Principles of Software Construction: Objects, Design, and Concurrency

Test case design

Claire Le Goues **Bogdan Vasilescu**

Carnegie Mellon University
School of Computer Science

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Administrative issues

- Canvas submissions
  - “Submit a link to your checkpoint commit here on Canvas in the form https://github.com/CMU-17-214/<reponame>/commit/<commitid>.”
- Waitlist-related homework 1 delays
- Zoom livestream & recordings
- Some OH are moving in person, check the calendar, they’re in TCS
- Reading quizzes <u>ahead</u> of lecture for full participation credit
- Quizzes will move to Canvas once the waitlisted students are on Canvas
- Homework 2 is due next week: testing
  - lots of useful stuff in recitation on Wednesday
- Homework 3 will be 2 weeks instead of 1 last semester

Last Week

- Contracts
- Exceptions
- Unit testing: small, simple, per-method tests

Little Quiz

https://forms.gle/NyCauRczqJZdSzmg8

Today

- Specifications
- Specification vs. Structural testing
- Testing Strategies
  - Structural Testing: Statement, branch, path coverage; limitations
  - Specification Testing: Boundary value analysis, combinatorial testing, decision tables
- Writing testable code & good tests

Specifications and testing are closely related

Q: What exactly do you test given some method?

- What it claims to do: specification testing – the contract
- What it does: structural testing

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How to Encode Specifications?

Most common: prose specification.

```
class Algorithms {
    /**
     * This method finds the
     * shortest distance between two
     * vertices. It returns -1 if
     * the two nodes are not
     * connected. */
    int shortestDistance(…) {…}
}
```

Recall the earlier example?
(Probably too unstructured)

How to Encode Specifications?

Most common: prose specification.

Document:

- Every parameter
- Return value
- Every exception (checked and unchecked)
- What the method does, including
  - Primary purpose
  - Any side effects
  - Any thread safety issues
  - Any performance issues

How to Encode Specifications?

Most common: prose specification.

Document:

- Every parameter
- Return value
- Every exception (checked and unchecked)
- What the method does, including
  - Primary purpose
  - Any side effects
  - Any thread safety issues
  - Any performance issues

Do **not** document implementation details

- Known as overspecification

This is Java code

Docstring Specification

```
class RepeatingCardOrganizer {
  ...








  public boolean isComplete(CardStatus card) {
    return card.getResults().stream()
      .filter(isSuccess -> isSuccess)
      .count() >= this.repetitions;
  }
}
```

This is Java code

Docstring Specification

```
class RepeatingCardOrganizer {
  ...
  /**
   * Checks if the provided card has been answered correctly the required
number of times.
   * @param card The {@link CardStatus} object to check.
   * @return {@code true} if this card has been answered correctly at least
{@code this.repetitions} times.
   */
  public boolean isComplete(CardStatus card) {
    return card.getResults().stream()
      .filter(isSuccess -> isSuccess)
      .count() >= this.repetitions;
  }
}
```

This is Java code

Docstring Specification

```java
  /**
   * Checks if the provided card has been answered correctly the required
number of times.
   * @param card The {@link CardStatus} object to check.
   * @return {@code true} if this card has been answered correctly at least
{@code this.repetitions} times.
   */
  public boolean isComplete(CardStatus card);

  // What is specified?
```


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This is Java code

Docstring Specification

```
/**
 * Checks if the provided card has been answered correctly the required number of times.
 * @param card The {@link CardStatus} object to check.
 * @return {@code true} if this card has been answered correctly at least {@code this.repetitions} times.
 */
public boolean isComplete(CardStatus card);

// What is specified?
// - What the method does (but not how)
```

This is Java code

Docstring Specification

```
/**
 * Checks if the provided card has been answered correctly the required
number of times.
 * @param card The {@link CardStatus} object to check.
 * @return {@code true} if this card has been answered correctly at least
{@code this.repetitions} times.
 */
public boolean isComplete(CardStatus card);

// What is specified?
// - What the method does (but not how)
// - Parameter type (no constraints)
```

This is Java code

Docstring Specification

```
/**
 * Checks if the provided card has been answered correctly the required number of times.
 * @param card The {@link CardStatus} object to check.
 * @return {@code true} if this card has been answered correctly at least {@code this.repetitions} times.
 */
public boolean isComplete(CardStatus card);

// What is specified?
// - What the method does (but not how)
// - Parameter type (no constraints)
// - Return constraints: "at least" this.repetitions correct answers
```


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Specification vs. Structural Testing

- Specification-based testing: test solely the specification
  - Ignores implementation, use inputs/outputs only
  - Typical objective: Cover all specified behavior
- Structural Testing: consider implementation
  - Typical objective: Optimize for various kinds of code coverage
    - Line, Statement, Data-flow, etc.

