

# **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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**ETH** zürich

# 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.”

9/9

0800 Antan started

1000 " stopped - antan ✓

1300 (032) MP - MC ~~1.98267000~~ 2.130476415 (23) 4.615925059 (-2)

(033) PRO 2 2.130476415

convd 2.130676415

Relays 6-2 in 033 failed special speed test

In Relay " 11.000 test.

Relays changed

1100 Started Cosine Tape (Sine check)

1525 Started Multi-Adder Test.

1545

Relay #70 Panel F (moth) in relay.

First actual case of bug being found.

1630 Antan started.

1700 closed down.

Relay 2145

Relay 337

# 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

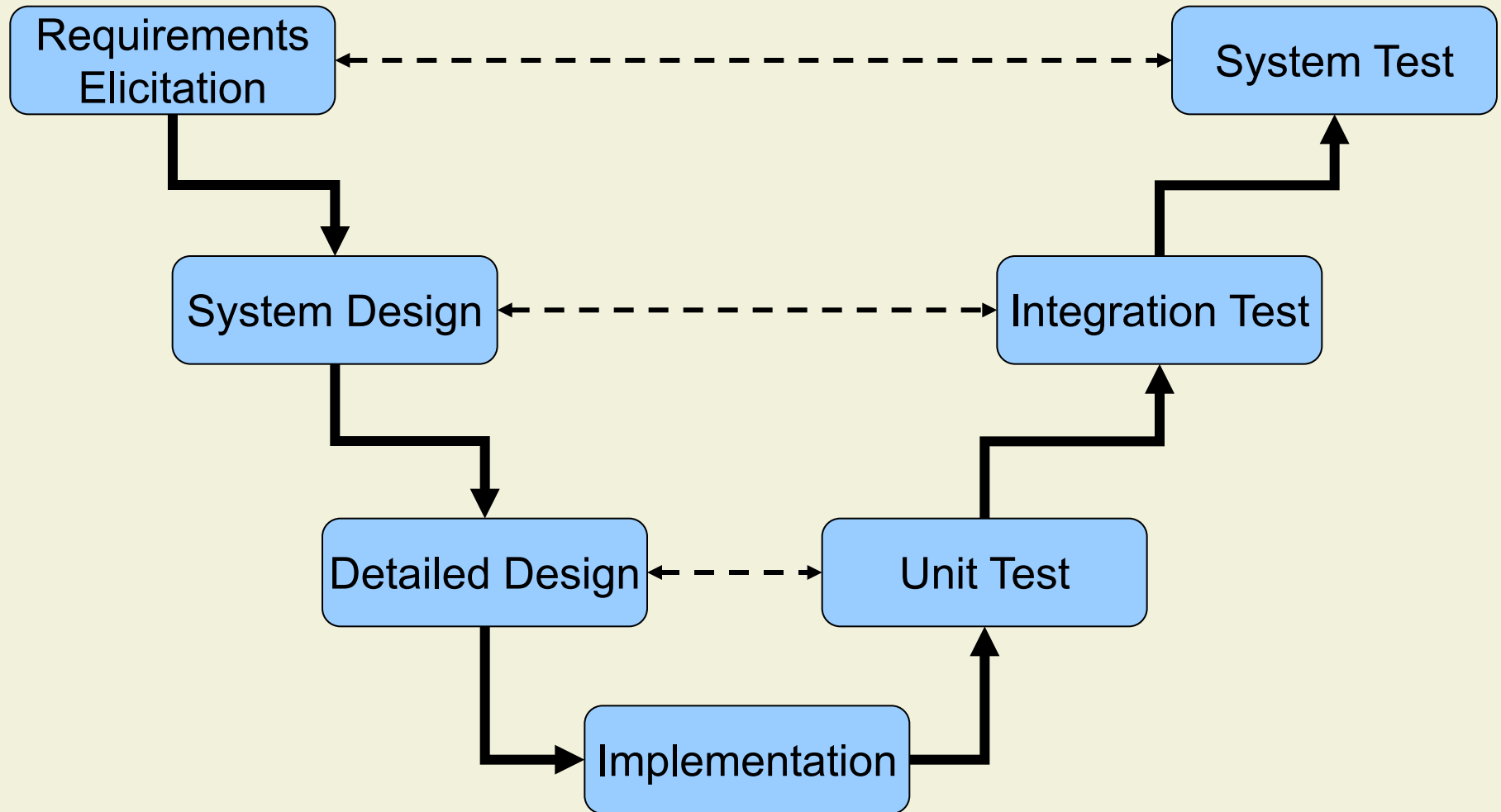
## 5.1 Test Stages

## 5.2 Test Strategies

## 5.3 Functional Testing

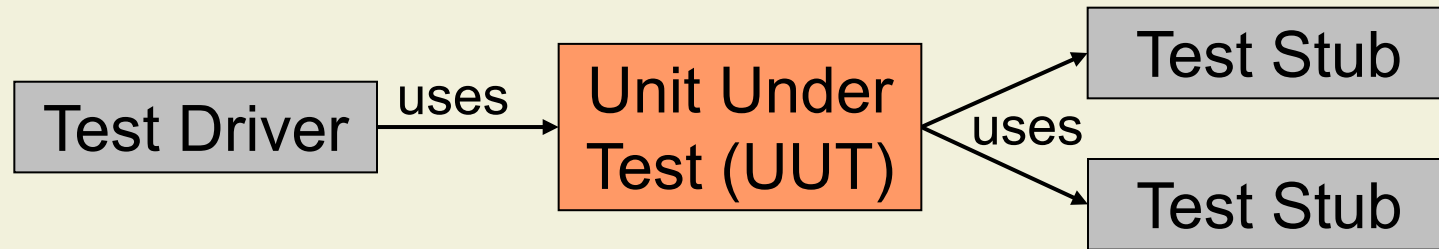
## 5.4 Structural Testing

# Test Stages





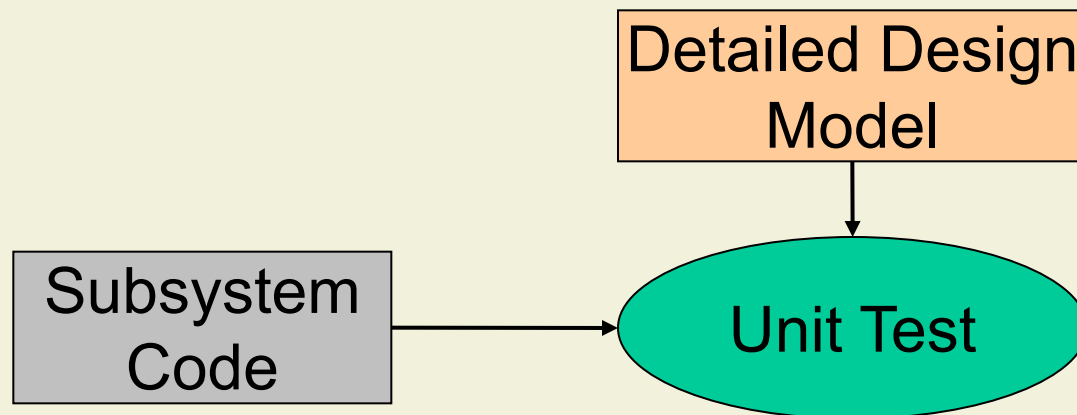
# Creation of Test Harness



- 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( ) { ... }  
}
```

Implement  
test driver

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

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

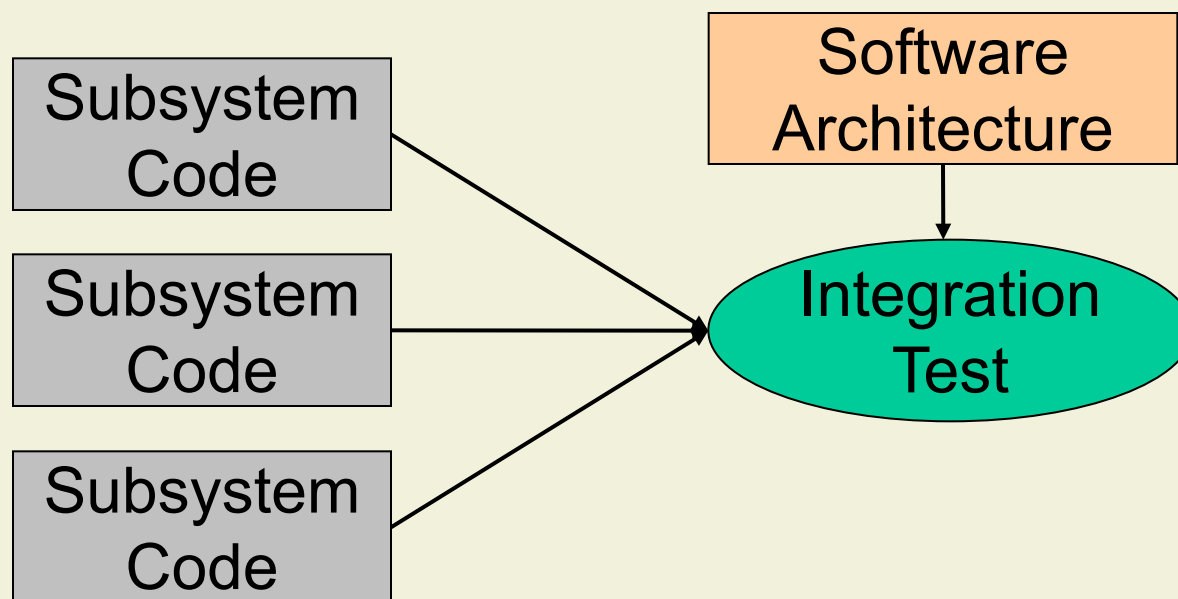
- Execute the test cases
- Re-execute test cases after every change
  - Automate as much as possible
  - For instance, before every commit to the repository
- Regression testing
  - Testing that everything that used to work **still works** after changes are made to the system
  - Also important for system 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

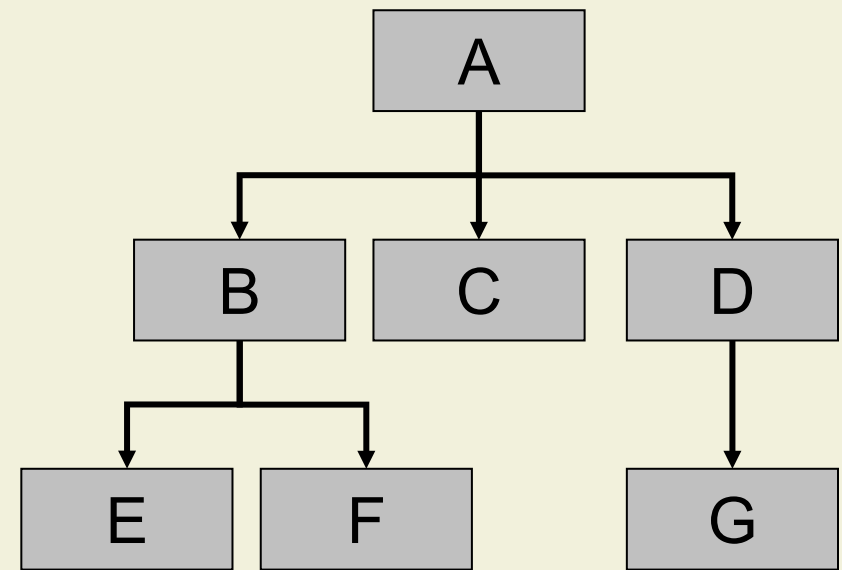


- Goal: Test interfaces between subsystems

# Integration Testing Strategy

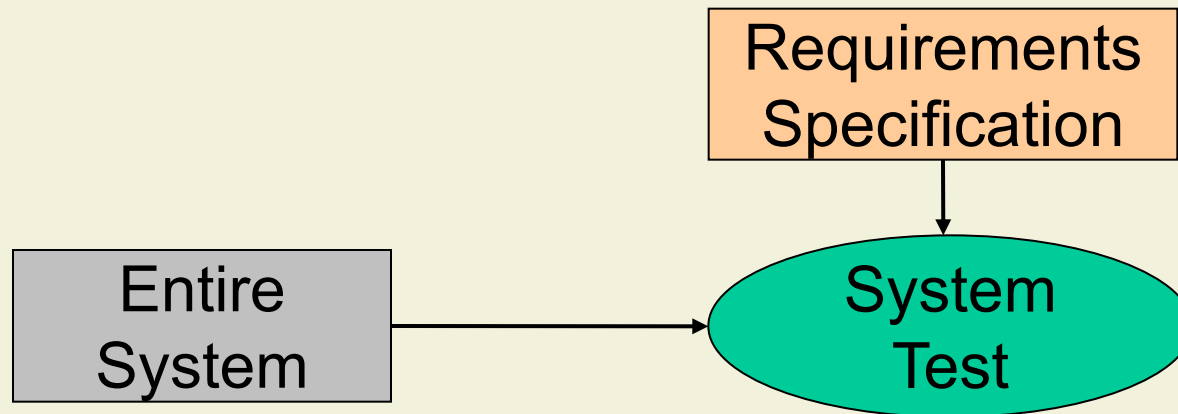
- The order in which the subsystems are selected for testing and integration
- Typical strategies
  - Big-bang integration (non-incremental)
  - Bottom-up integration
  - Top-down integration
- Selection criteria
  - Amount of test harness (stubs and drivers)
  - Scheduling concerns

Call hierarchy



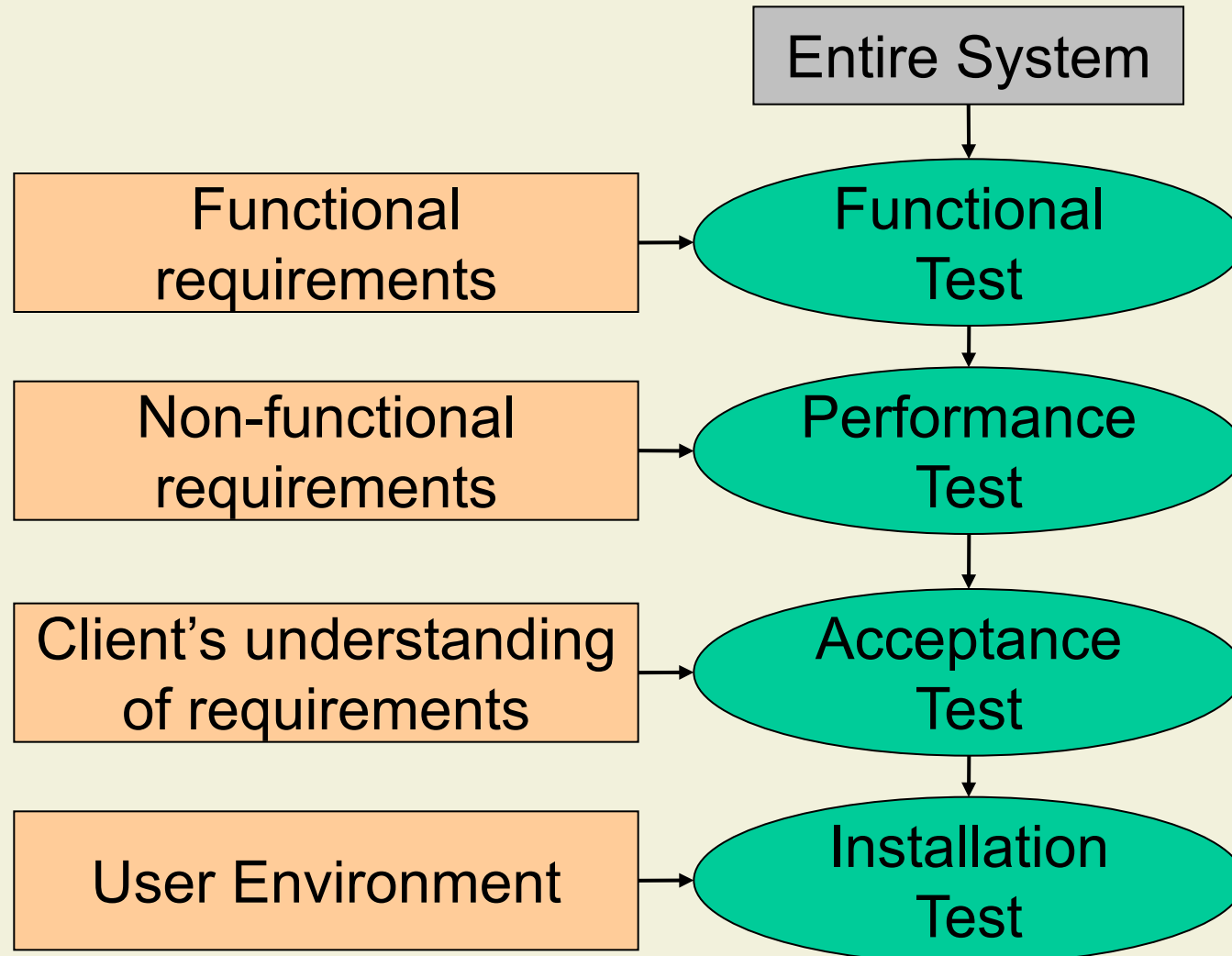
# System Testing

- 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 specification
  - Based on use cases
  - Alternative source: user manual
- Test cases describe
  - Input data
  - Flow of events
  - Results to check



# Acceptance Testing

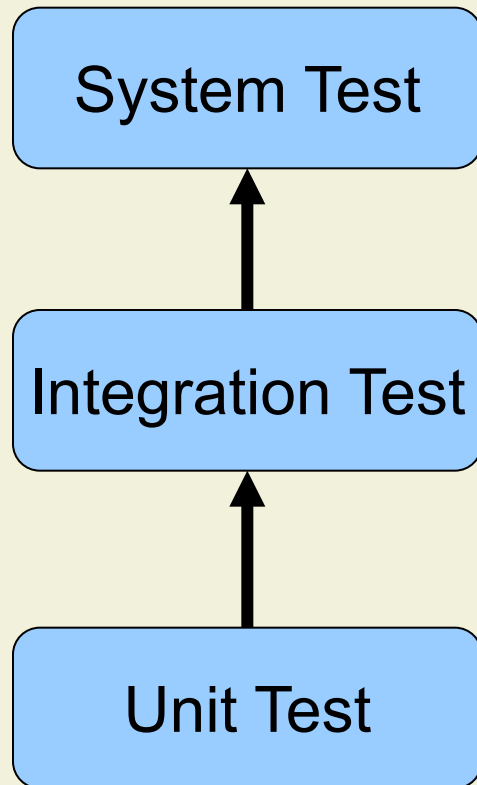
- Goal: Demonstrate that the system meets customer requirements and is ready to use
- Performed by the client, not by the developer
- Alpha test
  - Client uses the software at the developer's site
  - Software used in a controlled setting, with the developer ready to fix bugs
- Beta test
  - Conducted 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

# 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)

# 5. Testing

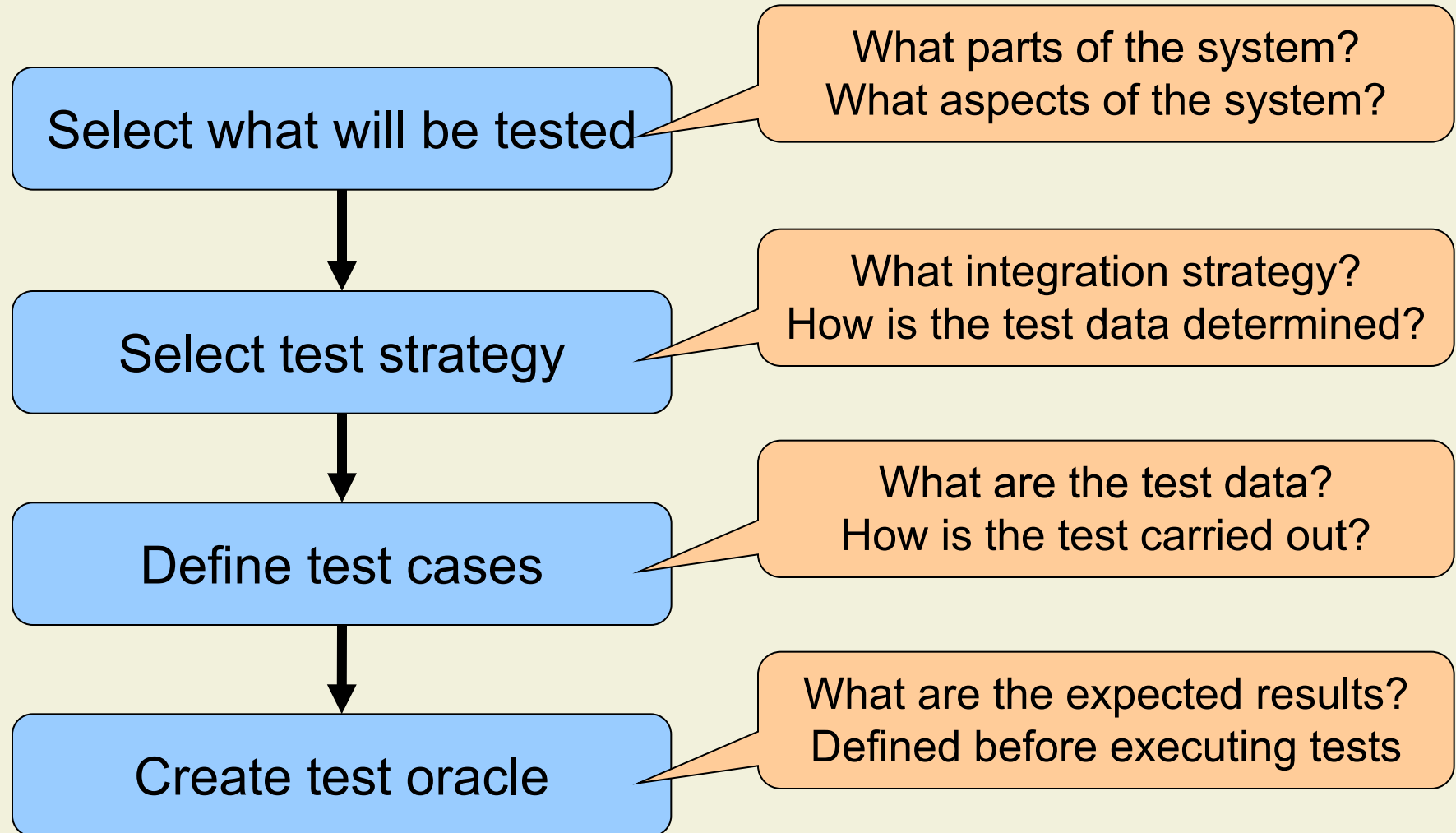
## 5.1 Test Stages

## 5.2 Test Strategies

## 5.3 Functional Testing

## 5.4 Structural Testing

# 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

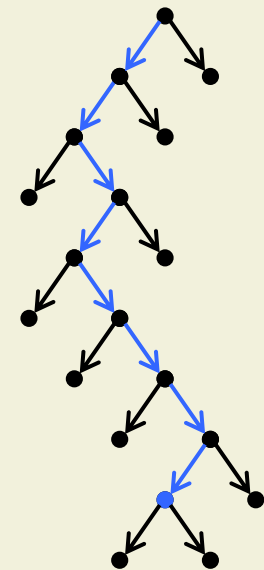
and this  
case

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

# 5. Testing

5.1 Test Stages

5.2 Test Strategies

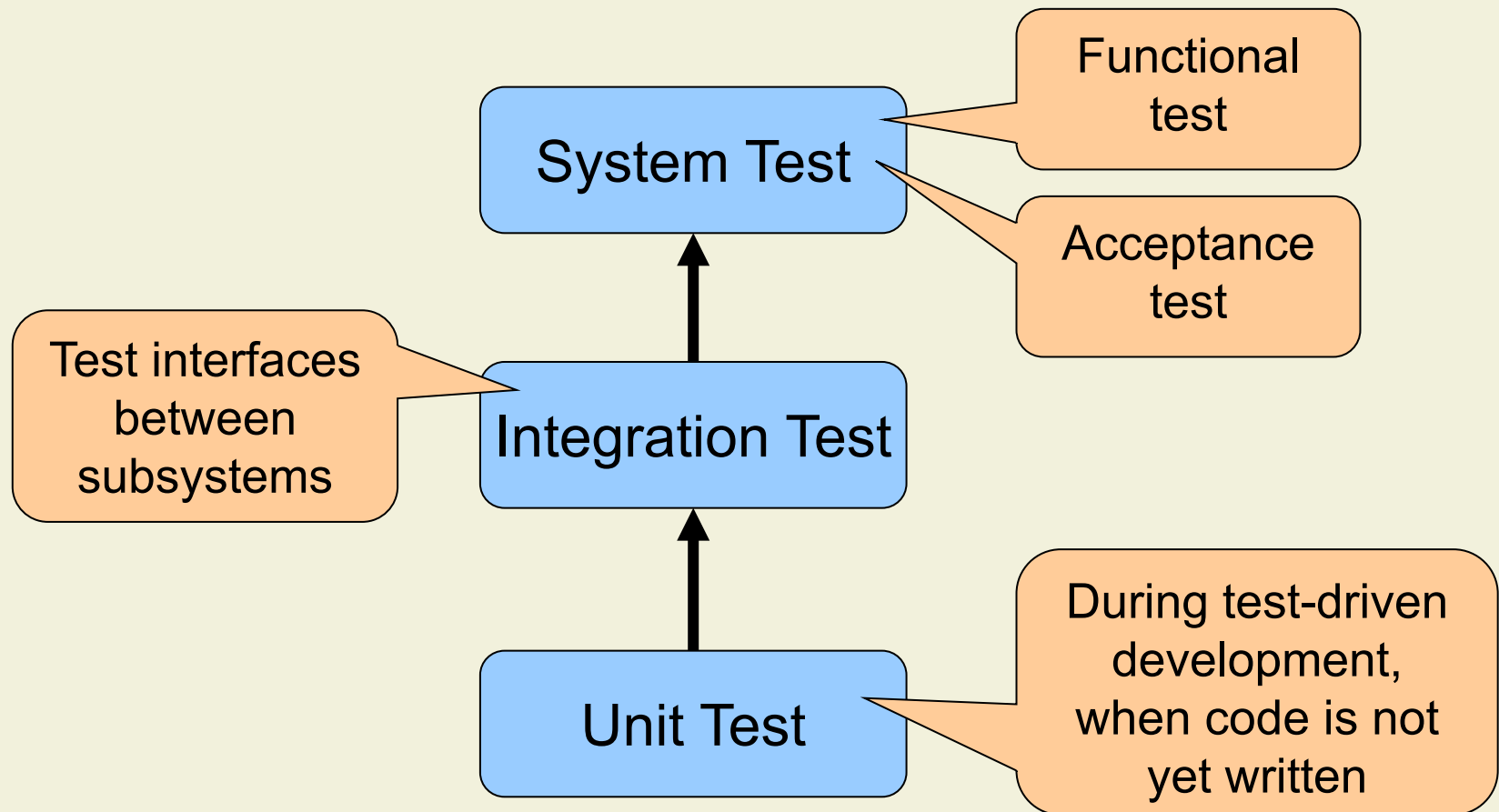
5.3 Functional Testing

5.4 Structural Testing



# Applications of Functional Testing

- Black-box test a unit against its requirements



# 5. Testing

## 5.1 Test Stages

## 5.2 Test Strategies

## 5.3 Functional Testing

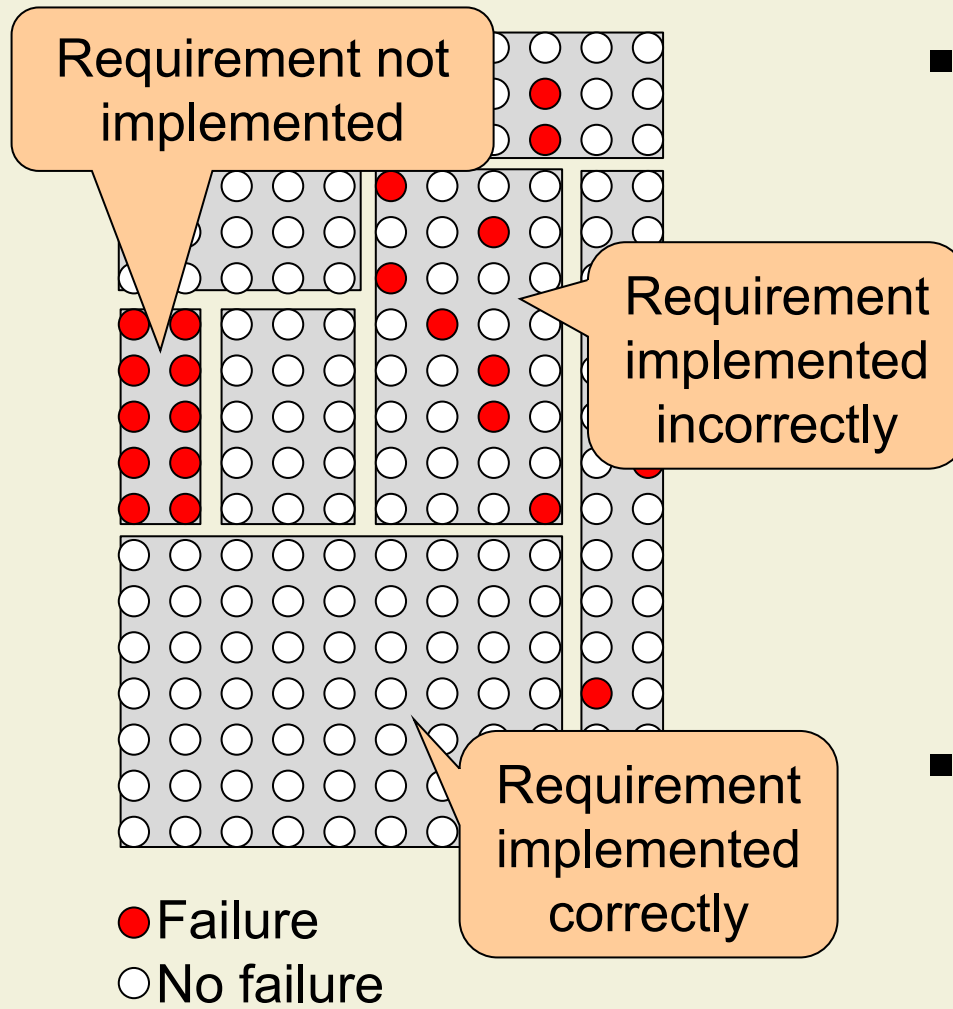
### 5.3.1 Partition Testing

### 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 $\in \{1, 3, 5, 7, 8, 10, 12\}$

year	
Leap years	(year <b>mod</b> 4 = 0 and year <b>mod</b> 100 $\neq$ 0) or year <b>mod</b> 400 = 0
