Software Architecture and Engineering

Testing

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Chair of Programming Methodology

The slides in this section are partly based on the courses "Software Engineering I" by Prof. Bernd Brügge, TU München and "Software Engineering" by Prof. Jan Vitek, Purdue University

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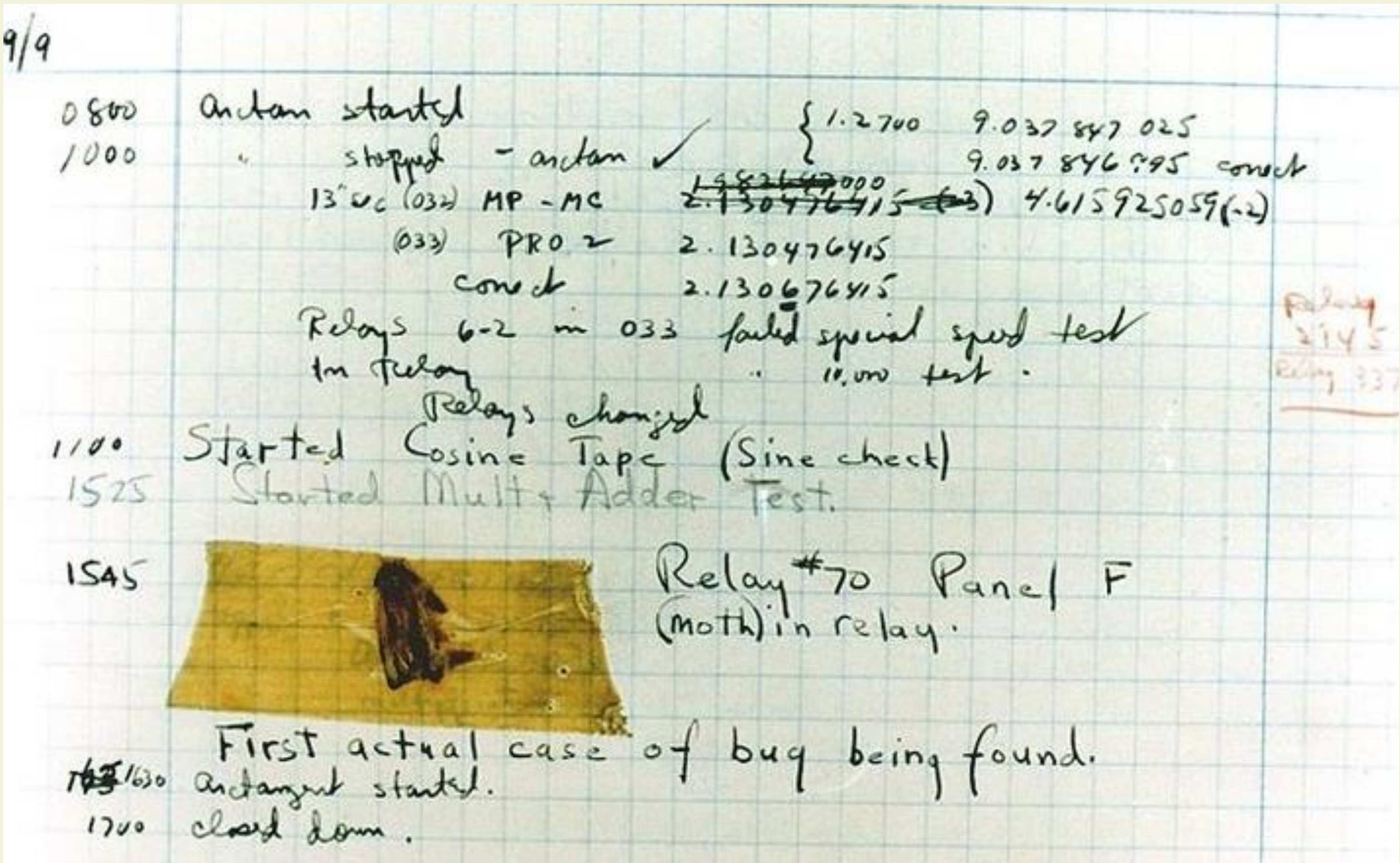
Why Does Software Contain Bugs?

- Our ability to predict the behavior of our implementations is limited
  - Software is extremely complex
  - No developer can understand the whole system

- We make mistakes
  - Unclear requirements, miscommunication
  - Wrong assumptions (e.g., behavior of operating system)
  - Design errors (e.g., capacity of data structure too small)
  - Coding errors (e.g., wrong loop condition)

“First actual case of bug being found.”



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Increasing Software Reliability

Fault Avoidance

- Detect faults statically without executing the program
- Includes development methodologies, reviews, and program verification

Fault Detection

- Detect faults by executing the program
- Includes testing

Fault Tolerance

- Recover from faults at runtime (e.g., transactions)
- Includes adding redundancy (e.g., n-version programming)

Goal of Testing

- An error is a deviation of the observed behavior from the required (desired) behavior
  - Functional requirements (e.g., user-acceptance testing)
  - Nonfunctional requirements (e.g., performance testing)
- Testing is a process of executing a program with the intent of finding an error
- A successful test is a test that finds errors

Limitations of Testing

Testing can only show the presence of bugs, not their absence. [E. W. Dijkstra]

- It is impossible to completely test any nontrivial module or any system
  - Theoretical limitations: termination
  - Practical limitations: prohibitive in time and cost

5. Testing

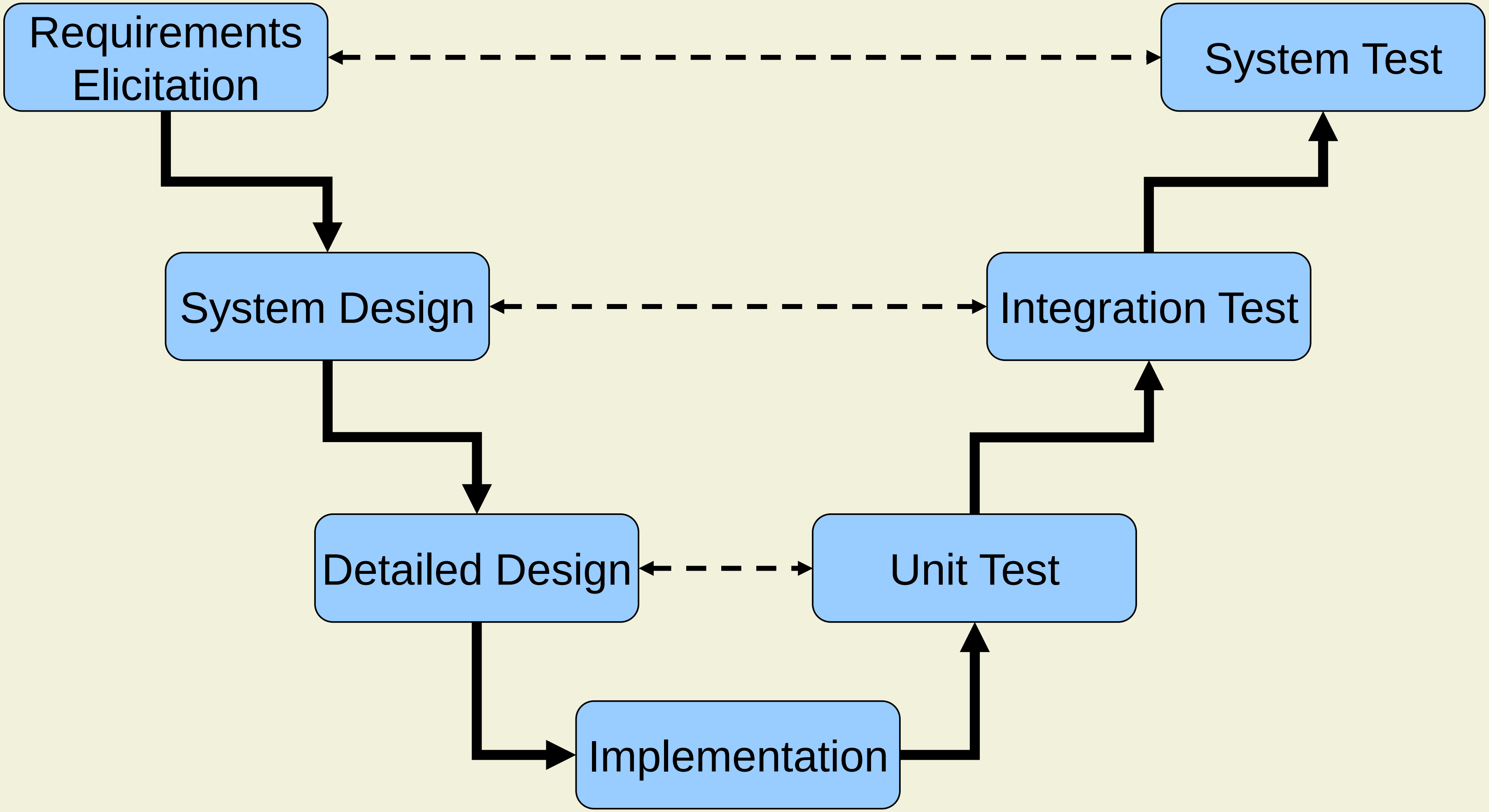
5.1 Test Stages

5.2 Test Strategies

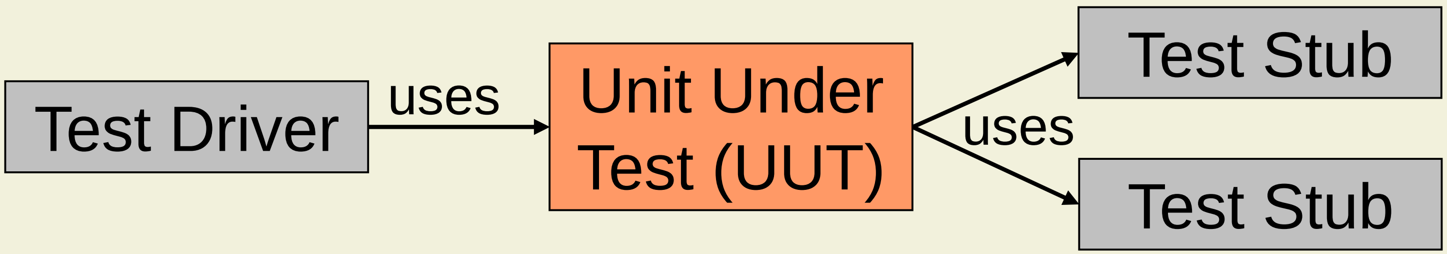
5.3 Functional Testing

5.4 Structural Testing

Test Stages


Requirements Elicitation
System Test
System Design
Integration Test
Detailed Design
Unit Test
Implementation

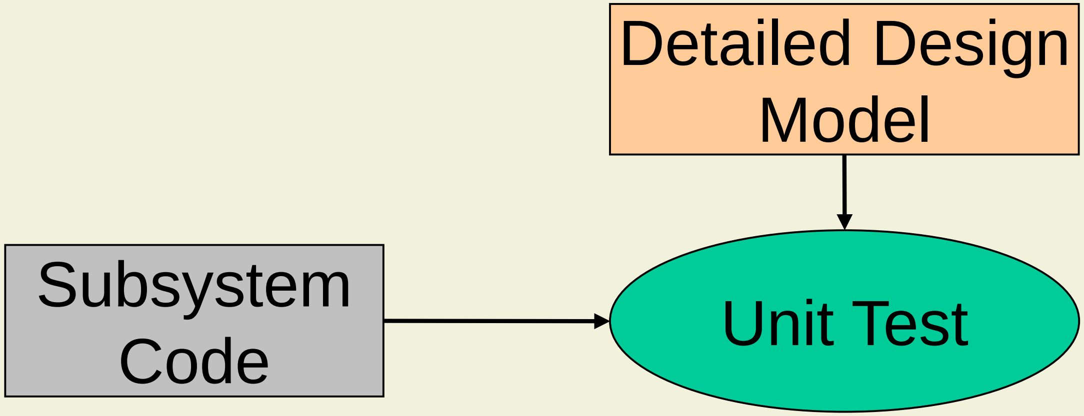
Creation of Test Harness



- Test driver
  - Applies test cases to UUT including setup and clean-up
- Test stub
  - Partial, temporary implementation of a component used by UUT
  - Simulates the activity of a missing component by answering to the calling sequence of the UUT and returning back fake data

Unit Testing

- Testing individual subsystems (collection of classes)



- Goal: Confirm that subsystem is correctly coded and carries out the intended functionality

Unit Test Example (JUnit)

```
class SavingsAccount {
  …
  public void deposit( int amount ) { … }
  public void withdraw( int amount ) { … }
  public int getBalance( ) { … }
}
```

```
@Test
public void withdrawTest( ) {
  SavingsAccount target = new SavingsAccount();
  target.deposit( 300 );
  int amount = 100;
  target.withdraw( amount );
  Assert.assertTrue( target.getBalance( ) == 200 );
}
```

Implement test driver

Create test data

Create test oracle

Unit Testing: Discussion

- To achieve a reasonable test coverage, one has to test each method with several inputs
  - To cover valid and invalid inputs
  - To cover different paths through the method

```
@Test
public void withdrawTest( ) {
  SavingsAccount target = new SavingsAccount();
  target.deposit( 500 );
  int amount = 0;
  target.withdraw( amount );
  Assert.assertTrue( target.getBalance( ) == 500 );
}
```

Boiler-plate code for creating test data and writing test oracles

Parameterized Unit Tests (NUnit)

- Parameterized test methods take arguments for test data
  - Decouple test driver (logic) from test data

```
[ Test ]
public void withdrawTest( int balance, int amount ) {
  SavingsAccount target = new SavingsAccount();
  target.deposit( balance );
  target.withdraw( amount );
  Assert.IsTrue( target.getBalance( ) == balance – amount );
}
```

- Test data can be specified as values, ranges, or random values
- Requires generic test oracles

Generic Test Oracles: Example

```
public static void bubbleSort( int[ ] a ) {
  for( int i = 0; i < a.Length - 1; i++ ) {
    for( int j = i + 1; j < a.Length; j++ ) {
      if( a[ i ] > a[ j ] )
      { int tmp = a[ i ]; a[ i ] = a[ j ]; a[ j ] = tmp; }
    }
  }
}
```

```
[ Test ]
public void bubbleSortTest( ) {
  int[ ] a = { 7, 2, 5, 2 };

  bubbleSort( a );

  int[ ] expected = { 2, 2, 5, 7 };
  Assert.AreEqual( expected, a );
}
```

Create test data

Create test oracle

Generic Test Oracles: Example

```
[ Test ]
public void bubbleSortTest( int[ ] a ) {
  int[ ] original = ( int[ ] ) a.Clone();

  bubbleSort( a );

  for( int i = 0; i < a.Length - 1; i++ )
    Assert.IsTrue( a[ i ] <= a[ i+1 ] );

  bool[ ] visited = new bool[ a.Length ];
  for( int i = 0; i < a.Length; i++ ) {
    int j;
    for ( j = 0; j < a.Length; j++ ) {
      if( !visited[ j ] && a[ i ] == original[ j ] )
      { visited[ j ] = true; break; }
    }
    Assert.IsFalse( j == a.Length );
  }
}
```

Save test data for later comparison

Check that array is sorted

Check that array is a permutation of original array

Value a[i] is not in the original array

Parameterized Unit Tests: Discussion

- Parameterized unit tests avoid boiler-plate code
- Writing generic test oracles is sometimes difficult
  - Analogous to writing strong postconditions
- Still several test methods are needed, for instance, for valid and invalid input
- Parameterized unit tests are especially useful when test data is generated automatically (see later)

Test Execution

- Execute the test cases
- Re-execute test cases after every change
  - Automate as much as possible
  - For instance, after each refactoring

- Regression testing
  - Testing that everything that used to work still works after changes are made to the system
  - Also important for system testing

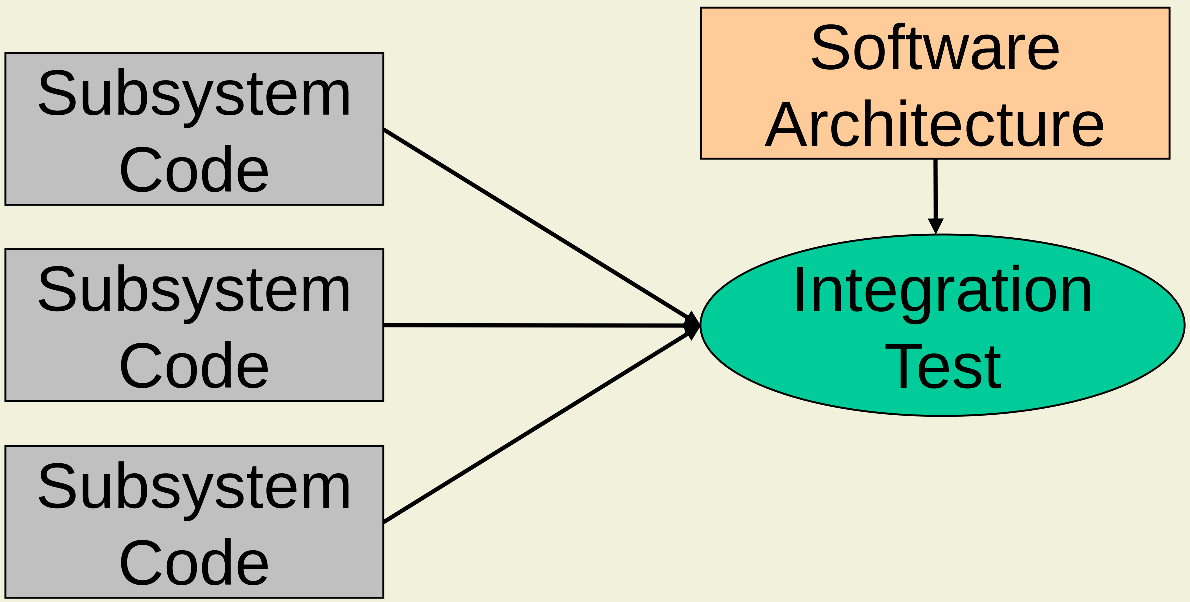
Eight Rules of Testing

1. Make sure all tests are fully automatic and check their own results
2. A test suite is a powerful bug detector that reduces the time it takes to find bugs
3. Run your tests frequently– every test at least once a day
4. When you get a bug report, start by writing a unit test that exposes the bug
5. Better to write and run incomplete tests than not run complete tests
6. Concentrate your tests on boundary conditions
7. Do not forget to test exceptions raised when things are expected to go wrong
8. Do not let the fear that testing can't catch all bugs stop you from writing tests that will catch most bugs

[M. Fowler]

Integration Testing

- Testing groups of subsystems and eventually the entire system

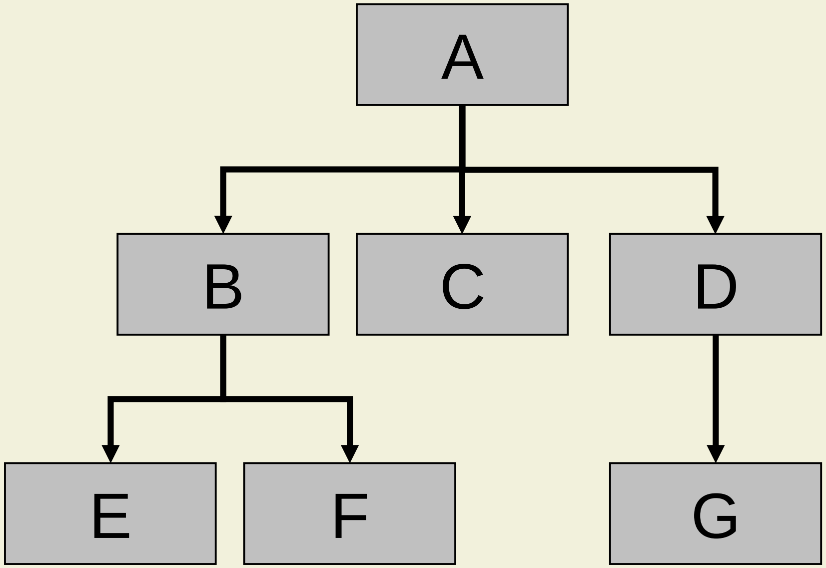


- Goal: Test interfaces between subsystems

Integration Testing Strategy

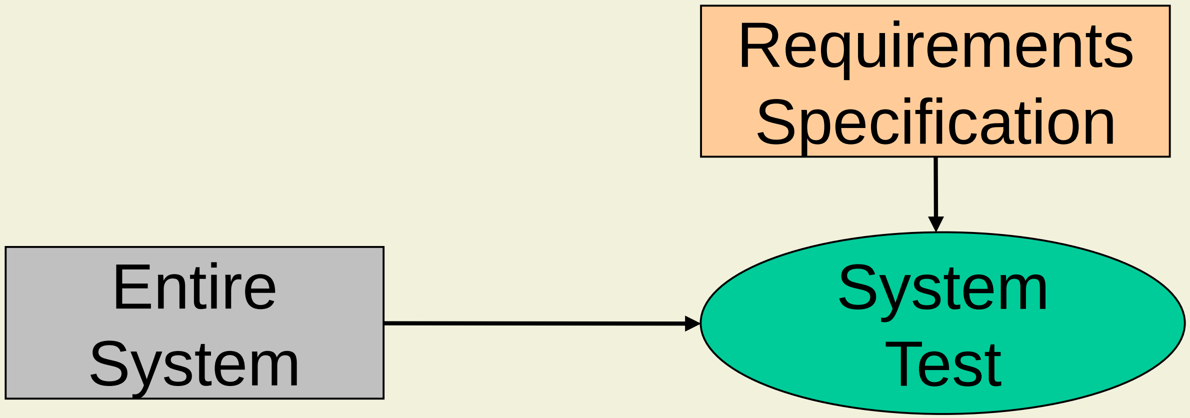
- The order in which the subsystems are selected for testing and integration
- Typical strategies
  - Big-bang integration (non-incremental)
  - Bottom-up integration
  - Top-down integration
- Selection criteria
  - Amount of test harness (stubs and drivers)
  - Scheduling concerns

Call hierarchy



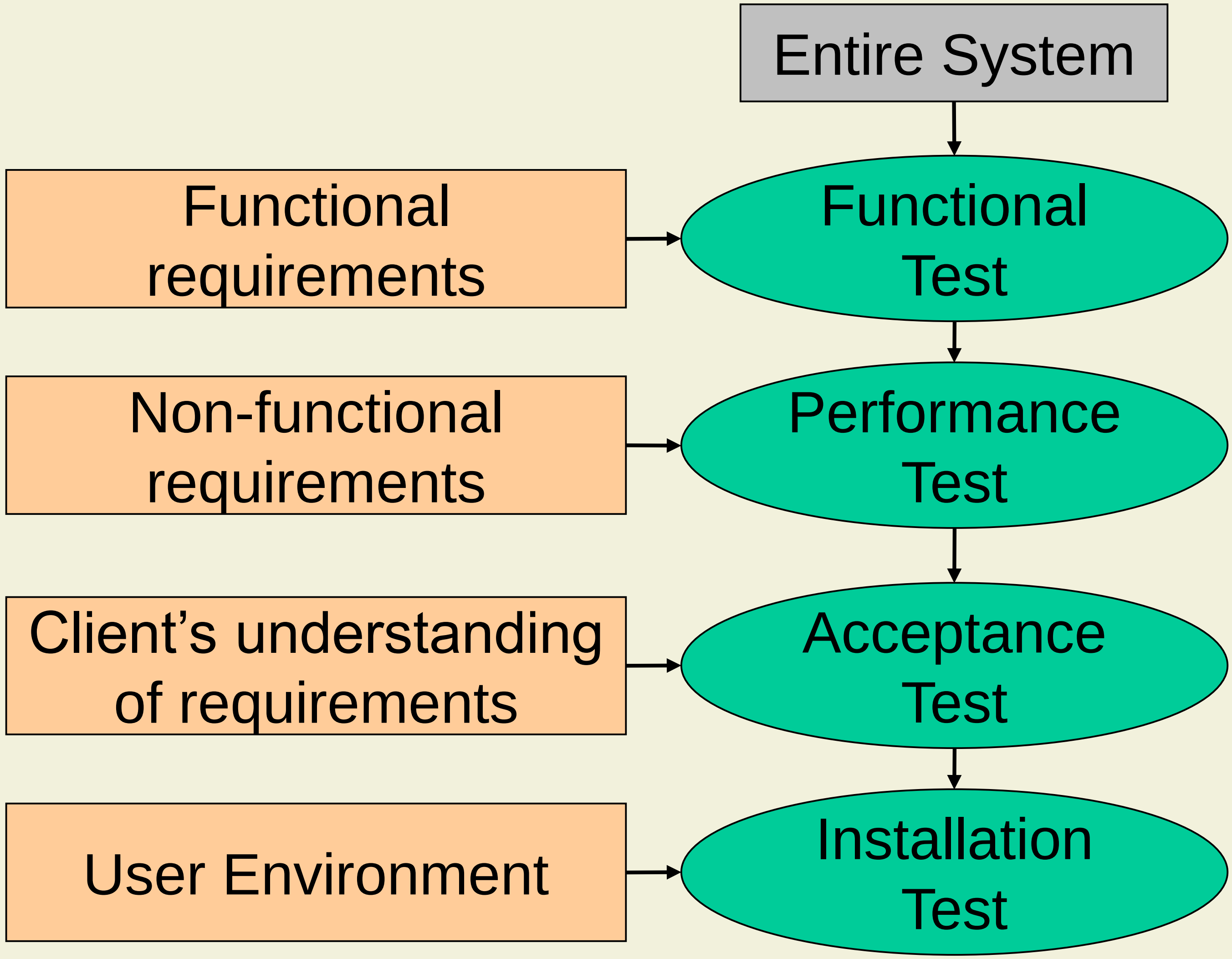
System Testing

- Testing the entire system



- Goal: Determine if the system meets the requirements (functional and non-functional)

