University of Sheffield

COM3529 Software Testing and Analysis

Regression Testing

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Roadmap

Beizer’s Maturity Model

Test Automation

Unit Testing

Control/Data-Flow Analysis

Code Coverage

Mutation Testing

Regression Testing

Fuzzing

Search-based Test Generation

Model-Based Testing

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Model-Based Testing

Motivation

Changes have been made to the system’s code

…or to the system’s environment

Have new faults been introduced that weren’t there before?

Can we **confidently** deploy the new version of the system?

Regression Testing is now standard in the software development industry

Typically based on a **regression test suite**

Scenarios

Regression testing can be **very costly**

Continuous Integration/ Continuous Development frameworks help

Running regression test suites overnight is common practice

Rerunning existing tests **may not always be possible**

e.g. if public interfaces have changed

For embedded systems, e.g. car controllers, retesting the software **in use** may take **months**. Simulation helps but is not a complete solution.

How to choose an optimal subset of regression tests?

Regression Testing Techniques

Minimisation – Could my test suite be smaller?

Typically based on a criterion, i.e., minimise while retaining ...

Prioritisation – In which order should I run my tests?

To detect new defects as soon as possible

Selection – Which tests should I run?

Given a (set of) line(s) of code

Minimisation

Minimisation

As software grows, so does the size of its test suite!

- Tests become **obsolete**, or **redundant**
- **Test maintainability** is rarely a priority in practice

Removing redundancy

- Many similar tests covering the same code!
- Coverage information from CI/CD, i.e., tests have been run before
- Keep only tests that execute changed (or deleted) code; deem other tests redundant wrt changes, so no need to re-execute them!

Minimisation Algorithm

Focus on code coverage, e.g., **branch coverage**

Alternative approaches exist, e.g., to preserve other properties

Given a regression test suite T, **find the smallest subset $T' \in T$ such that T' and T have the same coverage**

The hope is that preserving coverage leads to us preserving effectiveness, i.e., T' is as effective as T

Not necessarily **the** smallest test suite: If the cost of test execution varies then we may want a **cheapest-to-execute** test suite

Formalisation

Given a set of coverage goals $C = \{c_1, \ldots, c_k\}$(e.g., lines)

a.k.a. **test requirements**

And a test suite $T = \{t_1, \ldots, t_n\}$that meets/covers all of them

Where each $t_i \in T$ covers a given set C_{t_i} of coverage goals

Find the smallest $T' \in T$ such that $\bigcup_{t_i \in T'} C_{t_i} = C$

This corresponds to the **NP-complete Set Cover Problem**

Exact Solutions vs Heuristics

Test suites are usually large – otherwise no need to minimise them!

So, our problem instances are usually large, too

Typically infeasible to solve the problem exactly: we fall back upon heuristics: **How to find a good (small enough) test suite?**

A Simple Greedy Algorithm

Start with the empty set $\emptyset$.

Add a test t_i that covers **most goals** and remove it from the test pool

Iterations: add the next test that covers the most goals

Terminate when the test suite provides **full coverage**

A Simple Greedy Algorithm

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
A	x	x	x			x	x	x
B	x	x	x				x	x
C	x	x	x	x				
D					x	x	x	x
E	x	x	x			x	x	x

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C	x	x	x	x				
D					x	x	x	x
E	x	x	x			x	x	x

Starts with **A** and **E** (either order)

A Simple Greedy Algorithm

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
A	x	x	x			x	x	x
B	x	x	x				x	x
C	x	x	x	x				
D					x	x	x	x
E	x	x	x			x	x	x

Starts with **A** and **E** (either order)

Next, **B** is the obvious choice

A Simple Greedy Algorithm

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
A	x	x	x			x	x	x
B	x	x	x				x	x
C	x	x	x	x				
D					x	x	x	x
E	x	x	x			x	x	x

Starts with **A** and **E** (either order)

Next, **B** is the obvious choice

Finally, **C** and **D** (either order)

A Simple Greedy Algorithm

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
A	x	x	x			x	x	x
B	x	x	x				x	x
C	x	x	x	x				
D					x	x	x	x
E	x	x	x			x	x	x

Starts with **A** and **E** (either order)

Next, **B** is the obvious choice

Finally, **C** and **D** (either order)

Resulting set: **{A, E, B, C, D}**

A Simple Greedy Algorithm

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
A	x	x	x			x	x	x
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E	x	x	x			x	x	x

Starts with **A** and **E** (either order)

Next, **B** is the obvious choice

Finally, **C** and **D** (either order)

Resulting set: **{A, E, B, C, D}**

But could have just used {C, D}!

A Simple Greedy Algorithm

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
A	x	x	x			x	x	x
B	x	x	x				x	x
C	x	x	x	x				
D					x	x	x	x
E	x	x	x			x	x	x

Starts with **A** and **E** (either order)

Next, **B** is the obvious choice

Finally, **C** and **D** (either order)

Resulting set: **{A, E, B, C, D}**

But could have just used {C, D}!

Not always a good approach!

Additional Greedy

Take into account the coverage **already achieved**!

Start again with the empty set

Add one of the tests that covers most goals

Iterations: add a test that covers most **currently uncovered** goals

Terminate with **full coverage**

Effective wrt Set Cover Problem – good approximation

Additional Greedy

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
A	x	x	x			x	x	x
B	x	x	x				x	x
C	x	x	x	x				
D					x	x	x	x
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BE-AB-FH

Additional Greedy

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Starts with **A** or **E** (either one)

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Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
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Starts with **A** or **E** (either one)

Uncovered goals: **b_4** and **b_5**

Additional Greedy

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
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Starts with **A** or **E** (either one)

Uncovered goals: **b_4** and **b_5**

Add **C** and **D** (either order)

Additional Greedy

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
A	x	x	x			x	x	x
B	x	x	x				x	x
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Starts with **A** or **E** (either one)

Uncovered goals: **b_4** and **b_5**

Add **C** and **D** (either order)

Each covers one uncovered goal

Additional Greedy

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
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Starts with **A** or **E** (either one)

Uncovered goals: **b_4** and **b_5**

Add **C** and **D** (either order)

Each covers one uncovered goal

Resulting set: **{A, C, D}**

Additional Greedy

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
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E	x	x	x			x	x	x

Starts with **A** or **E** (either one)

Uncovered goals: **b_4** and **b_5**

Add **C** and **D** (either order)

Each covers one uncovered goal

Resulting set: **{A, C, D}**

Not optimal, but better!

Harrold et al (1993)

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
A	x	x	x			x	x	x
B	x	x	x				x	x
C	x	x	x	x				
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BE-AB-FH

Harrold et al (1993)

Idea: **Uniquely-covered** goals first

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
A	x	x	x			x	x	x
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Idea: **Uniquely-covered** goals first

b_4 uniquely-covered by **C**; so add **C**

Harrold et al (1993)

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
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Idea: **Uniquely-covered** goals first

b_4 uniquely-covered by **C**; so add **C**

b_5 uniquely-covered by **D**; so add **D**

Harrold et al (1993)

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
A	x	x	x			x	x	x
B	x	x	x				x	x
C	x	x	x	x				
D					x	x	x	x
E	x	x	x			x	x	x

Idea: **Uniquely-covered** goals first

b_4 uniquely-covered by **C**; so add **C**

b_5 uniquely-covered by **D**; so add **D**

Iterations: consider goals covered by two, three, etc tests

Harrold et al (1993)

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
A	x	x	x			x	x	x
B	x	x	x				x	x
C	x	x	x	x				
D					x	x	x	x
E	x	x	x			x	x	x

Idea: **Uniquely-covered** goals first

b_4 uniquely-covered by **C**; so add **C**

b_5 uniquely-covered by **D**; so add **D**

Iterations: consider goals covered by two, three, etc tests

Ties need resolution

Harrold et al (1993)

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
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D					x	x	x	x
E	x	x	x			x	x	x

Idea: **Uniquely-covered** goals first

b_4 uniquely-covered by **C**; so add **C**

b_5 uniquely-covered by **D**; so add **D**

Iterations: consider goals covered by two, three, etc tests

Ties need resolution

Terminate with **full coverage**

Harrold et al (1993)

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
A	x	x	x			x	x	x
B	x	x	x				x	x
C	x	x	x	x				
D					x	x	x	x
E	x	x	x			x	x	x

Idea: **Uniquely-covered** goals first

b_4 uniquely-covered by **C**; so add **C**

b_5 uniquely-covered by **D**; so add **D**

Iterations: consider goals covered by two, three, etc tests

Ties need resolution

Terminate with **full coverage**

Resulting set: **{C, D}**

Harrold et al (1993)

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
A	x	x	x			x	x	x
B	x	x	x		x		x	x
C	-	-	-	x				
D					x	x	x	x
E	x	x	x			x	x	x

Harrold et al (1993)

b_4 uniquely-covered by **C**; so **add C**

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
A	x	x	x			x	x	x
B	x	x	x		x		x	x
C	-	-	-	x				
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E	x	x	x			x	x	x

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A	x	x	x			x	x	x
B	x	x	x		x		x	x
C	-	-	-	x				
D					x	x	x	x
E	x	x	x			x	x	x

b_4 uniquely-covered by **C**; so **add C**

Next, **b_5** is covered by **2** tests: **B**, **D**

Harrold et al (1993)

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
A	x	x	x			x	x	x
B	x	x	x		x		x	x
C	-	-	-	x				
D					x	x	x	x
E	x	x	x			x	x	x

b_4 uniquely-covered by **C**; so **add C**

Next, **b_5** is covered by **2** tests: **B**, **D**

Tie resolution between **B** and **D**:

Harrold et al (1993)

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
A	x	x	x			x	x	x
B	x	x	x		x		x	x
C	-	-	-	x				
D					x	x	x	x
E	x	x	x			x	x	x

b_4 uniquely-covered by **C**; so **add C**

Next, **b_5** is covered by **2** tests: **B**, **D**

Tie resolution between **B** and **D**:

Look at goals covered by **3** tests

Harrold et al (1993)

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
A	x	x	x			x	x	x
B	x	x	x		x		x	x
C	-	-	-	x				
D					x	x	x	x
E	x	x	x			x	x	x

b_4 uniquely-covered by **C**; so **add C**

Next, **b_5** is covered by **2** tests: **B**, **D**

Tie resolution between **B** and **D**:

Look at goals covered by **3** tests

B : b_1, b_2, b_3 vs **D : b_6** ; so **add B**

Harrold et al (1993)

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
A	x	x	x			x	x	x
B	x	x	x		x		x	x
C	-	-	-	x				
D					x	x	x	x
E	x	x	x			x	x	x

b_4 uniquely-covered by **C**; so **add C**

Next, **b_5** is covered by **2** tests: **B**, **D**

Tie resolution between **B** and **D**:

Look at goals covered by **3** tests

B : b_1, b_2, b_3 vs **D : b_6** ; so **add B**

Next, **b_6** is covered by **3** tests: **A**, **D**, **E**

Harrold et al (1993)

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
A	x	x	x			x	x	x
B	x	x	x		x		x	x
C	-	-	-	x				
D					x	x	x	x
E	x	x	x			x	x	x

b$_4$ uniquely-covered by **C**; so **add C**

Next, **b$_5$** is covered by **2** tests: **B**, **D**

Tie resolution between **B** and **D**:

Look at goals covered by **3** tests

B : b$_1$, b$_2$, b$_3$ vs **D : b$_6$** ; so **add B**

Next, **b$_6$** is covered by **3** tests: **A**, **D**, **E**

Resulting set: **{C, B, A|D|E}**

Multi-Objective Approach

Metaheuristics, e.g., Genetic Algorithms

Enough improvements over Greedy to be worthwhile?

Problem generalisation: Find a regression test suite T' such that **there is no smaller test suite** that provides the same coverage as T'.

Optimise two objective functions: **maximise** coverage & **minimise** cost

More flexible than Greedy: other coverage criteria as added targets

Multi-objective optimisation algorithms return a set of solutions with trade-offs

Multi-Objective Approach

Pareto Dominance: Approach to comparing candidate solutions

Given two candidate solutions **x** and **y**, **x** Pareto-dominates **y** if **x** is **at least as good as y** on all objectives and **strictly better** than **y** on at least one objective

i.e., we would **never** choose **y** over **x**

Ideally, we want to find the **Pareto Front**: the set of solutions that are not Pareto-dominated by any other solution

Many metaheuristic algorithms, the most famous is probably the Non-dominated Sorting Genetic Algorithm II (NSGA-II); there is now NSGA-III

Prioritisation

Prioritisation

Goal: Find a good **test execution order**

Ideally, we would like any test failures to occur **as early as possible**

This can speed up software development, for example:

- Stop testing once we observe a failure
- Even if we plan to execute all tests, the sooner we find failures the sooner we can start trying to fix the code

Problem

Problem: We do not know in advance **which tests will fail**!

So, the best order is **unknown**

Idea: use metrics and historical information associated with faults

Prioritise tests that are deemed **more likely** to lead to failures

While quickly **maximising coverage**

Hope: **Find faults early**!

Using Coverage

We might only look at coverage

- Aim to achieve 100% coverage as quickly as possible
- Maximise coverage for a given budget (e.g. number of tests)
- Achieve coverage ‘quickly’ to get ‘good’ coverage whenever we stop

Greedy Algorithm

Start with A, then choose D, then C

To achieve 100% coverage faster, we should do C then D or viceversa

Suboptimal if we stop after one test

Test\branch	b_1	b_2	b_3	b_4	b_5	b_6	b_7	b_8
A	x	x	x			x	x	x
B	x	x	x				x	x
C	x	x	x	x				
D					x	x	x	x

Fitness Function for Coverage

Consider branch coverage (similar for other metrics)

How to assign a score/fitness to a particular order of tests?

Reward orders that are good for all prefixes

Standard Approach: use weighted average percentage of coverage over the sequence of tests

If we have n test cases, m branches, and TB_i is the number of the first test case that executes branch i, then the fitness is:

$$APC = 1 - \frac{TB_1 + \ldots + TB_m}{nm} + \frac{1}{2n}$$

Optimisation

Similar to minimisation, we might have multiple objectives

- Different forms of coverage.
- Prioritising tests for historically faulty components.
- Prioritising tests for components based on fault prediction techniques.

