Automated Documentation Inference to Explain Failed Tests

Sai Zhang

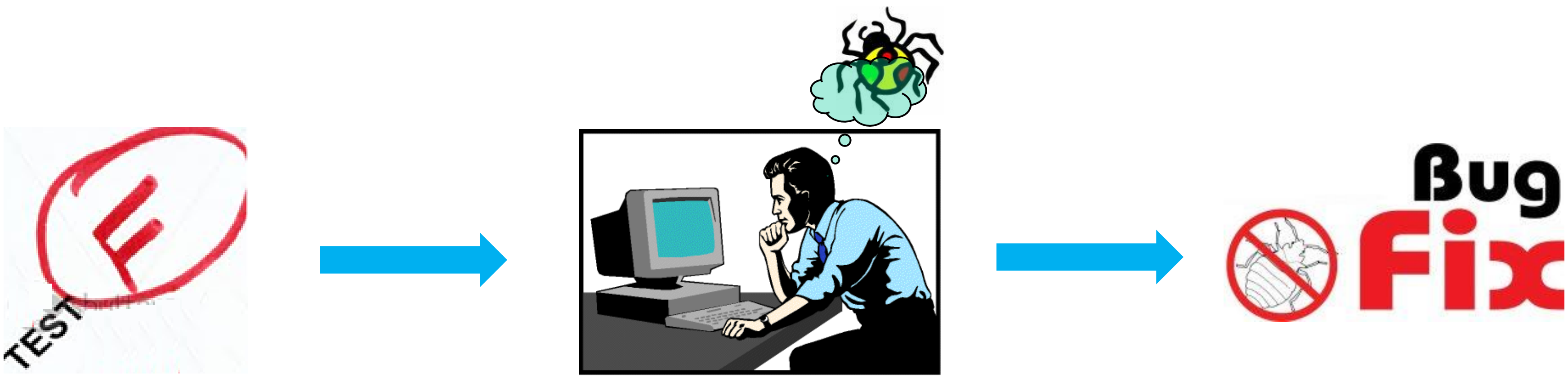
University of Washington

Joint work with: Cheng Zhang, Michael D. Ernst

A failed test reveals a potential bug

Before bug-fixing, programmers must:

- find code relevant to the failure
- understand why the test fails



Programmers often need to guess about relevant parts in the test and tested code

- Long test code
- Multiple class interactions
- Poor documentation

A failed test

```
public void test1() {
  int i = 1;
  ArrayList lst = new ArrayList(i);
  Object o = new Object();
  boolean b = lst.add(o);
  TreeSet ts = new TreeSet(lst);
  Set set = Collections.synchronizedSet(ts);
  assertTrue(set.equals(set));
}
```

Which parts of the test are most relevant to the failure?
(The test is minimized, and does not dump a useful stack trace.)

FailureDoc*: inferring explanatory documentation*

- FailureDoc infers **debugging clues**:
  - Indicates changes to the test that will make it pass
  - Helps programmers understand why the test fails

- FailureDoc provides a ***high-level*** description of the failure from the perspective of the test
  - Automated fault localization tools pinpoint the buggy statements without explaining why

Documenting the failed test

(The **red** part is generated by **FailureDoc**)

```
public void test1() {
  int i = 1;
  ArrayList lst = new ArrayList(i);
  //Test passes if o implements Comparable
  Object o = new Object();
  //Test passes if o is not added to lst
  boolean b = lst.add(o);
  TreeSet ts = new TreeSet(lst);
  Set set = Collections.synchronizedSet(ts);

  assertTrue(set.equals(set));
}
```

