Customized Program Mutation

(aka Mutation analysis for the real world:
Effectiveness, efficiency and proper tool support)

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A quick poll

What is a good mutation score?

A quick poll

What is a good mutation score?

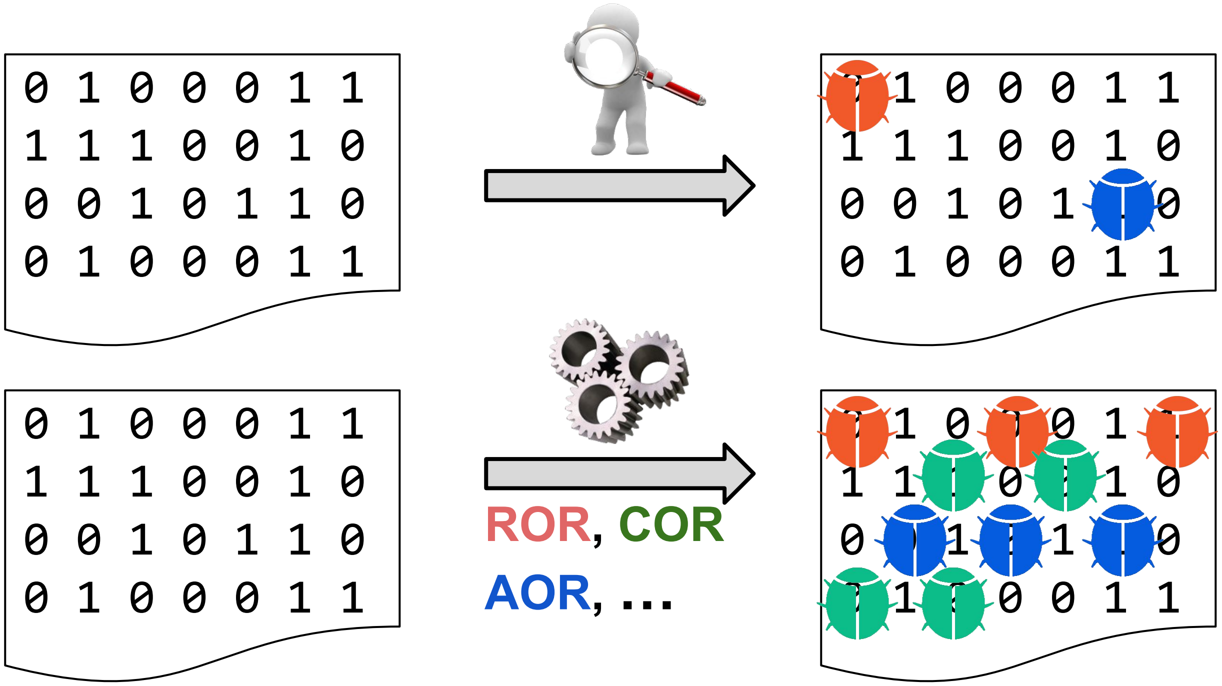
~100% is good **if** the **mutants** are **good proxies for real faults**.

Everything else is meaningless: the mutation score is heavily inflated due to a high degree of redundancy.

Big picture: the past, the present, and the future

Past: manual fault seeding

Present: generic program mutation



Big picture: the past, the present, and the future

Past: manual fault seeding

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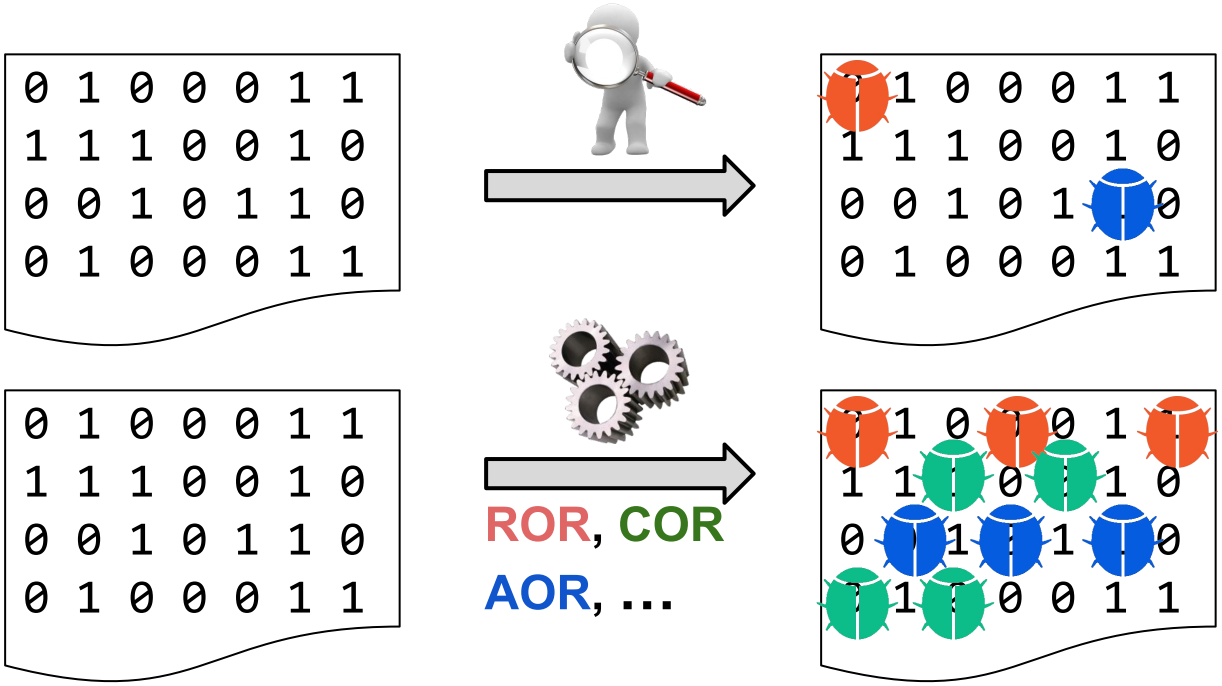
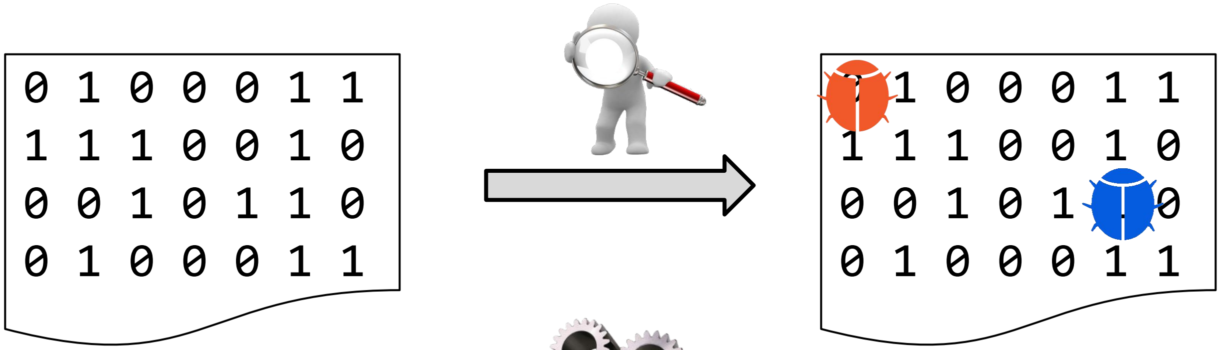


Problem: not all mutants are equally strong, and program **context affects mutant utility**.

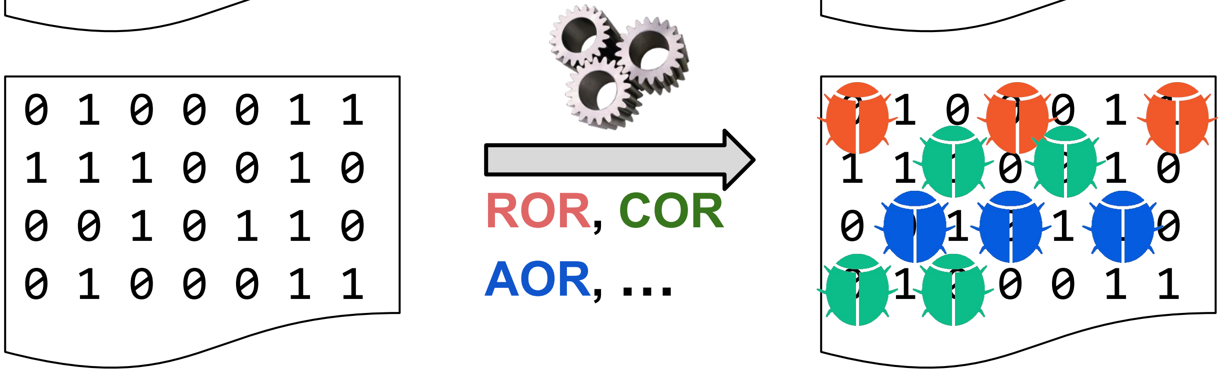
Solution: customize program mutations **to program context**.