Potential for Multi-Objective Optimisation

Test Selection

Test Selection

Minimisation aims to remove redundant tests

- **But is this the best idea in the long term?**
- A removed test may have been **useful to reveal a bug in the future**

Selection is an alternative to **minimisation**

- It's ok to keep large test suites in the codebase
- As long as which tests are run upon every change is decided carefully

Identification of affected code + Selection of tests to run

Test Selection

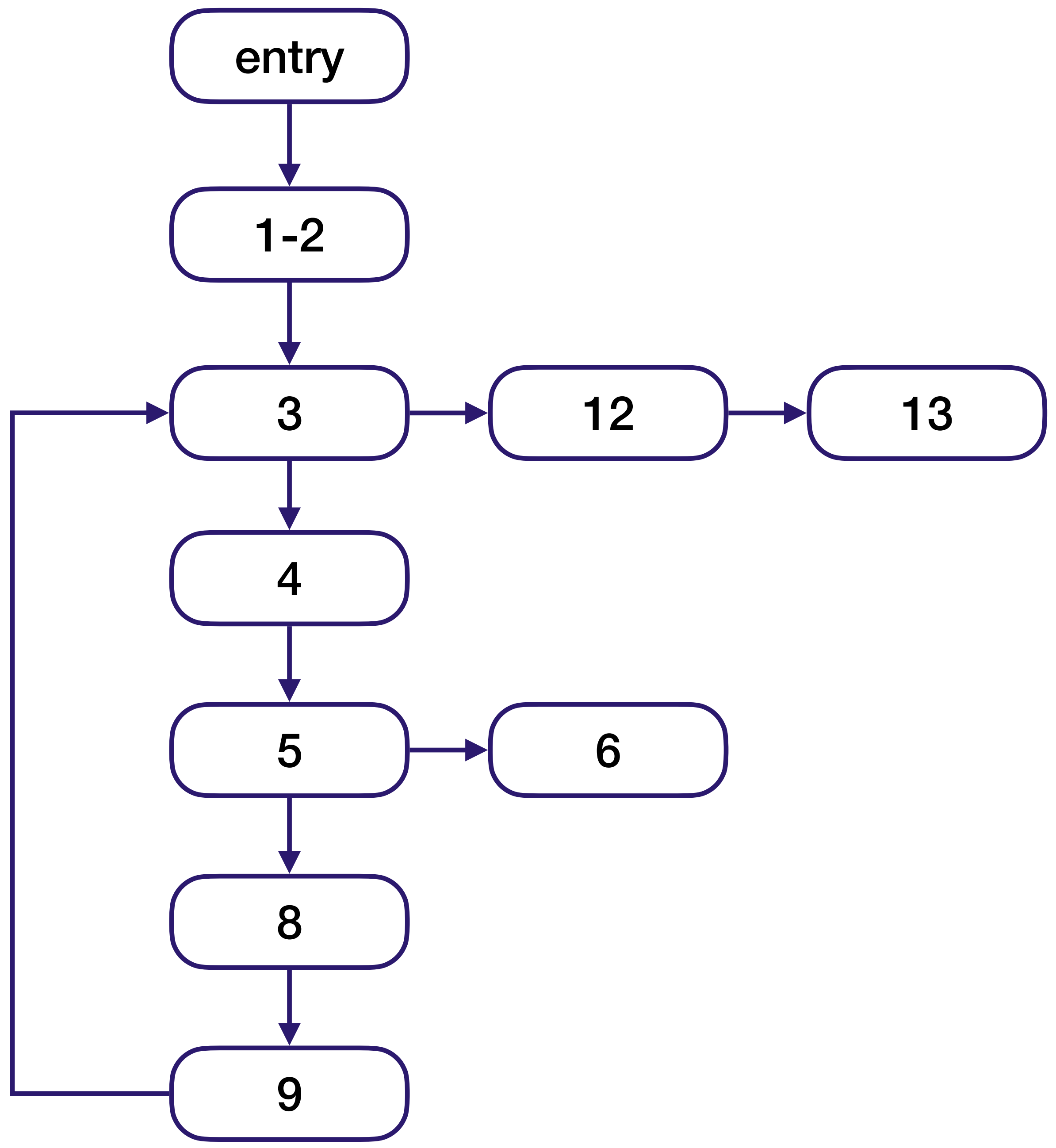
Identify **affected** code based on **parallel traversal** of the CFGs (control flow graphs) of the original and the modified versions

At each step: compare nodes for **lexicographical equivalence**

Difference found? **Select** tests traversing path from entry node to changed node, i.e., **modification-traversing tests**

An Average Example

```
public static int avg(File inputFile) throws Exception {
 1   int count = 0; int sum = 0;
 2   Scanner in = new Scanner(new FileReader(inputFile));
 3   while(in.hasNext()) {
 4       String line = in.next();
 5       if (! StringUtils.isNumeric(line)) {
 6           throw new NumberFormatException();
 7       } else {
 8           sum += Integer.parseInt(line);
 9           count++;
10       }
11   }
12   in.close();
13   return count > 0 ? sum / count : 0;
}
```



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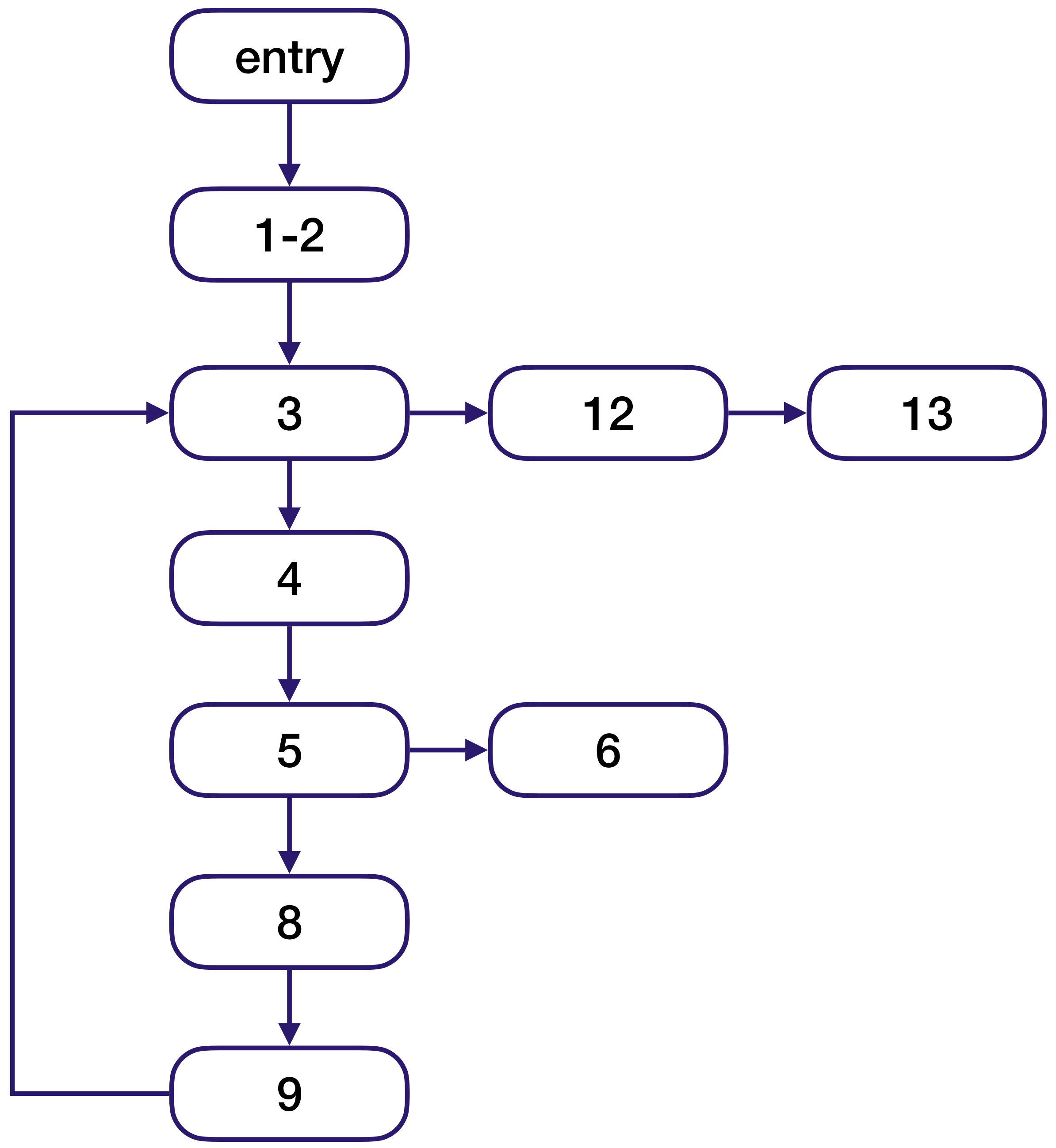

```
@Test
public void t1() throws Exception {
    assertEquals(0, TestSelection.avg(empty));
}
```

BE-AB-FH

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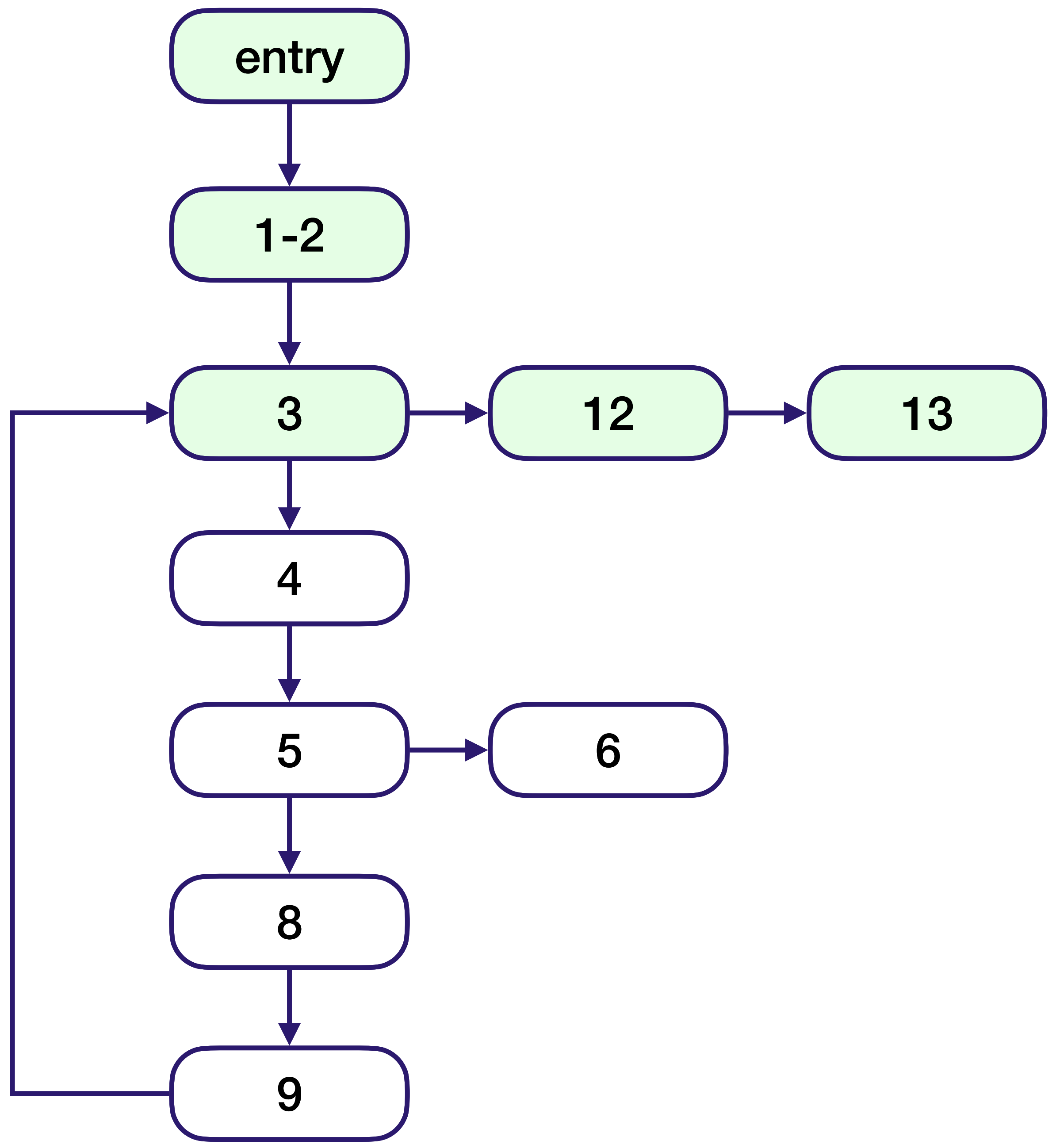

