UnitCon: Synthesizing Targeted Unit Tests for Java Runtime Exceptions

Sujin Jang, Yeonhee Ryou, Heewon Lee, Kihong Heo

KAIST Programming Systems Laboratory

Motivation

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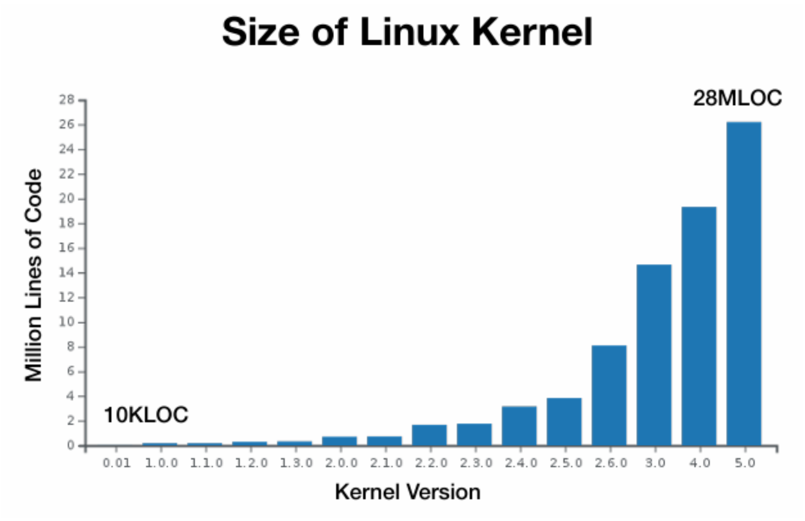
- Software is getting larger, with frequent changes.



Program	Commits (2024.3)	Active Developers (2024.3)
Linux Kernel	864	59
LLVM	3,525	56
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OpenSSL	80	17
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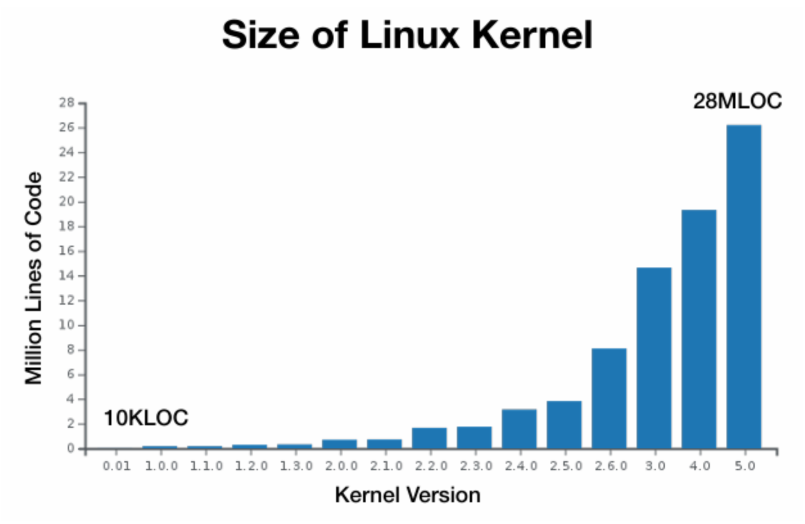

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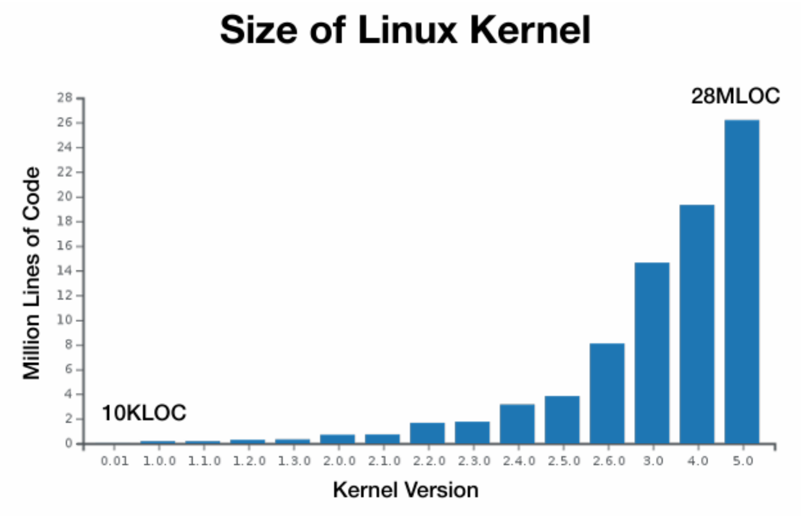

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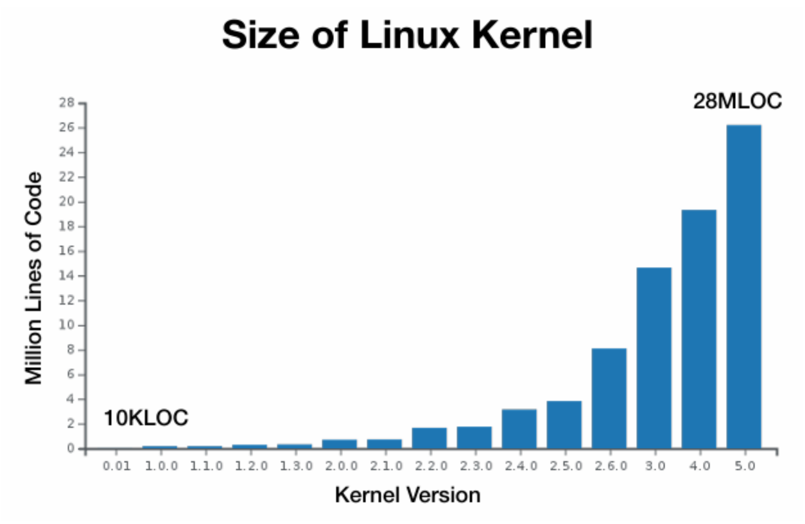

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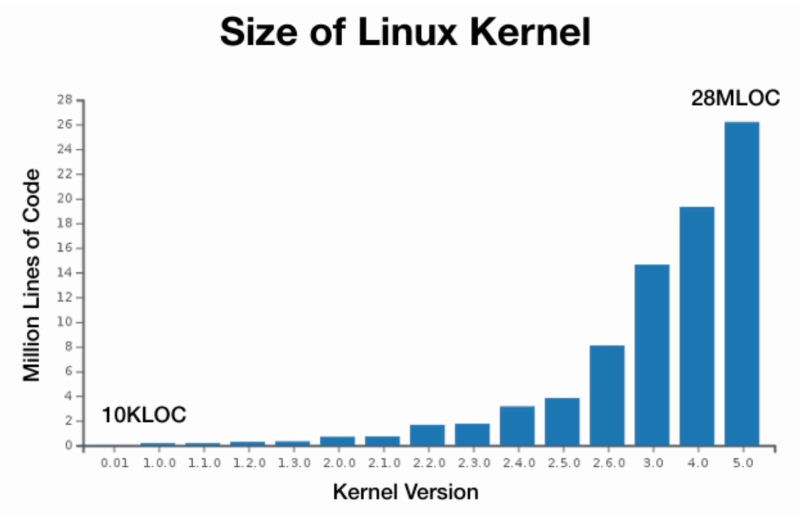

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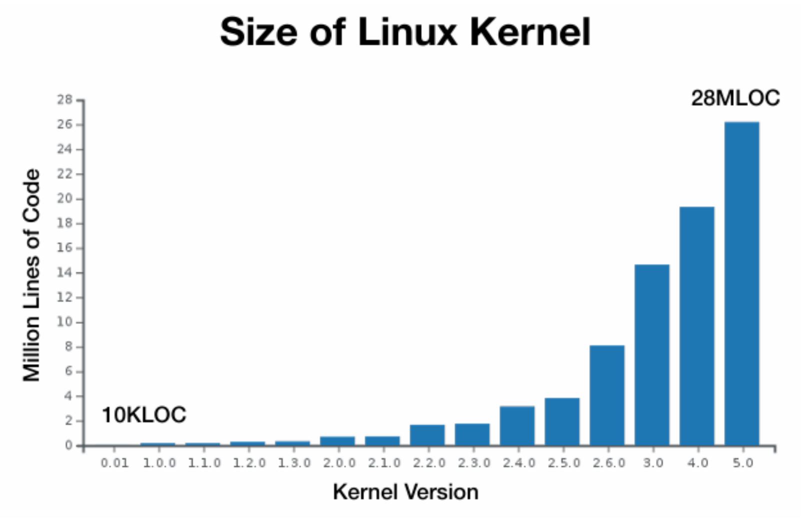
  - Aim to generate regression tests by maximizing code coverage.



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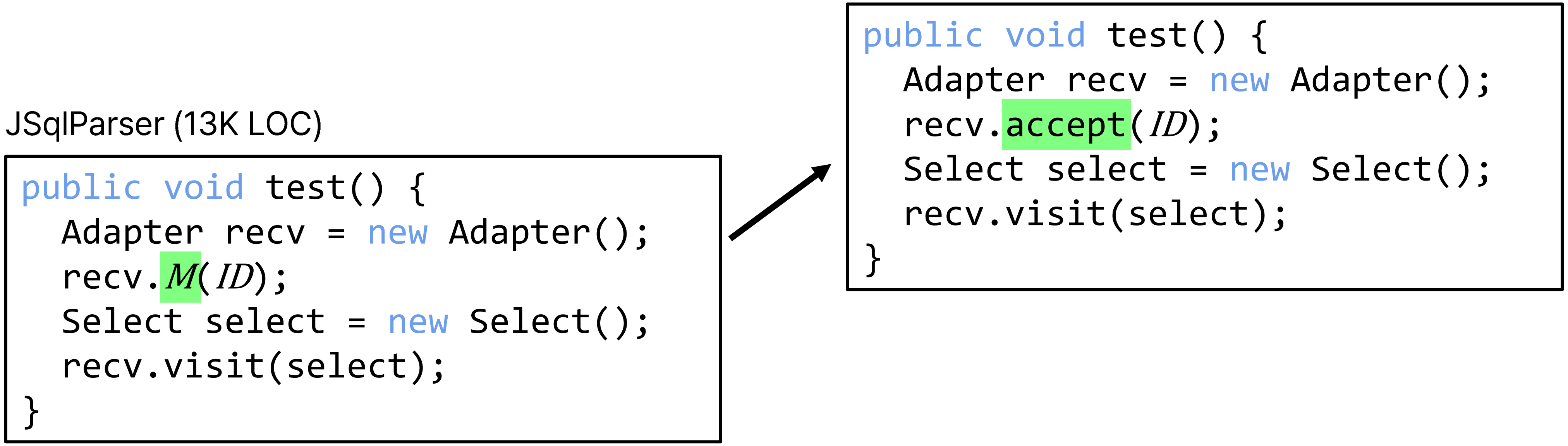

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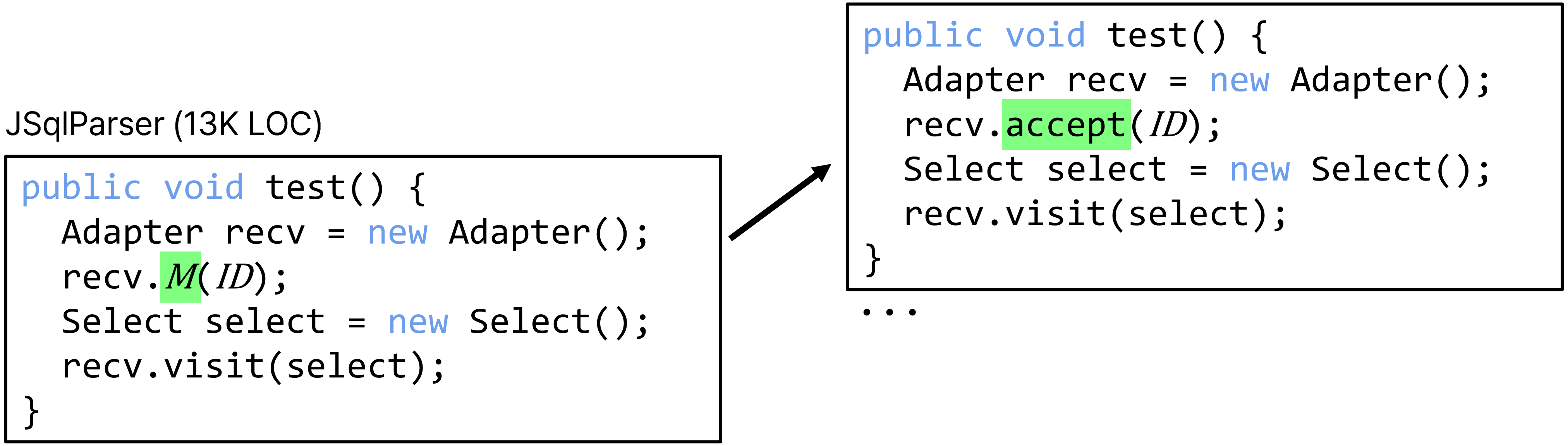

