct function for some “unit” of behavior
    - relative to a specification and usage profile
    - statistical approximation to correctness (100% reliable = correct)
- Safety:
  - preventing hazards
- Robustness
  - acceptable (degraded) behavior under extreme conditions

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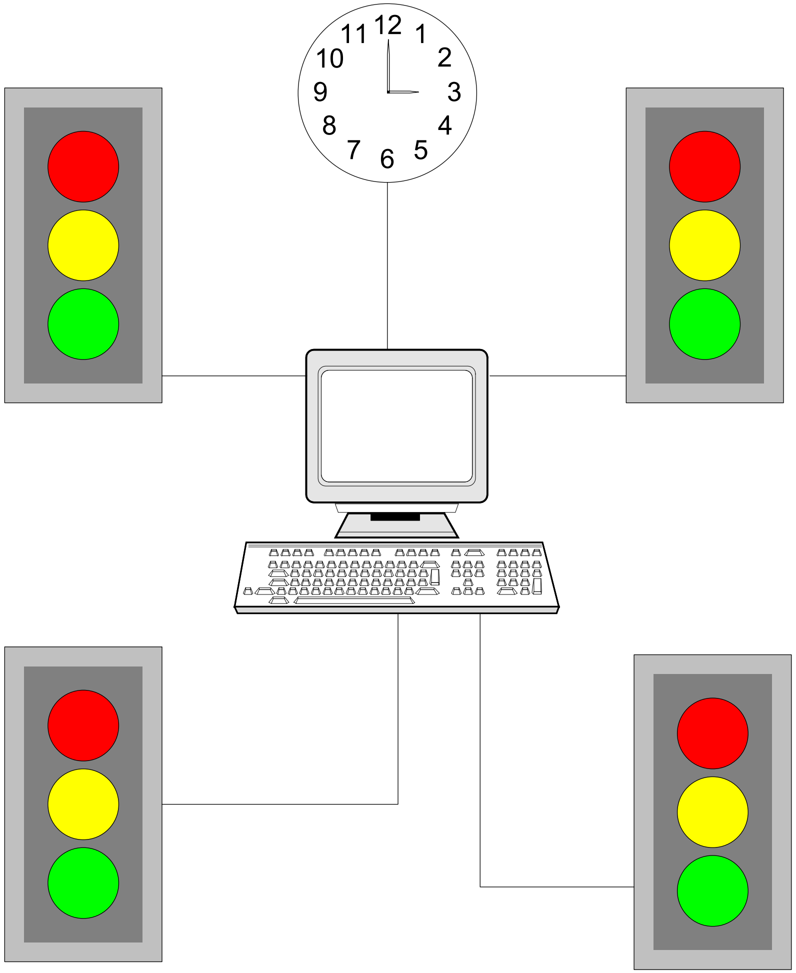
Example of Dependability Qualities



- **Correctness, reliability:** let traffic pass according to correct pattern and central scheduling
- **Robustness, safety:** Provide degraded function when possible; never signal conflicting greens.
  - Blinking red / blinking yellow is better than no lights; no lights is better than conflicting greens

Tools for Validation and Verification

- Software inspection analyses requirement documents, designs, and source code (the latter, often automatically)
  - It is a **static** method: It does not require an executable artefact, hence it can be applied throughout all the stages of software development.
- Software testing uses an executable representation of the system
  - It is a **dynamic** method: The product is exercised with test input data
  - The resulting output is checked against the specification.
  - If there is no agreement, an error is found which must be fixed.
  - Different forms according to the knowledge assumed for the system under study: black-box or white-box.

V&V and the Development Process

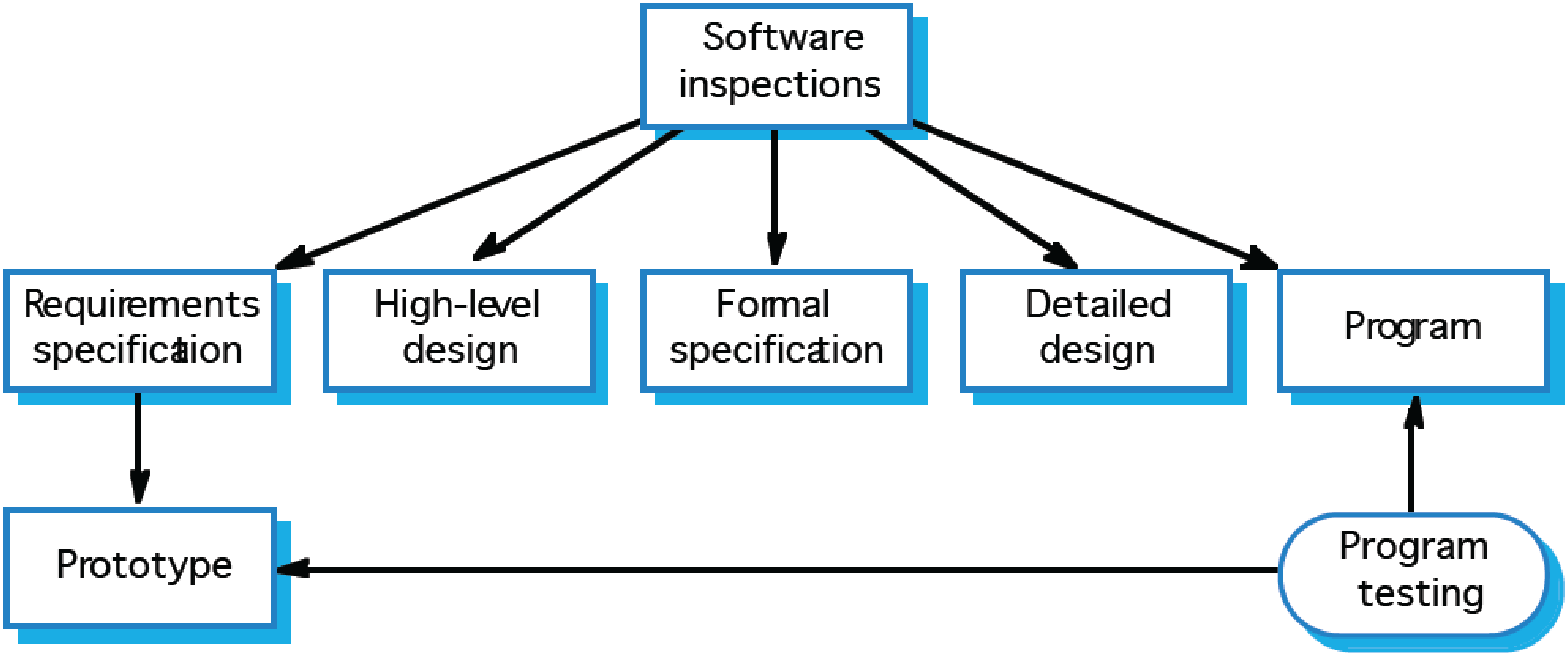


Figure taken from http://www.cs.st-andrews.ac.uk/ifs/Books/SE7/Presentations/index.html