Non-leap years	year <b>mod</b> 4 $\neq$ 0 or (year <b>mod</b> 100 = 0 and year <b>mod</b> 400 $\neq$ 0)

Invalid inputs missing

# 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 <b>mod</b> 4 = 0 and year <b>mod</b> 100 $\neq$ 0) or year <b>mod</b> 400 = 0
Non-leap years	year <b>mod</b> 4 $\neq$ 0 or (year <b>mod</b> 100 = 0 and year <b>mod</b> 400 $\neq$ 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 $\in \{4, 6, 9, 11\}$
Months with 31 days	month $\in \{1, 3, 5, 7, 8, 10, 12\}$
Invalid	month < 1 or month > 12

year	
Standard leap years	year <b>mod</b> 4 = 0 and year <b>mod</b> 100 $\neq$ 0
Standard non-leap years	year <b>mod</b> 4 $\neq$ 0
Special leap years	year <b>mod</b> 400 = 0
Special non-leap years	year <b>mod</b> 100 = 0 and year <b>mod</b> 400 $\neq$ 0

# 5. Testing

## 5.1 Test Stages

## 5.2 Test Strategies

## 5.3 Functional Testing

### 5.3.1 Partition Testing

### 5.3.2 Selecting Representative Values

### 5.3.3 Combinatorial Testing

## 5.4 Structural Testing

# 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  
 $x == \text{Integer.MIN\_VALUE}$

- 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 <b>mod</b> 4 = 0 and year <b>mod</b> 100 $\neq$ 0
Standard non-leap years	year <b>mod</b> 4 $\neq$ 0
Special leap years	year <b>mod</b> 400 = 0
Special non-leap years	year <b>mod</b> 100 = 0 and year <b>mod</b> 400 $\neq$ 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

[ 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 );

}

Expected result:  
an exception

All selected  
invalid values  
for month

All selected  
values for year

# 5. Testing

## 5.1 Test Stages

## 5.2 Test Strategies

## 5.3 Functional Testing

### 5.3.1 Partition Testing

### 5.3.2 Selecting Representative Values

### 5.3.3 Combinatorial Testing

## 5.4 Structural Testing

# 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 ( $12 \times 17 = 204$  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 $\in \{4, 6, 9, 11\}$
Months with 31 days	month $\in \{1, 3, 5, 7, 8, 10, 12\}$
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  $ax^2 + bx + c = 0$

	<b>a</b>	<b>b</b>	<b>c</b>
Valid	any value	any value	any value
Invalid	infinity, NaN	infinity, NaN	infinity, NaN

Boundary testing:  
 $a, b, c \in$   
 $\{ \text{Double.MIN\_VALUE}, -5, 0, 5, \text{Double.MAX\_VALUE} \}$

- $5^3 = 125$  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 $b^2 - 4ac > 0$	$a \neq 0$ and $b^2 - 4ac = 0$	$a \neq 0$ and $b^2 - 4ac < 0$

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 $b^2 - 4ac > 0$	$a \neq 0$ and $b^2 - 4ac = 0$	$a \neq 0$ and $b^2 - 4ac < 0$
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

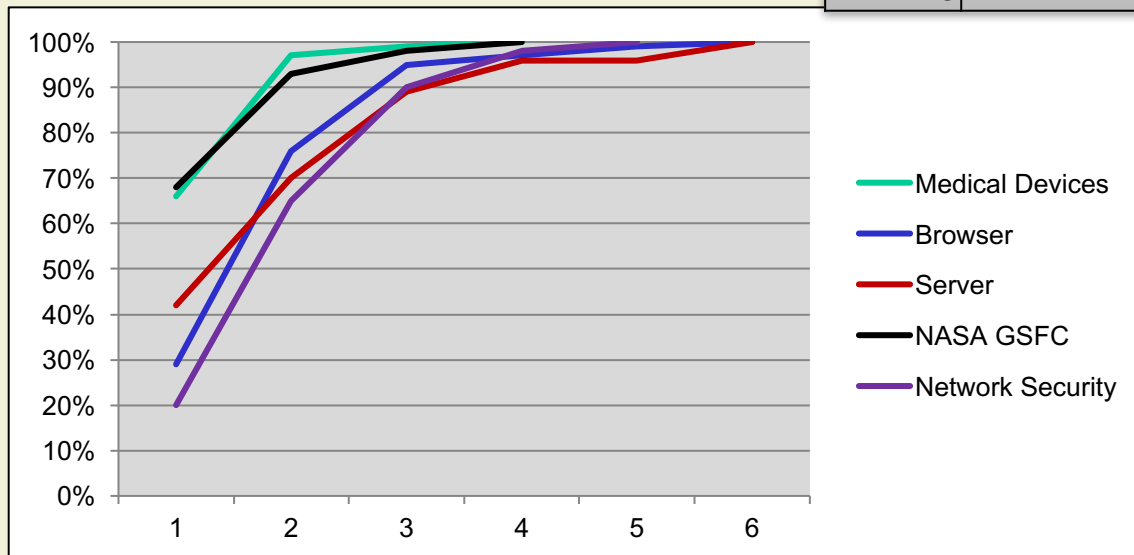
- Semantic constraints potentially reduce the number of test cases
  - They also help increasing the coverage
  
- But too many combinations remain
  - Especially when there are many input values, for instance, for the fields of objects



# 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

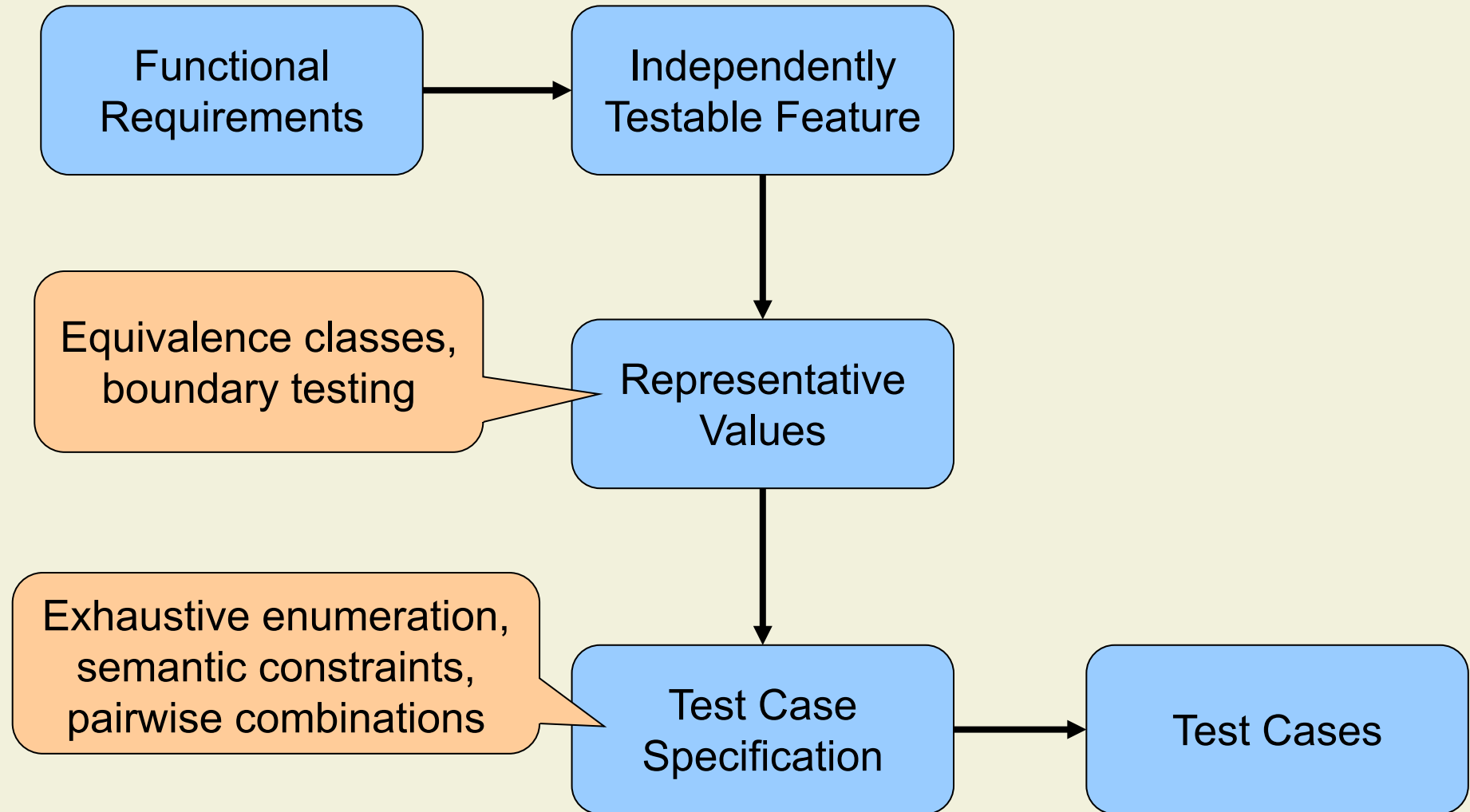
Two solutions	One solution	No solution
	$a = 0$ and $b \neq 0$	$a = 0$ , $b = 0$ , and $c \neq 0$
$a \neq 0$ and $b^2 - 4ac > 0$	$a \neq 0$ and $b^2 - 4ac = 0$	$a \neq 0$ and $b^2 - 4ac < 0$
$a = 0$ , $b = 0$ , $c = 0$		

- 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  
    int i;  
    for( 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

	<b>a</b>
Valid	any non-null array
Invalid	<b>null</b>

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

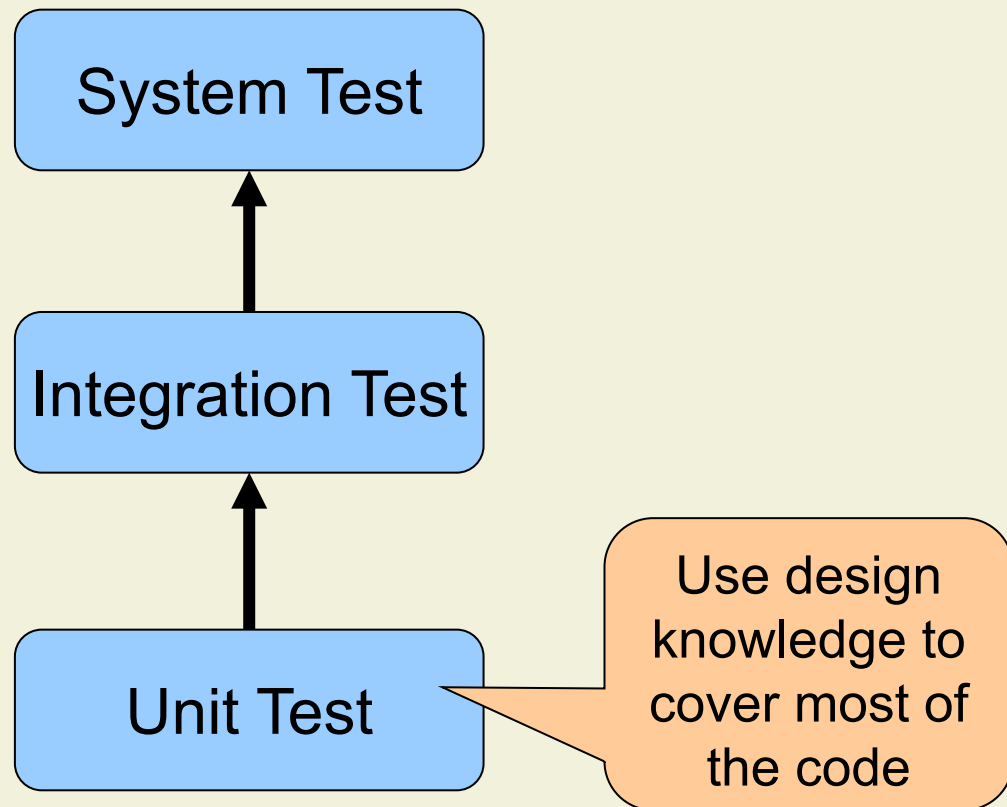
- The requirements give no clue that one should test with an array that is sorted in descending order

# 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

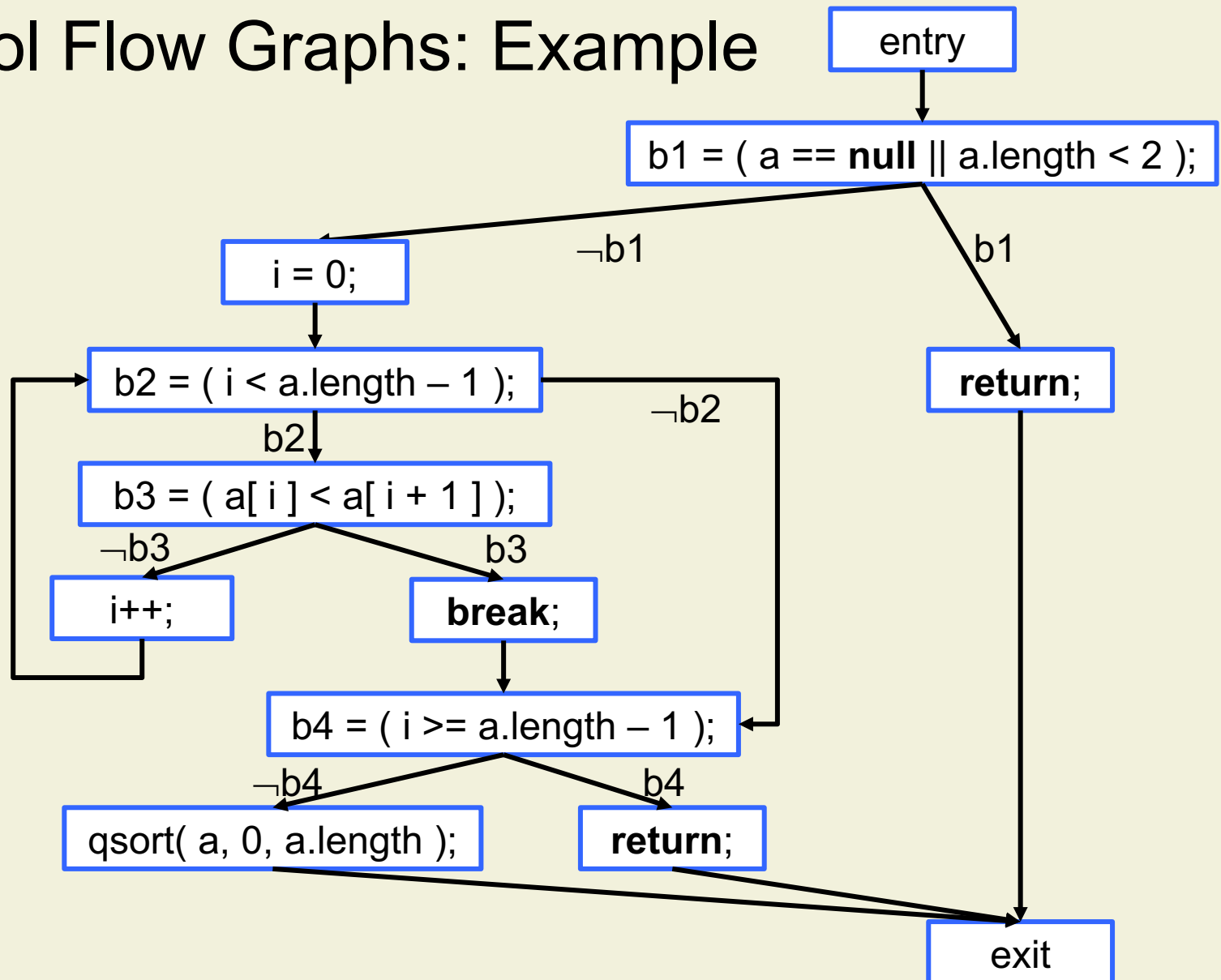
# Basic Blocks: Example

