CSE P 504

Advanced topics in Software Systems

Fall 2022

Statistical fault localization

November 14, 2022

Today

- Recap: invariants and metamorphic testing
- Automated debugging
  - **Statistical fault localization**
  - Automated patch generation
- Defect prediction

Recap: invariants and metamorphic testing

Kick-starting the discussion

Six groups (2 groups per question)

1. What is a program invariant? What guarantees does Daikon provide for its discovered invariants?
2. What is a partial test oracle, a follow-up test input, and a metamorphic relation?
3. How are invariants and metamorphic relations similar and how are they different? (Context: using them as partial test oracles in software testing.)

Post open questions/confusions to Slack (#lectures).

Recap: Pre/post-conditions and invariants

```
double avgAbs(double[] nums) {
 int n = nums.length;
 double sum = 0;

 int i = 0;
 while (i != n) {
   if(nums[i]>0) {
    sum = sum + nums[i];
   else {
    sum = sum - nums[i];
   }
   i = i + 1;
 }

 return sum / n;
}
```

Entry point

Exit point

Recap: data diversity and metamorphic testing

Simple case: related inputs with identical outcomes

- Expected output for a given input is unknown
- Two related inputs must result in the same output
- Example: `abs(x) == abs(-x)`

Generalization: related inputs and related outputs

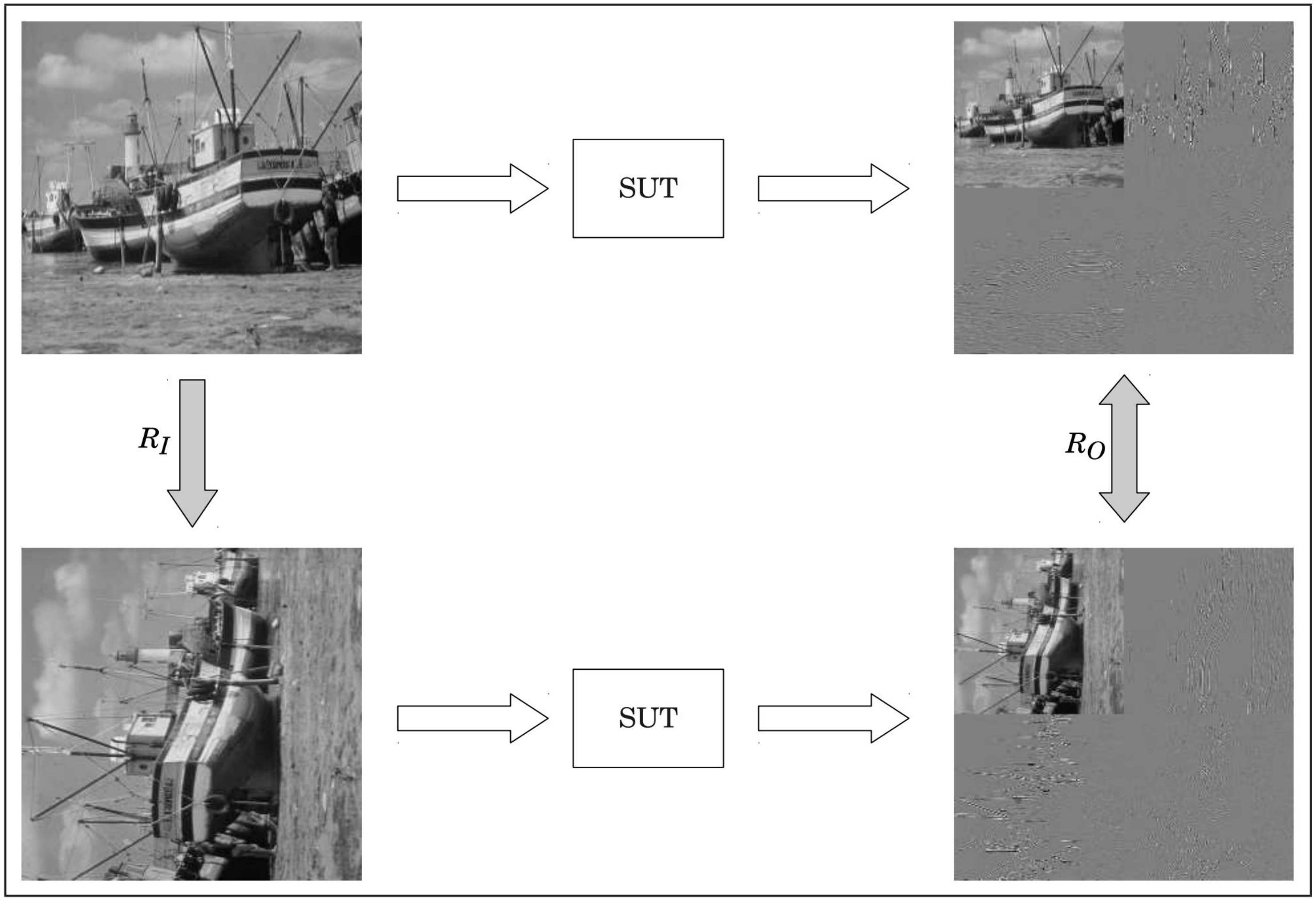
- Input i_1 yields (unknown) output o_1 (initial input)
- R_i: $i_1 \Longrightarrow i_2$ (follow-up input)
- R_o: $o_1 \Longrightarrow o_2$ (necessary condition)