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Structural Testing: a closer look

Takes into account the internal mechanism of a system (IEEE, 1990).

- Approaches include tracing data and control flow through a program

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Case Study

Assume various Wallets

```
public interface Wallet {

   boolean pay(int cost);

   int getValue();

}
```

DebitWallet.pay()

What should we test in this code?

```
public boolean pay(int cost) {
   if (cost <= this.money) {
       this.money -= cost;
       return true;
   }
   return false;
}
```


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DebitWallet.pay()

```
public boolean pay(int cost) {
    if (cost <= this.money) {
        this.money -= cost;
        return true;
    }
    return false;
}

new DebitWallet(100).pay(10);
```


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DebitWallet.pay()

```
public boolean pay(int cost) {
    if (cost <= this.money) {
        this.money -= cost;
        return true;
    }
    return false;
}

new DebitWallet(0).pay(10);
```


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CreditWallet.pay()

How about now?

```
public boolean pay(int cost, boolean useCredit) {
   if (useCredit) {
       if (this.credit + cost <= this.maxCredit) {
           this.credit += cost;
           return true;
       }
   }
   if (cost <= this.cash) {
       this.cash -= cost;
       return true;
   }
   return false;
}
```

CreditWallet.pay()

```
public boolean pay(int cost, boolean useCredit) {
   if (useCredit) {
       if (enoughCredit) {
           return true;
       }
   }
   if (enoughCash) {
       return true;
   }
   return false;
}
```

Exercise: think about as many test scenarios as you can

CreditWallet.pay()

```
public boolean pay(int cost, boolean useCredit) {
    if (useCredit) {
        if (enoughCredit) {
            return true;
        }
    }
    if (enoughCash) {
        return true;
    }
    return false;
}
```

Test case	useCredit	enough Credit	enough Cash	Result	Coverage
1	T	T	-	Pass	--

CreditWallet.pay()

```
public boolean pay(int cost, boolean useCredit) {
    if (useCredit) {
        if (enoughCredit) {
            return true;
        }
    }
    if (enoughCash) {
        return true;
    }
    return false;
}
```

Test case	useCredit	enough Credit	enough Cash	Result	Coverage
1	T	T	-	Pass	--
2	F	-	T	Pass	--
3	F	-	F	Fails	Statement

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Coverage

We have tested every statement; are we done?

Depends on desired **coverage**:

- Provide at least one test for distinct types of behavior
- Typically on control flow paths through the program
- Statement, branch, basis paths, MC/DC

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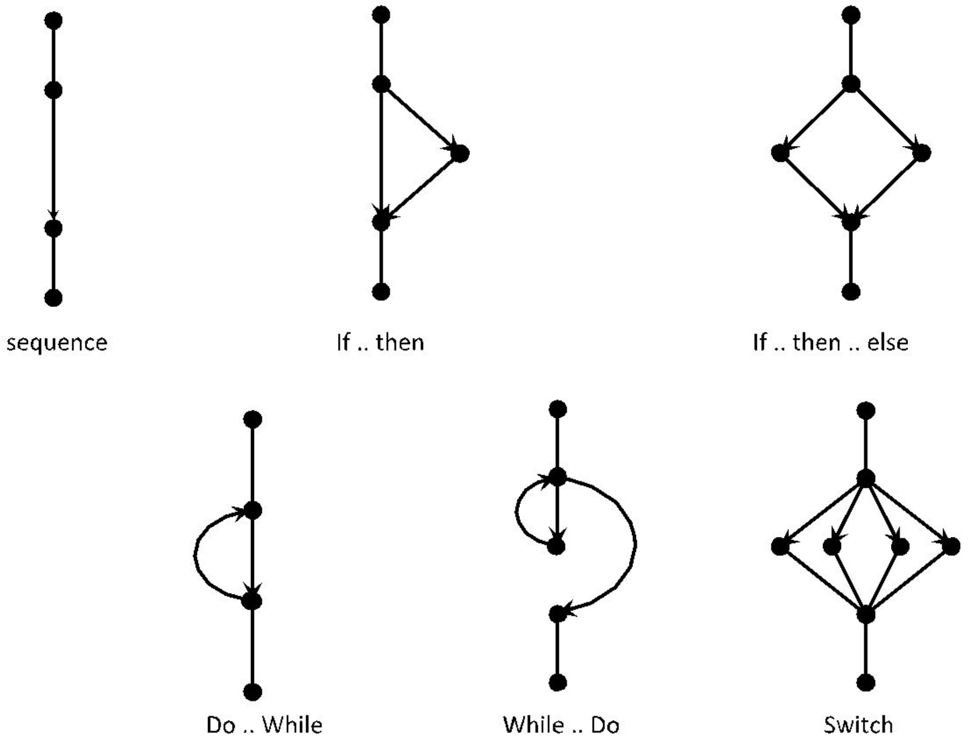
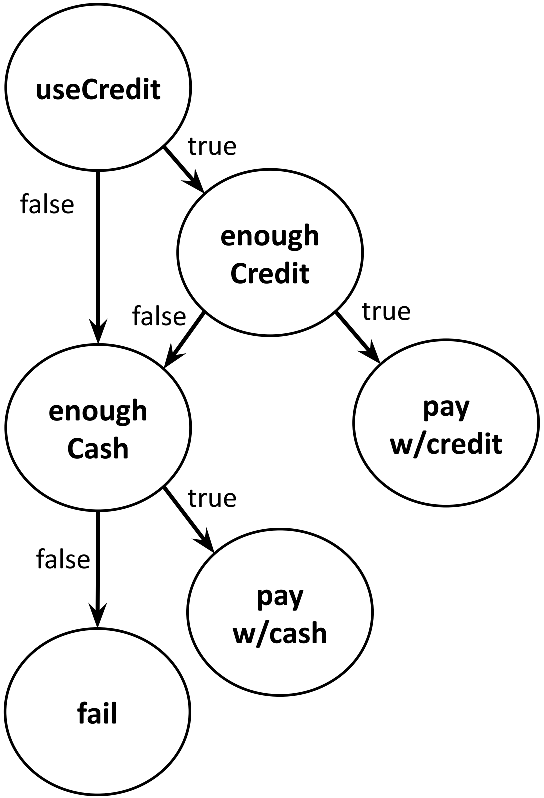
Structures in Code



