# Fault Localization

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## Fault Localization

- Debugging software is an expensive and mostly manual process
- Of all debugging activities, locating the faults, or fault localization, is the most challenging one
- Approaches have been investigated to help automate fault localization

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## Typical Fault Localization Techniques

- Tarantula
- Set Union & Set Intersection
- Nearest Neighbor
- Cause Transitions

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## What Is the Fault in the Following Buggy Program?

```
int mid(int x, int y, int z) {
   int m;
   m= z;
   if (y < z) {
     if (x < y) m = y;
     else if (x < z) m = y;        // should be m = x;
} else {
       if (x > y) m = y;
       else if ( x > z) m = x;
     }
   } return m;
}
```

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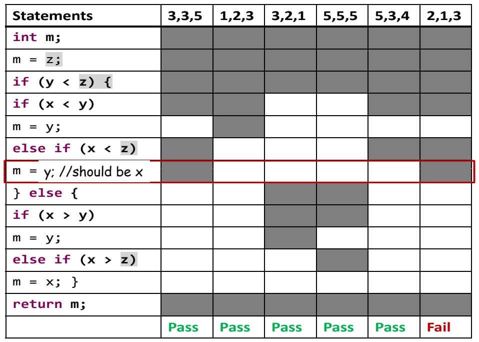
## Tarantula: Coverage-based Fault Localization



| Statements | 3,3,5 | 1,2,3 | 3,2,1 | 5,5,5 | 5,3,4 | 2,1,3 |
|---|---|---|---|---|---|---|
| `int m;` | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| `m = z;` | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| `if (y < z) {` | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| `if (x < y)` | ▨ | ▨ |  |  | ▨ | ▨ |
| `m = y;` |  | ▨ |  |  |  |  |
| `else if (x < z)` | ▨ |  |  |  | ▨ | ▨ |
| m = y; //should be x | ▨ |  |  |  |  | ▨ |
| `} else {` |  |  | ▨ | ▨ |  |  |
| `if (x > y)` |  |  | ▨ | ▨ |  |  |
| `m = y;` |  |  | ▨ |  |  |  |
| `else if (x > z)` |  |  |  | ▨ |  |  |
| `m = x; }` |  |  |  |  |  |  |
| `return m;` | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
|  | Pass | Pass | Pass | Pass | Pass | Fail |

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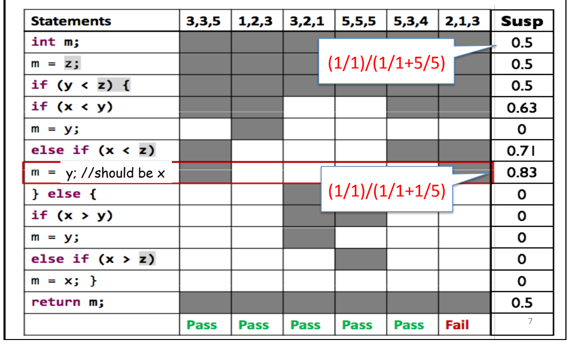
## Approach

- Insight
  - Entities in a program that are primarily executed by failed test cases are more likely to be faulty than those that are primarily executed by passed test cases
- Solution
  - Ranking based on suspiciousness

$$Suspicious(s) = \frac{fail(s)/totalfail}{fail(s)/totalfail + pass(s)/totalpass}$$

## Tarantula



| Statements | 3,3,5 | 1,2,3 | 3,2,1 | 5,5,5 | 5,3,4 | 2,1,3 | Susp |
|---|---|---|---|---|---|---|---|
| `int m;` | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | 0.5 |
| `m = z;` | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | 0.5 |
| `if (y < z) {` | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | 0.5 |
| `if (x < y)` | ▨ | ▨ |  |  | ▨ | ▨ | 0.63 |
| `m = y;` |  | ▨ |  |  |  |  | 0 |
| `else if (x < z)` | ▨ |  |  |  | ▨ | ▨ | 0.71 |
| `m = y; //should be x` | ▨ |  |  |  |  | ▨ | 0.83 |
| `} else {` |  |  | ▨ |  |  |  | 0 |
| `if (x > y)` |  |  | ▨ | ▨ |  |  | 0 |
| `m = y;` |  |  | ▨ |  |  |  | 0 |
| `else if (x > z)` |  |  |  | ▨ |  |  | 0 |
| `m = x; }` |  |  |  |  |  |  | 0 |
| `return m;` | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ | 0.5 |
|  | Pass | Pass | Pass | Pass | Pass | Fail |  |