Recap: data diversity and metamorphic testing

Generalization: related inputs and related outputs

- A metamorphic relation defines a program property, such that for any given input i_1:
  - $o_1 = p(i_1)$ ***p:*** ***SUT*** *(System under test)*
  - $i_2 = f(i_1)$ ***f:*** R_i *(Input relation)*
  - $o_2 = g(o_1)$ ***g:*** R_o *(Output relation)*
- A test case in metamorphic testing asserts on the necessary condition $o_2 = g(o_1)$.

Recap: data diversity and metamorphic testing

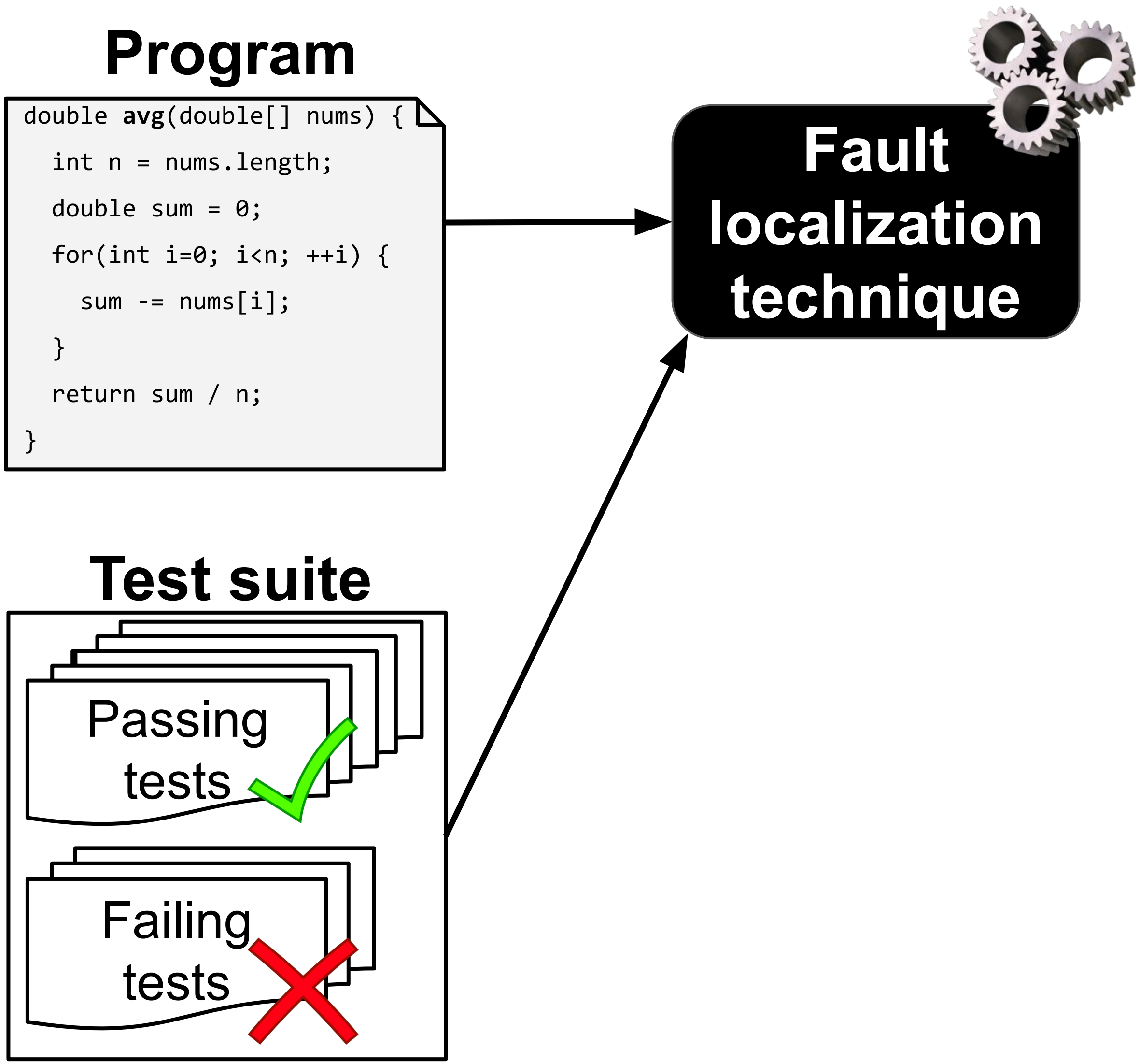


Statistical fault localization

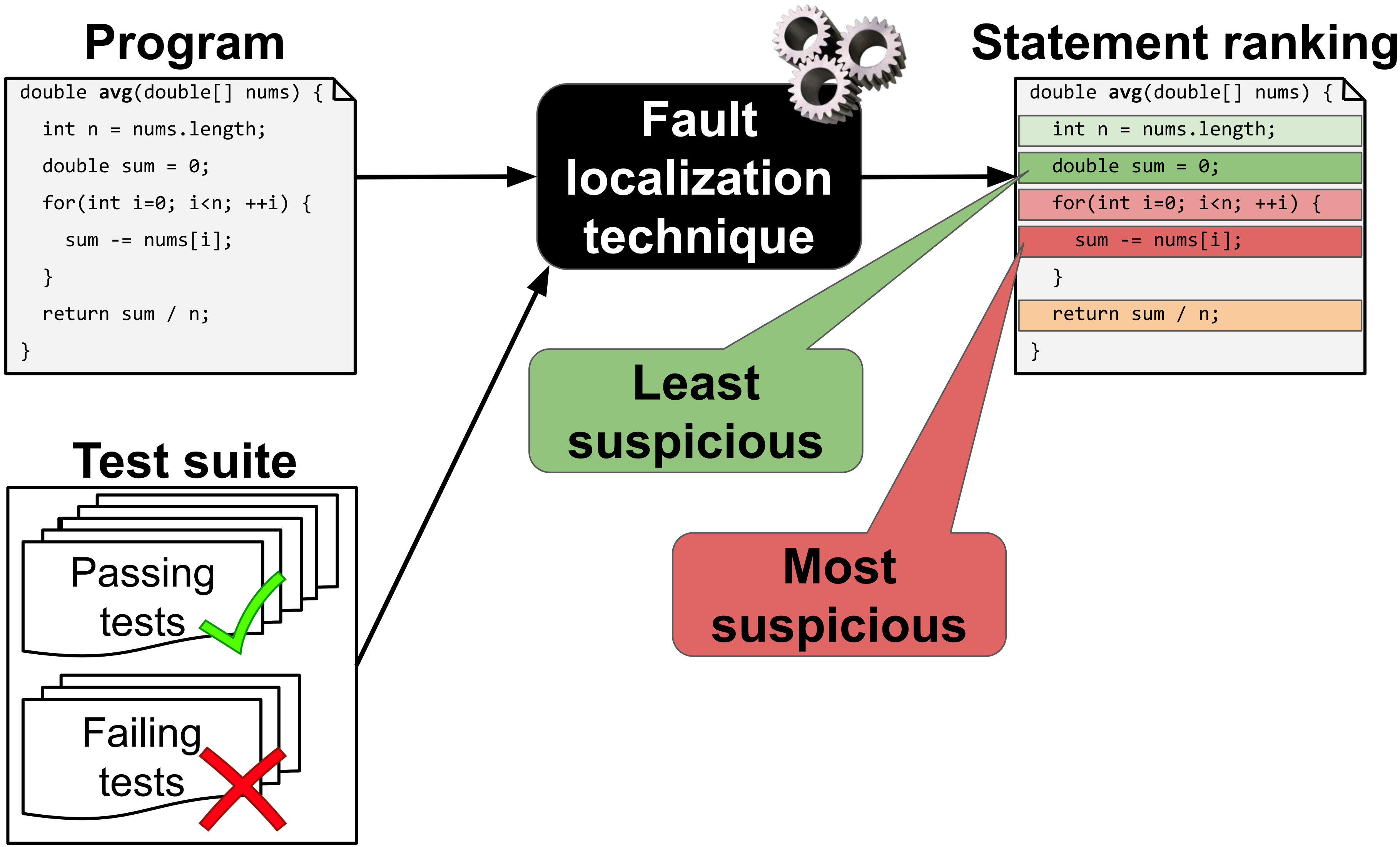
What is statistical fault localization?