Control-Flow of CreditCard.pay()

```
public boolean pay(int cost, boolean useCredit) {
   if (useCredit) {
       if (enoughCredit) {
           return true;
       }
   }
   if (enoughCash) {
       return true;
   }
   return false;
}
```



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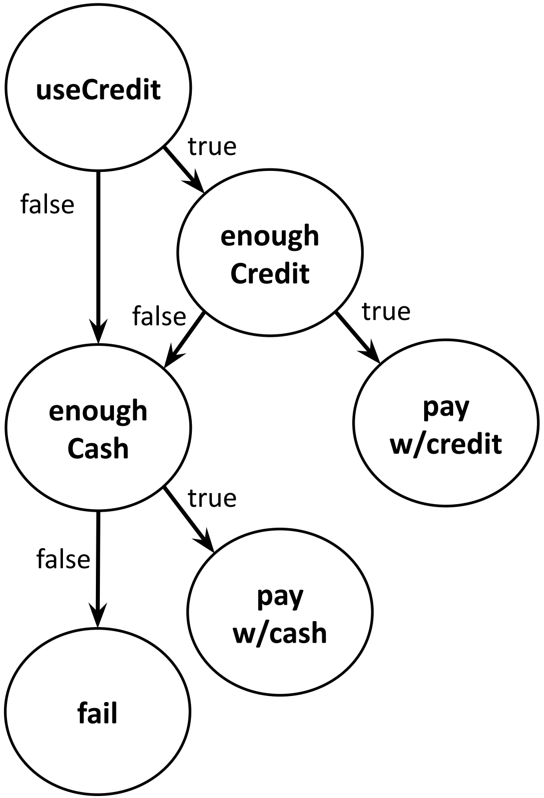
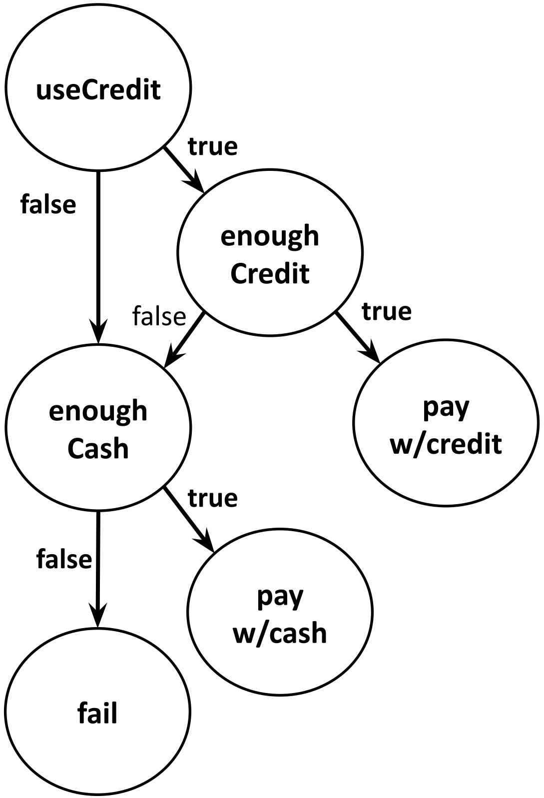
Control-Flow of CreditCard.pay()