Big picture: the past, the present, and the future

Past: manual fault seeding



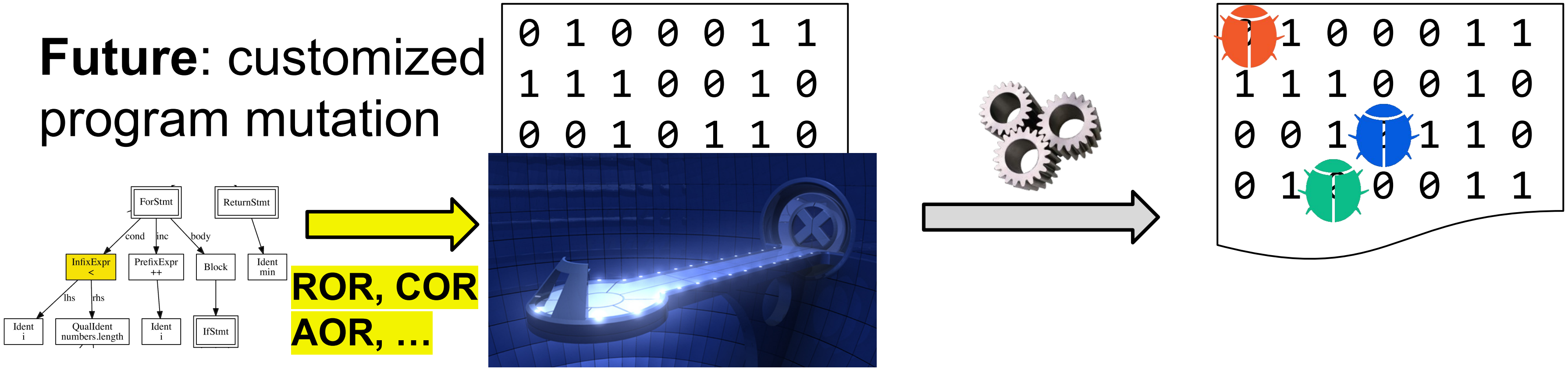
Present: generic program mutation



ROR, COR

AOR, …

Future: customized program mutation

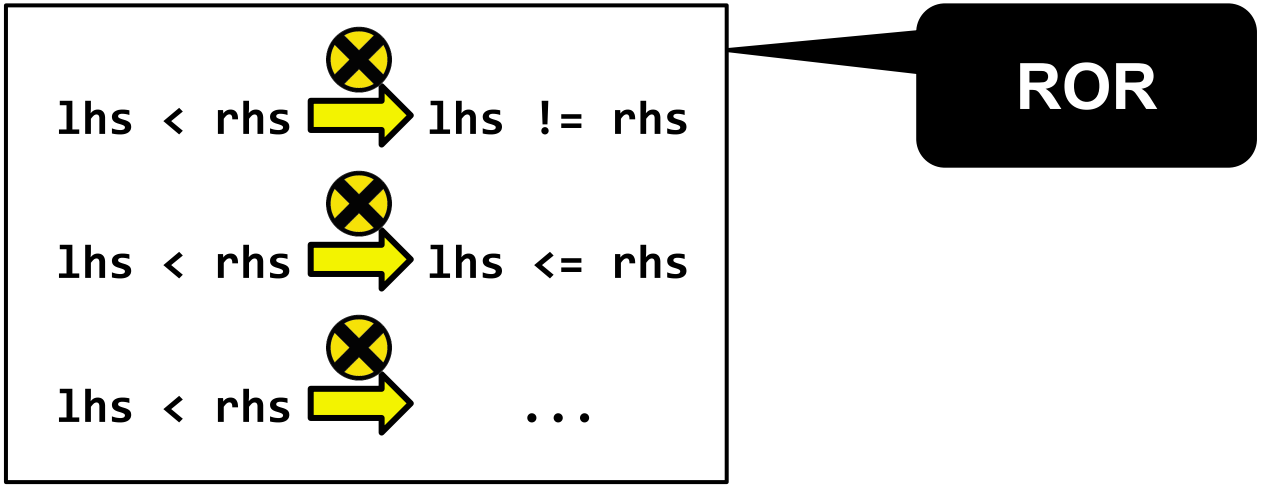


ROR, COR

AOR, …

Some terminology

Mutation operator vs. **mutation operator group**



`lhs < rhs` → `lhs != rhs`

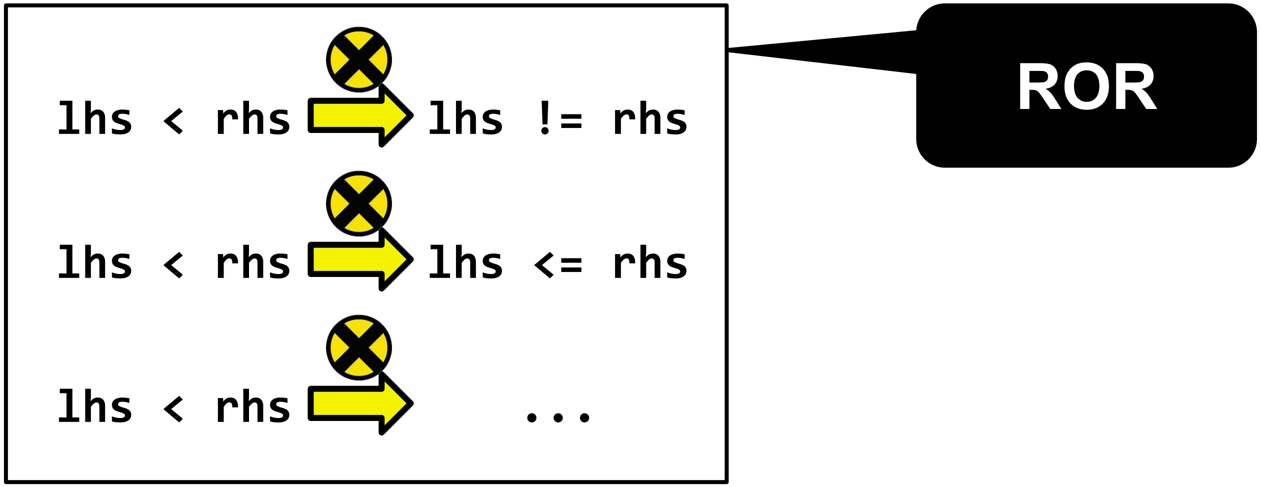
`lhs < rhs` → `lhs <= rhs`

`lhs < rhs` → `...`

ROR

Some terminology

Mutation operator vs. **mutation operator group**



`lhs < rhs` → `lhs != rhs`

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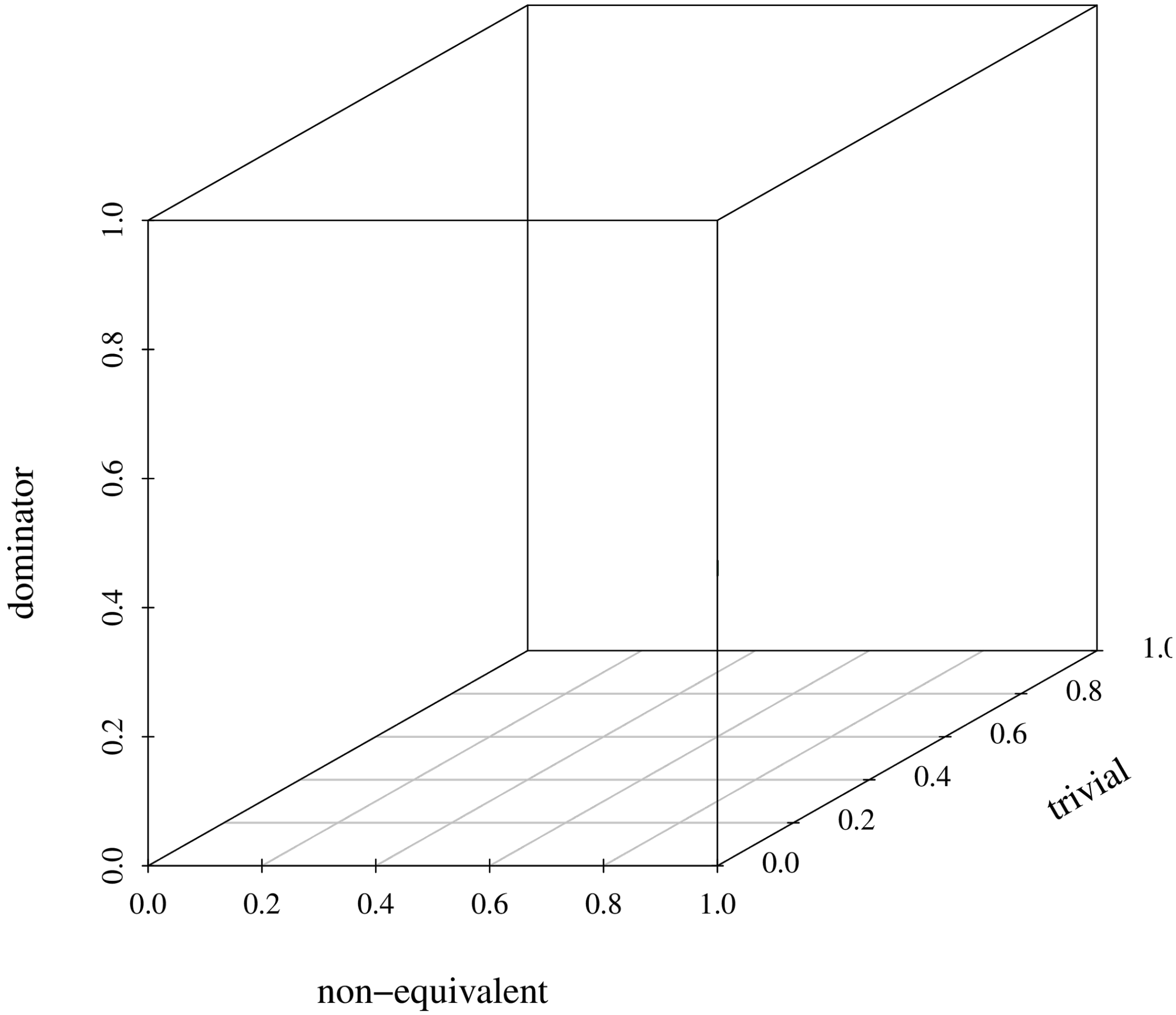
ROR

