Course Review

Ajitha Rajan

Software Faults, Errors & Failures

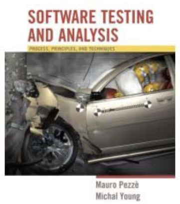
- Software Fault : A static defect in the software
- Software Failure : External, incorrect behavior with respect to the requirements or other description of the expected behavior
- Software Error : An incorrect internal state that is the manifestation of some fault

Summary: Why Do We Test Software ?

A tester's goal is to eliminate faults as early as possible

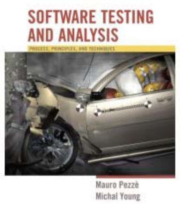
- **Improve quality**
- **Reduce cost**
- **Preserve customer satisfaction**

Functional testing



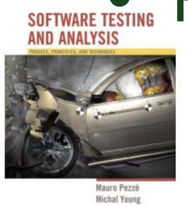
Functional testing

- 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



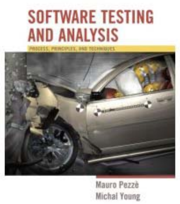
Systematic vs Random Testing

- 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*
- Functional testing is systematic testing



Functional testing: exploiting the specification

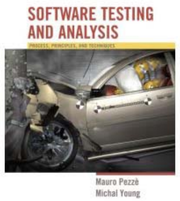
- Functional testing uses the specification (formal or informal) to partition the input space
  - E.g., specification of “roots” program suggests division between cases with zero, one, and two real roots
- Test each category, and boundaries between categories
  - No guarantees, but experience suggests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



Combinatorial testing

Combinatorial testing: Basic idea

- Identify distinct attributes that can be varied
  - In the data, environment, or configuration
  - Example: browser could be "IE" or "Firefox", operating system could be "Vista", "XP", or "OSX"
- Systematically generate combinations to be tested
  - Example: IE on Vista, IE on XP, Firefox on Vista, Firefox on OSX, ...
- Rationale: Test cases should be varied and include possible "corner cases"

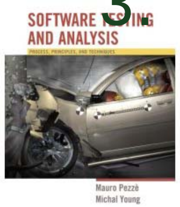


Key ideas in combinatorial approaches

- Category-partition testing
  - separate (manual) identification of values that characterize the input space from (automatic) generation of combinations for test cases
- Pairwise testing
  - systematically test interactions among attributes of the program input space with a relatively small number of test cases
- Catalog-based testing
  - aggregate and synthesize the experience of test designers in a particular organization or application domain, to aid in identifying attribute values

Category partition (manual steps)

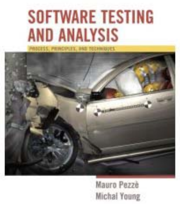
1. Decompose the specification into independently testable features
   - for each feature identify
     - parameters
     - environment elements
   - for each parameter and environment element identify elementary characteristics (categories)
2. Identify relevant values
   - for each characteristic (category) identify (classes of) values
     - normal values
     - boundary values
     - special values
     - error values
3. Introduce constraints



Example: Display Control

No constraints reduce the total number of combinations
□□□432 (3x4x3x4x3) test cases
if we consider all combinations

Display Mode	Language	Fonts	Color	Screen size
full-graphics	English	Minimal	Monochrome	Hand-held
text-only	French	Standard	Color-map	Laptop
limited-bandwidth	Spanish	Document-loaded	16-bit	Full-size
	Portuguese		True-color	

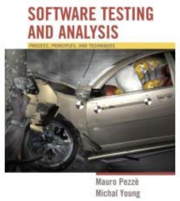


Pairwise combinations: 17 test cases

Language	Color	Display Mode	Fonts	Screen Size
English	Monochrome	Full-graphics	Minimal	Hand-held
English	Color-map	Text-only	Standard	Full-size
English	16-bit	Limited-bandwidth	-	Full-size
English	True-color	Text-only	Document-loaded	Laptop
French	Monochrome	Limited-bandwidth	Standard	Laptop
French	Color-map	Full-graphics	Document-loaded	Full-size
French	16-bit	Text-only	Minimal	-
French	True-color	-	-	Hand-held
Spanish	Monochrome	-	Document-loaded	Full-size
Spanish	Color-map	Limited-bandwidth	Minimal	Hand-held
Spanish	16-bit	Full-graphics	Standard	Laptop
Spanish	True-color	Text-only	-	Hand-held
Portuguese	-	-	Monochrome	Text-only
Portuguese	Color-map	-	Minimal	Laptop
Portuguese	16-bit	Limited-bandwidth	Document-loaded	Hand-held
Portuguese	True-color	Full-graphics	Minimal	Full-size
Portuguese	True-color	Limited-bandwidth	Standard	Hand-held

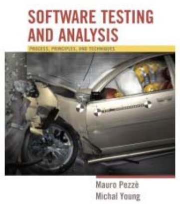
Next ...

- Category-partition approach gives us …
  – Separation between (manual) identification of parameter characteristics and values and (automatic) generation of test cases that combine them
  – Constraints to reduce the number of combinations
- Pairwise (or n-way) testing gives us …
  – Much smaller test suites, even without constraints
    - (but we can still use constraints)
- We still need …
  – Help to make the manual step more systematic



Catalog based testing

- Deriving value classes requires human judgment
- Gathering experience in a systematic collection can:
  - speed up the test design process
  - routinize many decisions, better focusing human effort
  - accelerate training and reduce human error
- Catalogs capture the experience of test designers by listing important cases for each possible type of variable
  - *Example: if the computation uses an integer variable a catalog might indicate the following relevant cases*
    - *The element immediately preceding the lower bound*
    - *The lower bound of the interval*
    - *A non-boundary element within the interval*
    - *The upper bound of the interval*
    - *The element immediately following the upper bound*



Catalog based testing process

Step1:

Analyze the initial specification to identify simple elements:

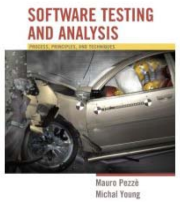
- Pre-conditions
- Post-conditions
- Definitions
- Variables
- Operations

Step 2:

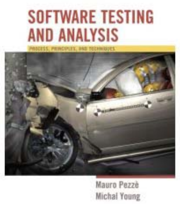
Derive a first set of test case specifications from pre-conditions, post-conditions and definitions

Step 3:

Complete the set of test case specifications using test catalogs

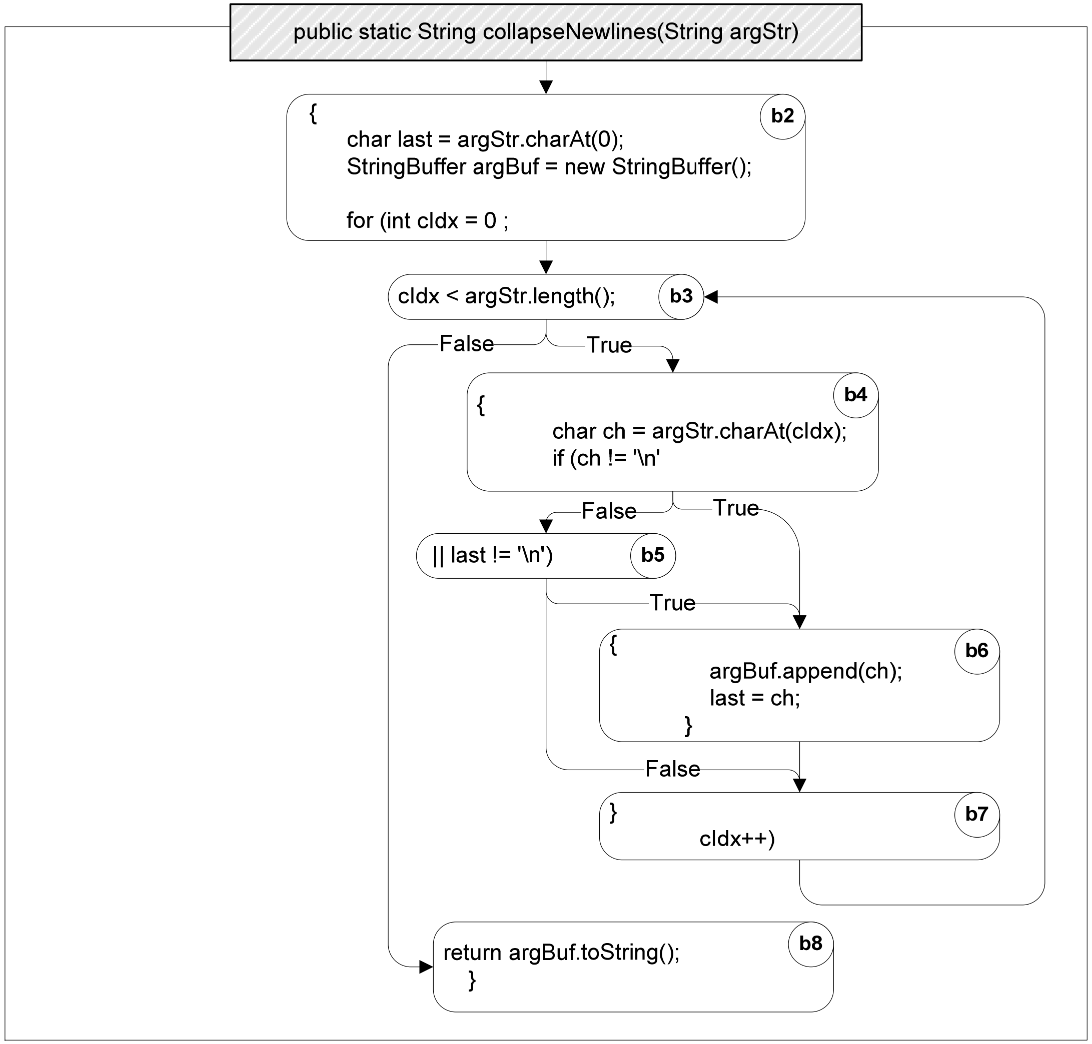


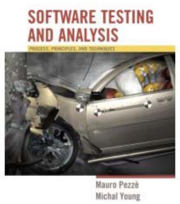
Finite Models



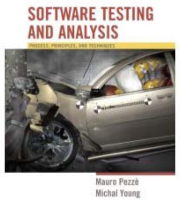
Example of Control Flow Graph

```
public static String collapseNewlines(String argStr)
  {
     char last = argStr.charAt(0);
     StringBuffer argBuf = new StringBuffer();

     for (int cIdx = 0 ; cIdx < argStr.length(); cIdx++)
     {
        char ch = argStr.charAt(cIdx);
        if (ch != '\n' || last != '\n')
        {
           argBuf.append(ch);
           last = ch;
        }
     }

     return argBuf.toString();
  }
```



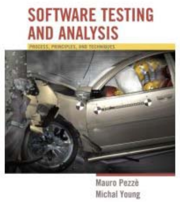


Structural Testing



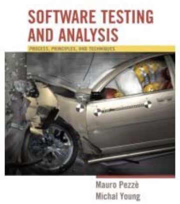
"Structural" testing

- Judging test suite thoroughness based on the *structure* of the program itself
  - Also known as "white-box", "glass-box", or "code-based" testing
  - To distinguish from functional (requirements-based, "black-box" testing)
    - "Structural" testing is still testing product functionality against its specification. Only the measure of thoroughness has changed.