System Testing Stages



Functional Testing

- Goal: Test functionality of system
  - System is treated as black box

- Test cases are designed from requirements analysis document
  - Based on use cases
  - Alternative source: user manual
- Test cases describe
  - Input data
  - Flow of events
  - Results to check

Acceptance Testing

- Goal: Demonstrate that the system meets customer requirements and is ready to use
- Performed by the client, not by the developer

- Alpha test
  - Client uses the software at the developer's site
  - Software used in a controlled setting, with the developer ready to fix bugs
- Beta test
  - Conducted at client's site (developer is not present)
  - Software gets a realistic workout in target environment

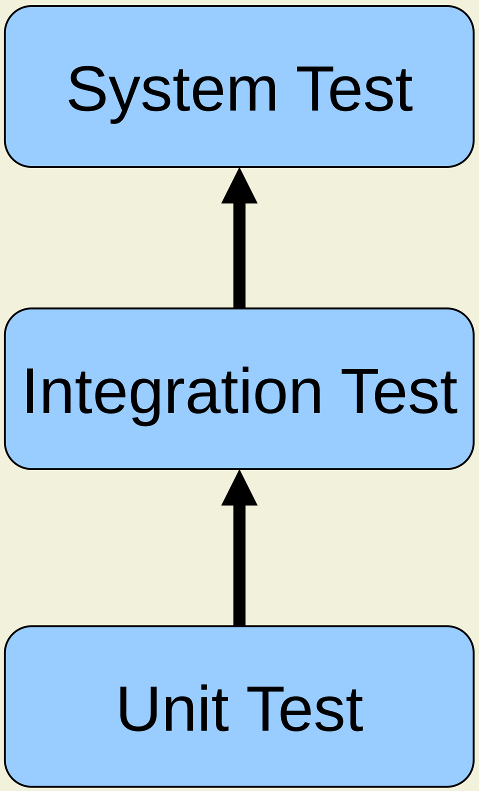
Independent Testing

- Programmers have a hard time believing they made a mistake
  - Plus a vested interest in not finding mistakes
  - Often stick to the data that makes the program work

- Designing and programming are constructive tasks
  - Testers must seek to break the software

- Testing is done best by independent testers

Independent Testing: Responsibilities



- Performed by independent test team
  - Exception: Acceptance test performed by client
- Performed by independent test team
- Performed by programmer
  - Requires detailed knowledge of the code
  - Immediate bug fixing

Independent Testing: Wrong Conclusions

- The developer should not be testing at all
  - “Test before you code”
- Testers get only involved once software is done
- Toss the software over the wall for testing
  - Testers and developers collaborate in developing the test suite
- Testing team is responsible for assuring quality
  - Quality is assured by a good software process

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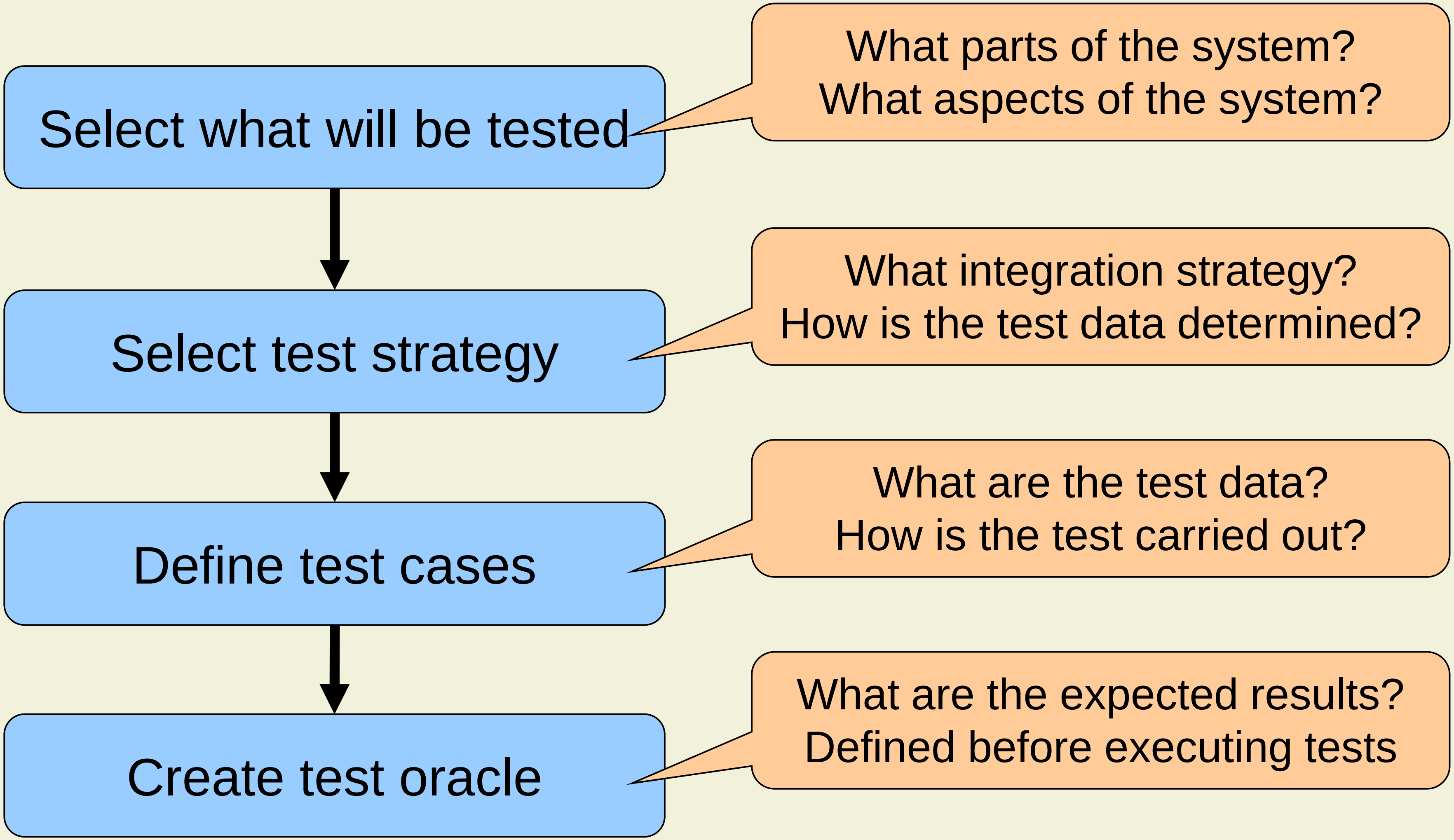
Testing Steps



Example: Solve Quadratic Equation

```
void roots( double a, double b, double c ) {
  double q = b*b – 4*a*c;
  if( q > 0 && a != 0 ) {
    numRoots = 2;
    double r = Math.sqrt( q );
    x1 = (-b + r) / (2 * a);
    x2 = (-b - r) / (2 * a);
  } else if( q == 0 ) {
    numRoots = 1;
    x1 = -b / (2 * a);
  } else {
    numRoots = 0;
  }
}
```

Fails if a==0 and b*b–4*a*c == 0

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

Strategy 1: Exhaustive Testing

- Check UUT for all possible inputs
  - Not feasible, even for trivial programs

```
void roots( double a, double b, double c ) {
  …
}
```

- Assuming that **double** represents 64-bit values, we get $(2^{64})^3 \approx 10^{58}$ possible values for a, b, c
- Programs with heap data structures have a much larger state space!

Strategy 2: Random Testing

- Select test data uniformly

```
void roots( double a, double b, double c ) {
  double q = b*b – 4*a*c;
  if( q > 0 && a != 0 ) {
    …
  } else if( q == 0 ) {
    numRoots = 1;
    x1 = -b / (2 * a);
  } else { … }
}
```

Fails if a==0 and b*b–4*a*c == 0

The likelihood of selecting a==0 and b==0 randomly is $1/10^{38}$

Random Testing: Observations

- Random testing focuses on generating test data fully automatically
- Advantages
  - Avoids designer/tester bias
  - Tests robustness, especially handling of invalid input and unusual actions
- Disadvantages
  - Treats all inputs as equally valuable

Strategy 3: Functional Testing

- Use requirements knowledge to determine test cases

Given three values, a, b, c, compute all solutions of the equation $ax^2 + bx + c = 0$

Two solutions	One solution	No solution
$a \neq 0$ and $b^2-4ac > 0$	$a = 0$ and $b \neq 0$ or $a \neq 0$ and $b^2-4ac = 0$	$a = 0$, $b = 0$, and $c \neq 0$ or $a \neq 0$ and $b^2-4ac < 0$

Test each case of the specification

Functional Testing: Observations

- Functional testing focuses on input/output behavior
  - Goal: Cover all the requirements
- Attempts to find
  - Incorrect or missing functions
  - Interface errors
  - Performance errors
- Limitations
  - Does not effectively detect design and coding errors (e.g., buffer overflow, memory management)
  - Does not reveal errors in the specification (e.g., missing cases)

Strategy 4: Structural Testing

- Use design knowledge about system structure, algorithms, data structures to determine test cases that exercise a large portion of the code

```
void roots( double a, double b, double c ) {
  double q = b*b – 4*a*c;
  if( q > 0 && a != 0 ) {
    …
  } else if( q == 0 ) {
    …
  } else {
    …
  }
}
```

Test this case

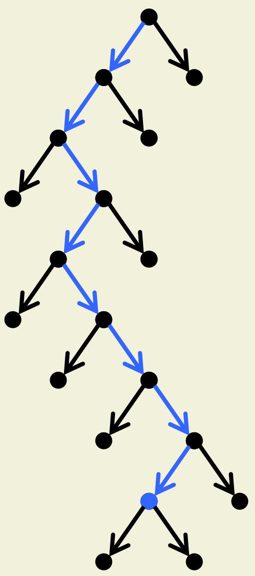
and this case

and this case

Error might still be missed, for instance, when case is tested with a==1, b==2, c==1

Structural Testing: Observations

- Structural testing focuses on thoroughness
  - Goal: Cover all the code
- Not well suited for system test
  - Focuses on code rather than on requirements, for instance, does not detect missing logic
  - Requires design knowledge, which testers and clients do not have (and do not care about)
  - Thoroughness would lead to highly-redundant tests



Testing Strategies: Summary

Functional testing

- Goal: Cover all the requirements
- Black-box test
- Suitable for all test stages

Structural testing

- Goal: Cover all the code
- White-box test
- Suitable for unit testing

Random testing

- Goal: Cover corner cases
- Black-box test
- Suitable for all test stages

Summary

- Main objective
  - Design tests that systematically uncover different classes of errors with a minimum amount of time and effort
  - A good test has a high probability of finding an error
  - A successful test uncovers an error
- Secondary benefits
  - Demonstrate that software appears to be working according to specification (functional and non-functional)
  - Data collected during testing provides indication of software reliability and software quality
  - Good testers clarify the specification (creative work)

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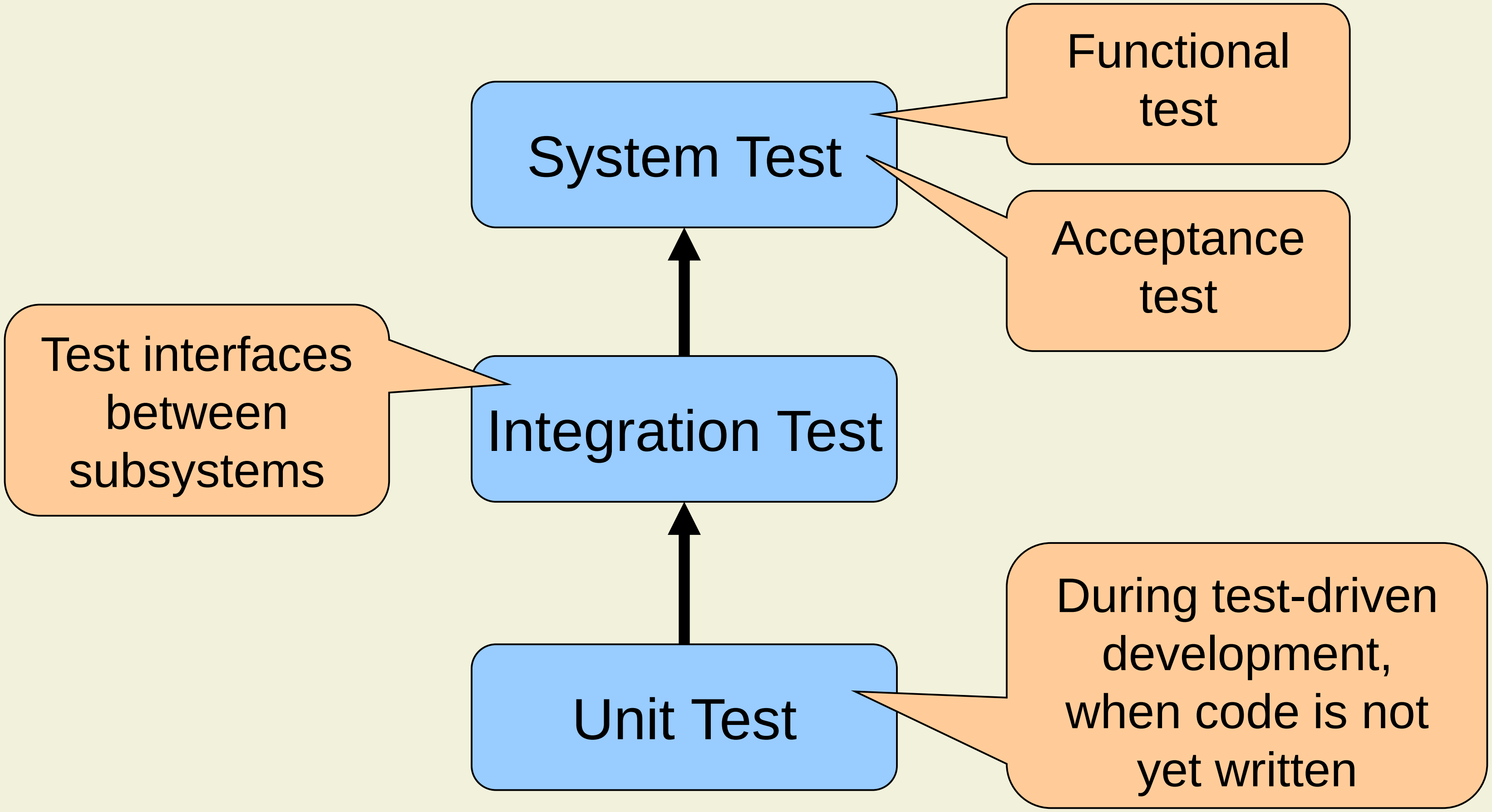
Applications of Functional Testing

- Black-box test a unit against its requirements



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5.3 Functional Testing

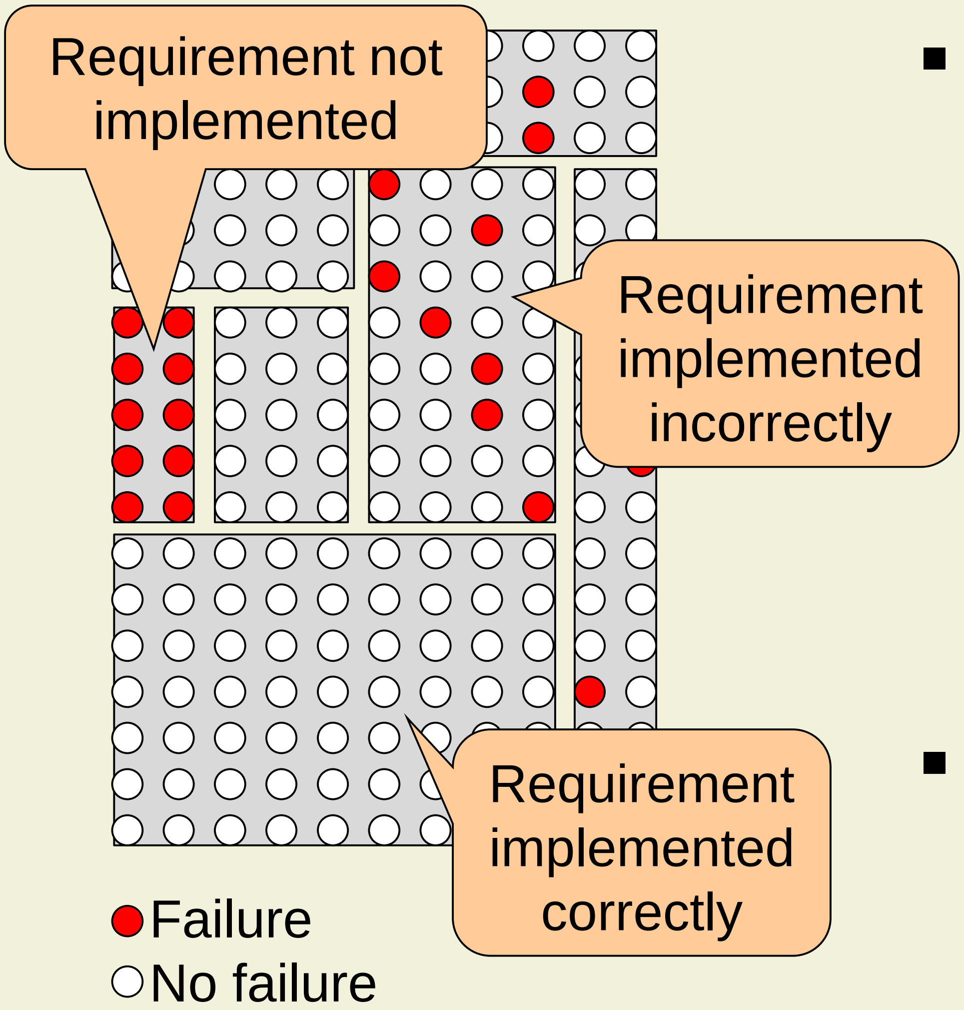
5.3.1 Partition Testing

5.3.2 Selecting Representative Values

5.3.3 Combinatorial Testing

5.4 Structural Testing

Finding Representative Inputs



- Divide inputs into equivalence classes
  - Each possible input belongs to one of the equivalence classes
  - Goal: some classes have higher density of failures
- Choose test cases for each equivalence class

Equivalence Classes: Example

Given a month (an integer in [1;12]) and a year (an integer), compute the number of days of the given month in the given year (an integer in [28;31])

month	
Month with 28 or 29 days	month = 2
Months with 30 days	month $\in$ {4, 6, 9, 11}
Months with 31 days	month $\in$ {1, 3, 5, 7, 8, 10, 12}

Invalid inputs missing

year	
Leap years	(year **mod** 4 = 0 and year **mod** 100 ≠ 0) or year **mod** 400 = 0
Non-leap years	year **mod** 4 ≠ 0 or (year **mod** 100 = 0 and year **mod** 400 ≠ 0)

Equivalence Classes: Example (cont'd)

Given a month (an integer in [1;12]) and a year (an integer), compute the number of days of the given month in the given year (an integer in [28;31])

month	
Month with 28 or 29 days	month = 2
Months with 30 days	month $\in$ {4, 6, 9, 11}
Months with 31 days	month $\in$ {1, 3, 5, 7, 8, 10, 12}
Invalid	month < 1 or month > 12

year	
Leap years	(year **mod** 4 = 0 and year **mod** 100 ≠ 0) or year **mod** 400 = 0
Non-leap years	year **mod** 4 ≠ 0 or (year **mod** 100 = 0 and year **mod** 400 ≠ 0)

Partitioning seems too coarse

Equivalence Classes: Example (cont'd)

Given a month (an integer in [1;12]) and a year (an integer), compute the number of days of the given month in the given year (an integer in [28;31])

month	
Month with 28 or 29 days	month = 2
Months with 30 days	month ∈ {4, 6, 9, 11}
Months with 31 days	month ∈ {1, 3, 5, 7, 8, 10, 12}
Invalid	month < 1 or month > 12

year	
Standard leap years	year **mod** 4 = 0 and year **mod** 100 ≠ 0
Standard non-leap years	year **mod** 4 ≠ 0
Special leap years	year **mod** 400 = 0
Special non-leap years	year **mod** 100 = 0 and year **mod** 400 ≠ 0

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Selecting Representative Values

- Once we have partitioned the input values, we need to select concrete values for the test cases for each equivalence class

- Input from a range of valid values
  - Below, within, and above the range
  - Also applies to multiplicities on aggregations

- Input from a discrete set of valid values
  - Valid and invalid discrete value
  - Instances of each subclass

Boundary Testing

Given an integer x, determine the absolute value of x

x	
Valid	all values

```
int abs( int x ) {
  if( 0 <= x ) return x;
  return –x;
}
```

Negative result for x==Integer.MIN_VALUE

- A large number of errors tend to occur at boundaries of the input domain
  - Overflows
  - Comparisons (‘<‘ instead of ‘<=‘, etc.)
  - Missing emptiness checks (e.g., collections)
  - Wrong number of iterations

Boundary Testing: Example

- Select elements at the “edge” of each equivalence class (in addition to values in the middle)
  - Ranges: lower and upper limit
  - Empty sets and collections

month	
Month with 28 or 29 days	month = 2
Months with 30 days	month $\in$ {4, 6, 9, 11}
Months with 31 days	month $\in$ {1, 3, 5, 7, 8, 10, 12}
Invalid	month < 1 or month > 12

There is only one value

Choose all values

Choose 1 and 12 plus one more

Choose MIN_VALUE, 0, 13, MAX_VALUE

Boundary Testing: Example (cont'd)

year	
Standard leap years	year **mod** 4 = 0 and year **mod** 100 ≠ 0
Standard non-leap years	year **mod** 4 ≠ 0
Special leap years	year **mod** 400 = 0
Special non-leap years	year **mod** 100 = 0 and year **mod** 400 ≠ 0

Choose for instance -200.004, -4, 4, 2012, 400.008

Choose for instance -200.003, -1, 1, 2011, 400.009

Choose for instance -200.000, 0, 2000, 400.000

Choose for instance -200.100, 1900, 400.100

Parameterized Unit Test for Leap Years

```
[ Test ]
public void TestDemo29(
    [ Values( -200004, -200000, -4, 0,4, 2000, 2012, 400000, 400008 ) ]
    int year )
{
  int d = Days( 2, year );
  Assert.IsTrue( d == 29 );
}
```

Only one value

All selected values for leap years and special leap years

Expected result

- Analogous test cases for February in non-leap year, months with 30 days, and months with 31 days

Parameterized Unit Test for Invalid Inputs

Expected result: an exception

```
[ Test ]
[ ExpectedException( typeof(ArgumentException) ) ]
public void TestDemoInvalid(
   [ Values( int.MinValue, 0, 13, int.MaxValue ) ] int month,
   [ Values( -200100, -200004, -200003, -200000, -4, -1, 0, 1, 4, 1900,
      2000, 2011, 2012, 400000, 400008, 400009, 400100 ) ] int year ) {
  int d = Days( month, year );
}
```