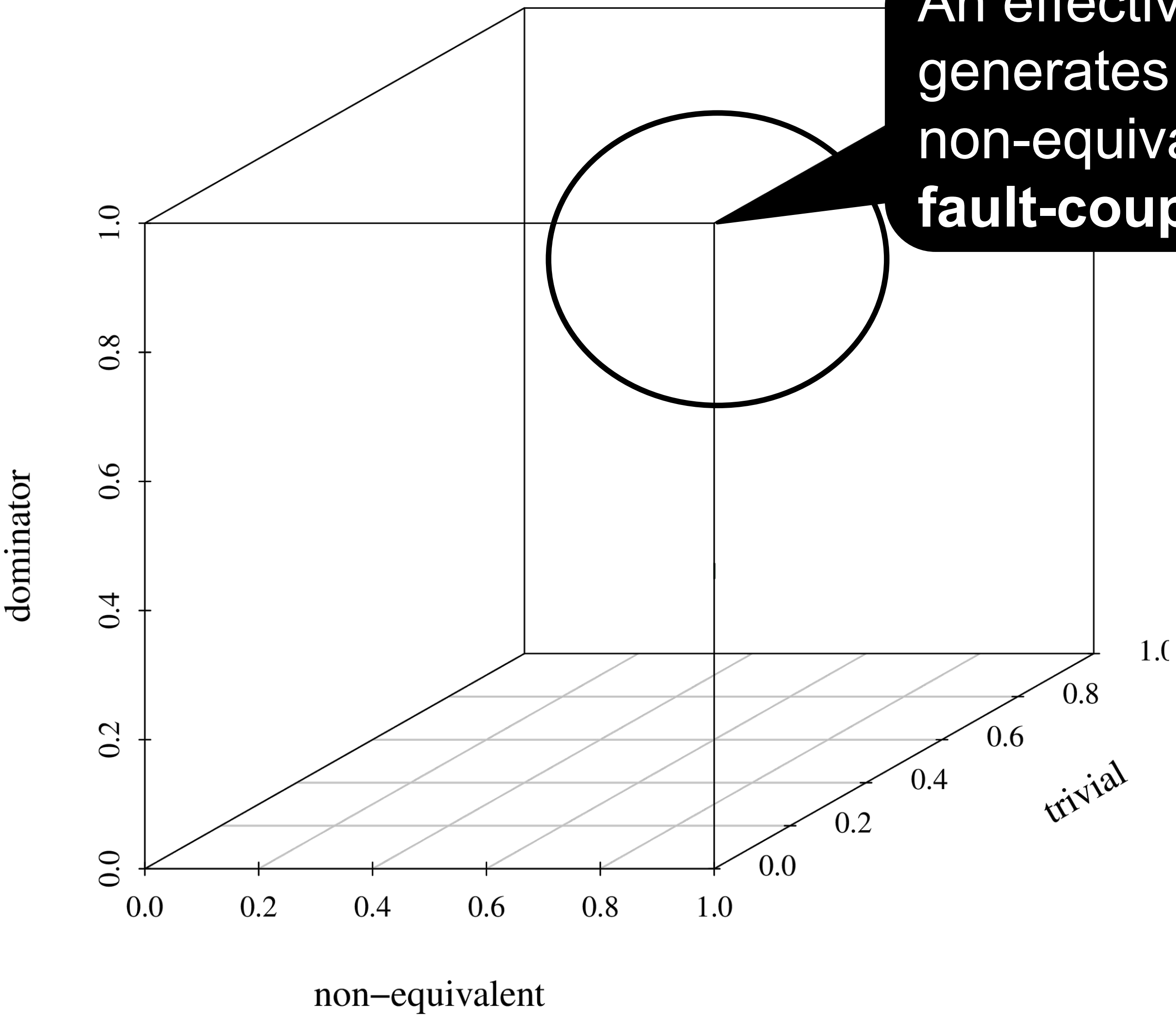
An effective mutant:

- is coupled to one or more real faults
- is NOT equivalent
- is NOT dominated by other mutants
- is NOT redundant or trivial

High-level goal: effective mutation operators



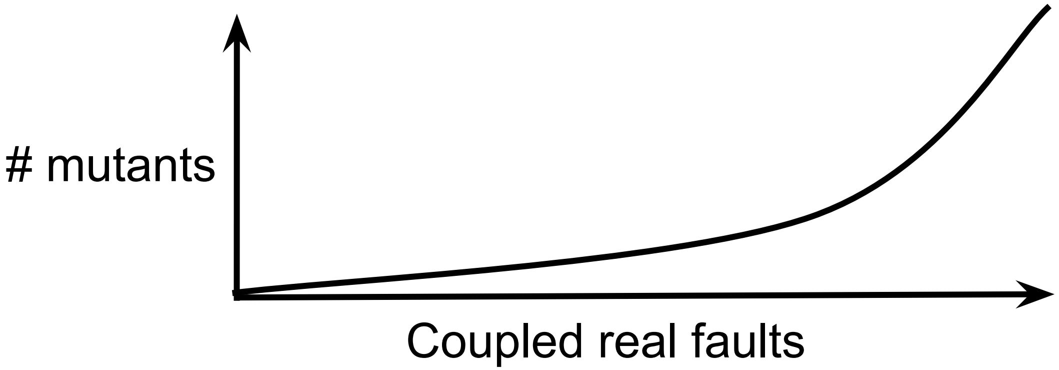
High-level goal: effective mutation operators



An effective mutation operator generates a large ratio of non-equivalent, non-trivial, **fault-coupled** dominators.

Fault-coupled mutants

- Mutants are not similar to real faults.
- BUT most real faults are coupled to some mutants.
- Number of mutants increases superlinear when fault-coupling is increased.



Gopinath et al., ISSRE’14, Pearson et al., ICSE’17, Just et al., FSE’14

Is selective mutation the solution?

No free lunch

- No selection strategy **for mutation operator groups** works equally well for all programs.

Program context matters!

Zhang et al., ICSE’10, Gopinath et al., ICSE’16, Kurtz et al., FSE’16

Program context: motivational example (1)

Original program

```
public double getAbsAvg(int[] nums) {
  double avg = 0;

  for (int i = 0; i < nums.length; ++i) {
    if (nums[i] < 1) {
      avg -= (double)nums[i] / nums.length;
    } else {
      avg += (double)nums[i] / nums.length;
    }
  }
  return avg;
}
```

Program context: motivational example (1)

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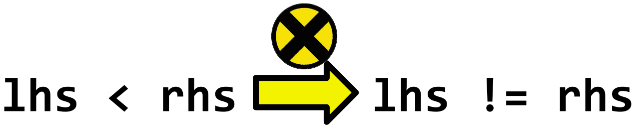
Mutation operator



`lhs < rhs` ⇨ `lhs != rhs`

Program context: motivational example (1)

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  return avg;
}
```

Mutation operator

`lhs < rhs` ⇨ **`lhs != rhs`**

`equivalent mutant`

`dominator mutant`

Context: different kinds of lexically enclosing statements (for vs. if)

Program context: motivational example (2)

Original program

```
public double getAbsAvg(int[] nums) {
  double avg = 0;

  for (int i = 0; i < nums.length; ++i) {
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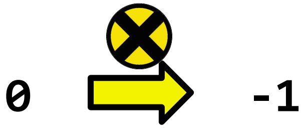
```

Mutation operator



Program context: motivational example (2)

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```
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    }
  }
  return avg;
}
```

Mutation operator

`0` → `-1`

🟩 **non-trivial mutant**

🟥 **trivial mutant**

Context: different data types (double vs. int)

Program context: motivational example (3)

