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Software Quality

Chapter 3

Advanced Testing Techniques

3.1 The Basics of Testing

3.2 Branch Coverage in Glass-Box Testing

3.3 Data flow Testing

3.4 Use-Case-Based Testing

3.5 Combinatorial Interaction Testing

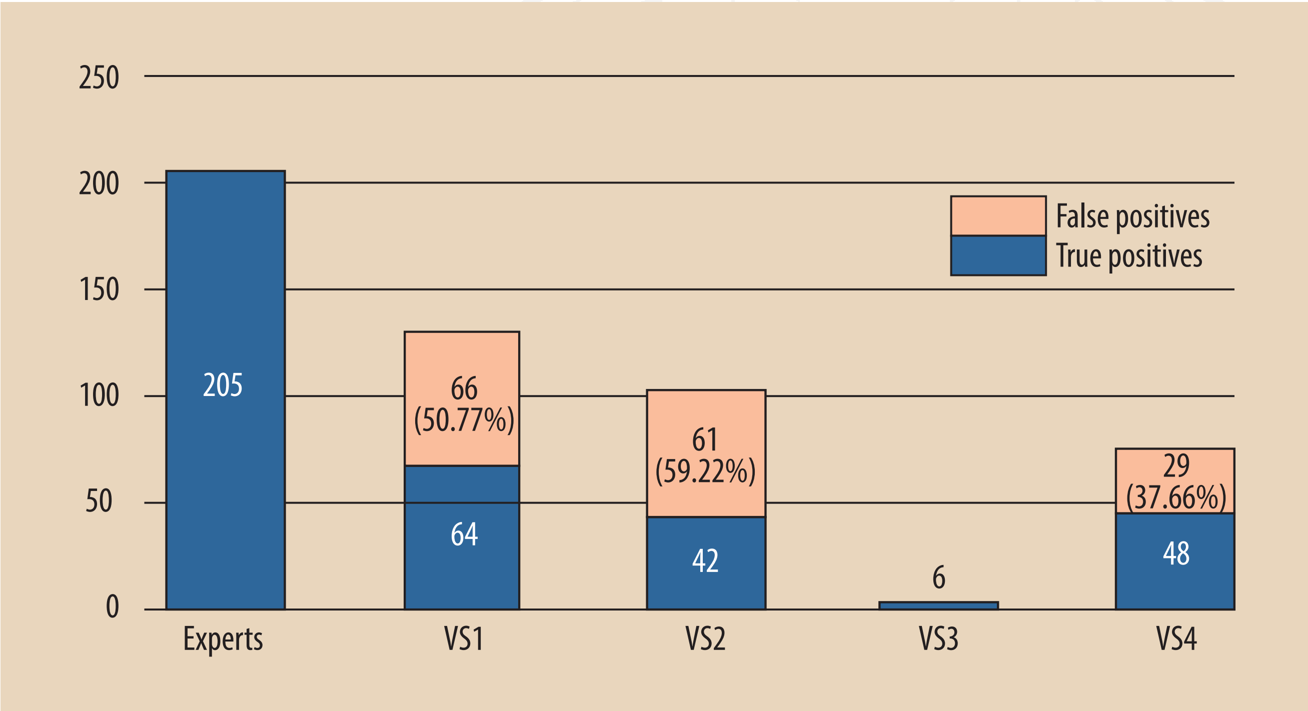
3.6 Test Automation

Testing

- The fact:
  Testing is the process of executing a program with the intent of finding errors. [Myers 1979]
- Our hope:
  The more thoroughly a program has been tested, the higher the probability that the program will behave as expected also in the non-tested cases
- Good to know:
  The correctness of a program can't be proven by testing (except in trivial cases); this is due to combinatorial explosion of input values to be tested

Testing vs. reviewing

Testing is not always the means of choice:



[Source:
Antunes and Vieira 2014]

Number of vulnerabilities detected with automated penetration testing vs. inspection by a team of security experts (VS1-VS4 are commercial vulnerability scanners).

Expected results must be known

- A crucial prerequisite for testing is knowing the expected results
  - Either from a specification
  - or by comparing the outcome with the results of a successful previous test run (so-called regression testing)

Testing systematics

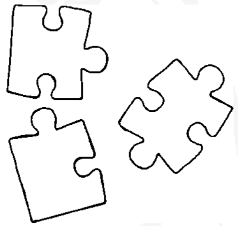
- “Let’s run it”: A developer “tests” with some ad-hoc created data – the test is passed when the results “look good”
- Throwaway-Test: Somebody creates test cases and executes them, but the tests
  - are not documented
  - can’t be repeated
  - don’t have defined criteria when to stop

Testing systematics – 2

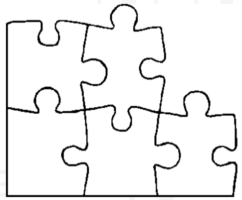
- Systematic test: Trained testers create, run and document the tests
  - Test is planned
  - Test procedure has been written beforehand
  - Test is executed according to test procedure
  - Expected and observed results are compared; any deviation is recorded
  - Searching and fixing defects are performed separately
  - A failed test is repeated after fixing the defects
  - Test results are documented
  - Test ends, when a pre-defined testing goal has been achieved

Forms of testing

- Artifacts to be tested may be modules, partial systems or systems
- Unit Test (or component test)