```
public void sort( int[ ] a ) {  
    if( a == null || a.length < 2 )  
        return;  
    int i;  
    for( 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 execution of basic block  $b$  if condition  $c$  holds
    - an edge  $(\text{entry}, a, \text{true})$  if  $a$  is the first basic block of  $p$
    - edges  $(b, \text{exit}, \text{true})$  for each basic block  $b$  that ends with a (possibly implicit) return statement

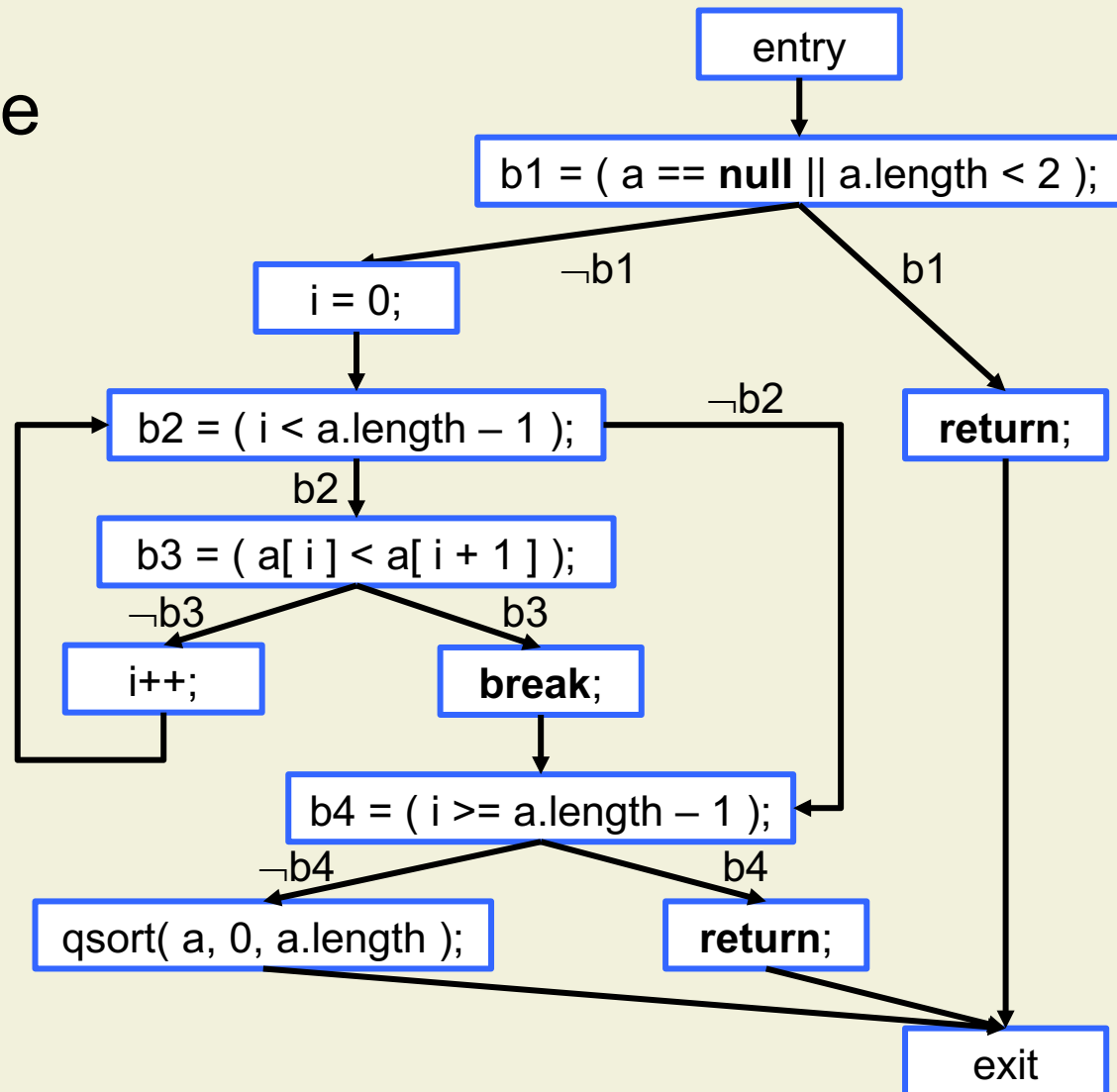
# Control Flow Graphs: Example





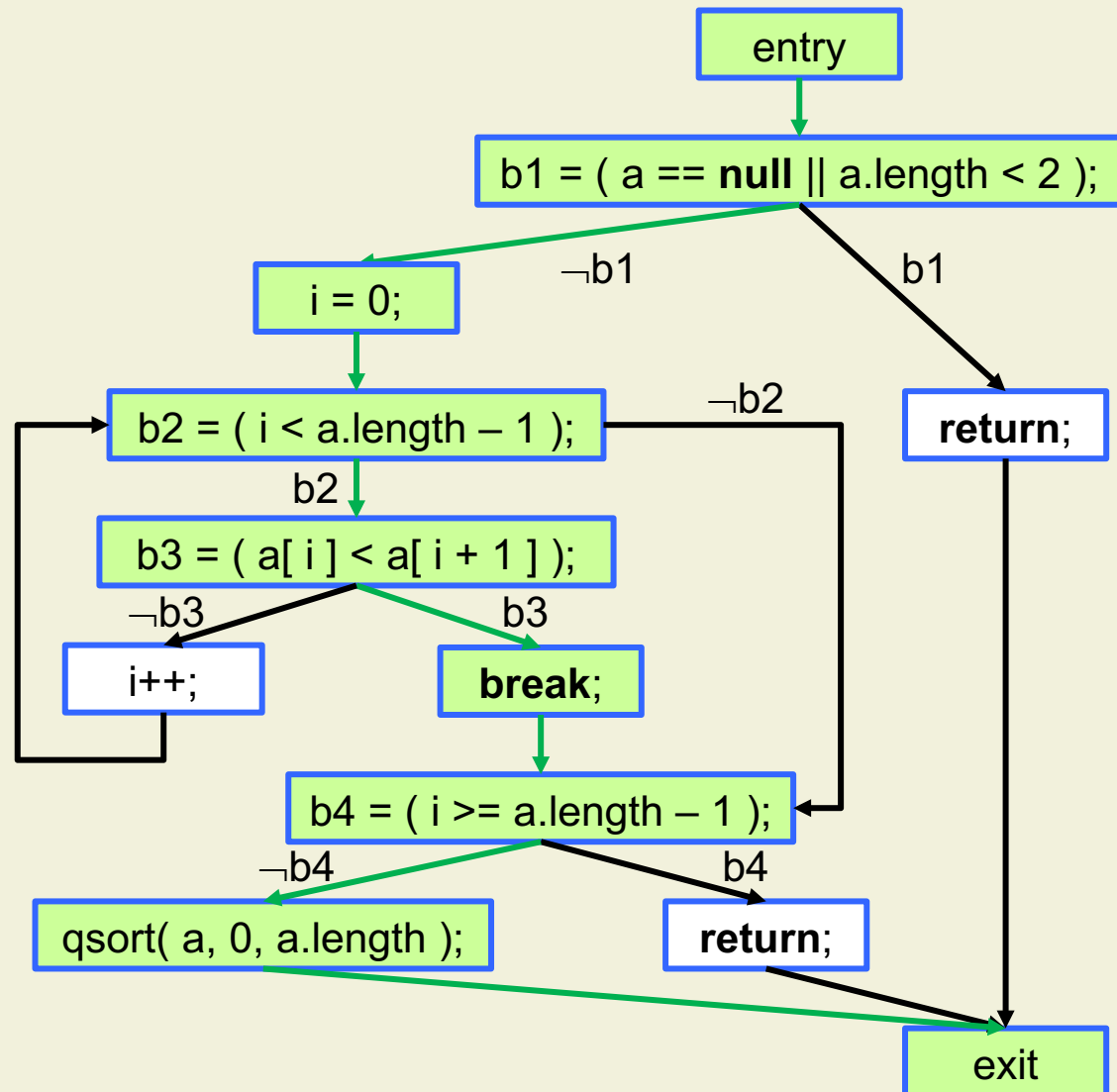
# Test Coverage

- 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

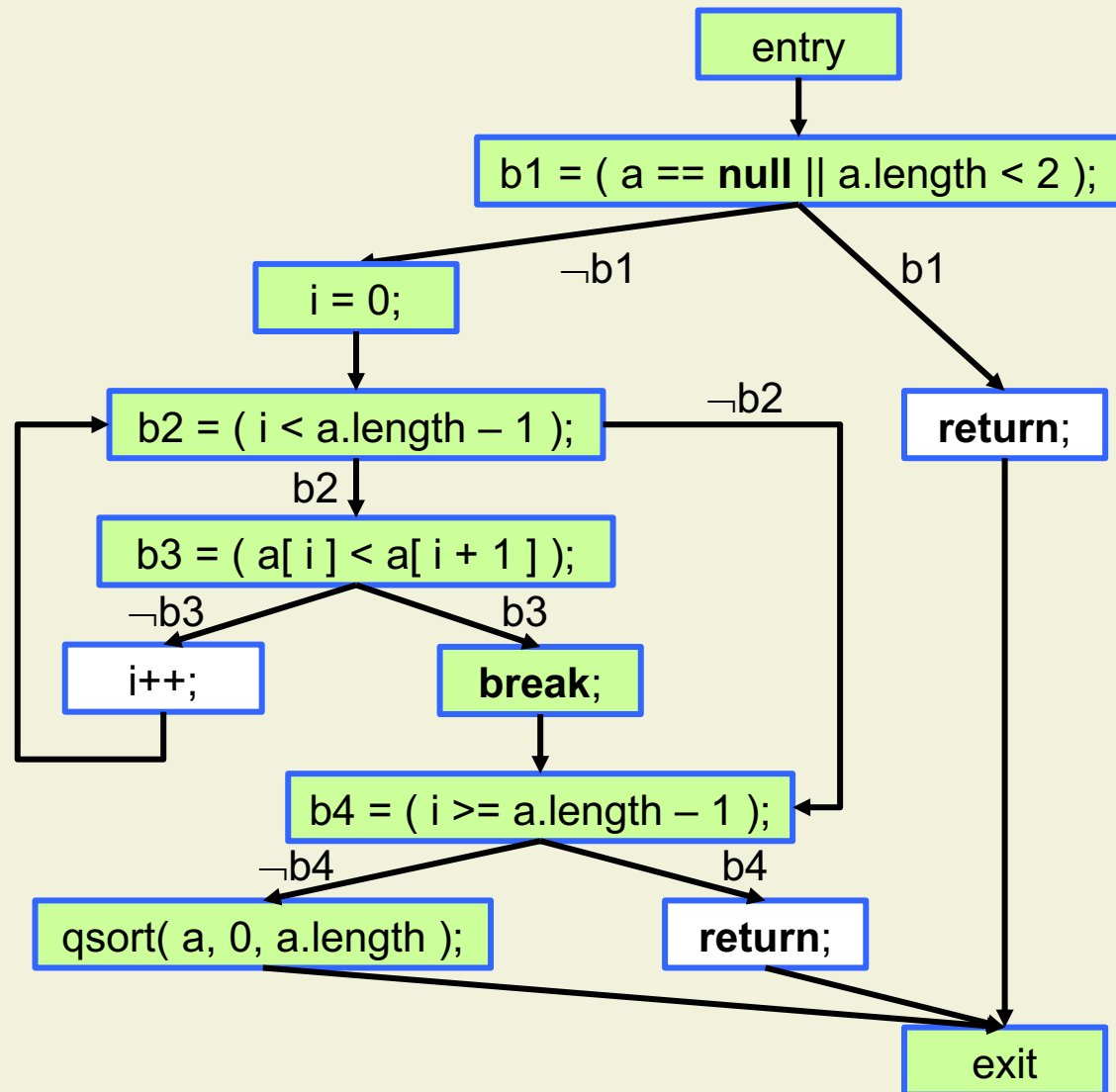
- Assess the quality of a test suite by measuring how much of the CFG it executes
- Idea: one can detect a bug in a statement only by executing the statement