Original program

```
public double getAbsAvg(int[] nums) {
  double avg = 0;

  for (int i = 0; i < nums.length; ++i) {
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Mutation operator

`lhs < rhs` ⊗⇒ **`lhs <= rhs`**

Program context: motivational example (3)

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```

Mutation operator

`lhs < rhs` ⊗⇨ `lhs <= rhs`

🟥 **trivial mutant**

🟩 **dominator mutant**

Context: different kinds of operands (variable vs. literal)

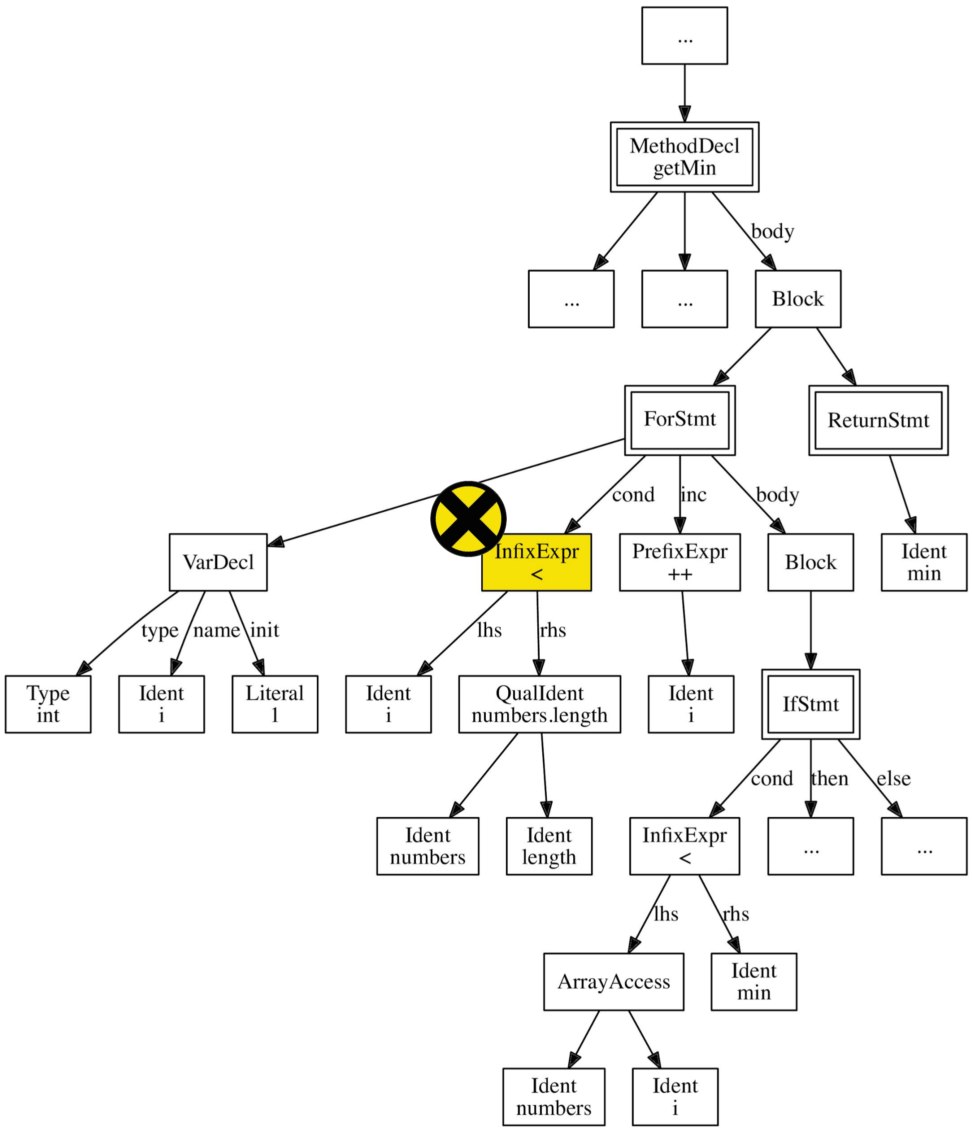
Program context: summary

- Program context affects mutant utility
  - Utility of mutation operators differs, even within a single mutation operator group (e.g., ROR).
  - Utility of a mutation operator differs, even within a single method.
- Different dimensions of program context
  - Kind of lexically enclosing statement
  - Kind and data type of operator and operands
  - Scope and visibility