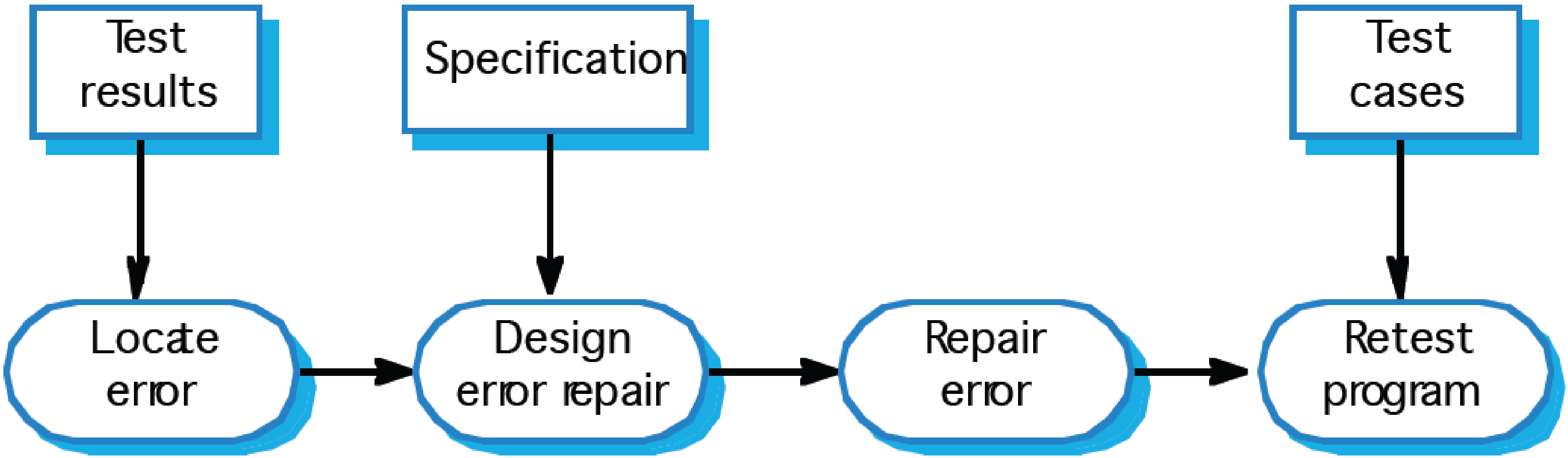
Important Point

- Software inspections can only check the agreement between a program and its specification.
- They cannot show that the software is operationally useful.
- Nor can they check nonfunctional properties (but may give hints).
- Software testing can only detect errors, not prove their absence.
- Testing all possible execution paths for nontrivial programs is impossible.
- They are not competing techniques, rather they are complementary.

Related Activity: Debugging

- Defect testing and debugging are distinct processes.
- Verification and validation is concerned with establishing the existence of defects in a program.
- Debugging is concerned with locating and repairing these errors.
- Debugging involves formulating a hypothesis about program behaviour then testing these hypotheses to find the system error.

The Debugging Process

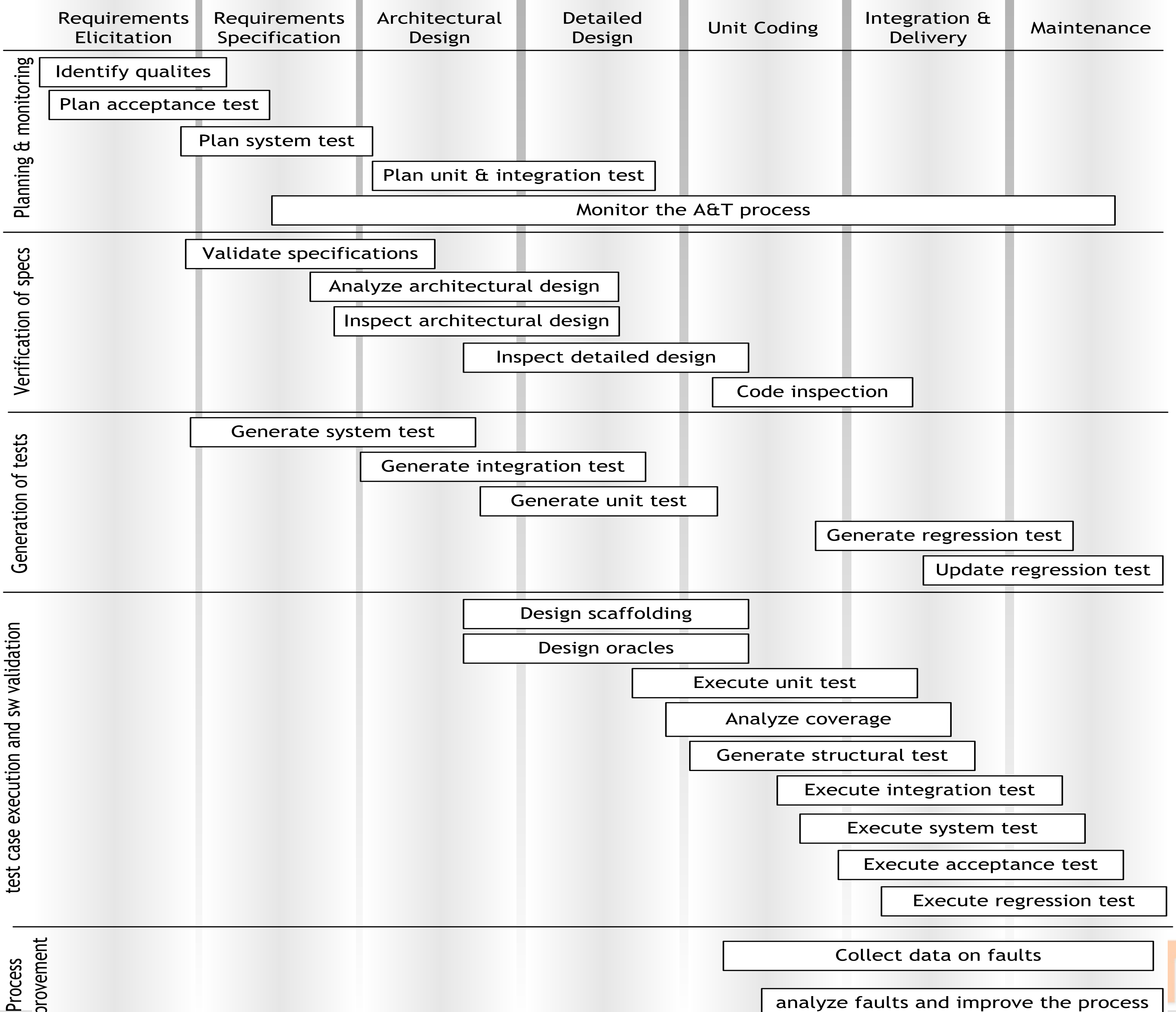


Key activity: regression testing

- Re-run the tests (or a subset of them) after a problem is fixed.
- It is not uncommon that a fix introduces errors elsewhere!