Fault localization technique

What is statistical fault localization?



What is statistical fault localization?



Statistical fault localization: how it works

Program

```
double avg(double[] nums) {
  int n = nums.length;
  double sum = 0;
  for(int i=0; i<n; ++i) {
    sum -= nums[i];
  }
  return sum / n;
}
```

Statistical fault localization: how it works

Program

```
double avg(double[] nums) {
  int n = nums.length;
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- Run all tests
  - t1 passes

Statistical fault localization: how it works

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```

- Run all tests
  - t1 passes
  - t2 passes

Statistical fault localization: how it works

Program

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  int n = nums.length;
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```

- Run all tests
  - t1 passes
  - t2 passes
  - t3 passes

Statistical fault localization: how it works

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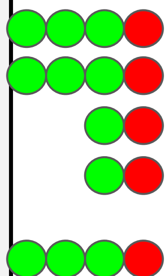

- Run all tests
  - t1 passes
  - t2 passes
  - t3 passes
  - t4 fails

Statistical fault localization: how it works

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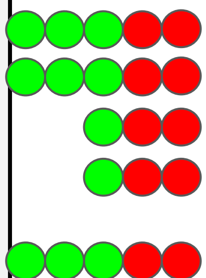

- Run all tests
  - t1 passes
  - t2 passes
  - t3 passes
  - t4 fails
  - t5 fails

Which line(s) seem(s) most suspicious?

Spectrum-based fault localization

Program

```
double avg(double[] nums) {
  int n = nums.length;
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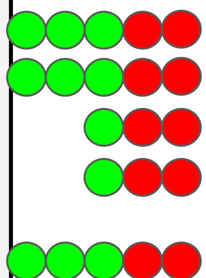

Spectrum-based FL (SBFL)

- **Compute** suspiciousness **per statement**
- Example:

$$S(s) = \frac{failed(s)/totalfailed}{failed(s)/totalfailed + passed(s)/totalpassed}$$

🔴 Statement **covered** by **failing test**
🟢 Statement **covered** by **passing test**

More 🔴 ➡ statement is more suspicious!

Spectrum-based fault localization

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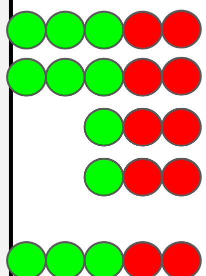