All selected invalid values for month

All selected values for year

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Combinatorial Testing

- Combining equivalence classes and boundary testing leads to many values for each input
  - Twelve values for month and 17 values for year in the Leap Year example
- Testing all possible combinations leads to a combinatorial explosion (12 x 17 = 204 tests)
- Reduce test cases to make effort feasible
  - Semantic constraints
  - Combinatorial selection
  - Random selection

Eliminating Combinations

- Inspect test cases for unnecessary combinations
  - Especially for invalid values
  - Use problem domain knowledge

month	
Month with 28 or 29 days	month = 2
Months with 30 days	month ∈ {4, 6, 9, 11}
Months with 31 days	month ∈ {1, 3, 5, 7, 8, 10, 12}
Invalid	month < 1 or month > 12

Test all combinations with year

Behavior is independent of year

- Reduces test cases from 204 to 17 + 4 + 3 + 4 = 28

Eliminating Combinations: NUnit Example

```
[ Test, Sequential ]
[ ExpectedException( typeof(ArgumentException) ) ]
public void TestDemoInvalid(
    [ Values( int.MinValue, 0, 13, int.MaxValue ) ] int month,
    [ Values( -200100, -200004, -200003, -200000 ) ] int year ) {
  int d = Days( month, year );
}
```

All selected invalid values for month

One value for year for each value for month

Selecting Object References

- Objects are different from values because they have identity

```
a1 = new Account( 1000 );
a2 = new Account( 1000 );
a1.transfer( a2, 500 );
```

```
a1 = new Account( 1000 );
a1.transfer( a1, 500 );
```

Might behave differently (e.g., deadlock)

- When selecting test data for objects, one has to consider object identities and aliasing
- Referenced objects lead to combination problem

Roots Example

Given three values, a, b, c, compute all solutions of the equation $ax^2 + bx + c = 0$

	a	b	c
Valid	any value	any value	any value
Invalid	infinity, NaN	infinity, NaN	infinity, NaN

Boundary testing:
a, b, c $\in$
{ Double.MIN_VALUE, -5,
0, 5, Double.MAX_VALUE }

- $5^3 = 125$ test cases for valid inputs

Roots Example (cont'd)

Given three values, a, b, c, compute all solutions of the equation $ax^2 + bx + c = 0$

Look at dependencies between inputs

Two solutions	One solution	No solution
$a \neq 0$ and $b^2 - 4ac > 0$	$a = 0$ and $b \neq 0$ or $a \neq 0$ and $b^2 - 4ac = 0$	$a = 0$, $b = 0$, and $c \neq 0$ or $a \neq 0$ and $b^2 - 4ac < 0$

Semantic constraints on combinations

Partitioning seems too coarse

Roots Example (cont'd)

Given three values, a, b, c, compute all solutions of the equation $ax^2 + bx + c = 0$

	Two solutions	One solution	No solution
Linear equation		$a = 0$ and $b \neq 0$	$a = 0$, $b = 0$, and $c \neq 0$
(Truly) quadratic equation	$a \neq 0$ and $b^2\text{-}4ac > 0$	$a \neq 0$ and $b^2\text{-}4ac = 0$	$a \neq 0$ and $b^2\text{-}4ac < 0$

Not all inputs are covered: a=b=c=0

Roots Example (cont'd)

Given three values, a, b, c, compute all solutions of the equation $ax^2 + bx + c = 0$; report an error if all three values are zero

	Two solutions	One solution	No solution
Linear equation		$a = 0$ and $b \neq 0$	$a = 0$, $b = 0$, and $c \neq 0$
(Truly) quadratic equation	$a \neq 0$ and $b^2\text{-}4ac > 0$	$a \neq 0$ and $b^2\text{-}4ac = 0$	$a \neq 0$ and $b^2\text{-}4ac < 0$
Invalid input	$a = 0$, $b = 0$, $c = 0$		

Roots Example: Summary

- Classifying the combinations according to semantic constraints did not reveal any irrelevant test cases

- But we did identify an omission in the specification
  - It is common that testers clarify the specification

- One option is to manually choose a manageable number of test cases such that there is at least one test case for each semantic constraint
  - Note that omitting test cases might leave errors such as arithmetic overflow undetected

Semantic Constraints: Discussion

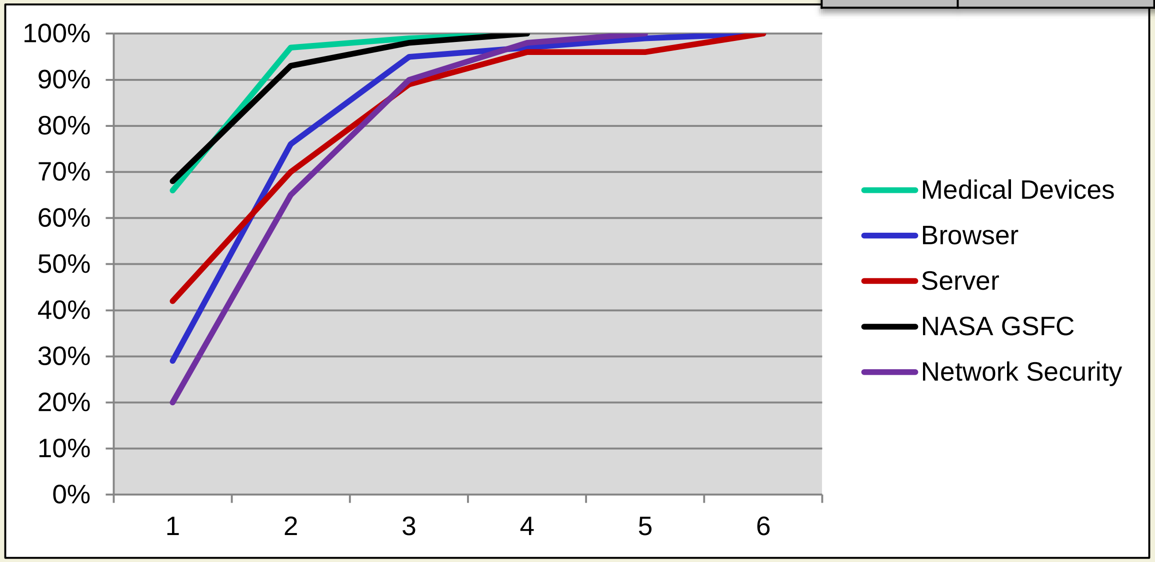
- Semantic constraints potentially reduce the number of test cases
  - They also help increasing the coverage

- But too many combinations remain
  - Especially when there are many input values, for instance, for the fields of objects

Influence of Variable Interactions

- Empirical evidence suggests that most errors do not depend on the interaction of many variables

Vars	Medical Devices	Browser	Server	NASA GSFC	Network Security
1	66%	29%	42%	68%	20%
2	97%	76%	70%	93%	65%
3	99%	95%	89%	98%	90%
4	100%	97%	96%	100%	98%
5		99%	96%		100%
6		100%	100%		



- Interactions of two or three variables trigger most errors

Pairwise-Combinations Testing

- Instead of testing all possible combinations of all inputs, focus on all possible combinations of each pair of inputs
  - Pairwise-combinations testing is identical to combinatorial testing for two or less inputs
- Example: Consider a method with four boolean parameters
  - Combinatorial testing requires $2^4 = 16$ test cases
  - Pairwise-combinations testing requires 5 test cases: TTTT, TFFF, FTFF, FFTF, FFFT
- Can be generalized to k-tuples (k-way testing)

Pairwise-Combinations Testing: Complexity

- For n parameters with d values per parameter, the number of test cases grows logarithmically in n and quadratic in d
  - Handles larger number of parameters, for instance, fields of objects
  - The number d can be influenced by the tester

- Result holds for large n and d, and for all k in k-way testing

Pairwise-Combinations Testing: Example

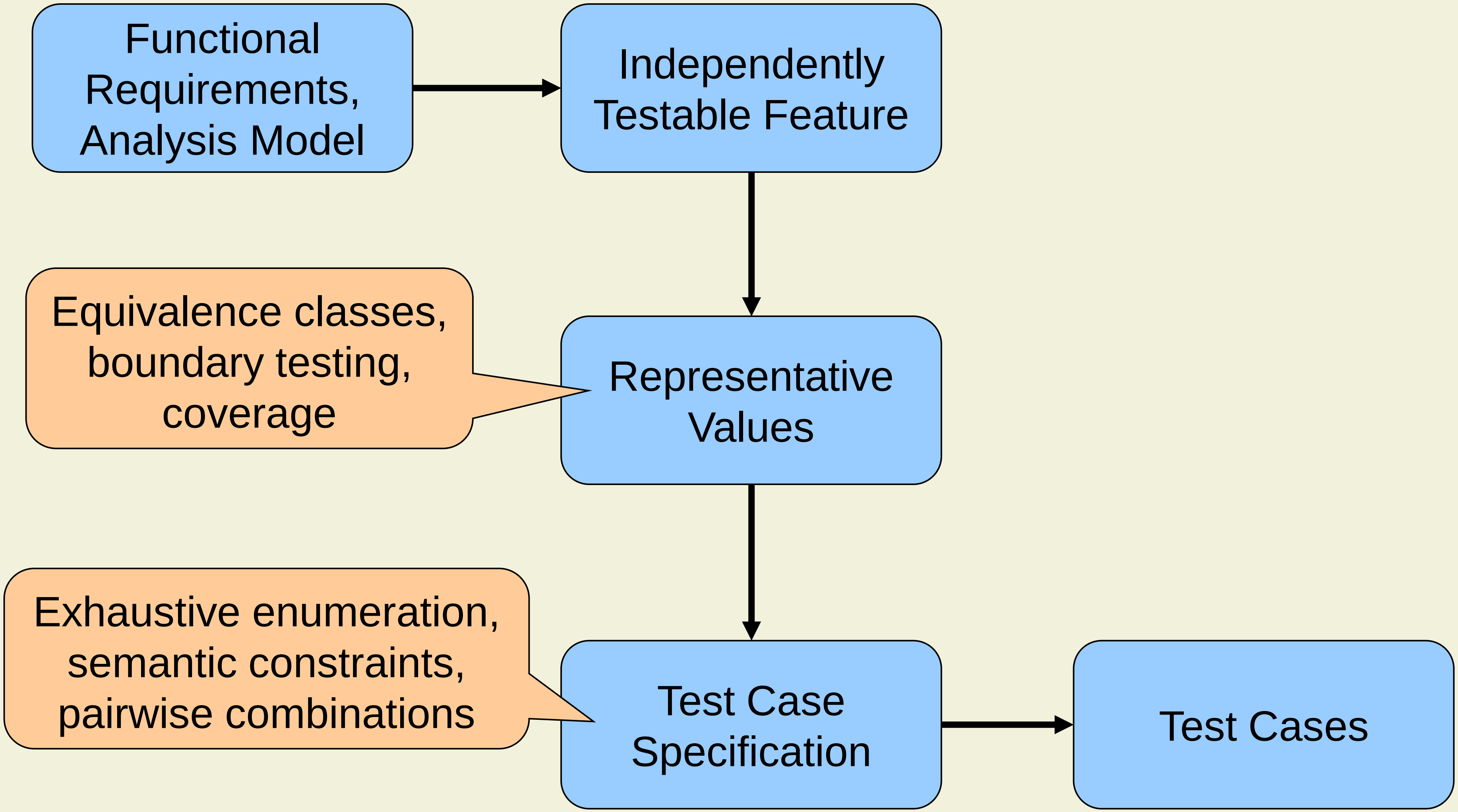
Two solutions	One solution	No solution
	$a = 0$ and $b \neq 0$	$a = 0$, $b = 0$, and $c \neq 0$
$a \neq 0$ and $b^2-4ac > 0$	$a \neq 0$ and $b^2-4ac = 0$	$a \neq 0$ and $b^2-4ac < 0$
$a = 0$, $b = 0$, $c = 0$		

- Three parameters, five values each
  - Double.MIN_VALUE, -5, 0, 5, Double.MAX_VALUE
  - $5^3 = 125$ test cases for combinatorial testing
  - 25 test cases for pairwise-combinations testing
- Bug is still detected (depends only on a and b)
- Some cases depend on three parameters, e.g., invalid input

Pairwise-Combinations Testing: Discussion

- Pairwise-combinations testing (or k-way testing) reduces the number of test cases significantly while detecting most errors
- Pairwise-combinations testing is especially important when many system configurations need to be tested
    - Hardware, operating system, database, application server, etc.
- Should be combined with other approaches to detect errors that are triggered by more complex interactions among parameters

Functional Testing: Summary



5. Testing

5.1 Test Stages

5.2 Test Strategies

5.3 Functional Testing

5.4 Structural Testing

Motivating Example

Given a non-null array of integers, sort the array in-place in ascending order

```
public void sort( int[ ] a ) {
  if( a == null || a.length < 2 ) // array is trivially sorted
    return;
  // check if array is already sorted
  for( int i = 0; i < a.length – 1; i++ )
    if( a[ i ] < a[ i + 1 ] )
      break;
  if( i >= a.length – 1 ) // array is already sorted
    return;
  // use quicksort to sort the array in ascending order
}
```

Error: check for sortedness should use ‘>’

Motivating Example: Functional Testing

Given a non-null array of integers, sort the array in-place in ascending order

	a
Valid	any non-null array
Invalid	**null**

Choose for instance { }, { 1 }, { 1, 2, 3 }

- The requirements give no clue that one should test with an array that is sorted in descending order

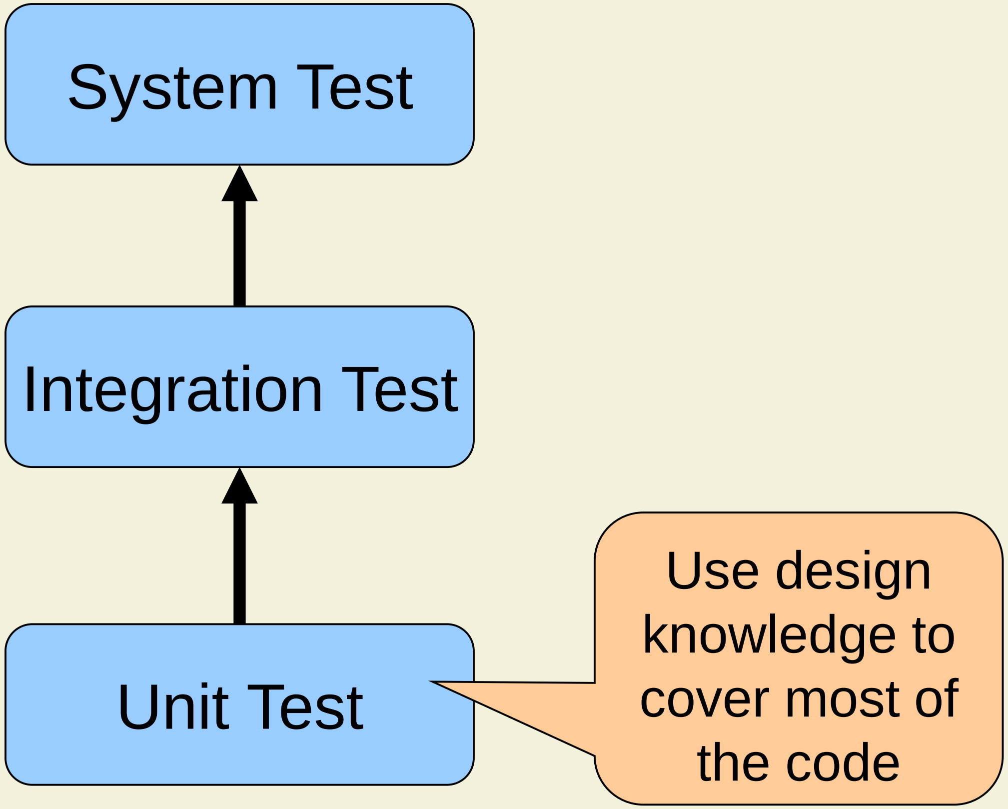
Motivating Example: Discussion

- Detailed design and coding introduce many behaviors that are not present in the requirements
  - Choice of data structures
  - Choice of algorithms
  - Optimizations such as caches

- Functional testing generally does not thoroughly exercise these behaviors
  - No data structure specific test cases, e.g., rotation of AVL-tree
  - No test cases for optimizations, e.g., cache misses

Applications of Structural Testing

- White-box test a unit to cover a large portion of its code



5. Testing

5.1 Test Stages
5.2 Test Strategies
5.3 Functional Testing
5.4 Structural Testing
    5.4.1 Control Flow Testing
    5.4.2 Advanced Topics of Control Flow Testing
    5.4.3 Data Flow Testing
    5.4.4 Interpreting Coverage

Basic Blocks

- A basic block is a sequence of statements such that the code in a basic block:
  - has one entry point: no code within it is the destination of a jump instruction anywhere in the program
  - has one exit point: only the last instruction causes the program to execute code in a different basic block

- Whenever the first instruction in a basic block is executed, the rest of the instructions are necessarily executed exactly once, in order

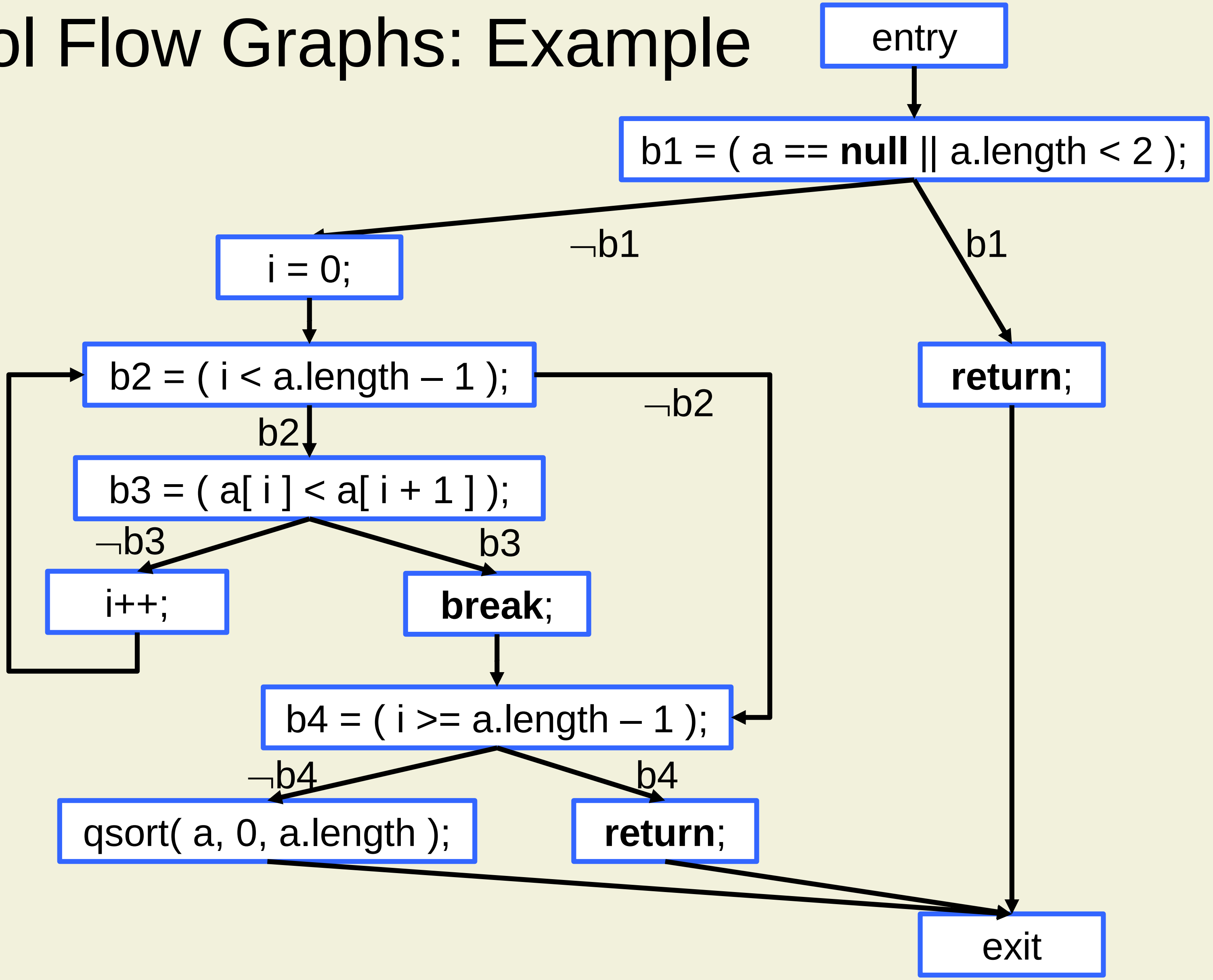
Basic Blocks: Example

```
public void sort( int[ ] a ) {
  if( a == null || a.length < 2 )
    return;
  for( int i = 0; i < a.length – 1; i++ ) {
    if( a[ i ] < a[ i + 1 ] )
      break;
  }
  if( i >= a.length – 1 )
    return;
  qsort( a, 0, a.length );
}
```

Intraprocedural Control Flow Graphs

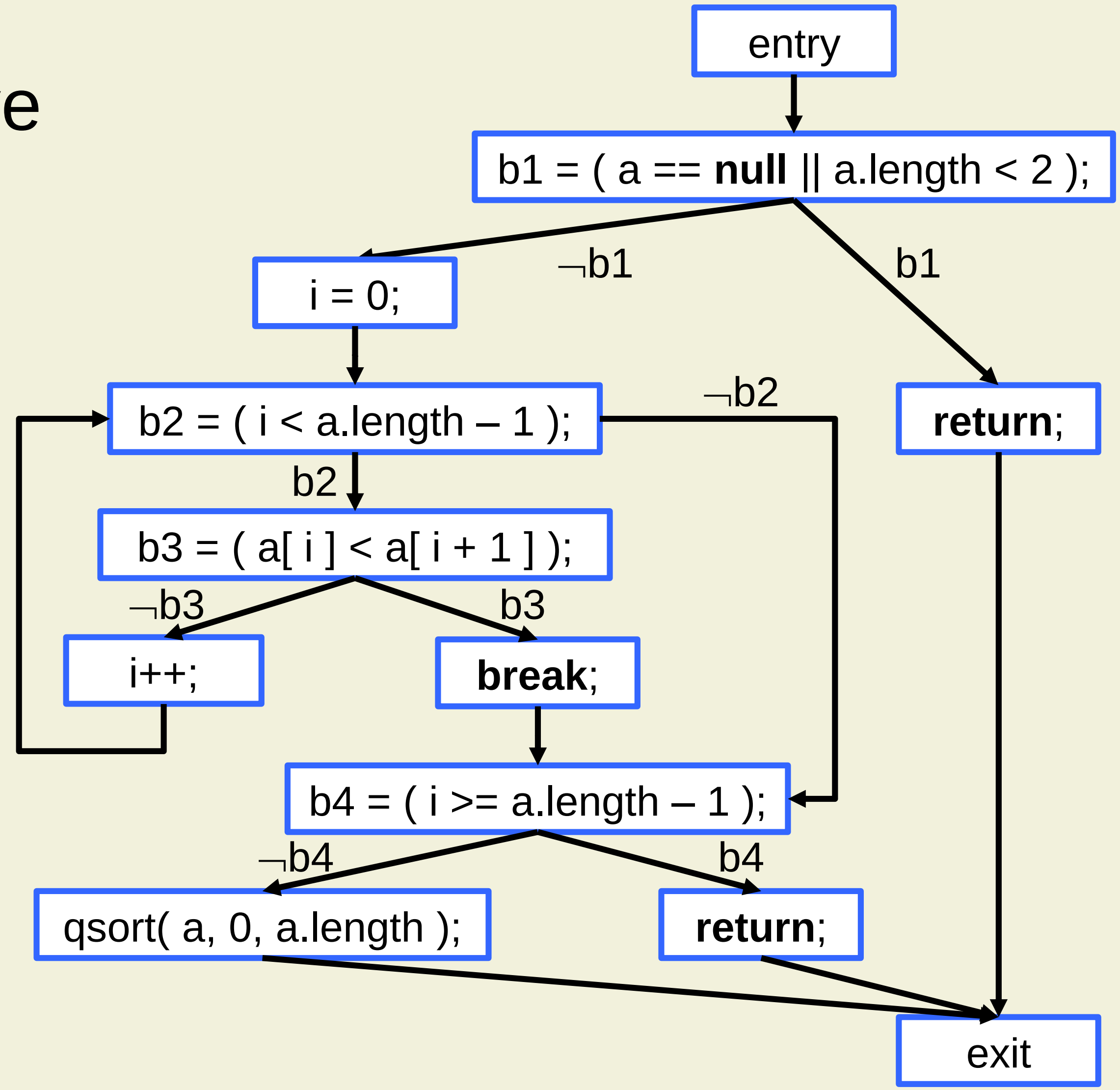
- An intraprocedural control flow graph (CFG) of a procedure p is a graph (N,E) where:
- N is the set of basic blocks in p plus designated entry and exit blocks
- E contains
  - an edge from a to b with condition c iff the execution of basic block a is succeeded by the excution of basic block b if condition c holds
  - an edge (entry, a, true) if a is the first basic block of p
  - edges (b, exit, true) for each basic block b that ends with an (implicit) return statement