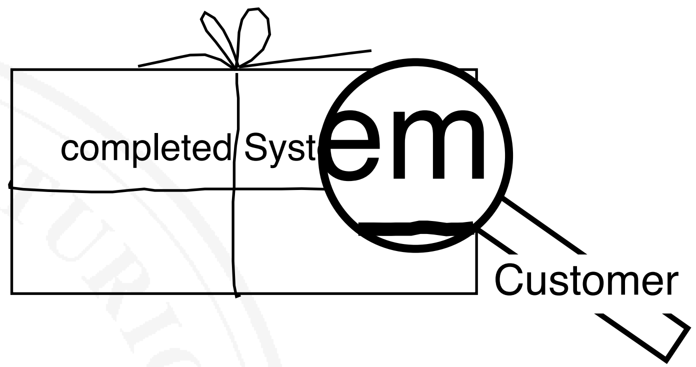
- Integration test



- System test

Forms of testing – 2

- Acceptance test
  - A special form of testing
  - Not about finding errors
  - But: demonstrate that the system satisfies its requirements; i.e., that the acceptance test cases don’t reveal any faults



The process of testing

- Planning
  - Testing strategy: what – when – how – for how long
  - Embed testing into the development plan:
    - Which documents to create
    - Deadlines and cost for test preparation, execution and evaluation
  - Who will be testing
- Preparation
  - Selection of test cases
  - Setting up the test environment / test harness
  - Writing the test procedure

The process of testing – 2

- Execution
  - Install test environment / test harness
  - Run tests according to test procedure; record results
  - Don't modify the tested artifact while executing a test
  - Repeat failed tests after fault fixing
- Evaluation
  - Assemble findings
- Fault fixing (no part of the testing process!)
  - Analyze errors/symptoms found
  - Find defects (debugging)
  - Fix defects

Determining test cases

- Deter-mining test cases
  - Black-box (function-oriented)
    - Function coverage
    - Output coverage
    - Exception coverage
    - Attribute coverage
    - Use case coverage
    - Combinatorial coverage
    - Equivalence classes
    - Boundary values
    - Cause-effect graphing
    - Statistical testing
    - Error guessing
    - Automatic test case generation
  - Glass-box (structure-oriented)
    - Control flow coverage
      - Statement coverage
      - Branch coverage
      - Path coverage
    - Dataflow analysis
    - Symbolic testing

Discussed in this chapter

3.1 The Basics of Testing

3.2 Branch Coverage in Glass-Box Testing

3.3 Data flow Testing

3.4 Use-Case-Based Testing

3.5 Combinatorial Interaction Testing

3.6 Test Automation

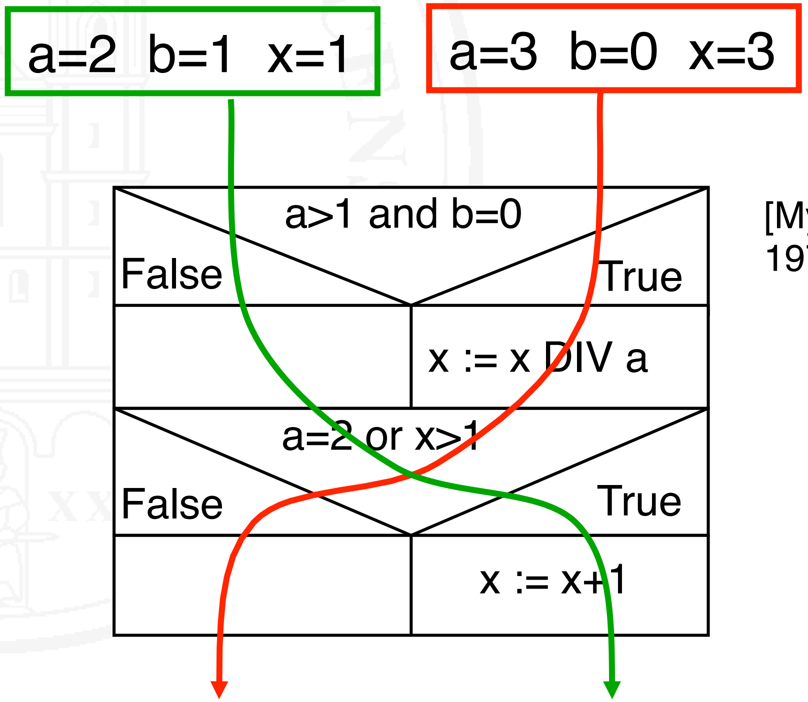
Branch coverage

[This section extends the discussion on Glass-Box-Testing in Chapter 8 of my 2nd year course on Software Engineering]

Branch coverage: create test cases such that all branches of the program are covered

For this fragment, two test cases achieve 100 % coverage:

```
...
VAR
   a,b,x: INTEGER;
...
BEGIN
...
IF (a>1) AND (b=0)
   THEN x := x DIV a;
IF (a=2) OR (x>1)
   THEN x := x+1;
...
```



[Myers 1979]

Branch coverage has a problem

Classic branch coverage has a problem:

Imagine, the specification states

$$x' = \begin{cases} x \text{ DIV } a & \text{if } a \geq 1 \;\&\; b = 0 \\ x & \text{else} \end{cases}$$

- Our test does not find the defect in the code **Why?**

The remedy: term coverage

- Cover not just all branches of a condition, but
- Create test cases such that every individual term makes the condition once true and once false
- In our example: Achieving term coverage for the first if-statement requires three test cases:
  - a=1 b=0 x=1 (first term makes condition false)
  - a=2 b=1 x=1 (second term makes condition false)
  - a=3 b=0 x=3 (both terms make condition true)
  - Achieves term coverage also for second if-statement