(1/1)/(1/1+5/5)

(1/1)/(1/1+1/5)

## Continuous Coloring

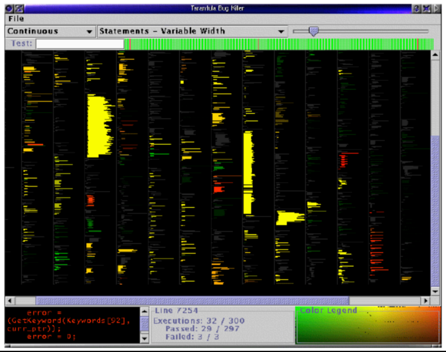
- Color of a statement is:

$$\text{color}(s) = \text{low color (red)} + \frac{\%\text{passed}(s)}{\%\text{passed}(s) + \%\text{failed}(s)} * \text{color range}$$

- Brightness of a statement is:

$$\text{bright}(s) = \max(\%\ \text{passed}(s), \%\ \text{failed}(s))$$

## Tarantula Display



```
    error =
(GetKeyword(Keywords[92],
curr_ptr));
    error = 0;
```

Line 7254
Executions: 32 / 300
Passed: 29 / 297
Failed: 3 / 3

## Evaluation

- RQ1: How often does Tarantula color the faulty statements in a program red or in a reddish color?
- RQ2: How often does Tarantula color nonfaulty statements in a program red or in a reddish color?

## Data Set

- Space program written in C
- 6218 LOC (executable)
- 13585 test cases
  - Generated test cases until the set contains at least 30 test cases that exercise nearly every statement and edge
  - Extracted 1000 randomly sized generated, near-decision-adequate test suites from this test pool

## Single-fault Versions (20 versions)

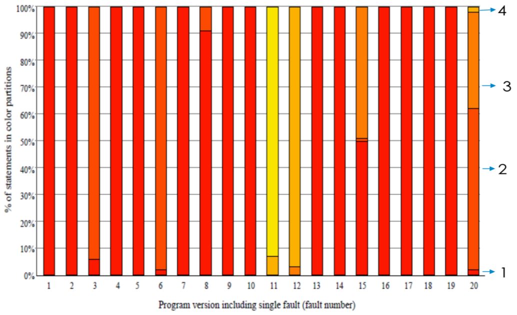


Figure 5: Resulting color of the faulty statements across all test suites for 20 versions of Space.

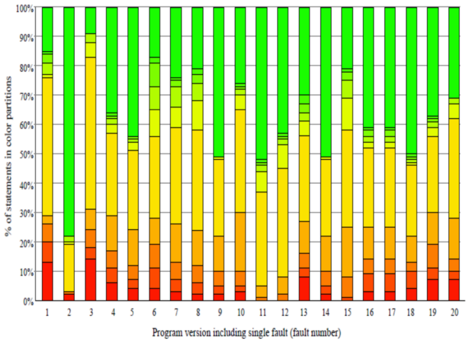
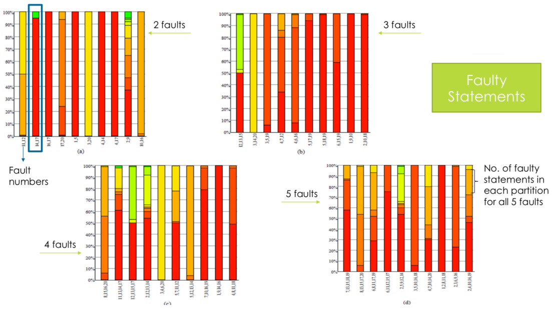
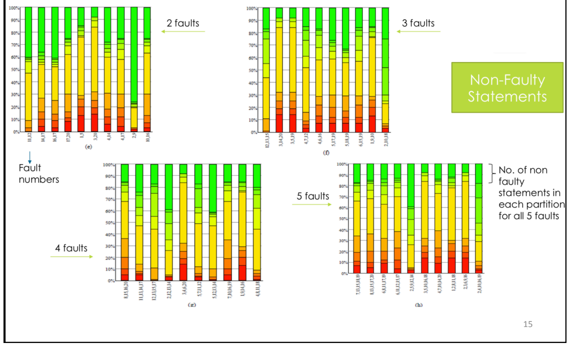


Figure 6: Resulting color of the nonfaulty statements across all test suites for 20 versions of Space.