Control Flow Graphs: Example



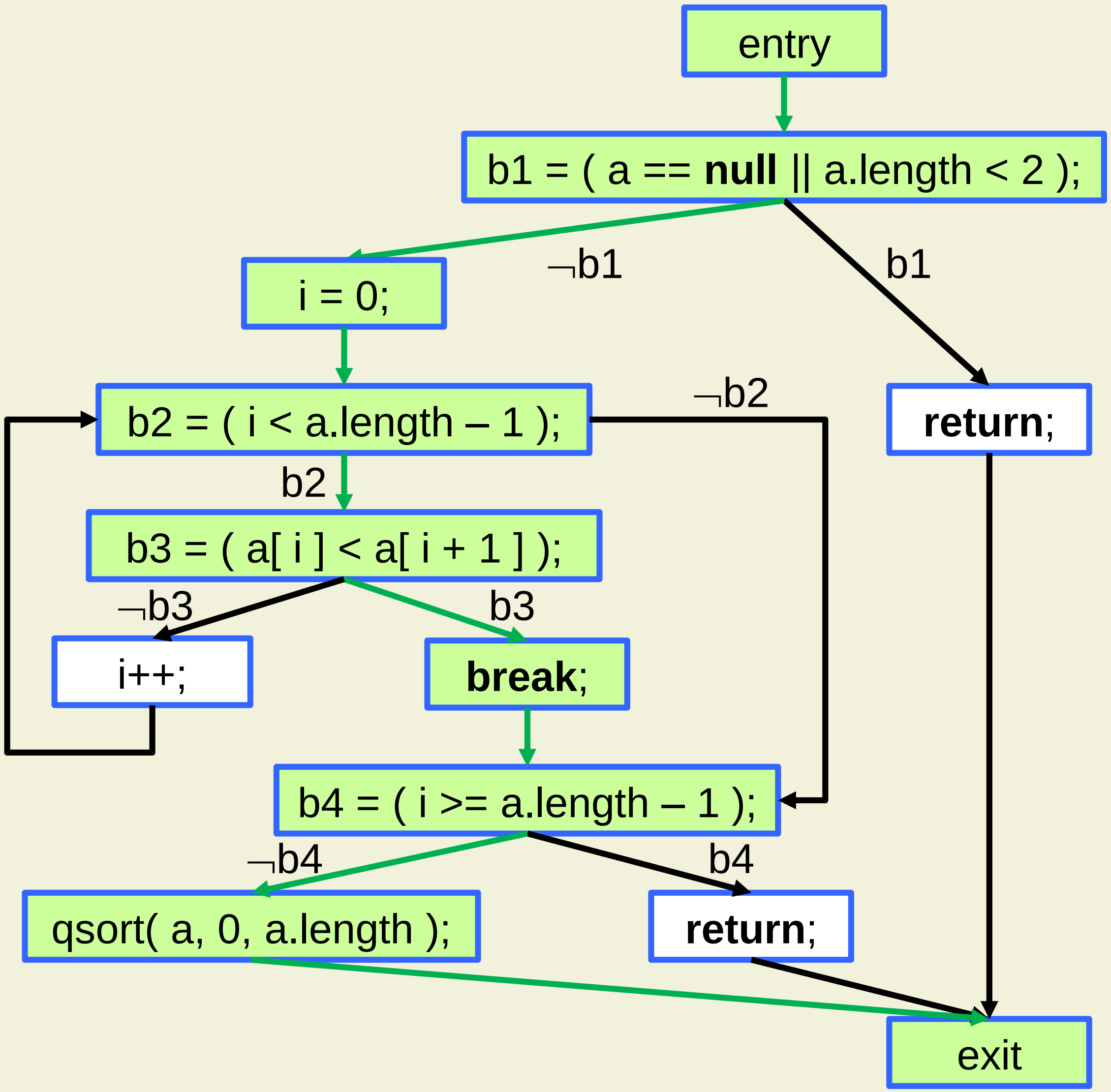
Test Coverage

- The CFG can serve as an adequacy criterion for test cases
- The more parts are executed, the higher the chance to uncover a bug
- “parts” can be nodes, edges, paths, etc.



Test Coverage: Example

- Consider the input
  a = { 3, 7, 5 }



Statement Coverage

- Assess the quality of a test suite by measuring how much of the CFG it executes

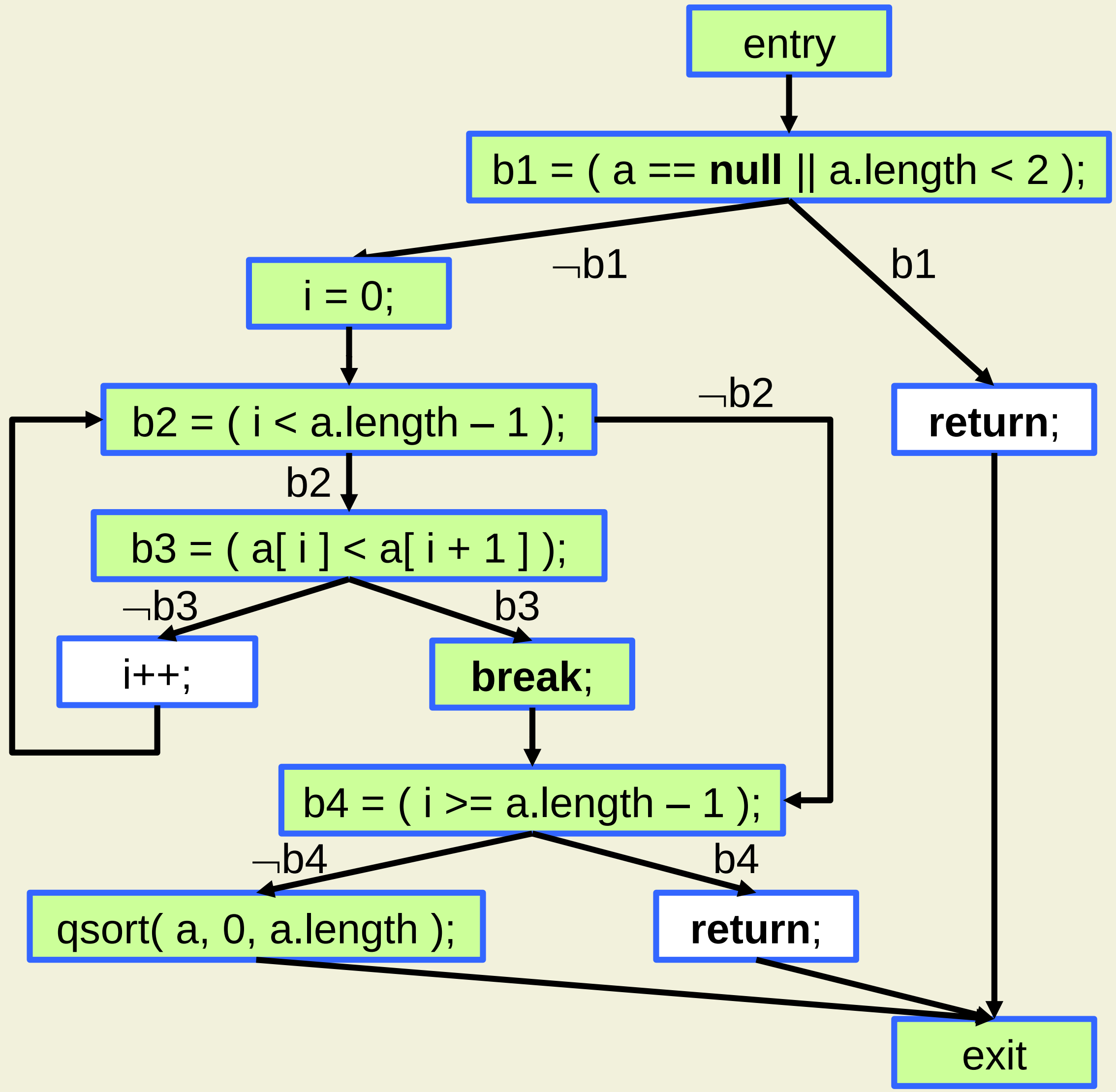
- Idea: one can detect a bug in a statement only by executing the statement

$$\text{Statement Coverage} = \frac{\text{Number of executed statements}}{\text{Total number of statements}}$$

  - Can also be defined on basic blocks

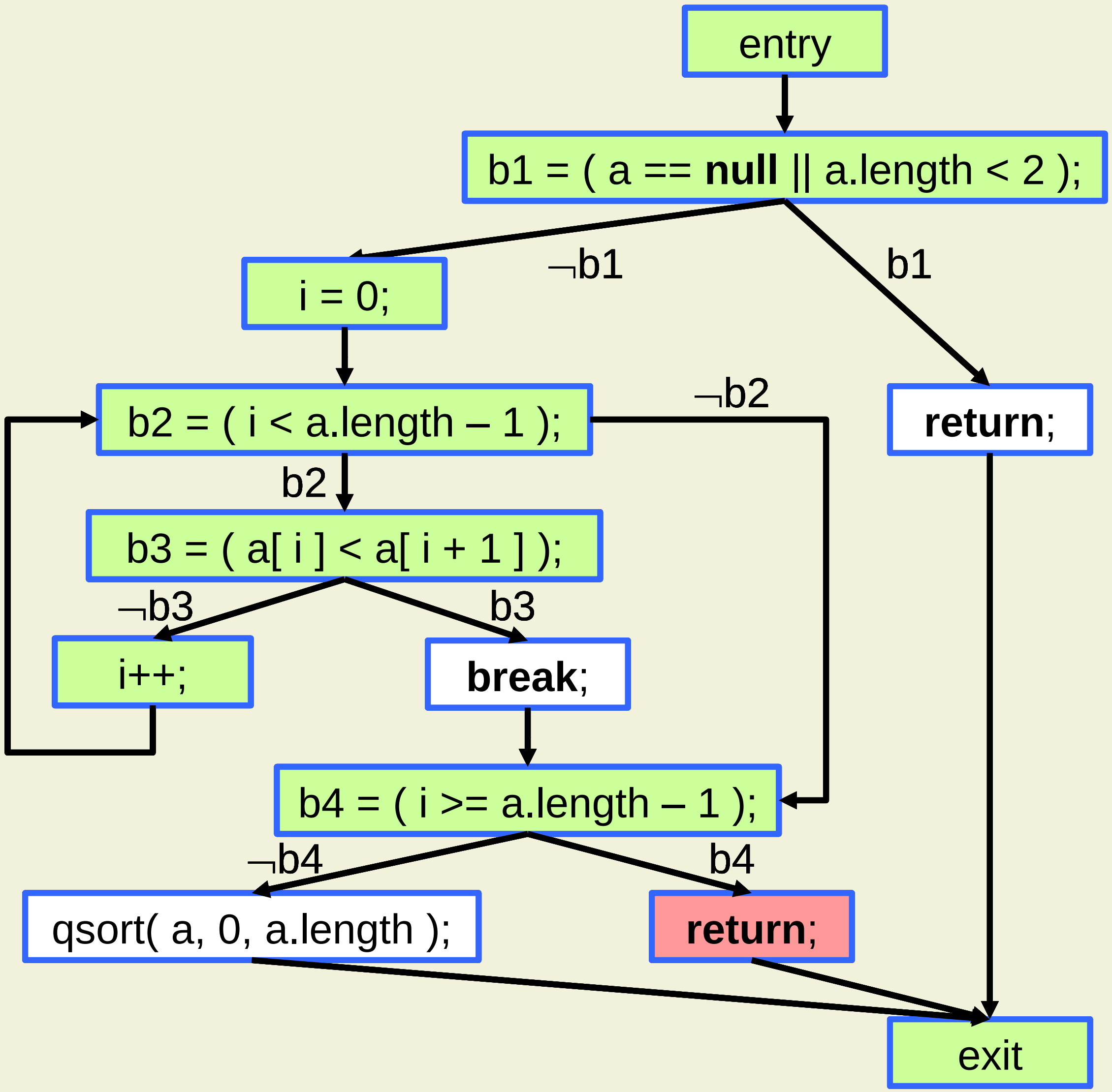
Statement Coverage: Example

- Consider the input a = { 3, 7, 5 }
- This single test case executes 7 out of 10 basic blocks
- Statement coverage: 70%



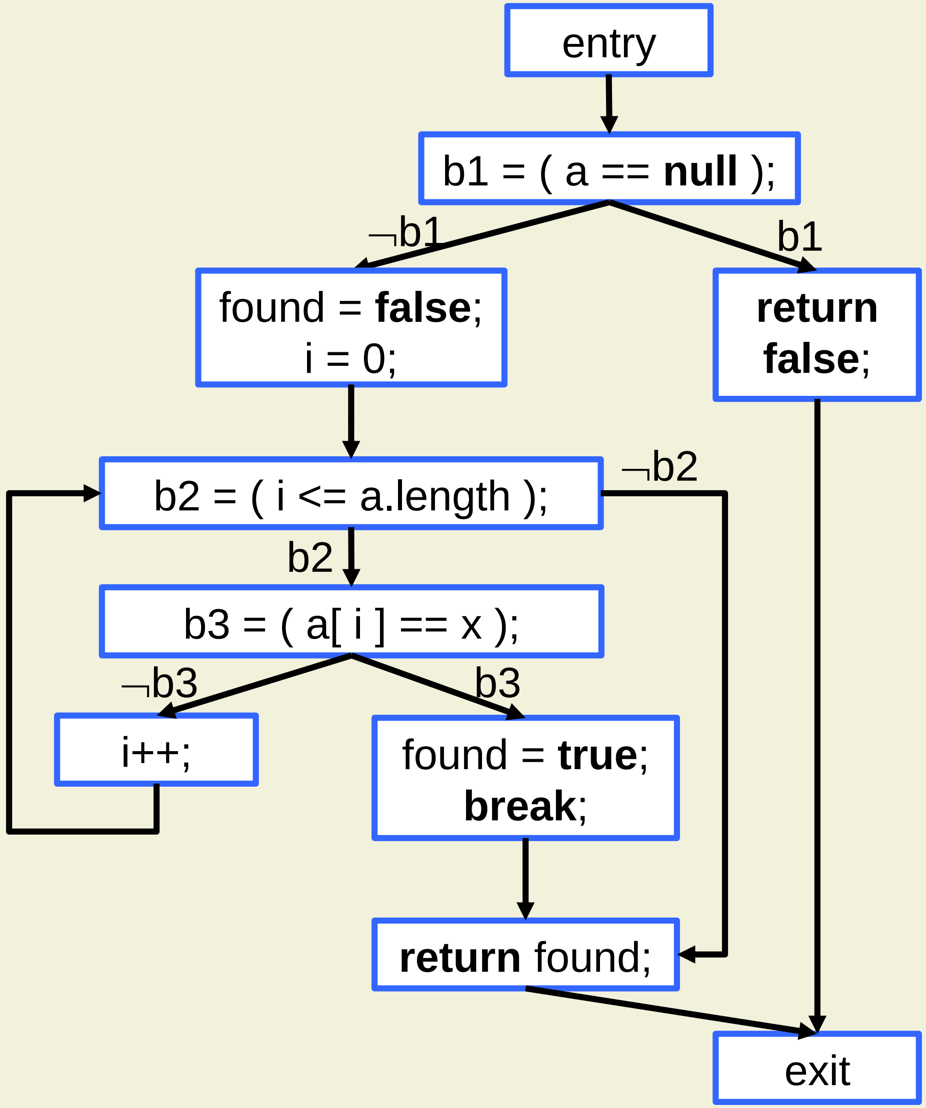
Statement Coverage: Example (cont'd)

- We can achieve 100% statement coverage with three test cases
  - a = { 1 }
  - a = { 5, 7 }
  - a = { 7, 5 }
- The last test case detects the bug



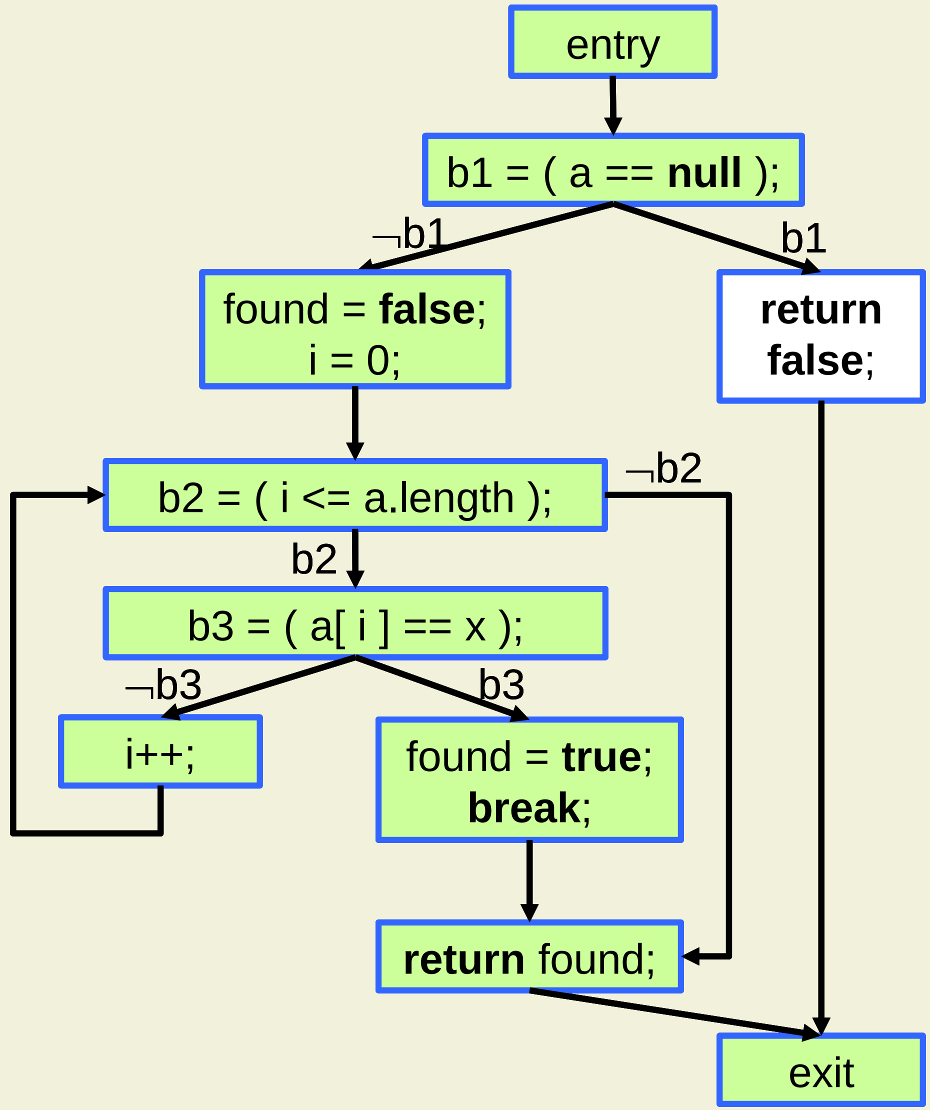
Statement Coverage: Discussion

```
boolean contains( int[ ] a, int x ) {
  if( a == null )  return false;
  boolean found = false;
  for( int i = 0; i <= a.length; i++ ) {
    if( a[ i ] == x ) {
      found = true;
      break;
    }
  }
  return found;
}
```



Statement Coverage: Discussion (cont'd)

- We can achieve 100% statement coverage with two test cases
  - a = **null**
  - a = { 1, 2 }, x = 2
- The test cases do not detect the bug!
- More thorough testing is necessary



Branch Coverage

- Idea: test all possible branches in the control flow

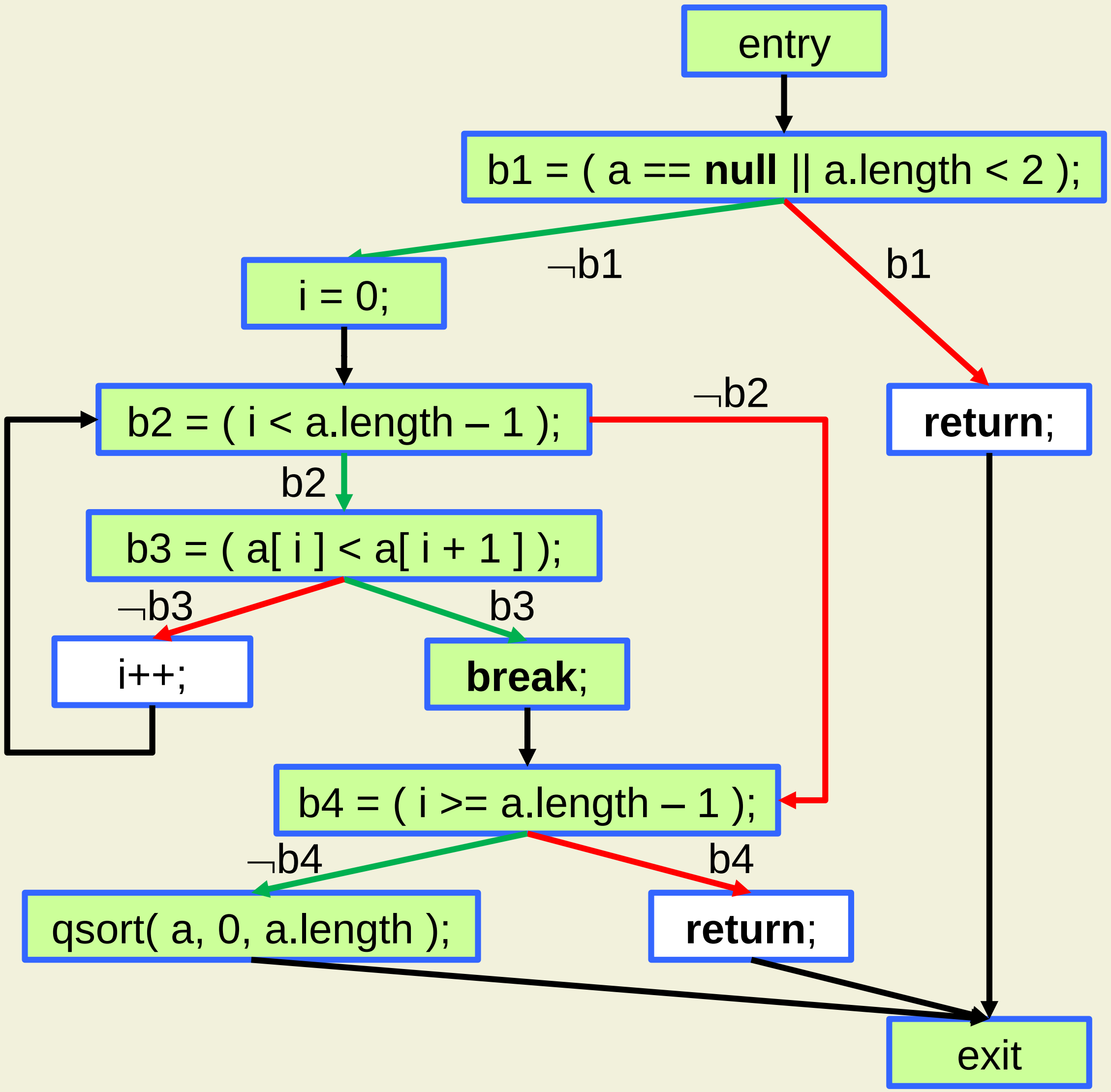
- An edge (m, n, c) in a CFG is a branch iff there is another edge (m, n', c') in the CFG with n ≠ n'

$$\text{Branch Coverage} = \frac{\text{Number of executed branches}}{\text{Total number of branches}}$$