Test case	useCredit	enough Credit	enough Cash	Result	Coverage
1	T	T	-	Pass	--
2	F	-	T	Pass	--
3	F	-	F	Fails	Statement



Control-Flow of CreditCard.pay()

Test case	useCredit	enough Credit	enough Cash	Result	Coverage
1	T	T	-	Pass	--
2	F	-	T	Pass	--
3	F	-	F	Fails	Statement



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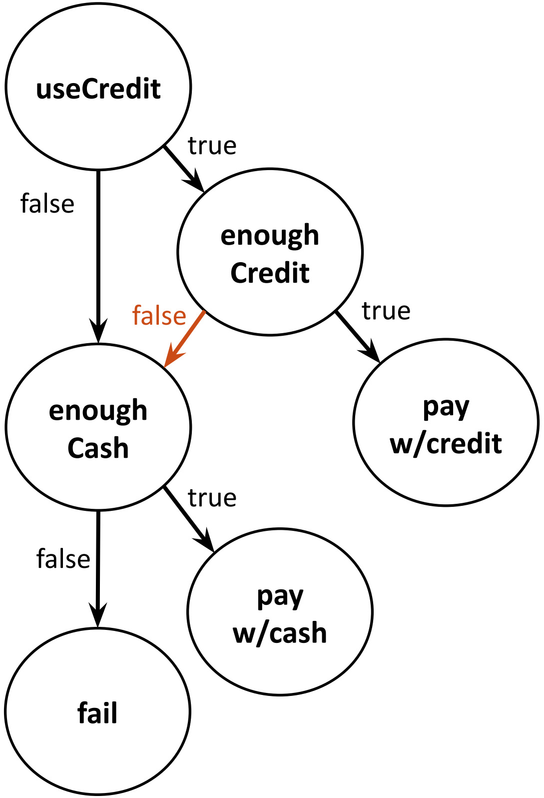
Control-Flow of CreditCard.pay()

Test case	useCredit	enough Credit	enough Cash	Result	Coverage
1	T	T	-	Pass	--
2	F	-	T	Pass	--
3	F	-	F	Fails	Statement



CreditWallet.pay()

```java
public boolean pay(int cost, boolean useCredit) {
   if (useCredit) {
      if (enoughCredit) {
         return true;
      }
   }
   if (enoughCash) {
      return true;
   }
   return false;
}
```

Test case	useCredit	enough Credit	enough Cash	Result	Coverage
1	T	T	-	Pass	--
2	F	-	T	Pass	--
3	F	-	F	Fails	Statement
4	T	F	T	Pass	Branch

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Path Coverage

We have seen every condition … what else is missing?

Path Coverage

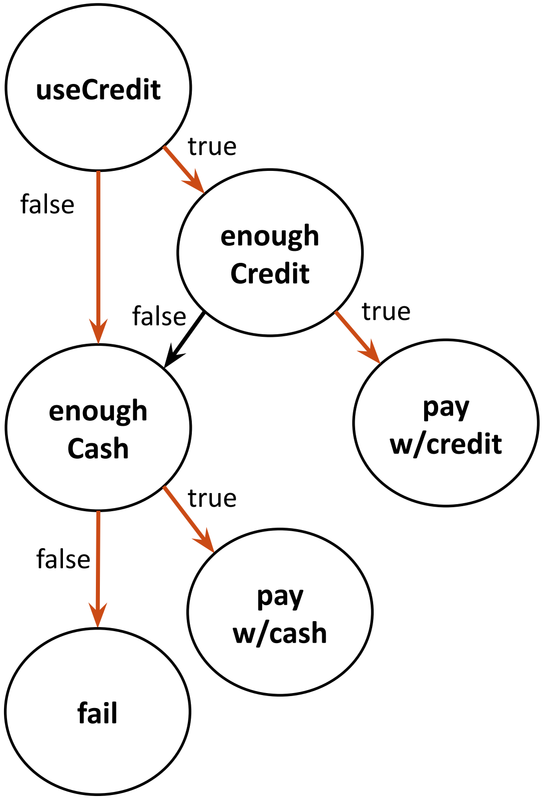
We have seen every condition … but not every path.