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

- 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%

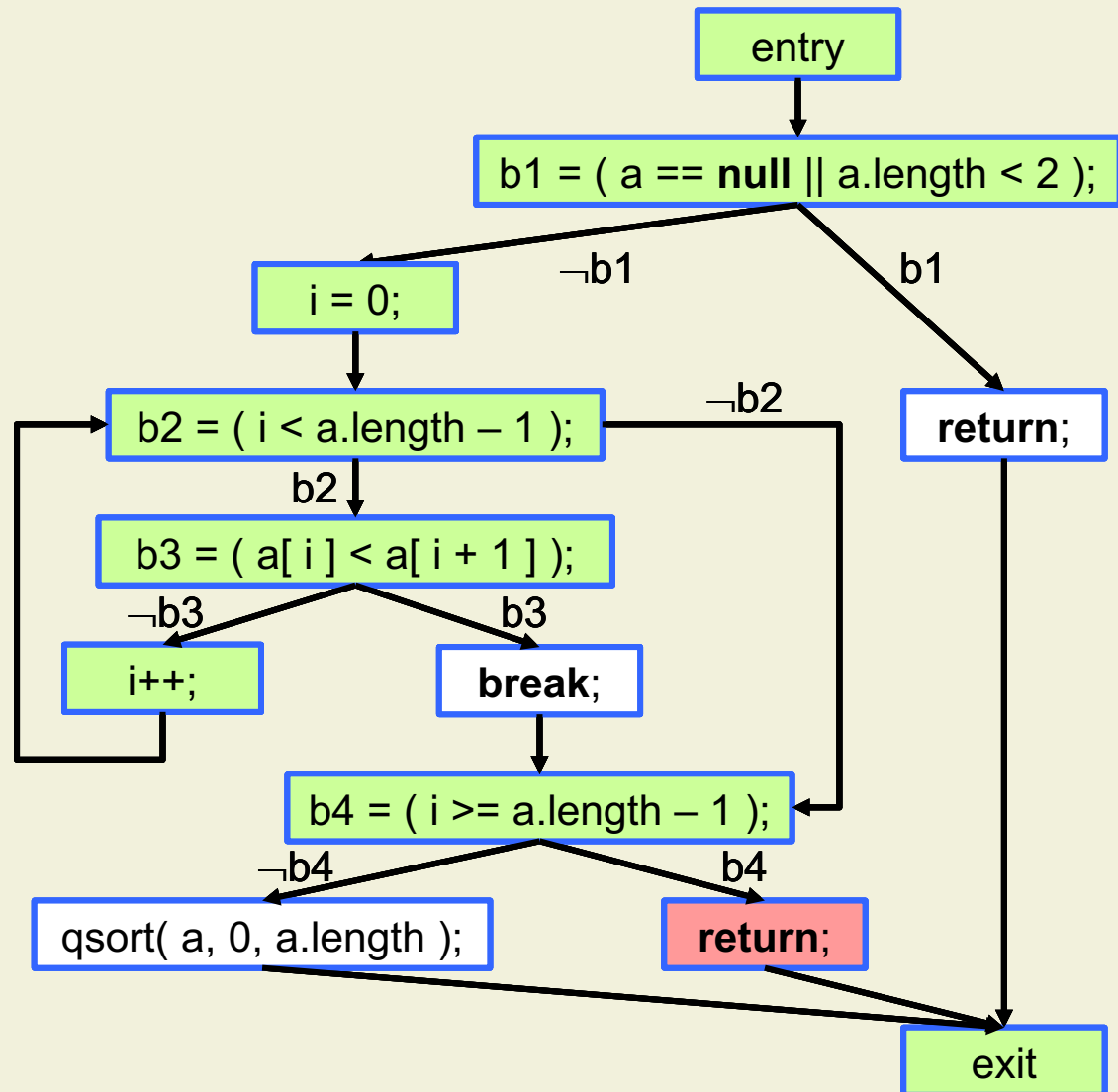


# Statement Coverage: Example (cont'd)

- We can achieve 100% statement coverage with three test cases

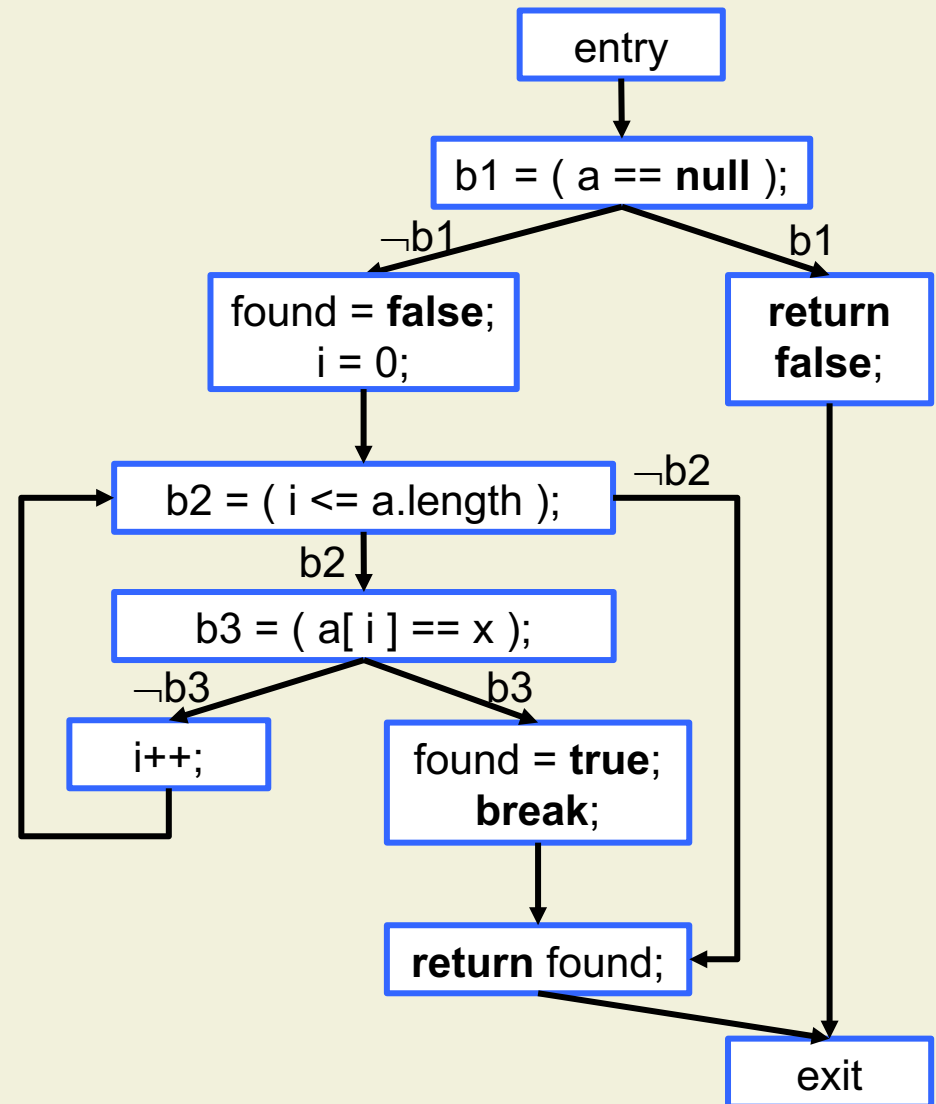
- $a = \{ 1 \}$
- $a = \{ 5, 7 \}$
- $a = \{ 7, 5 \}$

- The last test case detects the bug



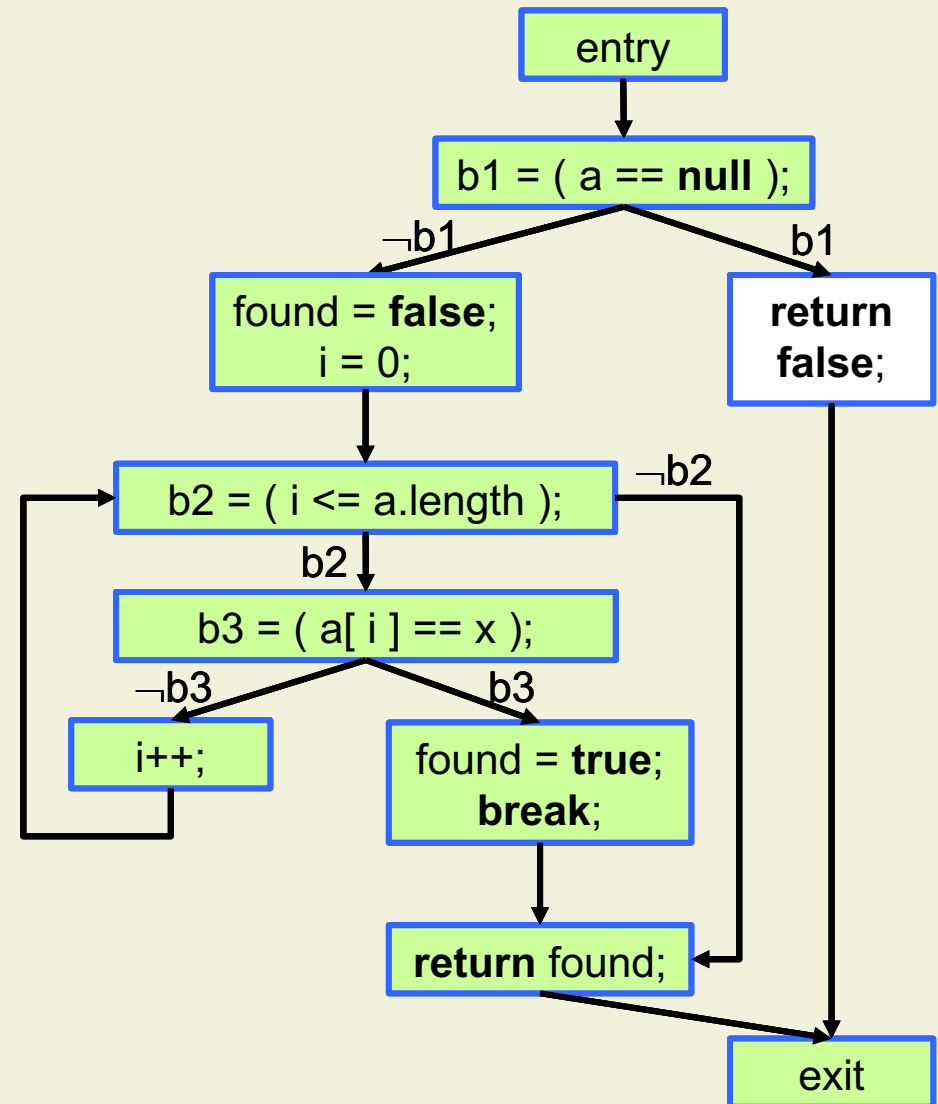
# Statement Coverage: Discussion

```
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  $n \neq n'$

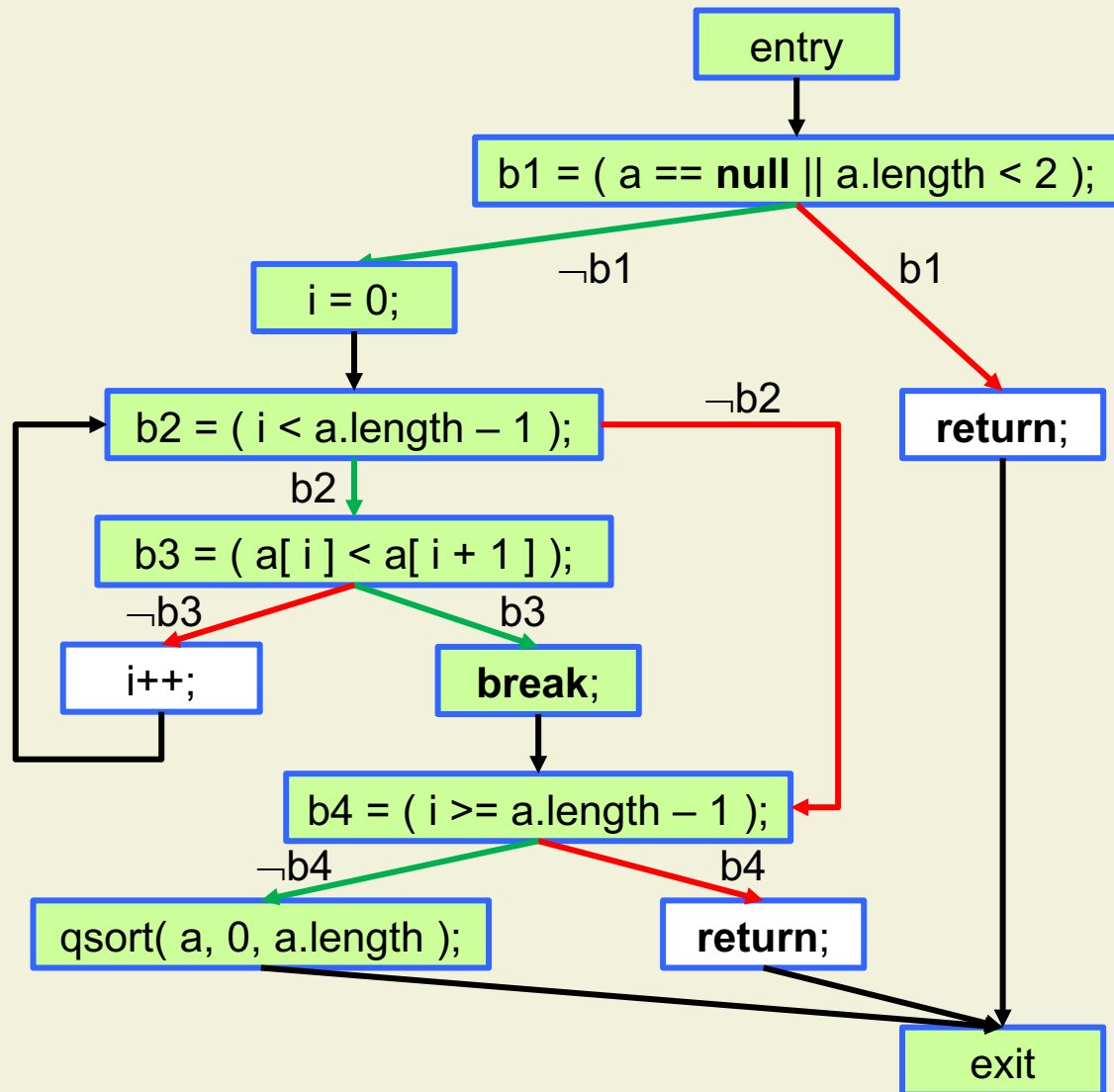
$$\text{Branch Coverage} = \frac{\text{Number of executed branches}}{\text{Total number of branches}}$$

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



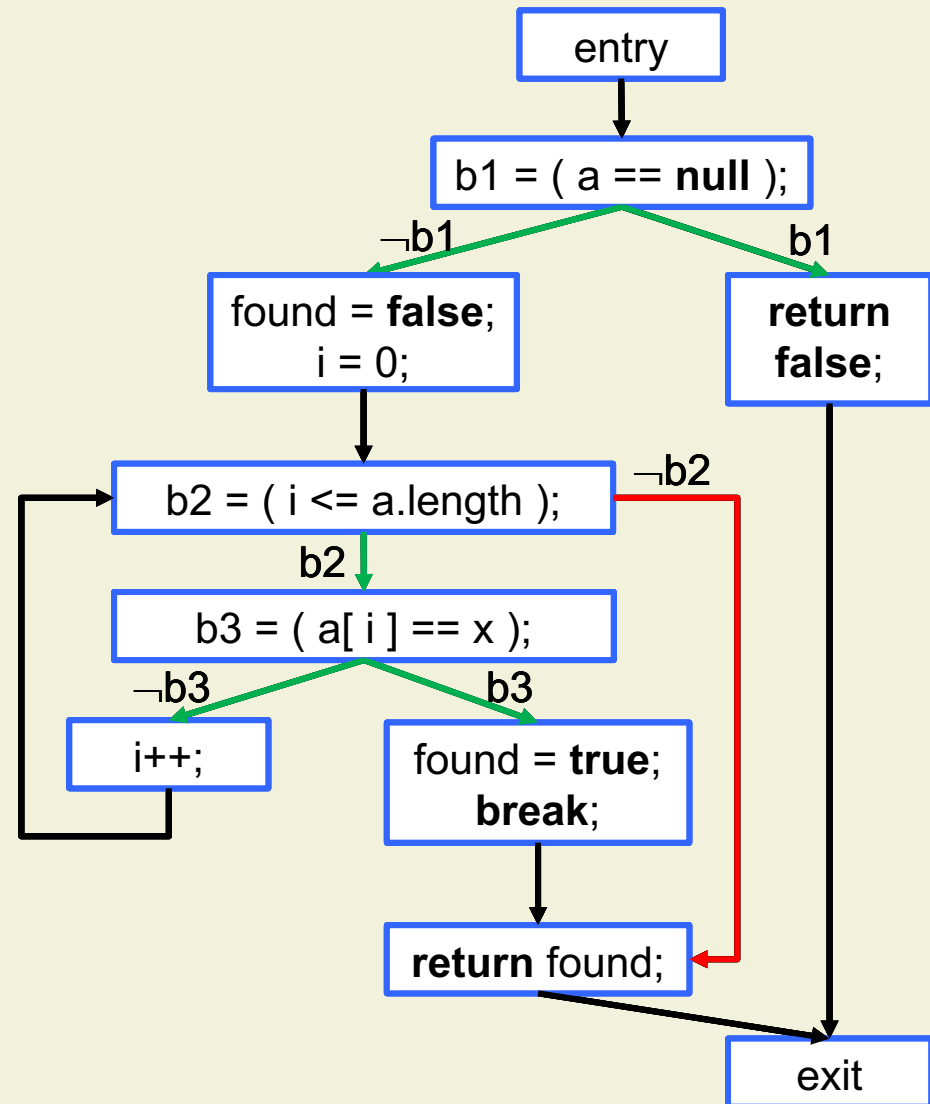
# Branch Coverage: Example 1

- 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



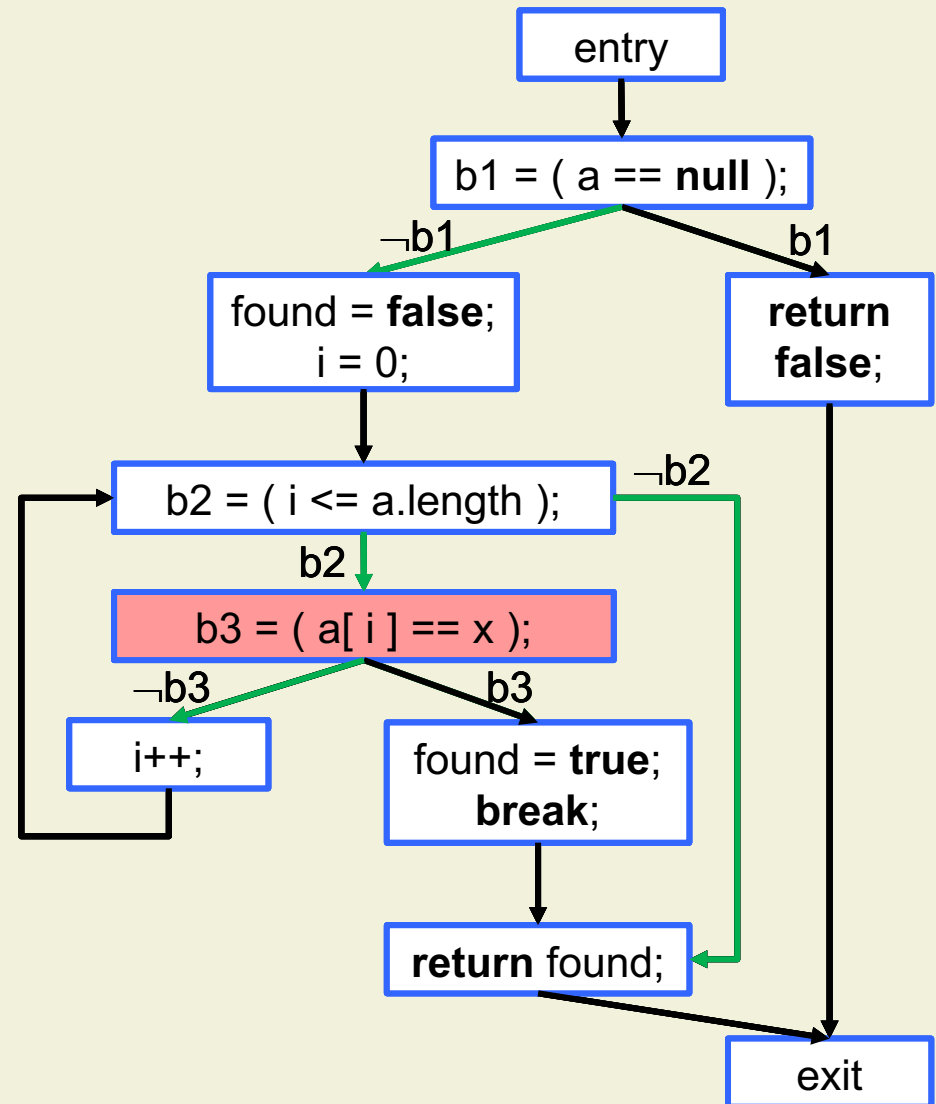
## Branch Coverage: Example 2

- 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

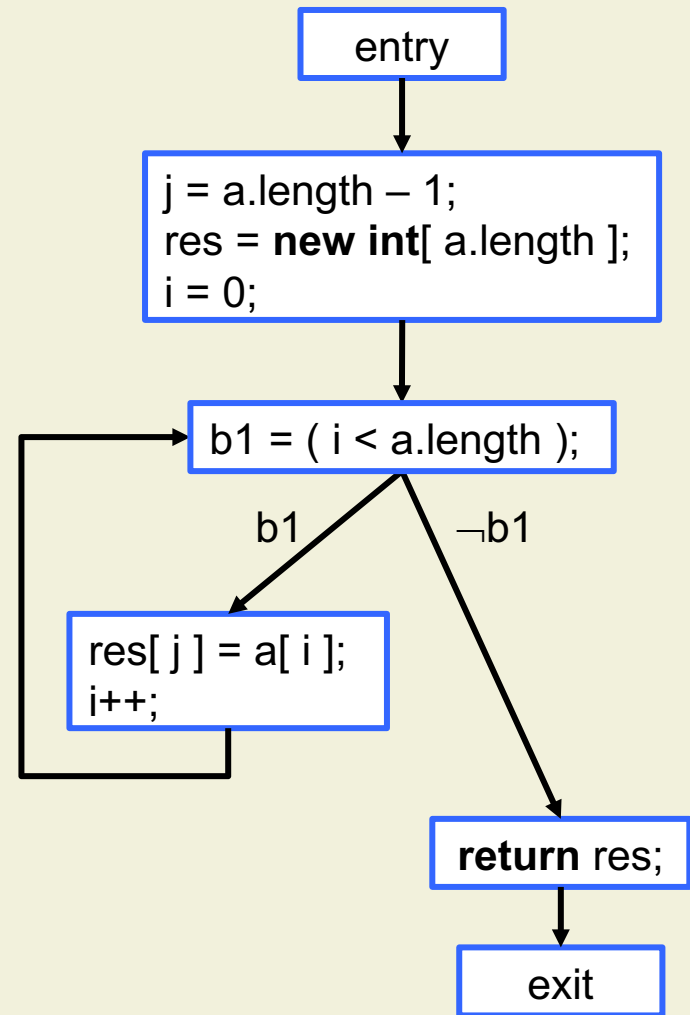


# Branch Coverage: Discussion

- 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

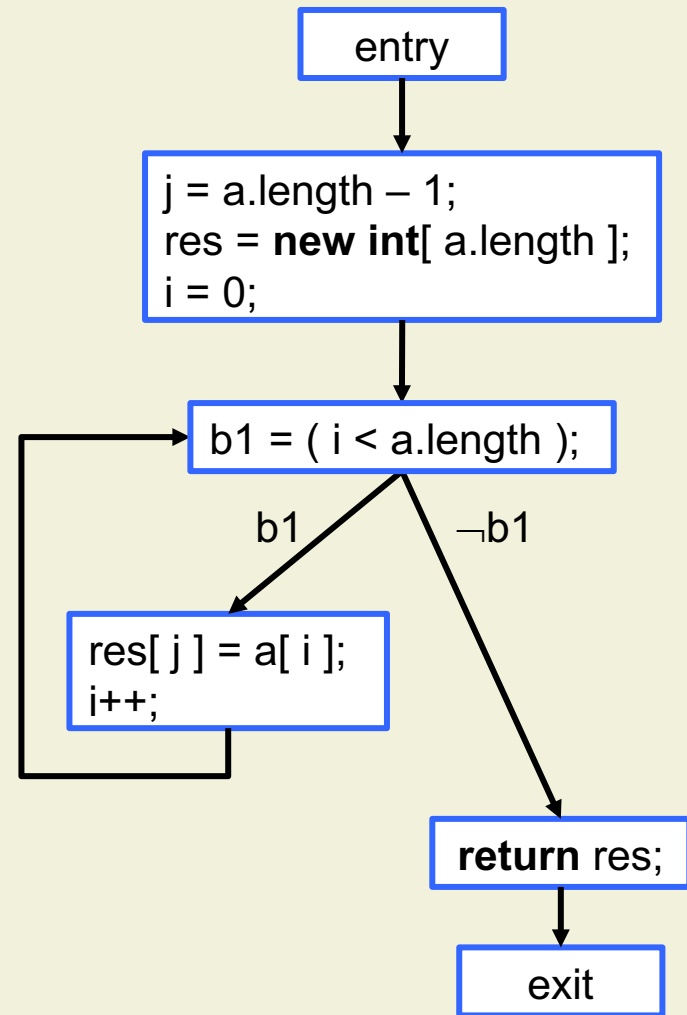
# Branch Coverage: Discussion (cont'd)