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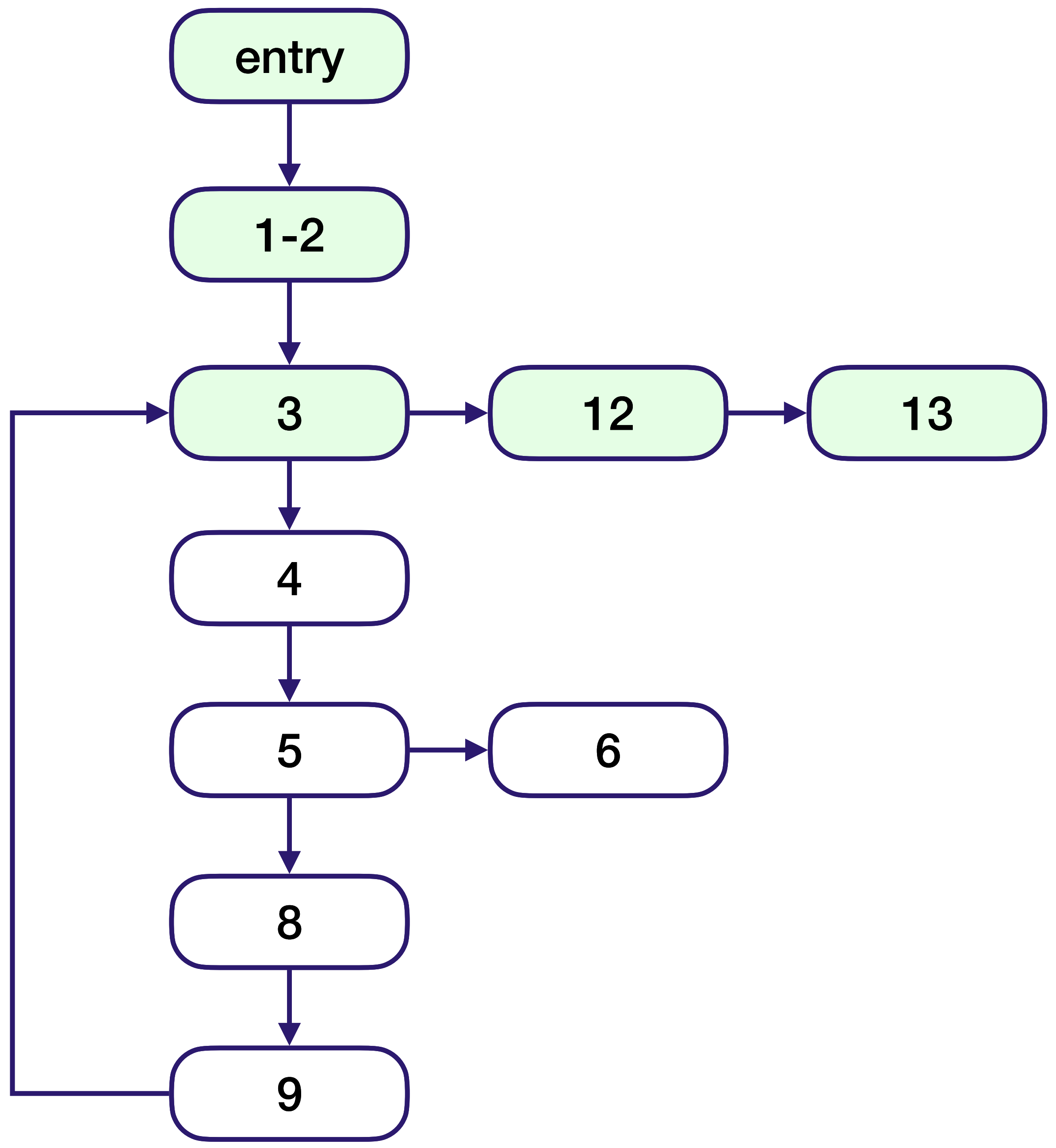
   }
```

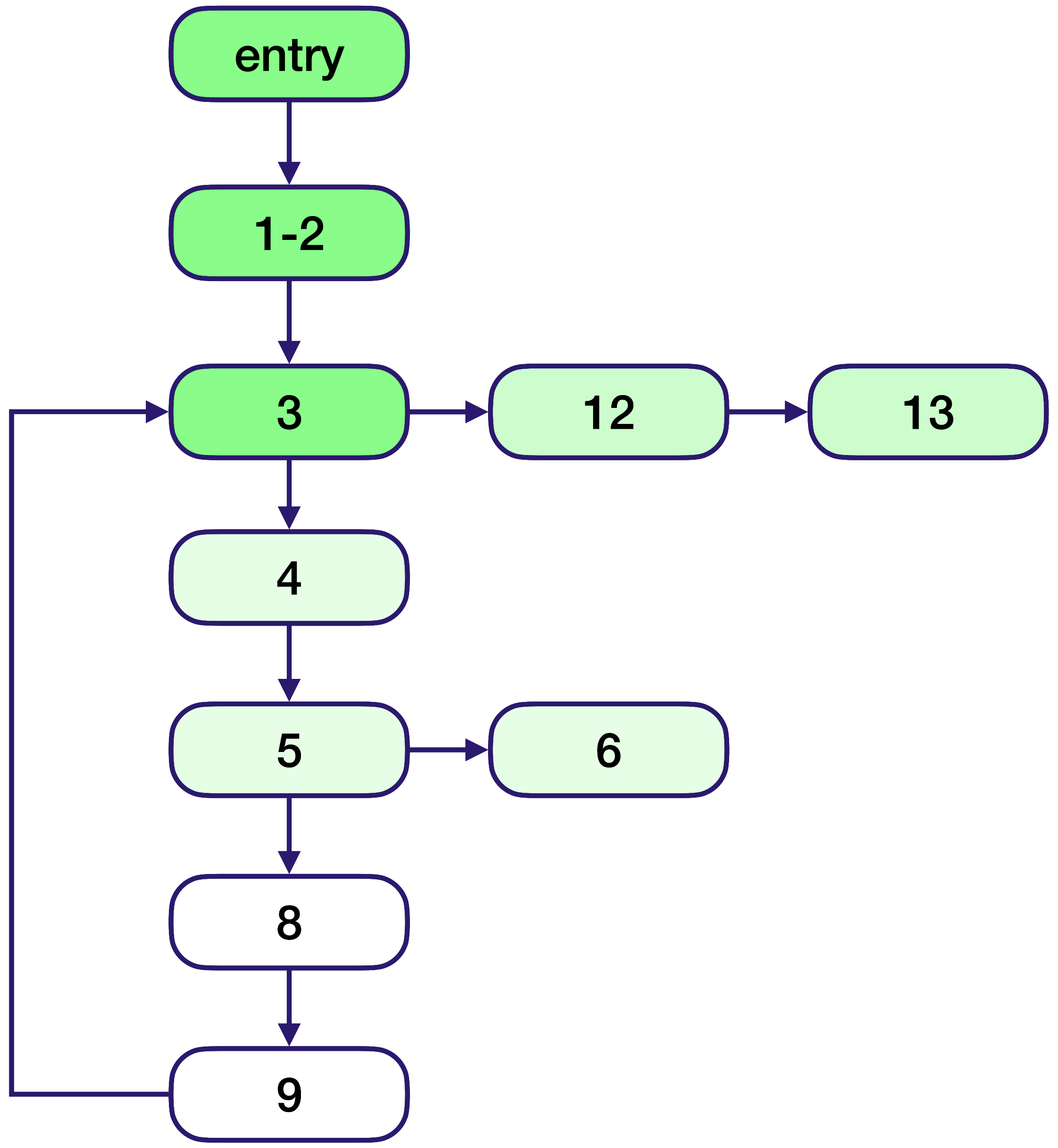


```
@Test
public void t1() throws Exception {
    assertEquals(0, TestSelection.avg(empty));
}

@Test
public void t2() throws Exception {
    assertThrows(NumberFormatException.class, () -> {
        TestSelection.avg(nonNumeric);
    });
}
```

An Average Example

```
public static int avg(File inputFile) throws Exception {
 1   int count = 0; int sum = 0;
 2   Scanner in = new Scanner(new FileReader(inputFile));
 3   while(in.hasNext()) {
 4       String line = in.next();
 5       if (! StringUtils.isNumeric(line)) {
 6           throw new NumberFormatException();
 7       } else {
 8           sum += Integer.parseInt(line);
 9           count++;
10       }
11   }
12   in.close();
13   return count > 0 ? sum / count : 0;
}
```



```
@Test
public void t1() throws Exception {
    assertEquals(0, TestSelection.avg(empty));
}

@Test
public void t2() throws Exception {
    assertThrows(NumberFormatException.class, () -> {
        TestSelection.avg(nonNumeric);
    });
}
```

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An Average Example

```
public static int avg(File inputFile) throws Exception {
 1   int count = 0; int sum = 0;
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 7       } else {
 8           sum += Integer.parseInt(line);
 9           count++;
10       }
11   }
12   in.close();
13   return count > 0 ? sum / count : 0;
}
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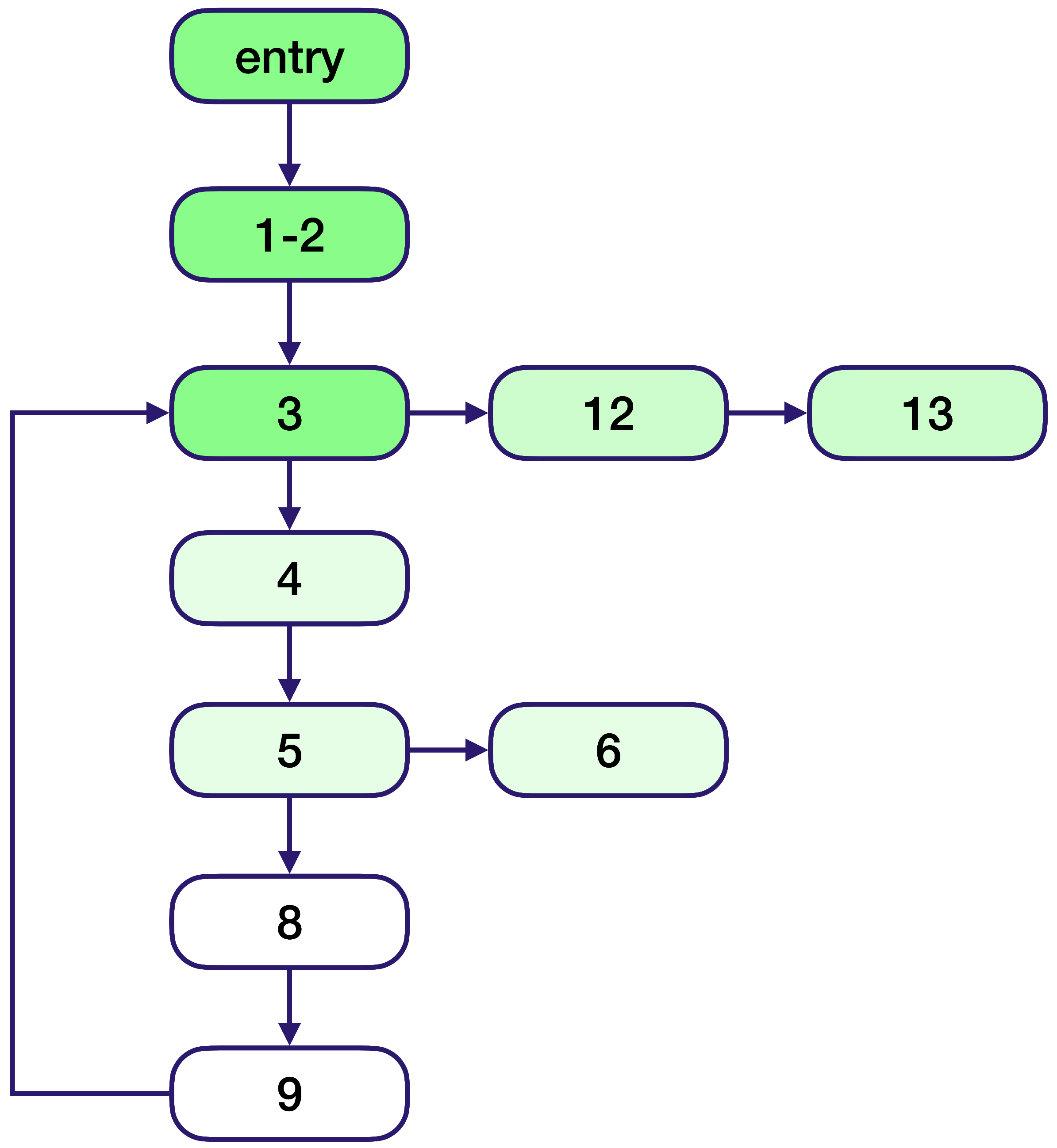


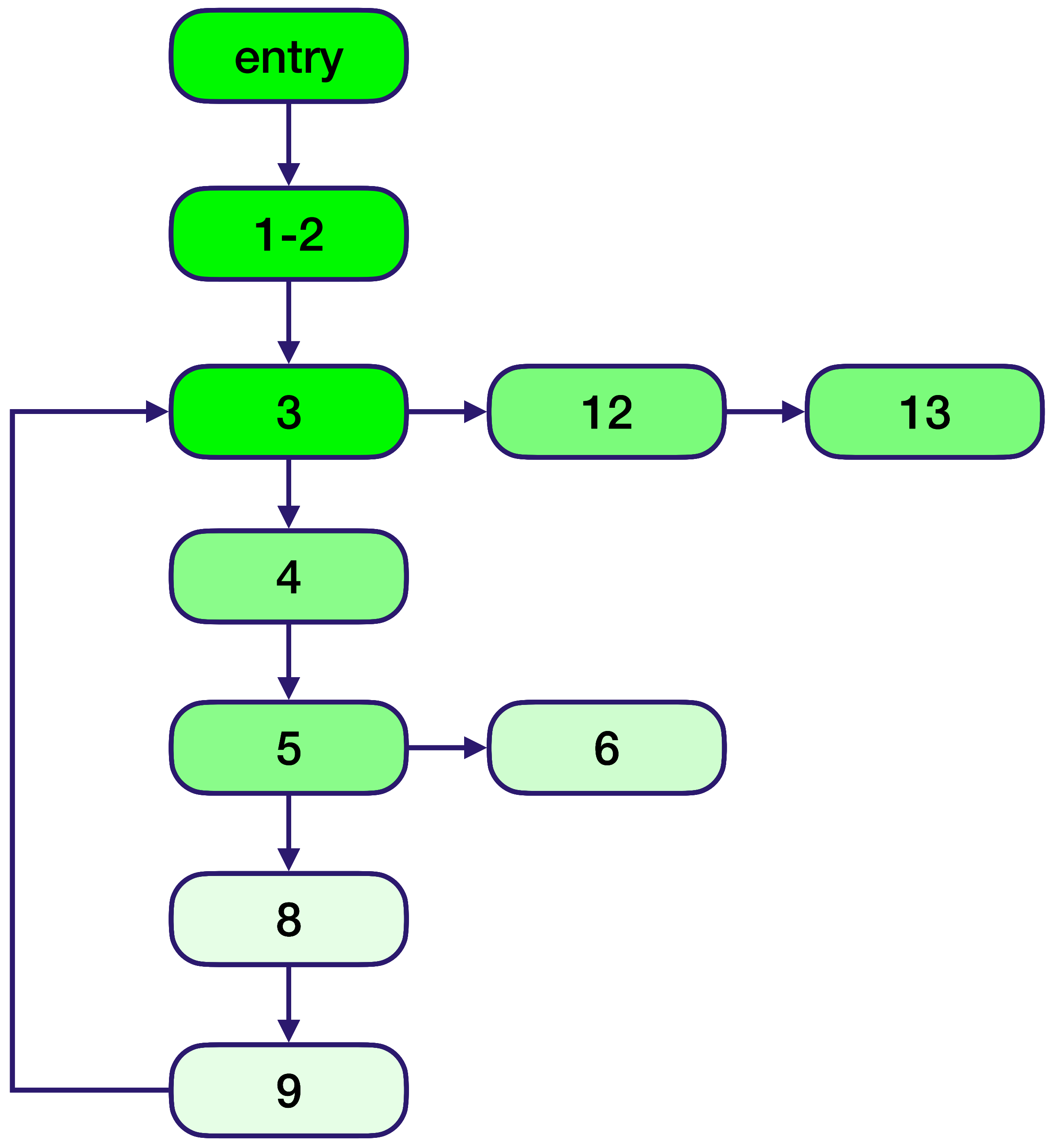
```
@Test
public void t1() throws Exception {
    assertEquals(0, TestSelection.avg(empty));
}

@Test
public void t2() throws Exception {
    assertThrows(NumberFormatException.class, () -> {
        TestSelection.avg(nonNumeric);
    });
}

@Test
public void t3() throws Exception {
    assertEquals(2, TestSelection.avg(numbers123));
}
```