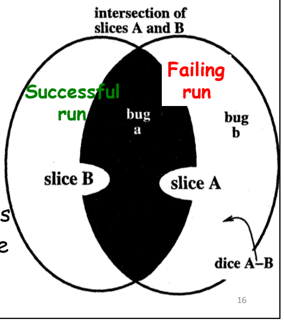
## Multiple fault (40 versions)





## Set Union & Set Intersection [3]

- Slice-based Fault Localization
  - A dynamic slice is the set of statements which ***do affect*** the value of the output
  - Dice: the set difference of two slices
  - dice (A – B) is effective to isolate bug b



## Formulas

- Set Union

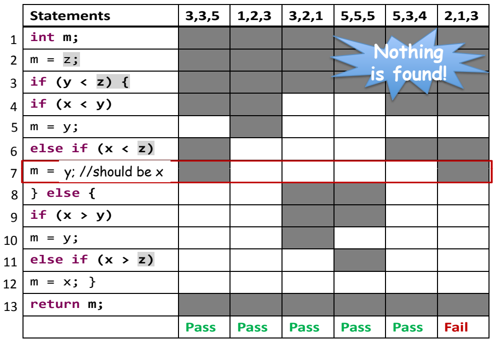
$$E_{initial} = E_f - \bigcup_{p \in P} E_p$$

- Set Intersection

$$E_{initial} = \bigcap_{p \in P} E_p - E_f$$

- What is the insight behind each formula?

## Set Union & Set Intersection



| | Statements | 3,3,5 | 1,2,3 | 3,2,1 | 5,5,5 | 5,3,4 | 2,1,3 |
|---|---|---|---|---|---|---|---|
| 1 | `int m;` | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| 2 | `m = z;` | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| 3 | `if (y < z) {` | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| 4 | `if (x < y)` | ▨ | ▨ | | | ▨ | ▨ |
| 5 | `m = y;` | | ▨ | | | | |
| 6 | `else if (x < z)` | ▨ | | | | ▨ | ▨ |
| 7 | `m = y; //should be x` | ▨ | | | | | ▨ |
| 8 | `} else {` | | | ▨ | ▨ | | |
| 9 | `if (x > y)` | | | ▨ | ▨ | | |
| 10 | `m = y;` | | | ▨ | | | |
| 11 | `else if (x > z)` | | | | ▨ | | |
| 12 | `m = x; }` | | | | | | |
| 13 | `return m;` | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| | | Pass | Pass | Pass | Pass | Pass | Fail |

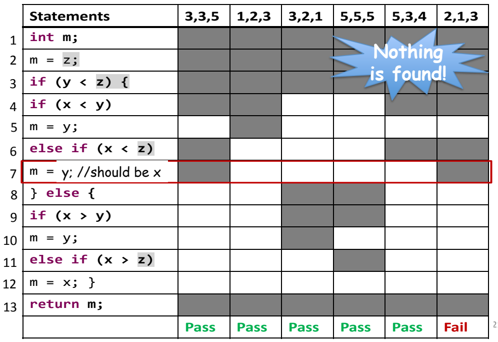
# Nearest Neighbor [4]

- Spectra-based Fault Localization
  - Spectrum: profiling data that shows the number of times each program line is executed
  - Given a set of passing tests and a failing test F, find the passing test P, which has the most similar spectrum as F
  - Calculate the distance metric

# Two Variants

- NN/perm
  - Frequency-marked statements
  - Sort statements based on frequency
  - Ulam edit distance
    - E.g., Dist([a, b, c, d], [a, c, d, b]) = 1 (move)
- NN/binary
  - 0-or-1 mark for each statement
  - No frequency is considered
  - Set subtraction is used to calculate distance