```
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;  
}
```



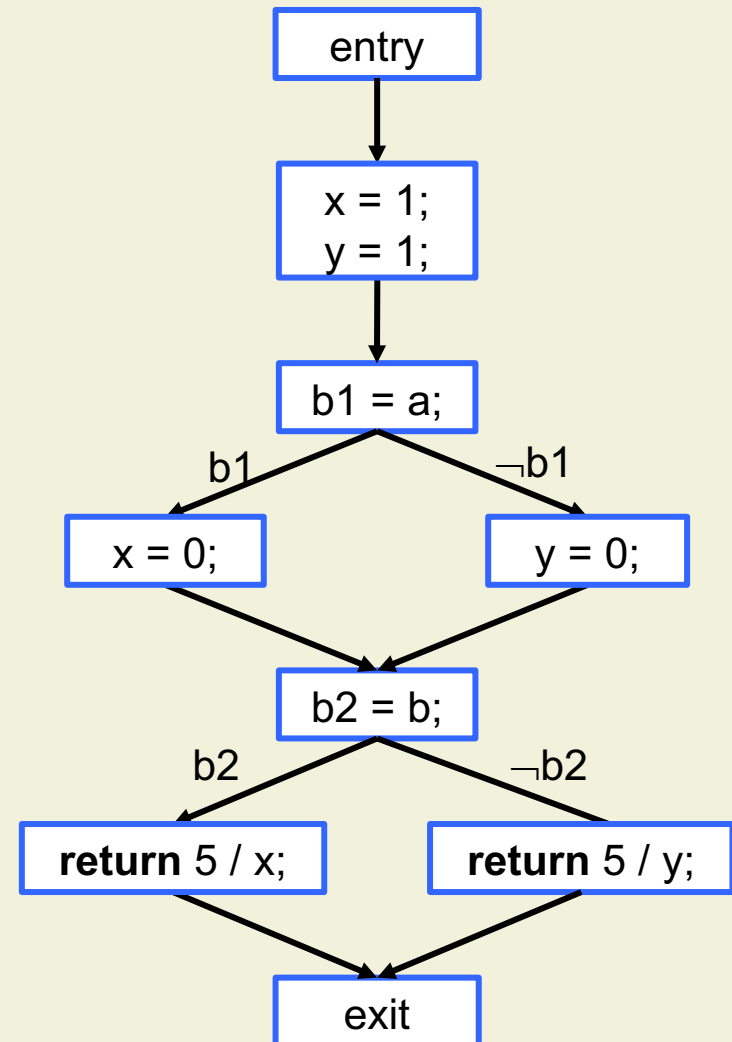
# Branch Coverage: Discussion (cont'd)

- 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



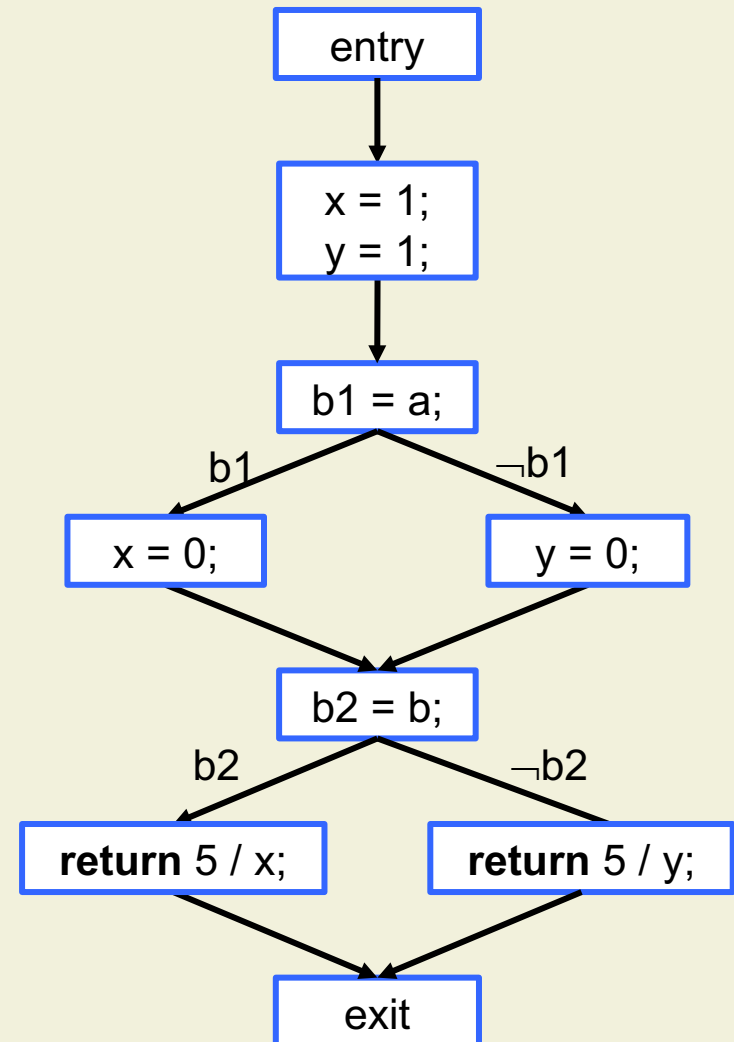
# Branch Coverage: Discussion (cont'd)

```
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
  - $a = \mathbf{true}$ ,  $b = \mathbf{false}$
  - $a = \mathbf{false}$ ,  $b = \mathbf{true}$
- The test cases do not detect the bug!
- More thorough testing is necessary





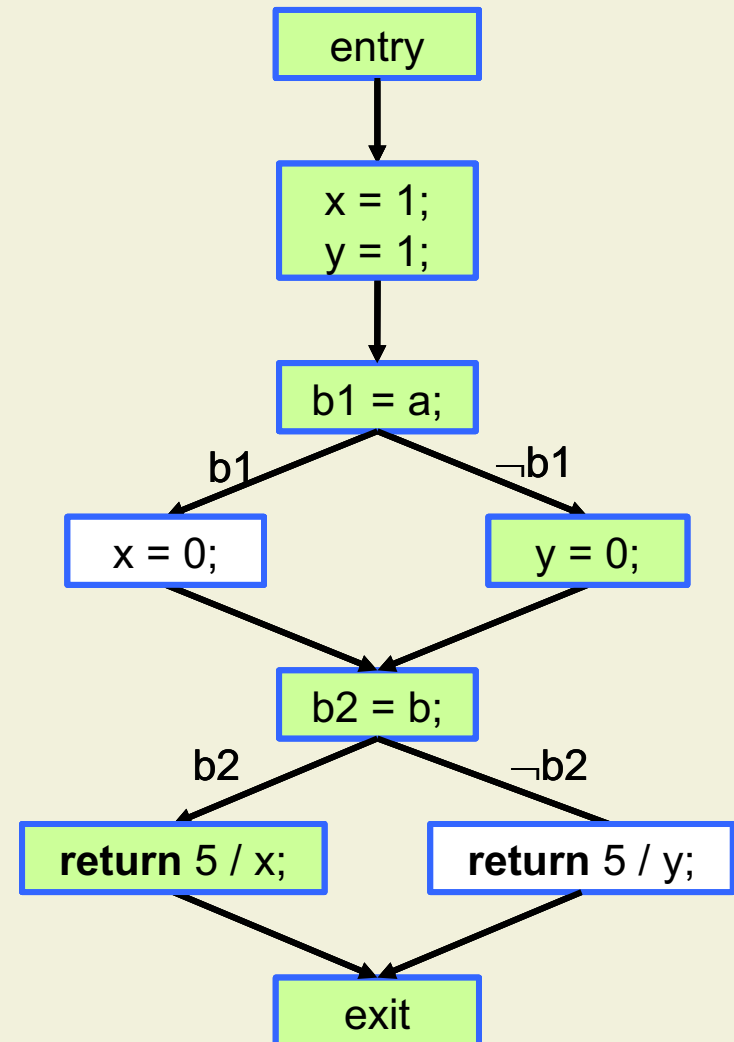
# Path Coverage

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

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

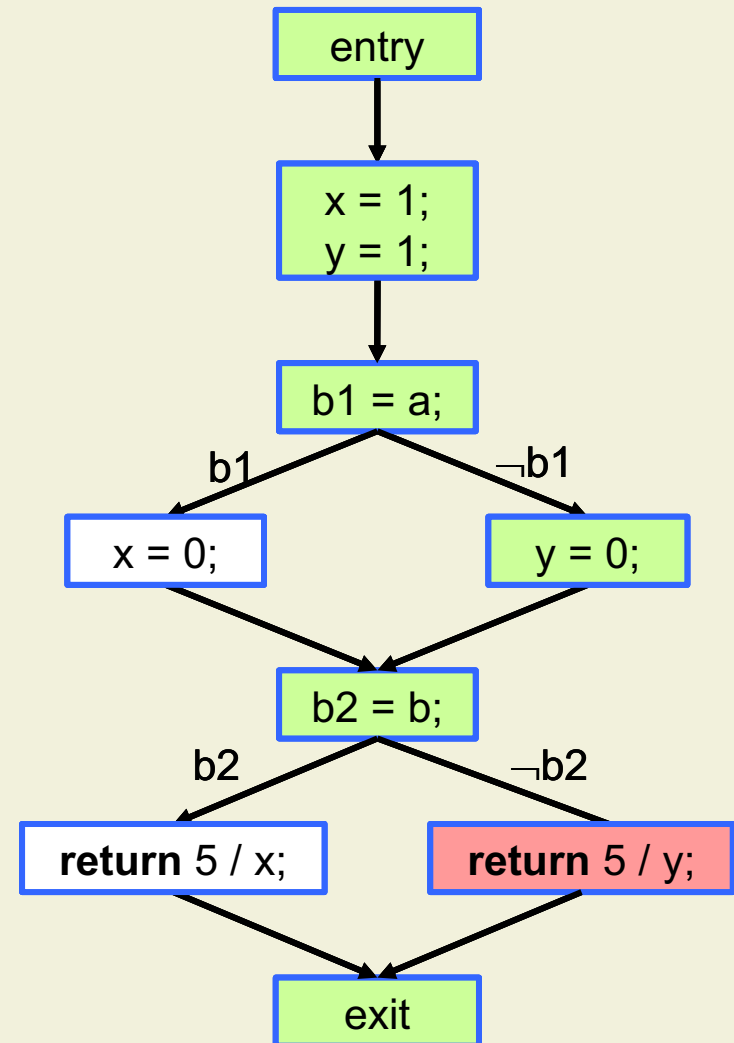
# Path Coverage: Example 1

- The two test cases
  - **a = true, b = false**
  - **a = false, b = true**execute two out of four paths
- Path coverage: 50%



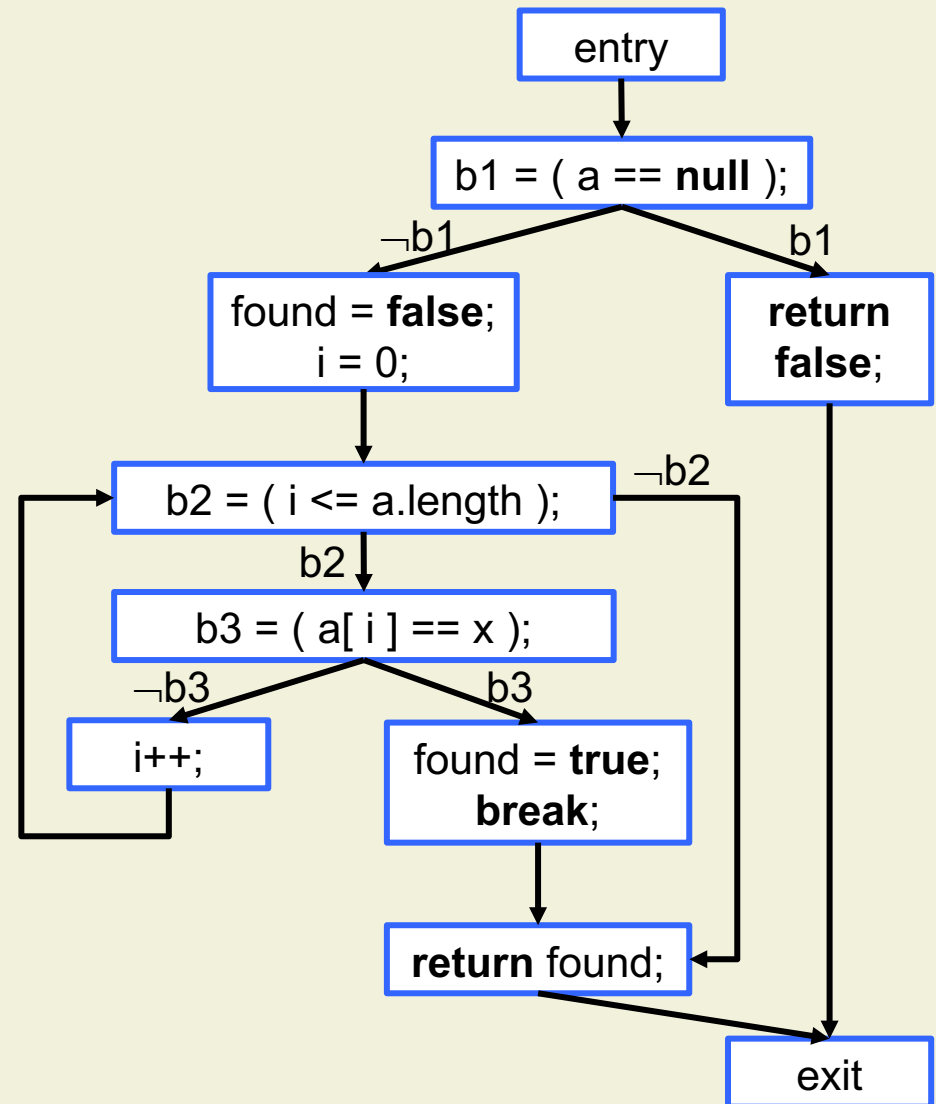
# Path Coverage: Example 1 (cont'd)

- We can achieve 100% path coverage with four test cases
  - $a = \mathbf{true}$ ,  $b = \mathbf{false}$
  - $a = \mathbf{false}$ ,  $b = \mathbf{true}$
  - $a = \mathbf{true}$ ,  $b = \mathbf{true}$
  - $a = \mathbf{false}$ ,  $b = \mathbf{false}$
- The two additional test cases detect the bugs