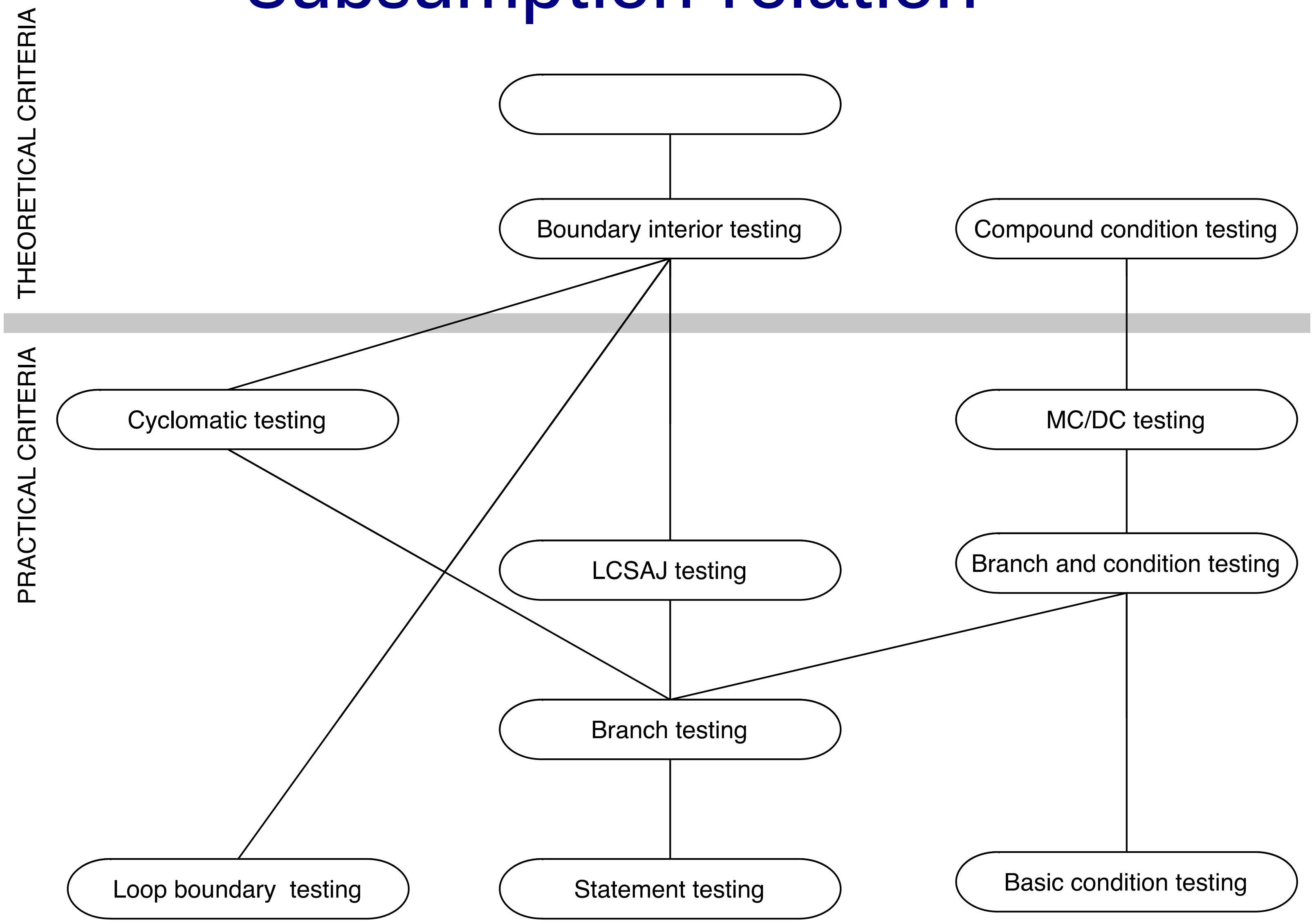


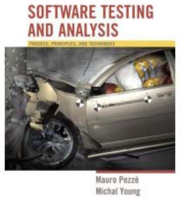
Structural testing *complements* functional testing

- 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



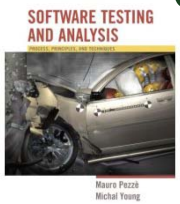
Subsumption relation





Summary

- We defined a number of adequacy criteria
  - NOT test design techniques!
- Different criteria address different classes of errors
- Full coverage is usually unattainable
  - Remember that attainability is an undecidable problem!
- …and when attainable, “inversion” is usually hard
  - How do I find program inputs allowing to cover something buried deeply in the CFG?
  - Automated support (e.g., symbolic execution) may be necessary
- Therefore, rather than requiring full adequacy, the “degree of adequacy” of a test suite is estimated by coverage measures
  - May drive test improvement



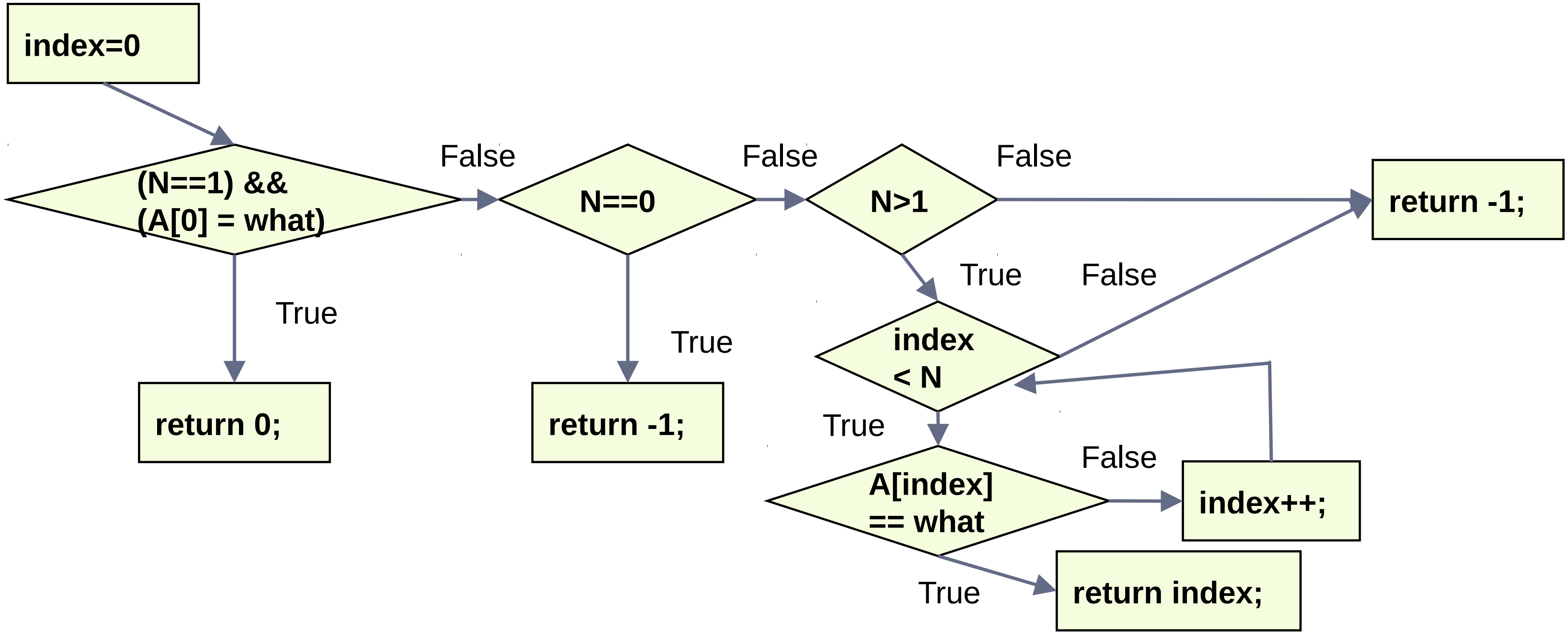
Activity

- Write tests that provide statement, branch, and basic condition coverage over the following code:

```
int search(string A[], int N, string what){
    int index = 0;
    if ((N == 1) && (A[0] == what)){
         return 0;
             } else if (N == 0){
                 return -1;
             } else if (N > 1){
             while(index < N){
                     if (A[index] == what)
                    return index;
                     else
                         index++;
                 }
             }
         return -1;
     }
```