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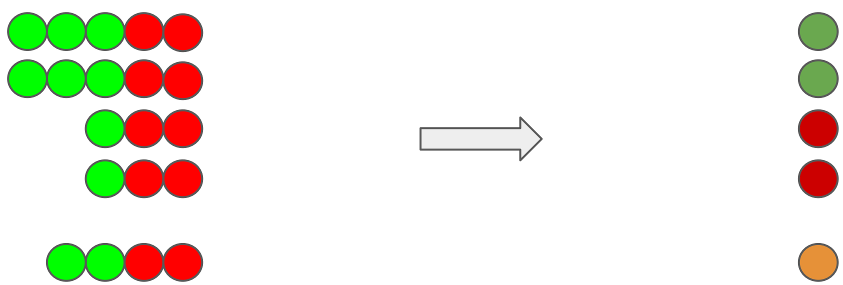
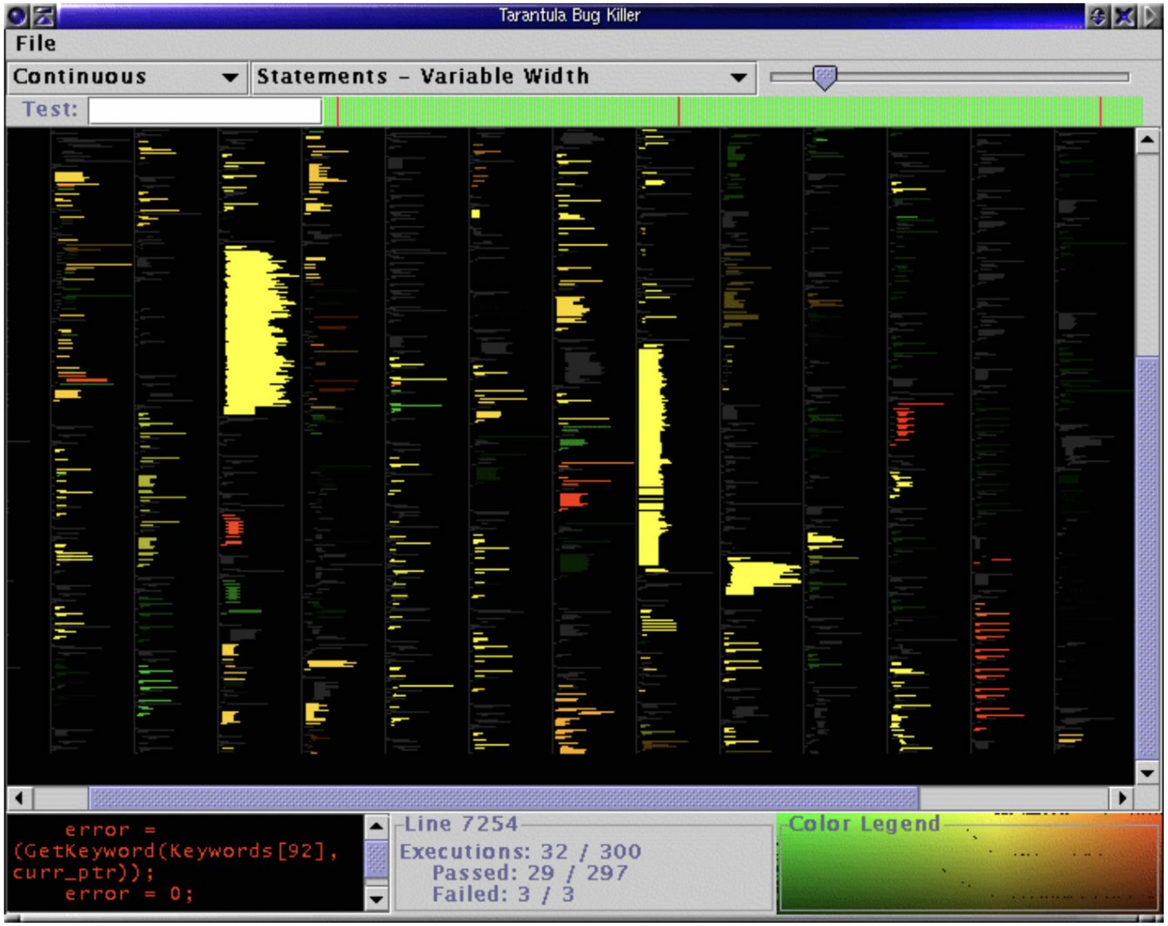
Visualization: the key idea behind Tarantula.



Jones et al., *Visualization of test information to assist fault localization*, ICSE'02

Spectrum-based fault localization



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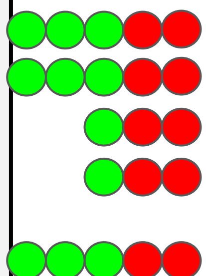


Spectrum-based FL (SBFL)

- **Compute** suspiciousness **per statement**
- Example:

$$S(s) = \frac{failed(s)/totalfailed}{failed(s)/totalfailed + passed(s)/totalpassed}$$

Suspiciousness formula: how to compute it (intuitively)?