In practice: MC/DC

[Chilenski and Miller 1994]

- MC/DC (Modified condition/decision coverage) is a term coverage criterion used for safety-critical systems
- Requires that for every conditional statement, every term in the condition expression has been shown to determine the value of the condition expression independently:

  Let $c = t_1\ op_1\ t_2\ op_2\ ...\ op_{i-1}\ t_i\ op_i\ ...\ t_n$ be a condition

  c needs to become once true and once false by varying t_i while keeping all other terms t_j $j \neq i$ constant
- For example, MC/DC is required by the FAA for avionics software

What is data flow testing?

- A glass-box (structure-oriented) test
- Based on analysis of data flow in a program:
  - Determine the control flow graph
  - Annotate the control flow graph:
    - Where are variables set or modified?
    - Where are variables used in computations?
    - Where are variables used as parts of a condition?
- Various coverage criteria
- Can also be used to assess the quality of a black-box test (in terms of achieved data flow coverage)

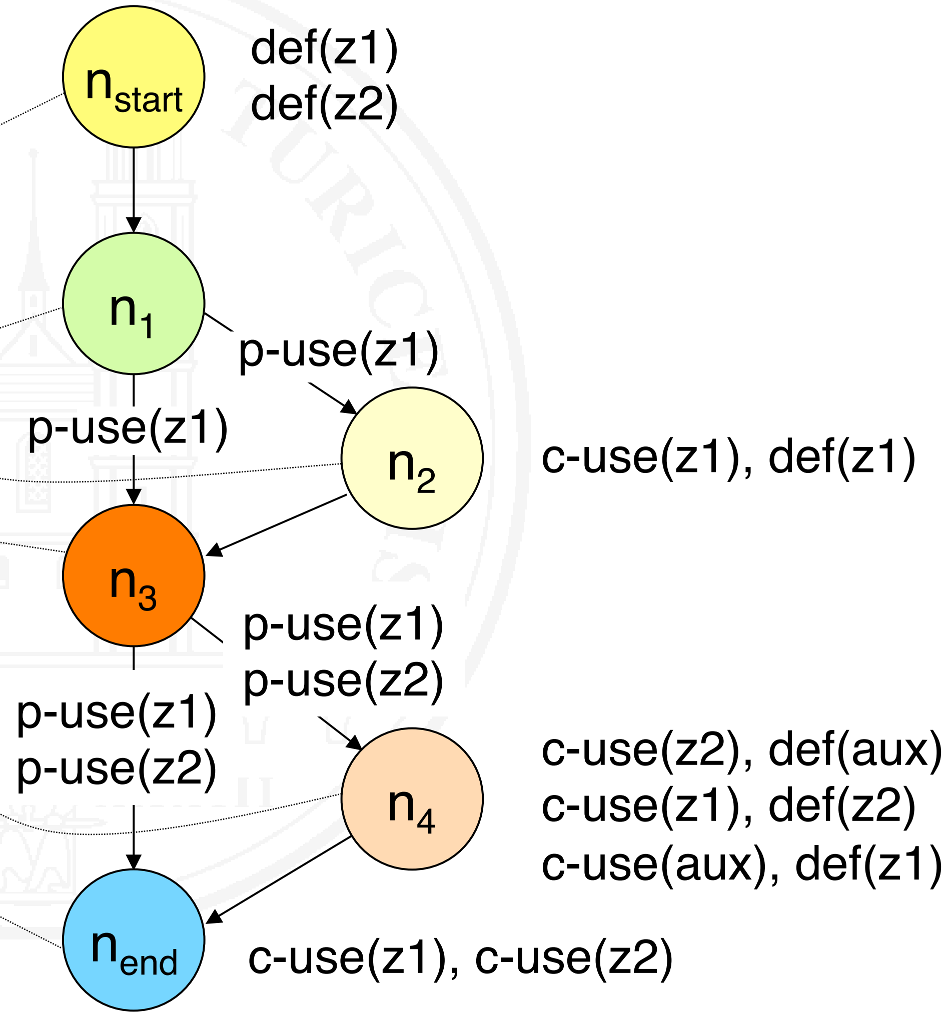
Example

def()	variable set/modified
c-use()	computational use
p-use()	predicative use

A small program in C:

```
void SortAbs1 (int& z1, int& z2)
/* Sorts the set {|z1|, z2} */
{
    int aux;
    if (z1 < 0) {
        z1 = -z1;
    }
    if (z1 > z2) {
        aux = z2;
        z2 = z1;
        z1 = aux;
    }
}
```

Annotated control flow graph:



Variable definitions and uses

- After constructing the control flow graph of a program, we characterize its data flow by annotating the graph:
  - n.def(x), iff variable x is set or modified in node n
  - n.c-use(x), iff variable x is used in a computation in node n
  - (n,m).p-use(x) iff variable x is used predicatively in a branching condition on edge (n,m)
- A path $(n_n, ..., n_m)$ in a control flow graph is called definition-clear with respect to variable x iff
  - def(x) in node n_n
  - c-use(x) in node n_m or p-use(x) on edge (n_{m-1},n_m)
  - Between the definition of x in n_n and its use in n_m or (n_{m-1},n_m) there is no other definition of x