An Average Example

```java
public static int avg(File inputFile) throws Exception {
 1   int count = 0; int sum = 0;
 2   Scanner in = new Scanner(new FileReader(inputFile));
 3   while(in.hasNext()) {
 4       String line = in.next();
 5       if (! StringUtils.isNumeric(line)) {
 6           throw new NumberFormatException();
 7       } else {
 8           sum += Integer.parseInt(line);
 9           count++;
10       }
11   }
12   in.close();
13   return count > 0 ? sum / count : 0;
}
```



```java
@Test
public void t1() throws Exception {
    assertEquals(0, TestSelection.avg(empty));
}

@Test
public void t2() throws Exception {
    assertThrows(NumberFormatException.class, () -> {
        TestSelection.avg(nonNumeric);
    });
}

@Test
public void t3() throws Exception {
    assertEquals(2, TestSelection.avg(numbers123));
}
```

An Average Example

```
public static int avg(File inputFile) throws Exception {
 1   int count = 0; int sum = 0;
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 3   while(in.hasNext()) {
 4       String line = in.next();
 5       if (! StringUtils.isNumeric(line)) {
 6           throw new NumberFormatException();
 7       } else {
 8           sum += Integer.parseInt(line);
 9           count++;
10       }
11   }
12   in.close();
13   return count > 0 ? sum / count : 0;
}
```

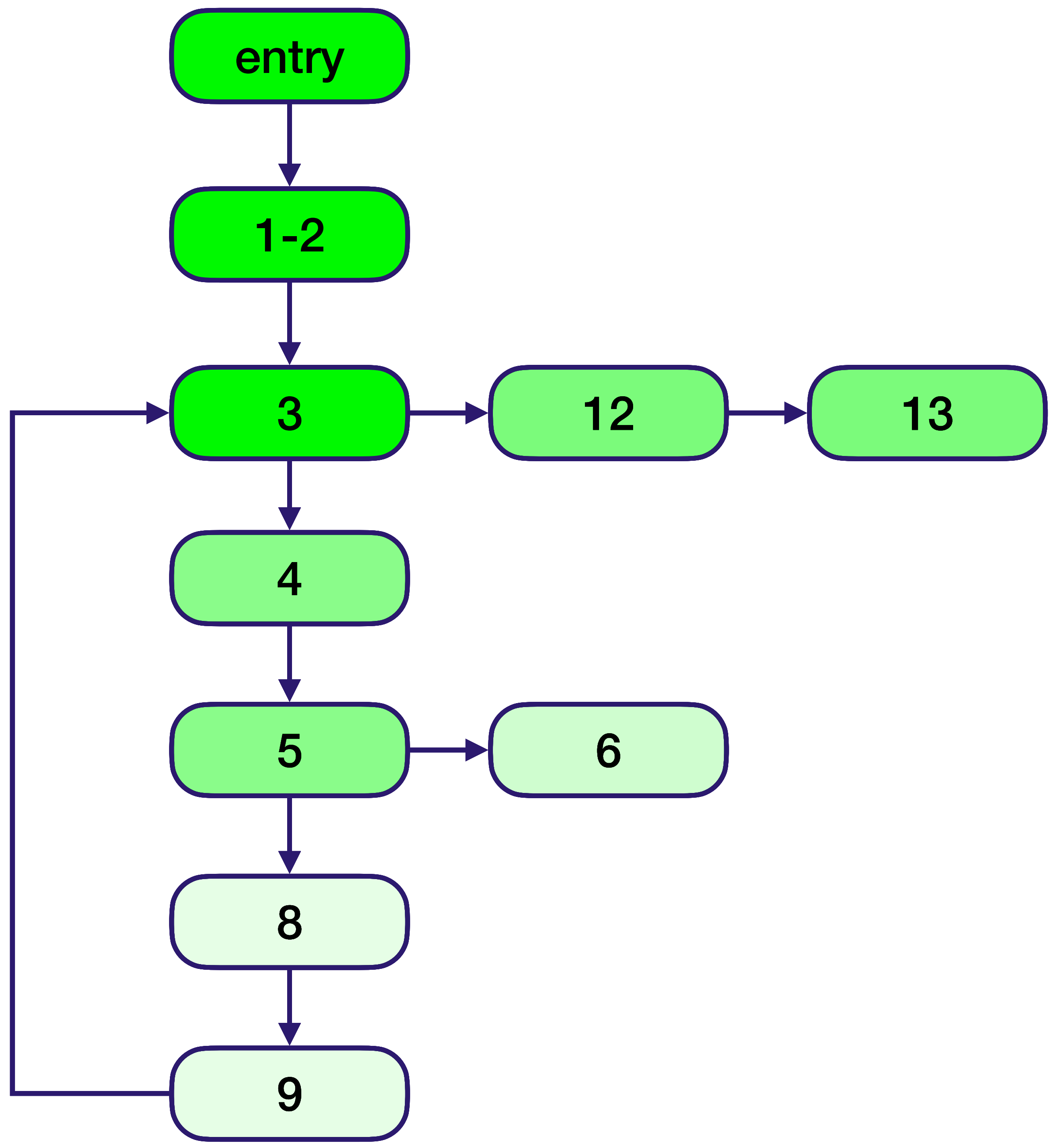

```
@Test
public void t1() throws Exception {
    assertEquals(0, TestSelection.avg(empty));
}

@Test
public void t2() throws Exception {
    assertThrows(NumberFormatException.class, () -> {
        TestSelection.avg(nonNumeric);
    });
}

@Test
public void t3() throws Exception {
    assertEquals(2, TestSelection.avg(numbers123));
}
```

Test	Edges Traversed

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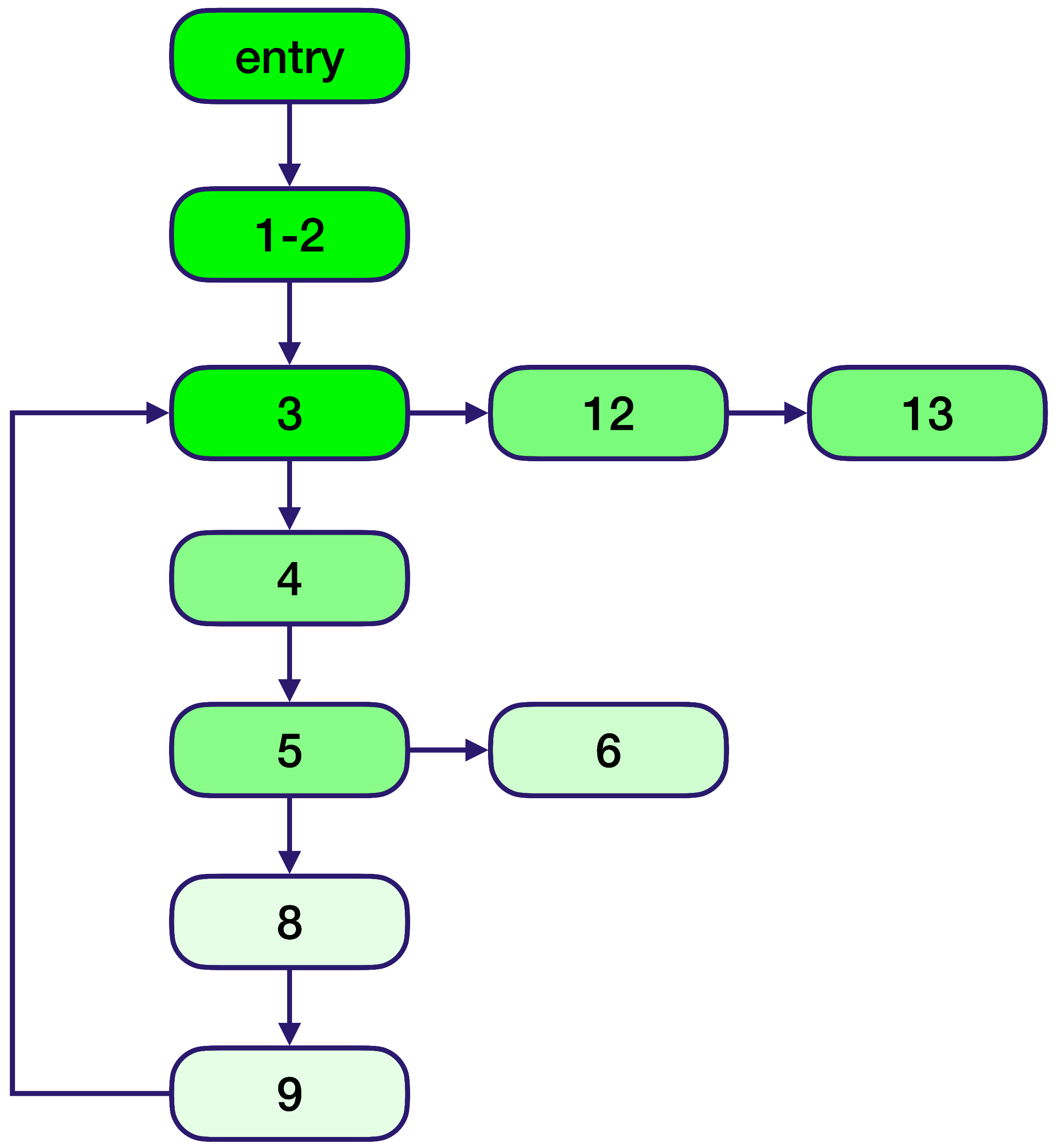
An Average Example

```
public static int avg(File inputFile) throws Exception {
 1   int count = 0; int sum = 0;
 2   Scanner in = new Scanner(new FileReader(inputFile));
 3   while(in.hasNext()) {
 4       String line = in.next();
 5       if (! StringUtils.isNumeric(line)) {
 6           throw new NumberFormatException();
 7       } else {
 8           sum += Integer.parseInt(line);
 9           count++;
10       }
11   }
12   in.close();
13   return count > 0 ? sum / count : 0;
}
```



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        TestSelection.avg(nonNumeric);
    });
}

@Test
public void t3() throws Exception {
    assertEquals(2, TestSelection.avg(numbers123));
}
```

Test	Edges Traversed
t1	(entry, 1-2), (1-2, 3), (3, 12), (12, 13)

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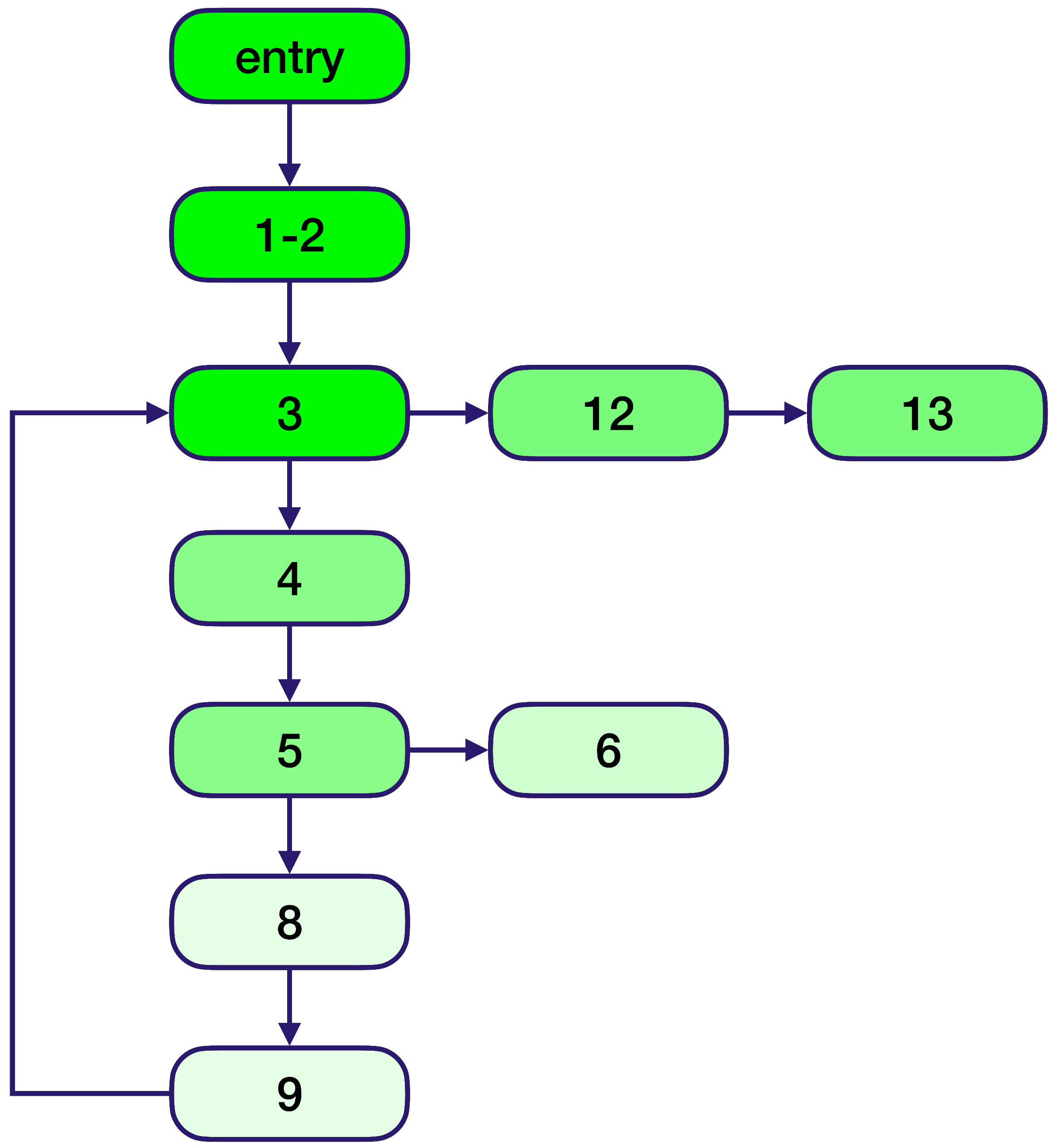
An Average Example

```
public static int avg(File inputFile) throws Exception {
 1  int count = 0; int sum = 0;
 2  Scanner in = new Scanner(new FileReader(inputFile));
 3  while(in.hasNext()) {
 4      String line = in.next();
 5      if (! StringUtils.isNumeric(line)) {
 6          throw new NumberFormatException();
 7      } else {
 8          sum += Integer.parseInt(line);
 9          count++;
10      }
11  }
12  in.close();
13  return count > 0 ? sum / count : 0;
}
```