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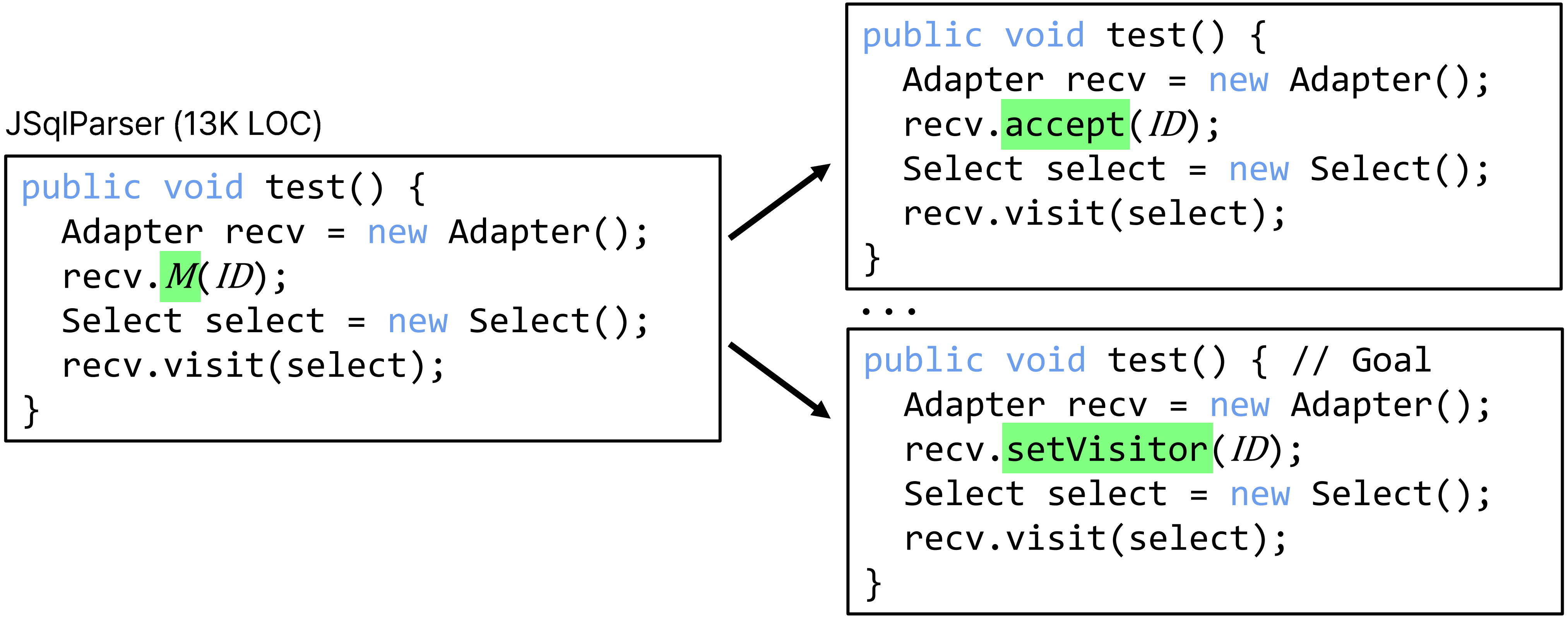

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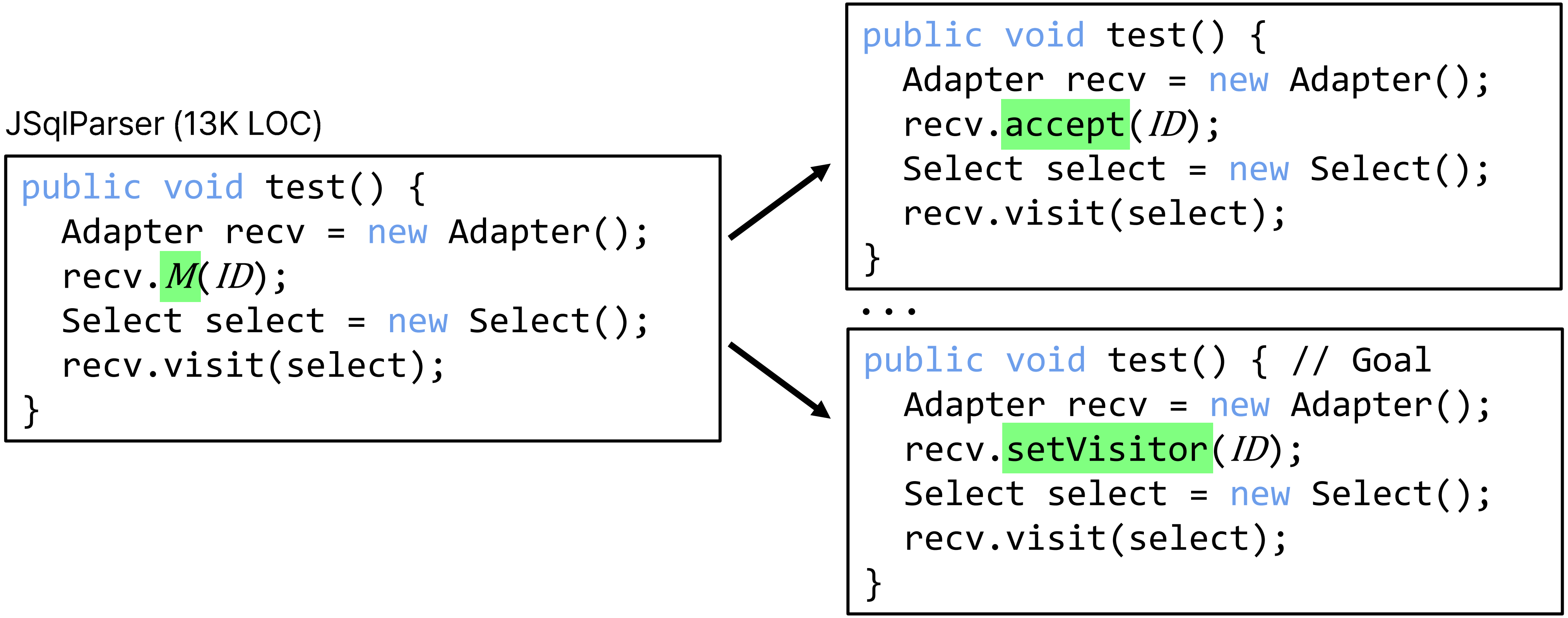

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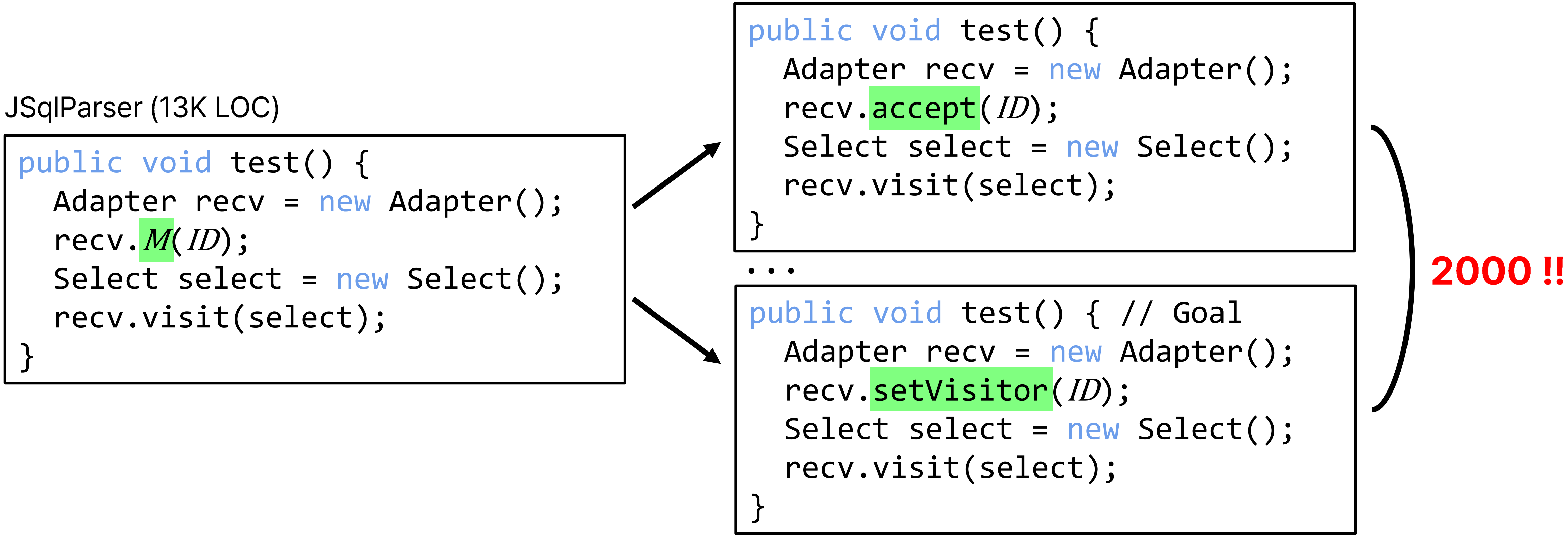

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  - Other tools (Randoop, EvoSuite) found the bug in **only 0 to 1** out of 10 runs.

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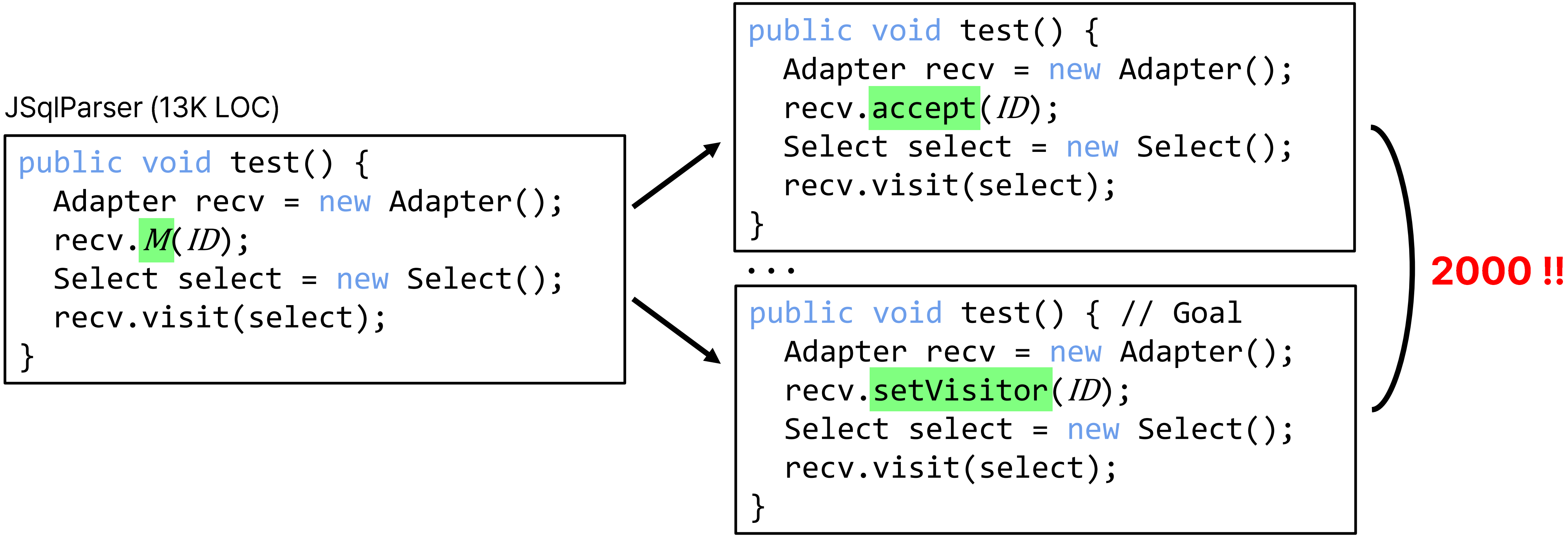

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2000 !!