  - Coding style and syntactic sugar
  - ...

Mutation operators need to be customized to program context!

Customized program mutation

Modeling program context using the AST



- The abstract syntax tree (AST) provides relevant context information for:
  - Mutated nodes
  - Parent nodes
  - Children nodes
- Can be augmented with project-specific context information:
  - Coding guidelines

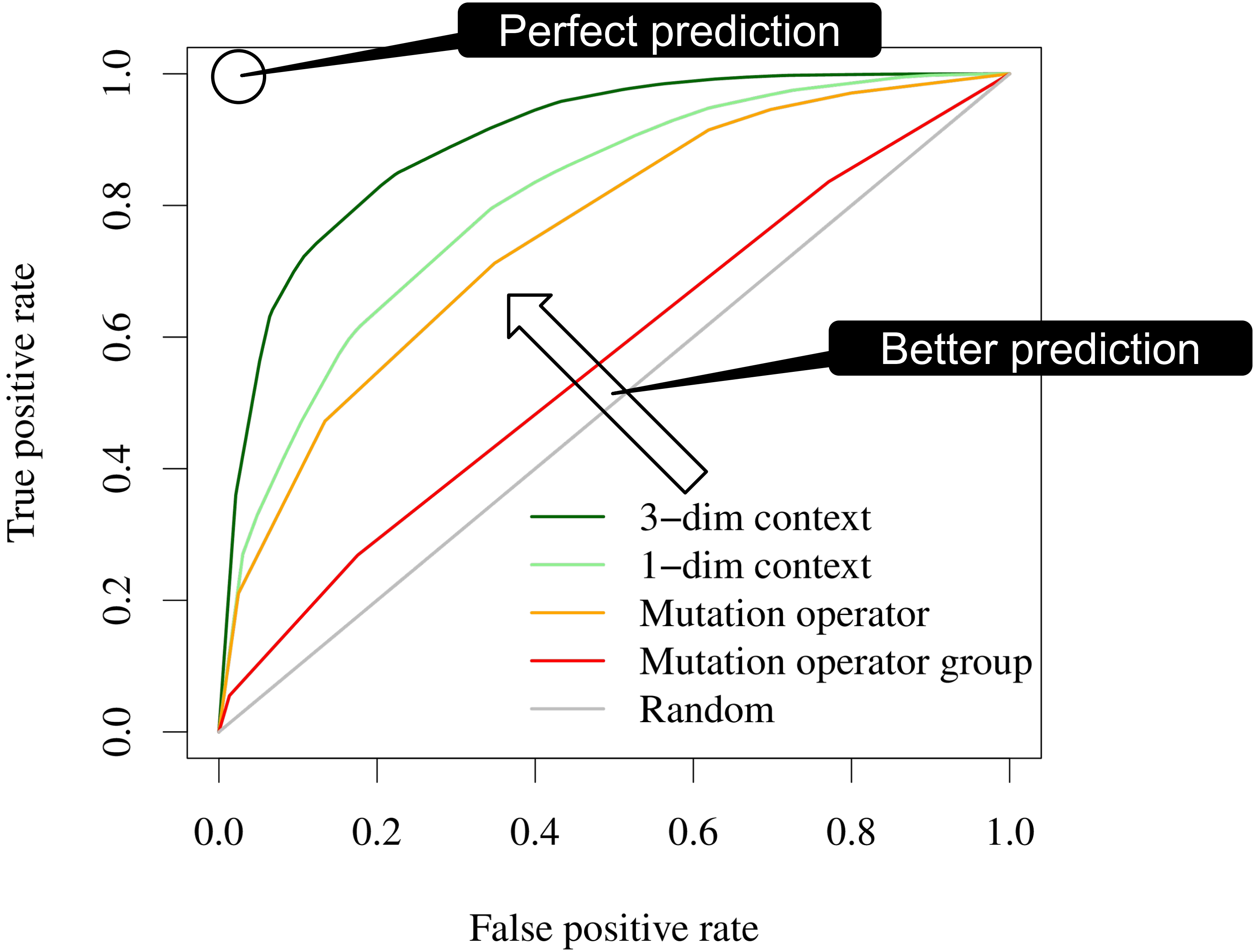
Some promising results

WARNING

- “Fresh out of the oven”
- Preliminary study
  - 100,000 mutants (5 open source projects)*.
  - Approximation of equivalent/dominator/trivial mutants, using thorough test suites*.
- Comparison of tree-based classifiers for mutant utility
  - Mutation operator groups
  - Mutation operators
  - Program context

**http://www.defects4j.org*

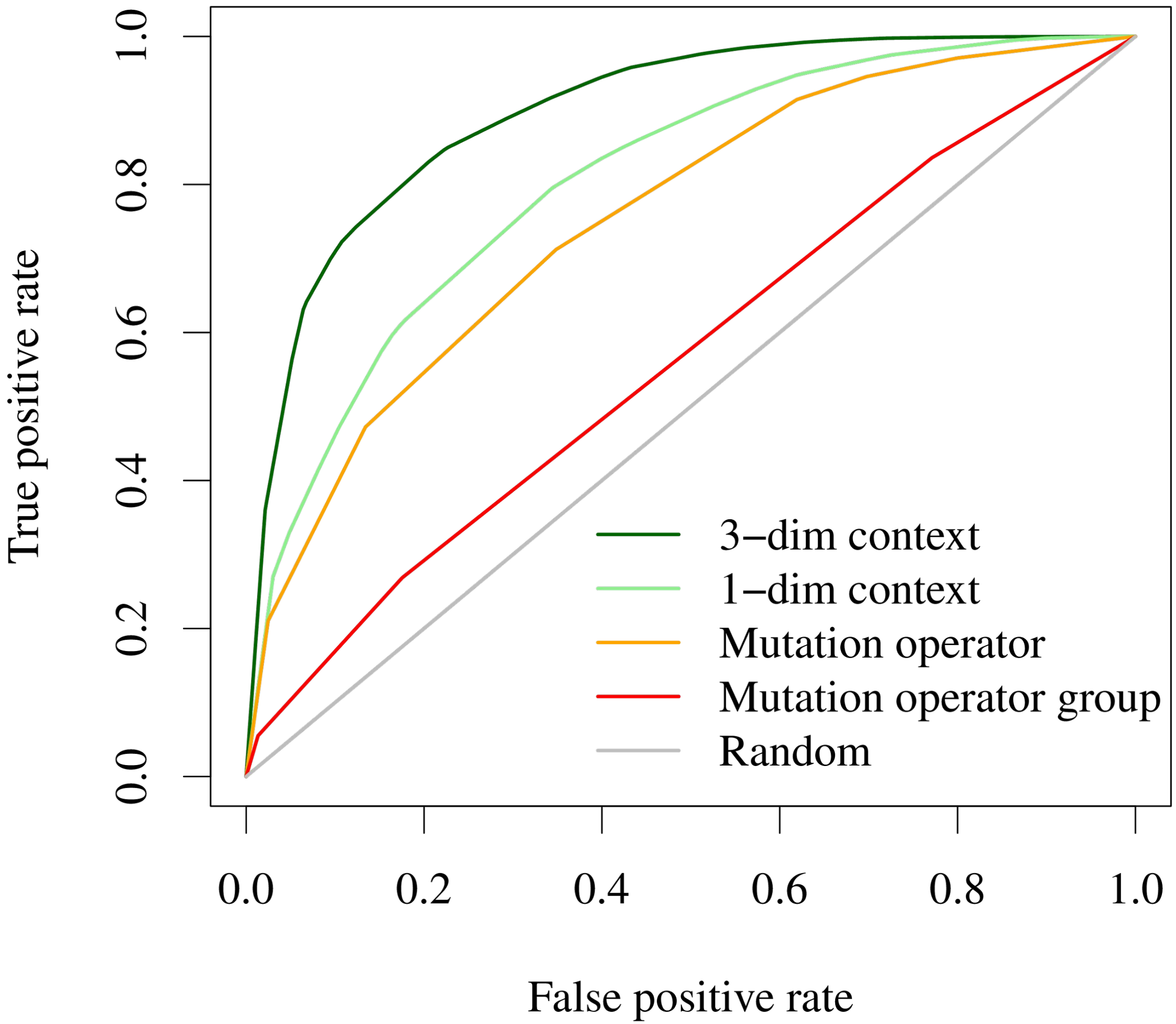
Classifiers for mutant utility (non-equivalent)