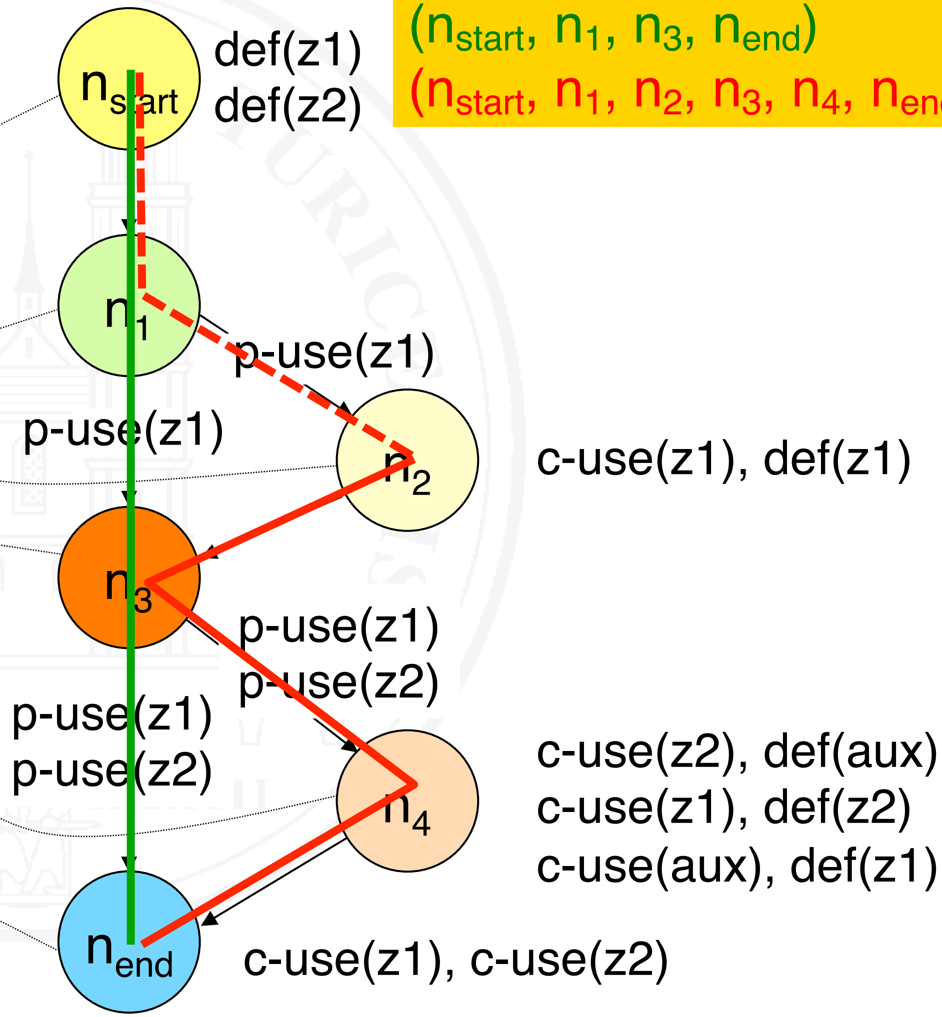
Test case derivation

Test cases are created such that the program executes definition-clear paths of some coverage class for all variables of the program:

- *all defs*-criterion: For all definitions of x, execute a definition-clear path to at least one use of x
- *all p-uses*-criterion: For all definitions of x, execute a definition-clear path to all predicative uses of x
- *all c-uses*-criterion: For all definitions of x, execute a definition-clear path to all computational uses of x

Test case derivation – Example 1: all-defs

```
void SortAbs1 (int& z1, int& z2)
/* Sorts the set {lz1l, z2} */
{
    int aux;
    if (z1 < 0) {
        z1 = -z1;
    }
    if (z1 > z2) {
        aux= z2;
        z2 = z1;
        z1 = aux;
    }
}
```