Mutation-based fault localization

Program

```
double avg(double[] nums) {
  int n = nums.length;
  double sum = 0;
  for(int i=0; i<n; ++i) {
    sum -= nums[i];
  }
  return sum / n;
}
```

Mutants

```
double avg(double[] nums) {
  int n = nums.length;
  double sum = 0;
  for(int i=0; i<n; ++i) {
    sum += nums[i];
  }
  return sum / n;
}
```

▲▲▲▲

Mutation-based FL (MBFL)

- **Compute** suspiciousness **per mutant**
- **Aggregate** results **per statement**
- Example:

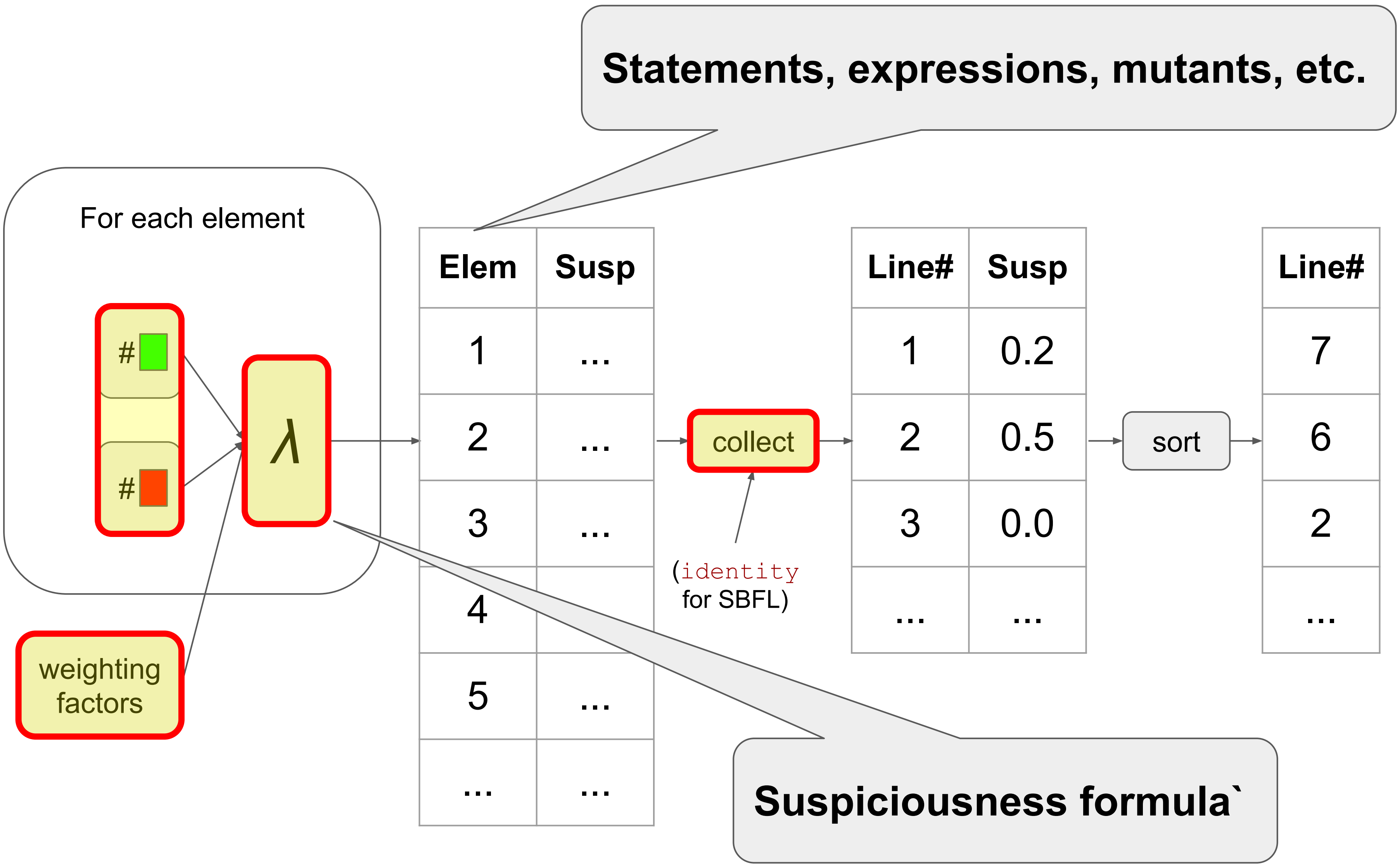
$$S(s) = \max_{m \in mut(s)} \frac{failed(m)}{\sqrt{totalfailed \cdot (failed(m) + passed(m))}}$$

▲ (red) Mutant **affects failing test** outcome

▲ (green) Mutant **breaks passing test**

More ▲ (red) → mutant is more suspicious!