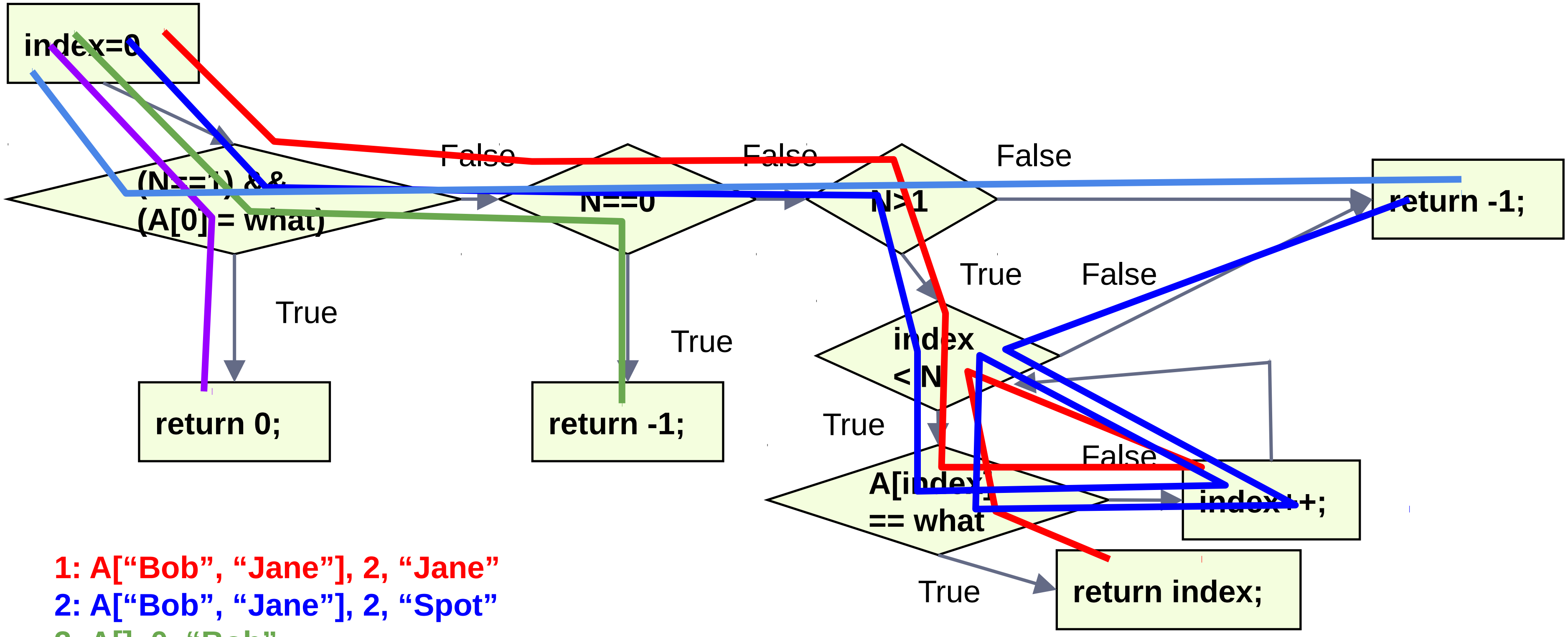
Activity - Possible Solution

- Write tests that provide statement, branch, and basic condition coverage over the following code:



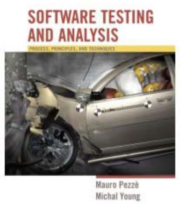
Activity - Possible Solution

- Write tests that provide statement, branch, and basic condition coverage over the following code:



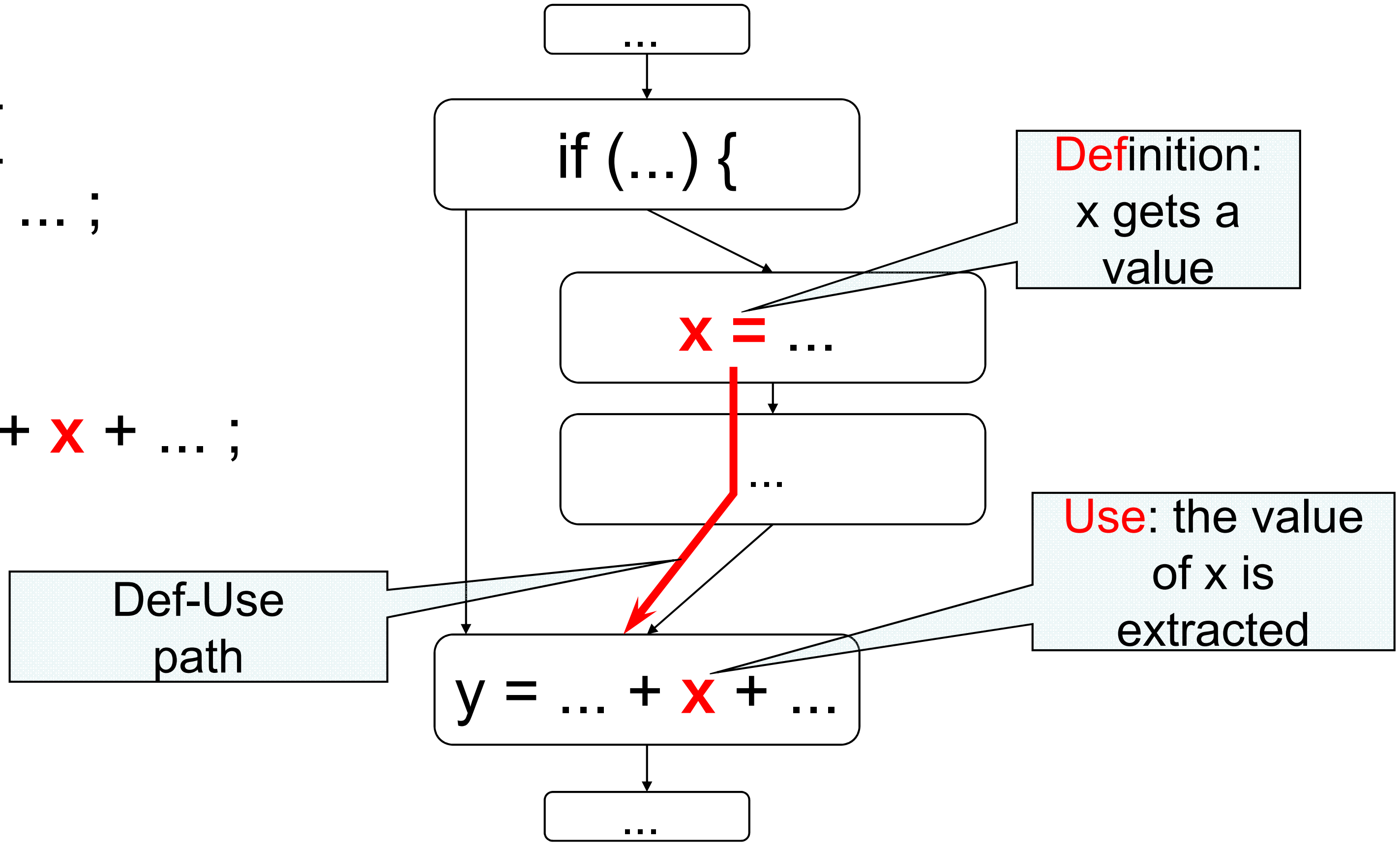
1: A["Bob", "Jane"], 2, "Jane"
2: A["Bob", "Jane"], 2, "Spot"
3: A[], 0, "Bob"
4. A["Bob"], 1, "Bob"
5. A["Bob"], 1, "Spot"

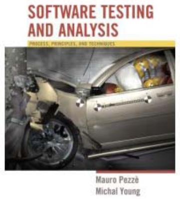
Dependence and Data Flow Models



Def-Use Pairs

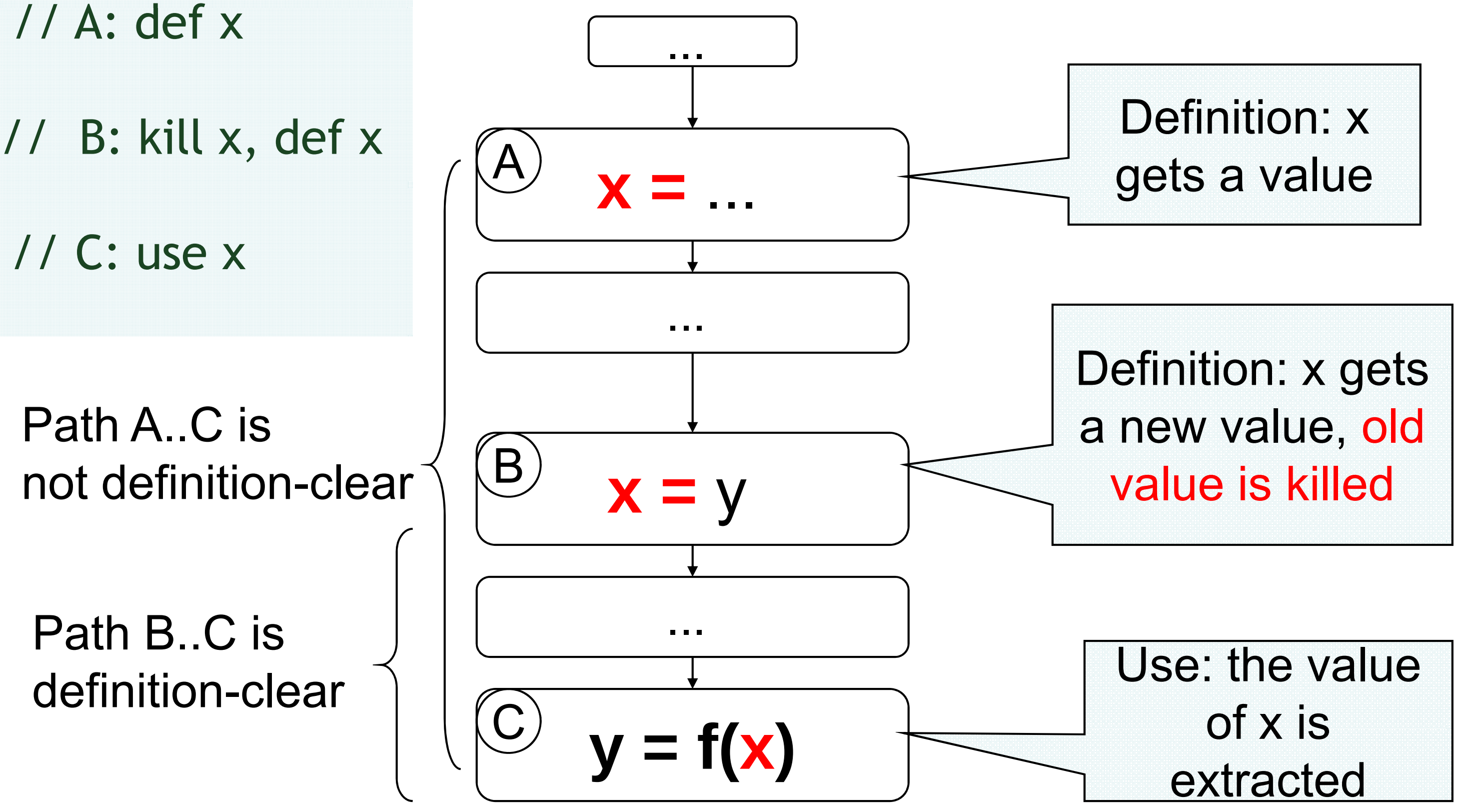
```
...
if (...) {
    x = ... ;
...
}
y = ... + x + ... ;
```