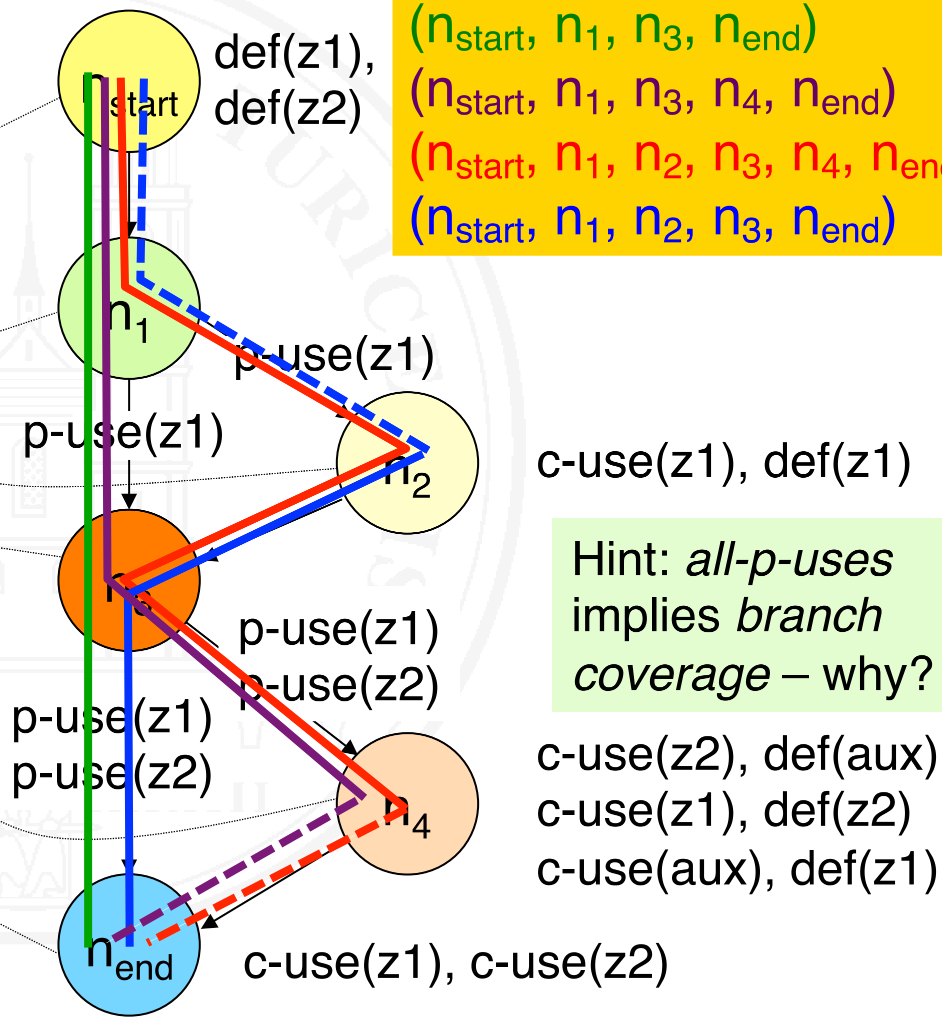
all-defs:

(n_{start}, n_1, n_3, n_{end})

(n_{start}, n_1, n_2, n_3, n_4, n_{end})

Test case derivation – Example 2: all-p-uses

```
void SortAbs1 (int& z1, int& z2)
/* Sorts the set {|z1|, z2} */
{
    int aux;
    if (z1 < 0) {
        z1 = -z1;
    }
    if (z1 > z2) {
        aux= z2;
        z2 = z1;
        z1 = aux;
    }
}
```



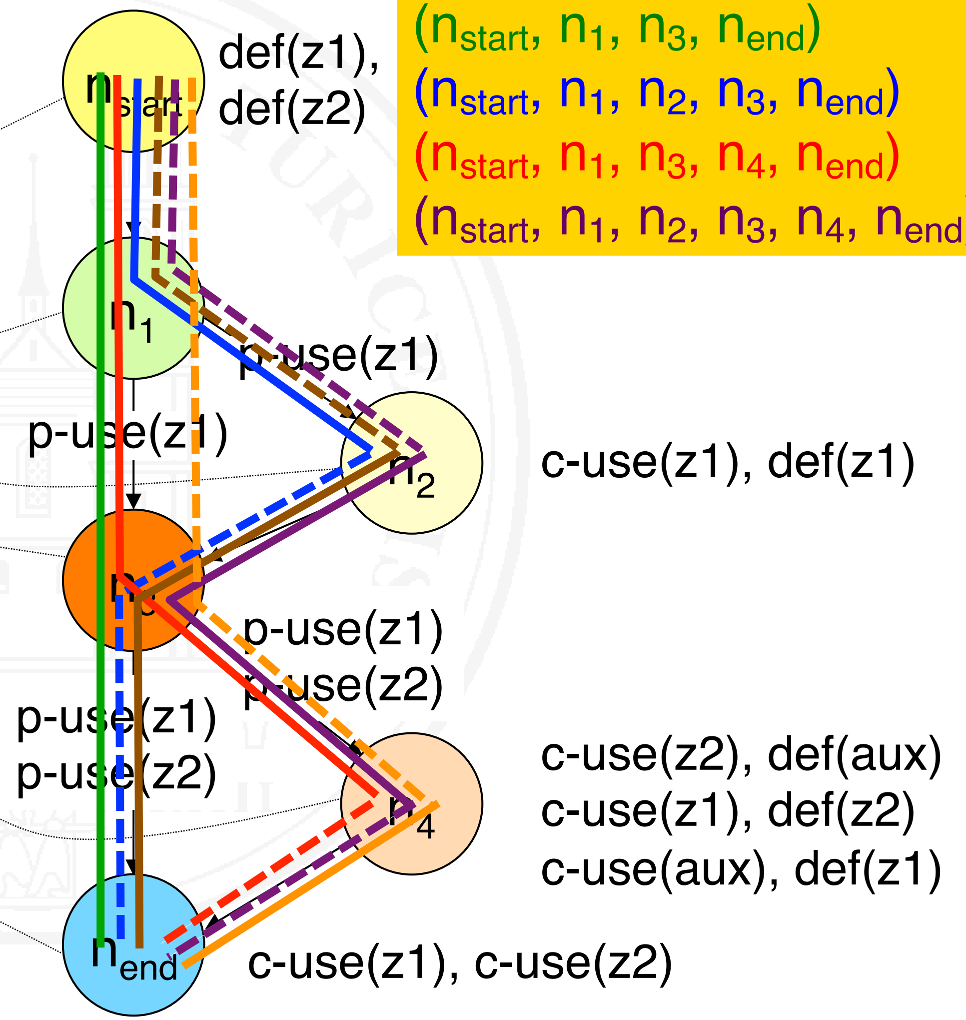
all-p-uses:

(n_{start}, n_1, n_3, n_{end})
(n_{start}, n_1, n_3, n_4, n_{end})
(n_{start}, n_1, n_2, n_3, n_4, n_{end})
(n_{start}, n_1, n_2, n_3, n_{end})

Hint: *all-p-uses* implies *branch coverage* – why?