- 3 conditions, each with two values = 8 permutations
- Some permutations are impossible
- Still one *path* left

Control-Flow of CreditCard.pay()

Paths:

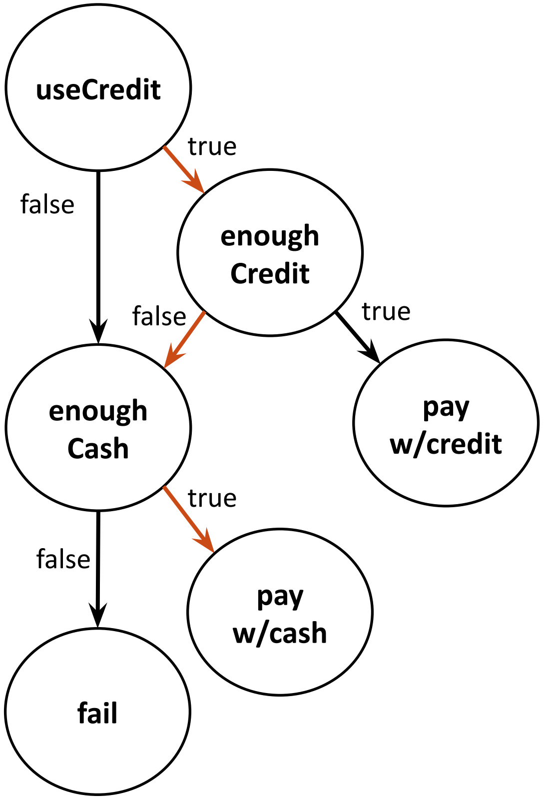
- {true, true}: pay w/credit
- {false, true}: pay w/cash
- {false, false}: fail



Control-Flow of CreditCard.pay()

Paths:

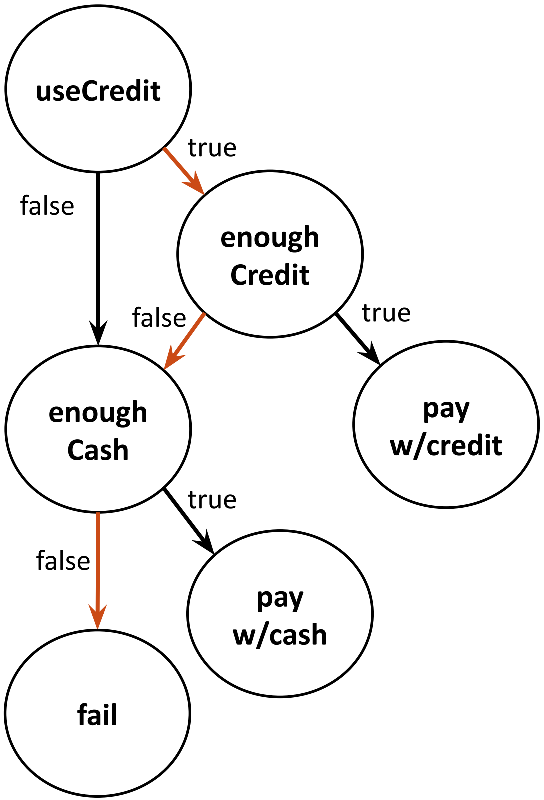
- {true, true}: pay w/credit
- {false, true}: pay w/cash
- {false, false}: fail
- {true, false, true}: pay w/cash after failing credit



Control-Flow of CreditCard.pay()

Paths:

- {true, true}: pay w/credit
- {false, true}: pay w/cash
- {false, false}: fail
- {true, false, true}: pay w/cash after failing credit
- {true, false, false}: try credit, but fail, **and** no cash



CreditWallet.pay()

```java
public boolean pay(int cost, boolean useCredit) {
   if (useCredit) {
       if (enoughCredit) {
           return true;
       }
   }
   if (enoughCash) {
       return true;
   }
   return false;
}
```

Test case	useCredit	enough Credit	enough Cash	Result	Coverage
1	T	T	-	Pass	--
2	F	-	T	Pass	--
3	F	-	F	Fails	Statement
4	T	F	T	Pass	Branch
5	T	F	F	Fails	(Basis) paths

BitCoinWallet.pay()

```
public boolean pay(int cost) {
   int currValue;
   while ((currValue = getValue()) < cost) {
       // Just wait.
   }
   this.btc -= cost / currValue;
   return true;
}

public int getValue() {
   return (int)
     (this.btc * Math.pow(2, 20*Math.random()));
}
```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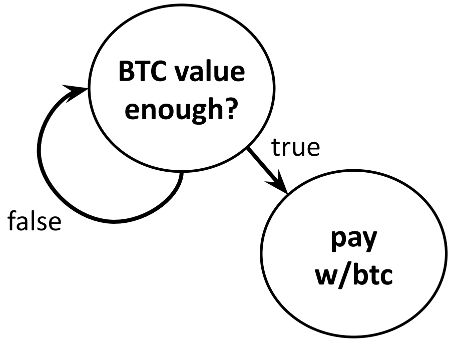
Control-flow of BitCoinWallet.pay()