Definition-Clear or Killing

```
x = ...       // A: def x
q = ...
x = y;       //  B: kill x, def x
z = ...
y = f(x);   // C: use x
```



Data flow testing

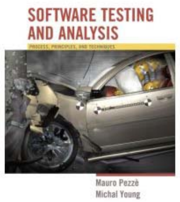
Terms

- DU pair: a pair of *definition* and *use* for some variable, such that at least one DU path exists from the definition to the use

  x = … is a *definition* of x

  = … x … is a *use* of x

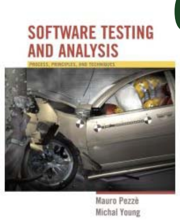
- DU path: a definition-clear path on the CFG starting from a definition to a use of a same variable
  - Definition clear: Value is not replaced on path
  - Note – loops could create infinite DU paths between a def and a use



Adequacy criteria

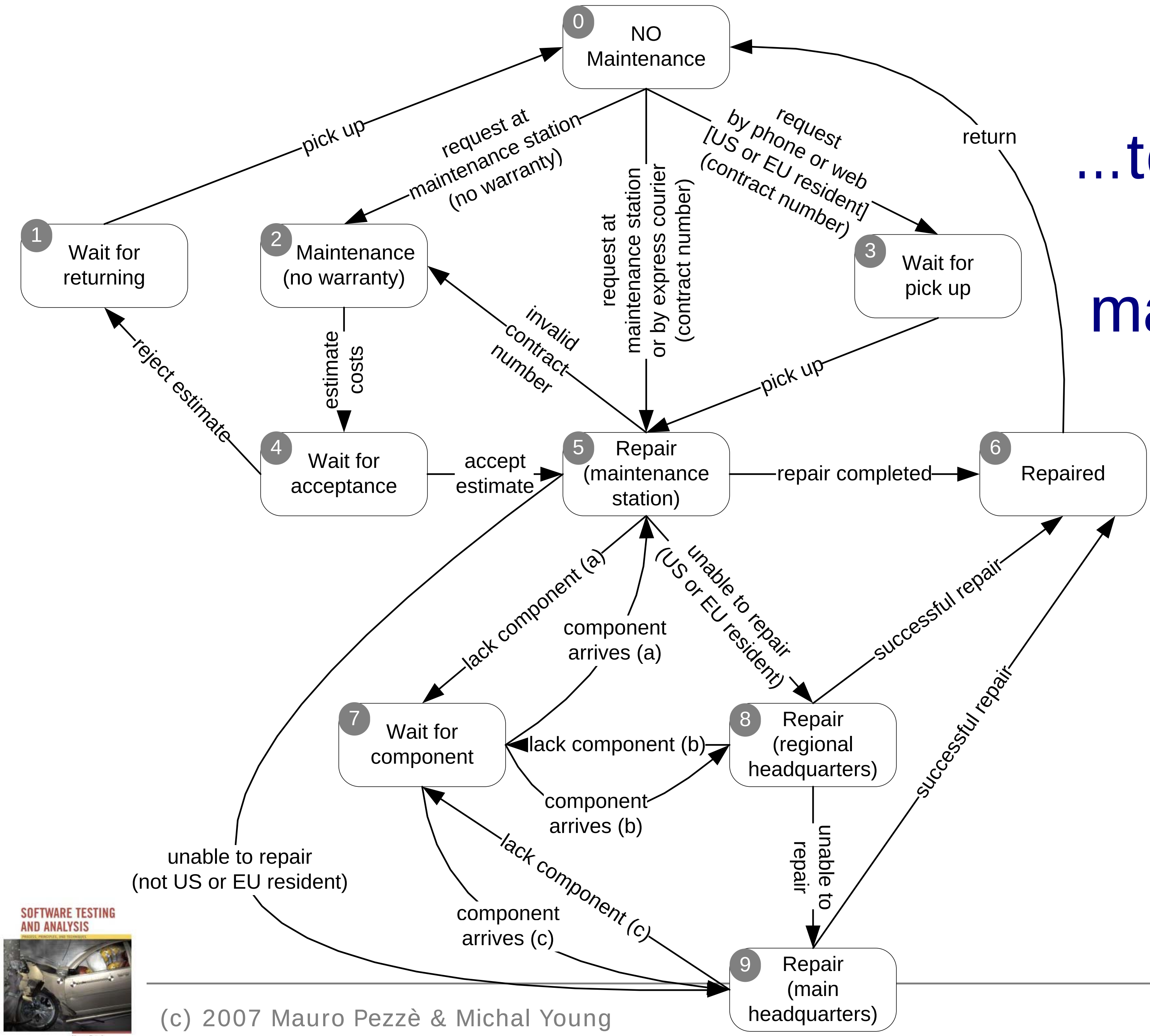
- All DU pairs: Each DU pair is exercised by at least one test case
- All DU paths: Each *simple* (non looping) DU path is exercised by at least one test case
- All definitions: For each definition, there is at least one test case which exercises a DU pair containing it
  - (Every computed value is used somewhere)

Corresponding coverage fractions can also be defined



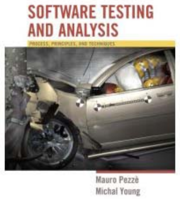
Model based testing

...to a finite state machine...



Testing Object Oriented Software

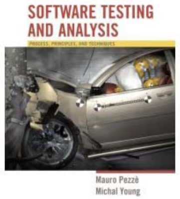
Chapter 15



Characteristics of OO Software

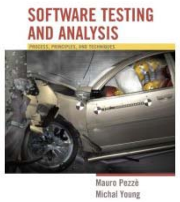
Typical OO software characteristics that impact testing

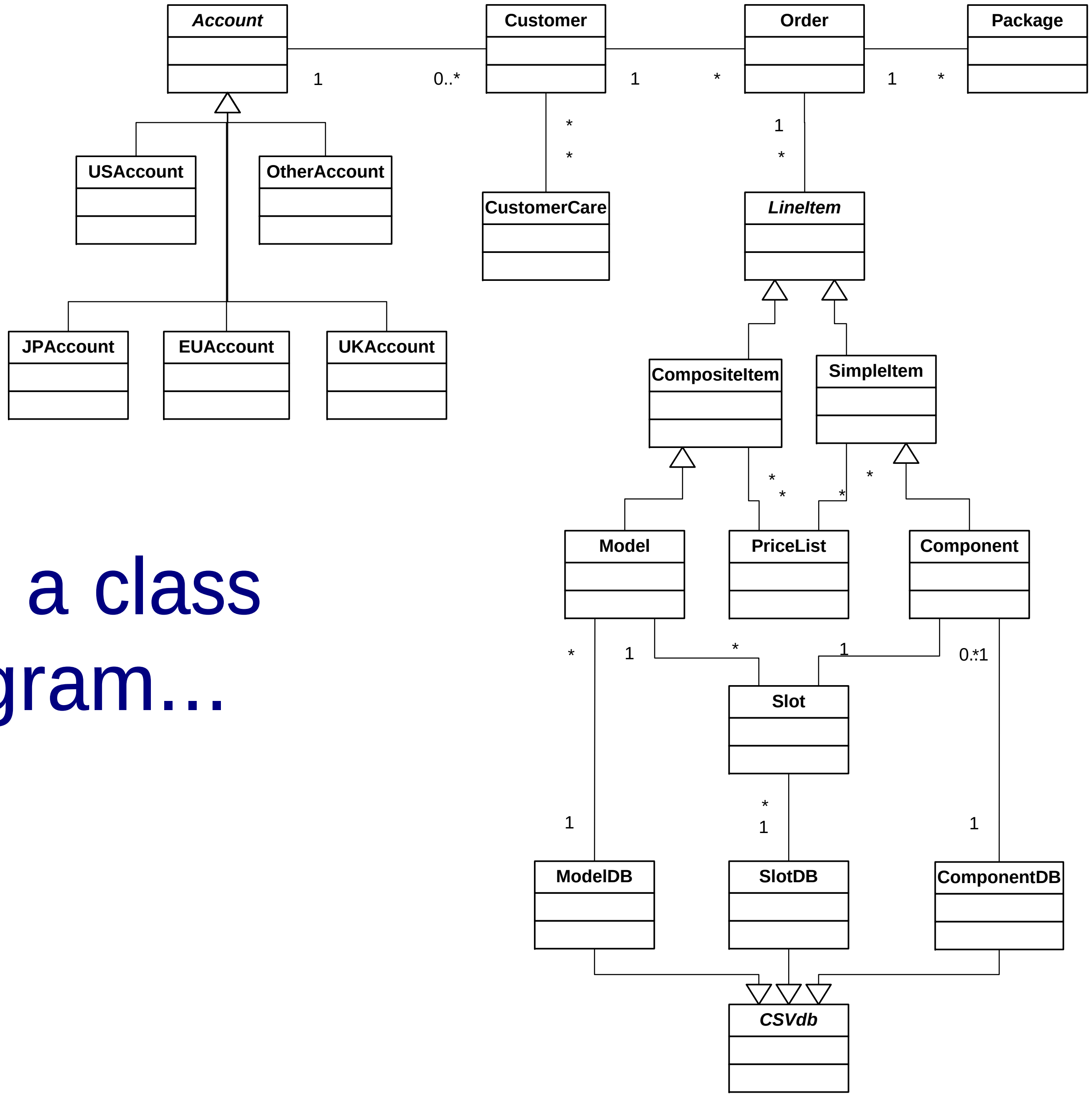
- State dependent behavior
- Encapsulation
- Inheritance
- Polymorphism and dynamic binding
- Abstract and generic classes
- Exception handling