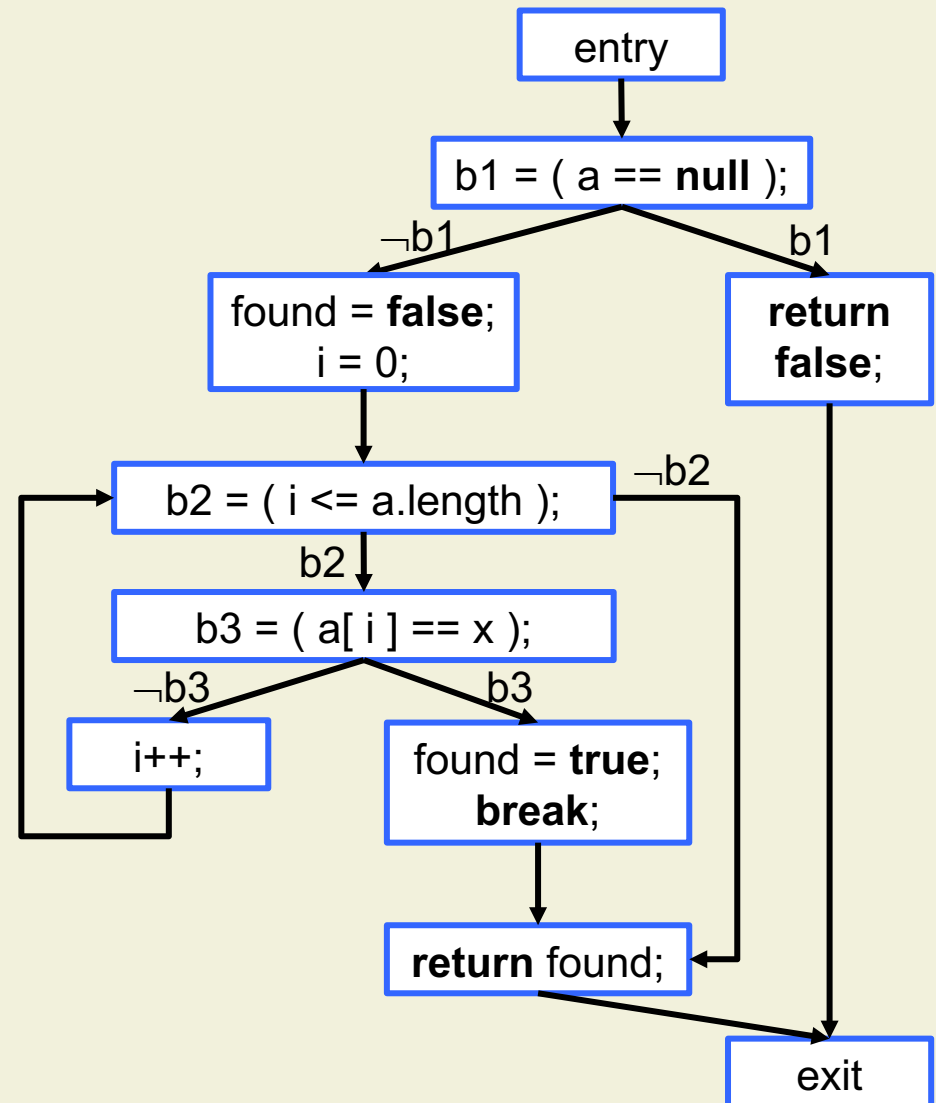
# Path Coverage: Example 2

```
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 (depends on input)
- An arbitrarily large number of test cases is needed for complete path coverage

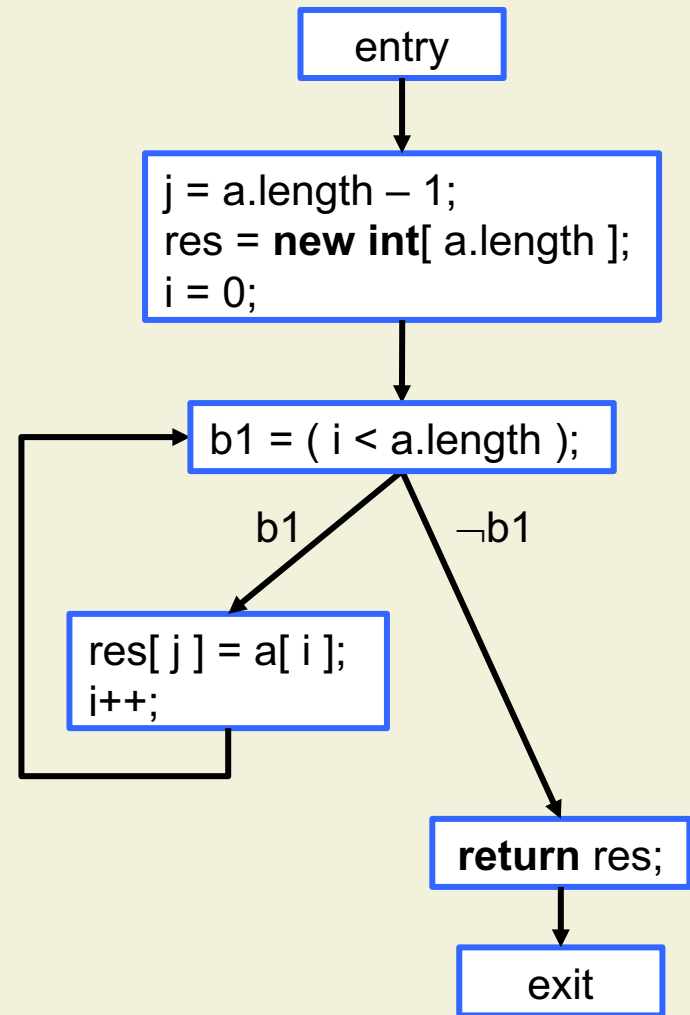


# Path Coverage: Discussion

- 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 (consecutive) iterations

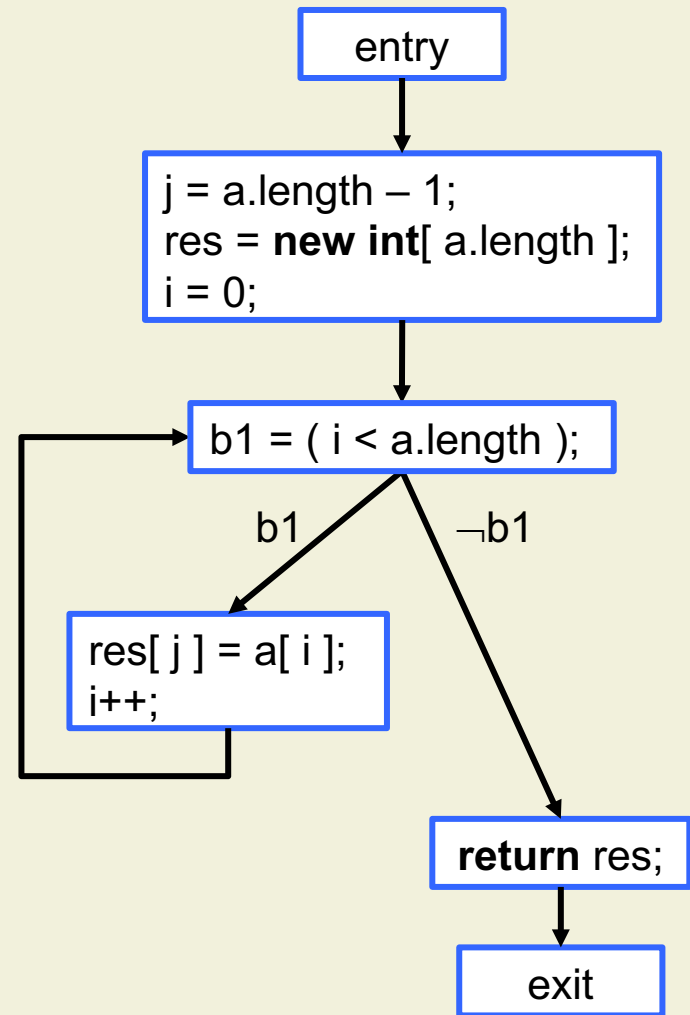
$$\text{Loop Coverage} = \frac{\text{Number of executed loops with 0, 1, and more than 1 iterations}}{\text{Total number of loops} * 3}$$

- 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%

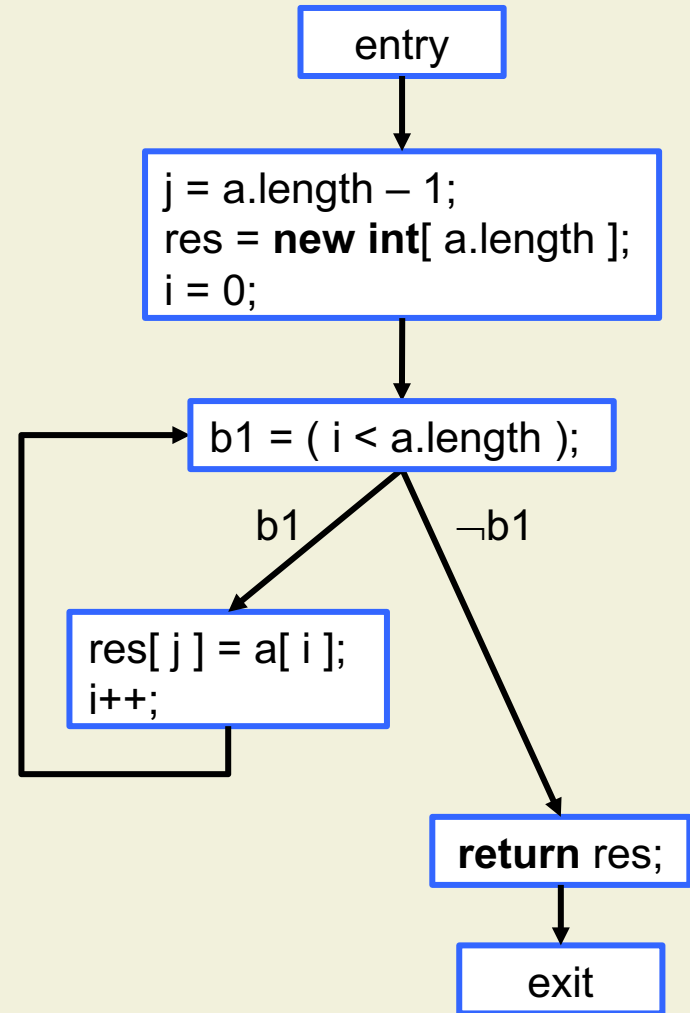


# Loop Coverage: Example

- 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 ) {  
        branchCovered[ 0 ] = true; x = 0;  
    } else {  
        branchCovered[ 1 ] = true; y = 0;  
    }  
    if( b ) {  
        branchCovered[ 2 ] = true;  
        return 5 / x;  
    } else {  
        branchCovered[ 3 ] = true;  
        return 5 / y;  
    }  
}
```

# 5. Testing

## 5.1 Test Stages

## 5.2 Test Strategies

## 5.3 Functional Testing

## 5.4 Structural Testing

### 5.4.1 Control Flow Testing

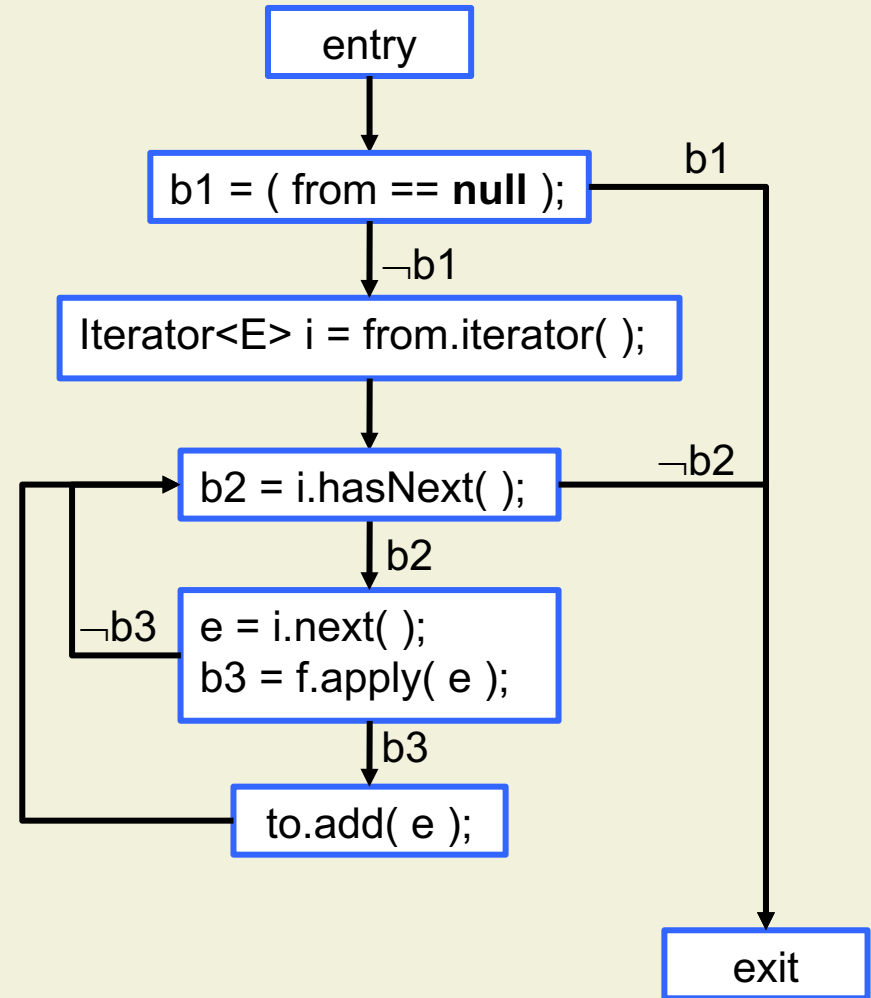
### 5.4.2 Advanced Topics of Control Flow Testing

### 5.4.3 Data Flow Testing

### 5.4.4 Interpreting Coverage

# 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 );  
    }  
}
```



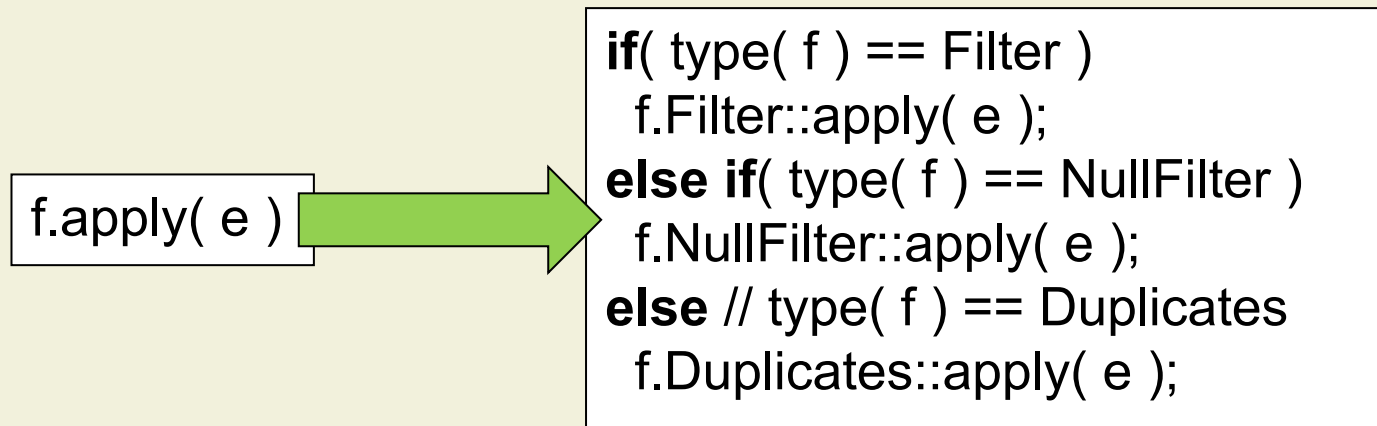
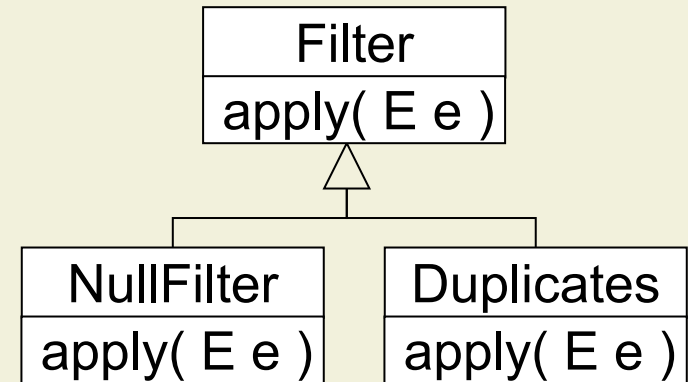
# Dynamically-Bound Method Calls

```
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



- 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

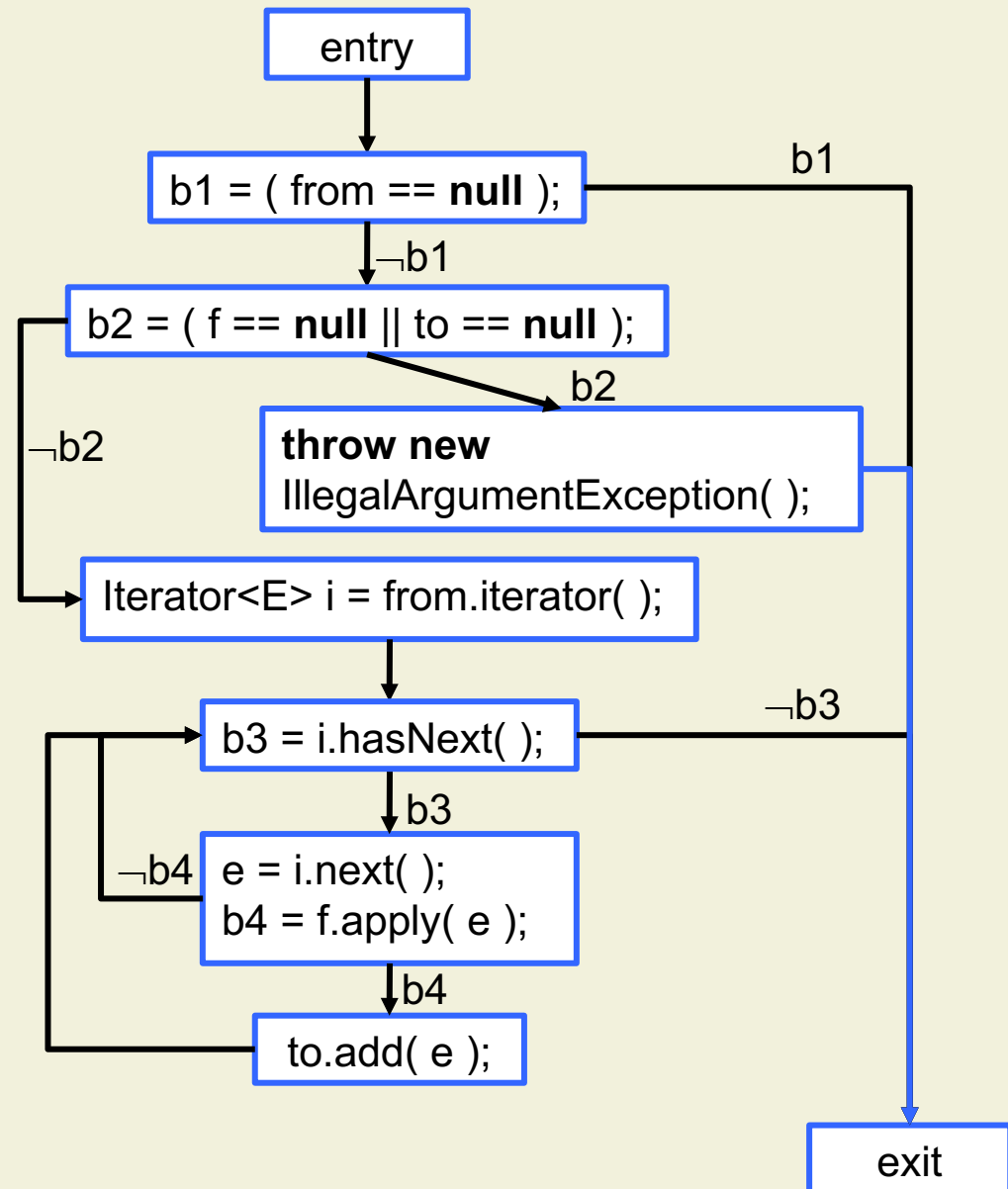


# Exceptions

```

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 );  
    }  
}
```

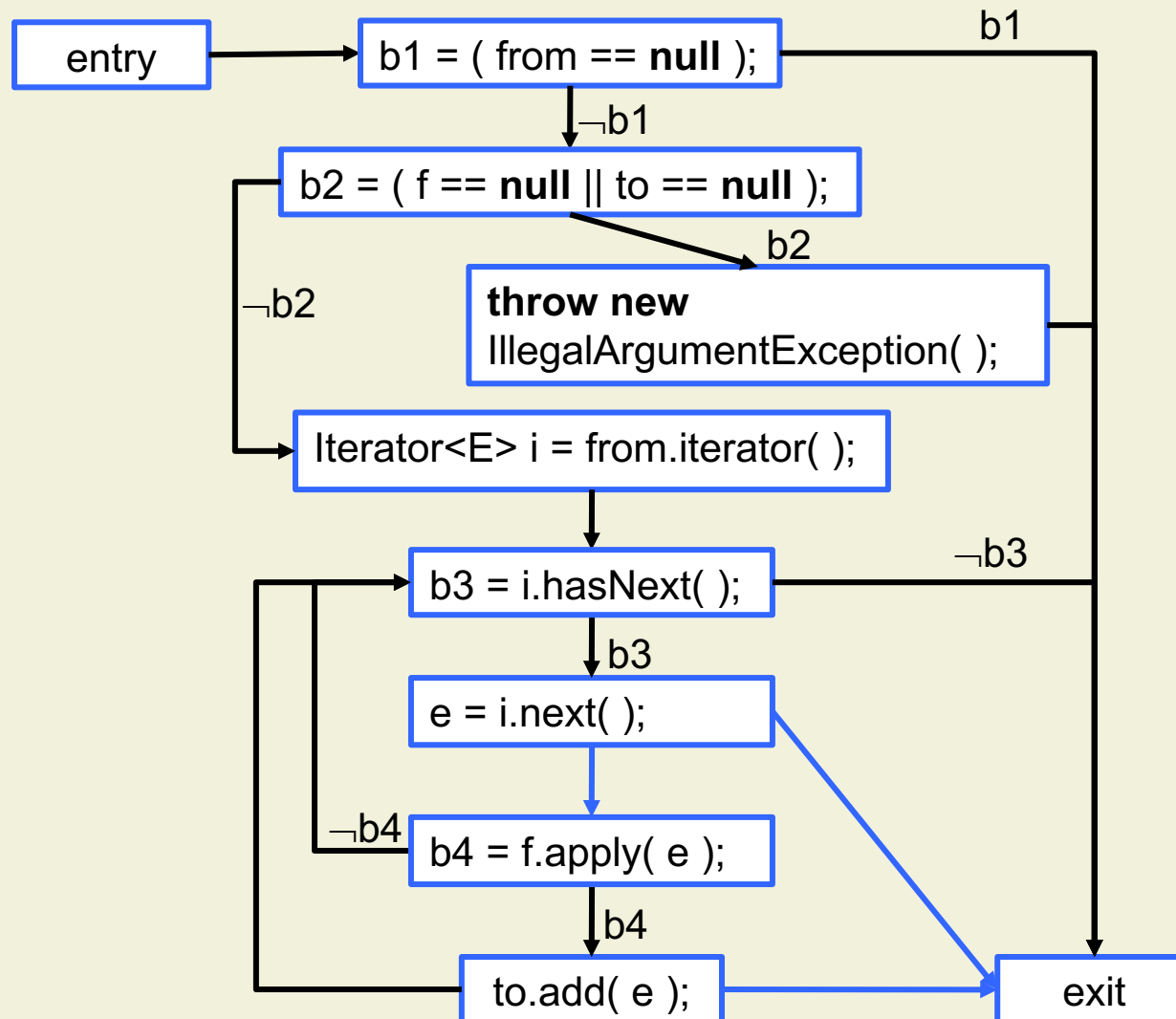
Might throw:

- NoSuchElementException

Might throw:

- UnsupportedOperationException
- ClassCastException
- NullPointerException
- IllegalArgumentException
- IllegalStateException

# Example: Documented Exceptions (cont'd)



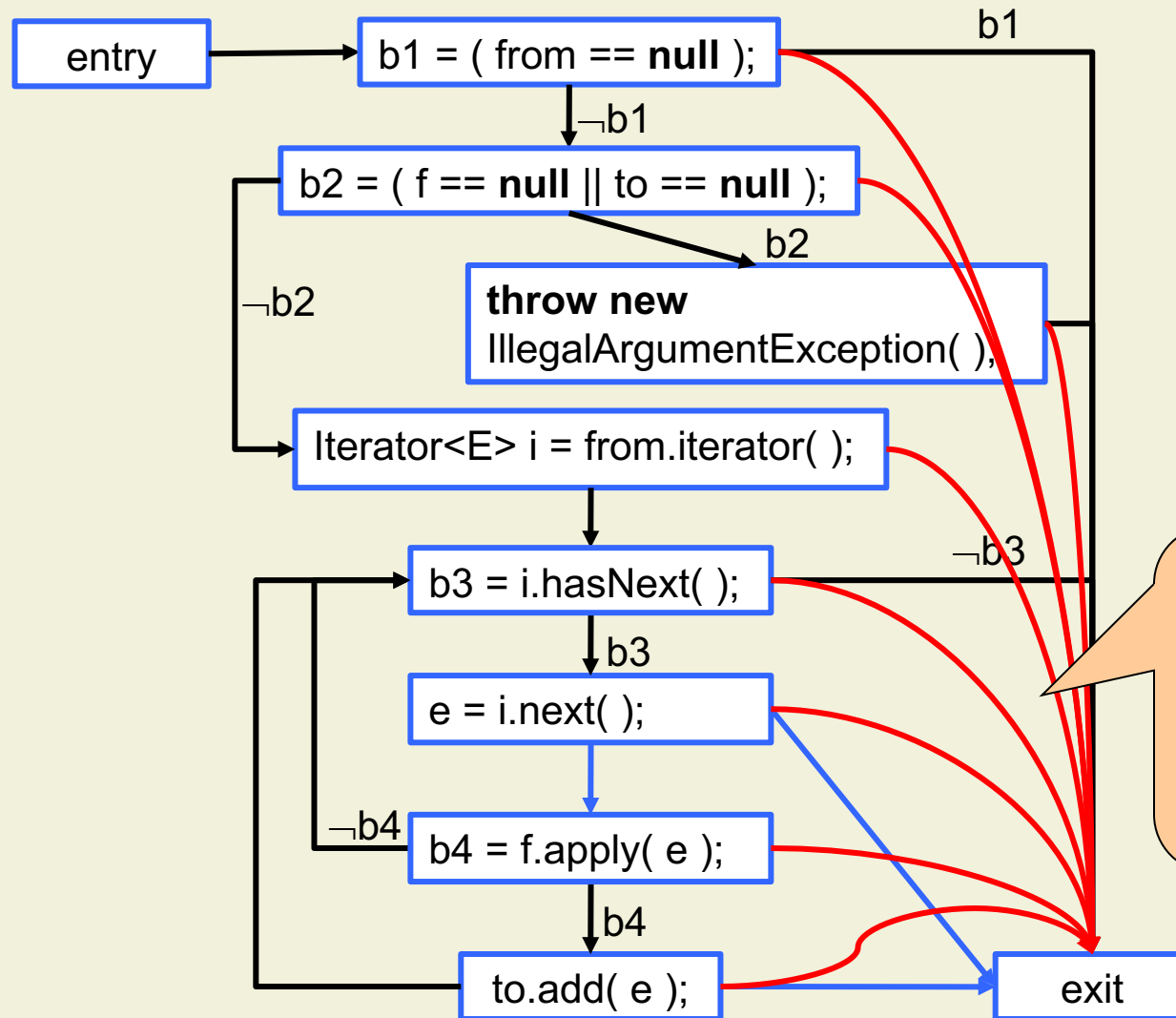
# Example: Undocumented Exceptions

```
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)



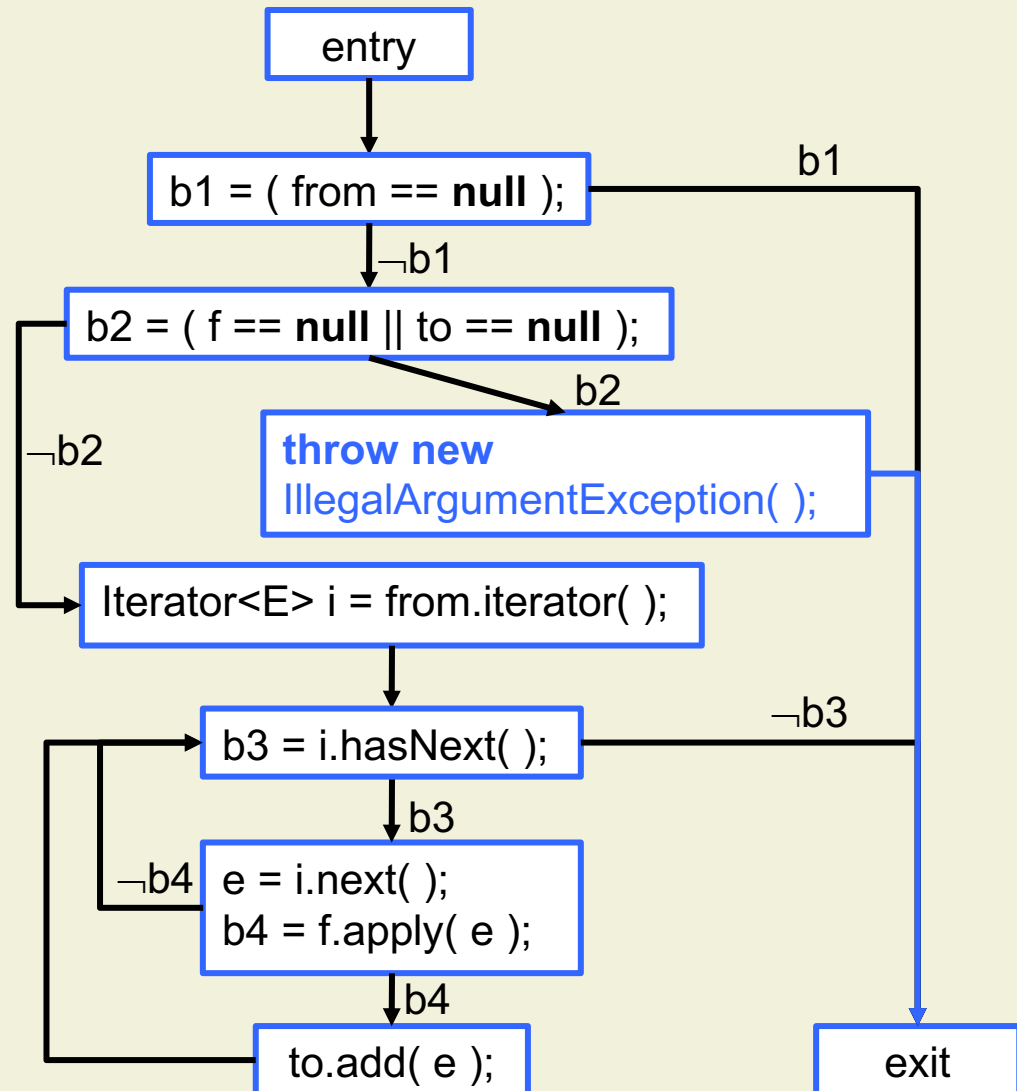
It is impractical to represent and test all exceptional control flow in the CFG

# Checked vs. Unchecked Exceptions

- Some 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 ) {  
    if( a == null || s == null )  
        throw new IllegalArgumentException( );  
    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 ) {  
    if( a == null || s == null )  
        throw new IllegalArgumentException( );  
    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

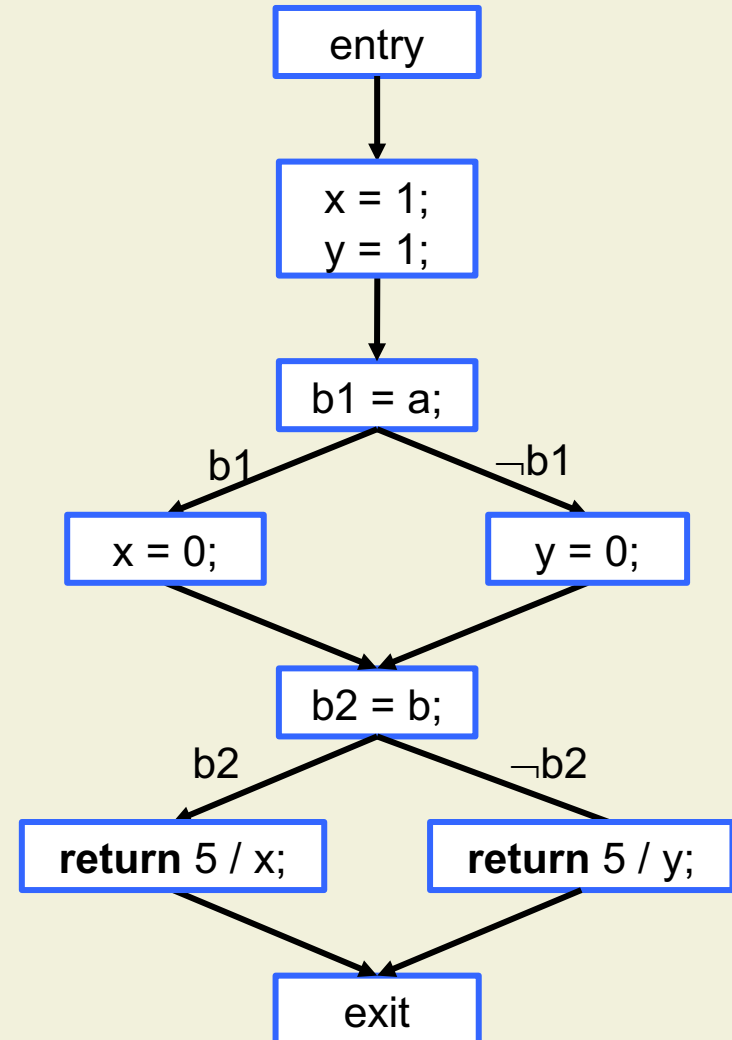
### 5.4.2 Advanced Topics of Control Flow Testing

### 5.4.3 Data Flow Testing

### 5.4.4 Interpreting Coverage

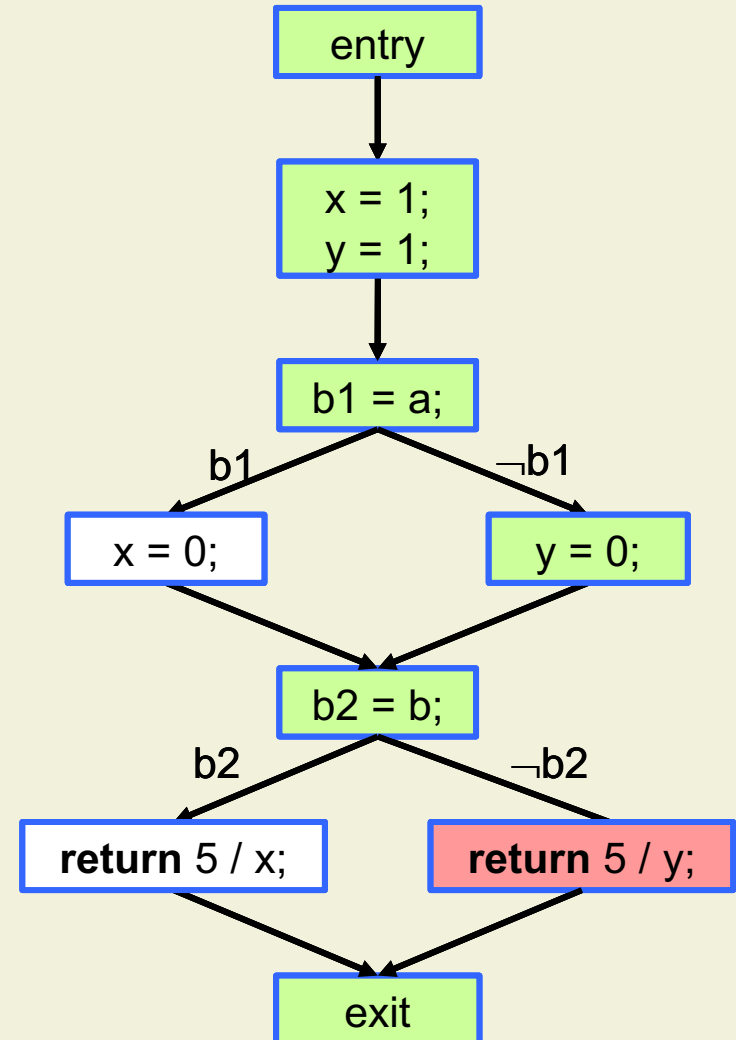
# Example Revisited

```
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

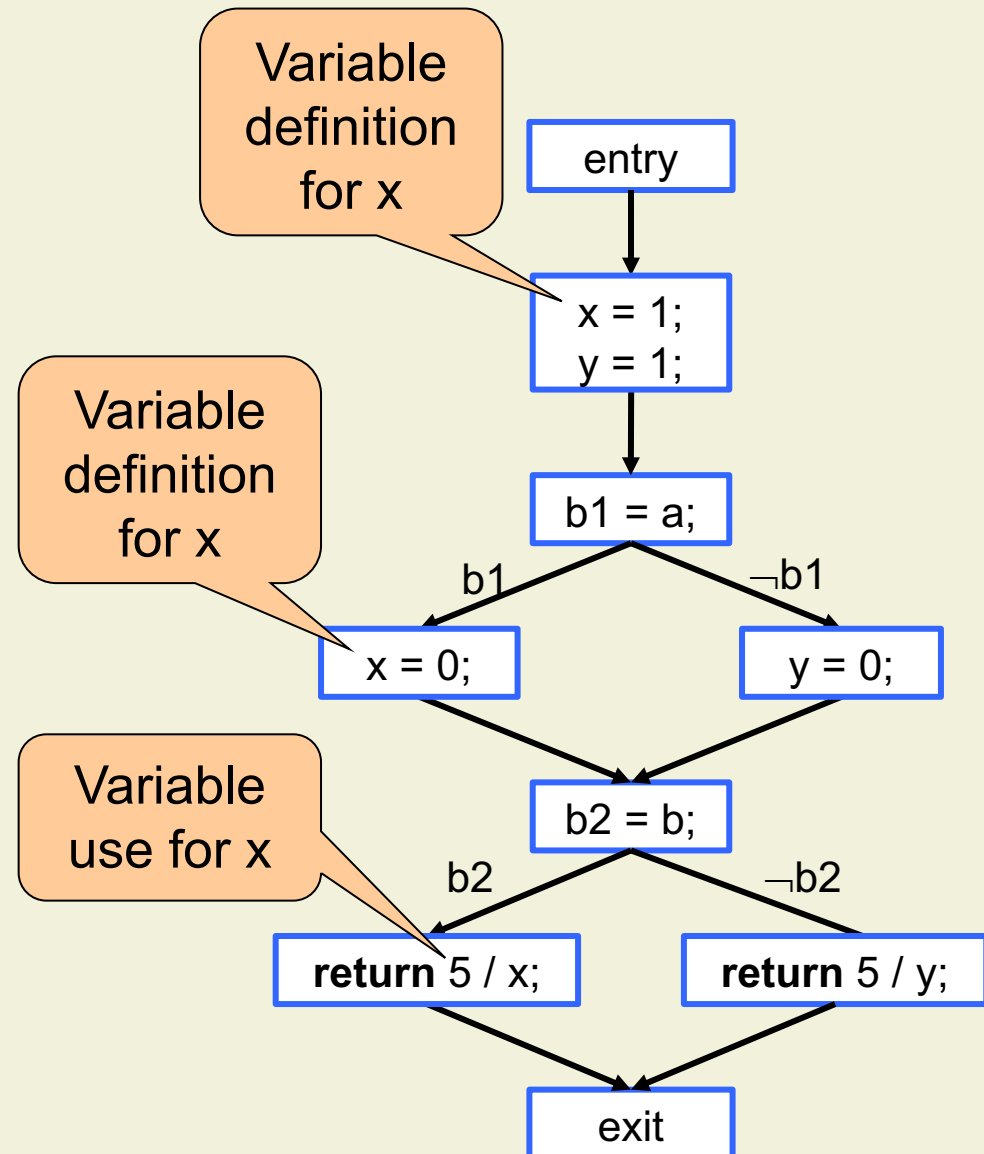
- A **variable definition** for a variable  $v$  is a basic block that assigns to  $v$ 
  - $v$  can be a local variable, formal parameter, field, or array element
- A **variable use** for a variable  $v$  is a basic block that reads the value from  $v$ 
  - In conditions, computations, output, etc.