# Nearest Neighbor



| | Statements | 3,3,5 | 1,2,3 | 3,2,1 | 5,5,5 | 5,3,4 | 2,1,3 |
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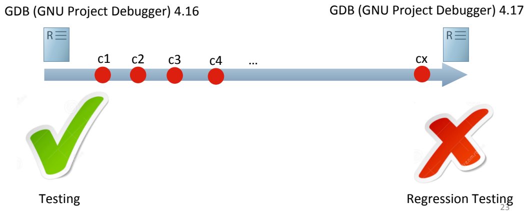
| 2 | `m = z;` | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| 3 | `if (y < z) {` | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| 4 | `if (x < y)` | ▨ | ▨ | | | ▨ | ▨ |
| 5 | `m = y;` | | ▨ | | | | |
| 6 | `else if (x < z)` | ▨ | | | | ▨ | ▨ |
| 7 | m = y; //should be x | ▨ | | | | | ▨ |
| 8 | `} else {` | | | ▨ | ▨ | | |
| 9 | `if (x > y)` | | | ▨ | ▨ | | |
| 10 | `m = y;` | | | ▨ | | | |
| 11 | `else if (x > z)` | | | | ▨ | | |
| 12 | `m = x; }` | | | | | | |
| 13 | `return m;` | ▨ | ▨ | ▨ | ▨ | ▨ | ▨ |
| | | Pass | Pass | Pass | Pass | Pass | Fail |

# Cause-Transitions [2]

- Leverage delta debugging to isolate failure-inducing variable values at specific program locations
- Identify the transition points between different failure-inducing variable values
- Consider the transition points as bug locations

# Delta Debugging (DD) [5]

- Problem Statement
  - Yesterday, my program worked. Today, it does not. Why?



# Definitions

- Configuration: the set of all applied changes $C = \{\Delta_1, \Delta_2, \ldots, \Delta_n\}$
  - $c \subseteq C$ represents a subset of changes
- Test: the function c → {✗, ✓, ?} to determine whether a configuration c leads to failure, success, or unresolved outcome of regression testing

## How to Find the Minimum Failing-Inducing Changes?

- Naïve approach
  - Brute-force search: too expensive
- Efficient approach
  - Delta debugging: Binary search

## Insight

- By finding the minimum set of changes whose application fails the test, Delta Debugging identifies bug-inducing changes

## Search for Single Failure-Inducing Change

- Suppose there are 8 changes with the 7th is the cause. How do you use binary search to find it?

## Conceptual Solution

| Step | Configuration | test |
|---|---|---|
| 1 | 1 2 3 4 | ✔ |
| 2 | 5 6 7 8 | ✗ |
| 3 | 5 6 | ✔ |
| 4 | 7 8 | ✗ |
| 5 | 7 | ✗ |

## How Does DD Localize Failure-Inducing Variable Values?

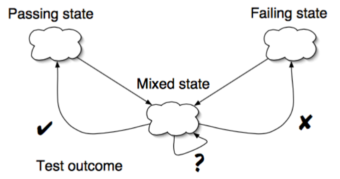
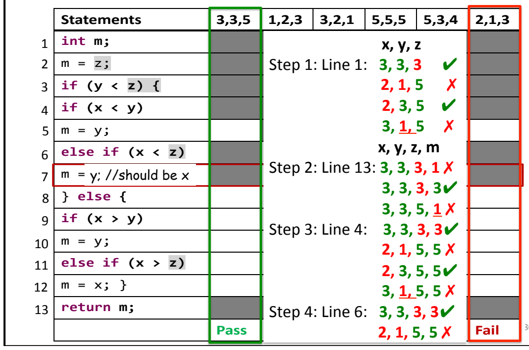


**Figure 2: Narrowing down state differences. By assessing whether a mixed state results in a passing (✔), a failing (✘), or an unresolved (?) outcome, Delta Debugging isolates a relevant difference.**

## Cause-Transitions



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| 4 | `if (x < y)` | ▨ |  |  |  |  | ▨ |
| 5 | `m = y;` |  |  |  |  |  |  |
| 6 | `else if (x < z)` | ▨ |  |  |  |  | ▨ |
| 7 | `m = y;` //should be x | ▨ |  |  |  |  | ▨ |
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| 9 | `if (x > y)` |  |  |  |  |  |  |
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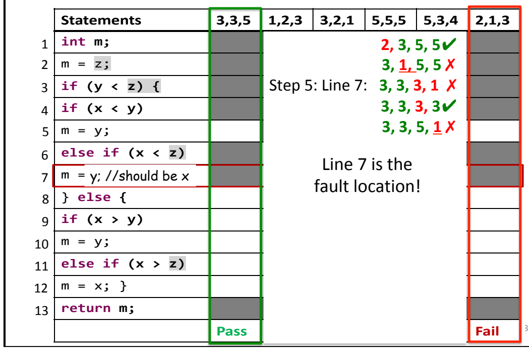
| 11 | `else if (x > z)` |  |  |  |  |  |  |
| 12 | `m = x; }` |  |  |  |  |  |  |
| 13 | `return m;` | ▨ |  |  |  |  | ▨ |
|  |  | Pass |  |  |  |  | Fail |