  - Conveniently define branch coverage to be 100% if the code contains no branches

Branch Coverage: Example 1

- Consider the input a = { 3, 7, 5 }
- This single test case executes 4 out of 8 branches
- Branch coverage: 50%
- Three test cases needed for 100% branch coverage

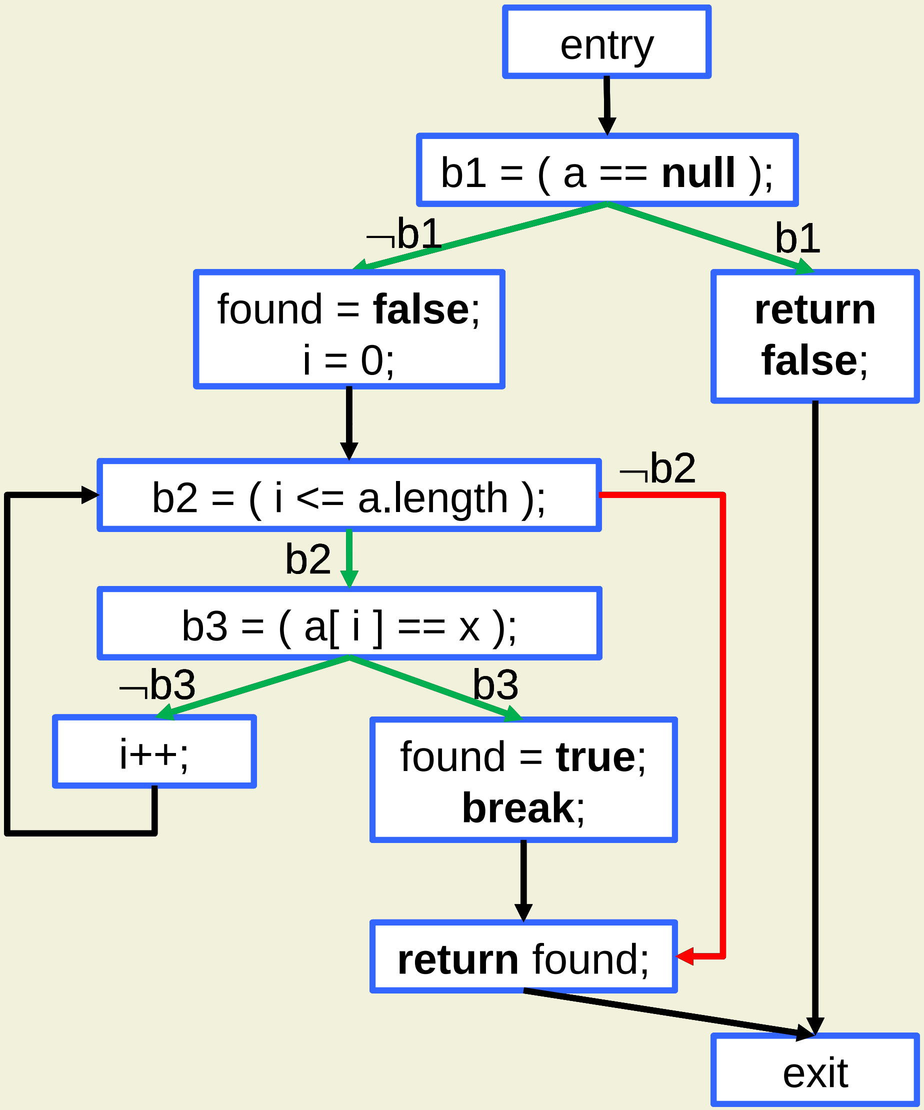


Branch Coverage: Example 2

- The two test cases
  - a = **null**
  - a = { 1, 2 }, x = 2

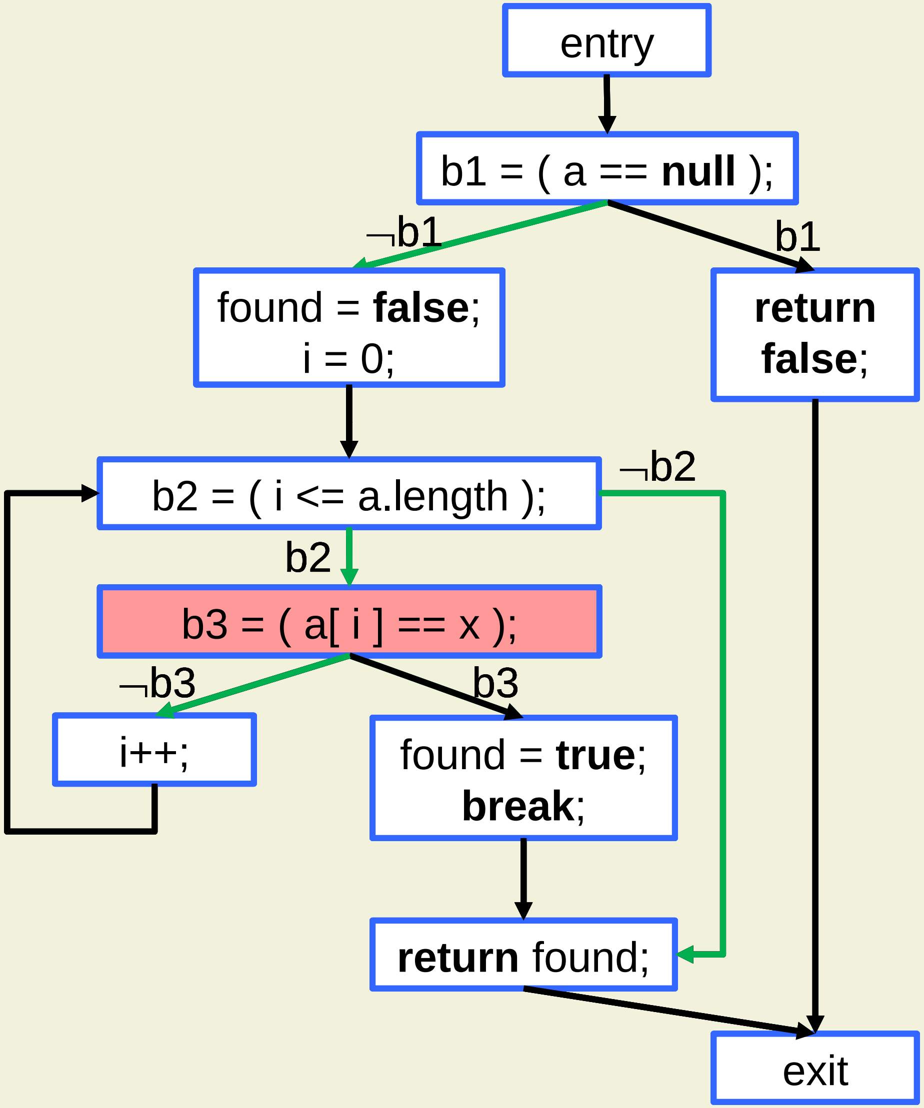
  execute 5 out of 6 branches

- Branch coverage: 83%



Branch Coverage: Example 2 (cont'd)

- Achieving 100% branch coverage would require a test case that runs the loop to the end
  - a = **null**
  - a = { 1 }, x = 1
  - a = { 1 }, x = 3
- The last test case detects the bug



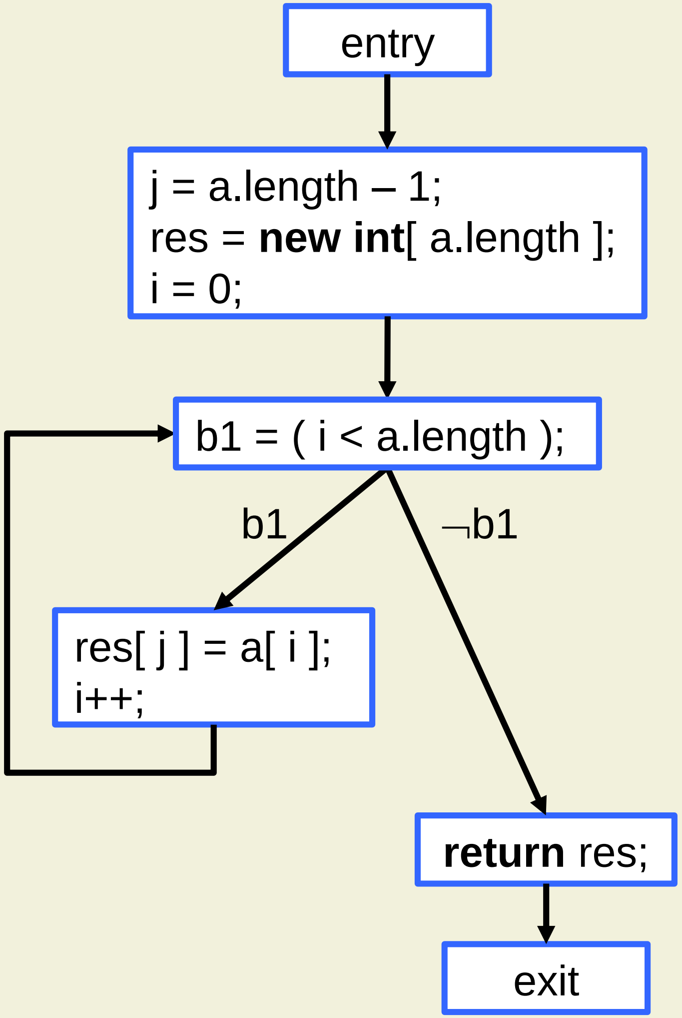
Branch Coverage: Discussion

- Branch coverage leads to more thorough testing than statement coverage
  - Complete branch coverage implies complete statement coverage
  - But "at least n% branch coverage" does not generally imply "at least n% statement coverage"

- Most widely-used adequacy criterion in industry

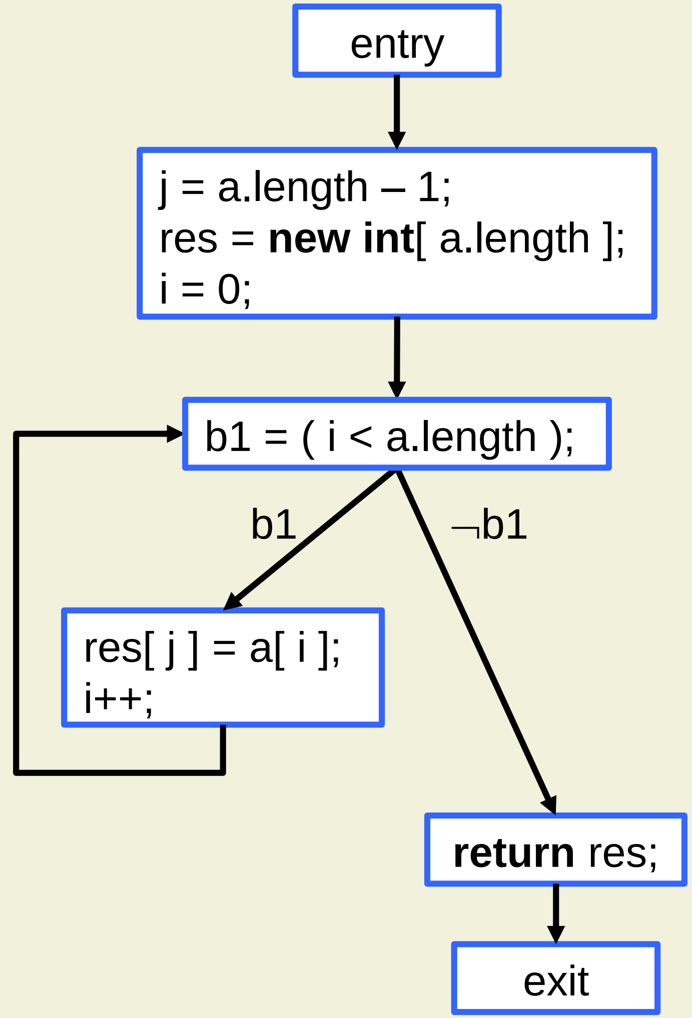
Branch Coverage: Discussion (cont'd)

```
int[ ] reverse( int[ ] a ) {
  int j = a.length – 1;
  int[ ] res = new int[ a.length ];
  for( int i = 0; i < a.length; i++ ) {
    res[ j ] = a[ i ];
  }
  return res;
}
```



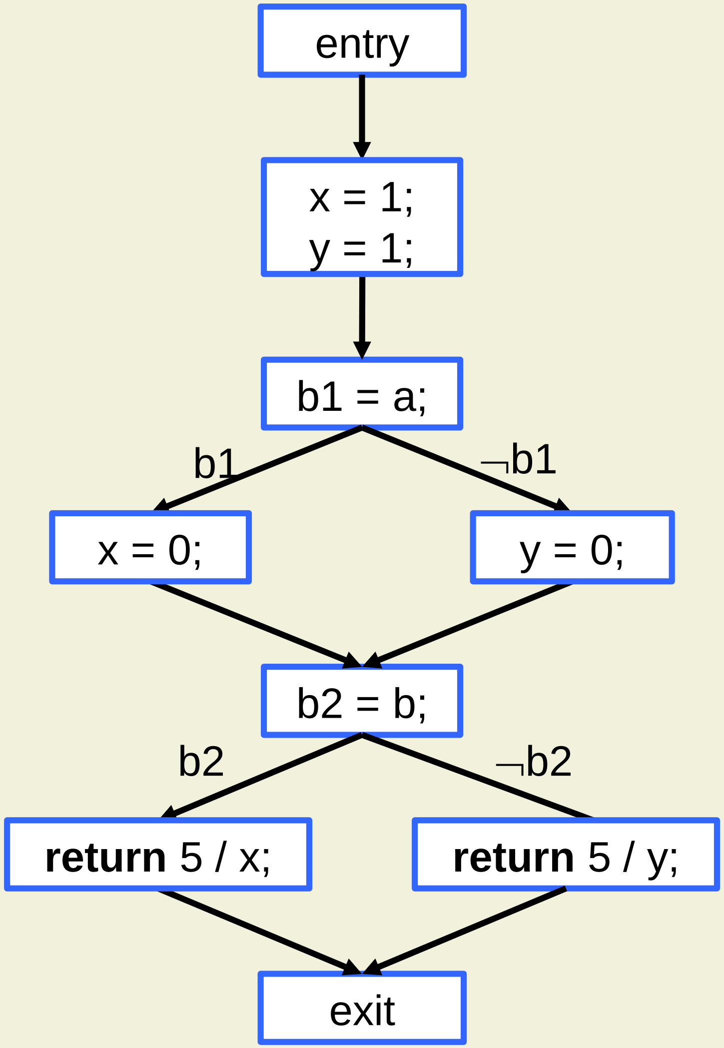
Branch Coverage: Discussion (cont'd)

- We can achieve 100% branch coverage with one test case
  - a = { 1 }
- The test case does not detect the bug!
- More thorough testing is necessary



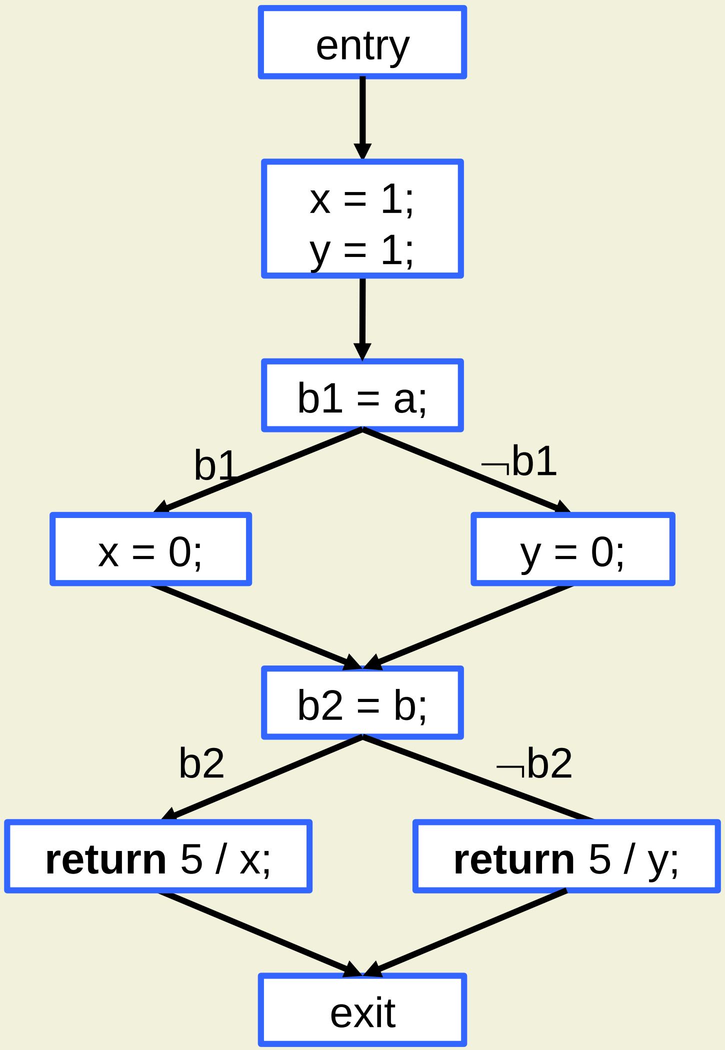
Branch Coverage: Discussion (cont'd)

```
int foo( boolean a, boolean b ) {
  int x = 1;
  int y = 1;
  if( a )
    x = 0;
  else
    y = 0;
  if( b )
    return 5 / x;
  else
    return 5 / y;
}
```



Branch Coverage: Discussion (cont'd)

- We can achieve 100% branch coverage with two test cases
  - a = **true**, b = **false**
  - a = **false**, b = **true**
- The test cases do not detect the bug!
- More thorough testing is necessary



Path Coverage

- Idea: test all possible paths through the CFG
- A path is a sequence of nodes $n_1, \ldots, n_k$ such that
  - n_1 = entry
  - n_k = exit
  - There is an edge (n_i, n_{i+1}, c) in the CFG

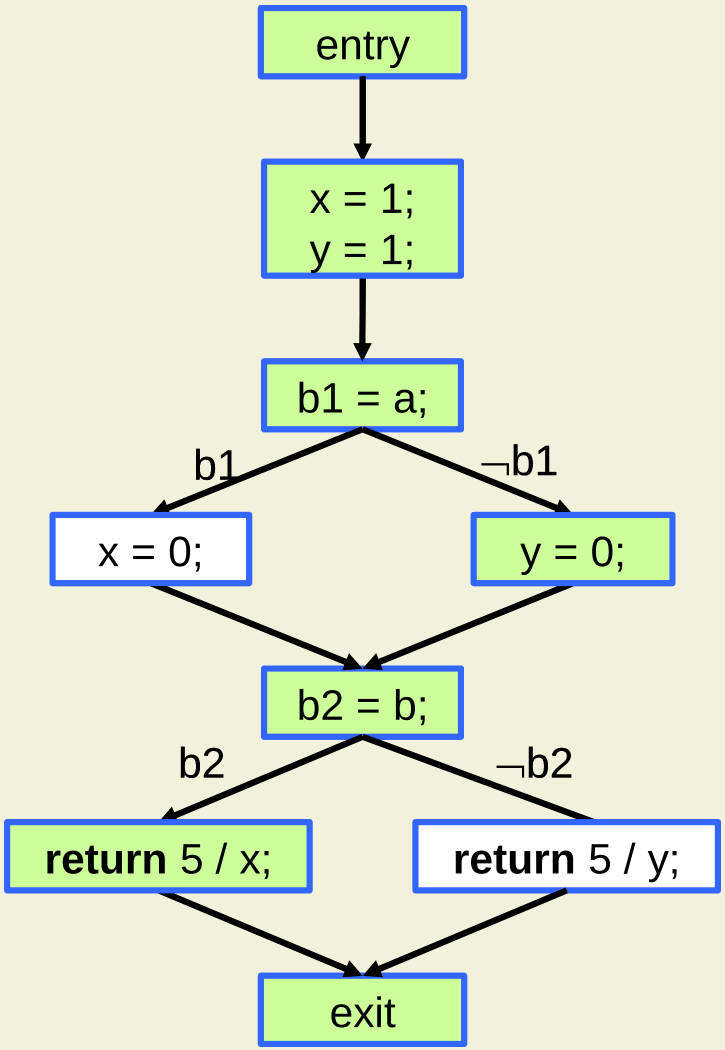
$$\text{Path Coverage} = \frac{\text{Number of executed paths}}{\text{Total number of paths}}$$

Path Coverage: Example 1

- The two test cases
  - a = **true**, b = **false**
  - a = **false**, b = **true**

  execute two out of four paths

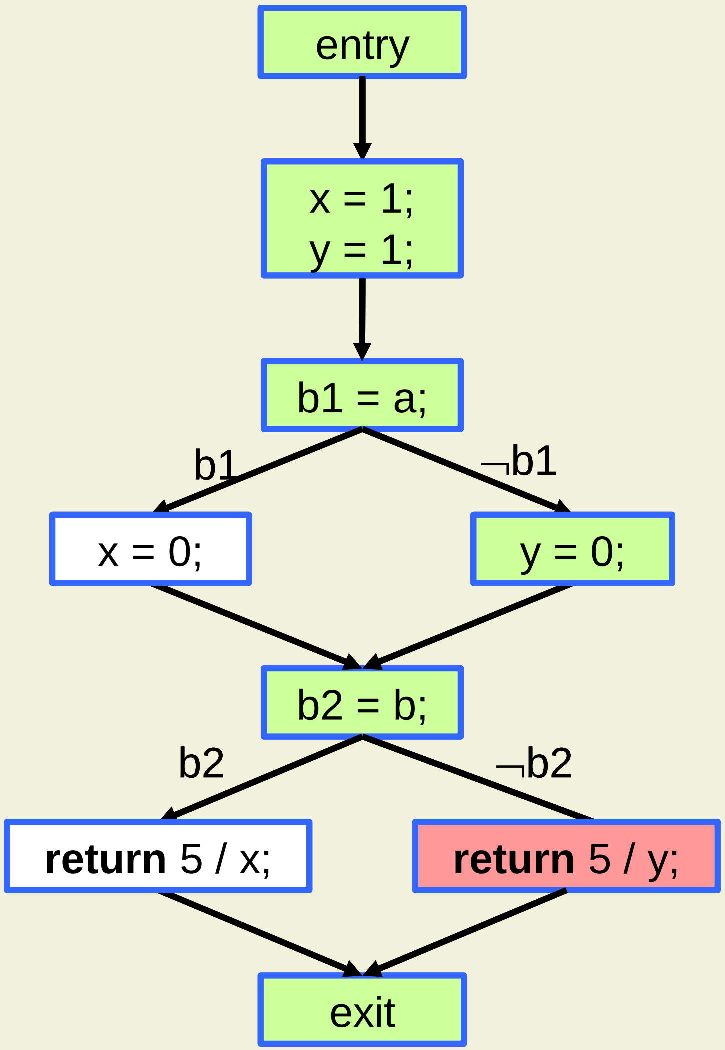
- Path coverage: 50%



Path Coverage: Example 1 (cont'd)