## Definition-Clear Paths

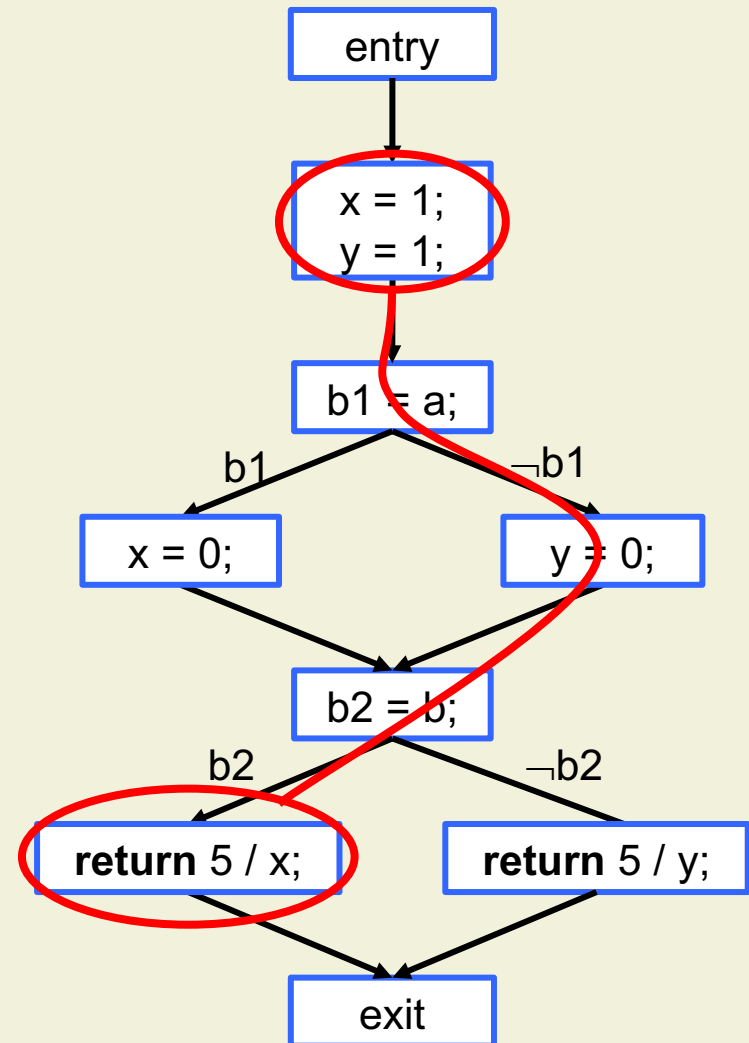
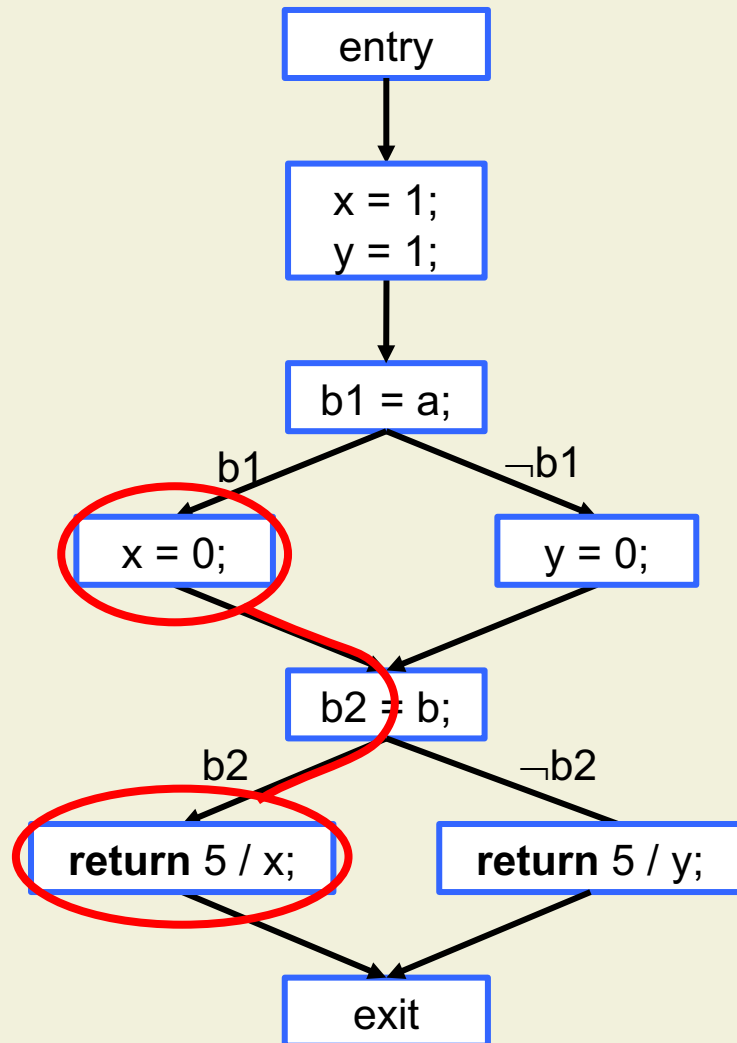
- A **definition-clear path** for a variable  $v$  is a path  $n_1, \dots, n_k$  in the CFG such that:
  - $n_1$  is a variable definition for  $v$
  - $n_k$  is a variable use for  $v$
  - No  $n_i$  ( $1 < i \leq k$ ) is a variable definition for  $v$   
( $n_k$  may be a variable definition if each 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  $d, \dots, u$  in the CFG
- We say **DU-pair** for definition-use pair



# Definition-Use Pairs: Examples



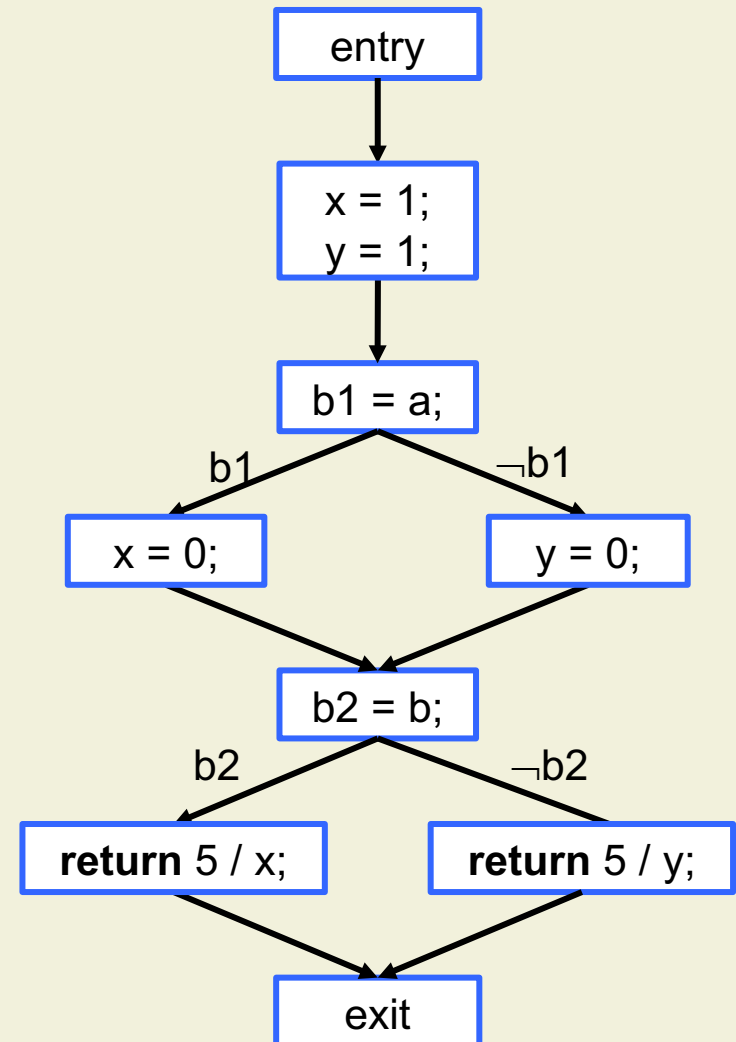
# DU-Pairs Coverage

- 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
  - $a = \mathbf{true}$ ,  $b = \mathbf{false}$
  - $a = \mathbf{false}$ ,  $b = \mathbf{true}$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

- $\text{pred}(n) = \{ m \mid (m,n,c) \text{ is an edge in the CFG} \}$
- $\text{succ}(m) = \{ n \mid (m,n,c) \text{ is an edge in the CFG} \}$
- $\text{gen}(n) = \{ v_n \mid n \text{ is a variable definition for } v \}$
- $\text{kill}(n) = \{ v_m \mid n \text{ is a variable definition for } v \text{ and } m \neq n \}$

## ■ We compute via fixpoint iteration

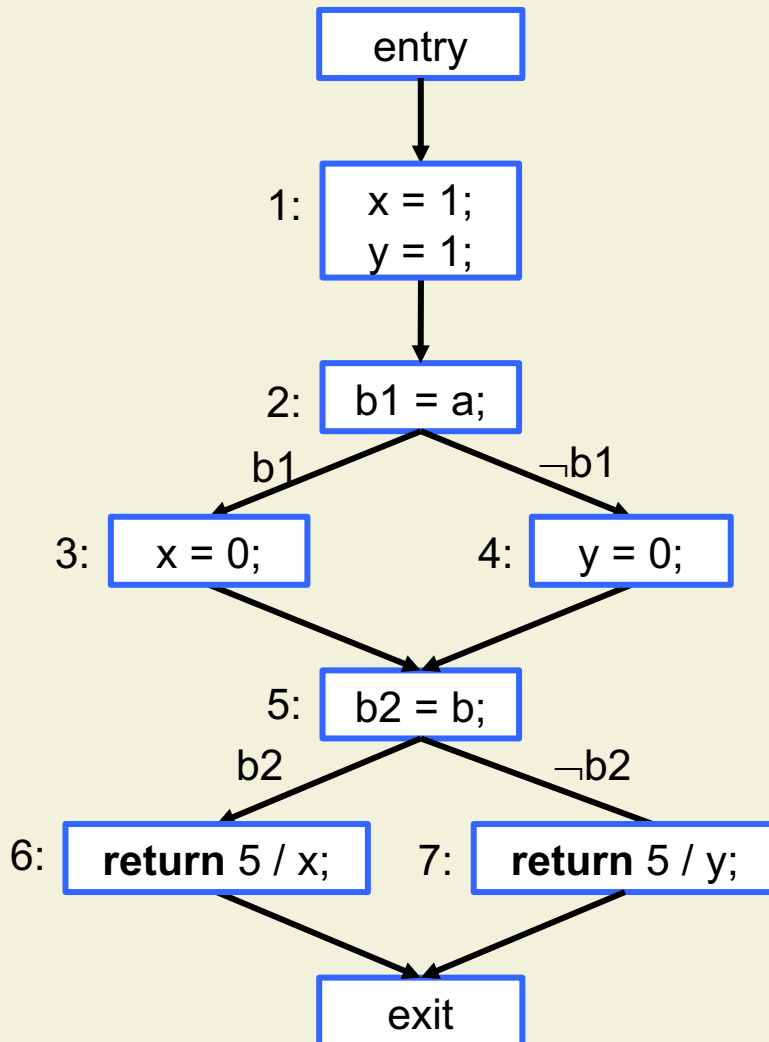
- $\text{Reach}(n)$ : The reaching definitions at the beginning of  $n$
- $\text{ReachOut}(n)$ : The reaching definitions at the end of  $n$



## Reaching Definitions: Algorithm (con't)

```
foreach node  $n$  do ReachOut(  $n$  ) :=  $\emptyset$  end  
worklist := nodes  
while worklist  $\neq \emptyset$  do  
   $n$  := any( worklist )  
  remove  $n$  from worklist  
  Reach(  $n$  ) :=  $\bigcup_{m \in \text{pred}(n)} \text{ReachOut}( m )$   
  ReachOut(  $n$  ) := Reach(  $n$  )  $\setminus$  kill(  $n$  )  $\cup$  gen(  $n$  )  
  if ReachOut(  $n$  ) has changed then  
    worklist := worklist  $\cup$  succ(  $n$  )  
  end  
end
```

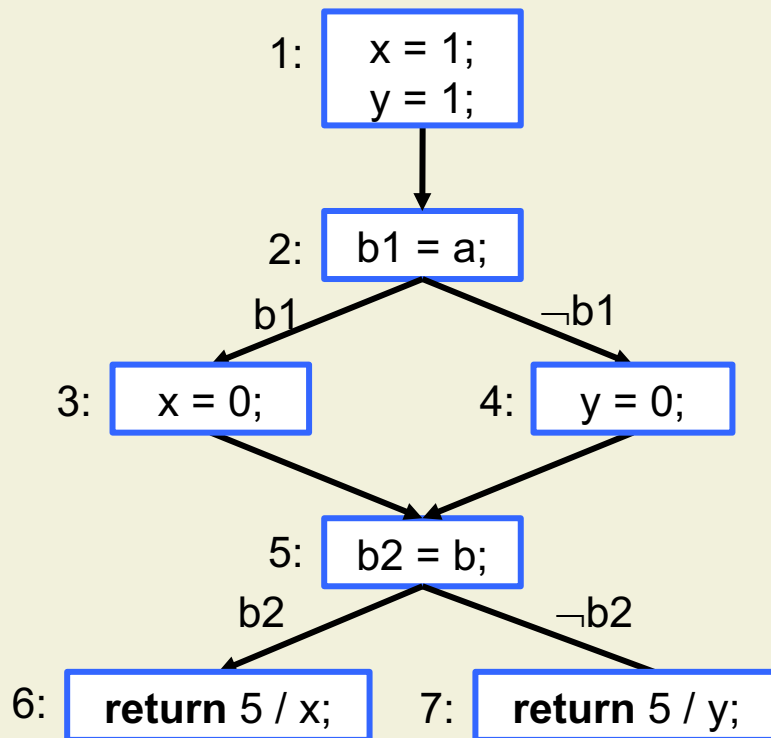
# Reaching Definitions: Example



n	Reach( n )	ReachOut( n )
1	$\emptyset$	
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	$\emptyset$
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)

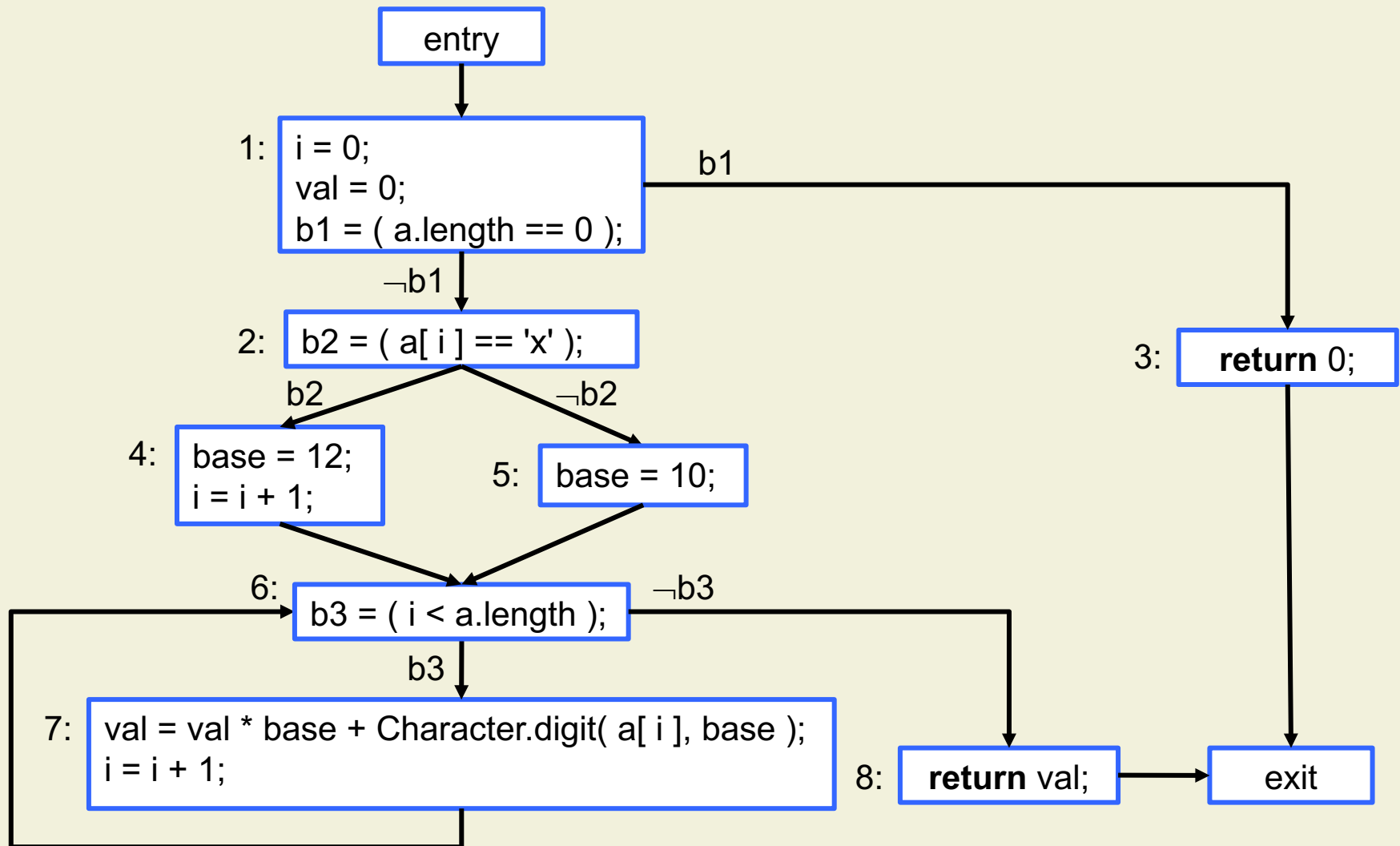
# Data Flow Testing Example

- Convert character sequence to integer
  - Input format:  $d_{\text{dec}}^*$  | 'x'( $d_{\text{hex}}^*$ ), 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

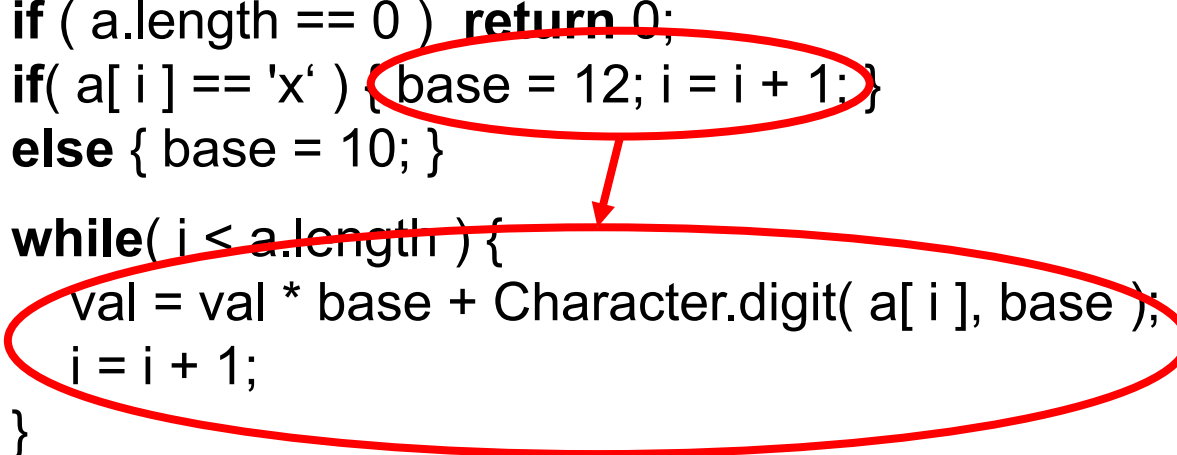
n	Reach( n )	ReachOut( n )
1	$\emptyset$	$i_1, val_1$
2	$i_1, val_1$	$i_1, val_1$
3	$i_1, val_1$	$i_1, val_1$
4	$i_1, val_1$	$i_4, val_1, base_4$
5	$i_1, val_1$	$i_1, val_1, base_5$
6	$i_1, i_4, i_7, val_1, val_7, base_4, base_5$	$i_1, i_4, i_7, val_1, val_7, base_4, base_5$
7	$i_1, i_4, i_7, val_1, val_7, base_4, base_5$	$i_7, val_7, base_4, base_5$
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  $\rightarrow$  Block
- Keep track of executed DU-pairs
  - useCover: Variable  $\times$  Block<sub>def</sub>  $\times$  Block<sub>use</sub>  $\rightarrow$   $\mathbb{N}$
- 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

# 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

# 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 than random testing, especially for large test suites