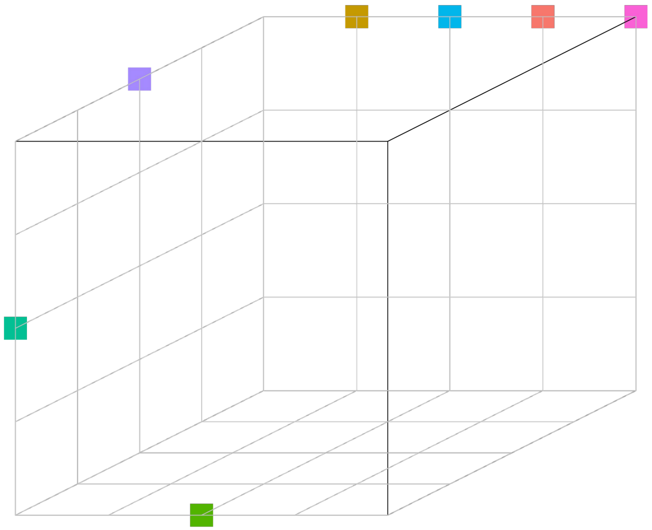
Common structure of SBFL and MBFL



What design decisions matter?

Defined and explored a design space for SBFL and MBFL

- 4 design factors (e.g., formula)

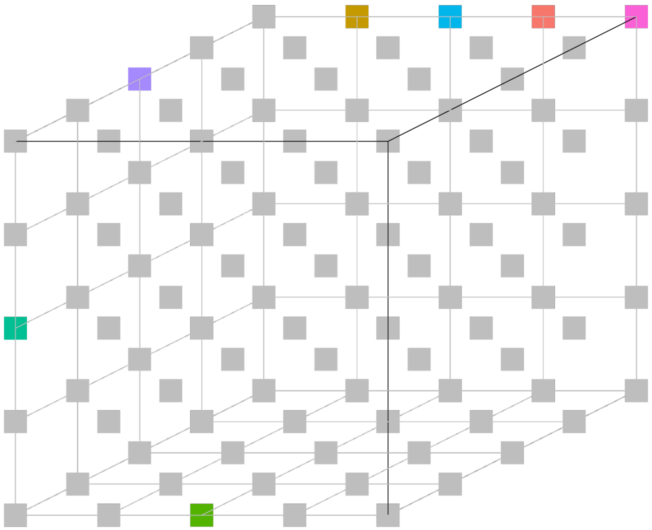


Pearson et al., *Evaluating and Improving Fault Localization*, ICSE’17

What design decisions matter?

Defined and explored a design space for SBFL and MBFL

- 4 design factors (e.g., formula)
- 156 FL techniques



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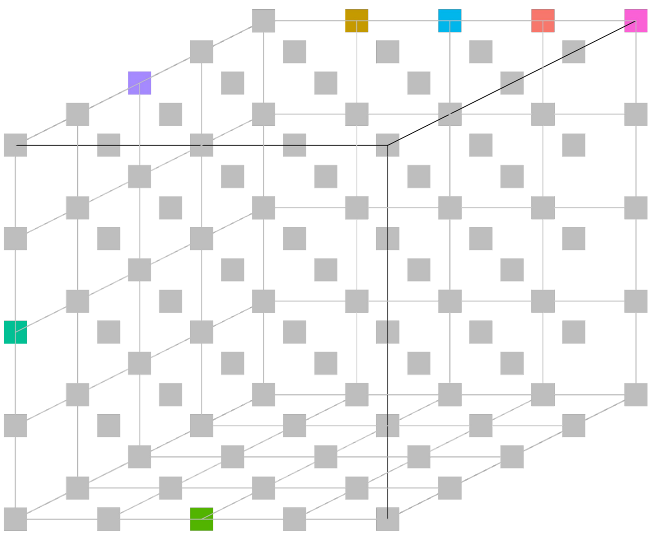

Results

- Most design decisions don't matter (in particular for SBFL)
- Definition of test-mutant interaction matters for MBFL
- Barinel, D*, Ochiai, and Tarantula are indistinguishable