Test case derivation – Example 3: all-c-uses

```
void SortAbs1 (int& z1, int& z2)
/* Sorts the set {|z1|, z2} */
{
    int aux;
    if (z1 < 0) {
        z1 = -z1;
    }
    if (z1 > z2) {
        aux= z2;
        z2 = z1;
        z1 = aux;
    }
}
```



all-c-uses:

(n_{start}, n_1, n_3, n_{end})

(n_{start}, n_1, n_2, n_3, n_{end})

(n_{start}, n_1, n_3, n_4, n_{end})

(n_{start}, n_1, n_2, n_3, n_4, n_{end})

Significance of data flow testing

- In theory very attractive
- Derivation of test cases requires considerable effort
- Supported by few tools only
- Low significance in today's practice of testing
- Data flow analysis is significant as an automated static analysis technique

The notion of use-case-based testing

- Defining test cases based on a use case model
- Belongs to the family of black-box (function-oriented) tests
- Goal: Cover all use cases
- Per use case
  - At least one test case for the normal course
  - At least one test case per alternate or exceptional course
- Dependencies between use cases should also be considered
- Suitable particularly for acceptance testing

Exercise: determining test cases

Create test cases for this use case:

Borrow Book

Actor(s): Library user

Trigger: A library user brings one or more books s/he wants to borrow to the check-out station

Normal course:

1. Read and validate user's library card
2. Scan book id and identify corresponding book record in database
3. Record the book to be borrowed and deactivate anti-theft label
4. If library user wants to borrow more than book, repeat steps 2 & 3
5. Print borrow slip for all books just borrowed
6. Hand over books to library user and terminate

Exercise: determining test cases – 2

Alternative courses:

1.1 No library card or scanned card is invalid: cancel transaction

2.1 Book has been reserved for another user: set book aside and proceed with step 4

2.2 Library user has overdue books to be returned: cancel transaction

The problem of combinatorial explosion

❍ Problem:
- Programs having numerous options of combining input data values
- Systems may have over hundred configuration options

❍ Principally, all possible combinations should be tested

➯ Number of test cases required grows exponentially: not feasible

Example: Apache Web Server [Yilmaz et al. 2014]
- 172 user-configurable options
- $1.8 \cdot 10^{55}$ possible configurations

Systematically testing combinations of options

[Yilmaz et al. 2014, Nie and Leung 2011]

- Combinatorial Interaction Testing (CIT)
  - Systematically tests a subset of all possible combinations
  - Test cases with given coverage requirements can be generated automatically
- t-way coverage: each valid combination of t out of n input options is covered by a test case

The pragmatic solution: pairwise testing

- Empirical observation: most errors due to input data combination errors can be detected when testing all possible pairs, i.e. achieving 2-way coverage
- The number of test cases required for exhaustive pairwise testing grows logarithmically only

$n = O(m^2 \log_2 k)$	k	Number of input fields
	m	Number of possible values per input field
	n	Required number of test cases for pairwise testing

- Testable also for rather large input data sets

Example

- 13 input fields (k=13) with three values each (m=3)
- Testing all combinations requires 3^{13} = 1 594 323 test cases
- For a full pairwise test,15 test cases suffice

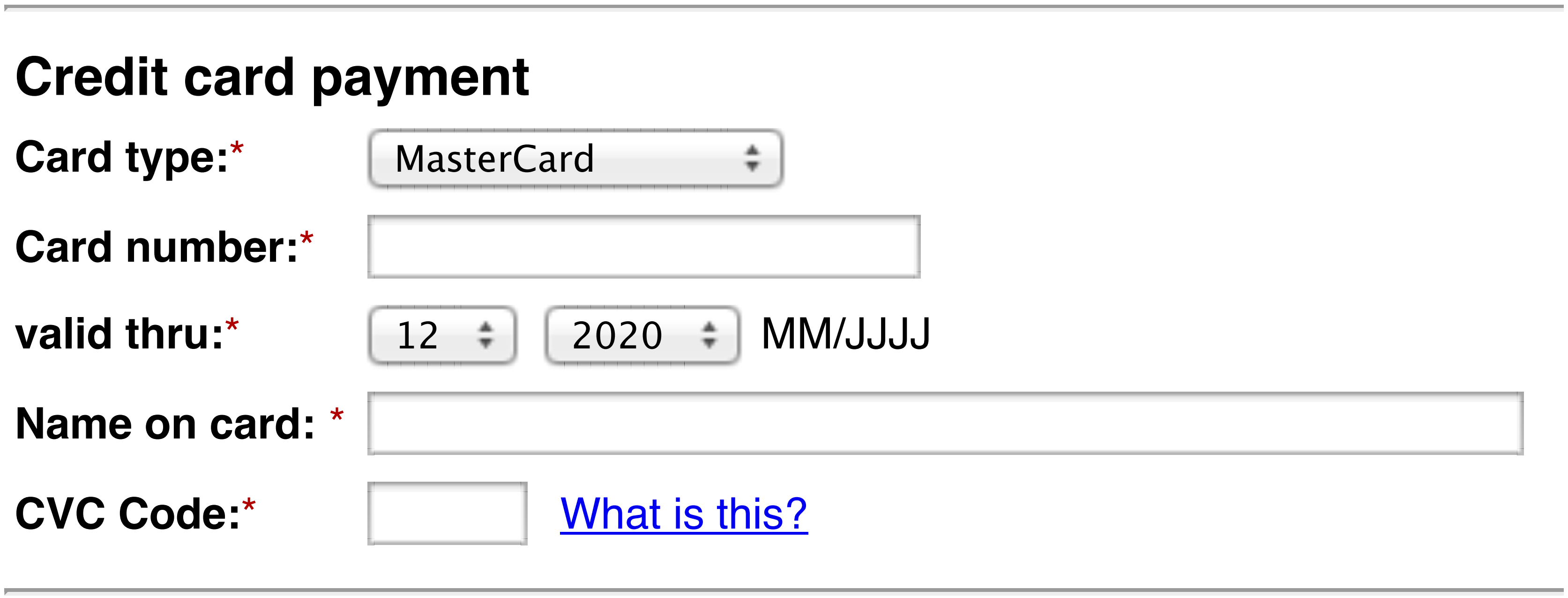
Algorithmically computed combination table for full pairwise test (k=13, m=3) [Cohen et al. 1997]