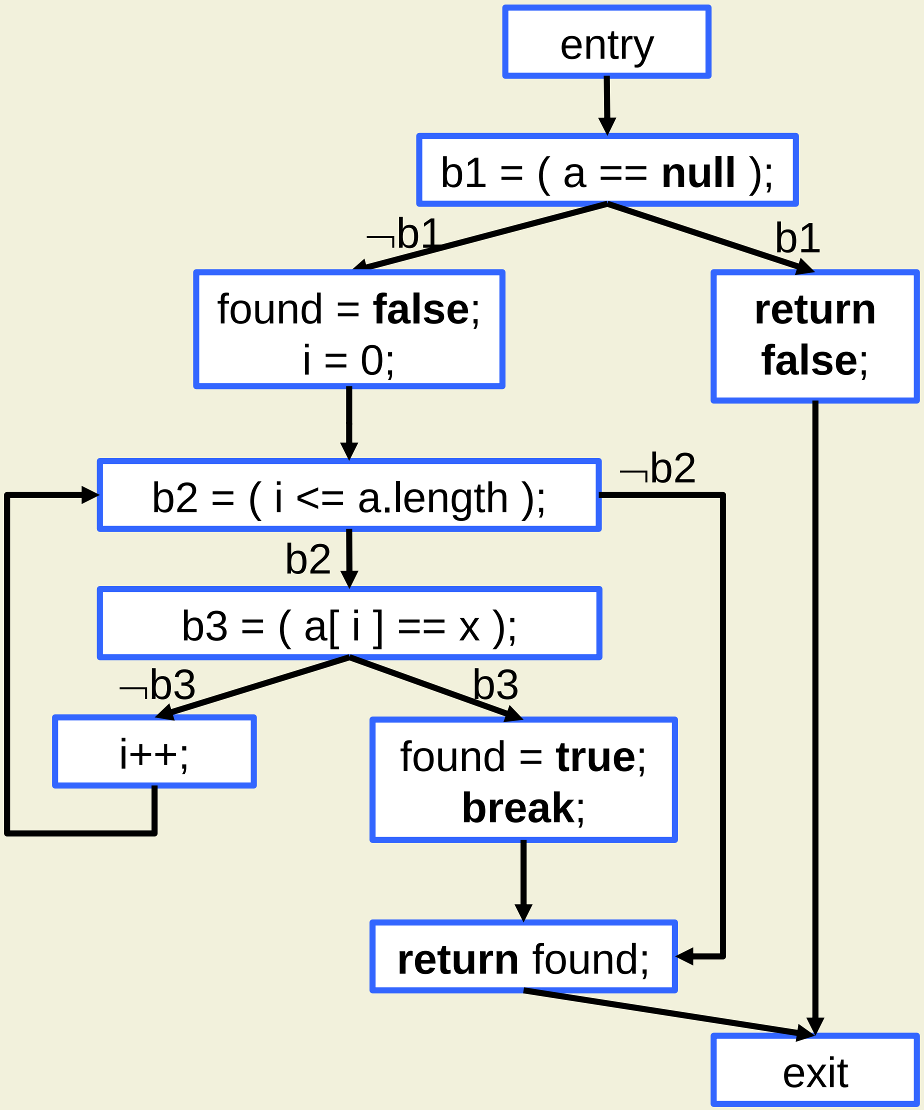
- We can achieve 100% path coverage with four test cases
  - a = **true**, b = **false**
  - a = **false**, b = **true**
  - a = **true**, b = **true**
  - a = **false**, b = **false**

- The two additional test cases detect the bugs



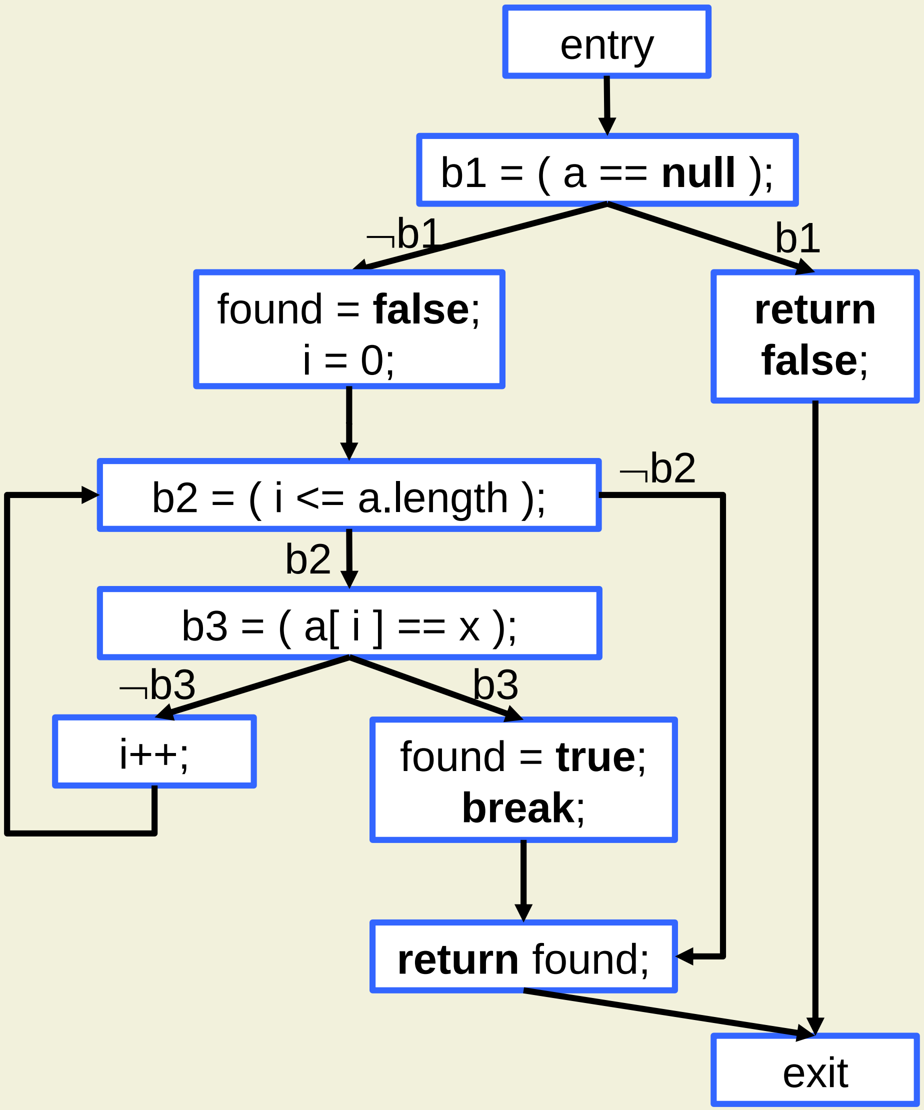
Path Coverage: Example 2

```
boolean contains( int[ ] a, int x ) {
  if( a == null )  return false;
  boolean found = false;
  for( int i = 0; i <= a.length; i++ ) {
    if( a[ i ] == x ) {
      found = true;
      break;
    }
  }
  return found;
}
```



Path Coverage: Example 2 (cont'd)

- Number of loop iterations is not known statically
- An arbitrarily large number of test cases is needed for complete path coverage



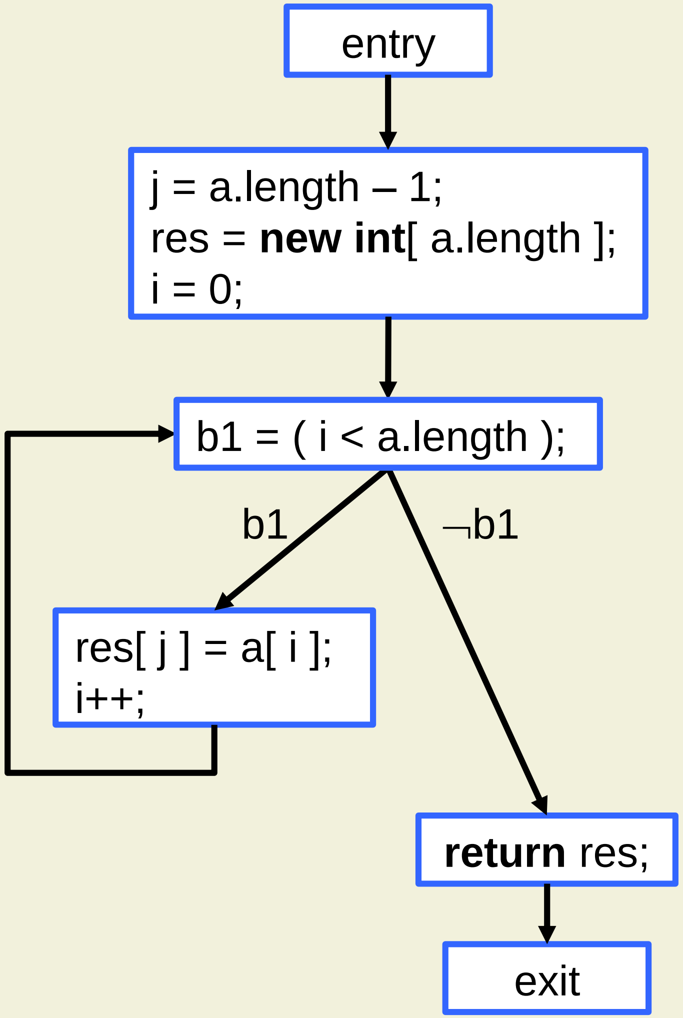
Path Coverage: Discussion

- Path coverage leads to more thorough testing than both statement and branch coverage
  - Complete path coverage implies complete statement coverage and complete branch coverage
  - But "at least n% path coverage" does not generally imply "at least n% statement coverage" or "at least n% branch coverage"

- Complete path coverage is not feasible for loops
  - Unbounded number of paths

Branch Coverage: Discussion (cont'd)

```
int[ ] reverse( int[ ] a ) {
  int j = a.length – 1;
  int[ ] res = new int[ a.length ];
  for( int i = 0; i < a.length; i++ ) {
    res[ j ] = a[ i ];
  }
  return res;
}
```



Loop Coverage

- Idea: for each loop, test zero, one, and more than one iterations

$$\text{Loop Coverage} = \frac{\text{Number of executed loops with 0, 1, and more than 1 iterations}}{\text{Total number of loops * 3}}$$

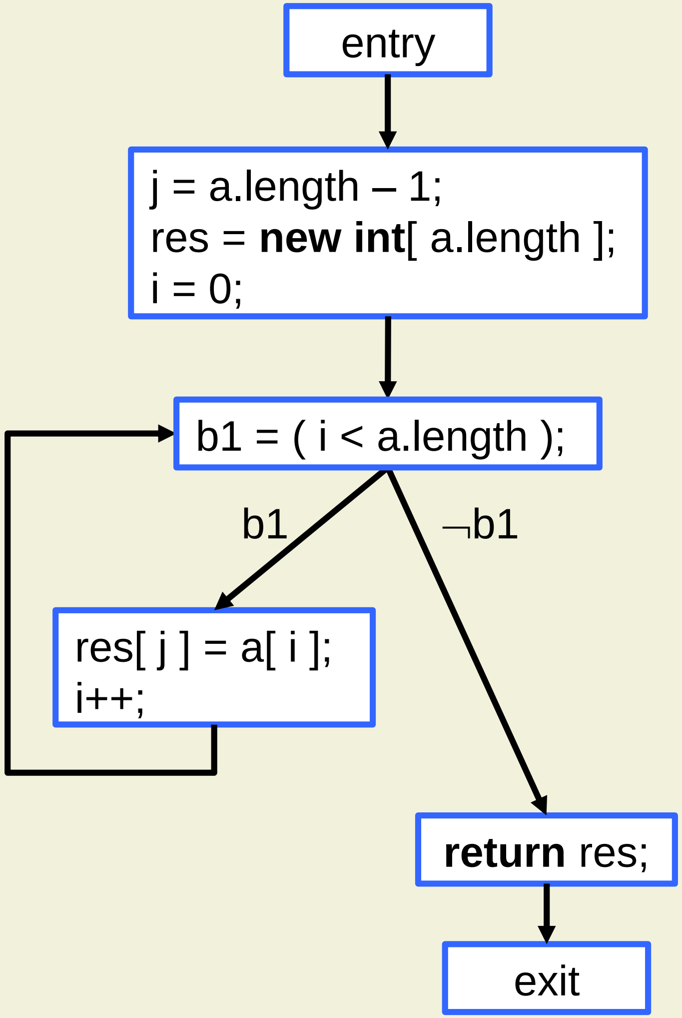
- Loop coverage is typically combined with other adequacy criteria such as statement or branch coverage

Loop Coverage: Example

- The test case
  - a = { 1 }

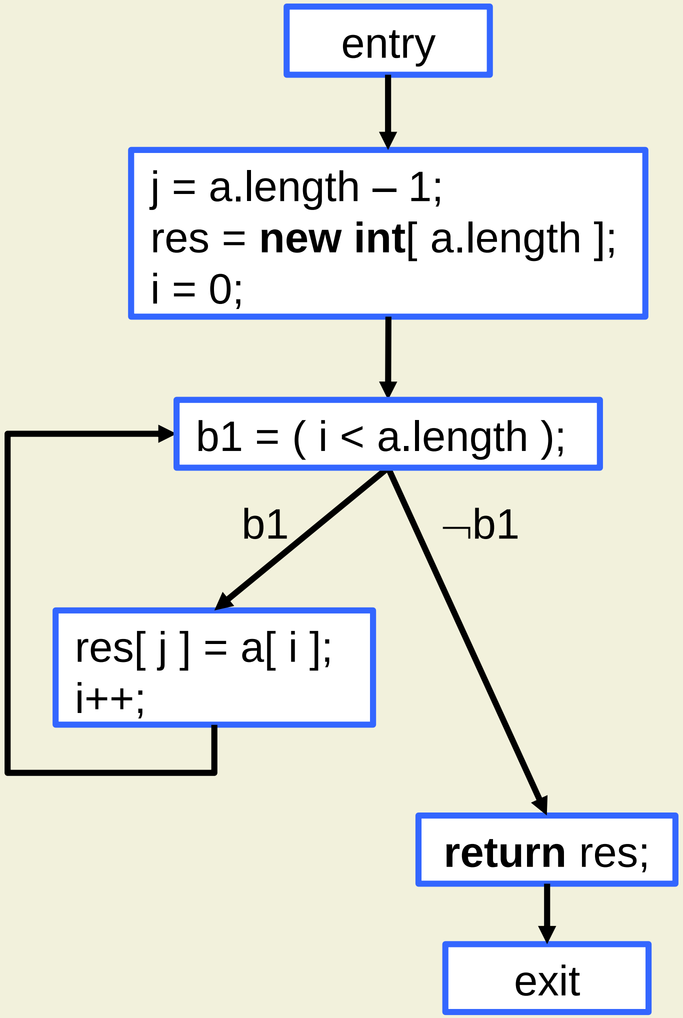
  executes one out of three possible cases for the loop

- Loop coverage: 33%



Loop Coverage: Example

- We can achieve 100% loop coverage with three test cases
  - a = { }
  - a = { 1 }
  - a = { 1, 2 }
- The last test case detects the bug



Measuring Coverage

- Coverage information is collected while the test cases execute

- Use code instrumentation or debug interface to count executed basic blocks, branches, etc.

```
int foo( boolean a, boolean b ) {
  int x = 1;  int y = 1;
  if( a ) {
    executedBranches[ 0 ]++;  x = 0;
  } else {
    executedBranches[ 1 ]++;  y = 0;
  }
  if( b ) {
    executedBranches[ 2 ]++;
    return 5 / x;
  } else {
    executedBranches[ 3 ]++;
    return 5 / y;
  }
}
```

5. Testing

5.1 Test Stages

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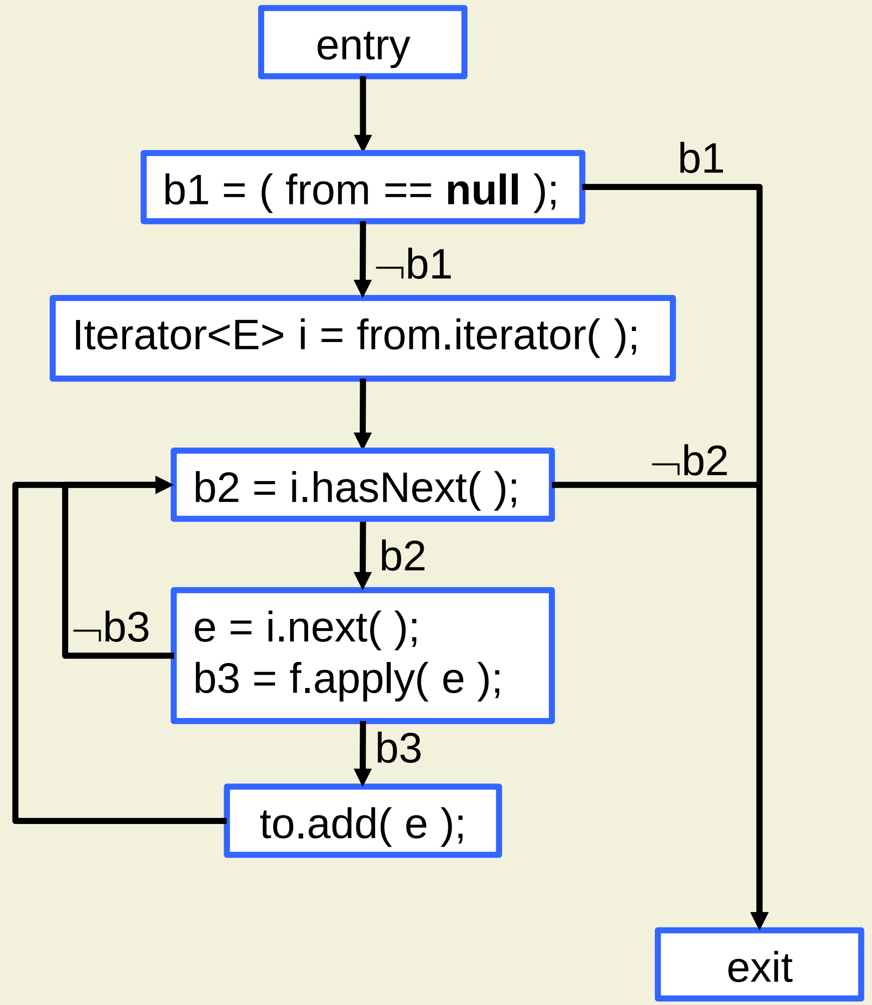
5.4 Structural Testing

- 5.4.1 Control Flow Testing
- 5.4.2 Advanced Topics of Control Flow Testing
- 5.4.3 Data Flow Testing
- 5.4.4 Interpreting Coverage

CFG: Method Calls

```
static <E> void filter(
              Collection<E> from,
              Filter<E> f,
              Collection<E> to ) {
  if( from == null ) return;
  Iterator<E> i = from.iterator( );
  while( i.hasNext( ) ) {
    E e = i.next( );
    if( f.apply( e ) )
      to.add( e );
  }
}
```



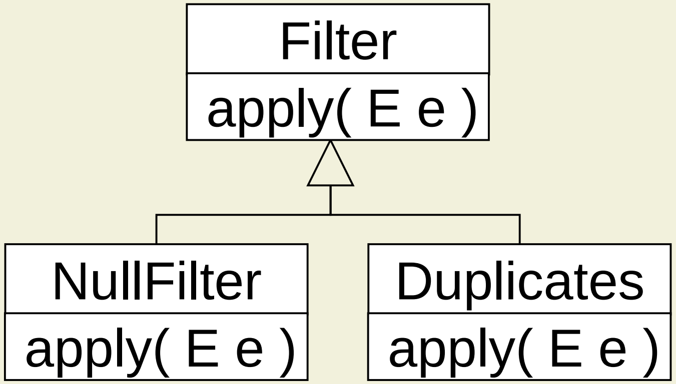
Dynamically-Bound Method Calls

```
static <E> void filter(
              Collection<E> from,
              Filter<E> f,
              Collection<E> to ) {
  if( from == null ) return;
  Iterator<E> i = from.iterator( );
  while( i.hasNext( ) ) {
    E e = i.next( );
    if( f.apply( e ) )
      to.add( e );
  }
}
```

- Intraprocedural CFGs treat method calls as simple statements
- Yet, calls invoke different code depending on the dynamic type of the receiver
- Testing should cover the possible behaviors

Testing Dynamically-Bound Method Calls

- A dynamically-bound method call can be regarded as a case distinction on the type of the receiver




```
f.apply( e )
```

```
if( type( f ) == Filter )
  f.Filter::apply( e );
else if( type( f ) == NullFilter )
  f.NullFilter::apply( e );
else // type( f ) == Duplicates
  f.Duplicates::apply( e );
```

- Now we can apply branch testing

Testing Dynamically-Bound Calls (cont'd)

- Treating dynamically-bound method calls as branches leads to a combinatorial explosion

- Use semantic constraints and pairwise-combinations testing

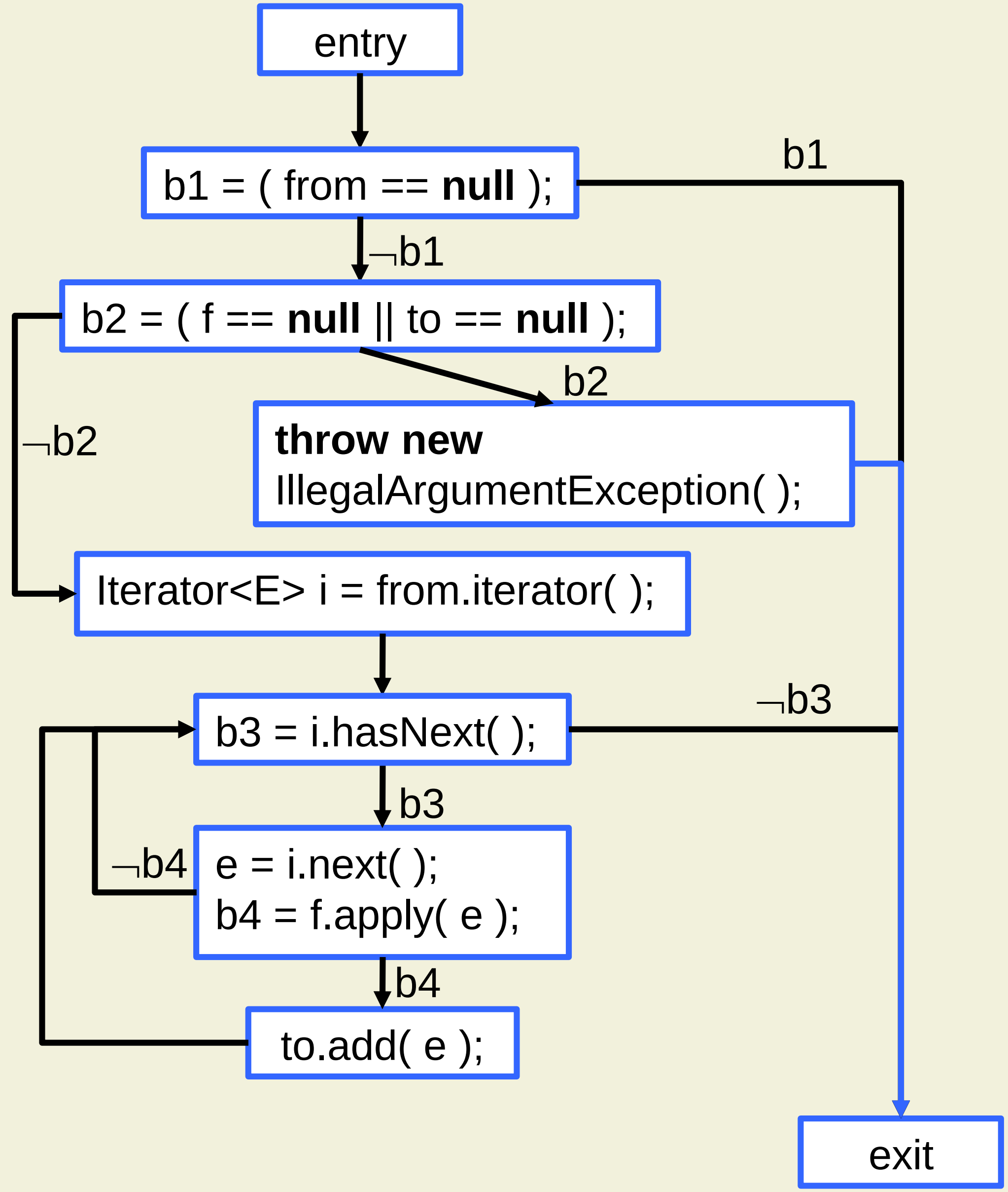
```
static <E> void filter(
              Collection<E> from,
              Filter<E> f,
              Collection<E> to ) {
  if( from == null ) return;
  Iterator<E> i = from.iterator( );
  while( i.hasNext( ) ) {
    E e = i.next( );
    if( f.apply( e ) )
      to.add( e );
```

Several different Filter classes in the program

java.util contains dozens of collection classes

Exceptions

```
static <E> void filter(
               Collection<E> from,
               Filter<E> f,
               Collection<E> to ) {
  if( from == null ) return;
  if( f == null || to == null )
    throw new
      IllegalArgumentException( );
  Iterator<E> i = from.iterator( );
  while( i.hasNext( ) ) {
    E e = i.next( );
    if( f.apply( e ) )
      to.add( e );
  }
}
```