Perfect prediction

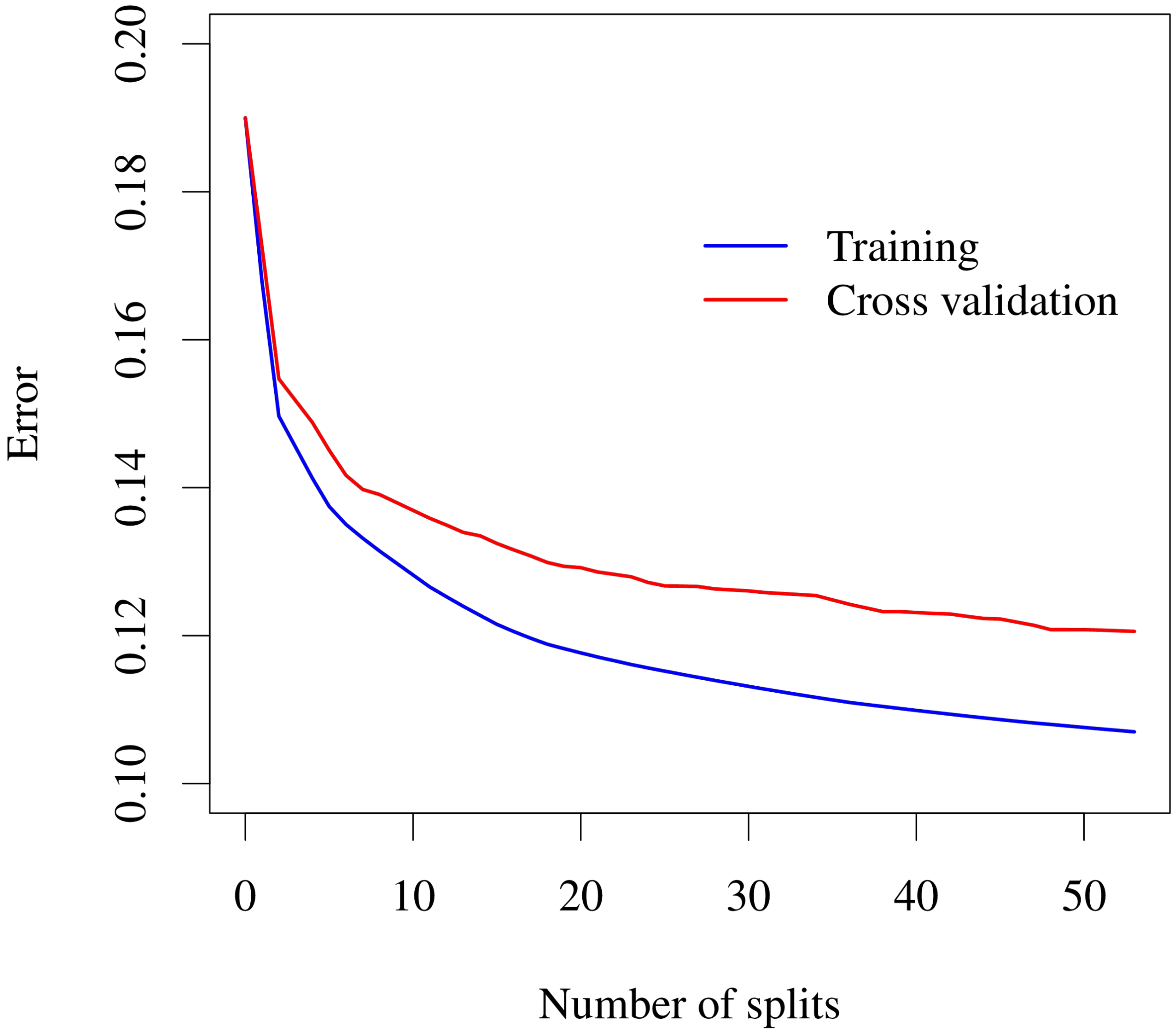
Better prediction

Classifiers for mutant utility (non-equivalent)

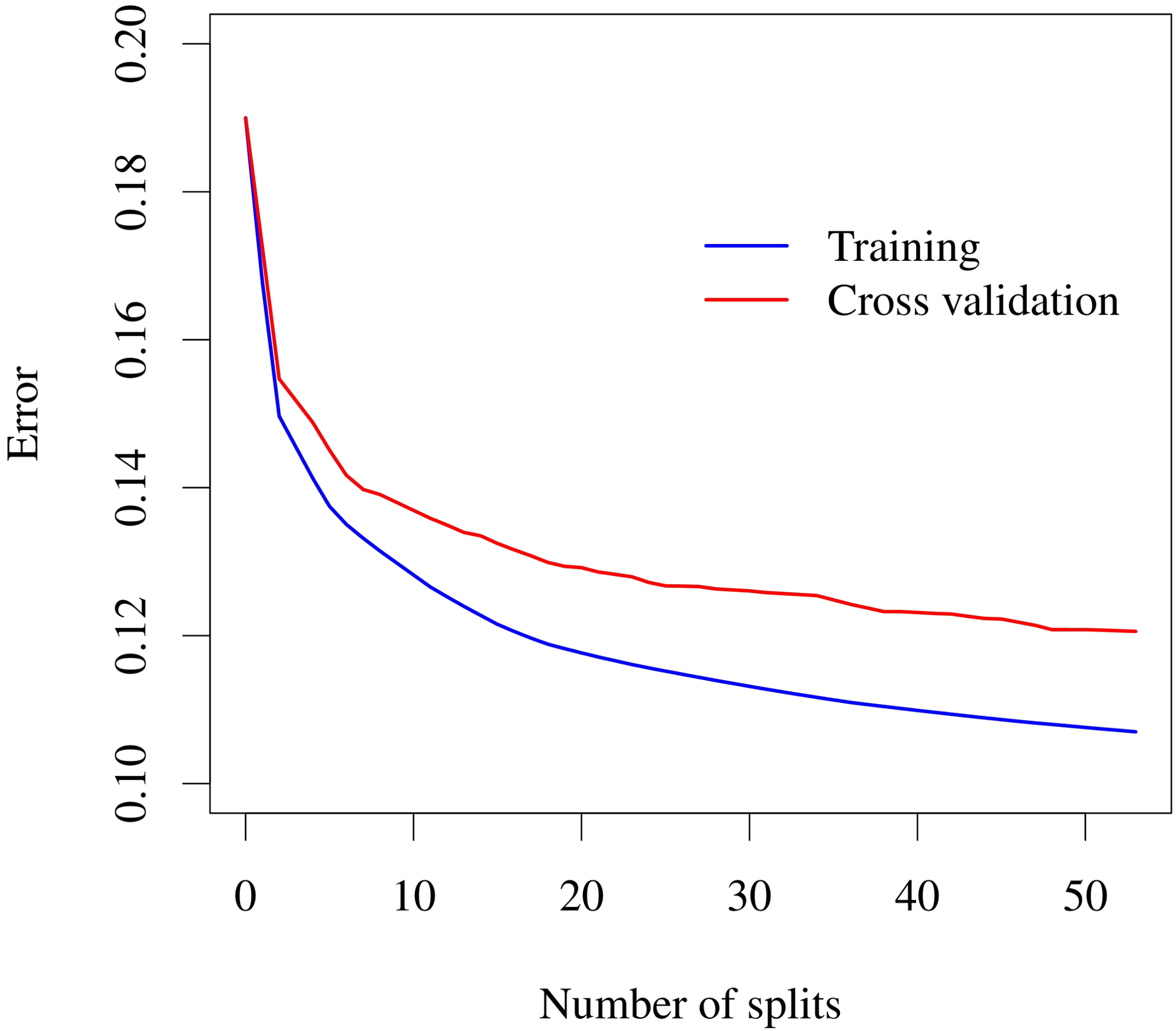


- **Mutation operator group is marginally better than random.**
- **Program context improves over mutation operator.**
- **Similar results for trivial mutants and dominator strength.**

Error rate of 3-dim context classifier (non-equivalent)

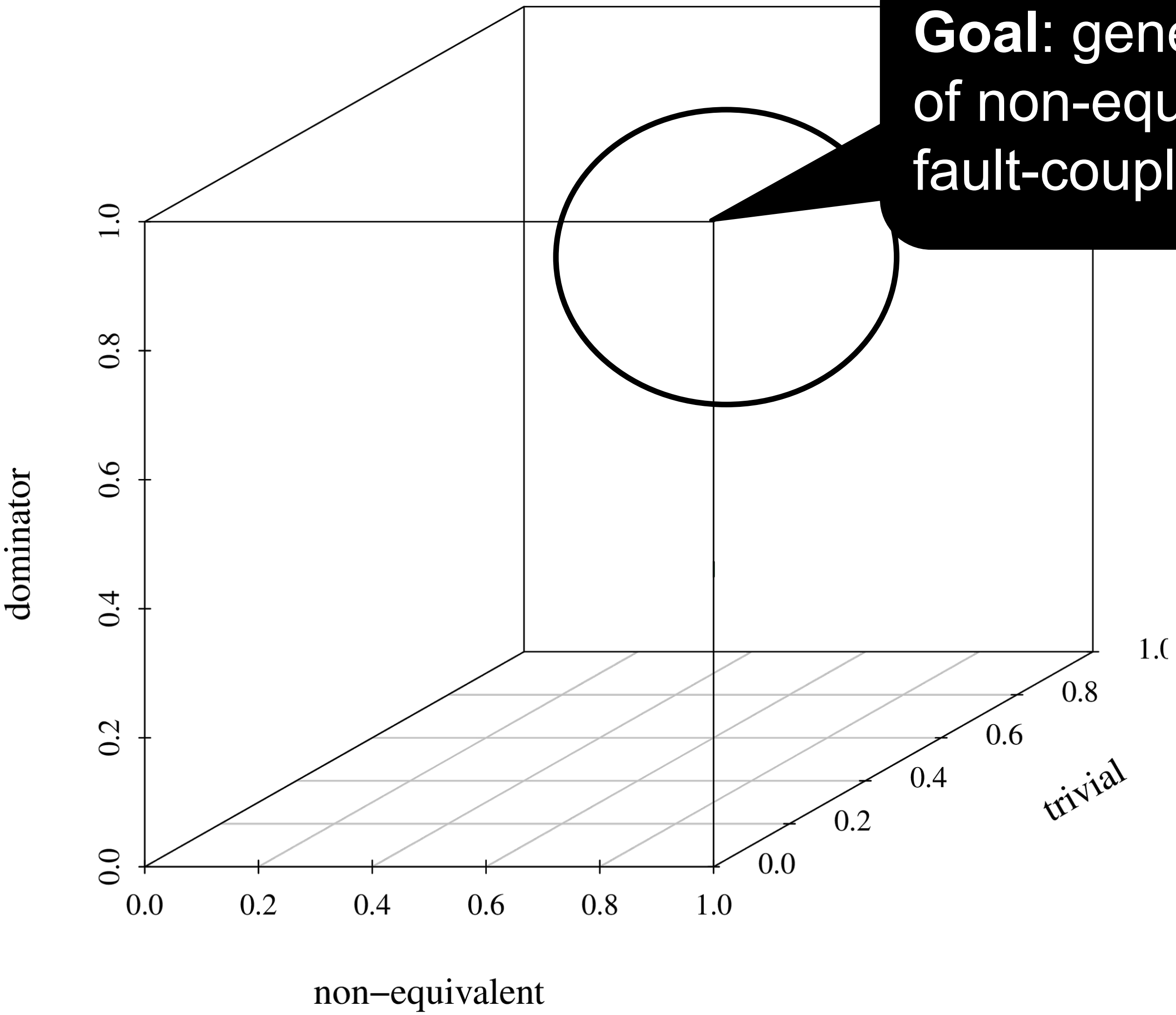


Error rate of 3-dim context classifier (non-equivalent)



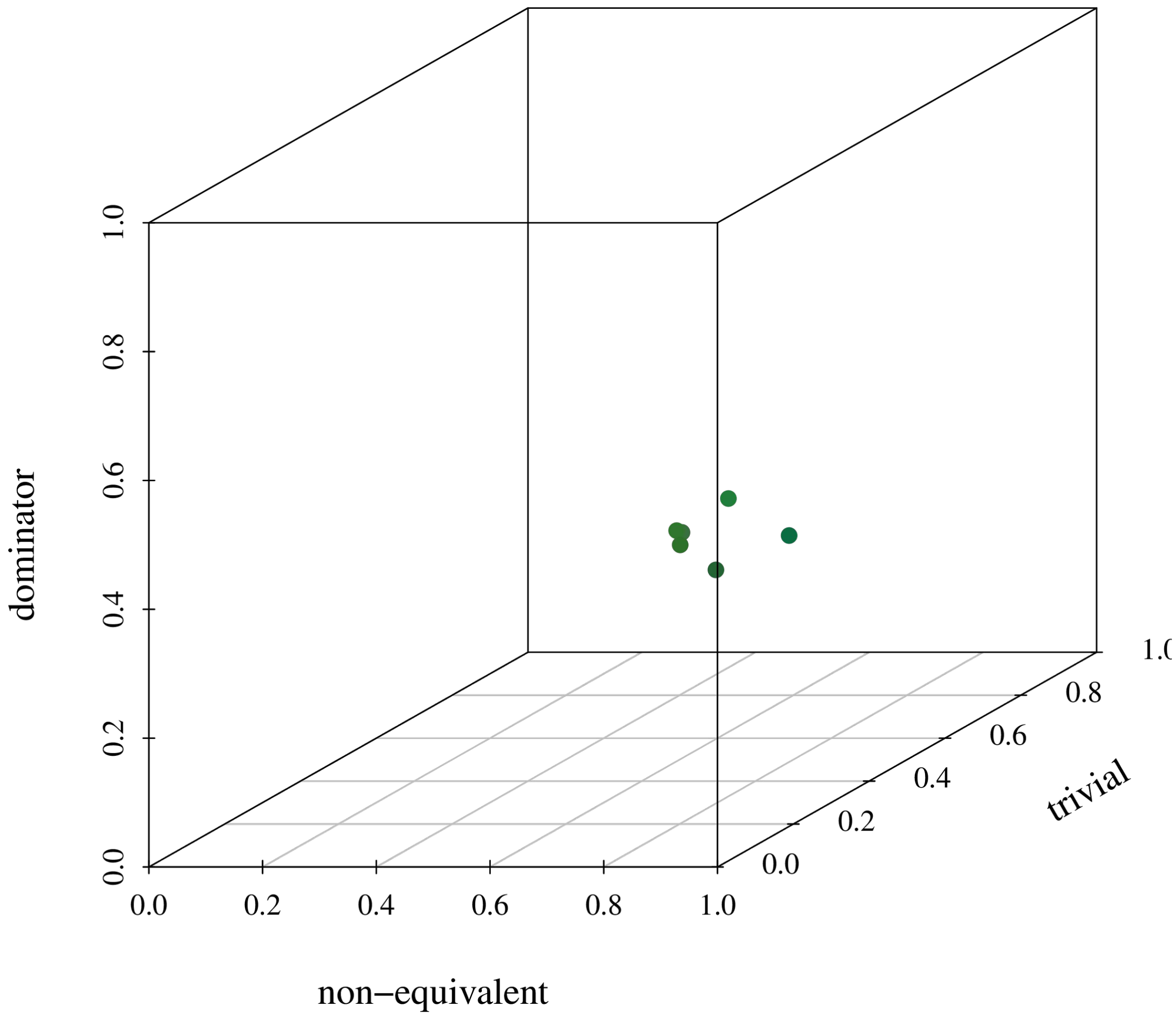
- **Training error shows room for improvements.**
- **Overfitting is NOT (yet) a problem.**
- **Similar results for trivial mutants and dominator strength.**

Recall the high-level goal

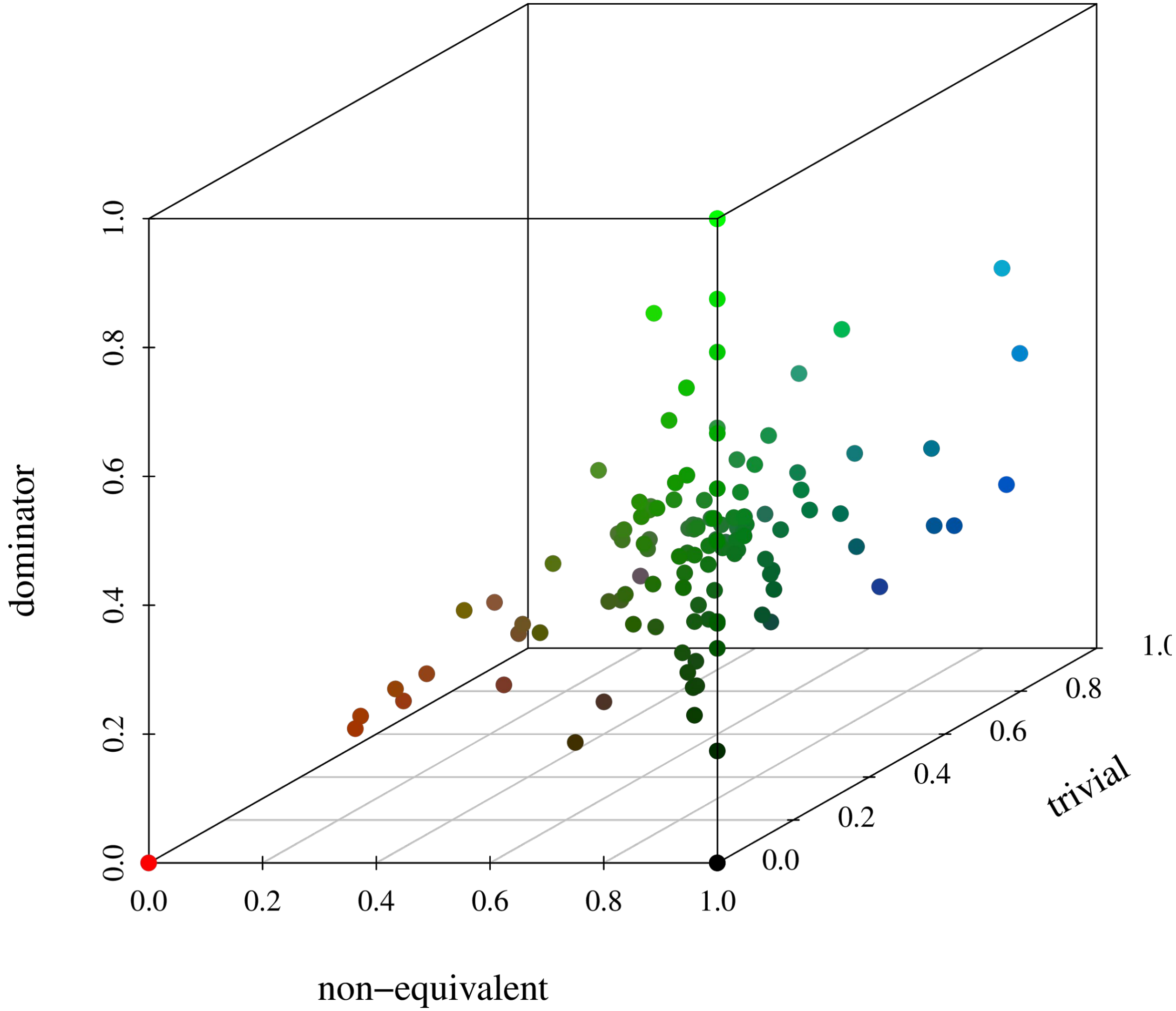


Goal: generate a large ratio of non-equivalent, non-trivial, fault-coupled dominators.

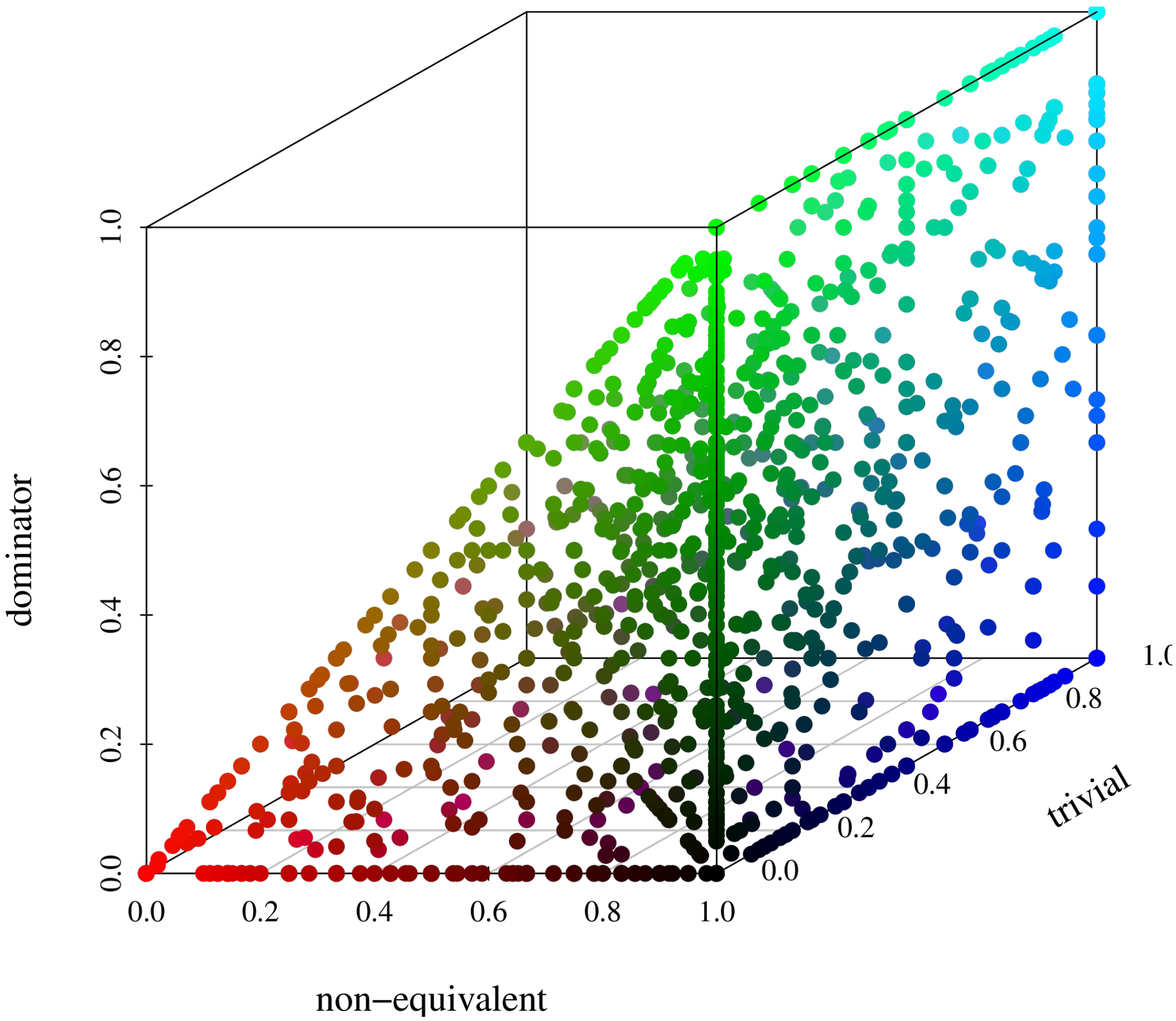