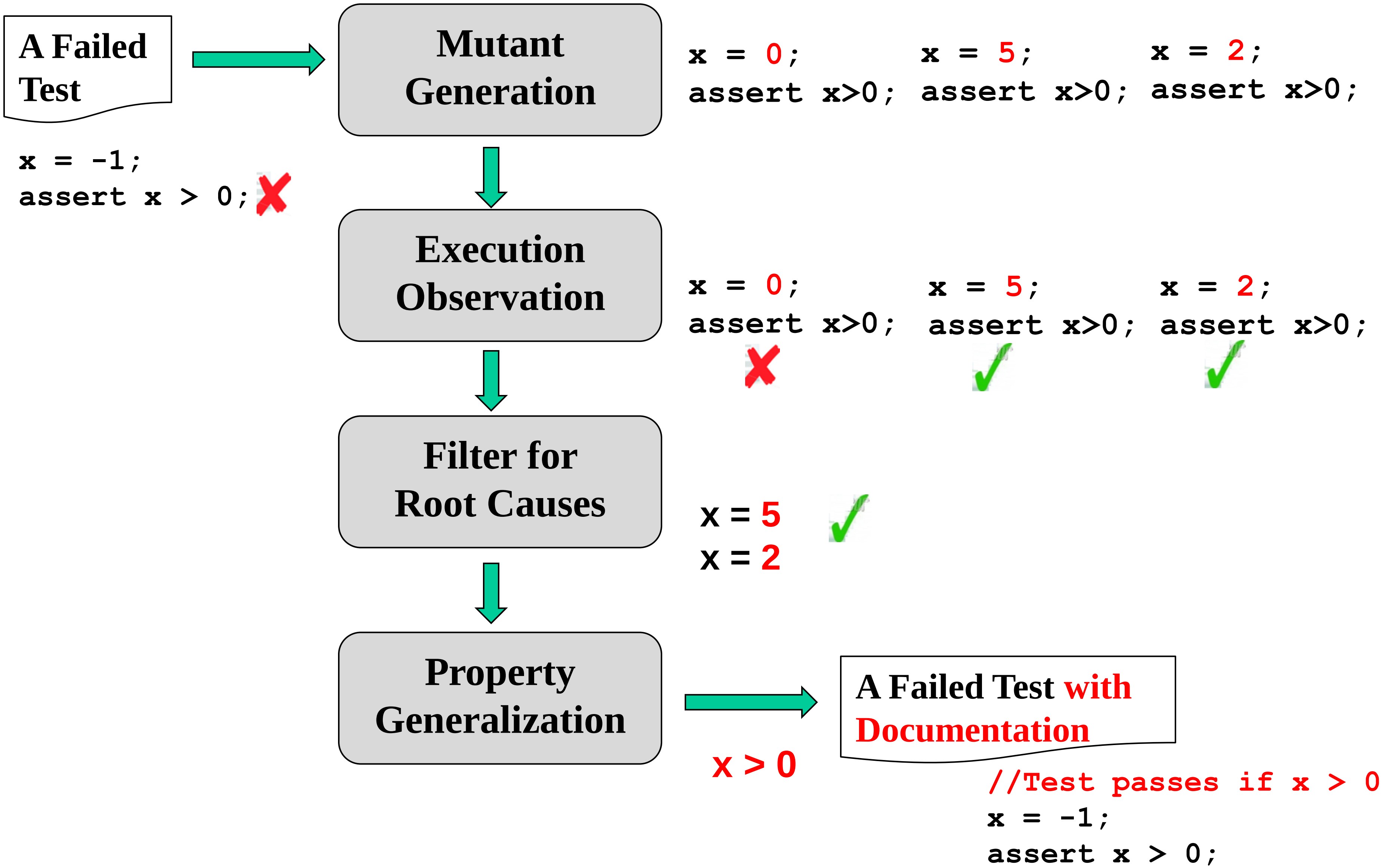
The documentation indicates:

- The `add` method should not accept a **non-Comparable** object, but it does.
- It is a **real** bug.