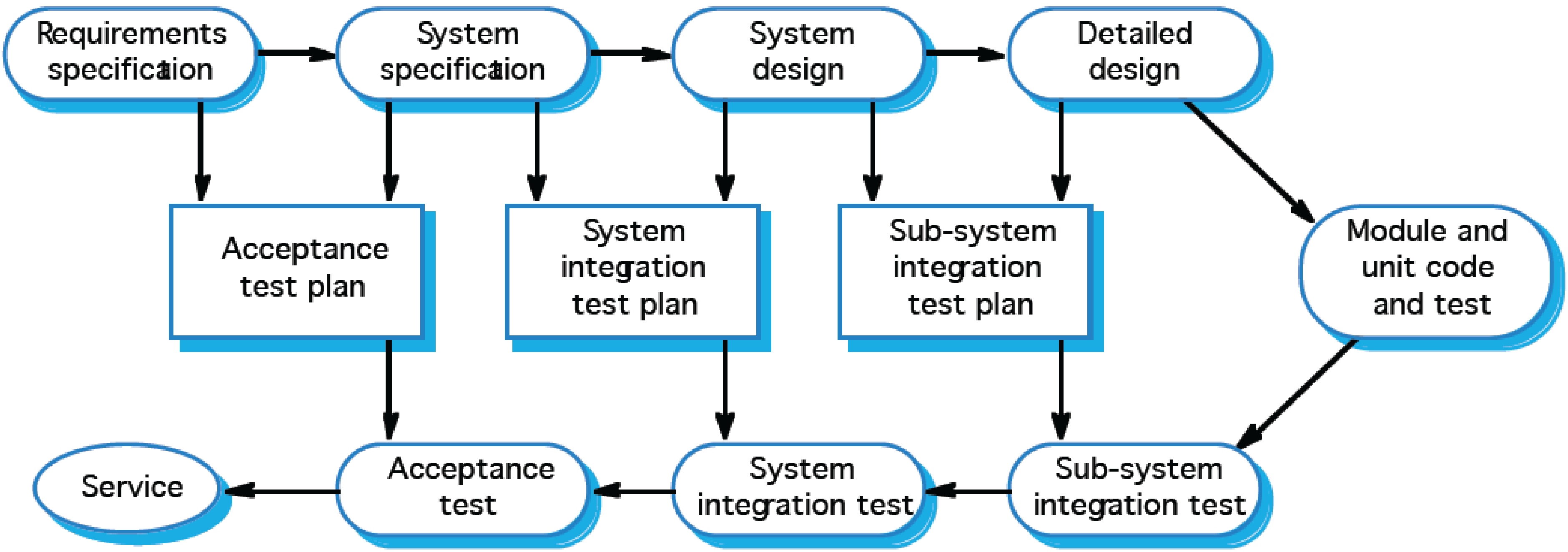
Software Qualities and Process

- Qualities cannot be added after development
  - Quality results from a set of inter-dependent activities
  - Analysis and testing are crucial but far from sufficient.
- Testing is not a phase, but a lifestyle
  - Testing and analysis activities occur from early in requirements engineering through delivery and subsequent evolution.
  - Quality depends on every part of the software process
- An essential feature of software processes is that software test and analysis is thoroughly integrated and not an afterthought



Taken from http://ix.cs.uoregon.edu/~michal/book/ (© Mauro Pezzè & Michal Young)

The V-Model of Development



- For instance, in an object-oriented design:

  classes → components → overall system

Figure taken from http://www.cs.st-andrews.ac.uk/ifs/Books/SE7/Presentations/index.html

Structure of a Software Test Plan

- Testing process
- Requirements traceability
  - Tests should cover at least all the requirements provided by the users.
- Tested items
  - Complete coverage of all artefacts is in general very difficult (too expensive). Items to be tested should be listed here.
- Testing schedule
- Test recording procedures
  - Results must be recorded to give the possibility of checking later whether tests have been done correctly.
- Hardware and software requirements
- Constraints
  - For example, staff shortages, deadlines, . . .

Software Inspections

- Empirical studies have shown that they are effective in detecting large amounts of errors in software.
- Many errors may be detected in a single inspection.
  - Recall, it is a static methods which does not require a running system.
  - With software testing, usually only one defect at a time may be discovered: the system usually crashes when an error occurs.
- They reuse domain and programming language knowledge: reviewers are likely to have seen the types of error that commonly arise.

Program Inspection

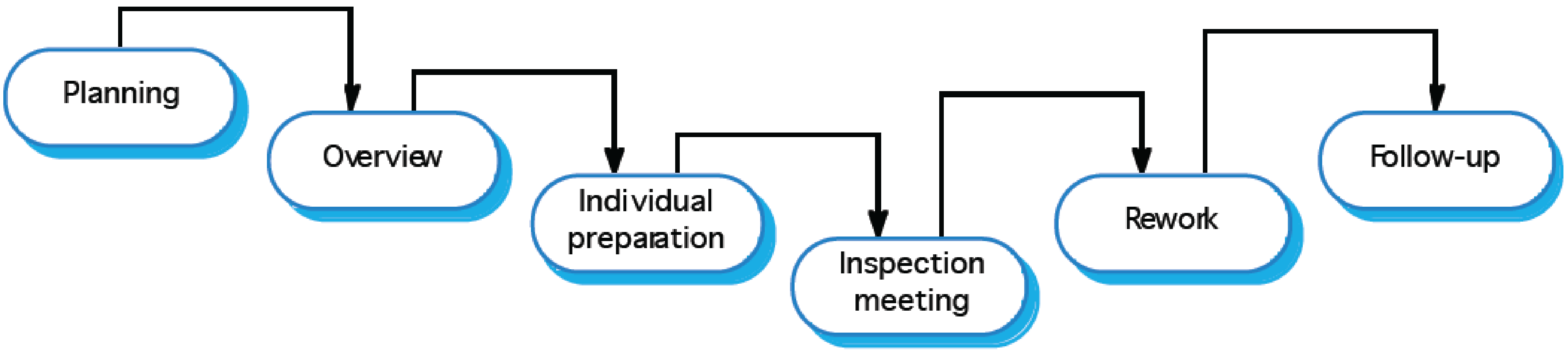
- It is a formal methodology for reviewing documents.
- It looks for defects such as logical errors, anomalies in the code, or non-compliance with standards.
- The process may have different variants according to the organisation in which it is performed.