x, y, z
Step 1: Line 1: 3, 3, 3 ✔
2, 1, 5 ✗
2, 3, 5 ✔
3, 1, 5 ✗
x, y, z, m
Step 2: Line 13: 3, 3, 3, 1 ✗
3, 3, 3, 3 ✔
3, 3, 5, 1 ✗
Step 3: Line 4: 3, 3, 3, 3 ✔
2, 1, 5, 5 ✗
2, 3, 5, 5 ✔
3, 1, 5, 5 ✗
Step 4: Line 6: 3, 3, 3, 3 ✔
2, 1, 5, 5 ✗

# Cause-Transitions



|  | Statements | 3,3,5 | 1,2,3 | 3,2,1 | 5,5,5 | 5,3,4 | 2,1,3 |
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| 2 | `m = z;` | ▨ |  |  |  |  | ▨ |
| 3 | `if (y < z) {` | ▨ |  |  |  |  | ▨ |
| 4 | `if (x < y)` | ▨ |  |  |  |  | ▨ |
| 5 | `m = y;` |  |  |  |  |  |  |
| 6 | `else if (x < z)` | ▨ |  |  |  |  | ▨ |
| 7 | `m = y; //should be x` | ▨ |  |  |  |  | ▨ |
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| 10 | `m = y;` |  |  |  |  |  |  |
| 11 | `else if (x > z)` |  |  |  |  |  |  |
| 12 | `m = x; }` |  |  |  |  |  |  |
| 13 | `return m;` | ▨ |  |  |  |  | ▨ |
|  |  | Pass |  |  |  |  | Fail |

Step 5: Line 7:
2, 3, 5, 5 ✓
3, 1, 5, 5 ✗
3, 3, 3, 1 ✗
3, 3, 3, 3 ✓
3, 3, 5, 1 ✗

Line 7 is the fault location!

# Evaluation

- Siemens suite
  - 7 programs, 132 fault versions, 21,631 test suites designed to expose the faults
  - 122 versions are usable by the authors
  - Each version contains exactly one fault
  - Each fault may span multiple statements or even functions

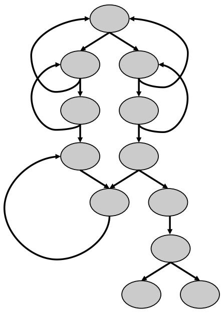
# Evaluation Method

- Basic Idea
  - Imagine an "ideal" debugger or a perfect programmer examines the ranked list of bug locations
  - The fewer locations/statements examined before the actual location, the higher score the report/tool gets
    - Tarantula: go through the ranked list
    - Other tools: PDG-based location examination

# PDG-Based Evaluation Method [6]

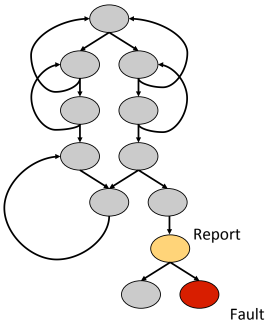
- Given a reported location, do breadth-first search of Program Dependency Graph (PDG)
  - Terminate the search when a real fault is found
  - Score is proportional to the unexplored part of the PDG
    - Score near 1.0 means the No. 1 reported location is the correct one.