```
@Test
public void t1() throws Exception {
    assertEquals(0, TestSelection.avg(empty));
}

@Test
public void t2() throws Exception {
    assertThrows(NumberFormatException.class, () -> {
        TestSelection.avg(nonNumeric);
    });
}

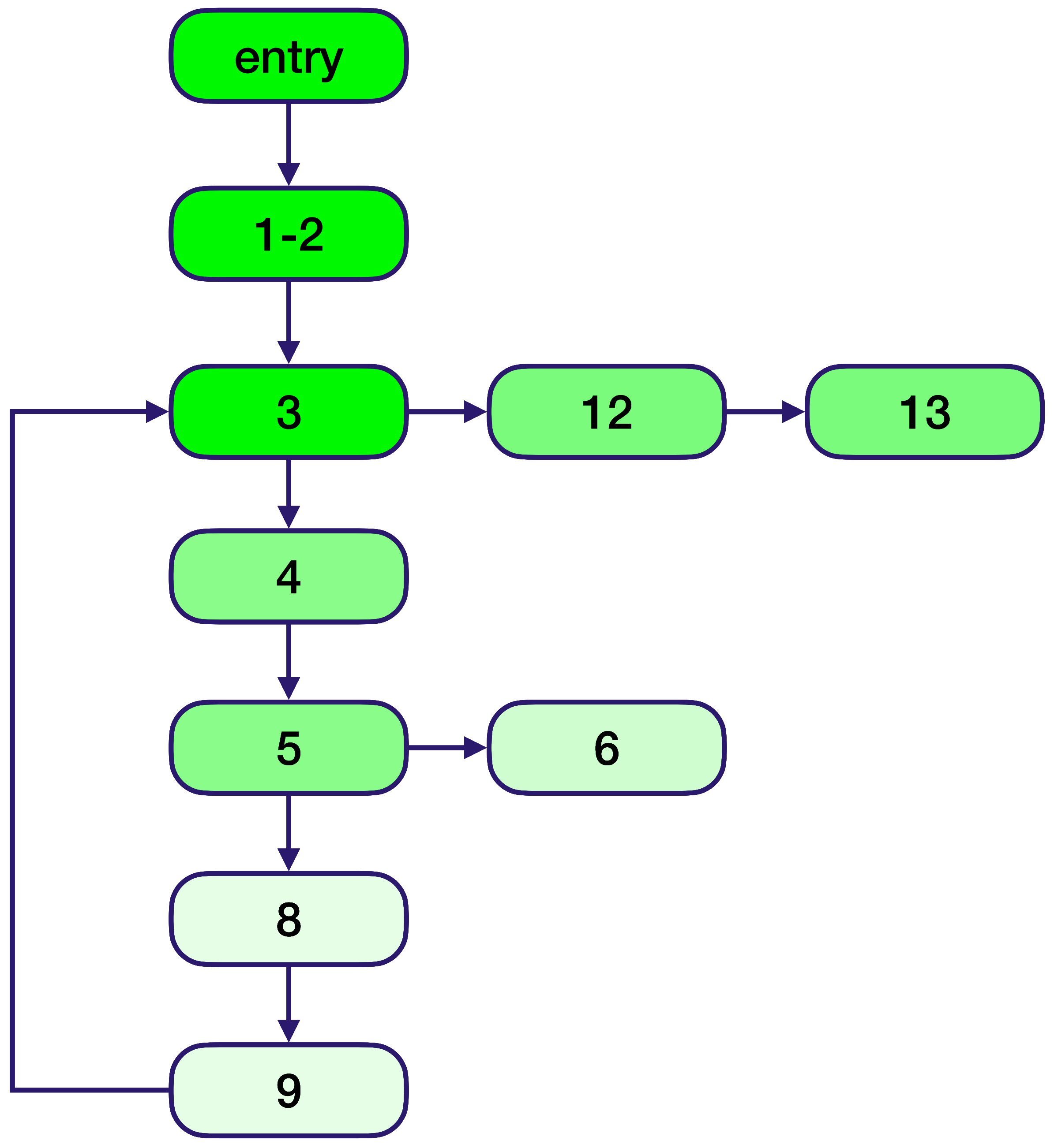
@Test
public void t3() throws Exception {
    assertEquals(2, TestSelection.avg(numbers123));
}
```

Test	Edges Traversed
t1	(entry, 1-2), (1-2, 3), (3, 12), (12, 13)
t2	(entry, 1-2), (1-2, 3), (3, 4), (4, 5), (5, 6)

BE-AB-FH

An Average Example

```
public static int avg(File inputFile) throws Exception {
 1  int count = 0; int sum = 0;
 2  Scanner in = new Scanner(new FileReader(inputFile));
 3  while(in.hasNext()) {
 4      String line = in.next();
 5      if (! StringUtils.isNumeric(line)) {
 6          throw new NumberFormatException();
 7      } else {
 8          sum += Integer.parseInt(line);
 9          count++;
10      }
11  }
12  in.close();
13  return count > 0 ? sum / count : 0;
}
```



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@Test
public void t1() throws Exception {
    assertEquals(0, TestSelection.avg(empty));
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    });
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public void t3() throws Exception {
    assertEquals(2, TestSelection.avg(numbers123));
}
```

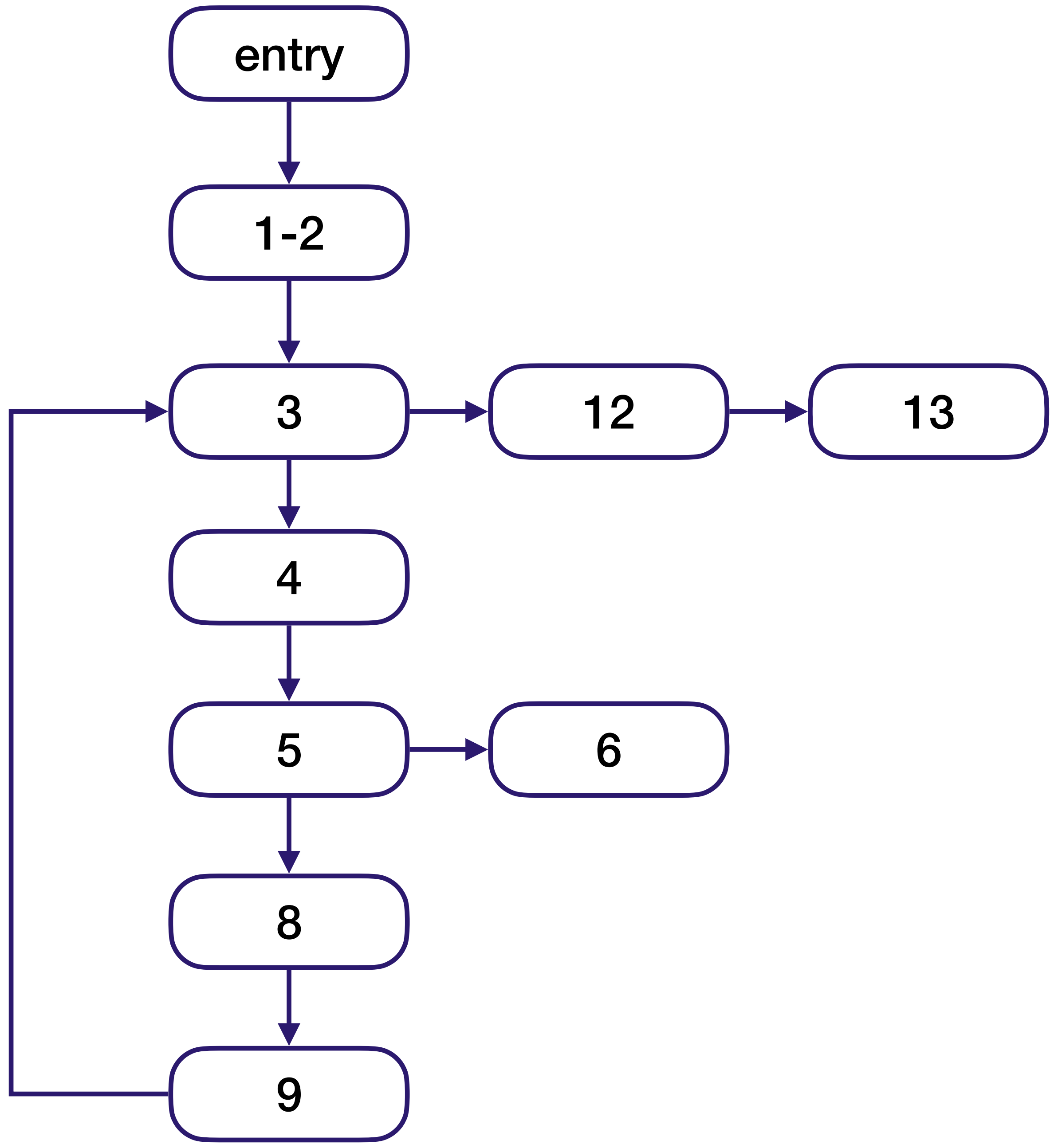
Test	Edges Traversed
t1	(entry, 1-2), (1-2, 3), (3, 12), (12, 13)
t2	(entry, 1-2), (1-2, 3), (3, 4), (4, 5), (5, 6)
t3	(entry, 1-2), (1-2, 3), (3, 4), (4, 5), (5, 8), (8, 9), (9, 3), (3, 12), (12, 13)

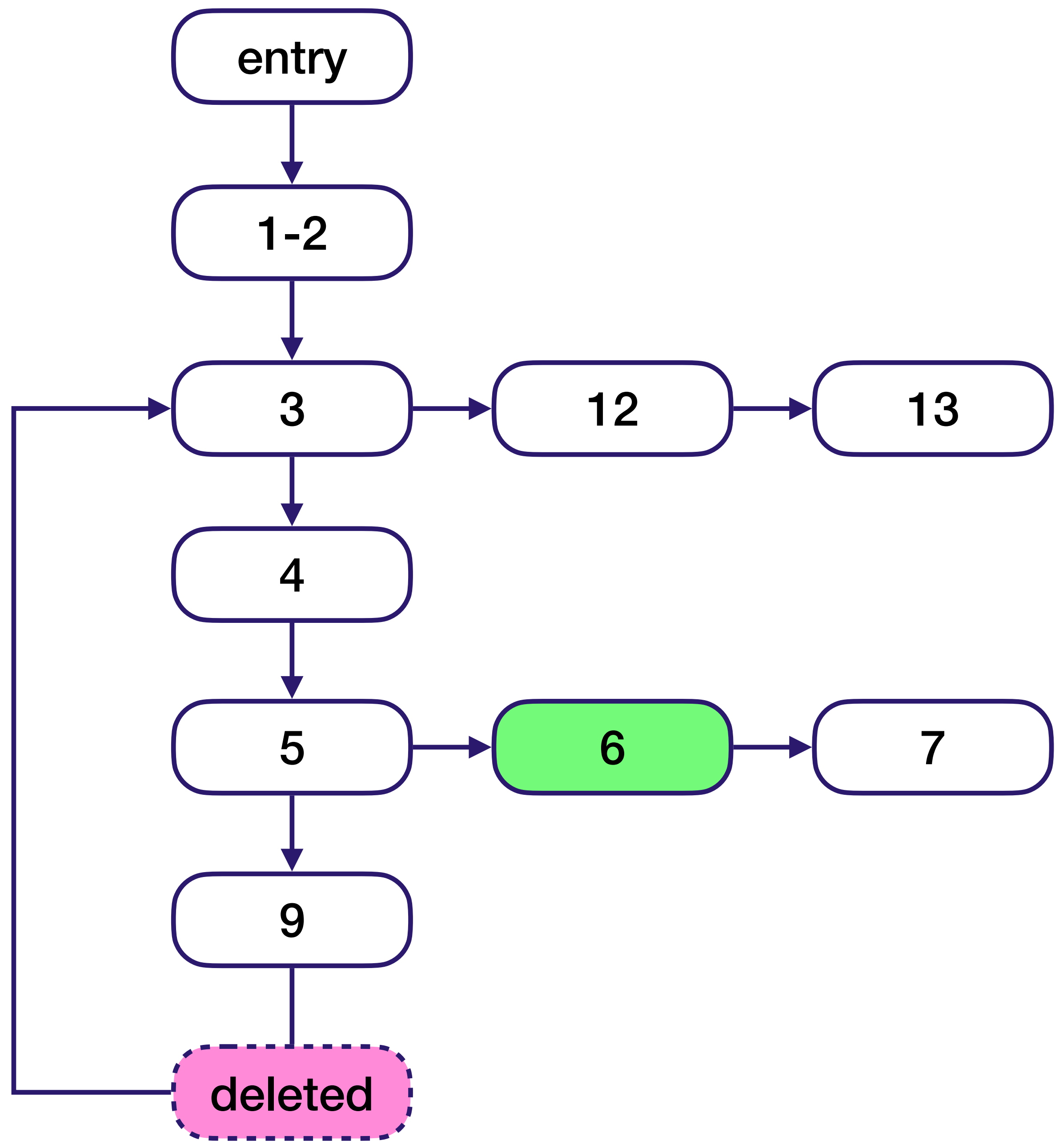
BE-AB-FH

An Average Example

```
public static int avg(File inputFile) throws Exception {
 1  int count = 0; int sum = 0;
 2  Scanner in = new Scanner(new FileReader(inputFile));
 3  while(in.hasNext()) {
 4      String line = in.next();
 5      if (! StringUtils.isNumeric(line)) {
 6          throw new Exception();
 7      } else {
 8          sum += Integer.parseInt(line);
 9          count++;
10      }
11  }
12  in.close();
13  return count > 0 ? sum / count : 0;
}
```

```
public static int avg(File inputFile) throws Exception {
 1  int count = 0; int sum = 0;
 2  Scanner in = new Scanner(new FileReader(inputFile));
 3  while(in.hasNext()) {
 4      String line = in.next();
 5      if (! StringUtils.isNumeric(line)) {
 6          System.err.println("Bad input");
 7          throw new Exception();
 8      } else {
 9          sum += Integer.parseInt(line);
10      }
11  }
12  in.close();
13  return count > 0 ? sum / count : 0;
}
```