- Typical pre-conditions
  - Availability of a precise specification.
  - Availability of syntactically correct code (or design).
  - An error check-list.
    - This is dependent on the programming language.
    - The weaker the typing, the longer the list.

Composition of the Reviewing Team

- Author
  - Responsible for fixing defects discovered during the review.
- Inspector
- Reader
  - Paraphrases the code during an inspection meeting.
- Scribe
  - Records the outcome of the inspection meeting.
- Moderator
  - Manages the process. Responsible for scheduling possible follow-up meetings.

The Program Inspection Process



- Planning is the responsibility of the moderator: choose a team, fix dates, ...
- At the overview the author presents the program under inspection.
- At the inspection meeting errors are reported. Meetings should be kept relatively short (e.g., under 2 h).
- Rework is the author's responsibility.
- Follow-up may be needed to assess the code in case of major changes required.

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Figure taken from http://www.cs.st-andrews.ac.uk/ifs/Books/SE7/Presentations/index.html

Typical Checks

- Data faults
  - Base indices for arrays? Possibility of buffer overflows?
- Control faults
  - For each conditional statement, is the condition correct? Are loops guaranteed to terminate? Are compound statements correctly bracketed?
- Input/output faults
  - Are all input variables used? Are output variables used? Can unexpected inputs cause corruption (e.g., null pointers)?
- Exception management
  - Have all possible error conditions been taken into account?

Automated Static Analysis (for code)

- Performed by software tools which process the source code in search of potentially dangerous situations.
  - E.g. FindBugs
- Does not replace program inspection by humans, as it checks for more mechanical errors:
  - Variables used before initialisations, variables declared but never used, variables never used between two successive assignments.
  - Unreachable code.
  - Return values of functions/methods that are not used.
- Static analysers are typically available in Integrated Development Environments.
- Much more useful for weakly typed languages.

Software Testing

- Component (or unit) testing
  - Testing of individual program components. The notion of component depends on the programming language under consideration.
  - Usually under the responsibility of the authors.
  - Tests are based on the developers' experience.
- System testing
  - Testing of integrated components that form a (sub-)system.
  - Usually under the responsibility of an independent team.
  - Tests are based on a system specification.

Goals of Software Testing

- Validation testing
  - Demonstrates that the software meets the requirements.
  - It is successful when the system operates as intended.
  - The system is exercised using typical input data.
  - Does not reveal the absence of faults though!
- Defect testing
  - Discover faults that may lead to unintended behaviour or failure.
  - It is successful when the test makes the system perform incorrectly.
  - Reveals the presence, not the absence of faults!
  - Guidelines on what to test
    - Functionality accessed from menus.
    - Combinations of functions accessed through the same menu (e.g., text formatting).
    - User input forms with correct and incorrect input.

Sources of Test Obligations

- Functional (black box, specification-based): from software specifications
  - Example: If spec requires robust recovery from power failure, test obligations should include simulated power failure
- Structural (white or glass box): from code
  - Example: Traverse each program loop one or more times.
- Model-based: from model of system
  - Models used in specification or design, or derived from code
  - Example: Exercise all transitions in communication protocol model
- Fault-based: from hypothesized faults (common bugs)
  - Example: Check for buffer overflow handling (common vulnerability) by testing on very large inputs

Functional testing

- Functional testing: Deriving test cases from program specifications
  - 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 specification = description of intended program behavior
  - either formal or informal

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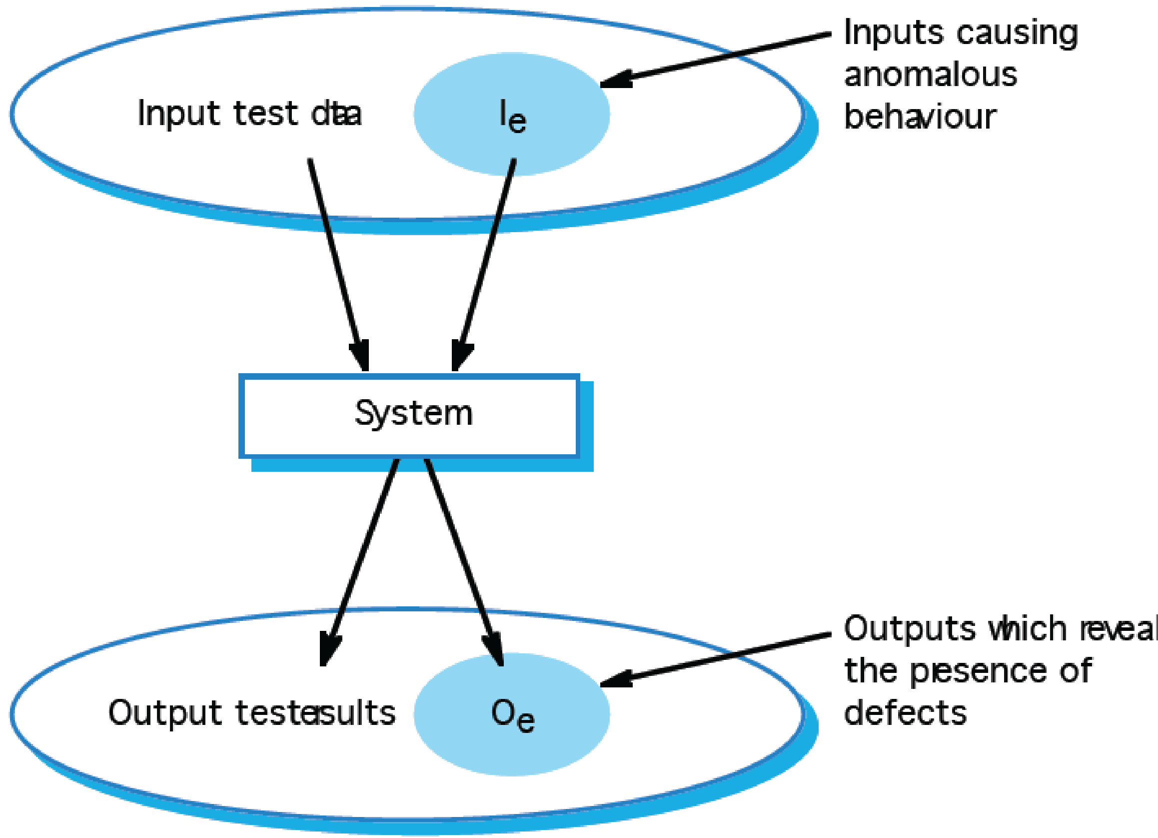
Black-Box Testing

- The system (or component) is treated as a black box.
- Behaviour understood by relating inputs to outputs.
- It is only concerned with the functionality, not its actual implementation.