# An Example [6]

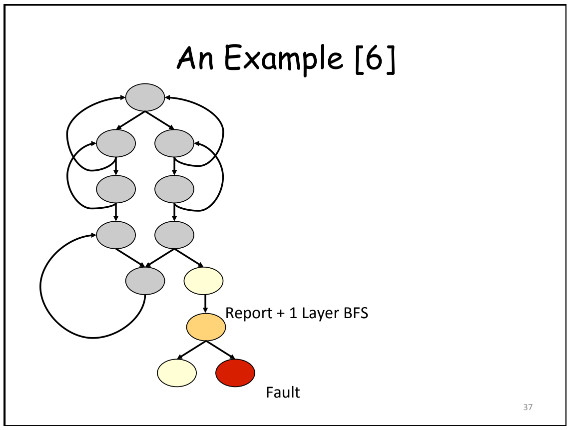


12 total nodes in PDG

# An Example [6]



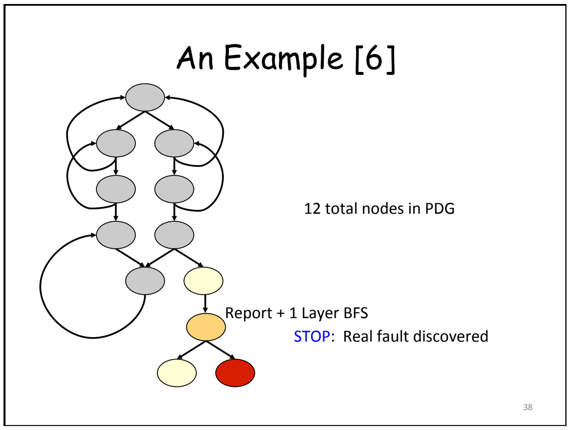
12 total nodes in PDG



## An Example [6]

Report + 1 Layer BFS

Fault

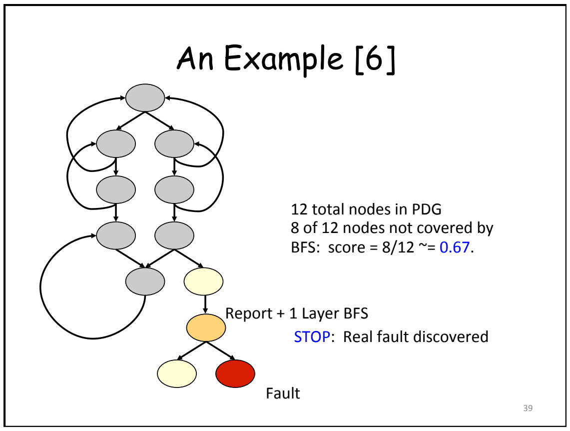


## An Example [6]

12 total nodes in PDG

Report + 1 Layer BFS

STOP: Real fault discovered



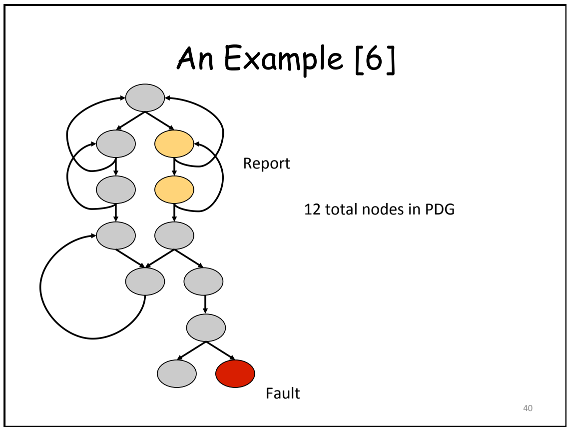
## An Example [6]

12 total nodes in PDG
8 of 12 nodes not covered by
BFS: score = 8/12 ~= 0.67.