	P1	*P2*	*P3*	*P4*	*P5*	*P6*	*P7*	*P8*	*P9*	*P10*	*P11*	*P12*	*P13*
1	0	0	0	0	0	0	0	0	0	0	0	0	0
2	1	1	1	1	1	1	1	1	1	0	0	0	0
3	2	2	2	2	2	2	2	2	2	0	0	0	0
4	0	0	0	1	1	1	2	2	2	1	1	1	0
5	1	1	1	2	2	2	0	0	0	1	1	1	0
6	2	2	2	0	0	0	1	1	1	1	1	1	0
7	0	0	0	2	2	2	1	1	1	2	2	2	0
8	2	2	2	1	1	1	0	0	0	2	2	2	0
9	1	1	1	0	0	0	2	2	2	2	2	2	0
10	0	1	2	0	1	2	0	1	2	0	1	2	1
11	1	2	0	1	2	0	1	2	0	1	2	0	1
12	2	0	1	2	0	1	2	0	1	2	0	1	1
13	0	2	1	0	2	1	0	2	1	0	2	1	2
14	2	1	0	2	1	0	2	1	0	2	1	0	2
15	1	0	2	1	0	2	1	0	2	1	0	2	2

Derivation of test cases

- There is no simple way of computing the minimum number of test cases manually
- Cohen et al. (1997) provide an algorithm
- Pairwise testing requires a tool for determining the required combinations of test cases
- Commercial testing tools typically include a generator for producing test cases for a full pairwise test automatically
- There is also a free Perl script for determining all pairs [Bach 2006]

Example: Testing a credit card payment app



Determine values to be tested for every input field based on finding equivalence classes on the sets of all potential values

Number of test cases

- Assume three equivalence classes per input field
- We have six fields with three test values each
- Testing all combinations requires $3^6 = 729$ test cases
- Pairwise test requires only 15 test cases
- How sensitive is pairwise testing in this example?
  Here’s the code for checking the CVC number:

```
<TD><P><INPUT TYPE="text" NAME="cardCVC" VALUE=""
      SIZE=6 MAXLENGTH=3>  <FONT SIZE="-1"
      FACE="Helvetica"><A HREF="http:///help/view/pk/en//CVC.shtml"
      TARGET="_blank" " title="">What is this?</A></FONT>
   </TD>
```


Analysis of test sensitivity

- Testing all possible combinations finds an error:
  For example, this test case fails:
  {American Express, 1234432156788765, "John Doe", 12, 2020, 1234}
  - Mastercard and Visa use a three digit CVC code, American Express uses four digits
  - However, entering a four digit CVC number is impossible as the programmer did not know about four-digit codes
- Every test case {American Express, •, •, •,•, 1234} finds this error ("•" stands for any input value)

➪ Pairwise testing suffices to find this error

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Manual vs. automatic testing

- Creative vs. routine tasks in testing

Testing strategy

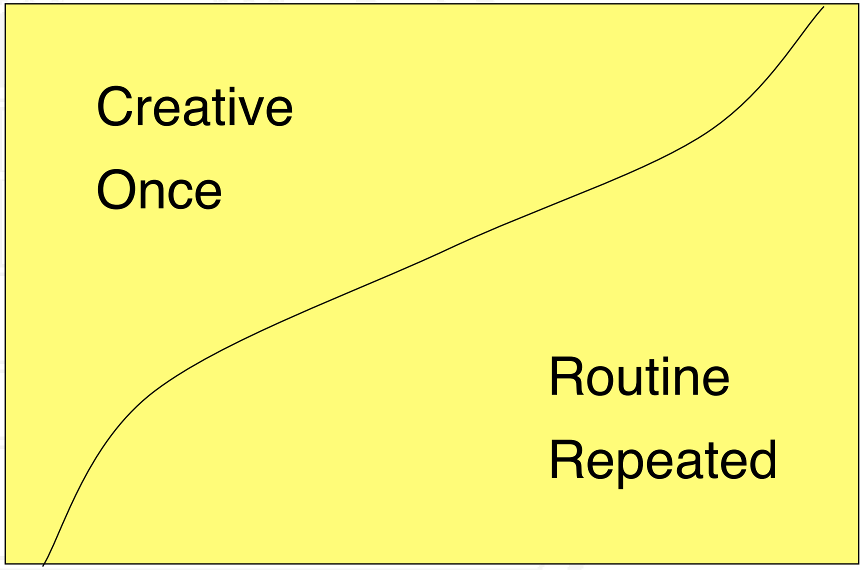
Determining test cases

Creating testing procedures

Setting up testing environment

Running tests

Test summary and evaluation



- Routine tasks are easier to automate than creative ones
- Automation of repeated tasks is efficient