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Why functional testing?

- The base-line technique for designing test cases
  - Timely
    - Often useful in refining specifications and assessing testability before code is written
  - Effective
    - finds some classes of fault (e.g., missing logic) that can elude other approaches
  - Widely applicable
    - to any description of program behavior serving as spec
    - at any level of granularity from module to system testing.
  - Economical
    - typically less expensive to design and execute than structural (code-based) test cases

Early functional test design

- Program code is not necessary
  - Only a description of intended behavior is needed
  - Even incomplete and informal specifications can be used
    - Although precise, complete specifications lead to better test suites
- Early functional test design has side benefits
  - Often reveals ambiguities and inconsistency in spec
  - Useful for assessing testability
    - And improving test schedule and budget by improving spec
  - Useful explanation of specification
    - or in the extreme case (as in XP), test cases are the spec

Functional vs. structural: Classes of faults

- Different testing strategies (functional, structural, fault-based, model-based) are most effective for different classes of faults
- Functional testing is best for missing logic faults
  - A common problem: Some program logic was simply forgotten
  - Structural (code-based) testing will never focus on code that isn't there!

Functional vs. structural: Granularity levels

- Functional test applies at all granularity levels:
  - Unit (from module interface spec)
  - Integration (from API or subsystem spec)
  - System (from system requirements spec)
  - Regression (from system requirements + bug history)
- Structural (code-based) test design applies to relatively small parts of a system:
  - Unit
  - Integration

Steps: From specification 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

Systematic vs. Random Testing

- Random (uniform):
  - Pick possible inputs uniformly
  - Avoids designer bias
    - A real problem: The test designer can make the same logical mistakes and bad assumptions as the program designer (especially if they are the same person)
  - But treats all inputs as equally valuable
- Systematic (non-uniform):
  - Try to select inputs that are especially valuable
  - Usually by choosing representatives of classes that are apt to fail often or not at all

Why Not Random?

- Non-uniform distribution of faults
- Example: Java class “roots” applies quadratic equation

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

  - Incomplete implementation logic: Program does not properly handle the case in which $b^2 - 4ac = 0$ and $a = 0$
  - Failing values are sparse in the input space — needles in a very big haystack. Random sampling is unlikely to choose $a = 0$ and $b = 0$

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Functional testing: exploiting specification

- Functional testing is systematic testing
- Functional testing uses the specification (formal or informal) to partition the input space
  - E.g., specification of “roots” program suggests division between cases with zero, one, and two real roots
- Test each category, and boundaries between categories
  - No guarantees, but experience suggests failures often lie at the boundaries (as in the “roots” program)

Partitioning

- Selecting relevant input data for testing.
- Based on the assumption that some inputs are somewhat similar: if one is troublesome, so will be all the others belonging to the same class
- Example:

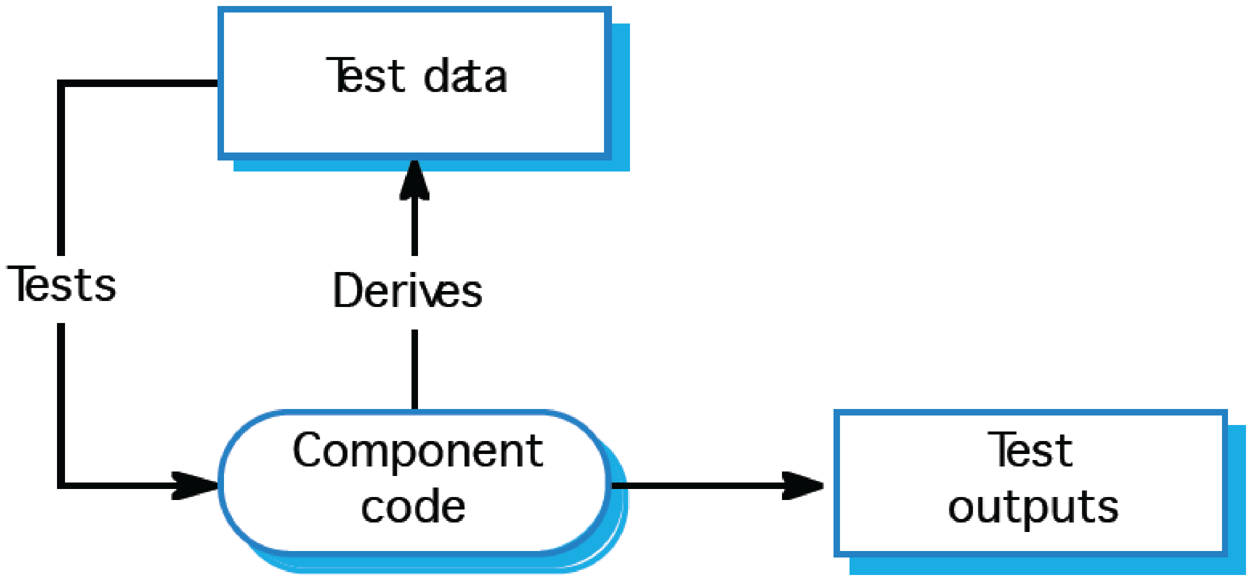
```
class Account {
  public float getBalance() { ... }
  public void withdraw(float amount) { ... }
}
```

- Partition the floats into:
  - Negative values
  - Zero
  - Positive values:
    - < getBalance()
    - == getBalance()
    - > getBalance()
  - Another dimension: more than two decimal digits!

Other General Testing Guidelines

- Design inputs that cause buffers to overflow
- Force invalid outputs to be generated
- Force computation results to be too large or too small

Structural Testing



- Also called white-box testing.
- Test cases are inferred from the program structure, which is required to be known.
- Can be done incrementally, knowledge of the program can be used to add further test cases.
- The objective is to test all program statements (not all path combinations).

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Figure taken from http://www.cs.st-andrews.ac.uk/ifs/Books/SE7/Presentations/index.html

Why structural (code-based) testing?