Interclass Testing

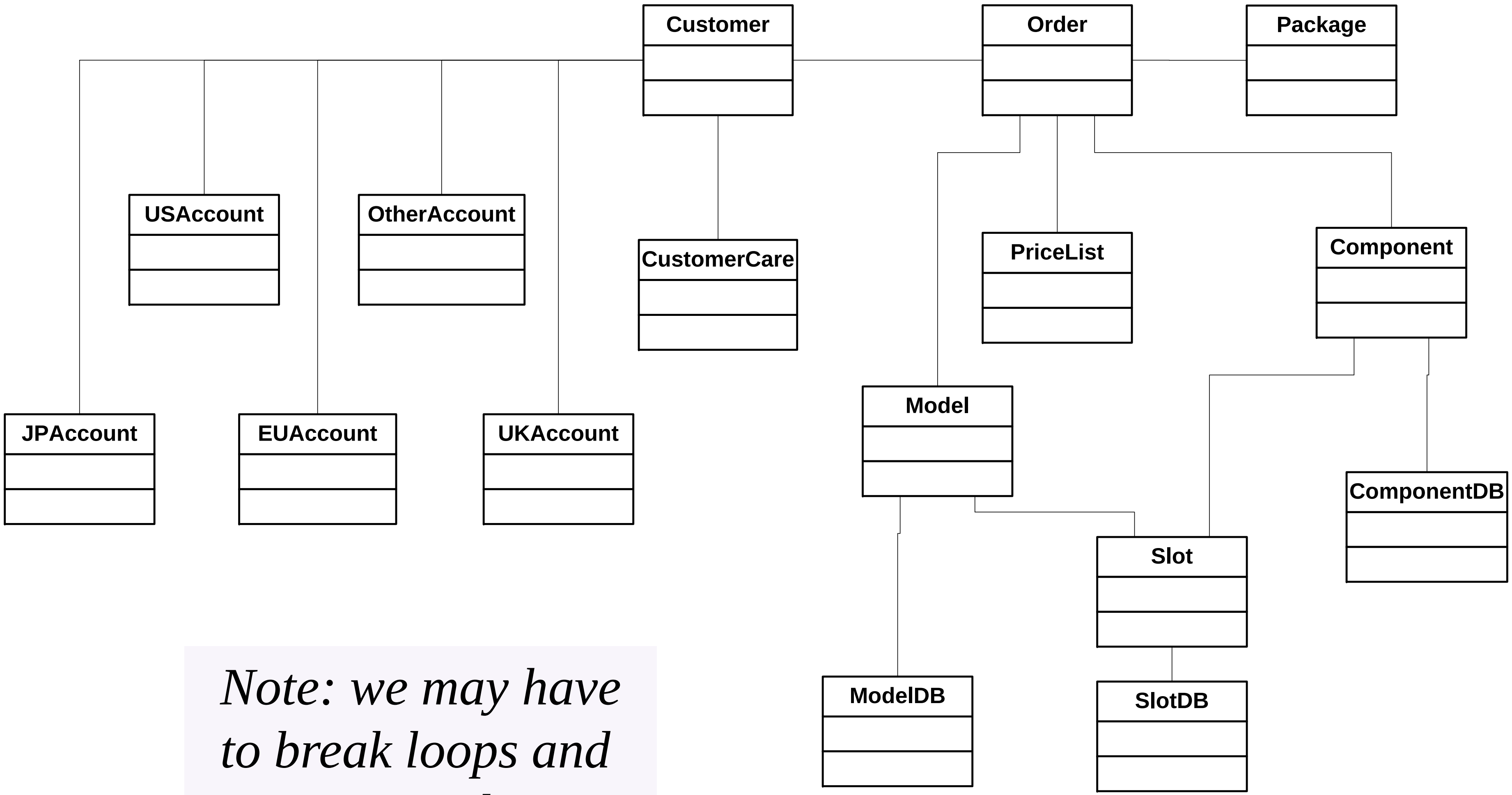
- The first level of *integration testing* for object-oriented software
  - Focus on interactions between classes
- Bottom-up integration according to “depends” relation
  - A depends on B: Build and test B, then A
- Start from use/include hierarchy
      - Implementation-level parallel to logical “depends” relation
    - Class A makes method calls on class B
    - Class A objects include references to class B methods
      - but only if reference means “is part of”



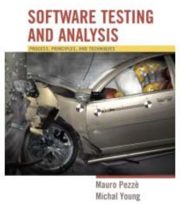


from a class diagram...

....to a hierarchy



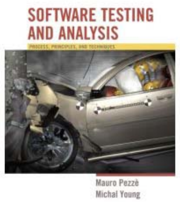
Note: we may have to break loops and generate stubs



Intraclass data flow testing

- Exercise sequences of methods
  - From setting or modifying a field value
  - To using that field value

- We need a control flow graph that encompasses more than a single method …



The intraclass control flow graph

Control flow for each method

+

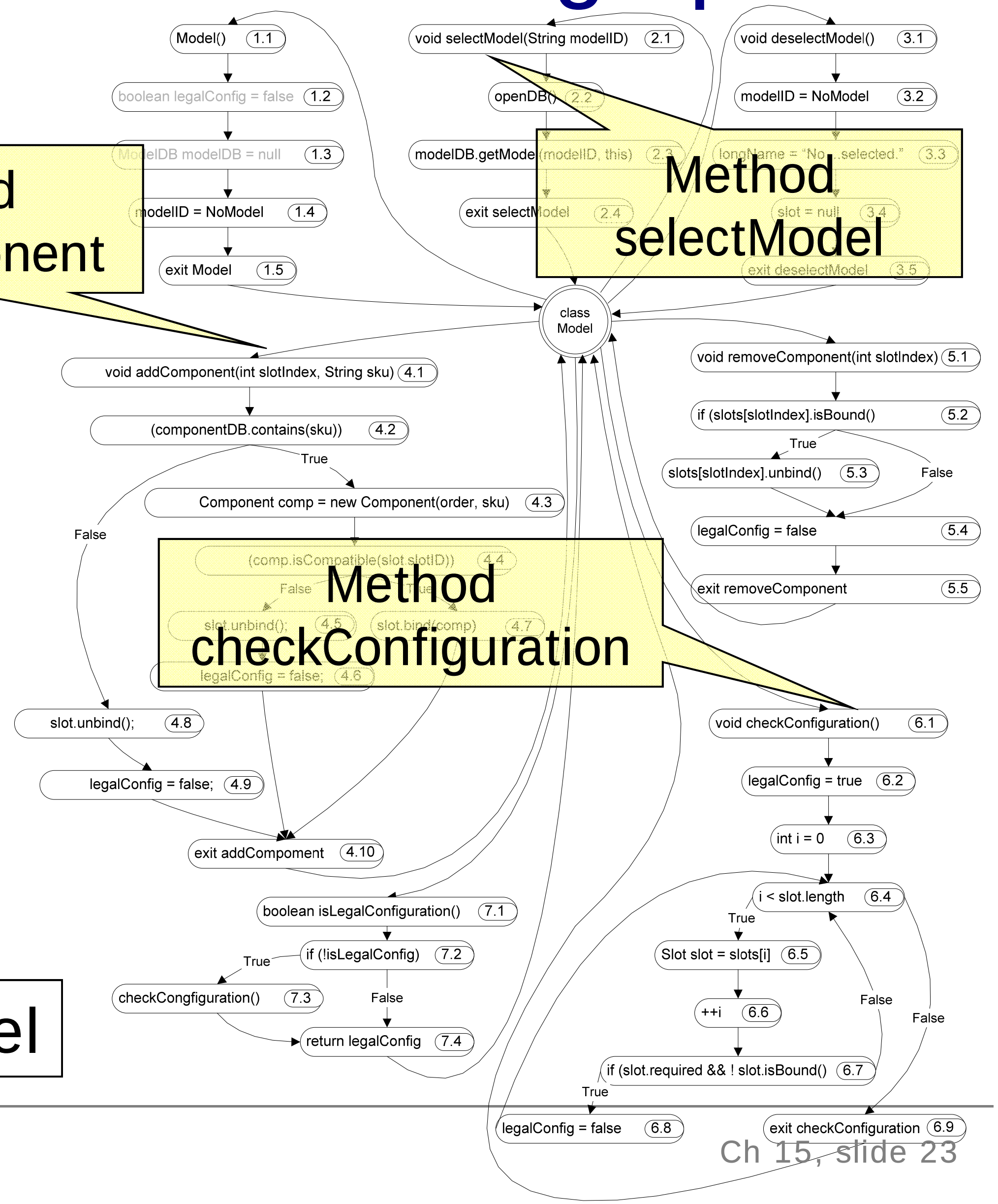
node for class

+

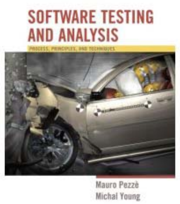
edges

- from node *class* to the start nodes of the methods
- from the end nodes of the methods to node *class*