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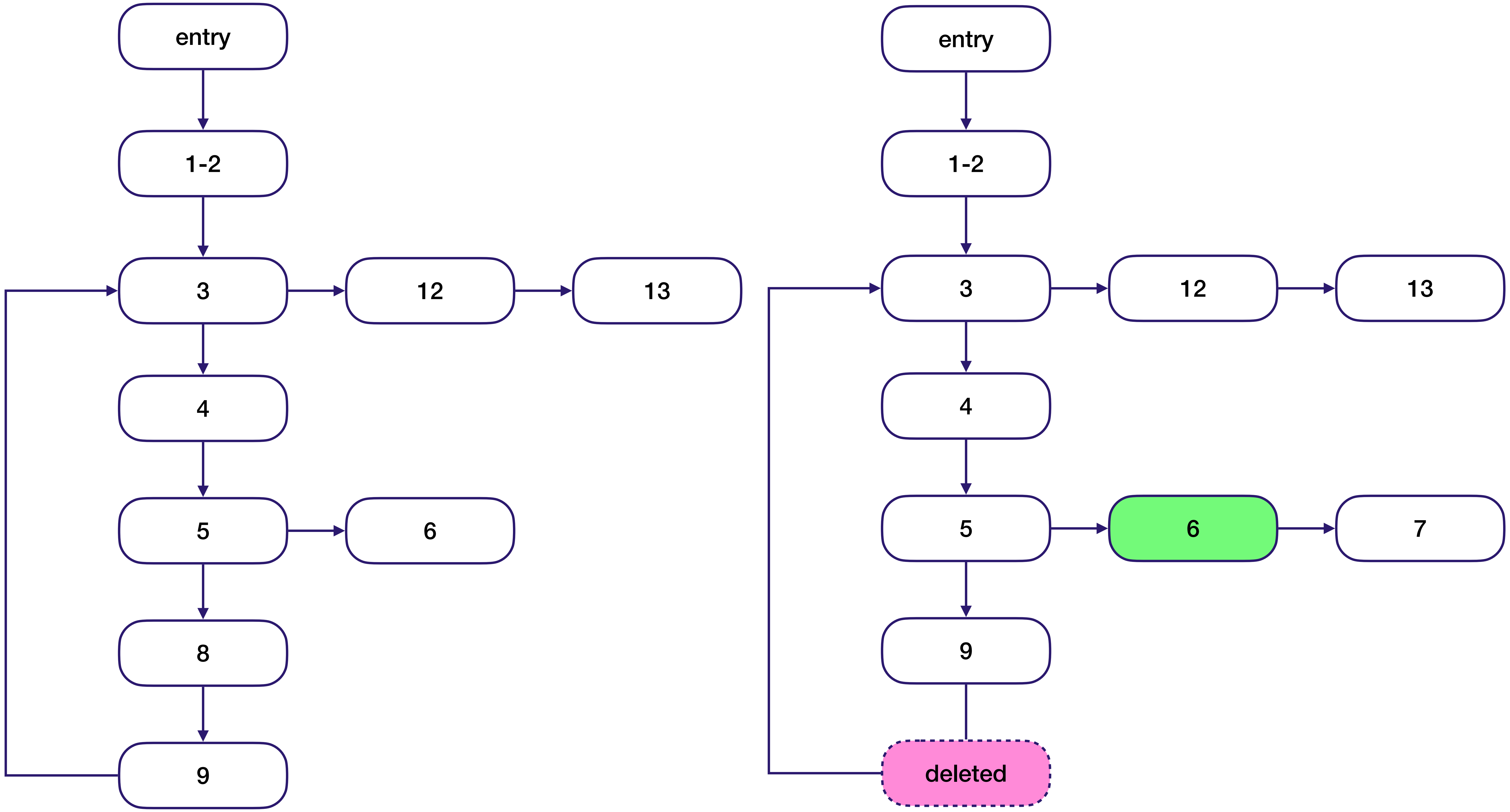
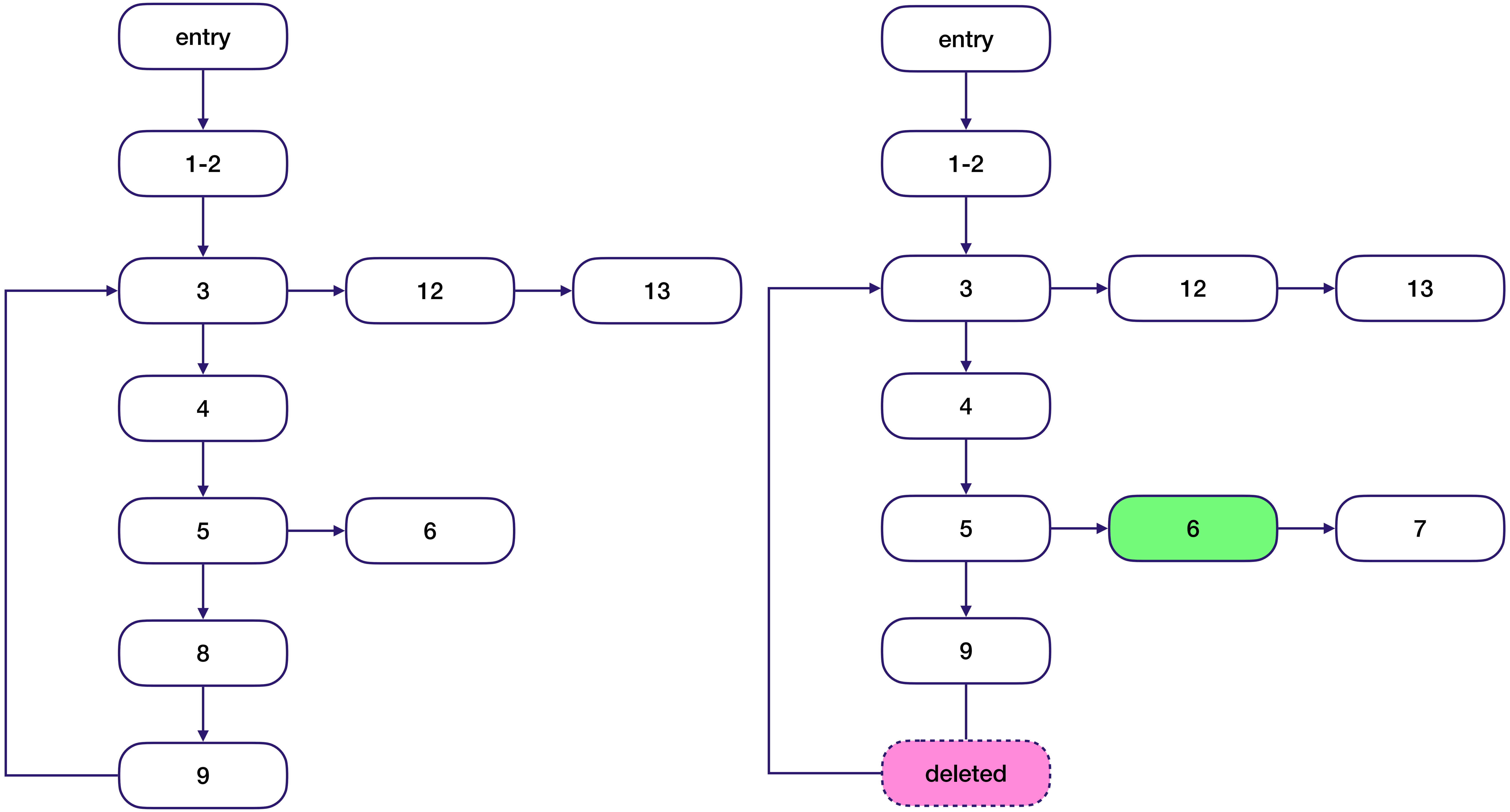
An Average Example



Test	Edges Traversed
t1	(entry, 1-2), (1-2, 3), (3, 12), (12, 13)
t2	(entry, 1-2), (1-2, 3), (3, 4), (4, 5), (5, 6)
t3	(entry, 1-2), (1-2, 3), (3, 4), (4, 5), (5, 8), (8, 9), (9, 3), (3, 12), (12, 13)

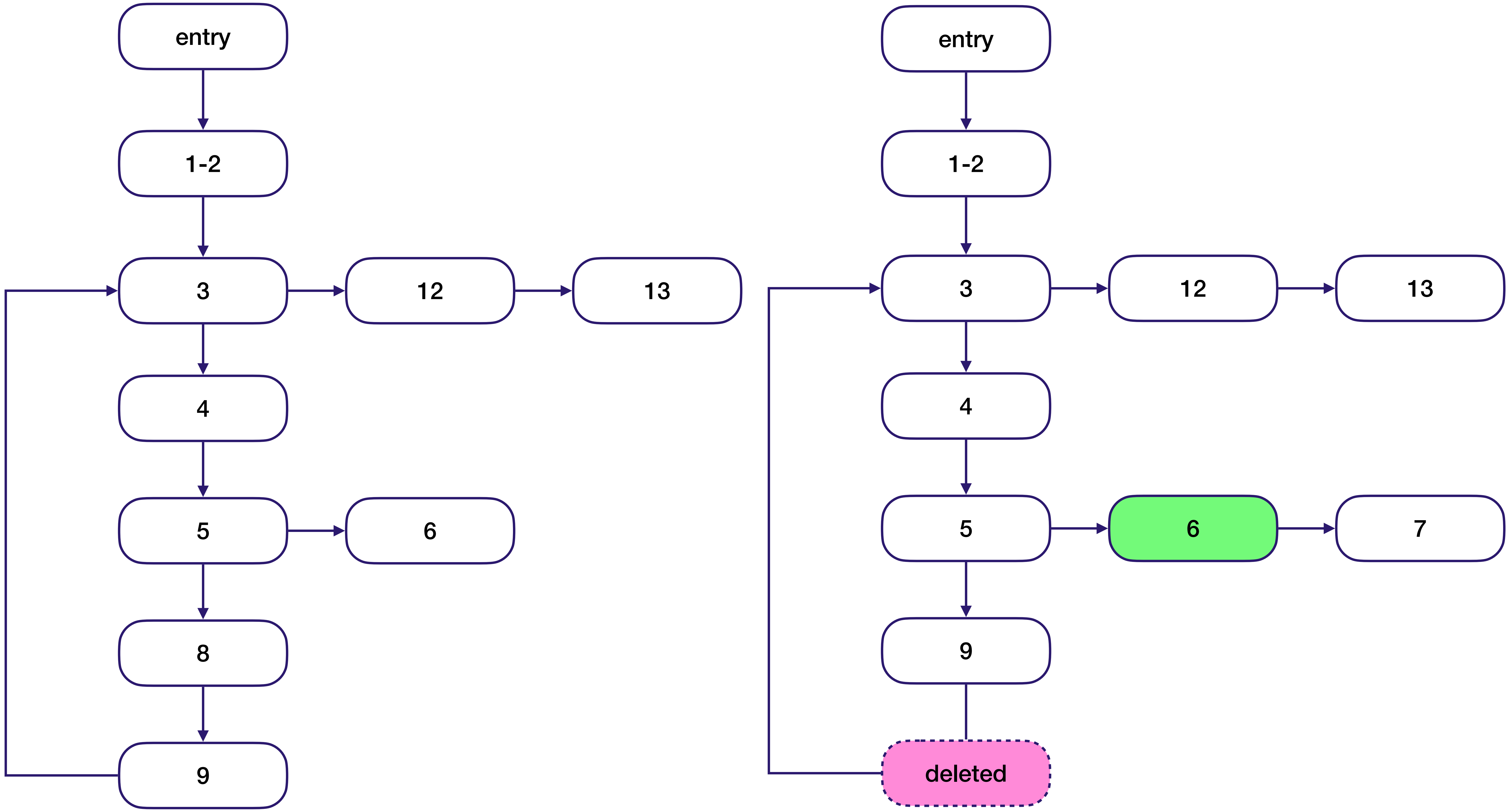
An Average Example

Start with **selection** = ∅



Test	Edges Traversed
t1	(entry, 1-2), (1-2, 3), (3, 12), (12, 13)
t2	(entry, 1-2), (1-2, 3), (3, 4), (4, 5), (5, 6)
t3	(entry, 1-2), (1-2, 3), (3, 4), (4, 5), (5, 8), (8, 9), (9, 3), (3, 12), (12, 13)

An Average Example

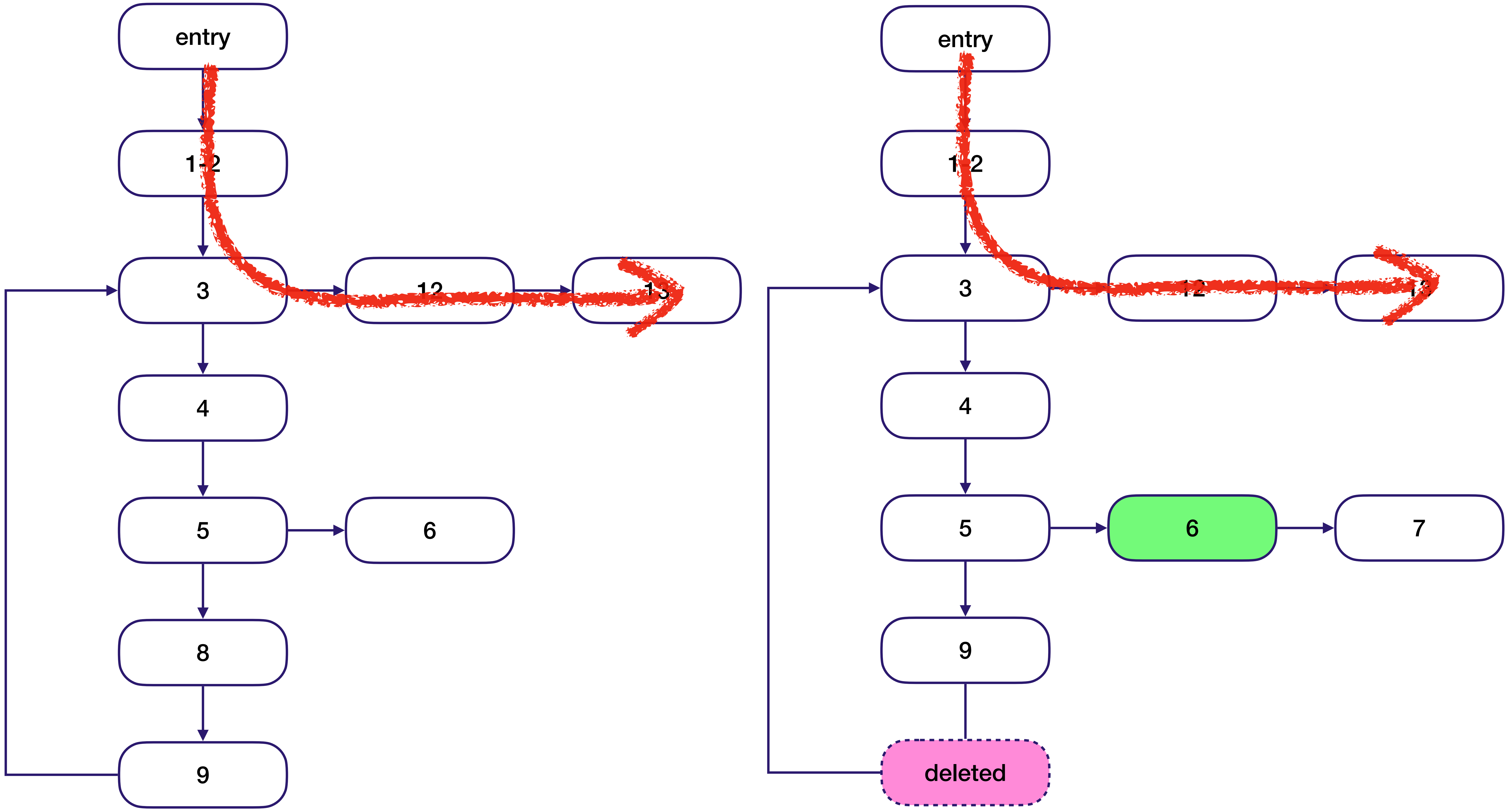


Start with **selection = ∅**

Traverse CFGs in parallel

Test	Edges Traversed
t1	(entry, 1-2), (1-2, 3), (3, 12), (12, 13)
t2	(entry, 1-2), (1-2, 3), (3, 4), (4, 5), (5, 6)
t3	(entry, 1-2), (1-2, 3), (3, 4), (4, 5), (5, 8), (8, 9), (9, 3), (3, 12), (12, 13)