Our Solution

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Program with
a specific location

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public void test() {
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  Visitor visitor = new Visitor();
  recv.setVisitor(visitor);
  Select select = new Select();
  recv.visit(select); // NPE
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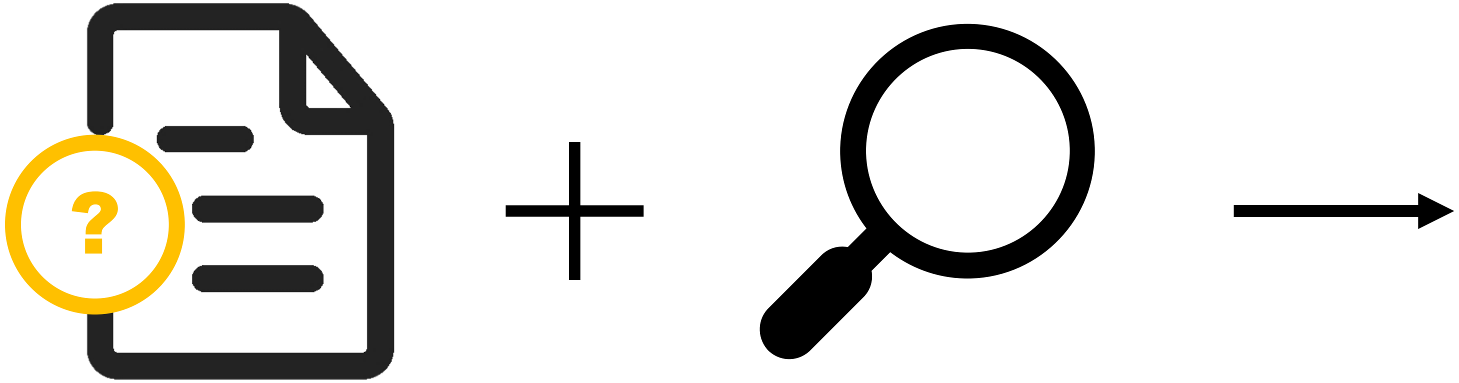
Program with a specific location

Targeted Unit Test

Our Solution



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Program with a specific location

Program Synthesis Guided by Static Analyzer

Targeted Unit Test

UnitCon System

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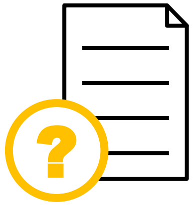
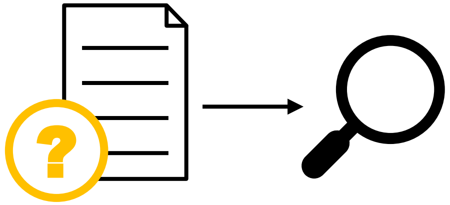


Program with
a target location

UnitCon System



Program with
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Static Analyzer

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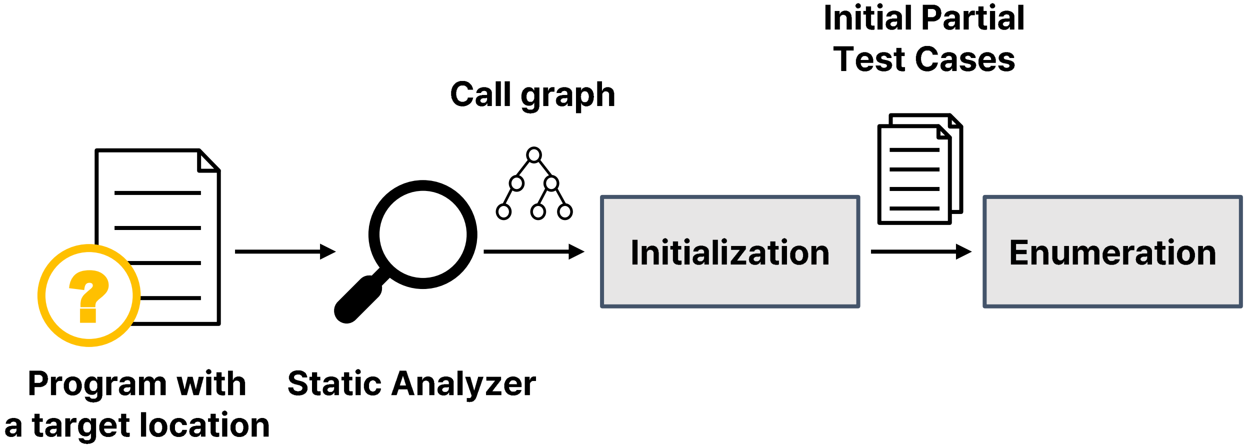


Initial Partial Test Cases

Call graph

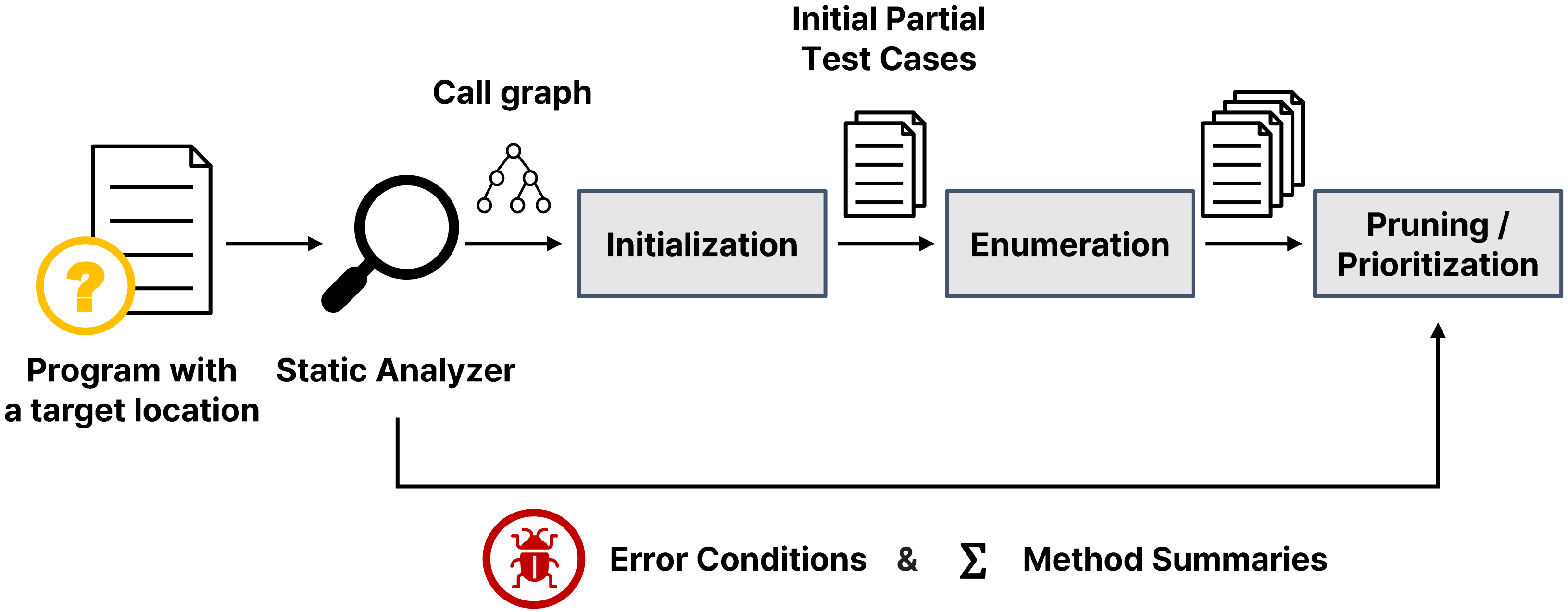
Initialization

Enumeration

Program with a target location

Static Analyzer

UnitCon System



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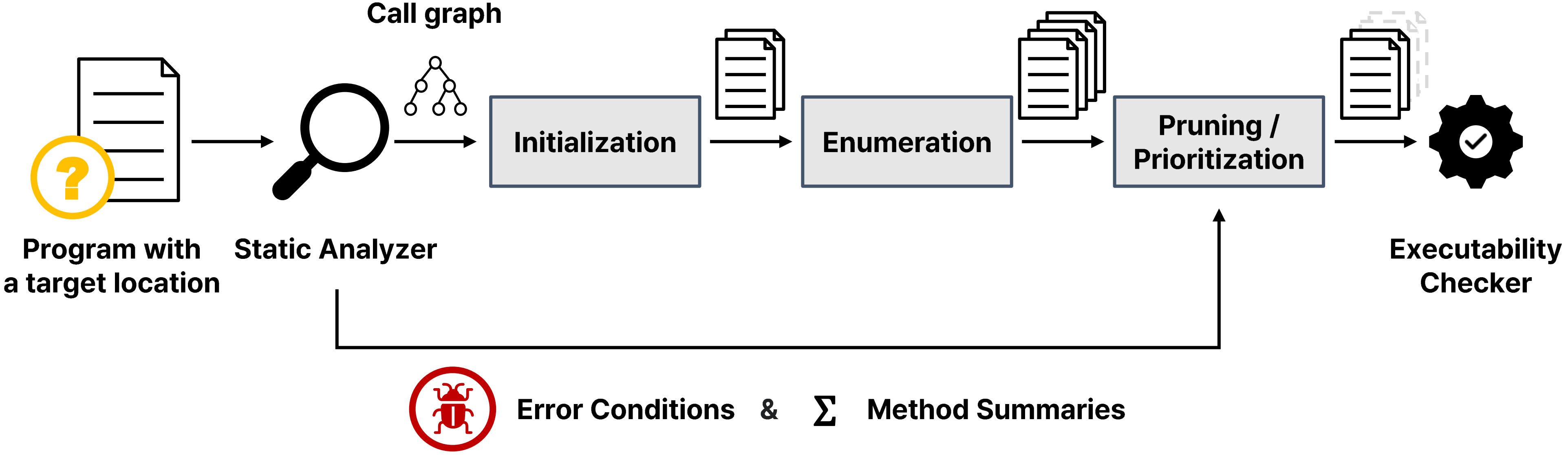

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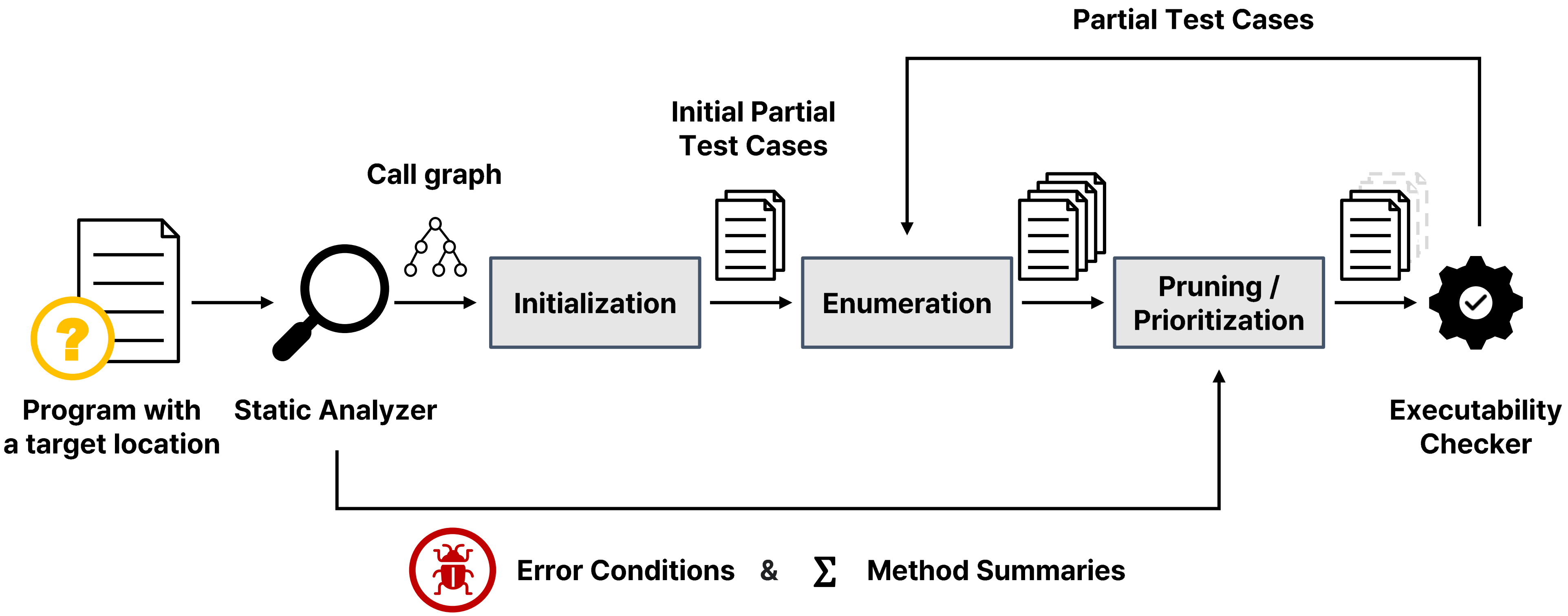