- One way of answering the question “What is missing in our test suite?”
  - If part of a program is not executed by any test case in the suite, faults in that part cannot be exposed
  - But what’s a “part”?
    - Typically, a control flow element or combination:
    - Statements (or CFG nodes), Branches (or CFG edges)
    - Fragments and combinations: Conditions, paths
- Complements functional testing: Another way to recognize cases that are treated differently
  - Recall fundamental rationale: Prefer test cases that are treated differently over cases treated the same

No guarantees

- Executing all control flow elements does not guarantee finding all faults
  - Execution of a faulty statement may not always result in a failure
    - The state may not be corrupted when the statement is executed with some data values
    - Corrupt state may not propagate through execution to eventually lead to failure
- What is the value of structural coverage?
  - Increases confidence in thoroughness of testing
    - Removes some obvious inadequacies

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Structural testing complements functional

- Control flow testing includes cases that may not be identified from specifications alone
  - Typical case: implementation of a single item of the specification by multiple parts of the program
  - Example: hash table collision (invisible in interface spec)
- Test suites that satisfy control flow adequacy criteria could fail in revealing faults that can be caught with functional criteria
  - Typical case: missing path faults

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Structural testing in practice

- Create functional test suite first, then measure structural coverage to identify see what is missing
- Interpret unexecuted elements
  - may be due to natural differences between specification and implementation
  - or may reveal flaws of the software or its development process
    - inadequacy of specifications that do not include cases present in the implementation
    - coding practice that radically diverges from the specification
    - inadequate functional test suites
- Attractive because automated
  - coverage measurements are convenient progress indicators
  - sometimes used as a criterion of completion
    - use with caution: does not ensure effective test suites

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Statement testing

- Adequacy criterion: each statement (or node in the CFG) must be executed at least once

- Coverage:

$$\frac{\#executed\ statements}{\#statements}$$

- Rationale: a fault in a statement can only be revealed by executing the faulty statement

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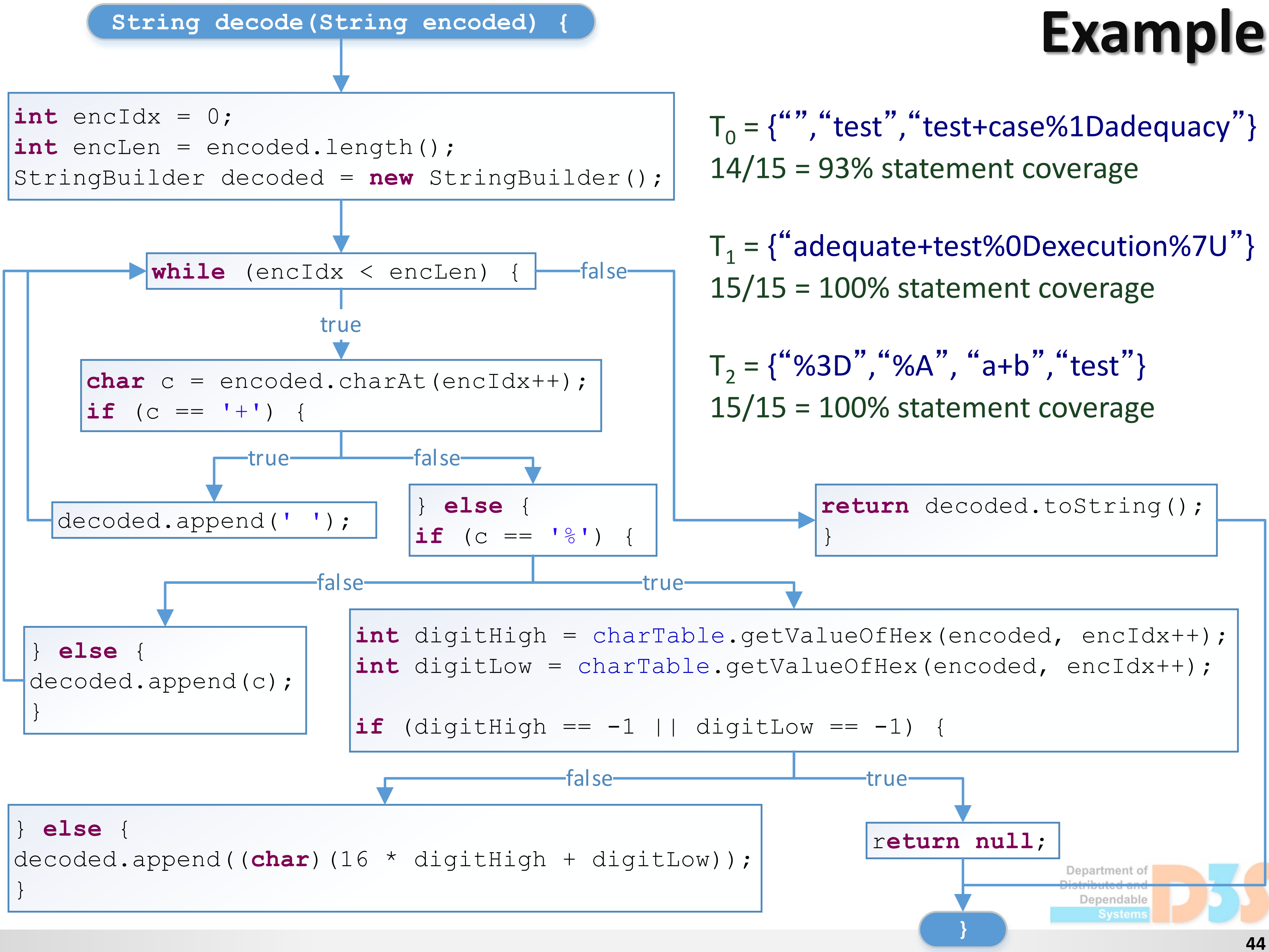
Example



T_0 = {“”,“test”,“test+case%1Dadequacy”}

14/15 = 93% statement coverage

T_1 = {“adequate+test%0Dexecution%7U”}

15/15 = 100% statement coverage

T_2 = {“%3D”,“%A”, “a+b”,“test”}

15/15 = 100% statement coverage

Statements or blocks?

- Nodes in a control flow graph often represent basic blocks of multiple statements
  - Some standards refer to basic block coverage or node coverage
  - Difference in granularity, not in concept
- No essential difference
  - 100% node coverage ⟺ 100% statement coverage
    - but levels will differ below 100%
  - A test case that improves one will improve the other
    - though not by the same amount, in general

Coverage is not size

- Coverage does not depend on the number of test cases
  - $T_0, T_1: T_1 >_{coverage} T_0$ $T_1 <_{\mathrm{cardinality}} \mathrm{T}_0$
  - $T_1, T_2: T_2 =_{coverage} T_1$ $T_2 >_{(cardinality)} T_1$

- Minimizing test suite size is seldom the goal
  - small test cases make failure diagnosis easier
  - a failing test case in T_2 gives more information for fault localization than a failing test case in T_1

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“All statements” can miss some cases