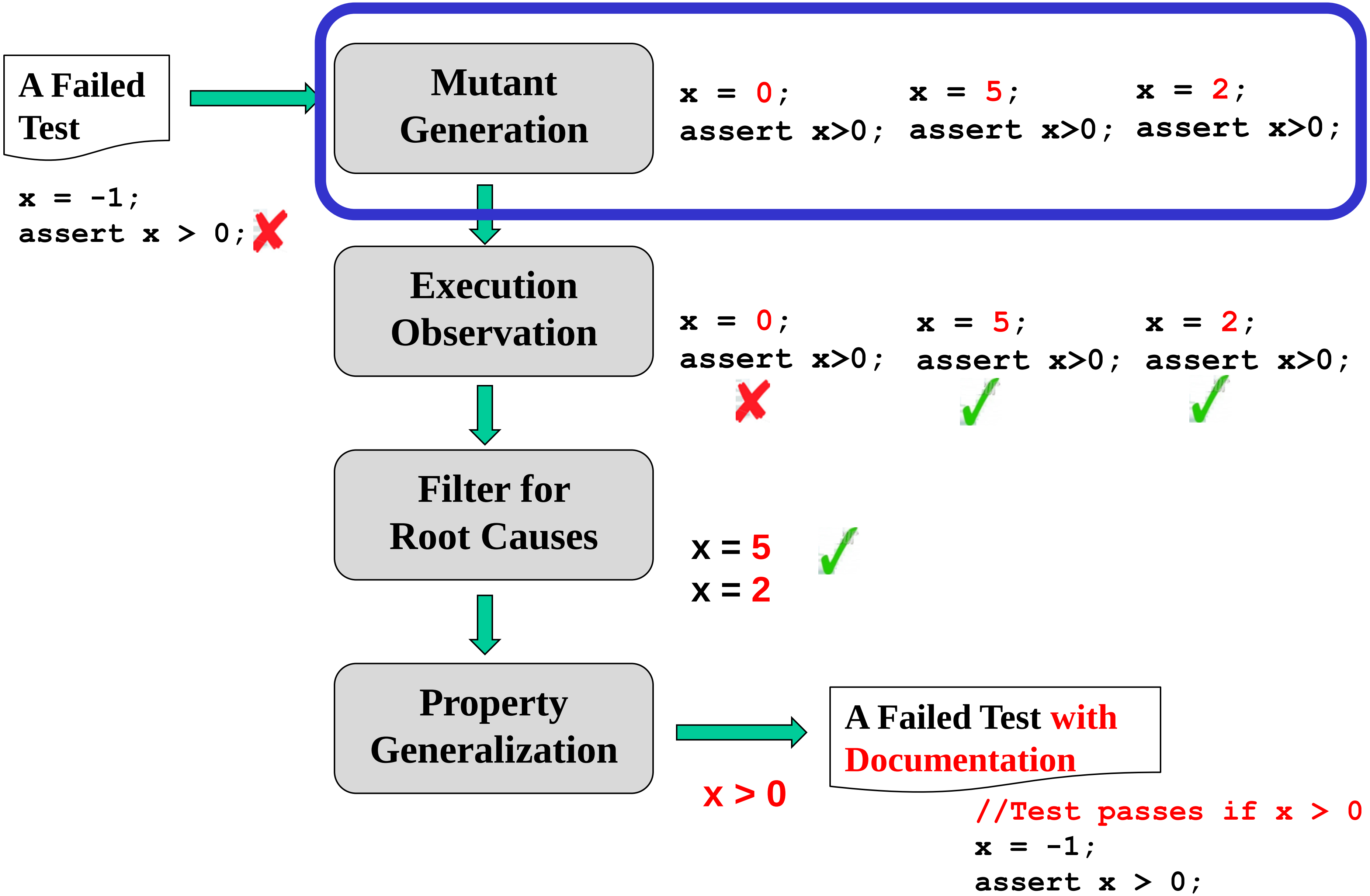
Outline

- Overview
- The **FailureDoc** technique
- Implementation & Evaluation
- Related work
- Conclusion

The architecture of FailureDoc



The architecture of FailureDoc



Mutant generation via value replacement

- Mutate the failed test by repeatedly replacing an existing input value with an alternative one
  - Generate a set of *slightly different* tests

Original test

```
...
Object o = new Object();
boolean b = lst.add(o);
...
```

Mutated test

```
...
Object o = new Integer(1);
boolean b = lst.add(o);
...
```

Original test

```
...
TreeSet t = new TreeSet(1);
Set s = synchronizedSet(t);
...
```

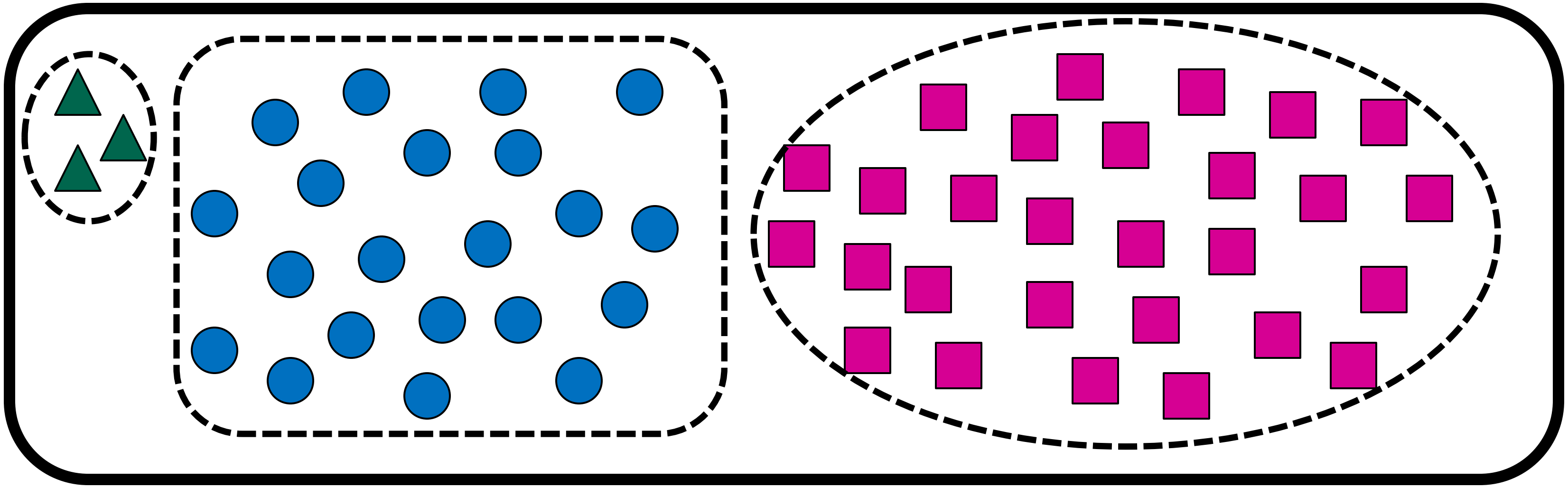
Mutated test

```
...
TreeSet t = new TreeSet();
t.add(10);
Set s = synchronizedSet(t);
...
```