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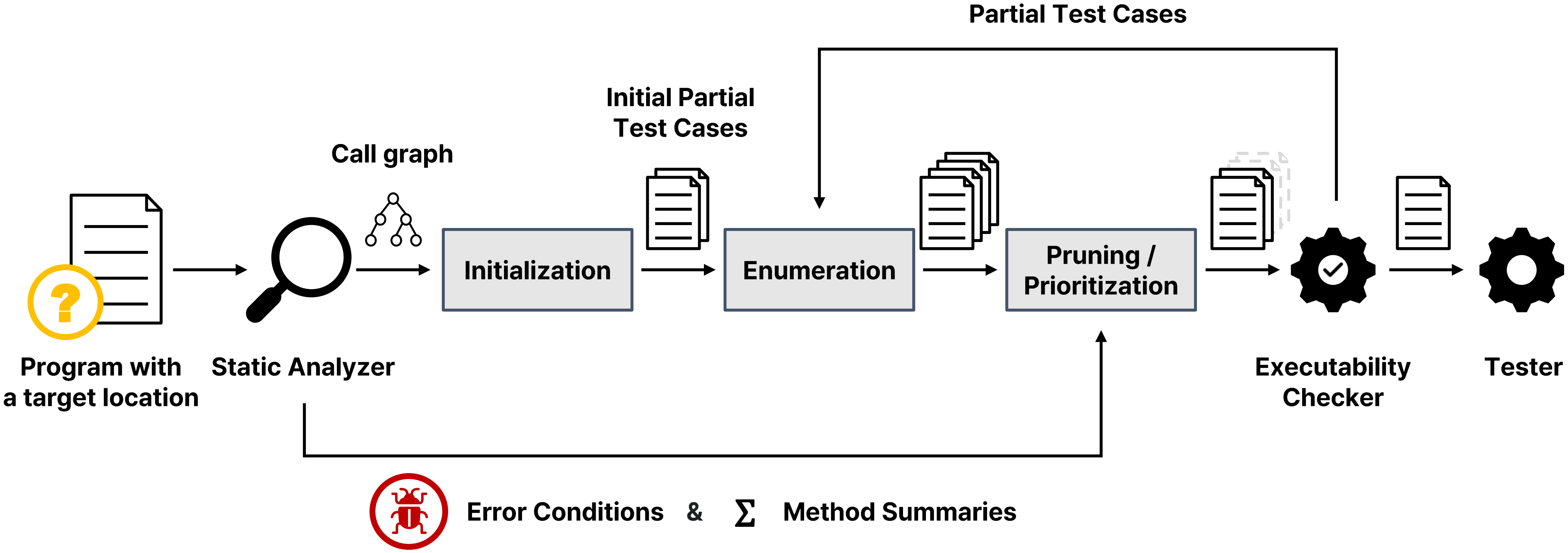


Partial Test Cases

Initial Partial Test Cases

Call graph

Program with a target location

Static Analyzer

Initialization

Enumeration

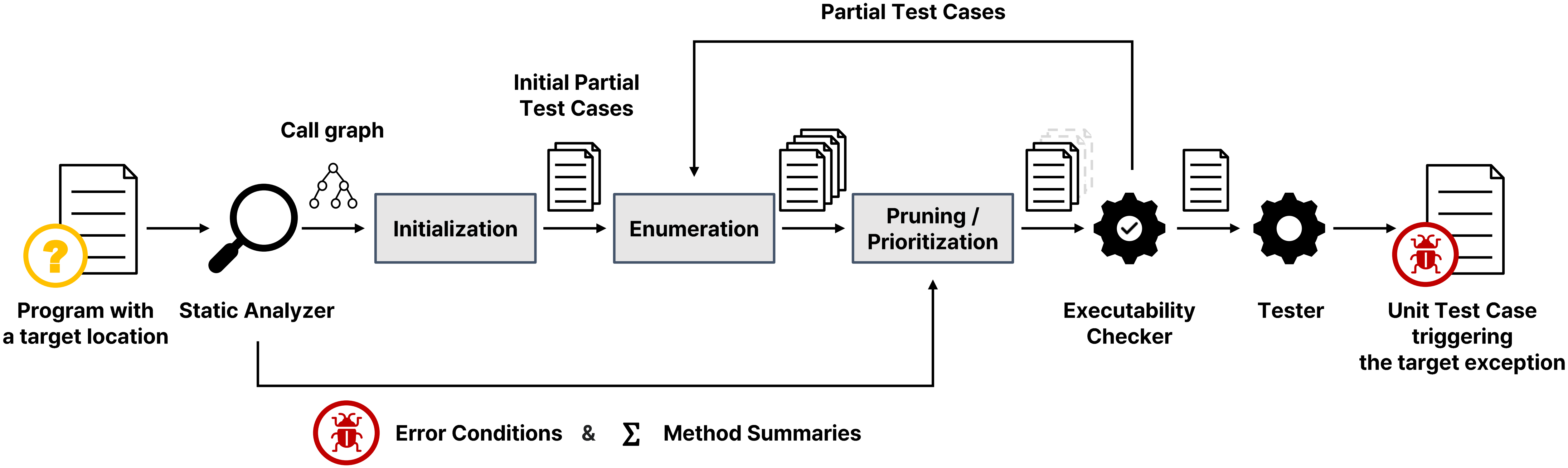
Pruning / Prioritization

Executability Checker

Tester

Error Conditions & Σ Method Summaries

UnitCon System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Up to **3.6 x** better performance
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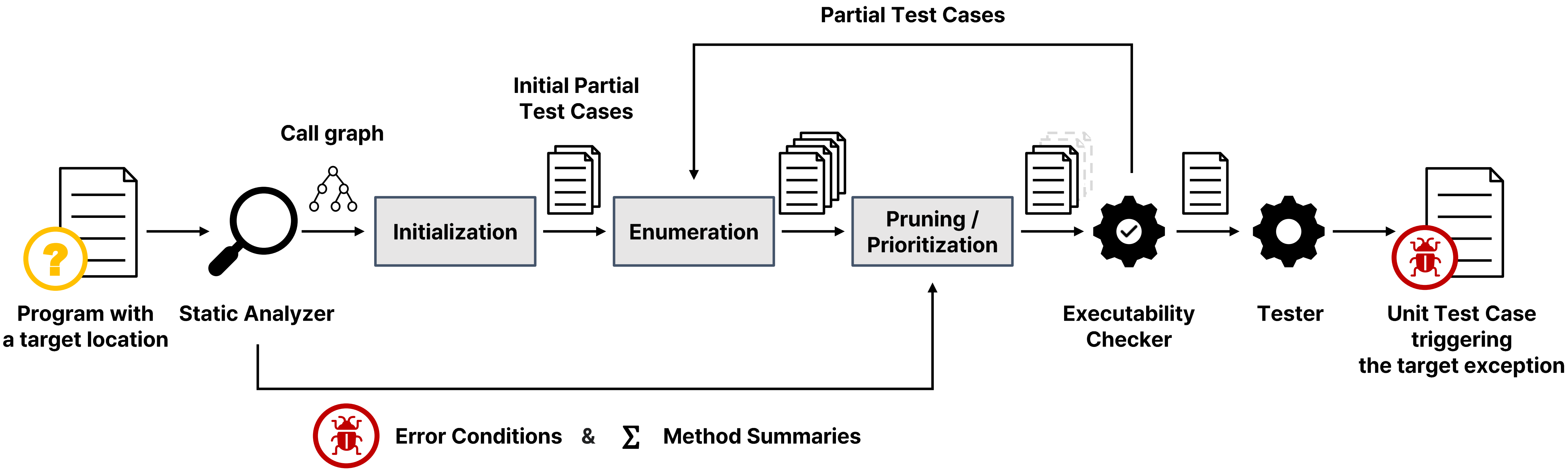
Found **21** new bugs
in open-source programs

UnitCon System



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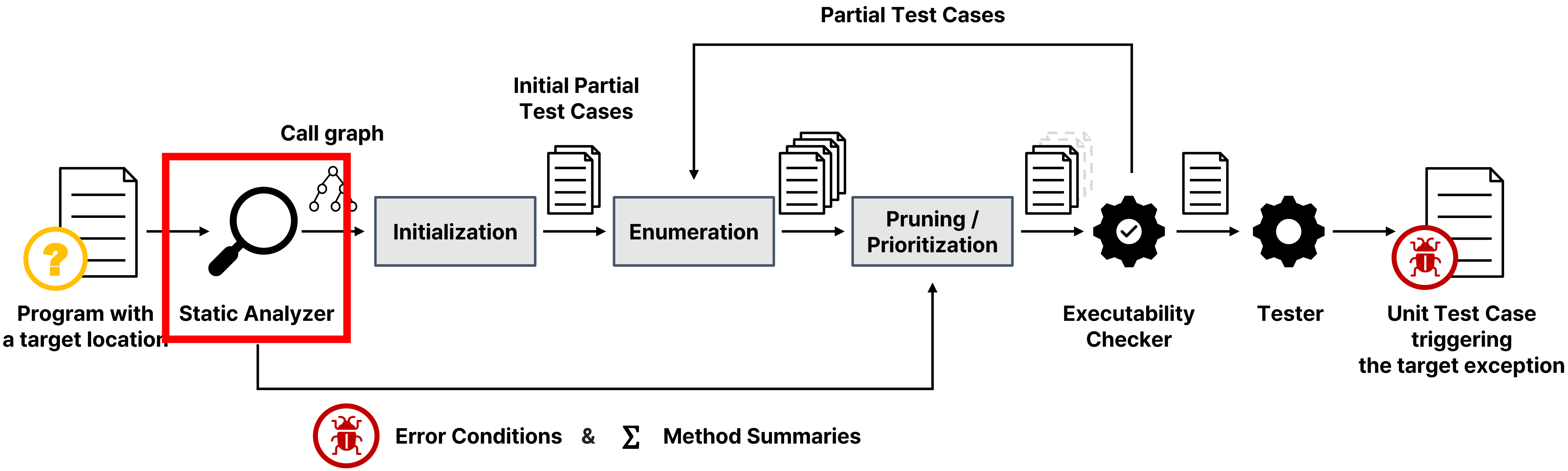
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select.getItemsList() == null
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`select.getItemsList() == null`

field `itemsList` of `select == null`

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`Adapter.visit(Select)`

Error Conditions

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Adapter.visit(Select)

Error Conditions

Object	Condition
select.itemsList	== null

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Error Conditions

Object	Condition
select.itemsList	== null
this.visitor	!= null

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  public void visit(Select select) {
    if (visitor != null) {
      ItemsList itemsList = select.getItemsList();
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public class Select {
  private List <Item> itemsList;

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  private Select usingSelect;

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}
```

Error Method

```
Adapter.visit(Select)
```

Error Conditions

Object	Condition
`select.itemsList`	`== null`
`this.visitor`	`!= null`

Example

```java
public class Adapter {
  private Visitor visitor;

  public void setVisitor(Visitor visitor) {
    this.visitor = visitor;
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  public void visit(Select select) {
    if (visitor != null) {
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Error Method

`Adapter.visit(Select)`

Error Conditions

Object	Condition
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this.visitor	!= null
select	!= null

Example

```java
public class Adapter {
  private Visitor visitor;

  public void setVisitor(Visitor visitor) {
    this.visitor = visitor;
  }

  public void visit(Select select) {
    if (visitor != null) {
      ItemsList itemsList = select.getItemsList();
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Error Method

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Adapter.visit(Select)
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Error Conditions

Object	Condition
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Example

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  public void setVisitor(Visitor visitor) {
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Error Method

`Adapter.visit(Select)`

Error Conditions

Object	Condition
select.itemsList	== null
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Method Summaries

Method	Memory

Example

```java
public class Adapter {
  private Visitor visitor;

  public void setVisitor(Visitor visitor) {
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  }

  public void visit(Select select) {
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Error Method

`Adapter.visit(Select)`

Error Conditions

Object	Condition
select.itemsList	== null
this.visitor	!= null
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Method Summaries

Method	Memory
Merge	{ usingSelect ↦ null }

Example

```java
public class Adapter {
  private Visitor visitor;

  public void setVisitor(Visitor visitor) {
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public class Merge {
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```

Error Method

`Adapter.visit(Select)`

Error Conditions

Object	Condition
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Method Summaries

Method	Memory
Merge	{ usingSelect ↦ null }
getUsingSelect	{ ret ↦ usingSelect }

Example