CFG: Exceptions

- Exceptions add a control flow edge from the basic block where the exception is thrown to the exit block or the block where the exception is caught
- Idea: Cover exceptional control flow like normal control flow during testing
  - Test oracle is checked when method terminates normally

```
[ Test ]
[ ExpectedException( typeof(ArgumentException) ) ]
public void TestDemoInvalid( … ) {
  int d = Days( month, year );
}
```

Example: Documented Exceptions

```
static <E> void filter(
               Collection<E> from,
               Filter<E> f,
               Collection<E> to ) {
  if( from == null ) return;
  if( f == null || to == null )
    throw new
      IllegalArgumentException( );
  Iterator<E> i = from.iterator( );
  while( i.hasNext( ) ) {
    E e = i.next( );
    if( f.apply( e ) )
      to.add( e );
  }
}
```

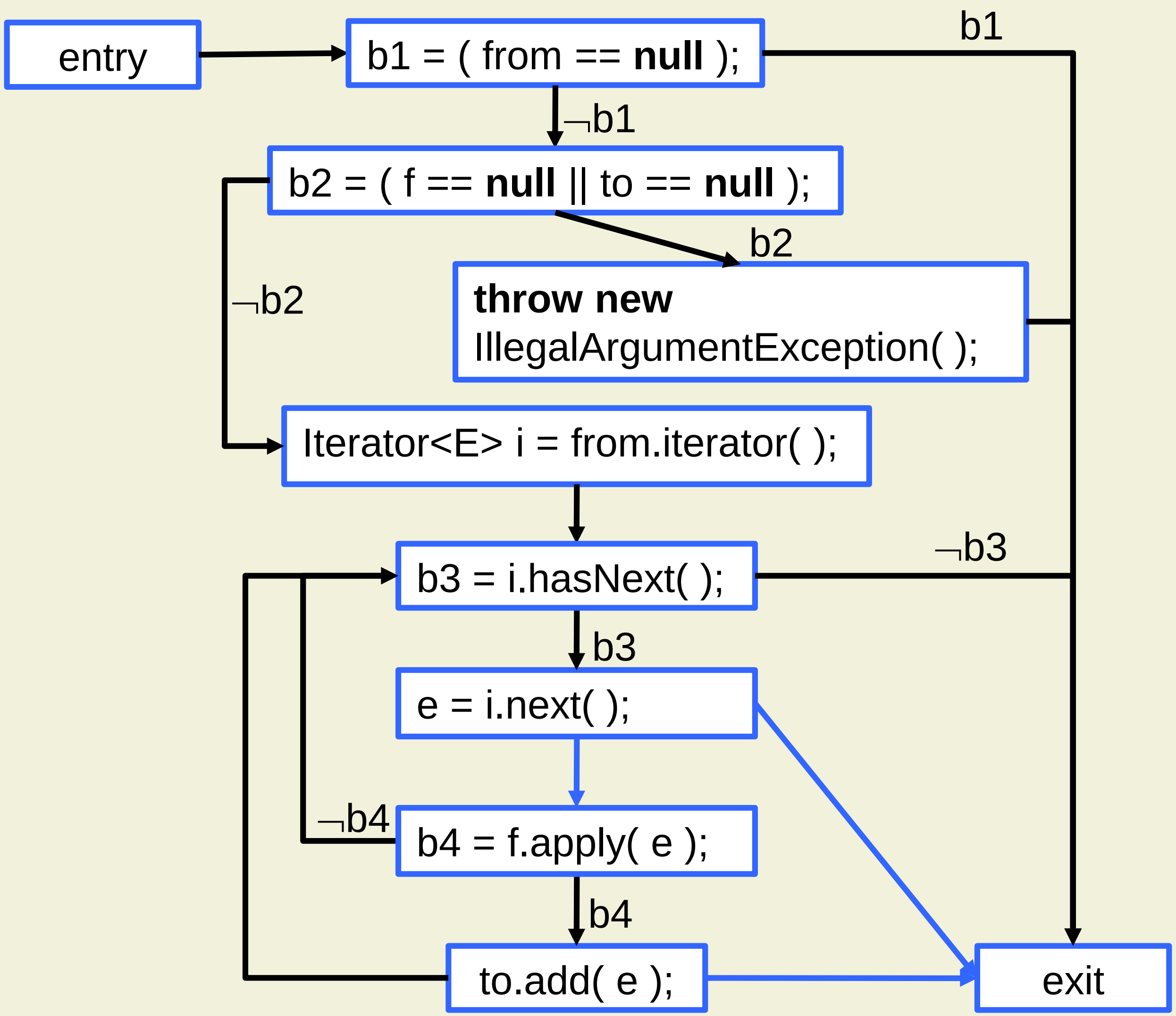
Might throw:

- NoSuchElementException

Might throw:

- UnsupportedOperationException
- ClassCastException
- NullPointerException
- IllegalArgumentException
- IllegalStateException

Example: Documented Exceptions (cont’d)



ETH zürich

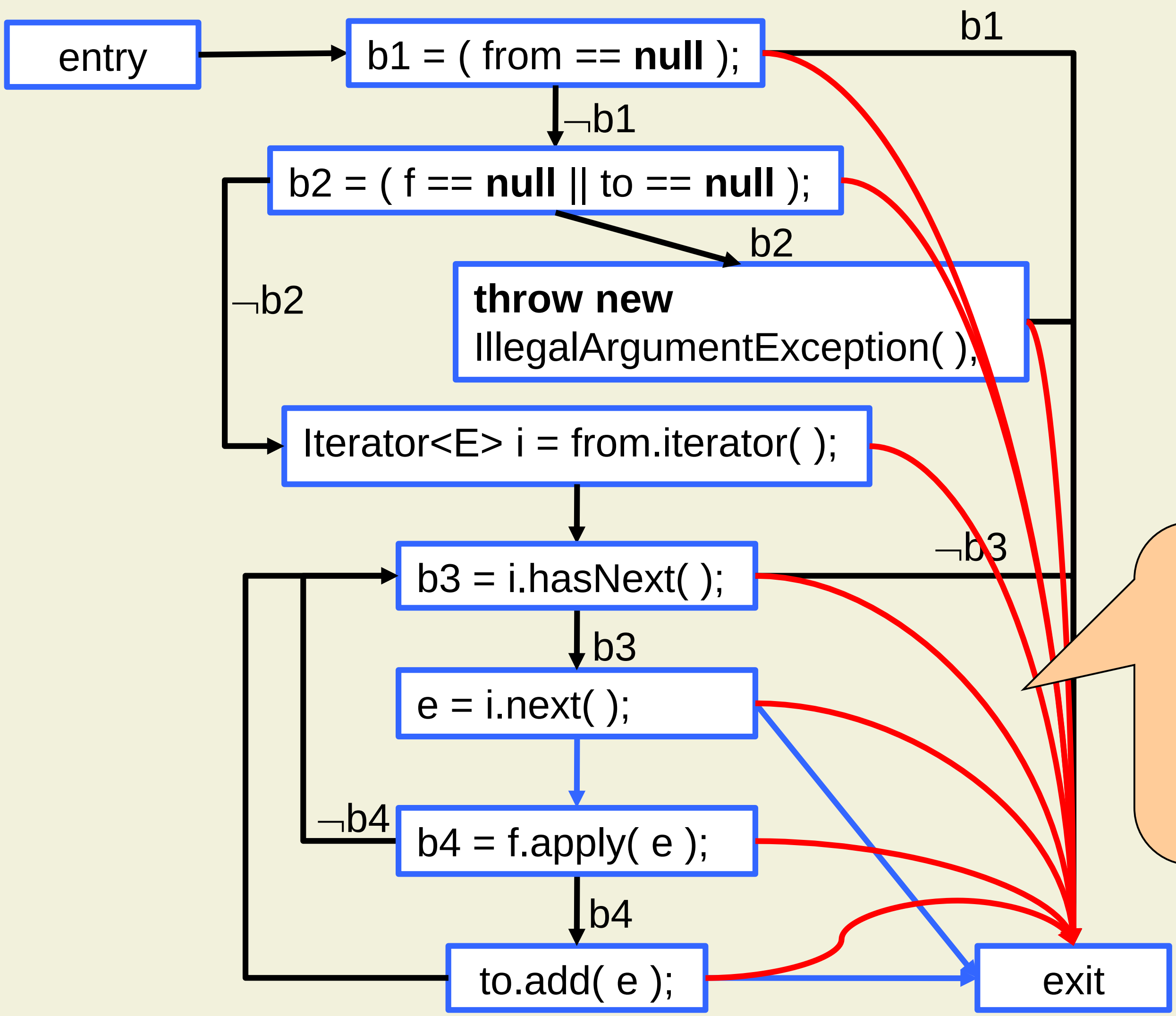
Example: Undocumented Exceptions

```
static <E> void filter(
            Collection<E> from,
            Filter<E> f,
            Collection<E> to ) {
  if( from == null ) return;
  if( f == null || to == null )
    throw new
      IllegalArgumentException( );
  Iterator<E> i = from.iterator( );
  while( i.hasNext( ) ) {
    E e = i.next( );
    if( f.apply( e ) )
      to.add( e );
  }
}
```

The example might also throw:

- ConcurrentModificationException
- NoClassDefFoundError
- NoSuchMethodError
- OutOfMemoryError
- StackOverflowError
- ThreadDeath
- VirtualMachineError
- etc.

Example: Undocumented Exceptions (cont’d)



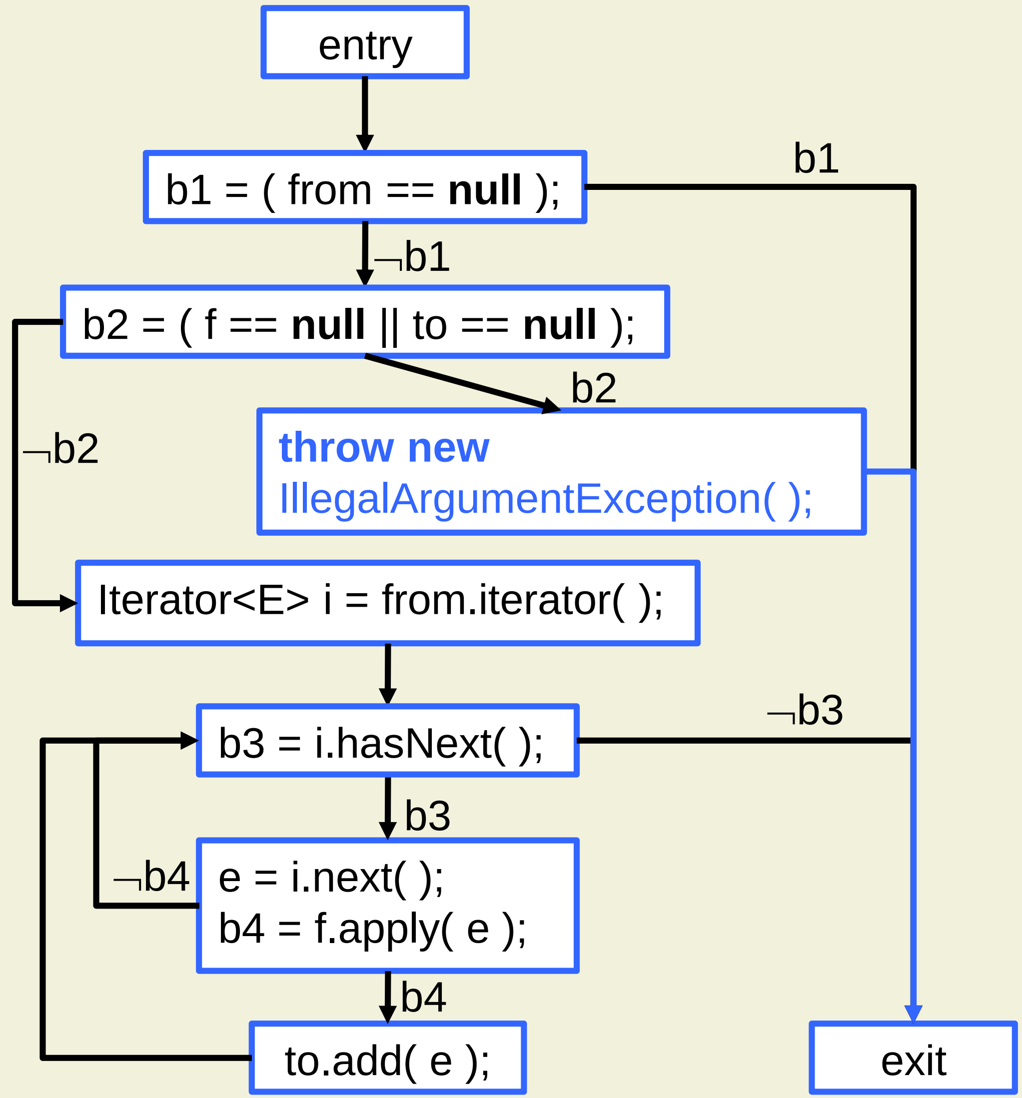
It is impractical to represent and test all exceptional control flow in the CFG

Checked vs. Unchecked Exceptions

- Many programming languages distinguish between checked and unchecked exceptions
- Checked exceptions represent invalid conditions outside the immediate control of the program
  - Invalid user input, database problems, network outages, absent files
- Unchecked exceptions represent defects in the program or the execution environment
  - Illegal arguments, null-pointer dereferencing, division by zero, assertion violation, etc.
  - In Java: all subclasses of RuntimeException and Error

Testing Unchecked Exceptions

- Unchecked exceptions are not supposed to occur
- When computing the CFG, ignore unchecked exceptions thrown by other methods and virtual machine
  - But consider **throw** statements



Unchecked Exceptions: Bad Example

```
static boolean contains( String[ ] a, String s ) {
  for( int i = 0; i < a.length; i++ ) {
    try {
      if( a[ i ].equals(s) )
        return true;
    } catch( NullPointerException e ) {
        i++;
    }
  }
  return false;
}
```

Exceptional control flow will not be covered

Bug remains undetected

- Never use unchecked exceptions to encode control flow!

Bad Example Fixed

```
static boolean contains( String[ ] a, String s ) {
  for( int i = 0; i < a.length; i++ ) {
    if( a[ i ] != null ) {
      if( a[ i ].equals(s) )
        return true;
    } else {
      i++;
    }
  }
  return false;
}
```

Normal control flow will be covered

Bug will be detected

Testing Checked Exceptions

- Checked exceptions represent regular control flow that needs to be tested
  - Include control flow in CFG, testing, and coverage

- In Java, checked exceptions are declared in method signatures

```
interface RemoteBuffer extends Remote {
  void put( String s ) throws RemoteException;
}
```

- For each call, add appropriate control flow edges

Checked Exceptions: Example

```
class Producer {
  RemoteBuffer b;

  void produce( ) throws RemoteException {
    boolean retried = false;
    boolean success = false;
    while( !success ) {
      try {
        b.put( "Product“ );
        success = true;
      } catch( RemoteException e ) {
        if( retried )  throw e;
      }
    }
  }
}
```

Exceptional control flow will be covered

Bug will be detected

Testing Exceptions: Summary

- Checked exceptions encode the program’s reaction to invalid conditions in the environment
  - Test like normal control flow
- Unchecked exceptions represent defects
  - Test unchecked exceptions explicitly thrown by method under test (argument validation, precondition check)
  - Unchecked exceptions thrown by methods being called indicate defect in method under test (precondition violation) or in the called method
  - Unchecked exceptions thrown by virtual machine indicate defect in method under test (e.g., infinite recursion) or deployment error (e.g., class not found)

5. Testing

5.1 Test Stages

5.2 Test Strategies

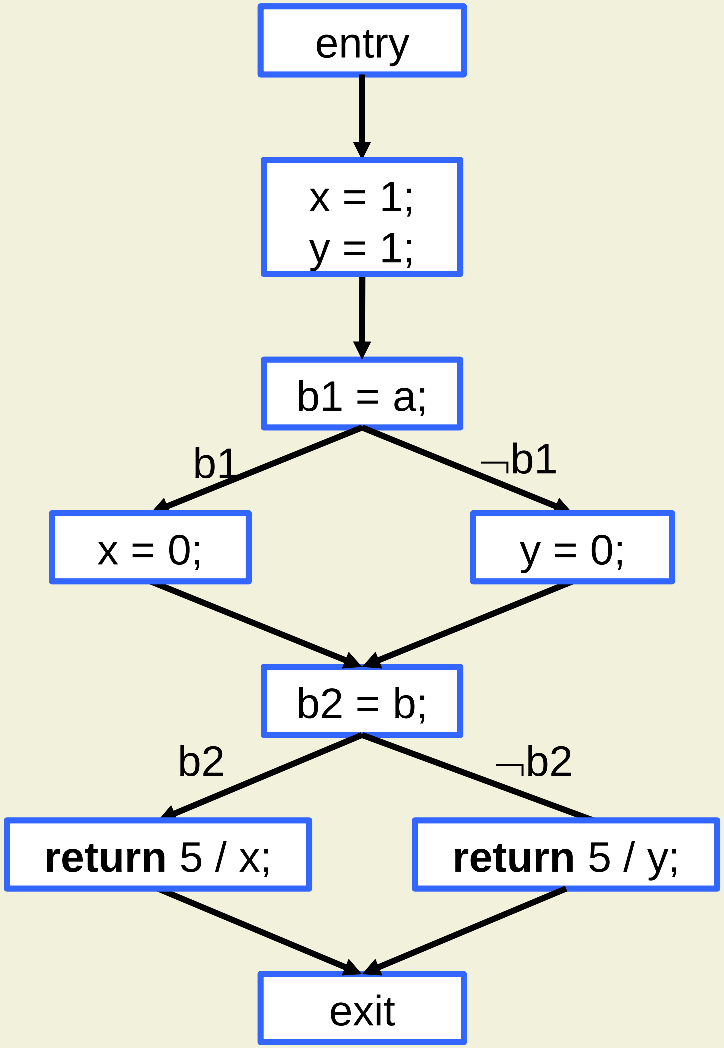
5.3 Functional Testing

5.4 Structural Testing

- 5.4.1 Control Flow Testing
- 5.4.2 Advanced Topics of Control Flow Testing
- 5.4.3 Data Flow Testing
- 5.4.4 Interpreting Coverage

Example Revisited

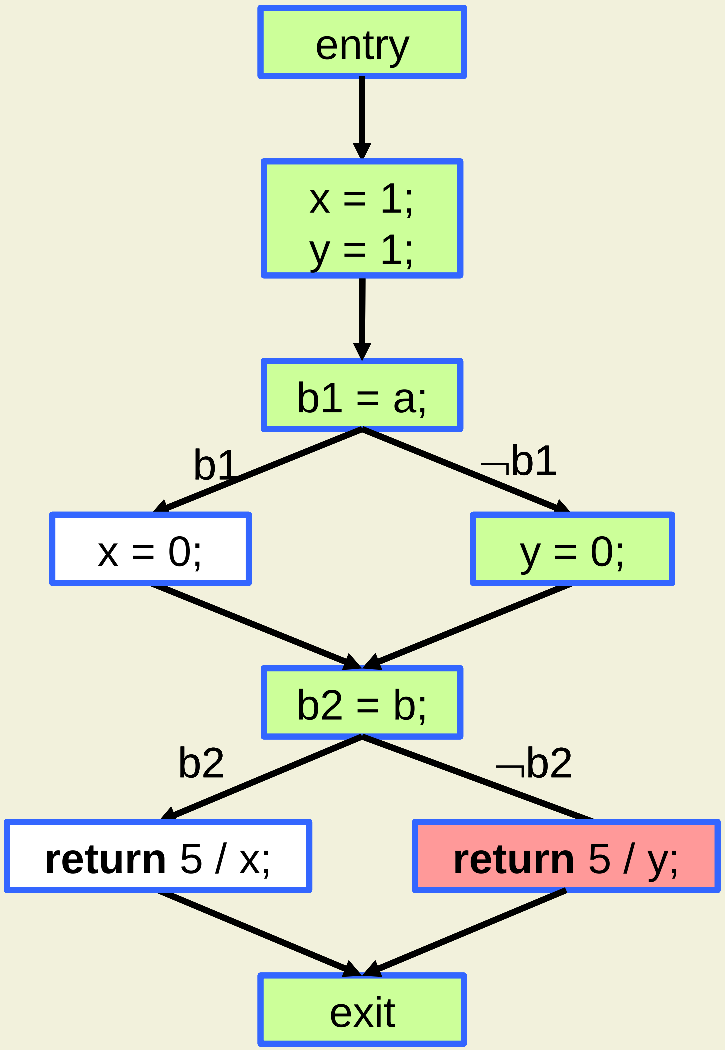
```
int foo( boolean a, boolean b ) {
  int x = 1;
  int y = 1;
  if( a )
    x = 0;
  else
    y = 0;
  if( b )
    return 5 / x;
  else
    return 5 / y;
}
```



Data Flow Testing

- Testing all paths is not feasible
  - Number grows exponentially in the number of branches
  - Loops

- Idea: Test those paths where a computation in one part of the path affects the computation of another



Variable Definition and Use

- A variable definition for a variable v is a basic block that assigns to v
  - v can be a local variable, formal parameter, field, or array element

- A variable use for a variable v is a basic block that reads the value from v
  - In conditions, computations, output, etc.