Report + 1 Layer BFS

STOP: Real fault discovered

Fault

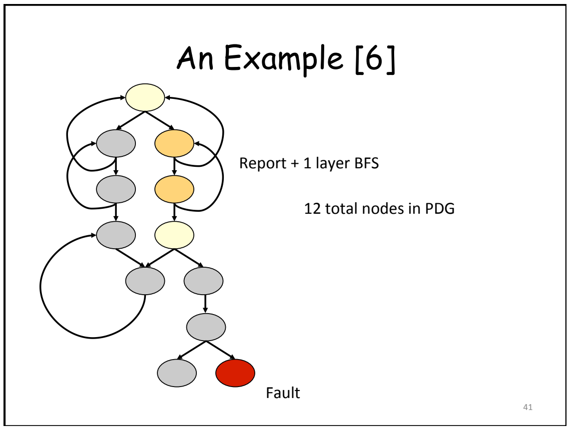


## An Example [6]

Report

12 total nodes in PDG

Fault

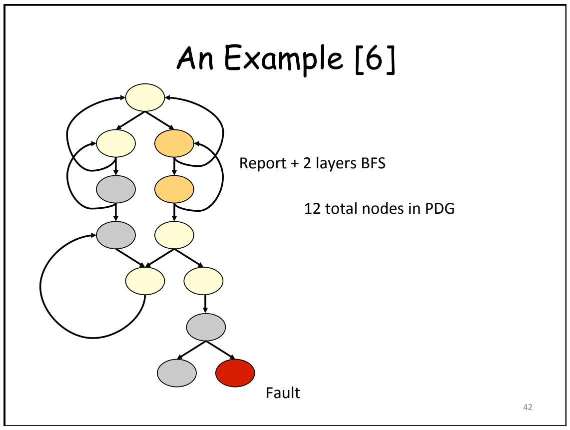


## An Example [6]

Report + 1 layer BFS

12 total nodes in PDG

Fault



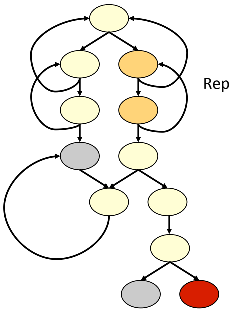
## An Example [6]

Report + 2 layers BFS

12 total nodes in PDG

Fault

# An Example [6]

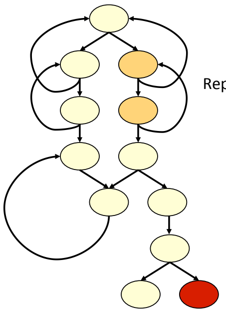


Report + 3 layers BFS

12 total nodes in PDG

Fault

# An Example [6]



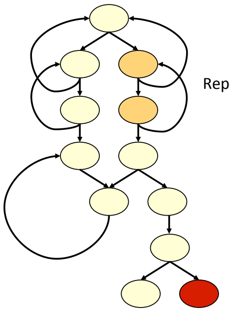
Report + 4 layers BFS

STOP: Real fault discovered

12 total nodes in PDG

Fault

# An Example [6]



Report + 4 layers BFS

12 total nodes in PDG
0 of 12 nodes not covered by
BFS: score = 0/12 ~= 0.00.

# Limitations [6]

- Isn't a misleading report worse than an empty report?
- Nobody really searches a PDG like that!

# Evaluation Results

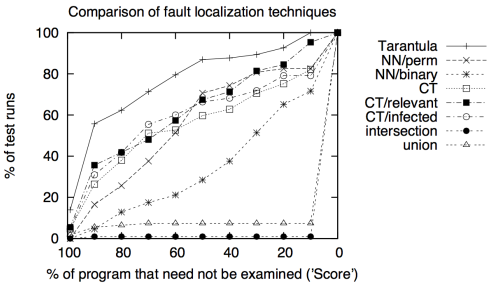
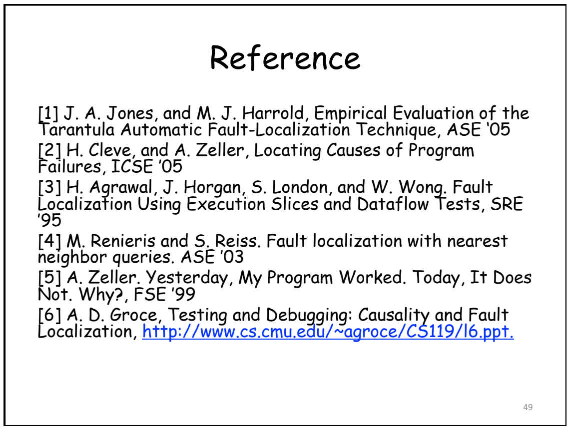


**Figure 2:** Comparison of the effectiveness of each technique.

# Evaluation Results

**Table 3: Average time expressed in seconds.**

| Program | Tarantula (computation only) | Tarantula (including I/O) | Cause Transitions |
|---|---|---|---|
| print_tokens | 0.0040 | 68.96 | 2590.1 |
| print_tokens2 | 0.0037 | 50.50 | 6556.5 |
| replace | 0.0063 | 75.90 | 3588.9 |
| schedule | 0.0032 | 30.07 | 1909.3 |
| schedule2 | 0.0030 | 30.02 | 7741.2 |
| tcas | 0.0025 | 12.37 | 184.8 |
| tot_info | 0.0031 | 8.51 | 521.4 |



# Reference

[1] J. A. Jones, and M. J. Harrold, Empirical Evaluation of the Tarantula Automatic Fault-Localization Technique, ASE '05

[2] H. Cleve, and A. Zeller, Locating Causes of Program Failures, ICSE '05

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