```java
public class Adapter {
  private Visitor visitor;

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Method Summaries

Method	Memory
Merge	{ usingSelect ↦ null }
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Example

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public class Merge {
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  public Select getUsingSelect() { return usingSelect; }
}
```

Error Method

`Adapter.visit(Select)`

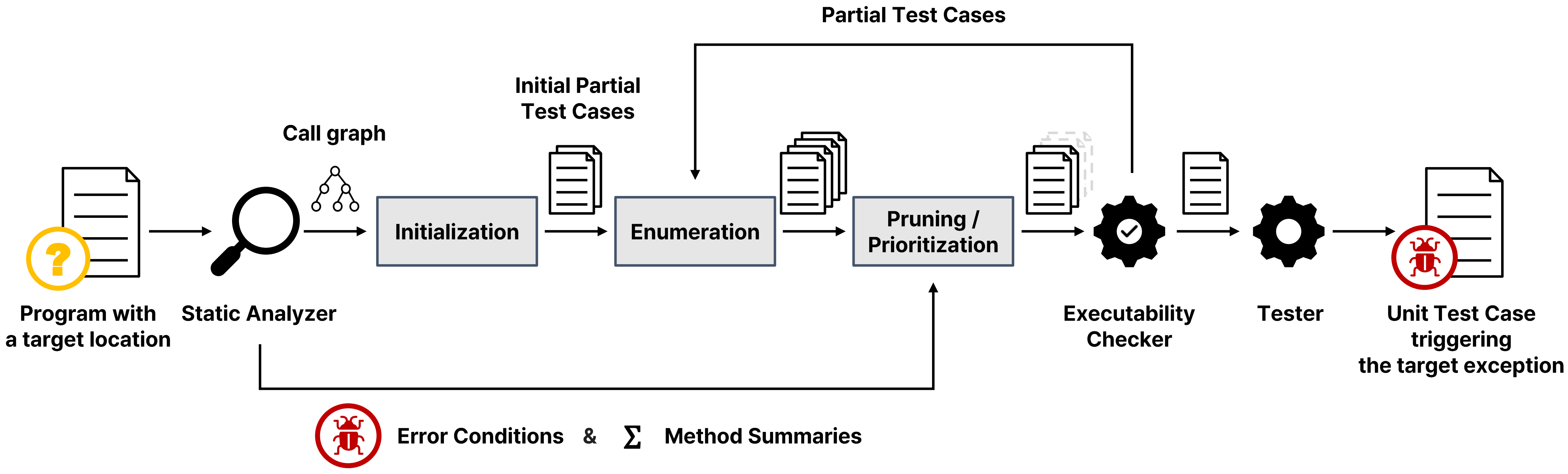
Error Conditions

Object	Condition
select.itemsList	== null
this.visitor	!= null
select	!= null

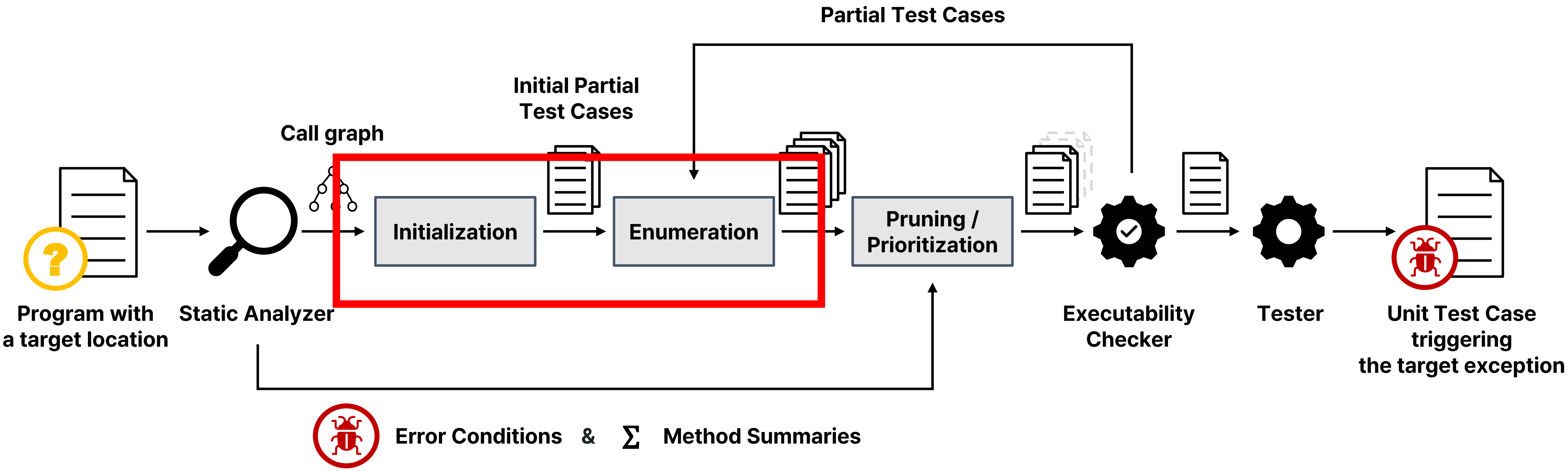
Method Summaries

Method	Memory
Merge	{ usingSelect ↦ null }
getUsingSelect	{ ret ↦ usingSelect }
...	...

UnitCon System



UnitCon System



Top-down enumerative search

Top-down enumerative search

- Expand test cases top-down based on defined rules.

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Rule form: `Before` → `After`

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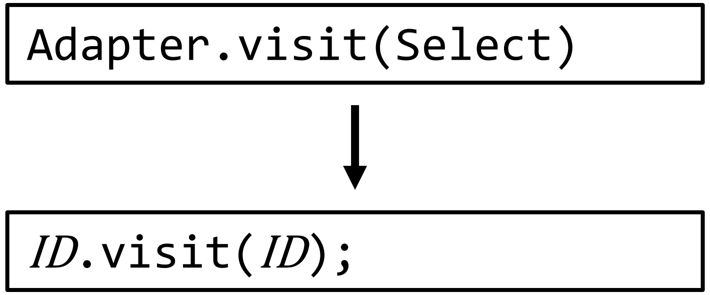


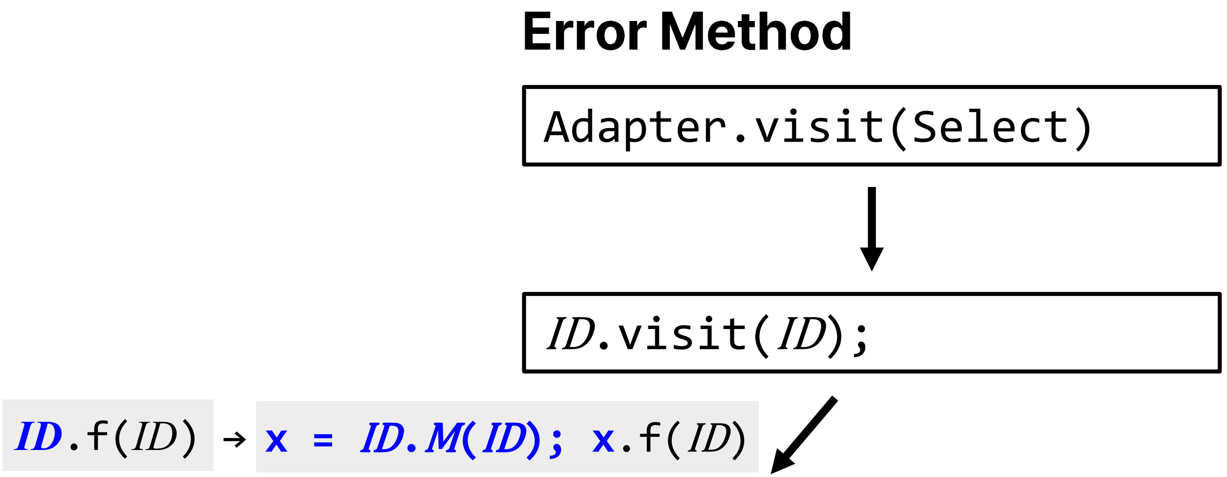
```
Adapter.visit(Select)
```

ID.visit(*ID*);

Top-down enumerative search

- Expand test cases top-down based on defined rules.

Rule form: `Before` → `After`



Error Method

`Adapter.visit(Select)`

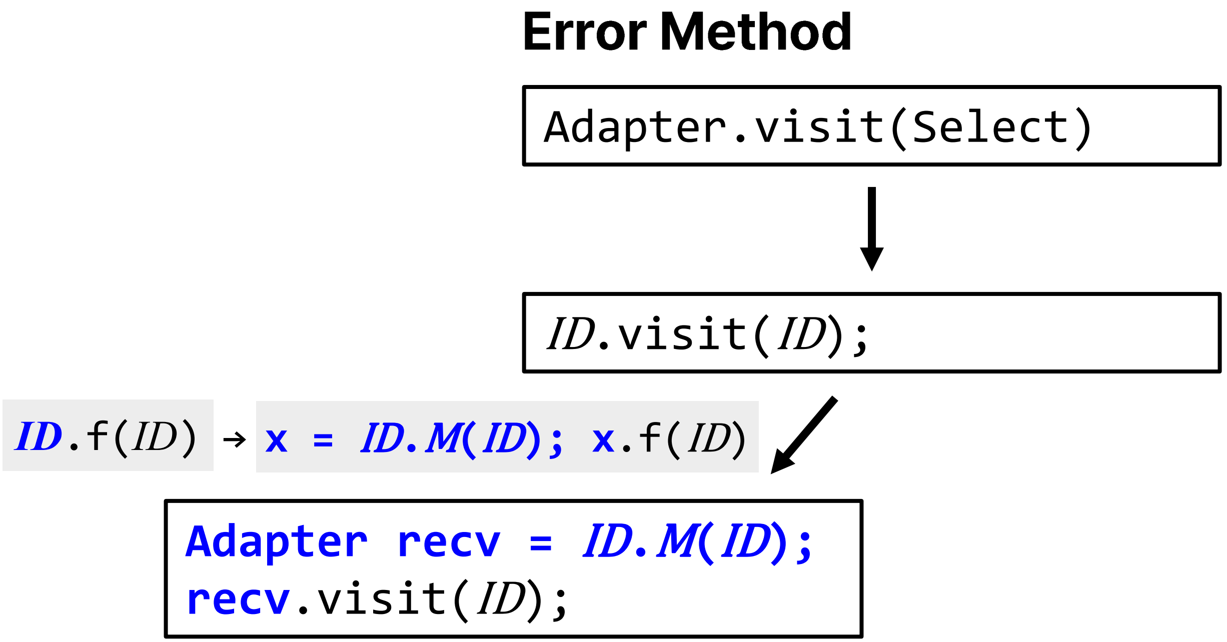
ID`.visit(`*ID*`);`

ID`.f(`*ID*`)` → `x = `*ID*`.`*M*`(`*ID*`); x.f(`*ID*`)`

Top-down enumerative search

- Expand test cases top-down based on defined rules.

Rule form: `Before` → `After`



Error Method