Value selection in replacement

- **Exhaustive selection** is inefficient
- **Random selection** may miss some values

- FailureDoc selects replacement candidates by:
  - mapping each value to an ***abstract*** domain using an *abstract object profile* representation
  - sample each abstract domain



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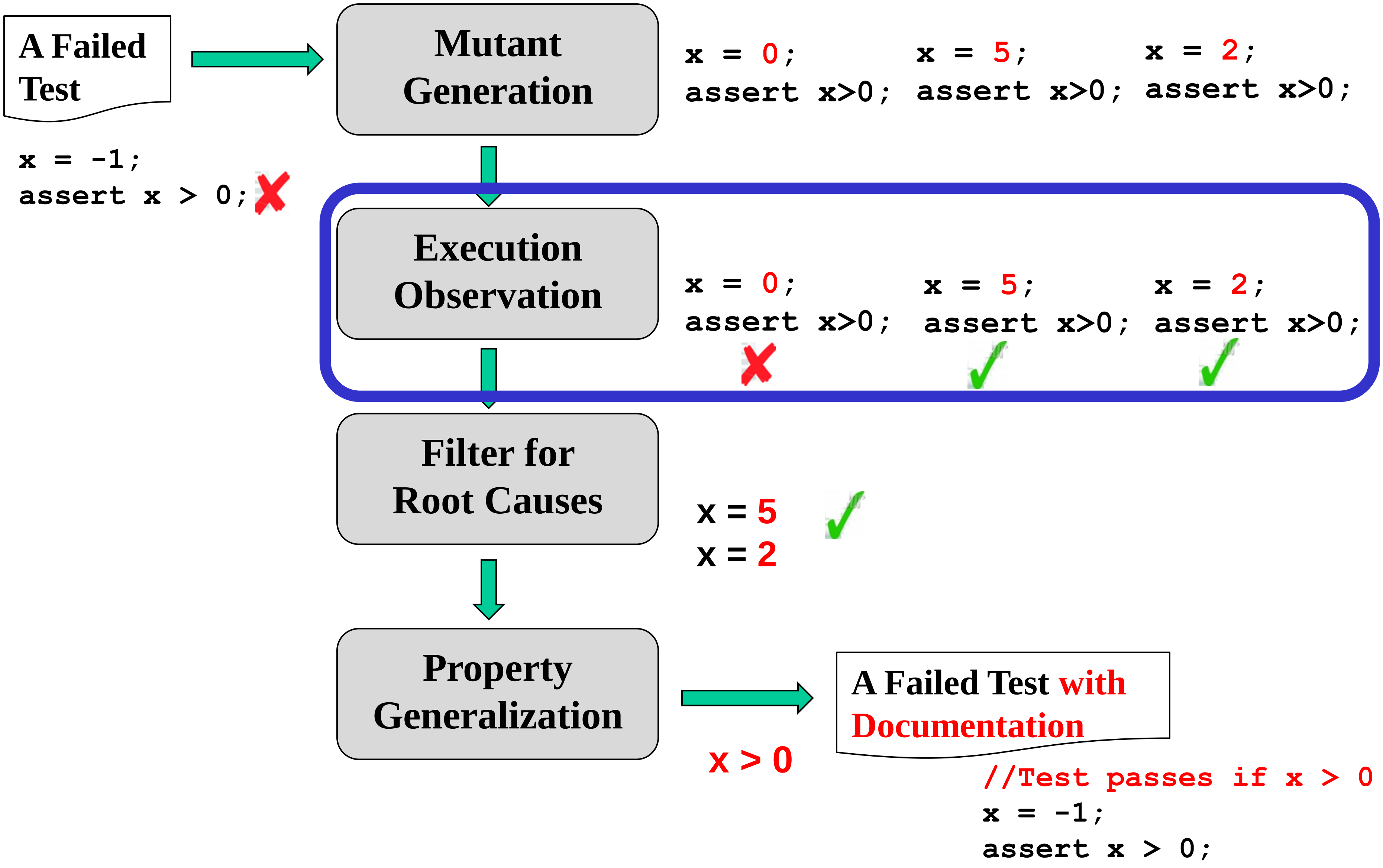


Execution result observation

- FailureDoc executes each mutated test, and classifies it as:
  - **Passing**
  - **Failing**
    - The same failure as the original failed test
  - **Unexpected exception**
    - A different exception is thrown