=> control flow through *sequences* of method calls



class Model



Mutation Testing

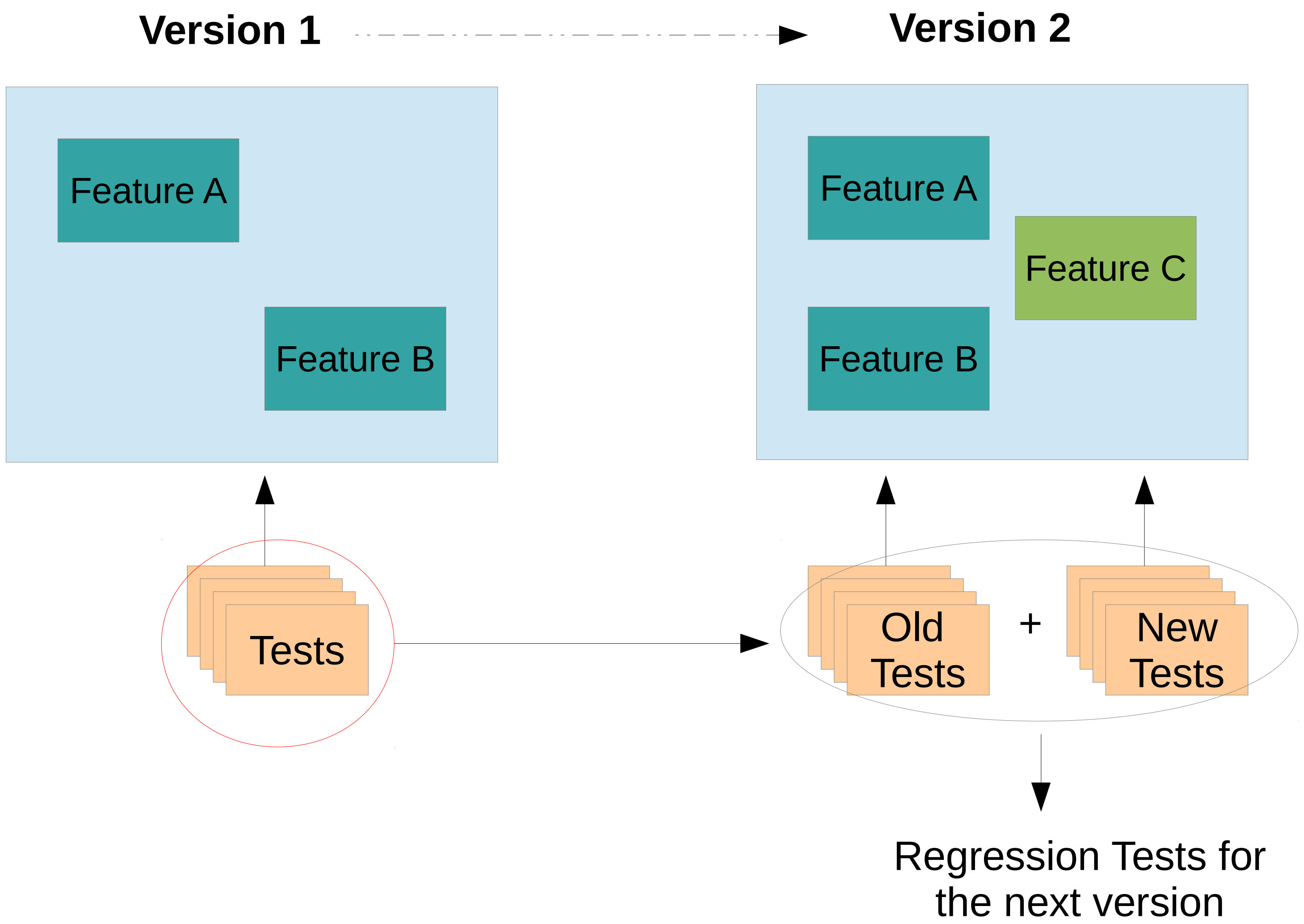
Example of Mutation Operators I

- Constant replacement
- Scalar variable replacement
- Scalar variable for constant replacement
- Constant for scalar variable replacement
- Array reference for constant replacement
- Array reference for scalar variable replacement
- Constant for array reference replacement
- Scalar variable for array reference replacement
- Array reference for array reference replacement
- Source constant replacement
- Data statement alteration
- Comparable array name replacement
- Arithmetic operator replacement
- Relational operator replacement
- Logical connector replacement
- Absolute value insertion
- Unary operator insertion
- Statement deletion
- Return statement replacement

Regression Testing

Ajitha Rajan

Example

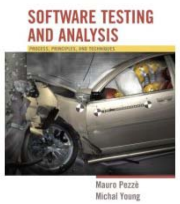


Version 1
Version 2
Feature A
Feature B
Feature A
Feature C
Feature B
Tests
Old Tests
+
New Tests
Regression Tests for the next version

Regression Test Optimization

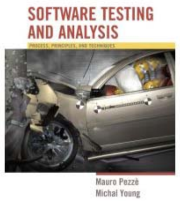
- Re-test All
- Regression Test Selection
- Regression Test Set Minimisation
- Regression Test Set Prioritisation

Integration and Component-based Software Testing

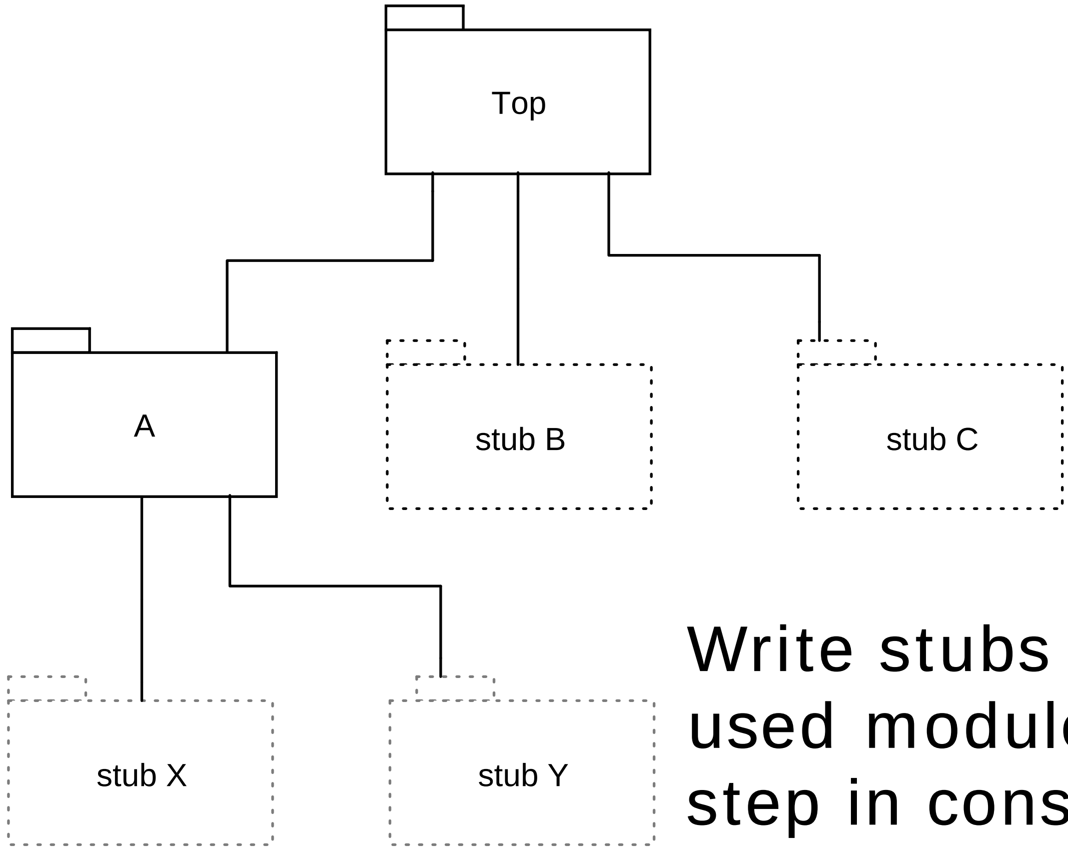


What is integration testing?

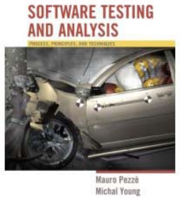
	Module test	Integration test	System test
Specification:	Module interface	**Interface specs, module breakdown**	Requirements specification
Visible structure:	Coding details	**Modular structure (software architecture)**	— none —
Scaffolding required:	Some	**Often extensive**	Some
Looking for faults in:	Modules	**Interactions, compatibility**	System functionality



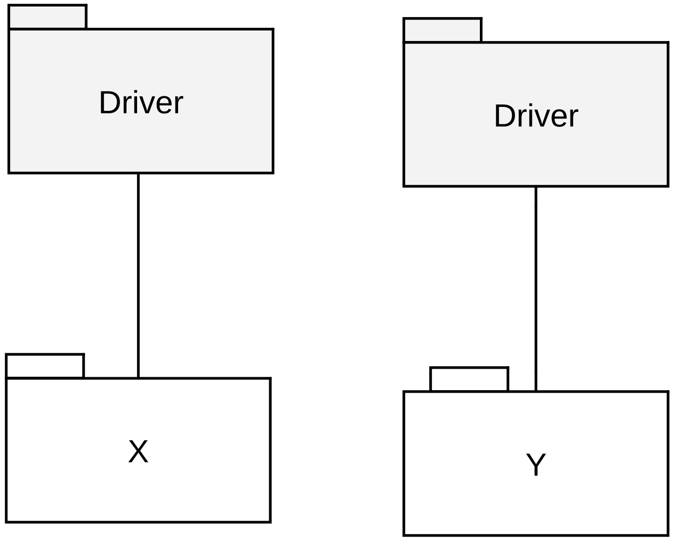
Top down ..



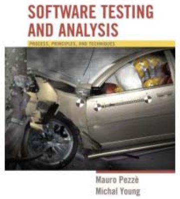
Write stubs of called or used modules at each step in construction



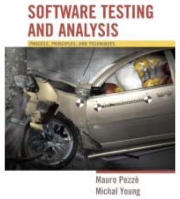
Bottom Up ..



... but we must construct drivers for each module (as in unit testing) ...



System, Acceptance, and Regression Testing

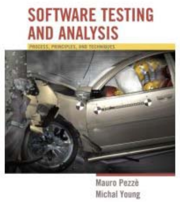


System Testing

- Key characteristics:
  - Comprehensive (the whole system, the whole spec)
  - Based on specification of observable behavior

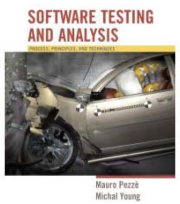
    Verification against a requirements specification, not validation, and not opinions
  - Independent of design and implementation

Independence: Avoid repeating software design errors in system test design



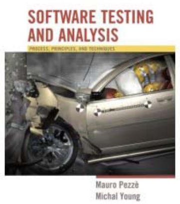
Global Properties

- Some system properties are inherently global
  - Performance, latency, reliability, ...
  - Early and incremental testing is still necessary, but provide only estimates
- A major focus of system testing
  - The only opportunity to verify global properties against actual system specifications
  - Especially to find unanticipated effects, e.g., an unexpected performance bottleneck



Context-Dependent Properties

- Beyond system-global: Some properties depend on the system context and use
  - Example: Performance properties depend on environment and configuration
  - Example: Privacy depends both on system and how it is used
    - Medical records system must protect against unauthorized use, and authorization must be provided only as needed
  - Example: Security depends on threat profiles
    - And threats change!
- Testing is just one part of the approach



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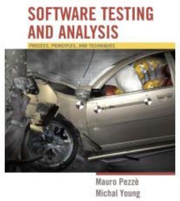
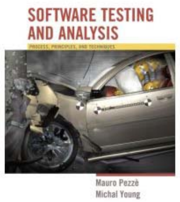
Acceptance testing