Advantages and limitations of test automation

- Advantages
  - Large number of test cases testable
  - Unloading routine tasks from human testers
  - Frequent or even continuous regression testing feasible
  - Improves testing productivity
- Limits
  - No full replacement for manual testing
  - Strongly dependent on quality of test oracle
  - Automation makes testing more efficient, not more effective
  - Efficiency gain must be balanced with creation effort
  - No means against insufficient time or inexperienced testers

Automating the selection of test cases

- Generating glass-box (structure-oriented) tests
  - Generating test cases that satisfy some given coverage criteria is possible
  - Problem: from where do we get the expected results?
- Generating user interface tests
  - Test cases for testing formal properties such as dead links or non-editable input fields can be generated

Automating the selection of test cases – 2

- Generating black-box (function-oriented) tests including a test oracle
  - Requires a formal specification
  - Practical application rather limited
- Support for test case selection, for example, computing the tuples required for pairwise testing

Automating the test procedure

Dependent on type of test:

- Unit test
- System test
- Acceptance test

- We need to automate not only test case execution, but also the comparison of observed and expected results

Automation – Unit and integration testing

- Test procedure written as a program:
  - One test method per test case
  - Comparison of observed and expected results is also part of the program
  - A testing framework
    - simplifies programming test cases
    - serves as test environment
    - visualizes results
- Most widely known unit testing framework:
  - JUnit [Gamma und Beck 2000]
  - Meanwhile also for other languages: CppUnit, PyUnit,...

Automation – System test

Problem: Actors in the system context must be simulated

- Technical devices: Technical test bed simulating sensors and actuators
- Neighboring systems: test harness with drivers and stubs
- Human interaction: scripting

Scripting human interaction

- Test automation with scripting works by
  - writing or recording scripts,
  - in scripting languages such as Apple script, Perl, Python, VBScript, ... ,
  - which then are executed automatically
- Where to script
  - On the presentation layer
    - physical
    - logical
  - On the function layer

Automation on presentation layer

- Physical: keys typed, mouse movement, mouse clicks,...
  - Realistic
  - Scripts rather low level: e.g., absolute screen coordinates
  - typically neither readable nor changeable
  - highly sensitive to minimal, even irrelevant changes
  - Comparison of expected and actual results difficult
- Logical: Select menu item, set radio button,...
  - Simulation of interaction dialog on a more abstract layer
  - Scripts are more stable, easier to read and easier to modify

Automation on functional layer

- Accessing system functions over
  - Application programmer interfaces (APIs)
  - Web interfaces or browser interfaces
- Does not test the user interface
- Stable, UI-independent test programs and scripts
- Comparison of observed and expected results easy
- APIs, Web interfaces or browser interfaces must exist
- Caution: potential opportunities for attacking a system

Influence of software architecture

The software architecture has a strong influence on the testability of a system on the function layer

- Layered, acyclic system structure (metaphor of layered virtual machines)
- Models and logic, presentation, and control clearly separated (Model-View-Controller pattern)

Automation: acceptance test

- Creating acceptance test cases from requirements
  - Formal specifications allow generation of test cases
  - Semi-formal models allow generating test case frameworks
- Generating acceptance test cases from examples
  For example: Fit [Cunnigham 2002]
  - User describes expected behavior in spreadsheet-like tables
  - Tester writes a “Fixture”, which maps the table to program code
  - Fit executes the test automatically and visualizes the results

Automation example: Fit

[Cunnigham 2002]

User specifies sample cases:

Payroll Fixtures, Weekly Compensation			
StandardHours	HolidayHours	Wage	Pay()
40	0	20	$800
45	0	20	$950
48	8	20	$1360

Programmer writes "Fixture":

```
public class WeeklyCompensation : ColumnFixture
{
    public int StandardHours;
    public int HolidayHours;
    public Currency Wage;
}
```

Fit executes tests and visualizes the results for the user:

Payroll Fixtures, Weekly Compensation			
StandardHours	HolidayHours	Wage	Pay()
40	0	20	$800
45	0	20	$950
48	8	20	$1360 *expected* $ 1040 *actual*

Automation of result evaluation: test oracles

- For every automatically executed test case, expected and observed results must be compared. Options:
  - Comparison during program execution
  - Comparison after program execution
- An automated mechanism which compares expected and observed results is called a test oracle
- Challenges
  - Writing a test oracle can be very demanding and difficult, in particular when human behavior is involved
  - Faults in the oracle yield false positive test results
  - Oracles can't distinguish between significant and accidental discrepancies: leads to false-negative test results

Automation of result evaluation – 2

- Executable test procedures required, including test oracle
  - Programmed test procedures
  - Testing scripts
- Set-up, execution and evaluation of a test are automatable to a large extent
  - Example: Cruisecontrol is a tool for automated unit and integration testing

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