Original test

```
...
int i = 1;
ArrayList lst = new ArrayList(i);
...
```

Mutated test

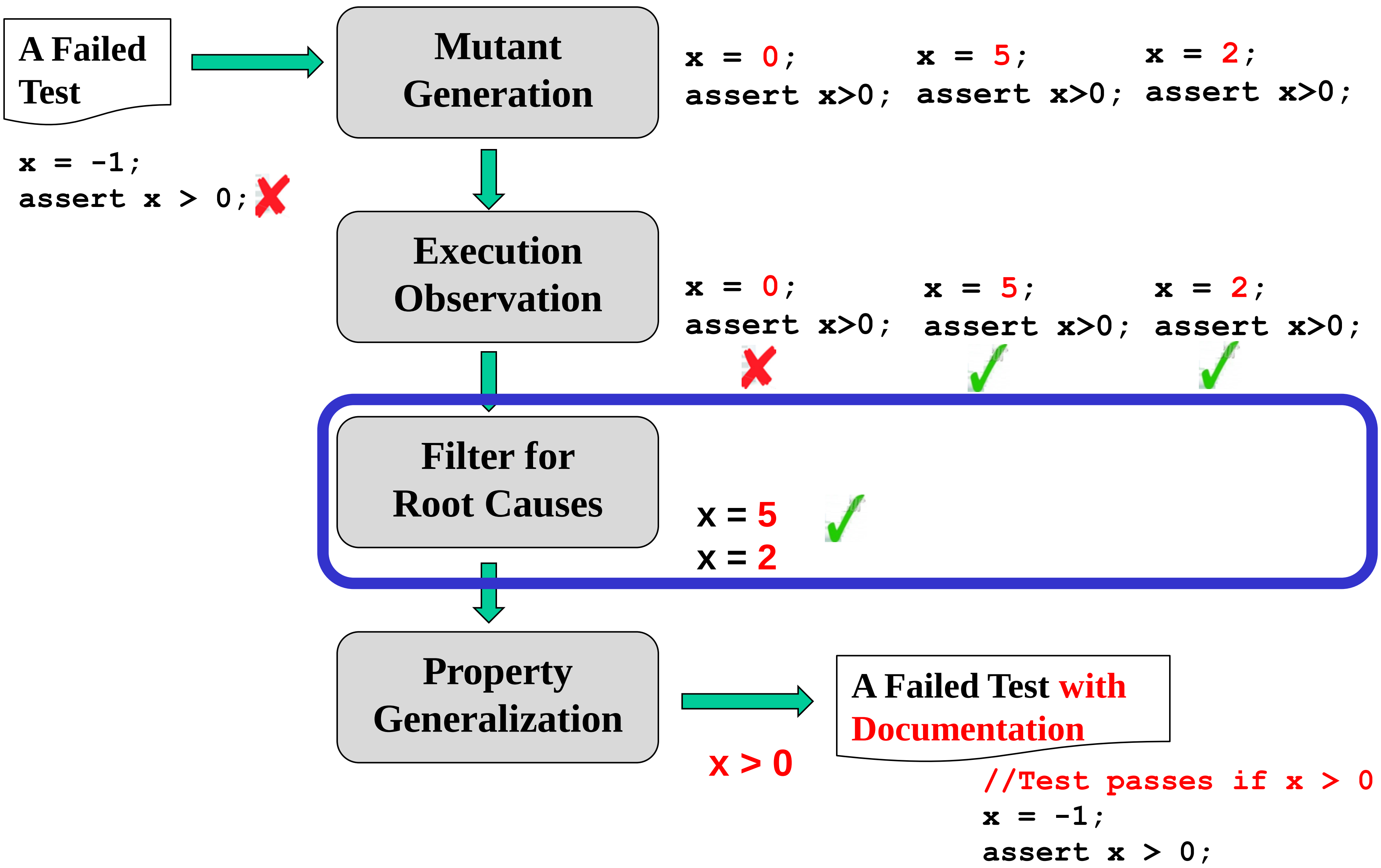
```
...
int i = -10;
ArrayList lst = new ArrayList(i);
...
```

Unexpected exception: `IllegalArgumentException`

Record expression values in test execution

- After value replacement, FailureDoc only needs to record expressions that can affect the test result:
  - Computes **a backward static slice** from the assertion in passing and failing tests
  - **Selectively** records expression values in the slice

The architecture of FailureDoc



Statistical failure correlation

- A statistical algorithm isolates suspicious statements in a failed test
  - A variant of the CBI algorithms [Liblit'05]
  - Associate a suspicious statement with a set of failure-correcting objects

- Characterize the *likelihood* of each observed value **v** to be a failure-correcting object
  - Define 3 metrics: ***Pass***, ***Increase***, and ***Importance*** for each observed value **v** of each statement

***Pass*(v)**: the percentage of passing tests when **v** is observed

Original test	Observed value in a mutant
`public void test1() {`	
`int i = 1;`	
`ArrayList lst = new ArrayList(i);`	
`Object o = new Object();`	
`boolean b = lst.add(o);`	**b** = false
`TreeSet ts = new TreeSet(lst);`	
`Set set = synchronizedSet(ts);`	
`//This assertion fails`	
`assertTrue(set.equals(set));`	**PASS!**
`}`	