```
Adapter.visit(Select)
```

```
ID.visit(ID);
```

`ID.f(ID)` → `x = ID.M(ID); x.f(ID)`

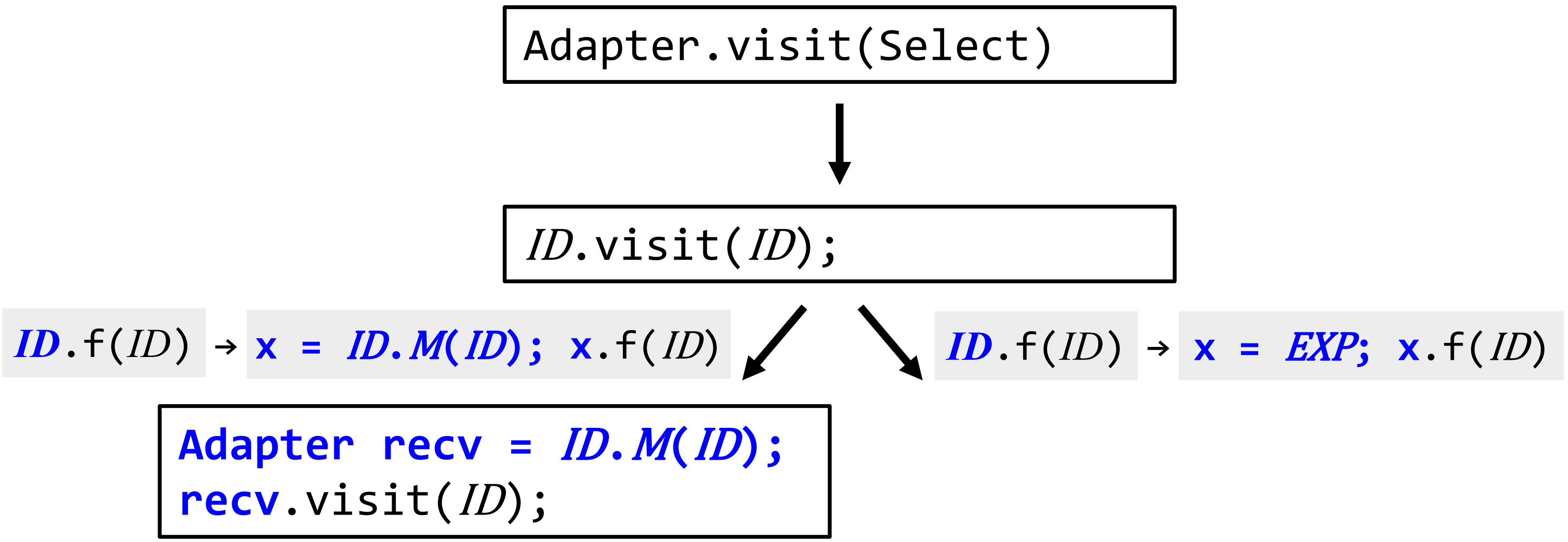
```
Adapter recv = ID.M(ID);
recv.visit(ID);
```

Top-down enumerative search

- Expand test cases top-down based on defined rules.

Rule form: `Before` → `After`

Error Method



`Adapter.visit(Select)`

`ID``.visit(`*`ID`*`);`

`ID``.f(`*`ID`*`)` → `x = `*`ID.M(ID)`*`; x.f(`*`ID`*`)`

`ID``.f(`*`ID`*`)` → `x = `*`EXP`*`; x.f(`*`ID`*`)`

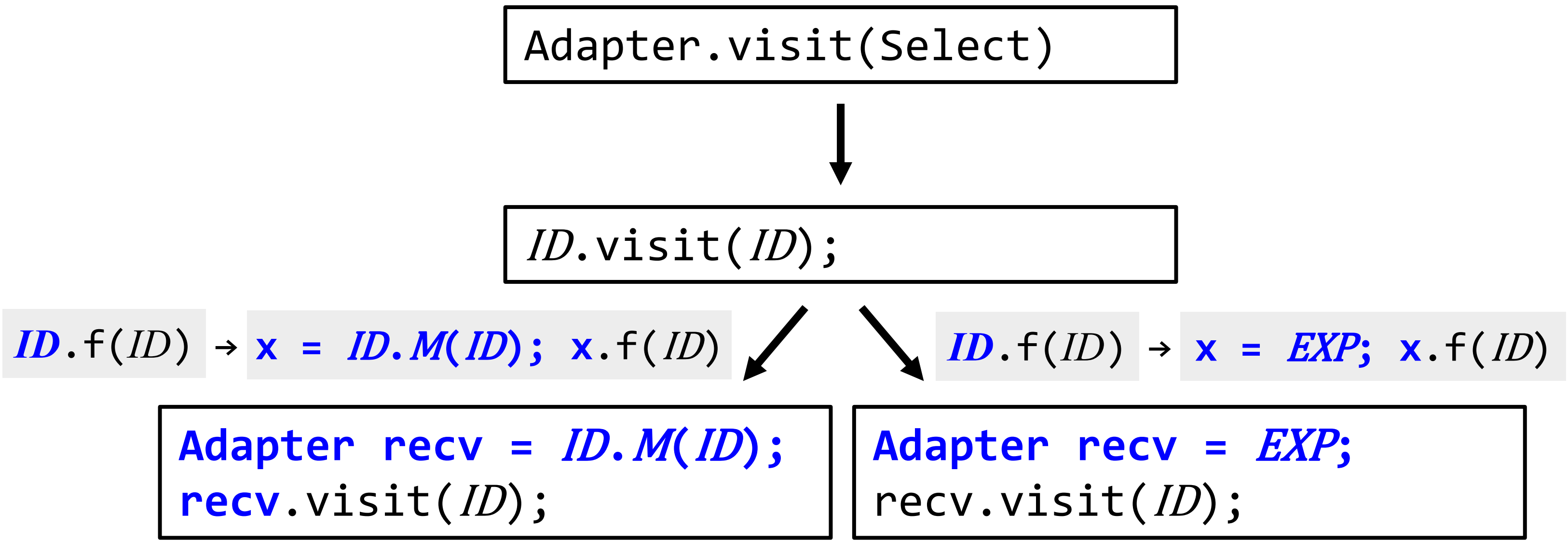
```
Adapter recv = ID.M(ID);
recv.visit(ID);
```

Top-down enumerative search

- Expand test cases top-down based on defined rules.

Rule form: `Before` → `After`

Error Method



```
Adapter.visit(Select)
```

```
ID.visit(ID);
```

`ID.f(ID)` → `x = ID.M(ID); x.f(ID)`

`ID.f(ID)` → `x = EXP; x.f(ID)`

```
Adapter recv = ID.M(ID);
recv.visit(ID);
```

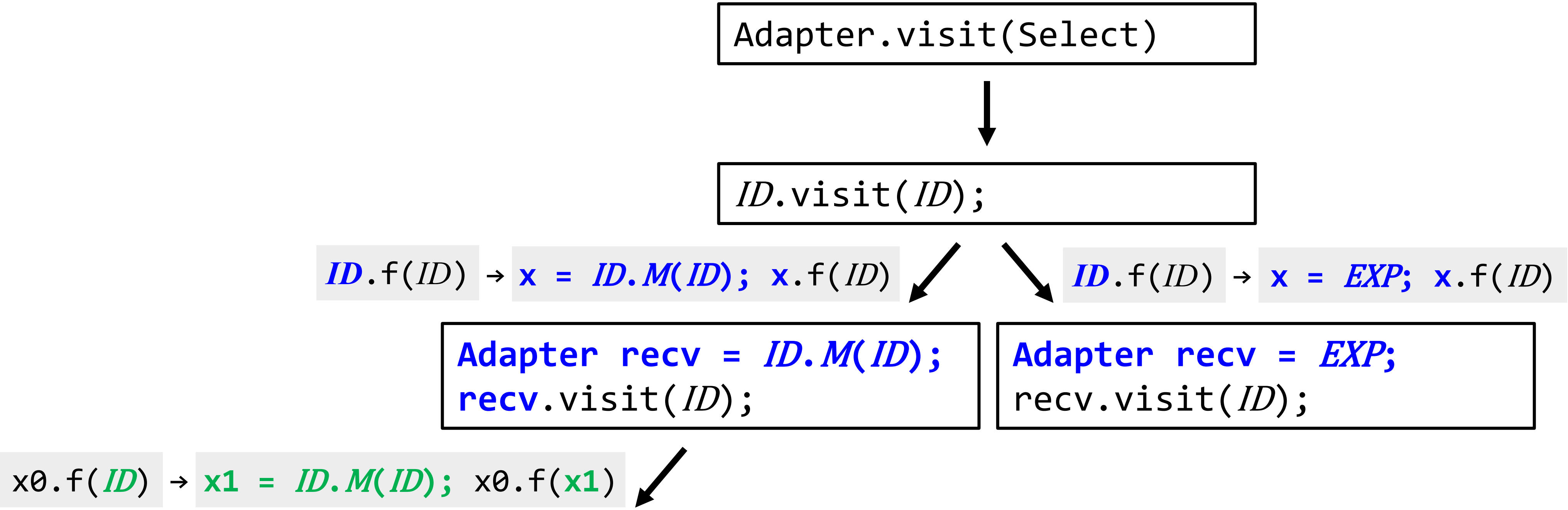
```
Adapter recv = EXP;
recv.visit(ID);
```

Top-down enumerative search

- Expand test cases top-down based on defined rules.

Rule form: **Before** → **After**

Error Method



Adapter.visit(Select)

ID.visit(*ID*);

ID.f(*ID*) → **x = *ID*.*M*(*ID*); x**.f(*ID*)

ID.f(*ID*) → **x = *EXP*; x**.f(*ID*)

Adapter recv = *ID*.*M*(*ID*);
recv.visit(*ID*);

Adapter recv = *EXP*;
recv.visit(*ID*);

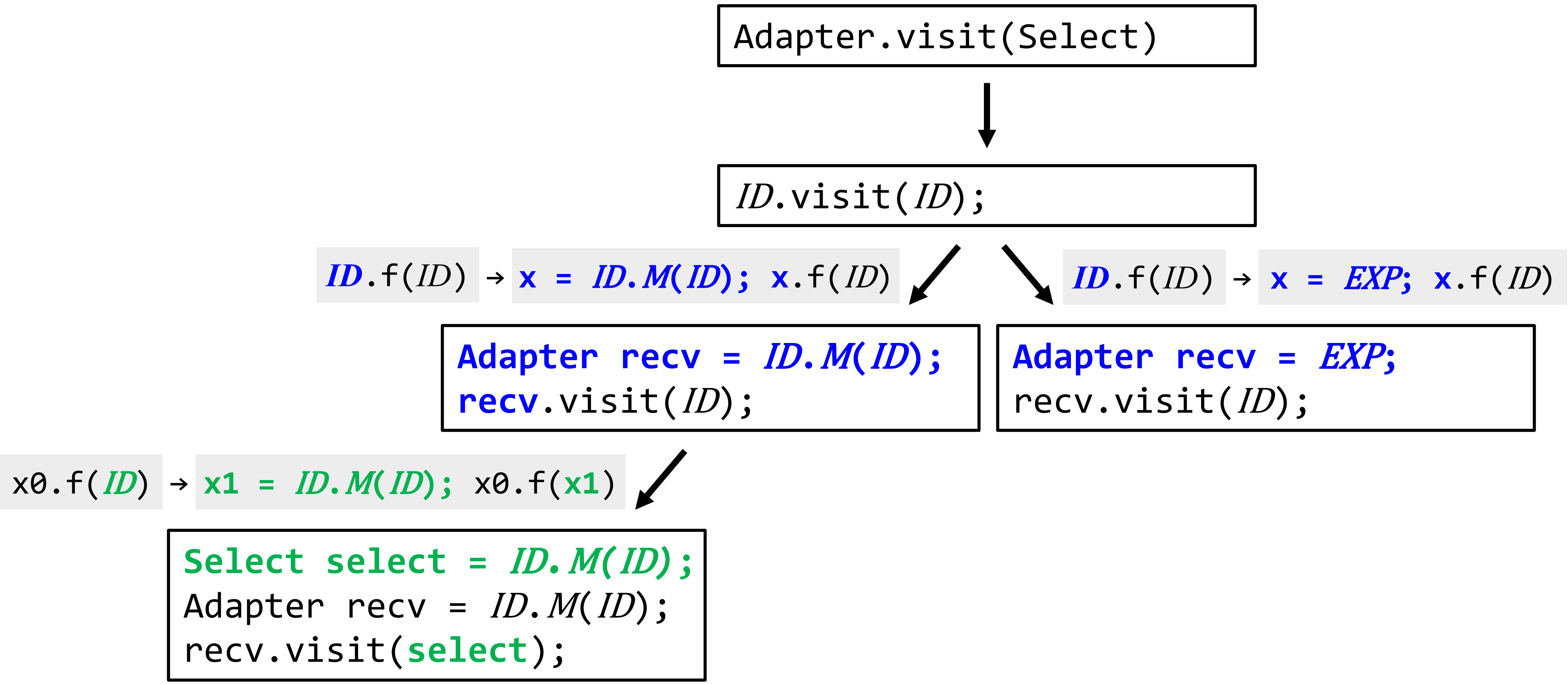
x0.f(***ID***) → **x1 = *ID*.*M*(*ID*);** x0.f(**x1**)

Top-down enumerative search

- Expand test cases top-down based on defined rules.

Rule form: `Before` → `After`

Error Method