Definition-Clear Paths

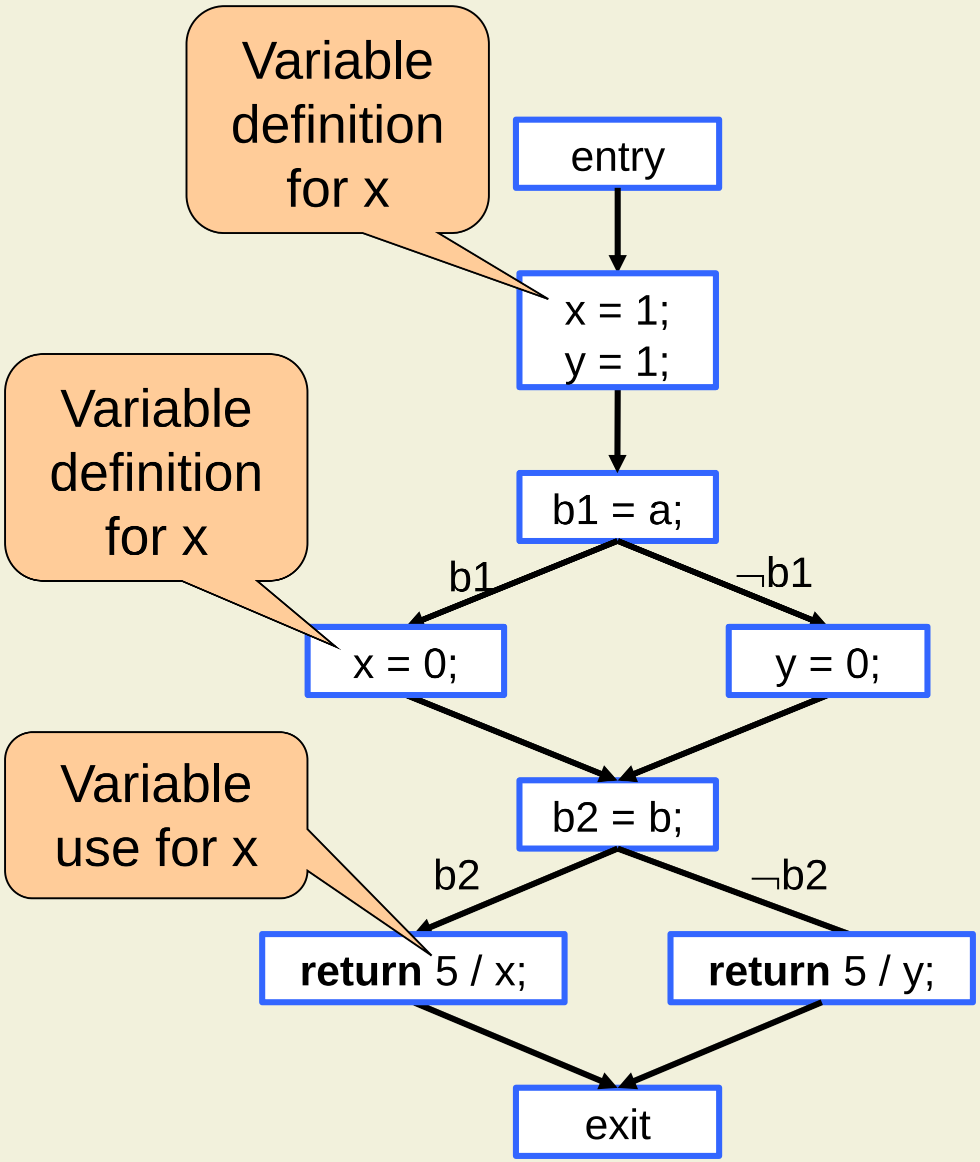
- A definition-clear path for a variable v is a path $n_1, \ldots, n_k$ in the CFG such that:
  - n_1 is a variable definition for v
  - n_k is a variable use for v
  - No n_i $(1 < i \leq k)$ is a variable definition for v
    (n_k may be a variable definition if each assignment to v occurs after a use)

- Note: definition-clear paths do not go from entry to exit (in contrast to our earlier definition of path)

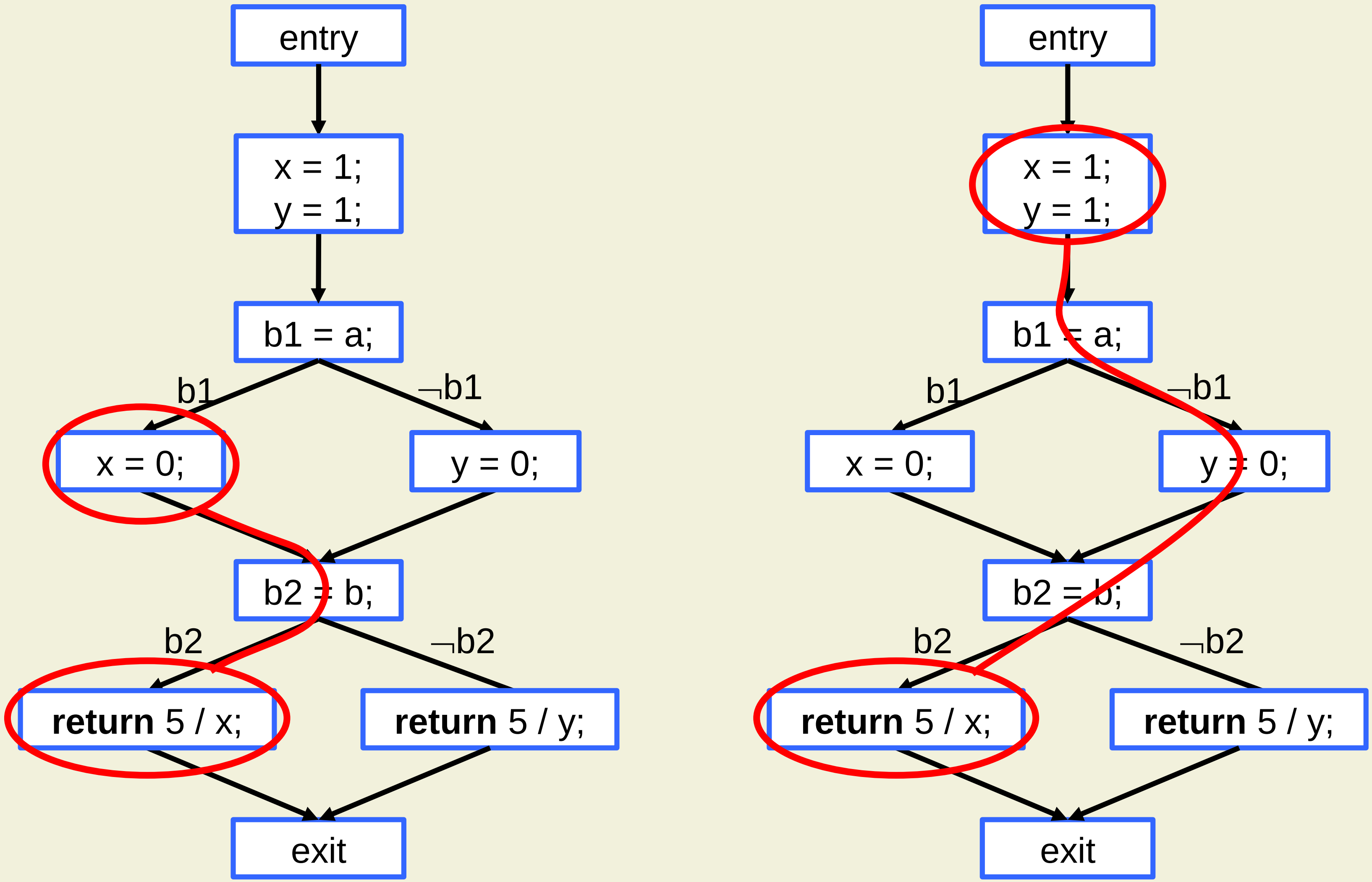
Definition-Use Pairs

- A definition-use pair for a variable v is a pair of nodes (d,u) such that there is a definition-clear path d, …, u in the CFG

- We say DU-pair for definition-use pair



Definition-Use Pairs: Examples



DU-Pairs Coverage

- Idea: test all paths that provide a value for a variable use

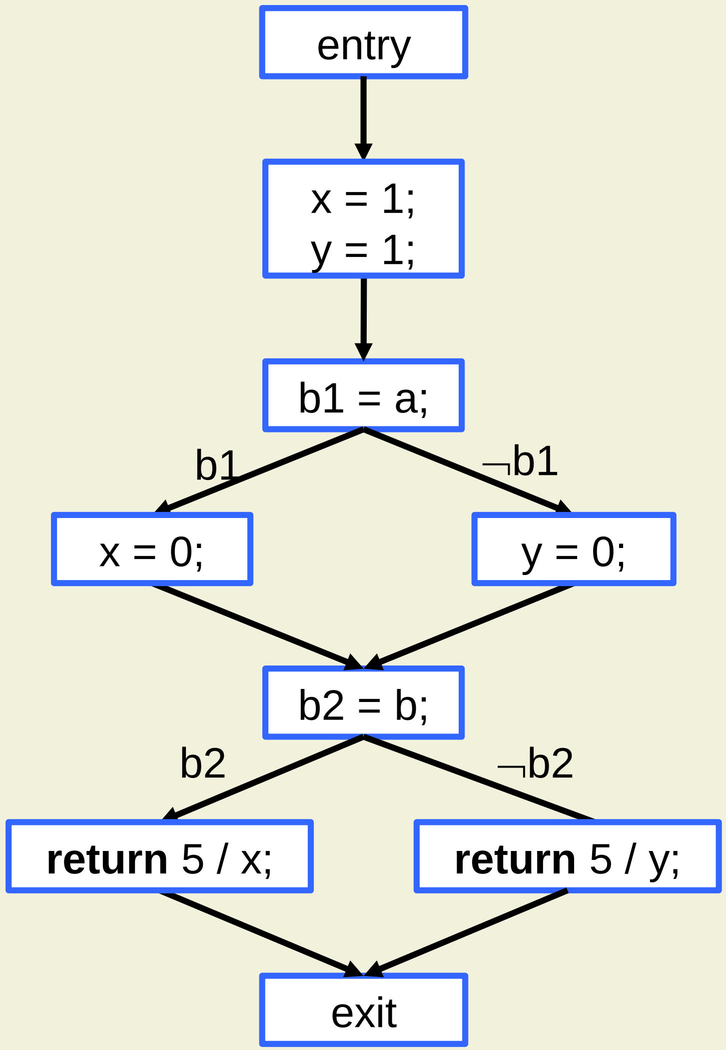
$$\text{DU-Pairs Coverage} = \frac{\text{Number of executed DU-Pairs}}{\text{Total number of DU-Pairs}}$$

DU-Pairs Coverage: Example

- The two test cases
  - a = **true**, b = **false**
  - a = **false**, b = **true**

  achieve 100% branch coverage, but only 50% DU-pairs coverage

- In this example, DU-pairs coverage is equivalent to path coverage



Determining all DU-Pairs

- DU-Pairs are computed using a static reaching-definitions analysis
- For each node n and for each variable v, compute all variable definitions for v that possibly reach n via a definition-clear path
- The reaching definitions at a node n are:
  - The reaching definitions of n’s predecessors in the CFG
  - minus the definitions killed by one of n’d predecessors
  - plus the definitions made by one of n’d predecessors

Reaching Definitions: Algorithm

- Input
  - pred(n) = { m | (m,n,c) is an edge in the CFG }
  - succ(m) = { n | (m,n,c) is an edge in the CFG }
  - gen(n) = { v_n | n is a variable definition for v }
  - kill(n) = { v_m | n is a variable definition for v and m ≠ n }
- We compute via fixpoint iteration
  - Reach(n): The reaching definitions at the beginning of n
  - ReachOut(n): The reaching definitions at the end of n

Reaching Definitions: Algorithm (con't)

foreach node n **do** ReachOut(n) := $\varnothing$ **end**

worklist := nodes

while worklist $\neq \varnothing$ **do**

  n := **any**(worklist)

  remove n from worklist

  Reach(n) := $\bigcup_{m \in pred(n)}$ ReachOut(m)

  ReachOut(n) := Reach(n) \ kill(n) $\cup$ gen(n)

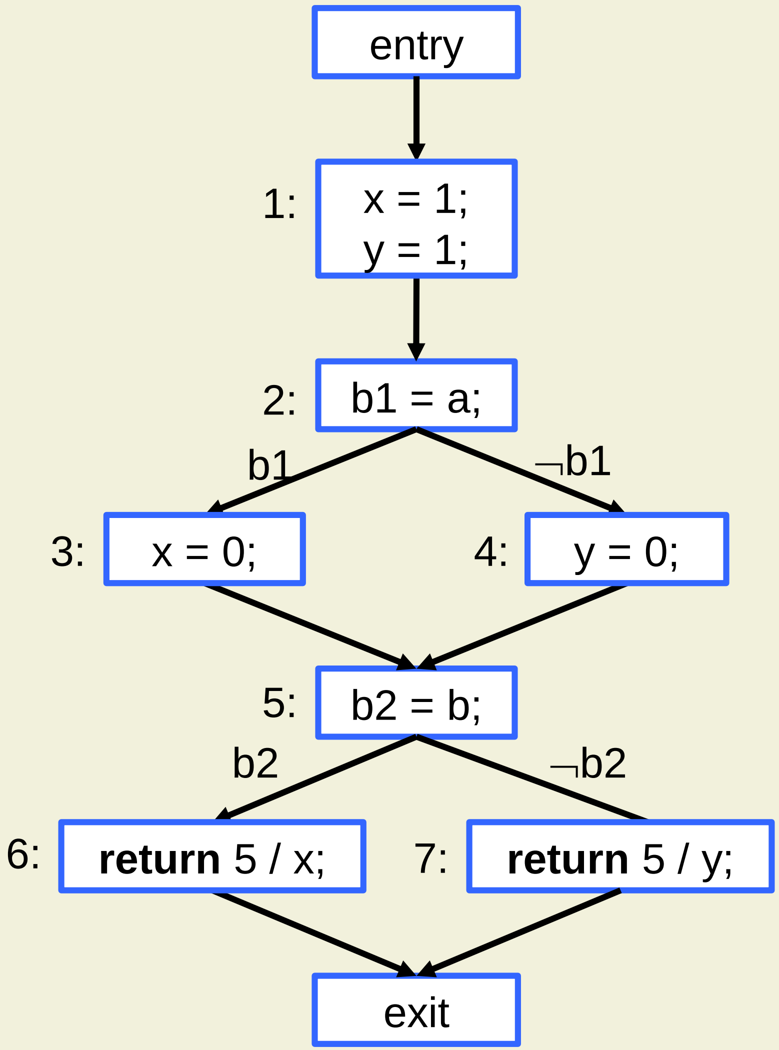
  if ReachOut(n) has changed **then**

    worklist := worklist $\cup$ succ(n)

  end

end

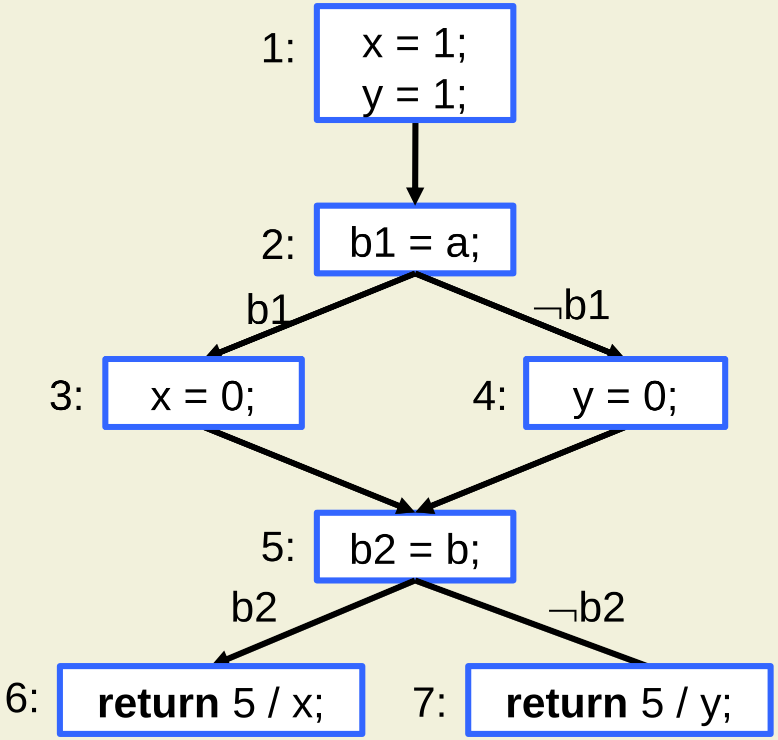
Reaching Definitions: Example



n	Reach(n)	ReachOut(n)
1	∅	
2	x_1, y_1	x_1, y_1
3	x_1, y_1	x_3, y_1
4	x_1, y_1	x_1, y_4
5	x_1, x_3, y_1, y_4	x_1, x_3, y_1, y_4
6	x_1, x_3, y_1, y_4	x_1, x_3, y_1, y_4
7	x_1, x_3, y_1, y_4	x_1, x_3, y_1, y_4

From Reaching Definitions to DU-Pairs

- The set of DU-pairs is easily determined as $\{ (d,u) \mid u \text{ is a variable use for } v \text{ and } v_d \in \text{Reach}(u) \}$



n	Reach(n)
1	$\varnothing$
2	x_1, y_1
3	x_1, y_1
4	x_1, y_1
5	x_1, x_3, y_1, y_4
6	x_1, x_3, y_1, y_4
7	x_1, x_3, y_1, y_4

- DU-pairs for x: (1,6), (3,6)
- DU-pairs for y: (1,7), (4,7)

Data Flow Testing Example

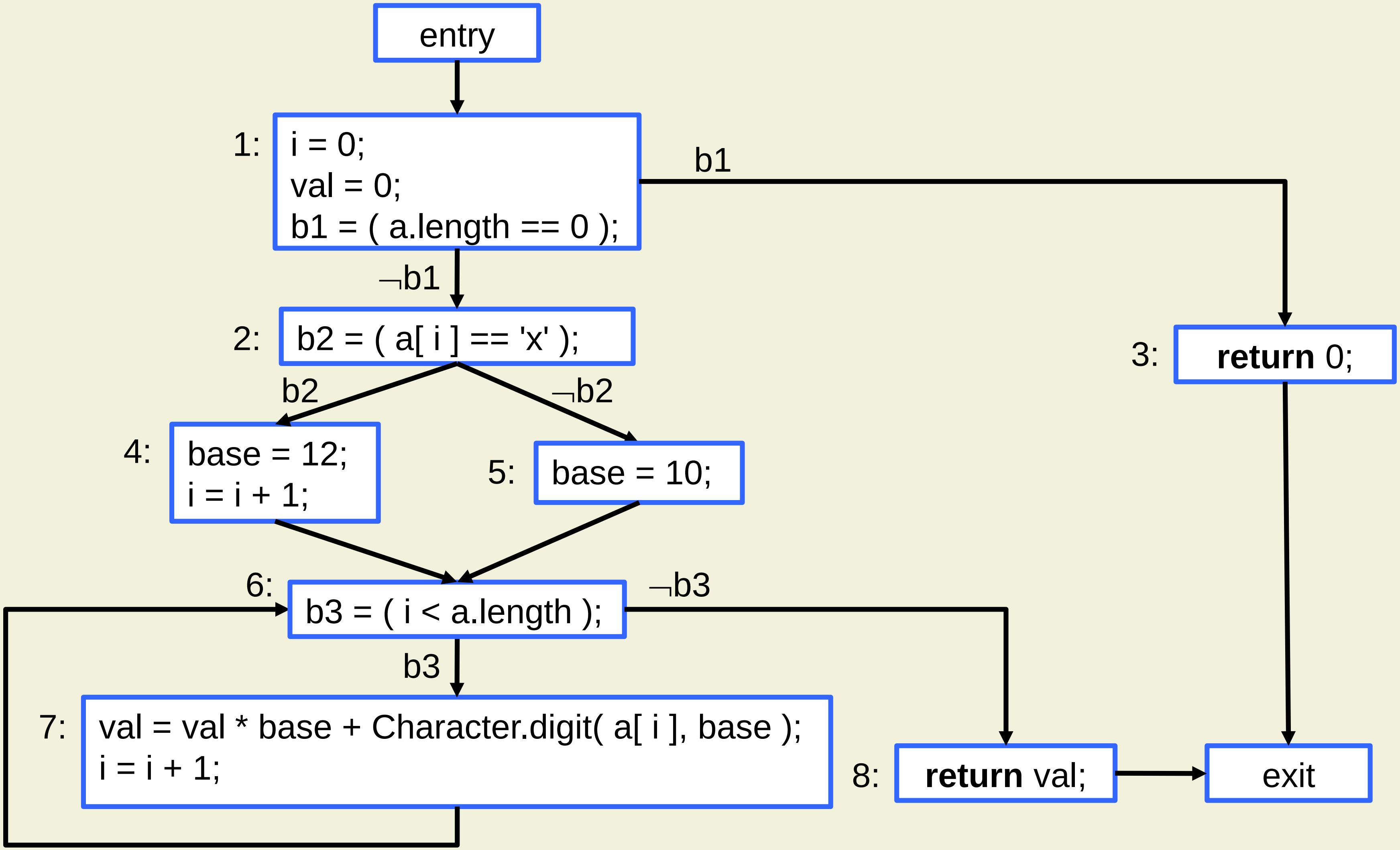
- Convert character sequence to integer
  - Input format: d_{dec}* | ‘x’(d_{hex}*), where d is a (decimal or hexadecimal) digit

```
static int convert( char[ ] a ) {
  int base;  int i = 0;  int val = 0;
  if ( a.length == 0 )  return 0;
  if( a[ i ] == 'x' ) { base = 12; i = i + 1; }
  else { base = 10; }

  while( i < a.length ) {
      val = val * base + Character.digit( a[ i ], base );
      i = i + 1;
  }
  return val;
}
```

We assume here that all inputs are of the required format

Data Flow Testing Example: CFG



Data Flow Testing Example: DU-Pairs

n	Reach(n)	ReachOut(n)
1	$\emptyset$	i_1, val_1
2	i_1, val_1	i_1, val_1
3	i_1, val_1	i_1, val_1
4	i_1, val_1	i_4, val_1, $base_4$
5	i_1, val_1	i_1, val_1, $base_5$
6	i_1, i_4, i_7, val_1, val_7, $base_4$, $base_5$	i_1, i_4, i_7, val_1, val_7, $base_4$, $base_5$
7	i_1, i_4, i_7, val_1, val_7, $base_4$, $base_5$	i_7, val_7, $base_4$, $base_5$
8	i_1, i_4, i_7, val_1, val_7, $base_4$, $base_5$	i_1, i_4, i_7, val_1, val_7, $base_4$, $base_5$

- We get 14 DU-pairs
- DU-pairs for i: (1,2), (1,4), (1,6), (4,6), (7,6), (1,7), (4,7), (7,7)
- DU-pairs for val: (1,7), (7,7), (1,8), (7,8)
- DU-pairs for base: (4,7), (5,7)

Data Flow Testing Example: Bug

- Consider the test cases
  - a = { }
  - a = { ‘x’ }
  - a = { ‘1’ }
  - a = { ‘1’, ‘2’ }
- The bug is not detected!

```
static int convert( char[ ] a ) {
  int base;  int i = 0;  int val = 0;
  if ( a.length == 0 )  return 0;
  if( a[ i ] == 'x' ) { base = 12; i = i + 1; }
  else { base = 10; }
  while( i < a.length ) {
    val = val * base + Character.digit( a[ i ], base );
    i = i + 1;
  }
  return val;
}
```

- Branch and loop coverage: 100%
- DU-pairs missed: (4,7) for i, base (coverage 86%)

Data Flow Testing Example: Observation

- DU-pairs for i and val include (7,7)
- Complete DU-pairs coverage requires more than one loop iteration

```
static int convert( char[ ] a ) {
  int base;  int i = 0;  int val = 0;
  if ( a.length == 0 )  return 0;
  if( a[ i ] == 'x' ) { base = 16; i = i + 1; }
  else { base = 10; }

  while( i < a.length ) {
    val = val * base + Character.digit( a[ i ], base );
    i = i + 1;
  }
  return val;
}
```

Determining all DU-Pairs: Heap Structures

```
static void repeat( int[ ] from, int[ ] to ) {
  int i = 0;
  if ( from.length == 0 )  return;
  while ( i < to.length ) {
    to[ i ] = to[ i ] + from[ i % from.length ];
    i = i + 1;
  }
}
```

- Determining whether a definition and a usage refer to the same heap location, a static analysis would need arithmetic and aliasing information
- Static analysis has to over-approximate

Measuring DU-Pairs Coverage

- Keep track of currently active definitions
  - defCover: Variable → Block

- Keep track of executed DU-pairs
  - useCover: Variable × $\text{Block}_{\text{def}}$ × $\text{Block}_{\text{use}}$ → $\mathbb{N}$

- Maps can be encoded as arrays, indexed by identifiers for variables and basic blocks

Measuring DU-Pairs Coverage: Example

```
int foo( boolean a, boolean b ) {
  int x = 1;  defCover[ "x" ] = 0;
  int y = 1;  defCover[ "y" ] = 0;
  if( a ) {
    x = 0; defCover[ "x" ] = 1;
  } else {
    y = 0; defCover[ "y" ] = 2;
  }
  if( b ) {
    useCover[ "x", defCover[ "x" ], 3 ]++;
    return 5 / x;
  } else {
    useCover[ "y", defCover[ "y" ], 4 ]++;
    return 5 / y;
  }
}
```

Current variable definition for x is basic block 0

Current variable definition for x is basic block 1

DU-pair for variable x with current definition and use-block 3 has been executed

Data Flow Testing: Discussion

- Data flow testing complements control flow testing
  - Choose test cases that maximize branch and DU-pairs coverage

- Like with path coverage, not all DU-pairs are feasible
  - Static analysis over-approximates data flow
  - Complete DU-pairs coverage might not be possible

Data Flow Testing: Discussion (cont'd)

- DU-pairs coverage is not the only adequacy criterion for data flow testing
  - All definitions, all predicate-usages, all simple-DU-paths, etc.

- DU-pair "anomalies" may point to errors
  - Use before definition (not possible for locals in Java)
  - Double definition without use
  - Termination after definition without use

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Interpreting Coverage

- High coverage does not mean that code is well tested
  - But: low coverage means that code is not well tested
  - Make sure you do not blindly optimize coverage but develop test suites that test the code well

- Coverage tools do not only measure coverage metrics, they also identify which parts of the code have not been tested

Experimental Evaluation: Approach

- Several studies investigate the benefit of coverage metrics
  - Andrews et al.: “Using Mutation Analysis for Assessing and Comparing Testing Coverage Criteria”, TR SCE-06-02, 2006
- Approach
  - Seed defects in the code
  - Develop test suites that satisfy various coverage criteria
  - Measure how many of the seeded defects are found by the test suits
  - Extrapolate to “real” defects in the code

Experimental Evaluation: Some Findings

- The test suite size grows exponentially in the coverage
- More demanding coverage criteria lead to larger test suites, but do not detect more bugs
  - Block, decision, data flow coverage
- There is no significant difference in the cost-efficiency of the various coverage metrics
- All adequacy criteria lead to test suites that detect more bugs then random testing, especially for large test suites