An Average Example



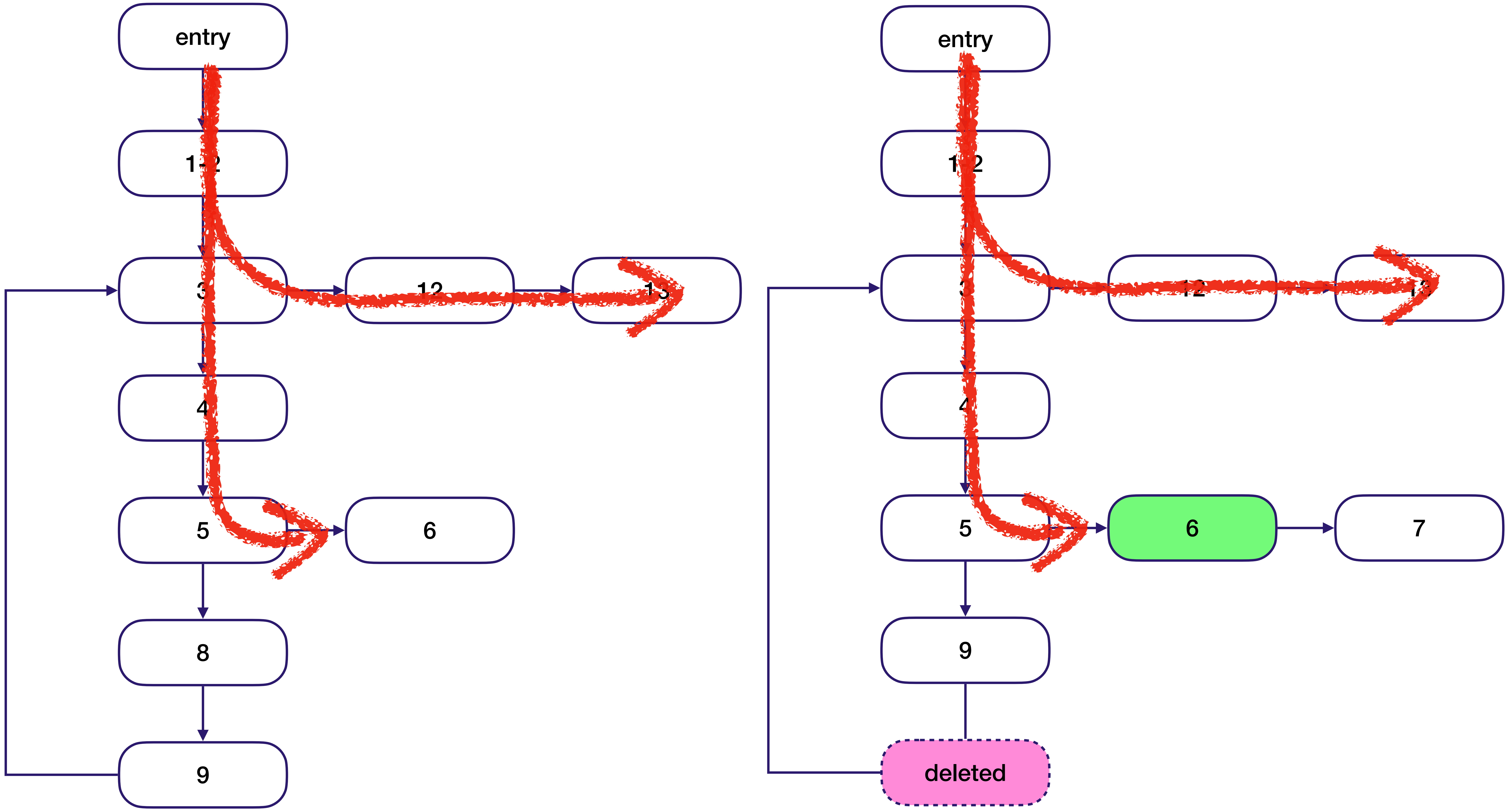
Start with **selection = ∅**

Traverse CFGs in parallel

To spot differences

Test	Edges Traversed
t1	(entry, 1-2), (1-2, 3), (3, 12), (12, 13)
t2	(entry, 1-2), (1-2, 3), (3, 4), (4, 5), (5, 6)
t3	(entry, 1-2), (1-2, 3), (3, 4), (4, 5), (5, 8), (8, 9), (9, 3), (3, 12), (12, 13)

An Average Example



Start with **selection = ∅**

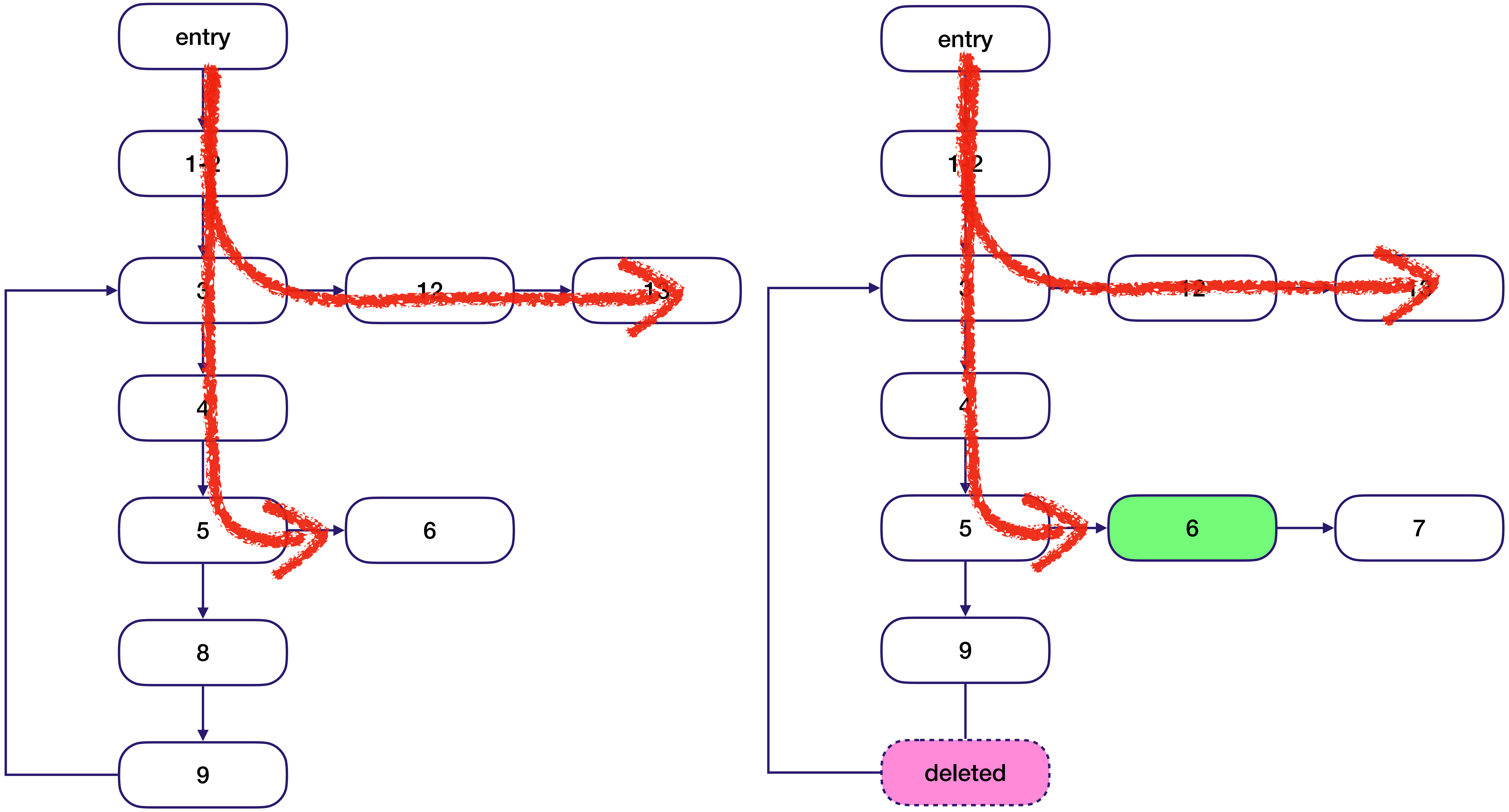
Traverse CFGs in parallel

To spot differences

Once difference is found

Test	Edges Traversed
t1	(entry, 1-2), (1-2, 3), (3, 12), (12, 13)
t2	(entry, 1-2), (1-2, 3), (3, 4), (4, 5), (5, 6)
t3	(entry, 1-2), (1-2, 3), (3, 4), (4, 5), (5, 8), (8, 9), (9, 3), (3, 12), (12, 13)

An Average Example



Start with **selection = ∅**

Traverse CFGs in parallel

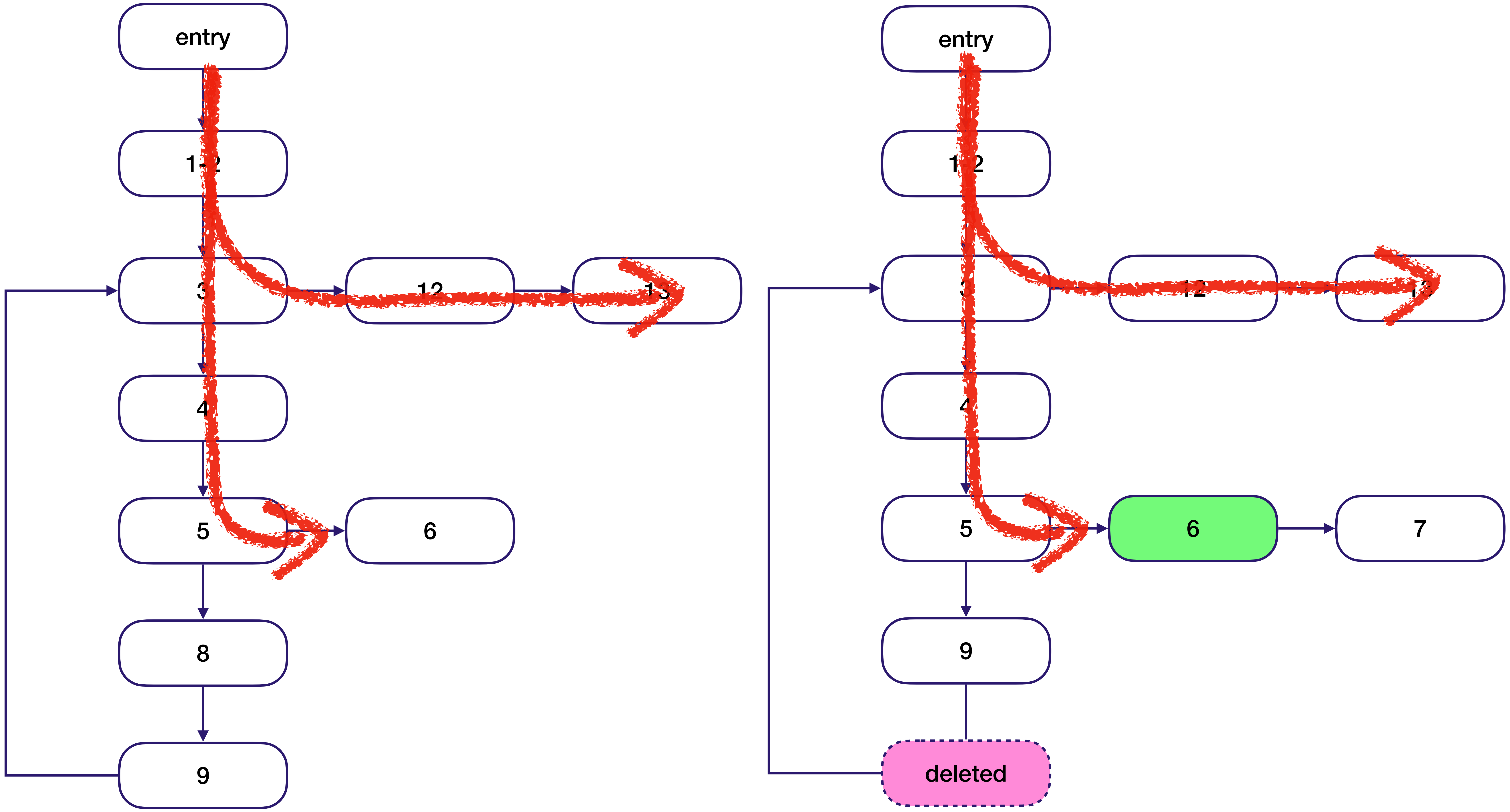
To spot differences

Once difference is found

Add test to selection

Test	Edges Traversed
t1	(entry, 1-2), (1-2, 3), (3, 12), (12, 13)
t2	(entry, 1-2), (1-2, 3), (3, 4), (4, 5), (5, 6)
t3	(entry, 1-2), (1-2, 3), (3, 4), (4, 5), (5, 8), (8, 9), (9, 3), (3, 12), (12, 13)