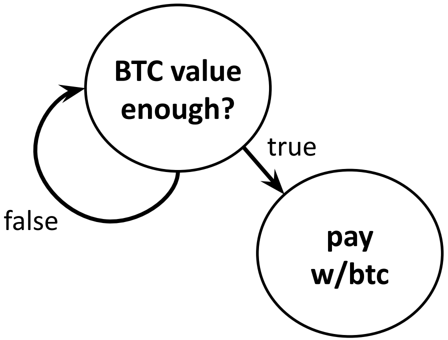
What are all the paths?



Control-flow of BitCoinWallet.pay()

What are all the paths?

- {true}
- {false, true}
- {false, false, true}
- {false, false, false, true}
- ...

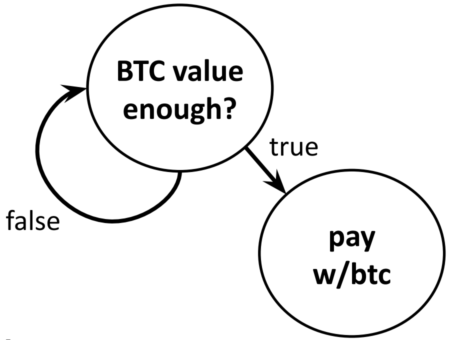


Control-flow of BitCoinWallet.pay()

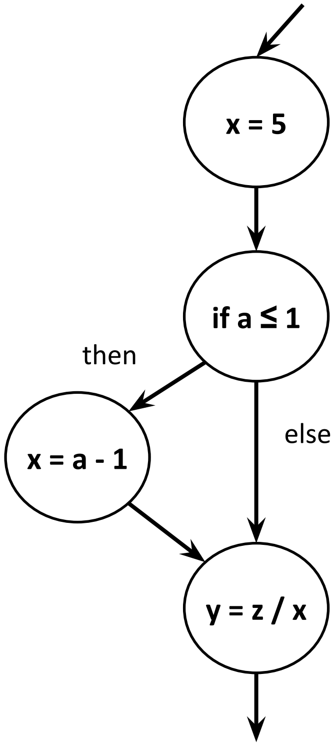
Perfect “general” path coverage is elusive

But “adequate” coverage criteria exist:

- Basis paths: each path must cover one new *edge*
  - {true} and {false, true} are sufficient
  - As is just {false, true}
- Loop adequacy: iterate each loop zero, one, and 2+ times

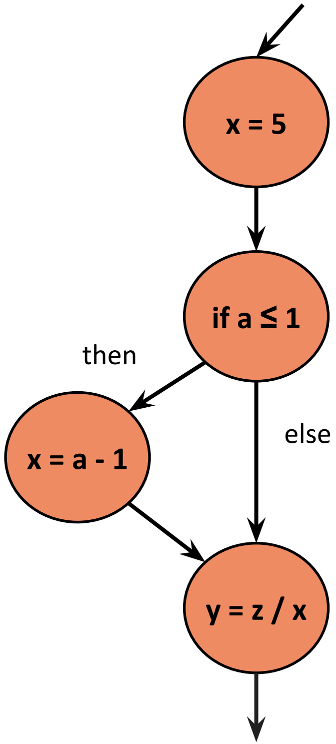


Coverage and Quality



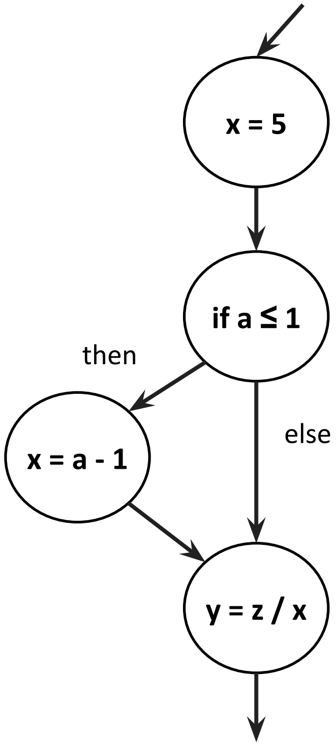
Question 1: Is there a defect?

Coverage and Quality



Question 2: Can we achieve 100% **statement** coverage and miss the defect?

Coverage and Quality



Question 3: Can we achieve 100% **branch** coverage and miss the defect?

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Audience Q&A Session

ⓘ Start presenting to display the audience questions on this slide.