```
Adapter.visit(Select)
```

```
ID.visit(ID);
```

`ID.f(ID)` → `x = ID.M(ID); x.f(ID)`

```
Adapter recv = ID.M(ID);
recv.visit(ID);
```

`ID.f(ID)` → `x = EXP; x.f(ID)`

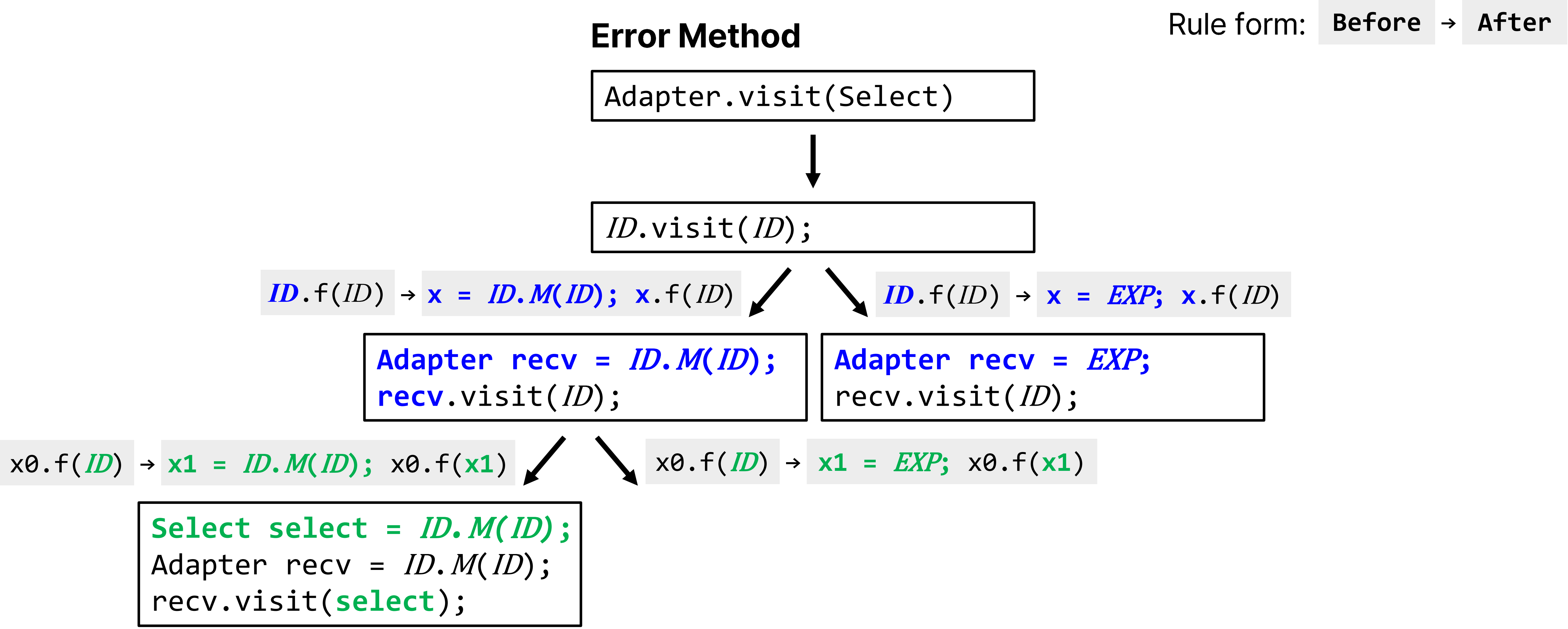
```
Adapter recv = EXP;
recv.visit(ID);
```

`x0.f(ID)` → `x1 = ID.M(ID); x0.f(x1)`

```
Select select = ID.M(ID);
Adapter recv = ID.M(ID);
recv.visit(select);
```

Top-down enumerative search

- Expand test cases top-down based on defined rules.



Rule form: `Before` → `After`

Error Method

```
Adapter.visit(Select)
```

```
ID.visit(ID);
```

`ID.f(ID)` → `x = ID.M(ID); x.f(ID)`

`ID.f(ID)` → `x = EXP; x.f(ID)`

```
Adapter recv = ID.M(ID);
recv.visit(ID);
```

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Adapter recv = EXP;
recv.visit(ID);
```

`x0.f(ID)` → `x1 = ID.M(ID); x0.f(x1)`

`x0.f(ID)` → `x1 = EXP; x0.f(x1)`

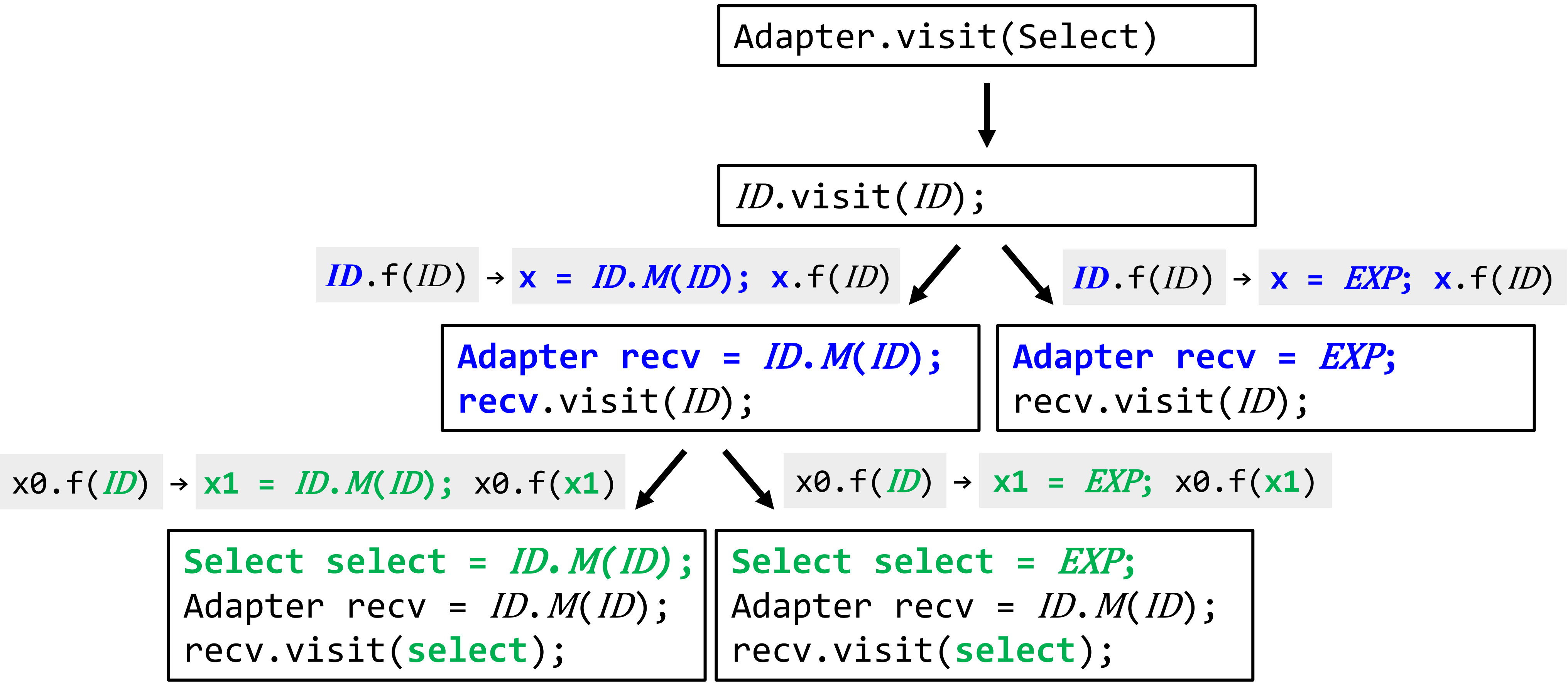
```
Select select = ID.M(ID);
Adapter recv = ID.M(ID);
recv.visit(select);
```

Top-down enumerative search

- Expand test cases top-down based on defined rules.

Rule form: `Before` → `After`

Error Method



```
Adapter.visit(Select)
```

```
ID.visit(ID);
```

`ID.f(ID)` → `x = ID.M(ID); x.f(ID)`

```
Adapter recv = ID.M(ID);
recv.visit(ID);
```

`ID.f(ID)` → `x = EXP; x.f(ID)`

```
Adapter recv = EXP;
recv.visit(ID);
```

`x0.f(ID)` → `x1 = ID.M(ID); x0.f(x1)`

```
Select select = ID.M(ID);
Adapter recv = ID.M(ID);
recv.visit(select);
```

`x0.f(ID)` → `x1 = EXP; x0.f(x1)`

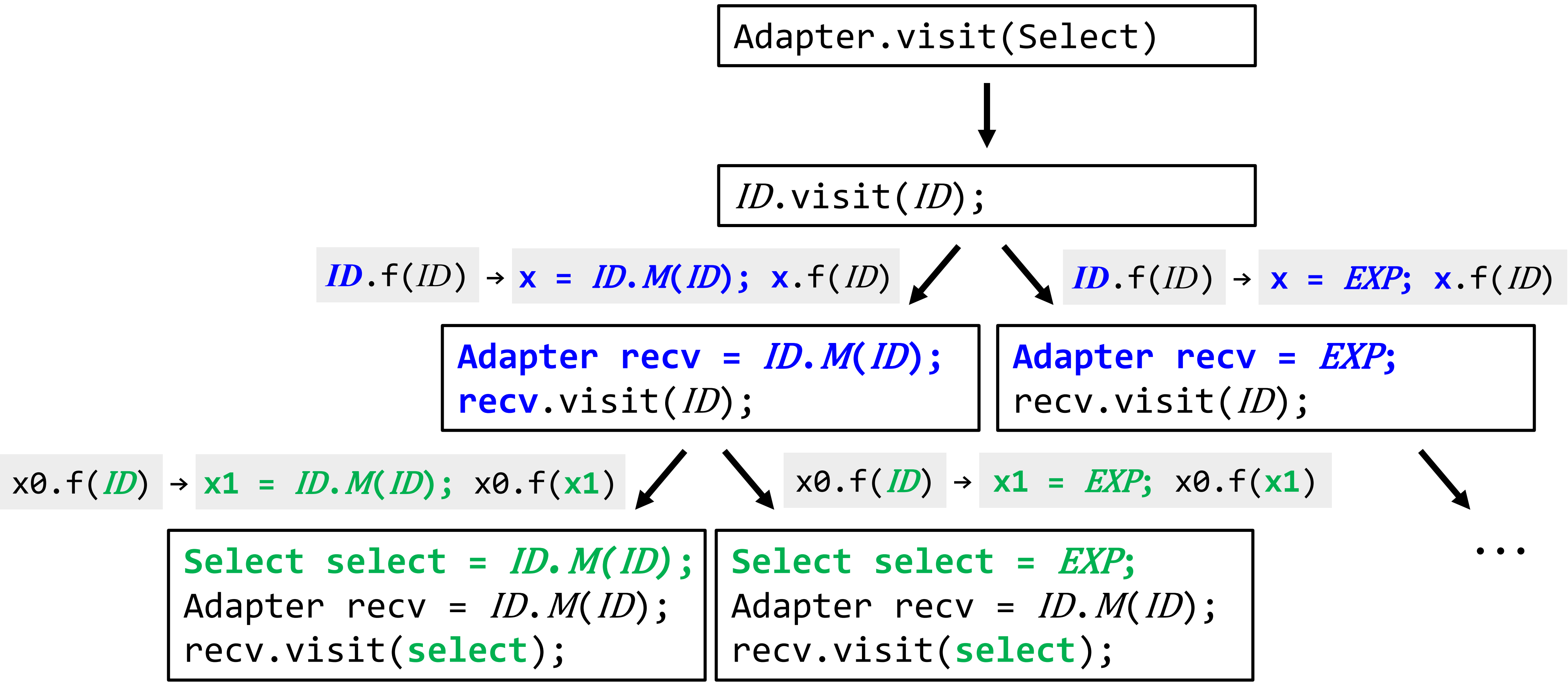
```
Select select = EXP;
Adapter recv = ID.M(ID);
recv.visit(select);
```

Top-down enumerative search

- Expand test cases top-down based on defined rules.