An Average Example



Start with **selection = ∅**

Traverse CFGs in parallel

To spot differences

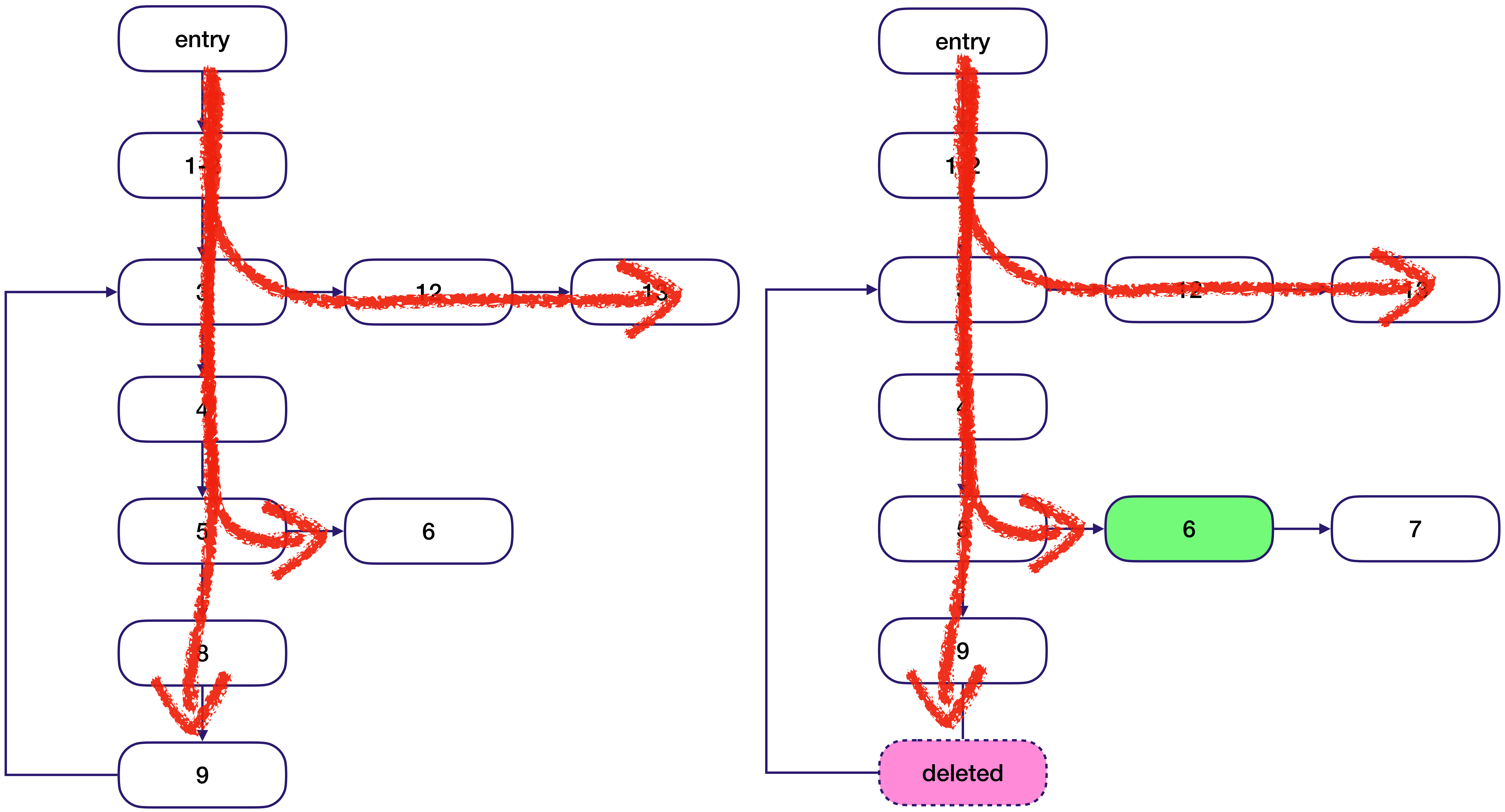
Once difference is found

Add test to selection

selection = { t2 }

Test	Edges Traversed
t1	(entry, 1-2), (1-2, 3), (3, 12), (12, 13)
t2	(entry, 1-2), (1-2, 3), (3, 4), (4, 5), (5, 6)
t3	(entry, 1-2), (1-2, 3), (3, 4), (4, 5), (5, 8), (8, 9), (9, 3), (3, 12), (12, 13)

An Average Example



Start with **selection = ∅**

Traverse CFGs in parallel

To spot differences

Once difference is found

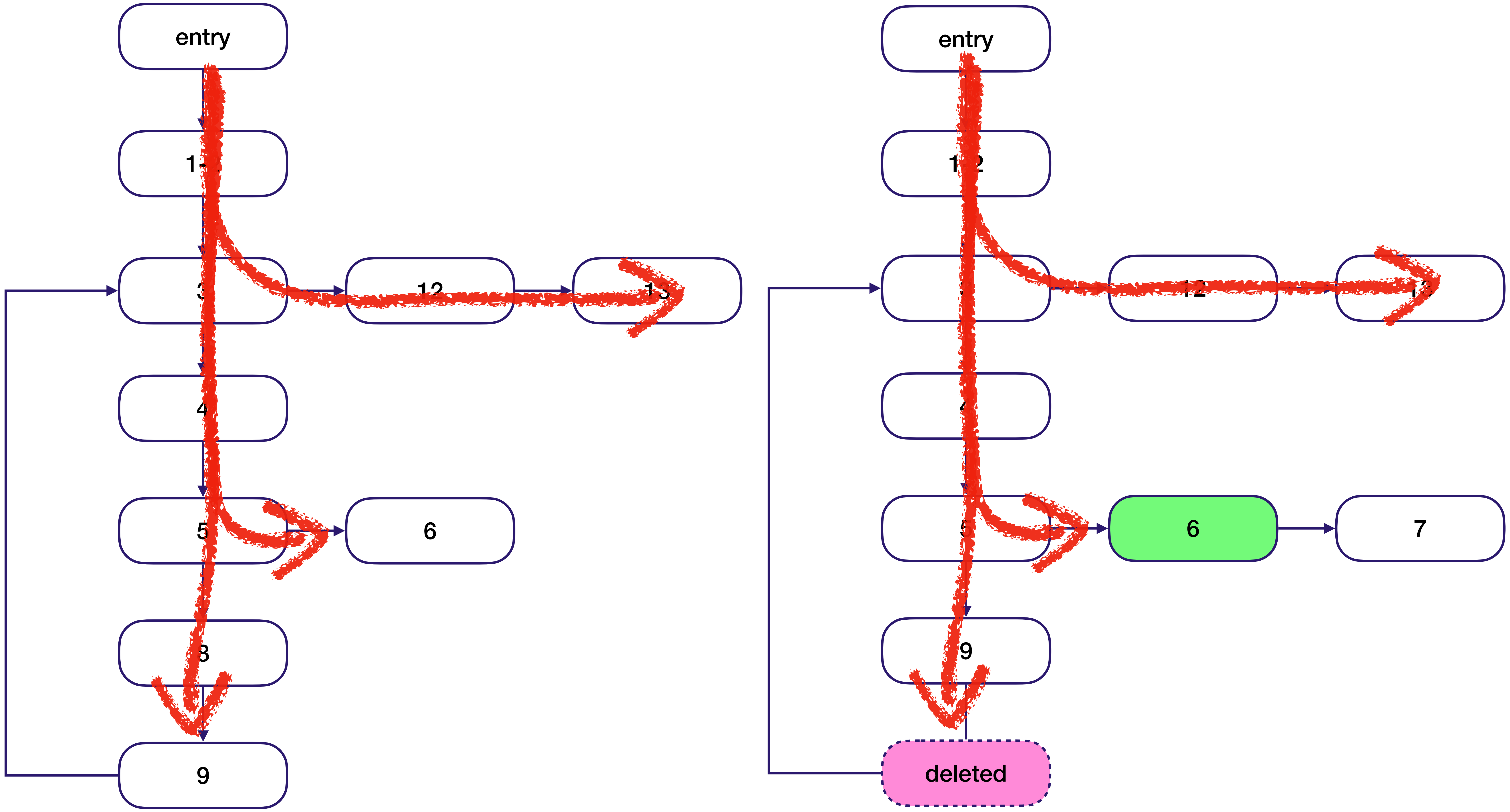
Add test to selection

selection = { t2 }

Repeat recursively

Test	Edges Traversed
t1	(entry, 1-2), (1-2, 3), (3, 12), (12, 13)
t2	(entry, 1-2), (1-2, 3), (3, 4), (4, 5), (5, 6)
t3	(entry, 1-2), (1-2, 3), (3, 4), (4, 5), (5, 8), (8, 9), (9, 3), (3, 12), (12, 13)

An Average Example



Start with **selection = ∅**

Traverse CFGs in parallel

To spot differences

Once difference is found

Add test to selection

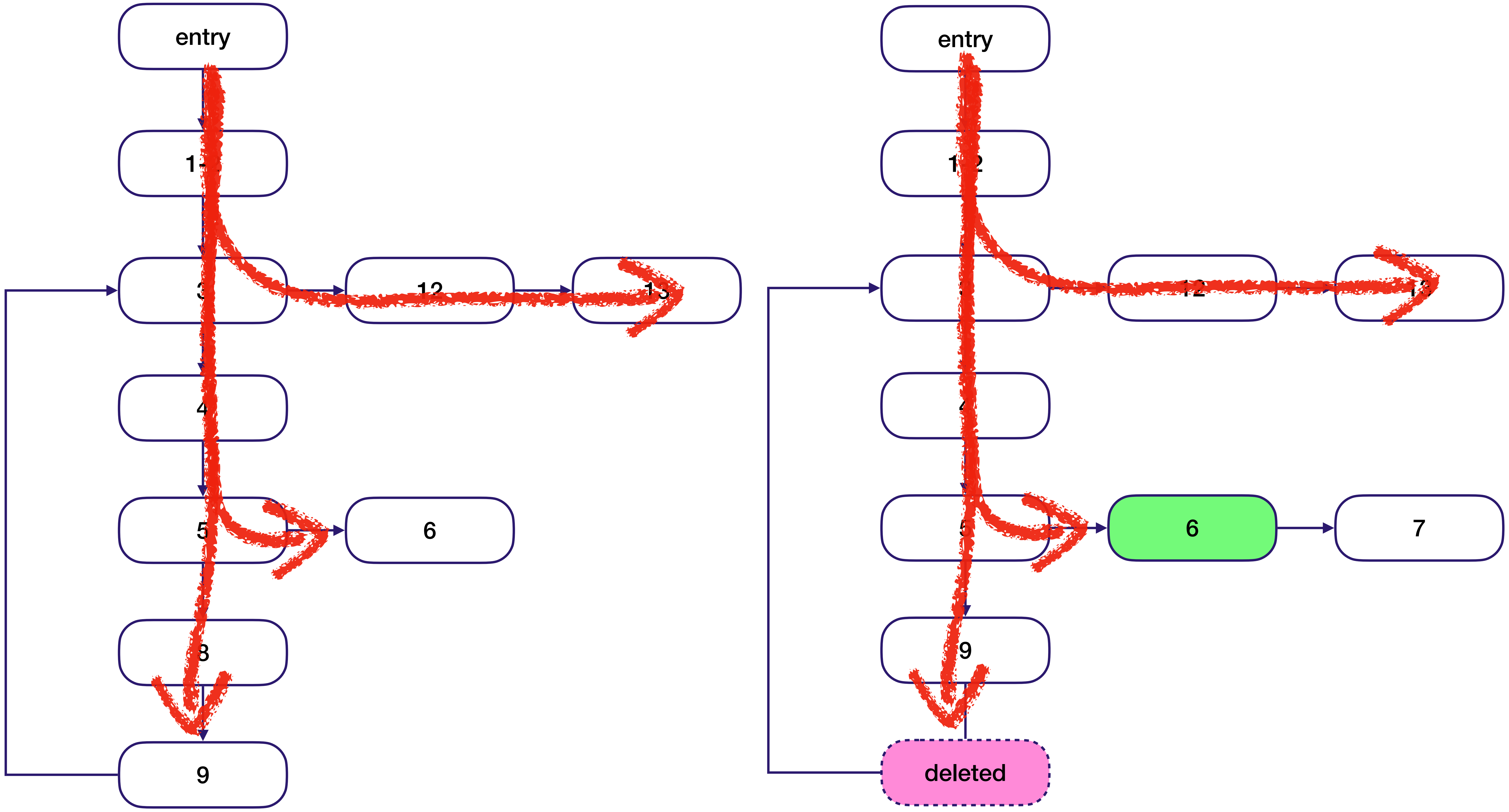
selection = { t2 }

Repeat recursively

selection = { t2, t3 }

Test	Edges Traversed
t1	(entry, 1-2), (1-2, 3), (3, 12), (12, 13)
t2	(entry, 1-2), (1-2, 3), (3, 4), (4, 5), (5, 6)
t3	(entry, 1-2), (1-2, 3), (3, 4), (4, 5), (5, 8), (8, 9), (9, 3), (3, 12), (12, 13)

An Average Example



Test	Edges Traversed
t1	(entry, 1-2), (1-2, 3), (3, 12), (12, 13)
t2	(entry, 1-2), (1-2, 3), (3, 4), (4, 5), (5, 6)
t3	(entry, 1-2), (1-2, 3), (3, 4), (4, 5), (5, 8), (8, 9), (9, 3), (3, 12), (12, 13)

Start with **selection = ∅**

Traverse CFGs in parallel

To spot differences

Once difference is found

Add test to selection

selection = { t2 }

Repeat recursively

selection = { t2, t3 }

Complete traversal of CFGs

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Research Highlights

Harrold MJ, Gupta R, Soffa ML. **A methodology for controlling the size of a test suite**. ACM Transactions on Software Engineering and Methodology (TOSEM) 2(3):270–285 (1993)

Hadi Hemmati: **Chapter Four - Advances in Techniques for Test Prioritization**. Advances in Computing, vol 112: 185-221 (2019).

Rothermel G, Harrold MJ. **A safe, efficient regression test selection technique**. ACM Transactions on Software Engineering and Methodology (TOSEM) 6(2):173–210 (1997)

Summary

- Multiple scenarios in which test suites will be used
  - Continuous Integration helps with automation of test execution
  - **Regression Testing** helps **find bugs** early
- Benefits to minimisation, prioritisation and selection
  - Simple heuristics – Can be expressed as **optimisation problems**
  - Many different approaches, from simple greedy algorithms to multi-objective evolutionary algorithms