Complete statement coverage may not imply executing all branches in a program

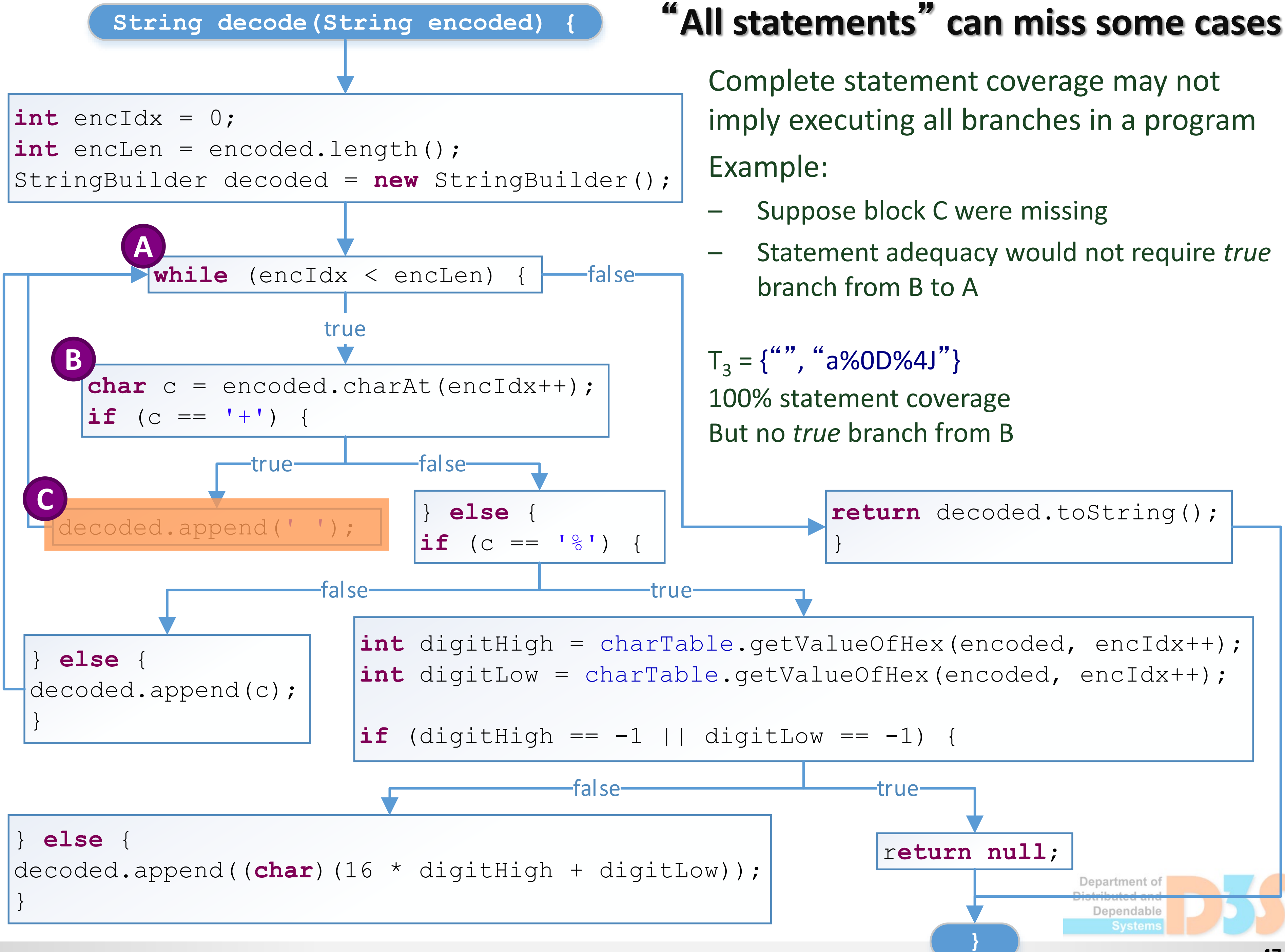
Example:

- Suppose block C were missing
- Statement adequacy would not require *true* branch from B to A

T_3 = {“”, “a%0D%4J”}

100% statement coverage

But no *true* branch from B



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Branch testing

- Adequacy criterion: each branch (edge in the CFG) must be executed at least once
- Coverage:

$$\frac{\#executed\ branches}{\#branches}$$

  - T3 = {“”, “a%0D%4J”}
  - 100% Stmt Cov. 88% Branch Cov. (7/8 branches)

  - T2 = {“%3D”, “%A”, “a+b”, “test”}
  - 100% Stmt Cov. 100% Branch Cov. (8/8 branches)

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Statements vs. branches

- Traversing all edges of a graph causes all nodes to be visited
  - So test suites that satisfy the branch adequacy criterion for a program P also satisfy the statement adequacy criterion for the same program
- The converse is not true (see T_3)
  - A statement-adequate (or node-adequate) test suite may not be branch-adequate (edge-adequate)

“All branches” can still miss conditions

- Sample fault: missing operator (negation)

  digit_high == 1 || digit_low == -1

- Branch adequacy criterion can be satisfied by varying only digit_low
  - The faulty sub-expression might never determine the result
  - We might never really test the faulty condition, even though we tested both outcomes of the branch

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Condition testing

- Branch coverage exposes faults in how a computation has been decomposed into cases
  - intuitively attractive: check the programmer’s case analysis
  - but only roughly: groups cases with the same outcome
- Condition coverage considers case analysis in more detail
  - also individual conditions in a compound Boolean expression
    - e.g., both parts of digit_high == 1 || digit_low == -1

Basic condition testing

- Adequacy criterion: each basic condition must be executed at least once

- Coverage:

$$\frac{\#truth\ values\ taken\ by\ all\ basic\ conditions}{2\ *\ \#\ basic\ conditions}$$

Basic conditions vs branches

- Basic condition adequacy criterion can be satisfied without satisfying branch coverage
- T_4 = {"first+test%9Ktest%K9"}
  - satisfies basic condition adequacy
  - does not satisfy branch condition adequacy
- Branch and basic condition are not comparable
  - neither implies the other

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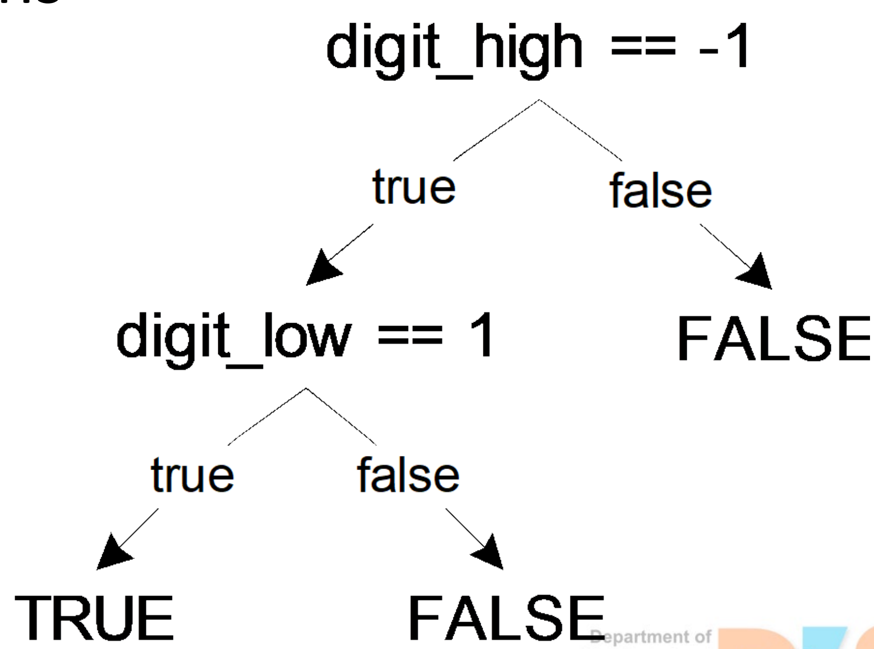
Covering branches and conditions