Effectiveness: mutation operator groups



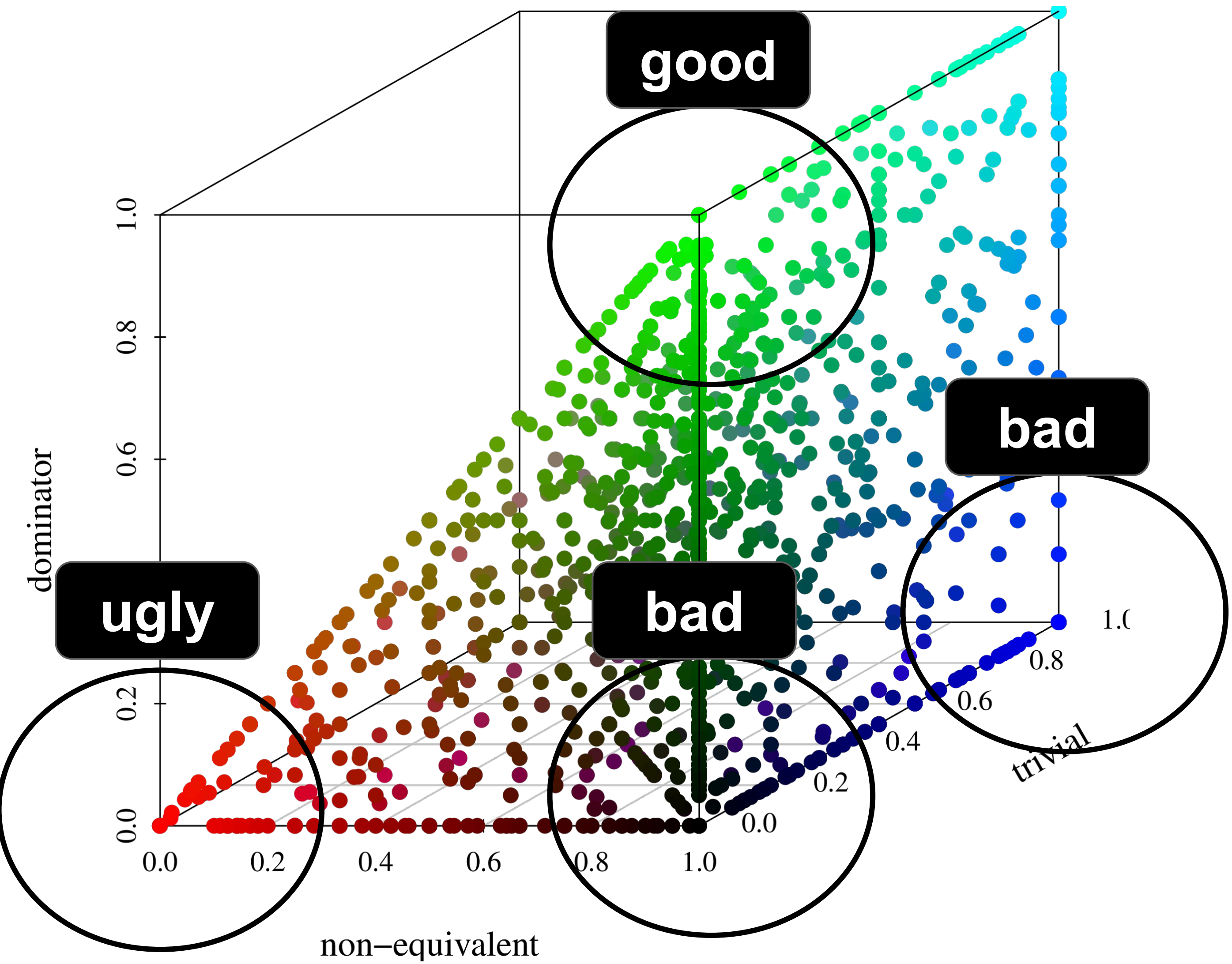
Effectiveness: mutation operators



Effectiveness: mutation operators + program context



Customized program mutation



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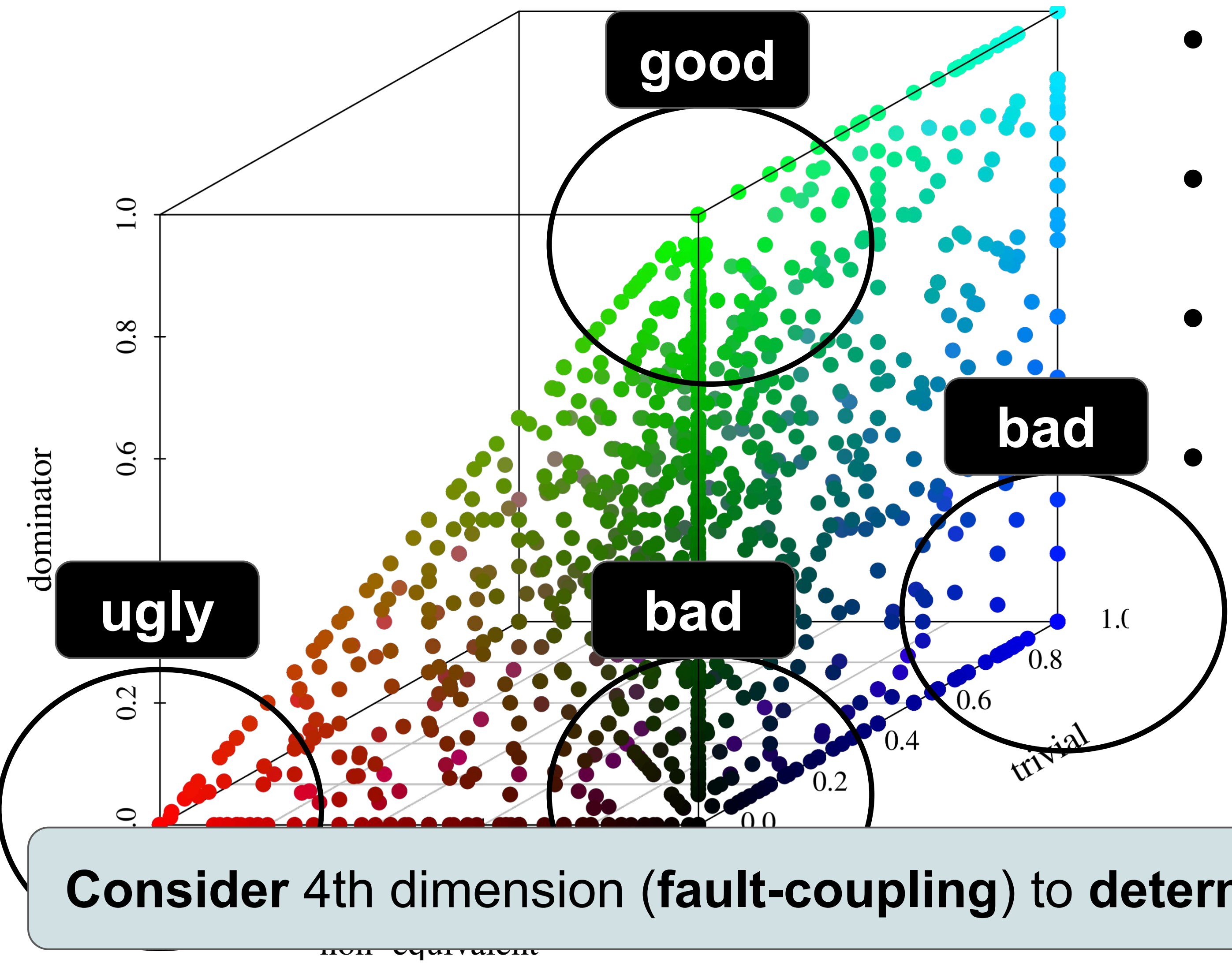
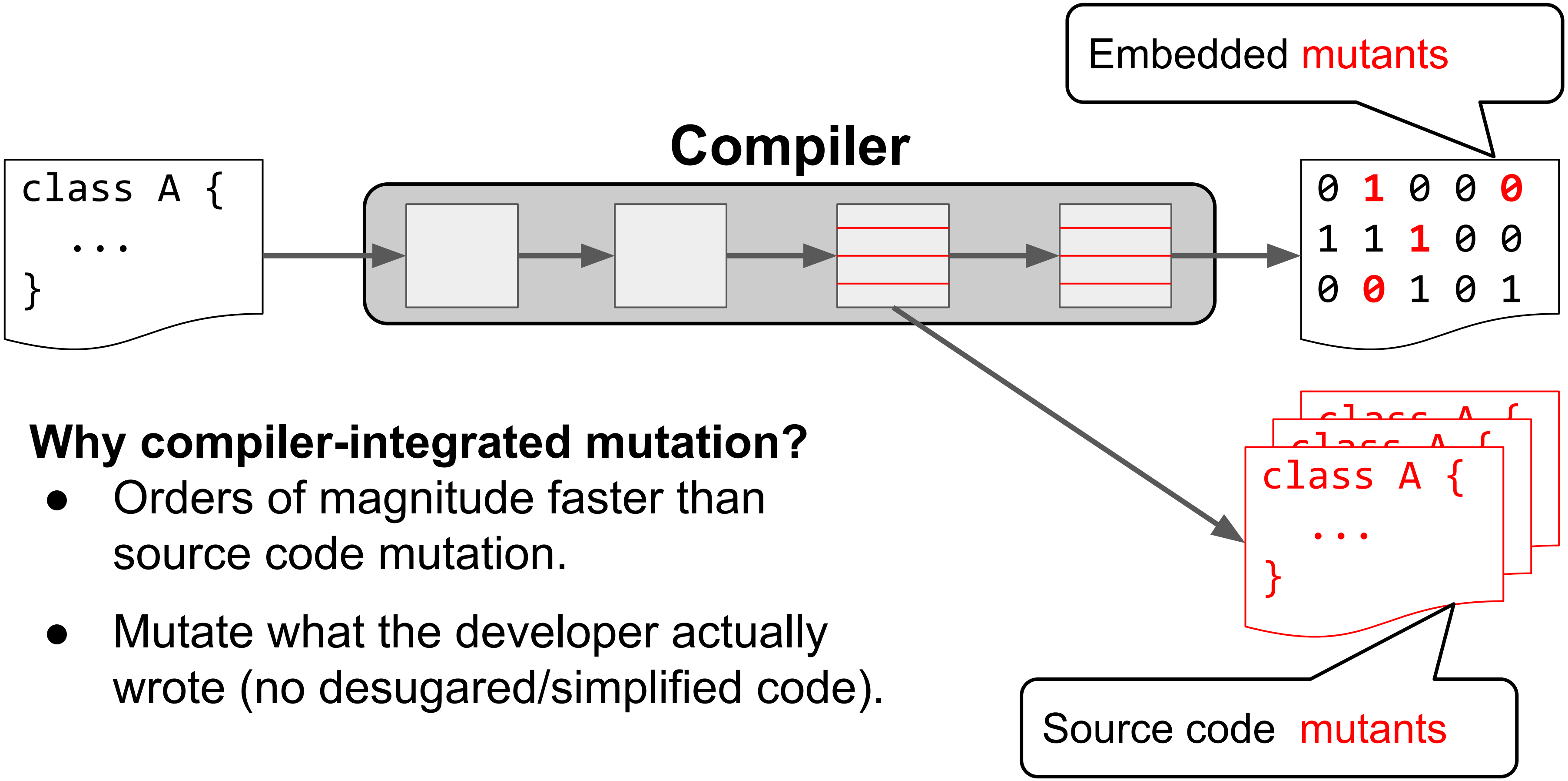


- **Generate dominator mutants.**
- **Don’t generate equivalent mutants.**
- **Avoid redundant mutants.**
- **Avoid trivial mutants.**

Consider 4th dimension (**fault-coupling**) to **determine thresholds**!

Tool support

Major: overview

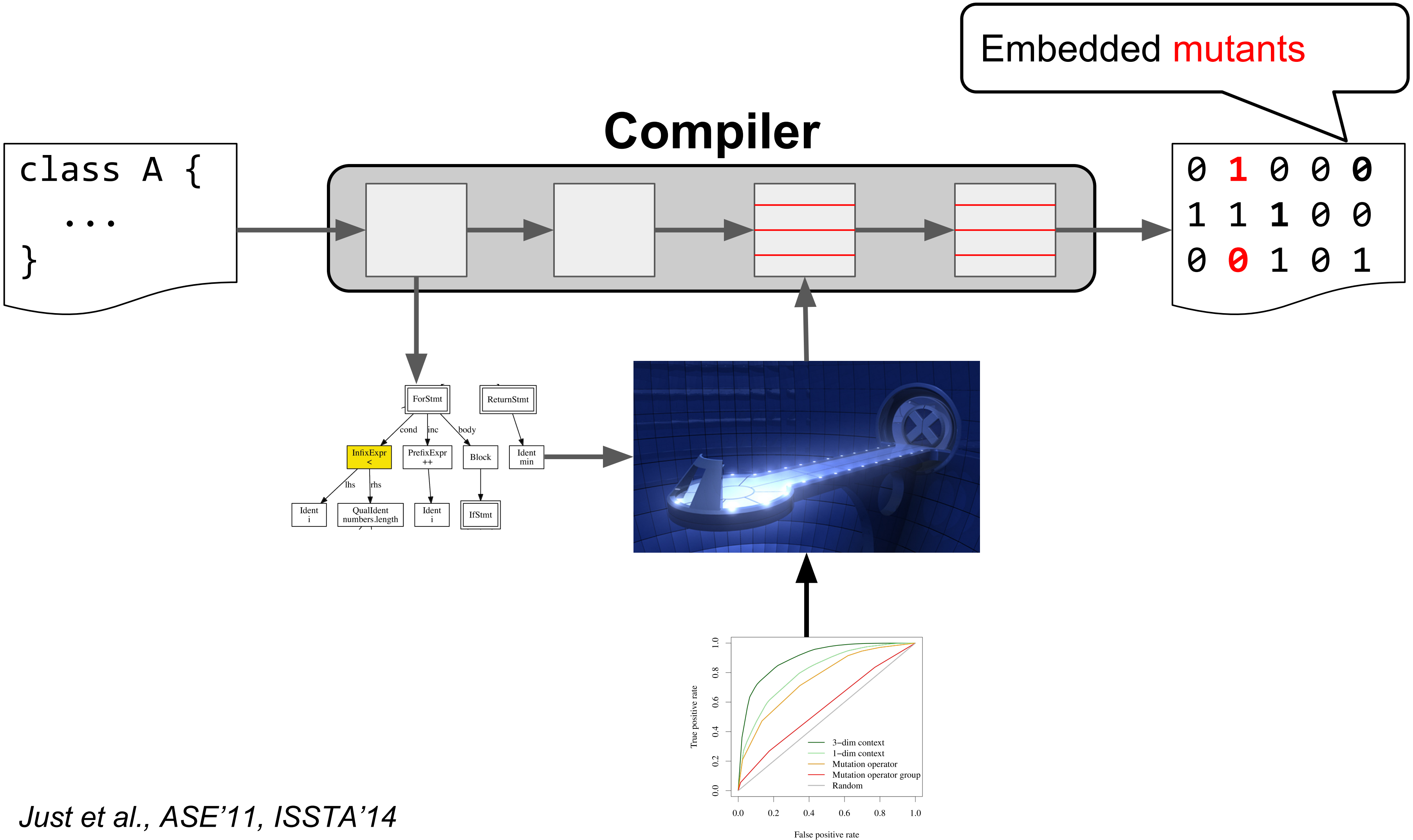


Why compiler-integrated mutation?

- Orders of magnitude faster than source code mutation.
- Mutate what the developer actually wrote (no desugared/simplified code).

Just et al., ASE'11, ISSTA'14
http://www.mutation-testing.org

Major: customized program mutation



Embedded mutants

Compiler