Outline

- Structural Testing Strategies
- **Writing testable code & good tests**
- Specification Testing Strategies

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Writing Testable Code

What is the problem with this?

```java
public boolean hasHeader(String path) throws IOException {
   List<String> lines = Files.readAllLines(Path.of(path));
   return !lines.get(0).isEmpty()
}

// complete control-flow coverage!
hasHeader(“cards.csv”) // true
```


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Writing Testable Code

What is the problem with this?

```
public boolean hasHeader(String path) throws IOException {
   List<String> lines = Files.readAllLines(Path.of(path));
   return !lines.get(0).isEmpty()
}

// to achieve a ‘false’ output without having a test input file:
try {
   Path tempFile = Files.createTempFile(null, null);
   Files.write(tempFile,"\n".getBytes(StandardCharsets.UTF_8));
   hasHeader(tempFile.toFile().getAbsolutePath()); // false
} catch (IOException e) {
   e.printStackTrace();
}
```

Writing Testable Code

Exercise: rewrite to make this easier

- And: what would you test?

```
public boolean hasHeader(String path) throws IOException {
   List<String> lines = Files.readAllLines(Path.of(path));
   return !lines.get(0).isEmpty()
}
```

Writing Testable Code

Aim to write easily testable code

- Which is almost by definition more modular

```
public List<String> getLines(String path) throws IOException {
   return Files.readAllLines(Path.of(path));
}

public boolean hasHeader(List<String> lines) {
   return !lines.get(0).isEmpty()
}

// Test:
// - hasHeader with empty, non-empty first line
// - getLines (if you must) with null, real path
```

Writing Testable Code

What is the problem with this?

```java
public String[] getHeaderParts(List<String> lines) {
   if (!lines.isEmpty()) {
       String header = lines.get(0);
       if (header.contains(",")) {
           return header.split(",");
       } else {
           return new String[0];
       }
   } else {
       return null;
   }
}
```

Writing Testable Code

Split functionality into easily testable **units**

```
public String getFirstLine(List<String> lines) {
    if (!lines.isEmpty()) {
        return lines.get(0);
    } else {
        return null;
    }
}

public String[] getHeaderParts(String header) {
    if (header.contains(",")) {
        return header.split(",");
    } else {
        return new String[0];
    }
}
```


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Clean Testing

What is the problem with this?

```
public String[] getHeaderParts(String header) {
   if (header.contains(",")) {
       return header.split(",");
   } else {
       return null;
   }
}

@Test
public void testGetHeaderParts() {
   for (String header : List.of("line", "", "one,two")) {
      String[] parts = getHeaderParts(line);
      if (header.contains(",")) assertNull(parts);
      else assertEqual(header.split(","), parts.length);
   }
}
```


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Clean Testing

Keep tests simple, small

```
public String[] getHeaderParts(String header) {
   if (header.contains(",")) {
       return header.split(",");
   } else {
       return null;
   }
}

@Test
public void testGetHeaderPartsNoComma() {
   String[] parts = getHeaderParts("line");
   assertNull(parts);
}

@Test
...
```


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Testing Best Practices

Coverage is useful, but no substitute for your insight

- Cannot capture all paths
  - Especially beyond “unit”
  - Write testable code
- You may be testing buggy code
  - (add regression tests)
- Aim for at least branch coverage
  - And think through scenarios that demand more

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Bonus: Coding like the tour the france

```
public boolean foo() {
    try {
        synchronized () {
            if () {
            } else {
            }
            for () {
                if () {
                    if () {
                        if () {
                            if ()
                            {
                                if () {
                                    for () {
                                    }
                                }
                            }
                        } else {
                            if () {
                                for () {
                                    if () {
                                    } else {
                                    }
                                    if () {
                                    } else {
                                        if () {
                                        }
                                    }
                                    if () {
                                        if () {
                                            if () {
                                                for () {
                                                }
                                            }
                                        }
                                    } else {
                                    }
                                }
                            } else {
                            }
                        }
                    }
                }
            }
```

https://thedailywtf.com/articles/coding-like-the-tour-de-france

Outline

- Structural Testing Strategies
- Writing testable code & good tests
- **Specification Testing Strategies**

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Audience Q&A Session

ⓘ Start presenting to display the audience questions on this slide.

Back to Specification Testing

What would you test differently in this situation?

- Previously identified five paths through the code.
    - Are there still five given only specification?
- Should we test anything new?

```
/** Pays with credit if useCredit is set and enough
  * credit is available; otherwise, pays with cash if
  * enough cash is available; otherwise, returns false.
  */
public boolean pay(int cost, boolean useCredit);
```


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Back to Specification Testing

What would you test differently in this situation?