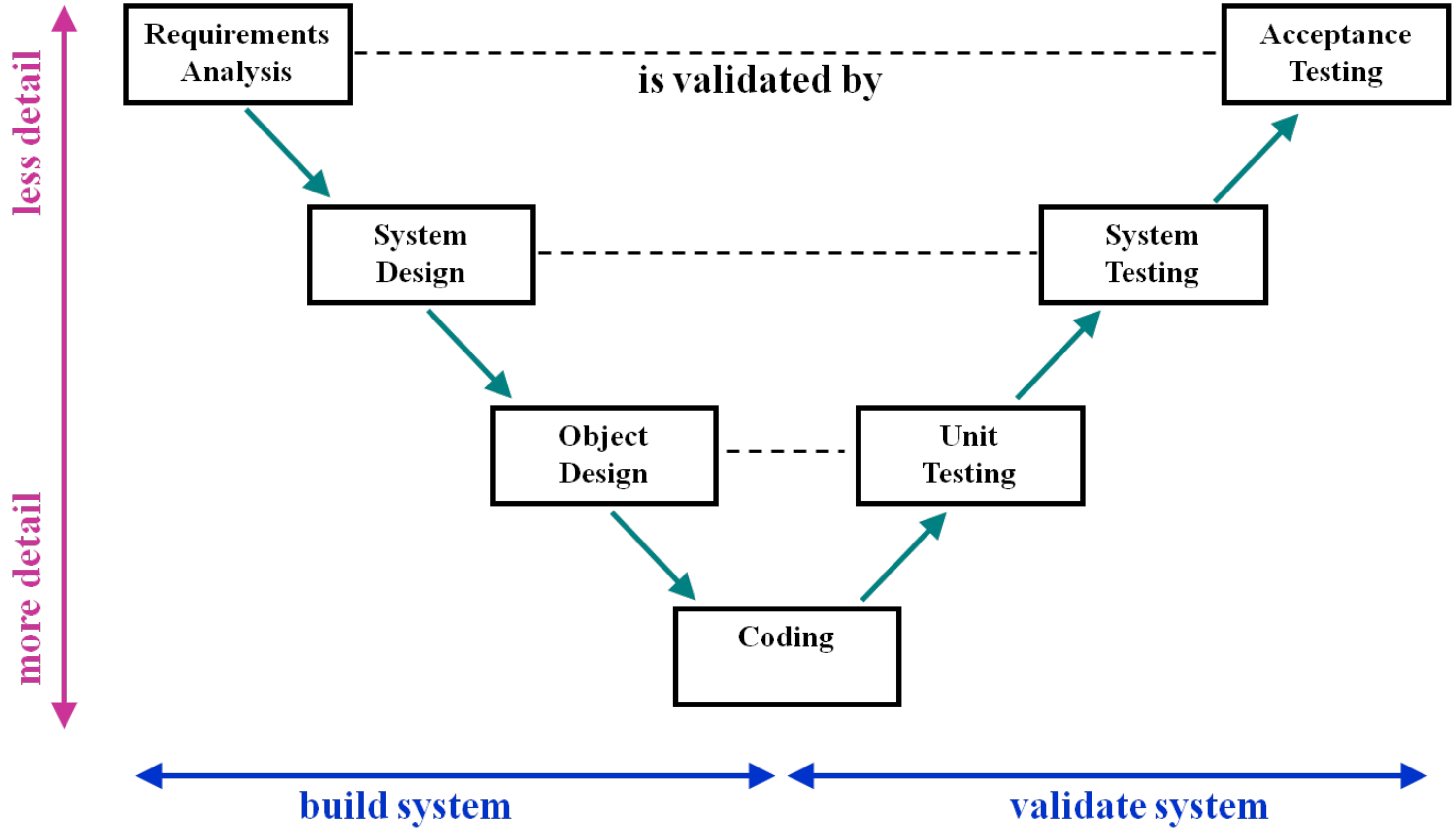


Estimating Dependability

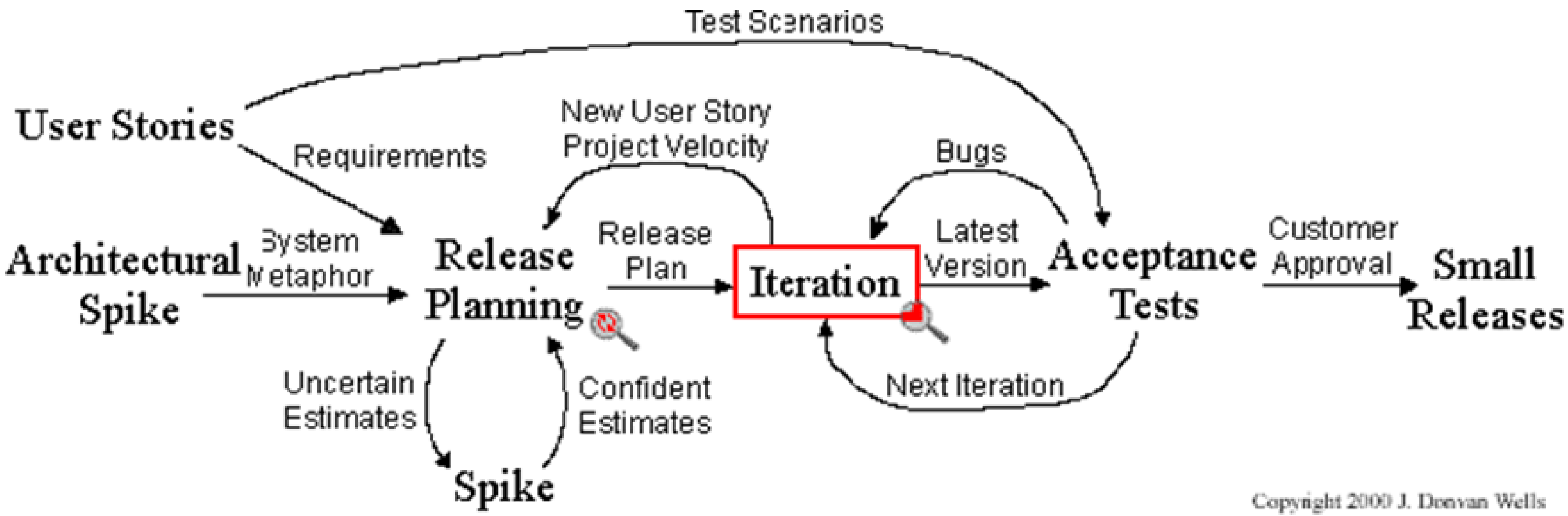
- Measuring quality, not searching for faults
  - Fundamentally different goal than systematic testing
- Quantitative dependability goals are statistical
  - Reliability
  - Availability
  - Mean time to failure
  - …
- Requires valid statistical samples from *operational profile*
  - Fundamentally different from systematic testing



V-model

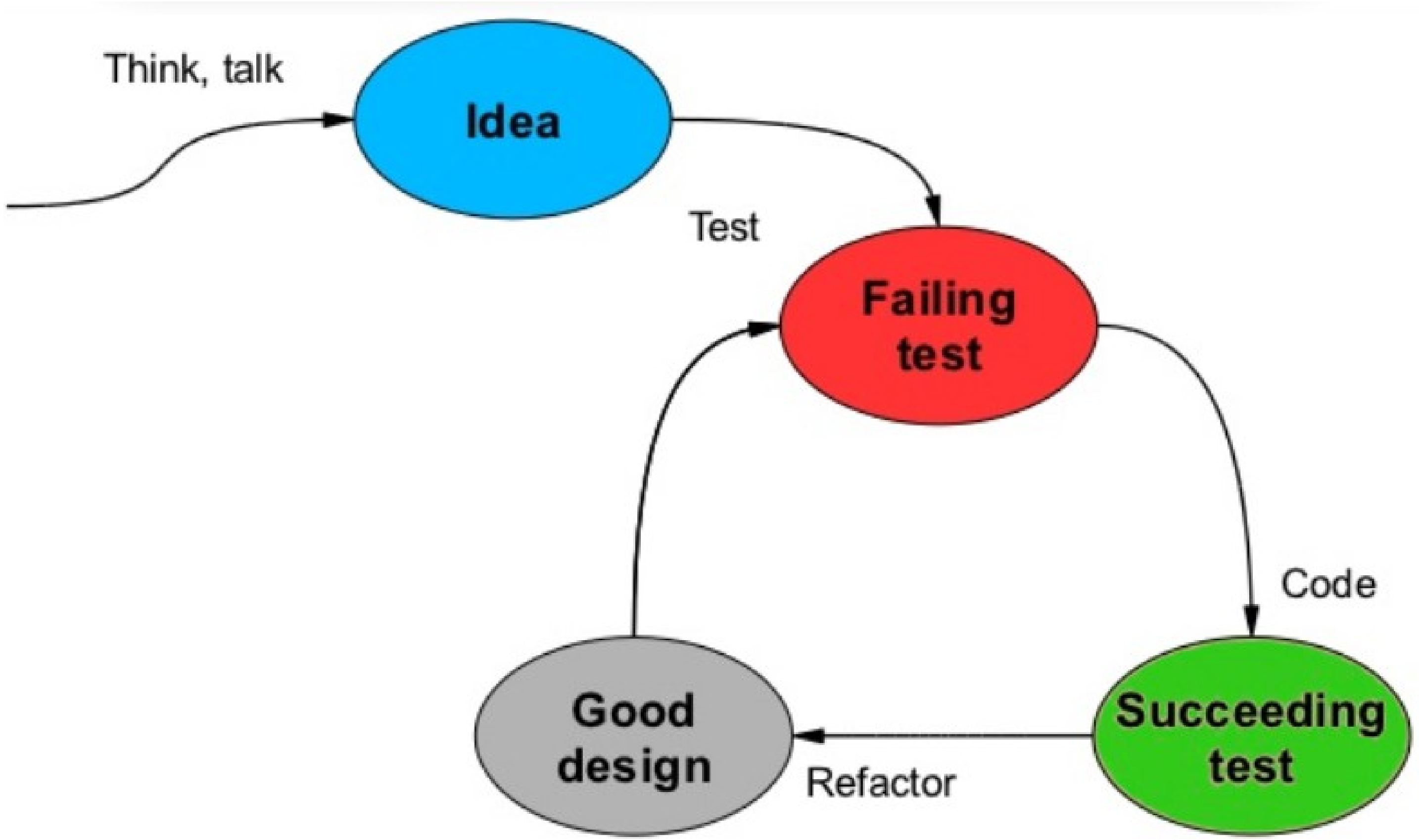

Requirements Analysis
is validated by
Acceptance Testing
System Design
System Testing
Object Design
Unit Testing
Coding
less detail
more detail
build system
validate system

eXtreme Programming (XP)