***Pass*(b=false) = 1**

The test always passes, when **b** is observed as **false**

***Pass*(v)**: the percentage of passing tests when **v** is observed

Original test	**Observed value in a mutant**
`public void test1() {`	
`  int i = 1;`	
`  ArrayList lst = new ArrayList(i);`	
`  Object o = new Object();`	
`  boolean b = lst.add(o);`	
`  TreeSet ts = new TreeSet(lst);`	`ts` = ***an empty set***
`  Set set = synchronizedSet(ts);`	
`  //This assertion fails`	
`  assertTrue(set.equals(set));`	**PASS!**
`}`	

***Pass*(`ts` = *an empty set*) = 1**

The test always passes, when **`ts`** is observed as *an empty set*!

***Pass*(v)**: the percentage of passing tests when **v** is observed

Original test	**Observed value in a mutant**
`public void test1() {` `  int i = 1;`	**i = 10**

`  ArrayList lst = new ArrayList(i);`
`  Object o = new Object();`
`  boolean b = lst.add(o);`
`  TreeSet ts = new TreeSet(lst);`
`  Set set = synchronizedSet(ts);`
`  //This assertion fails`	

`  assertTrue(set.equals(set));` `}`	**FAIL!**

Pass(`i=10`) **= 0**

Test *never* passes, when `i` is observed as `10`.

***Increase*(v)**: indicating root cause for test passing

Original test	**Observed value in a mutant**
`public void test1() {`	
`  int i = 1;`	Changing `b`'s **initializer** to false implies `ts` is an empty set
`  ArrayList lst = new ArrayList(i);`	
`  Object o = new Object();`	
`  boolean b = lst.add(o);`	**b** = false
`  TreeSet ts = new TreeSet(lst);`	`ts` = *an empty set*
`  Set set = synchronizedSet(ts);`	
`  //This assertion fails`	
`  assertTrue(set.equals(set));`	**PASS!**
`}`	

Increase(`b = false`) = 1
Increase(`ts` = *an empty set*) = 0

Distinguish the *difference* each observed value makes

Importance (v) :

- harmonic mean of ***increase***(v) and the *ratio of passing tests*
- balance sensitivity and specificity
- prefer high score in both dimensions

Algorithm for isolating suspicious statements

Input: a failed test **`t`**

Output: suspicious statements with their *failure-correcting* objects

Statement **`s`** is suspicious if its f*ailure-correcting object set* $FC_s \neq \emptyset$

FC_s = {**`v`** |

*Pass(***`v`***)* = 1 ∧ **/* v corrects the failed test */**

*Increase(***`v`***)* > 0 ∧ **/* v is a root cause */**

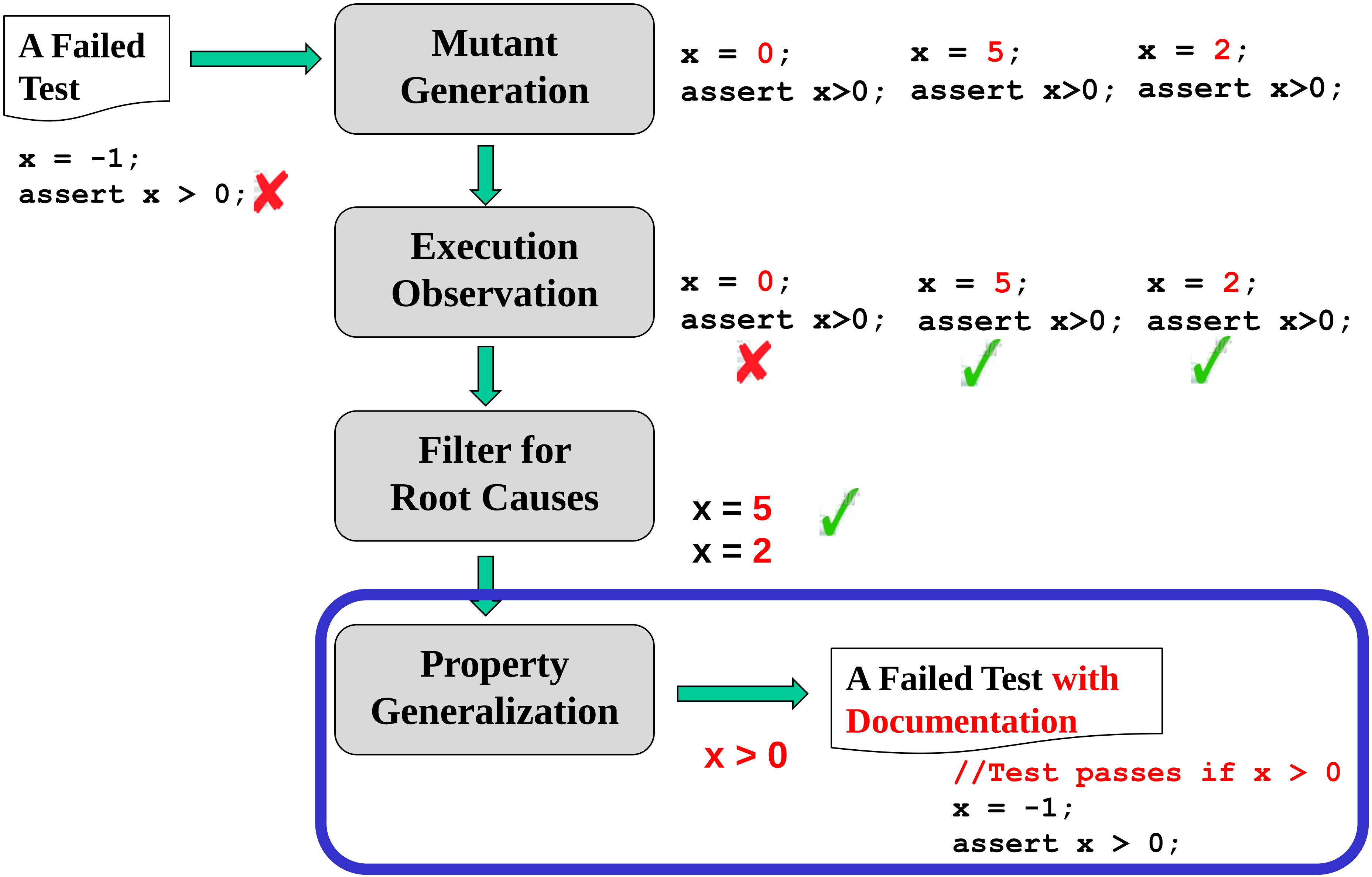
*Importance(***`v`***)* > *threshold* **/* balance sensitivity & specificity */**