- Branch and condition adequacy:
  - cover all conditions and all decisions
- Compound condition adequacy:
  - Cover all possible evaluations of compound conditions
  - Cover all branches of a decision tree



Compound conds.: exponential complexity

```
(((a || b) && c) || d) && e
```

Test Case	a	b	c	d	e
1	T	—	T	—	T
2	F	T	T	—	T
3	T	—	F	T	T
4	F	T	F	T	T
5	F	F	—	T	T
6	T	—	T	—	F
7	F	T	T	—	F
8	T	—	F	T	F
9	F	T	F	T	F
10	F	F	—	T	F
11	T	—	F	F	—
12	F	T	F	F	—
13	F	F	—	F	—

Short-circuit evaluation often reduces this to a more manageable number, but not always.

Modified condition/decision (MC/DC)

- Motivation: Effectively test important combinations of conditions, without exponential blowup in test suite size
  - "Important" combinations means: Each basic condition shown to independently affect the outcome of each decision
- Requires:
  - For each basic condition C, two test cases,
  - values of all evaluated conditions except C are the same
  - compound condition as a whole evaluates to true for one and false for the other

MC/DC: linear complexity

```
(((a || b) && c) || d) && e
```

Test Case	a	b	c	d	e	outcome
1	**T**	F	**T**	F	**T**	T
2	F	**T**	T	F	T	T
3	T	F	F	**T**	T	T
6	T	F	T	F	**F**	F
11	T	F	**F**	**F**	T	F
13	**F**	**F**	T	F	T	F

- N+1 test cases for N basic conditions
- Red values independently affect the output of the decision
- Required by the RTCA/DO-178B standard

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Comments on MC/DC

- MC/DC is
  - basic condition coverage
  - branch coverage
  - plus one additional condition:
    every condition must independently affect the decision's output
- It is subsumed by compound conditions and subsumes all other criteria discussed so far
  - stronger than statement and branch coverage
- A good balance of thoroughness and test size (and therefore widely used)

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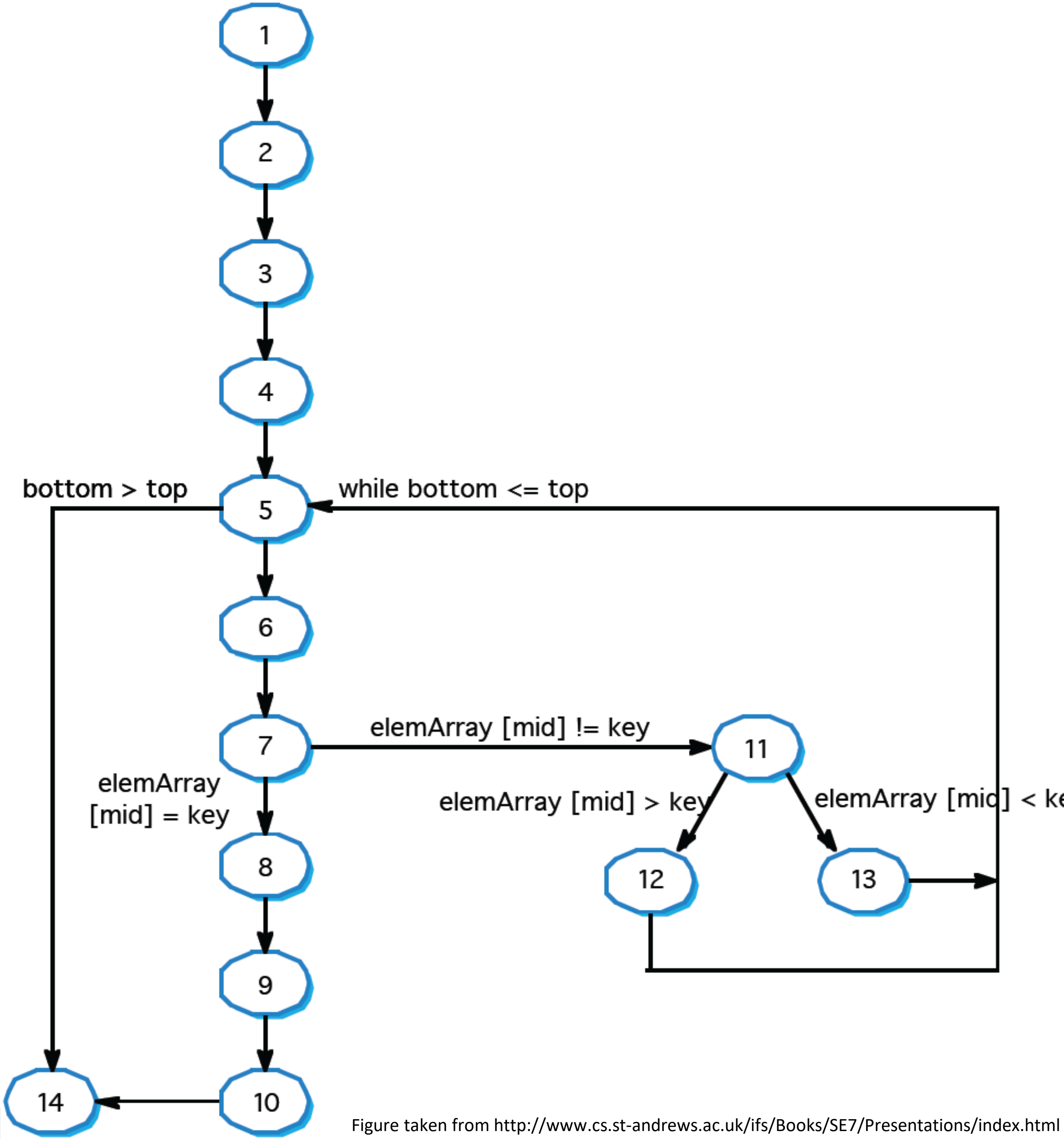
Path Testing

- Ensures that each test input covers a different path in the control flow of the system
- May use a high-level representation with a graph where nodes represent statements, and arcs denote the flow of control.
- Exhaustive path coverage may be expensive to guarantee in realistic scenarios.

Path Testing



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