- “if useCredit is set and enough credit is available”:
  - Test both true, either/both false
- “pays with cash if enough cash is available; otherwise”:
  - Test true, false
- Could to this with as few as three test cases

```java
/** Pays with credit if useCredit is set and enough
  * credit is available; otherwise, pays with cash if
  * enough cash is available; otherwise, returns false.
  */
public boolean pay(int cost, boolean useCredit);
```

Specification Testing

We need a *strategy* to identify plausible mistakes

Specification Testing

We need a *strategy* to identify plausible mistakes

- Random: avoids bias, but inefficient
  - Yet potentially *very* valuable, because automatable
  - Not for today

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Boundary Value Testing

We need a *strategy* to identify plausible mistakes

- Boundary Value Testing: errors often occur at boundary conditions
  - E.g.:

```
/** Returns true and subtracts cost if enough
  * money is available, false otherwise.
  */
public boolean pay(int cost) {
   if (cost < this.money) {
       this.money -= cost;
       return true;
   }
   return false;
}
```


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Boundary Value Testing

We need a *strategy* to identify plausible mistakes

- Boundary Value Testing: errors often occur at boundary conditions
  - Identify equivalence partitions: regions where behavior should be the same
    - `cost <= money: true, cost > money: false`
    - Boundary value: `cost == money`

```
/** Returns true and subtracts cost if enough
  * money is available, false otherwise.
  */
public boolean pay(int cost) {
   if (cost < this.money) {
       this.money -= cost;
       return true;
   }
   return false;
}
```

Boundary Value Testing

We need a *strategy* to identify plausible mistakes

- Boundary Value Testing: errors often occur at boundary conditions
  - Select: a nominal/normal case, a boundary value, and an abnormal case
  - Useful for few *categories* of behavior (e.g., null/not-null) per value
- Test: `cost < credit, cost == credit, cost > credit,`
  `cost < cash, cost == cash, cost > cash`

```
/** Pays with credit if useCredit is set and enough
  * credit is available; otherwise, pays with cash if
  * enough cash is available; otherwise, returns false.
  */
public boolean pay(int cost, boolean useCredit);
```


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Combinatorial Testing

We need a *strategy* to identify plausible mistakes

- Combinatorial Testing: focus on tuples of boundary values
  - Captures bugs in **interactions** between risky inputs
  - Rarely need to test pairs of “invalid” values (cost too high for credit & cash)

```
/** Pays with credit if useCredit is set and enough
  * credit is available; otherwise, pays with cash if
  * enough cash is available; otherwise, returns false.
  */
public boolean pay(int cost, boolean useCredit);
```

Combinatorial Testing

We need a *strategy* to identify plausible mistakes

- Combinatorial Testing: focus on tuples of boundary values
  - Captures bugs in **interactions** between risky inputs
  - Rarely need to test pairs of “invalid” values (cost too high for credit & cash)
- Include: {cost > credit && cost == cash}
- Maybe: {cost < credit && cost == cash}

```java
/** Pays with credit if useCredit is set and enough
  * credit is available; otherwise, pays with cash if
  * enough cash is available; otherwise, returns false.
  */
public boolean pay(int cost, boolean useCredit);
```


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Decision Tables

We need a *strategy* to identify plausible mistakes

- Decision Tables
  - You've seen one already
  - Enumerate condition options
    - Leave out impossibles
    - Identify "don't-matter" values
  - Useful for redundant input domains

Test case	useCredit	enough Credit	enough Cash	Result
1	T	T	-	Pass
2	F	-	T	Pass
3	F	-	F	Fails
4	T	F	T	Pass
5	T	F	F	Fails

Specification Tests

So what is the right granularity?

- It depends
- We are still aiming for coverage
  - Just of specifications, and their innumerable implementations
  - BVA (& its cousins), decision tables tend to provide good coverage

Structural Testing vs. Specification Testing

You will ***typically have both*** code & (prose) specification

- Test specification, but know that it can be underspecified
- Test implementation, but not to the point that it cannot change
- Use testing strategies that leverage both
    - There is a fair bit of overlap; e.g., BVA yields <u>useful</u> branch coverage

Further Testing Strategies

Many more aspects, some later in this course:

- Stubbing/Mocking, to avoid testing dependencies
- Integration testing: scenarios that span units
  - With unit testing one should not test for an expected usage scenario
    - e.g., in HW2: that everything gets called from Main
  - This lets one make some simplifying assumptions
    - e.g., that every card is seen equally often
- Beyond correctness: performance, security

Summary

Testing comprehensively is hard

- Tailor to your task: specification vs. structural testing
    - Do not assume unstated specifications for HW 2; spend your energy wisely
- Pick a strategy, or a few
    - Be systematic; defend your decisions
- Tomorrow's recitation covers:
    - Unit test best practices
    - Test organization
    - Running tests, coverage