}

Failure-correcting objects for the example

Original test	Failure-correcting object set
`public void test1() {`	
`int i = 1;`	
`ArrayList lst = new ArrayList(i);`	
`Object o = new Object();`	**o** ∈ { 100, (byte)1, “hi”}
`boolean b = lst.add(o);`	**b** ∈ { false }
`TreeSet ts = new TreeSet(lst);`	
`Set set = synchronizedSet(ts);`	
`//This assertion fails`	
`assertTrue(set.equals(set));`	
`}`	

The architecture of FailureDoc



Property generalization

- Generalize properties for failure-correcting objects
  - Use a Daikon-like technique
  - E.g., property of the object set: **`{100, "hi!", (byte)1}`** is: *all values are comparable*.

- Rephrase properties into readable documentation
  - Employ a small set of templates:

    `x instanceof Comparable` ⇒ **`x`** implements **`Comparable`**

    `x.add(y)` replaced by **`false`** ⇒ **`y`** is not added to **`x`**

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Research questions

- **RQ1:** can FailureDoc infer explanatory documentation for failed tests?

- **RQ2**: is the documentation useful for programmers to understand the test and fix the bug?

Evaluation procedure

- An experiment to explain 12 failed tests from 5 subjects
  - All tests were automatically generated by Randoop [Pacheco'07]
  - Each test reveals a distinct real bug

- A user study to investigate the documentation's usefulness
  - 16 CS graduate students
  - Compare the **time cost** in **test understanding** and **bug fixing** :
    1. **Original** tests (**undocumented**) **vs. FailureDoc**
    2. **Delta debugging** **vs. FailureDoc**

Subjects used in explaining failed tests

Subject	Lines of Code	# Failed Tests	Test size
Time and Money	2,372	2	81
Commons Primitives	9,368	2	150
Commons Math	14,469	3	144
Commons Collections	55,400	3	83
java.util	48,026	2	27

- Average test size: 41 statements
- Almost all failed tests involve complex interactions between multiple classes
  - Hard to tell why they fail by simply looking at the test code

Results for explaining failed tests

- FailureDoc infers meaningful documentation for 10 out of 12 failed tests
  - Time cost is **acceptable**: **189 seconds** per test
  - Documentation is **concise**: **1 comment per 17 lines** of test code
  - Documentation is **accurate**: each comment indicates a different way to make the test pass, and is ***never in conflict*** with each other
- FailureDoc fails to infer documentation for 2 tests:
  - no way to use value replacement to correct them

Feedback from developers

- We sent all documented tests to subject developers, and got positive feedback

- Feedback from a Commons Math developer:

> *I think these comments are helpful. They give a hint about what to look at. … the comment showed me exactly the variable to look at.*

- Documented tests and communications with developers are available at: *http://www.cs.washington.edu/homes/szhang/failuredoc/bugreports/*

User study: how useful is the documentation?