Pearson et al., *Evaluating and Improving Fault Localization*, ICSE'17

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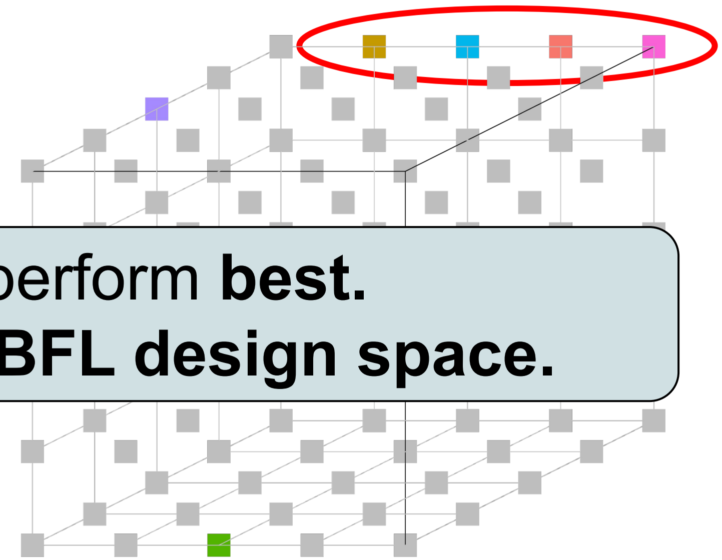

Existing **SBFL techniques** perform **best.**
No breakthroughs in the **MBFL/SBFL design space.**

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Effectiveness of SBFL and MBFL

- Top-10 useful for practitioners[1].
- Top-200 useful for automated patch generation[2].

Technique	Top-5	Top-10	Top-200
Hybrid	36%	45%	85%
DStar (*best SBFL*)	30%	39%	82%
Metallaxis (*best MBFL*)	29%	39%	77%

What assumptions underpin these results? Are they realistic?

[1]Kochhar et al., *Practitioners' Expectations on Automated Fault Localization*, ISSTA'16
[2]Long and Rinard, *An analysis of the search spaces for generate and validate patch generation systems*, ICSE'16

Automated patch generation

Automatic patch generation (program repair)

Generate-and-validate Approaches

What are the **main components** of a (generate-and-validate) patch generation approach?

Automatic patch generation (program repair)

Generate-and-validate Approaches

Main components:

- **Fault localization**
- Mutation + fitness evaluation
- Patch validation

Defect prediction

Defect prediction: the addressed problem

Problem

- QA is limited...

Defect prediction: the addressed problem

Problem

- QA is limited...by time and money.

Defect prediction: the addressed problem

Problem

- QA is limited...by time and money.
- How should we allocate limited QA resources?

Defect prediction: the addressed problem

Problem

- QA is limited...by time and money.
- How should we allocate limited QA resources?
  - Focus on components that are most error-prone.
  - Focus on components that are most likely to fail in the field.

How do we know what components are critical or error-prone?

Defect prediction: a bird's-eye view

Model

- Learn a model from historic data (same project vs. different project)

Defect prediction: a bird's-eye view

Model

- Learn a model from historic data (same project vs. different project)

Predictions

- Classification: is a file/method buggy
- Ranking: how many bugs does a file/method contain

Granularity

- Most research has focused on file-level granularity

Defect prediction: a bird's-eye view

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Which type of prediction and what granularity are most useful?

Defect prediction: a bird's-eye view

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What types of metrics matter?

Defect prediction: metrics

Change metrics

- Source-code changes
- Code churn
- Previous bugs

Code metrics

- Complexity metrics (e.g., size, McCabe, dependencies)
- Design metrics (e.g., inheritance hierarchy)

Organizational metrics

- Team structure
- Contribution structure
- Communication

What metrics are most important?

Defect prediction: some results

Predictor	Precision	Recall
Pre-Release Bugs	73.80%	62.90%
Test Coverage	83.80%	54.40%
Dependencies	74.40%	69.90%
Code Complexity	79.30%	66.00%
Code Churn	78.60%	79.90%
Org. Structure	86.20%	84.00%

From: N. Nagappan, B. Murphy, and V. Basili. The influence of organizational structure on software quality. ICSE 2008.

In-class exercise: fault localization