http://www.extremeprogramming.org/map/project.html

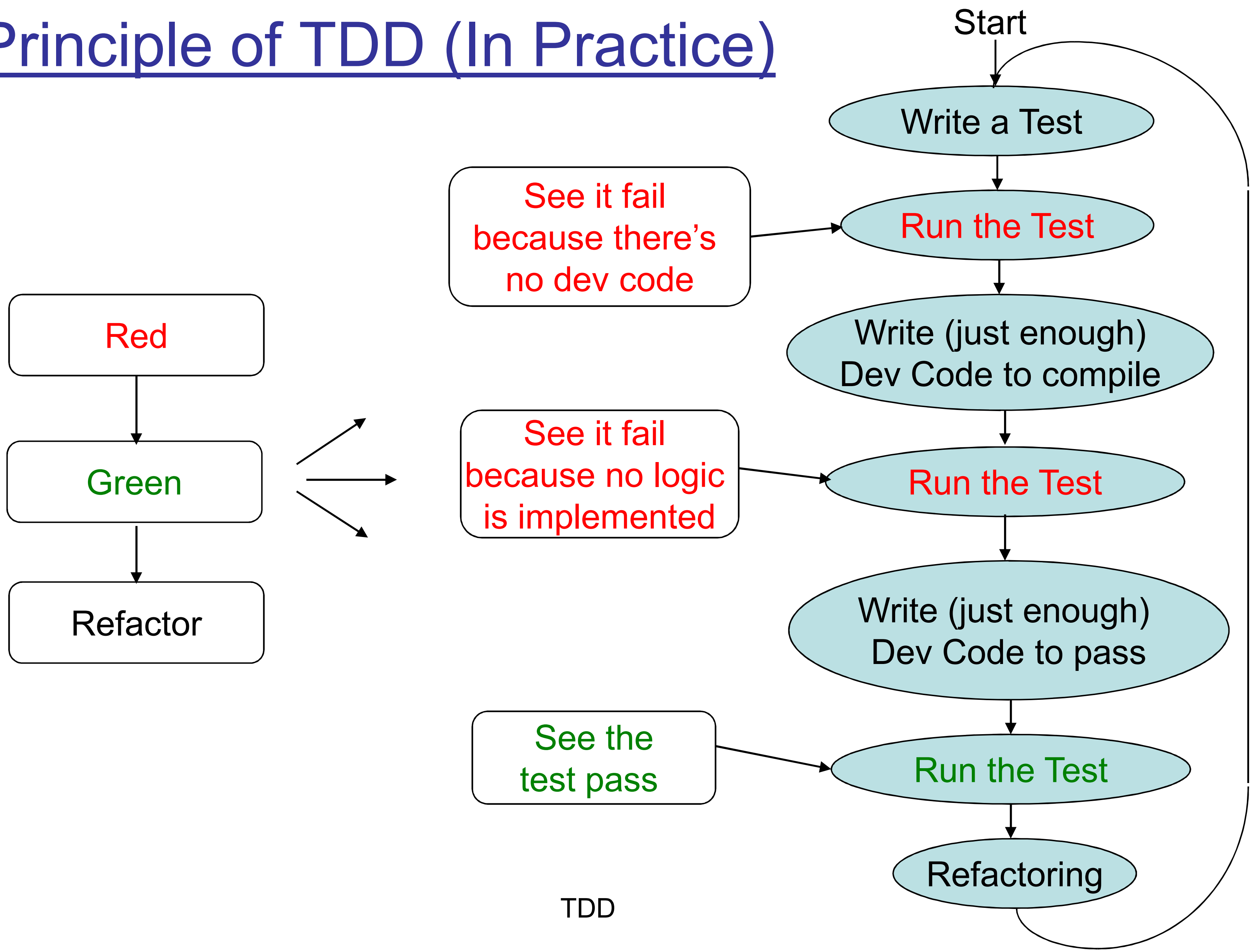
HOW DOES TDD HELP



TDD CYCLE

- Write Test Code
  - Guarantees that every functional code is testable
  - Provides a specification for the functional code
  - Helps to think about design
  - Ensure the functional code is tangible
- Write Functional Code
  - Fulfill the requirement (test code)
  - Write the simplest solution that works
  - Leave Improvements for a later step
  - The code written is only designed to pass the test
    - no further (and therefore untested code is not created).
- Refactor
  - Clean-up the code (test and functional)
  - Make sure the code expresses intent
  - Remove code smells
  - Re-think the design
  - Delete unnecessary code

Principle of TDD (In Practice)



Security testing vs “regular” testing

- “Regular” testing aims to ensure that the program meets customer requirements in terms of features and functionality.
- Tests “normal” use cases
  - ⇨ Test with regards to common expected usage patterns.

- Security testing aims to ensure that program fulfills security requirements.
  - Often non-functional.
  - More interested in misuse cases
    - ⇨ Attackers taking advantage of “weird” corner cases.

Common security testing approaches

Often difficult to craft e.g. unit tests from non-functional requirements

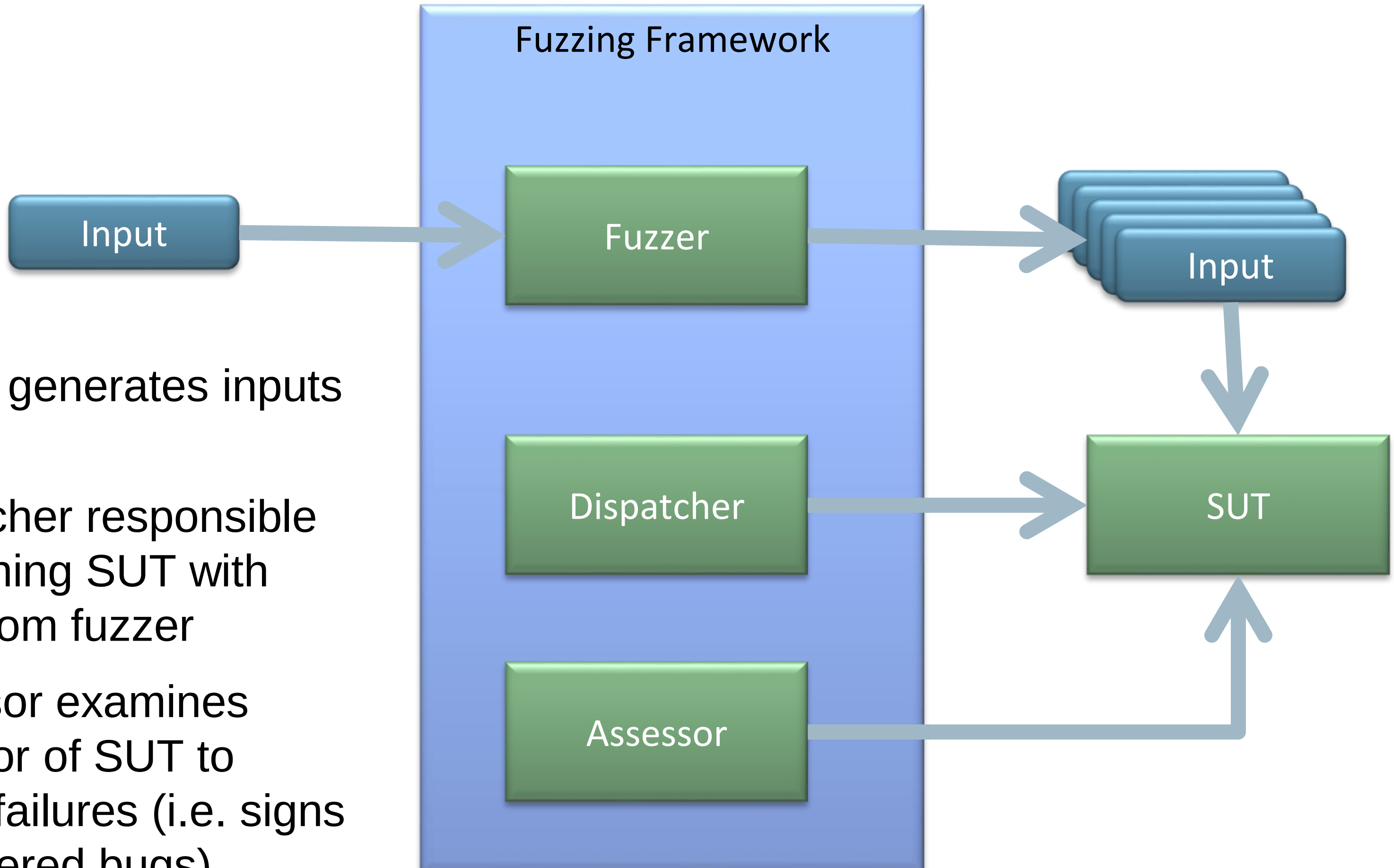
Two common approaches:

- Test for known vulnerability types
- Attempt directed or random search of program state space to uncover the “weird corner cases”

In today’s lecture:

- Penetration testing (briefly)
- Fuzz testing or “fuzzing”
- Concolic testing

Fuzz testing architecture



- Fuzzer generates inputs to SUT
- Dispatcher responsible for running SUT with input from fuzzer
- Assessor examines behavior of SUT to detect failures (i.e. signs of triggered bugs)

Fuzzing components: Input generation

Simplest method: Completely random

- Won’t work well in practice – Input deviates too much from expected format, rejected early in processing.

Two common methods:

- Mutation based fuzzing
- Generation based fuzzing

Fuzzing outlook

- Mutation-based fuzzing can typically only find the “low-hanging fruit” – shallow bugs that are easy to find
- Generation-based fuzzers almost invariably gives better coverage, but requires much more manual effort

- Current research in fuzzing attempts to combine the “fire and forget” nature of mutation-based fuzzing and the coverage of generation-based.
  - **Evolutionary fuzzing** combines mutation with genetic algorithms to try to “learn” the input format automatically. Recent successful example is “American Fuzzy Lop” (AFL)
  - **Whitebox fuzzing** generates test cases based on the control-flow structure of the SUT. Our next topic…

Concolic testing

Idea: Combine concrete and symbolic execution

- Concolic execution (CONCrete and symbOLIC)

Concolic execution workflow:

1. Execute the program for real on some input, and record path taken.
2. Encode path as query to SMT solver and negate one branch condition
3. Ask the solver to find new satisfying input that will give a different path

Reported bugs are always accompanied by an input that triggers the bug (generated by SMT solver)

⇨ Complete – Reported bugs are always real bugs

Greybox fuzzing

- Probability of hitting a “deep” level of the code decreases exponentially with the “depth” of the code for mutation based fuzzing.

- Similarly, the time required for solving an SMT query is high, and increases exponentially with the depth of the path constraint.

- Black-box fuzzing is too “dumb” and whitebox fuzzing may be “too smart”
  - Idea of greybox fuzzing is to find a sweet spot in between.

```
if(condtion1)
   if(condtion2)
      if(condtion3)
         if(condtion4)
            bug();
```

Mutational fuzzer would need to guess correct values of all four condtions in one go to reach bug!