- Participants: 16 graduate students majoring in CS
  - Java experience: max = 7, min = 1, avg = 4.1 **years**
  - JUnit experience: max = 4, min = 0.1, avg = 1.9 **years**

- 3 experimental treatments:
  - ***Original*** *tests (**undocumented**)*
  - ***Delta-debugging-annotated*** *tests*
  - ***FailureDoc-documented*** *tests*

- Measure:
  - time to **understand why a test fails**
  - time to **fix the bug**
  - 30-min time limit per test

Results of comparing ***undocumented tests*** *with* ***FailureDoc***

Goal	Success Rate		Average Time Used (min)	
	JUnit	**FailureDoc**	**JUnit**	**FailureDoc**
Understand Failure	75%	75%	22.6	19.9
Understand Failure + Fix Bug	35%	35%	27.5	26.9

JUnit: Undocumented Tests
FailureDoc: Tests with FailureDoc-inferred documentation

Conclusion:

- FailureDoc helps participants *understand a failed test* 2.7 mins (or 14%) *faster*
- FailureDoc *slightly speeds up* the bug fixing time (0.6 min faster)

Results of comparing ***Delta debugging*** *with* ***FailureDoc***

Goal	**Success Rate**		**Average Time Used (min)**	
	DD	**FailureDoc**	**DD**	**FailureDoc**
Understand Failure	75%	75%	21.7	20.0
Understand Failure + Fix Bug	40%	45%	26.1	26.5

DD: Tests annotated with **D**elta-**D**ebugging-isolated faulty statements
Delta debugging can only isolate faulty statements in 3 tests

FailureDoc: Tests with FailureDoc-inferred documentation

Conclusion:

- FailureDoc helps participants *fix more bugs*
- FailureDoc helps participants to *understand a failed test faster* (1.7 mins or 8.5%)
- Participants spent *slightly more time* (0.4 min) in fixing a bug on average with FailureDoc, though more bugs were fixed

Feedback from Participants

- Overall feedback
  - FailureDoc is useful
  - FailureDoc is *more useful* than Delta Debugging
- Positive feedback

  The comment at line 68 did provide information *very close to* the bug!

  The comments are useful, because they indicate *which variables are suspicious*, and help me *narrow the search space.*

- Negative feedback

  The comments, though [they] give useful information, can *easily be misunderstood*, when I am *not familiar* with the [program].

Experiment discussion & conclusion

- Threats to validity
  - Have not used human-written tests yet.
  - Limited user study, small tasks, a small sample of people, and unfamiliar code (is 30 min per test enough?)
- Experiment conclusion
  - FailureDoc can infer *concise and meaningful* documentation
  - The inferred documentation is *useful* in understanding a failed test

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Related work

- **Automated test generation**

  Random [Pacheco'07], Exhaustive [Marinov'03], Systematic [Sen'05] **…**

  Generate new tests instead of explaining the existing tests

- **Fault localization**

  Testing-based [Jones'04], delta debugging [Zeller'99], statistical [Liblit'05] **…**

  Localize the bug in the tested code, but doesn't explain why a test fails

- **Documentation inference**

  Method summarization [Sridhara'10], Java exception [Buse'08], software changes [Kim'09, Buse'10], API cross reference [Long'09]

  Not applicable to tests (e.g., different granularity and techniques)

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Future Work

- FailureDoc proposes *a different abstraction* to help programmers *understand a failed test*, and *fix a bug*.

  Is there a better way?

- Which information is *more useful* for programmers?
  - Fault localization: pinpointing the buggy program entities
  - Simplifying a failing test
  - Inferring explanatory documentation
  - ….

  Need more experiments and studies

Contributions

- *FailureDoc*: an automated technique to explain failed tests
  - Mutant Generation
  - Execution Observation
  - Statistical Failure Correlation
  - Property Generalization
- An open-source tool implementation, available at:

http://failuredoc.googlecode.com/

- An experiment and a user study to show its usefulness
  - Also compared with Delta debugging

[Backup slides]

Comparison with Delta debugging

- ***Delta debugging***:
  - **Inputs**: A passing and a failing version of a program
  - **Output**: failure-inducing edits
  - **Methodology**: systematically explore the change space

- ***FailureDoc***:
  - **Inputs**: a single failing test
  - **Outputs**: high-level description to explain the test failure
  - **Methodology**: create a set of slightly-different tests, and generalize the failure-correcting edits

Comparison with the CBI algorithm

- The ***CBI*** algorithm:
  - **Goal**: identify likely buggy predicates in the *tested code*
  - **Input:** a large number of executions
  - **Method**: use the *boolean* value of an instrumented predicate as the feature vector

- Statistical failure correlation in ***FailureDoc***
  - **Goal**: identify failure-relevant statements in *a test*
  - **Input***:* a single failed execution
  - **Method**:
    - use *multiple observed values* to isolate suspicious statements.
    - associate each suspicious statement with a set of *failure-correcting objects*