```
class A {
  ...
}
```

```
0 1 0 0 0
1 1 1 0 0
0 0 1 0 1
```

Just et al., ASE’11, ISSTA’14
http://www.mutation-testing.org

Acknowledgments

Bob Kurtz

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Jeff
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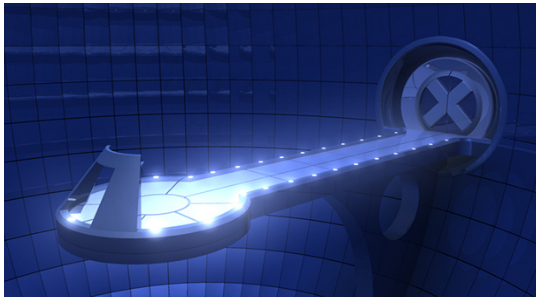
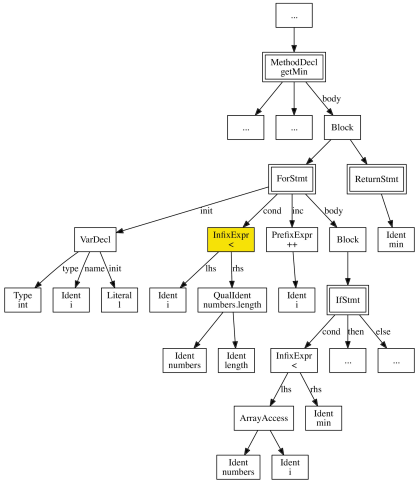
Andrew
McCallum

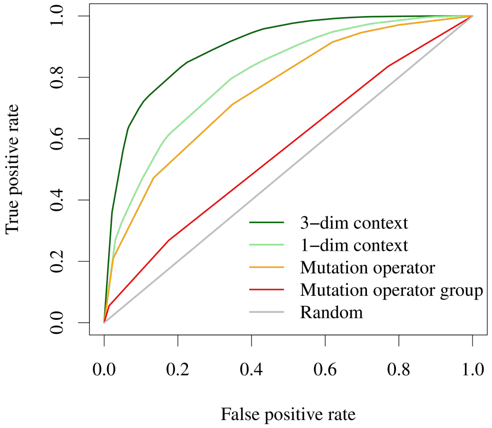
Miltos
Allamanis

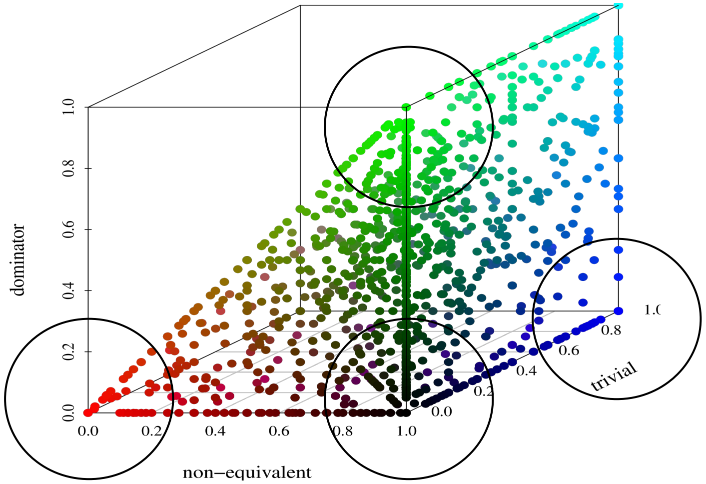
Customized program mutation

- Effectiveness of mutation operators differs even within operator groups
- Program context affects mutant utility
- Different dimensions of program context









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