Rule form: `Before` → `After`

Error Method



`Adapter.visit(Select)`

ID.visit(*ID*);

ID.f(*ID*) → x = *ID*.*M*(*ID*); x.f(*ID*)

ID.f(*ID*) → x = *EXP*; x.f(*ID*)

Adapter recv = *ID*.*M*(*ID*);
recv.visit(*ID*);

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x0.f(*ID*) → x1 = *ID*.*M*(*ID*); x0.f(x1)

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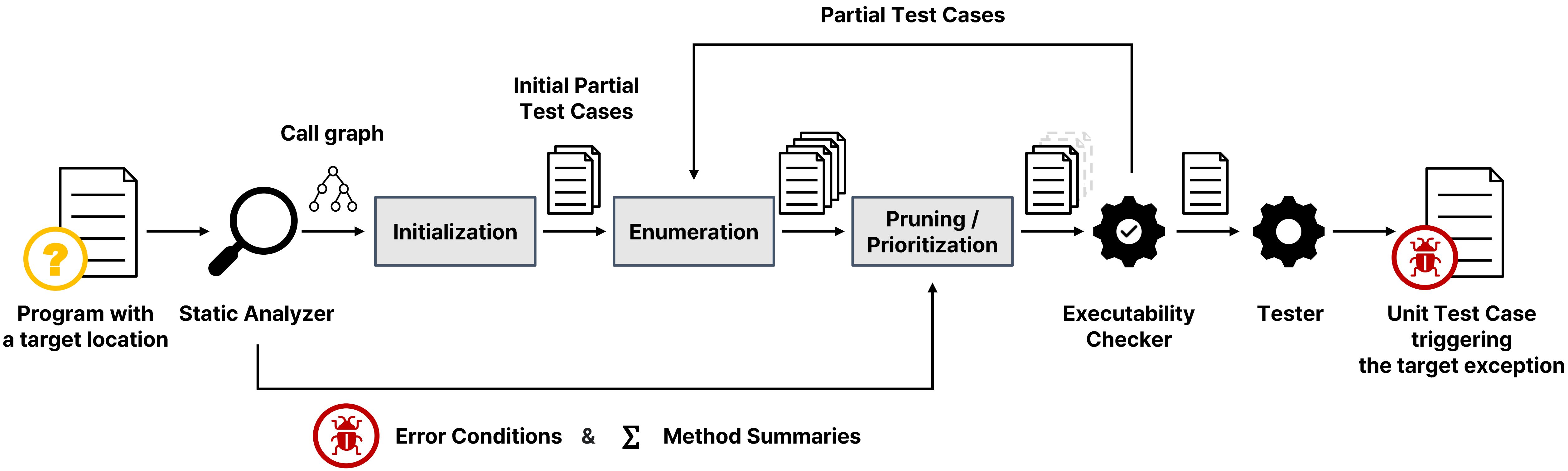
Adapter recv = *ID*.*M*(*ID*);
recv.visit(select);

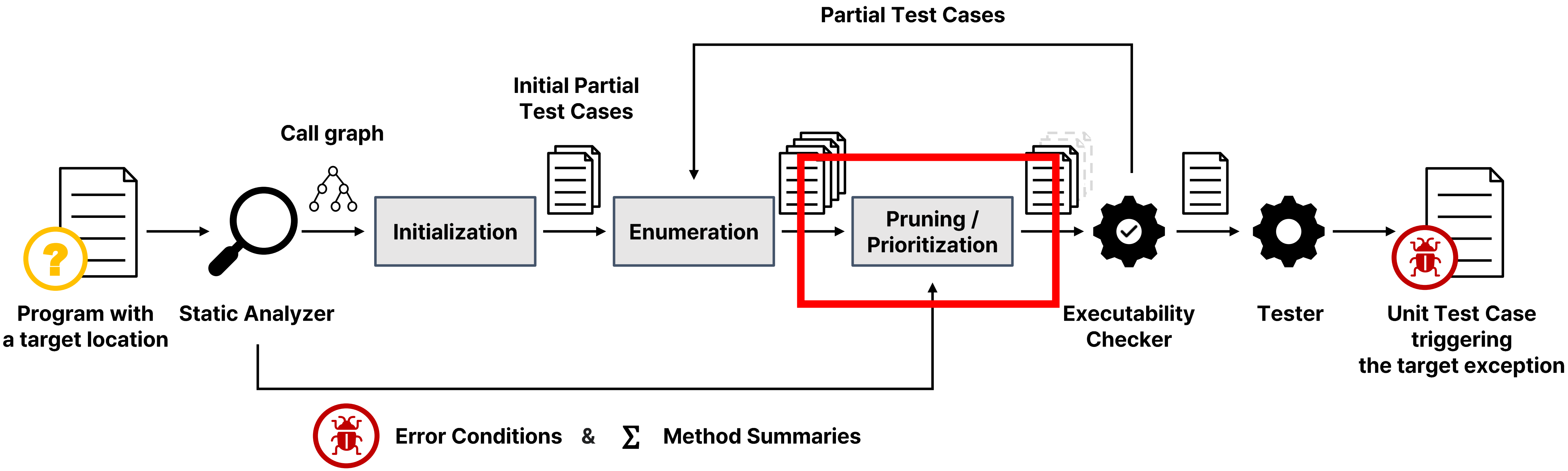
Select select = *EXP*;
Adapter recv = *ID*.*M*(*ID*);
recv.visit(select);

…

UnitCon System


Partial Test Cases
Initial Partial Test Cases
Call graph
Initialization
Enumeration
Pruning / Prioritization
Program with a target location
Static Analyzer
Executability Checker
Tester
Unit Test Case triggering the target exception
Error Conditions & Σ Method Summaries

UnitCon System


Partial Test Cases
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Error Conditions & ∑ Method Summaries

Pruning

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- Discard partial test cases with identical semantics.

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Current partial test case

```
Adapter recv = ID.M(ID);

Select select =
recv.visit(select);
```

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```
Adapter recv = ID.M(ID);

Select select = 
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```

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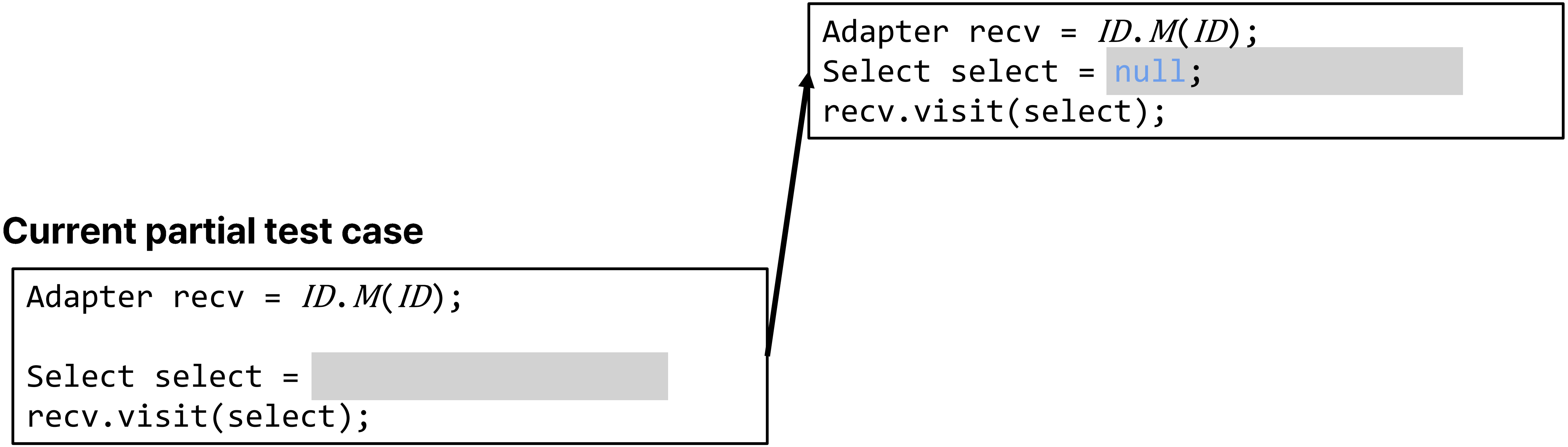


Current partial test case

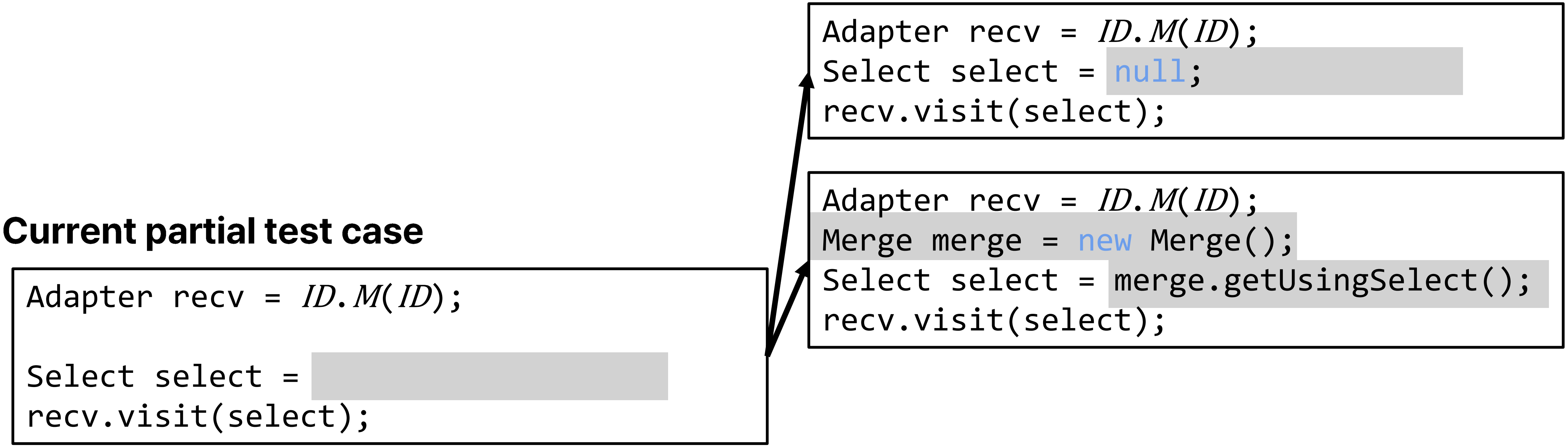
```
Adapter recv = ID.M(ID);

Select select = 
recv.visit(select);
```

```
Adapter recv = ID.M(ID);
Select select = null;
recv.visit(select);
```

Pruning

- Discard partial test cases with identical semantics.



Current partial test case

```
Adapter recv = ID.M(ID);

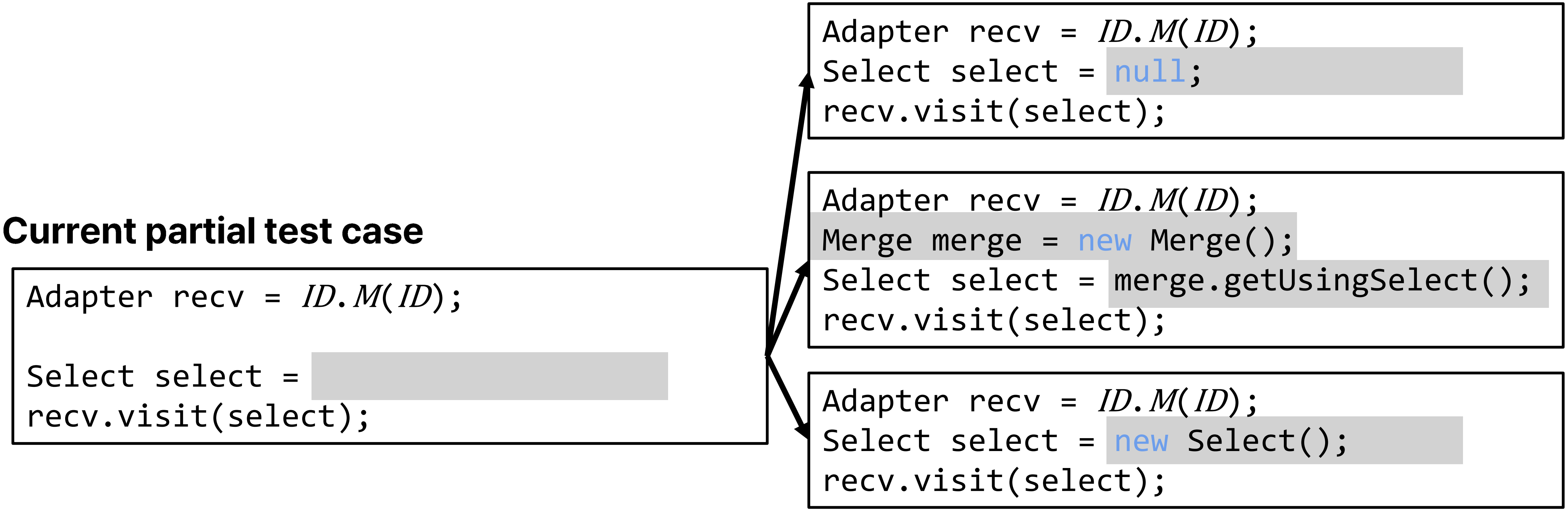
Select select = 
recv.visit(select);
```

```
Adapter recv = ID.M(ID);
Select select = null;
recv.visit(select);
```

```
Adapter recv = ID.M(ID);
Merge merge = new Merge();
Select select = merge.getUsingSelect();
recv.visit(select);
```

Pruning

- Discard partial test cases with identical semantics.



Current partial test case

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Adapter recv = ID.M(ID);

Select select = 
recv.visit(select);
```

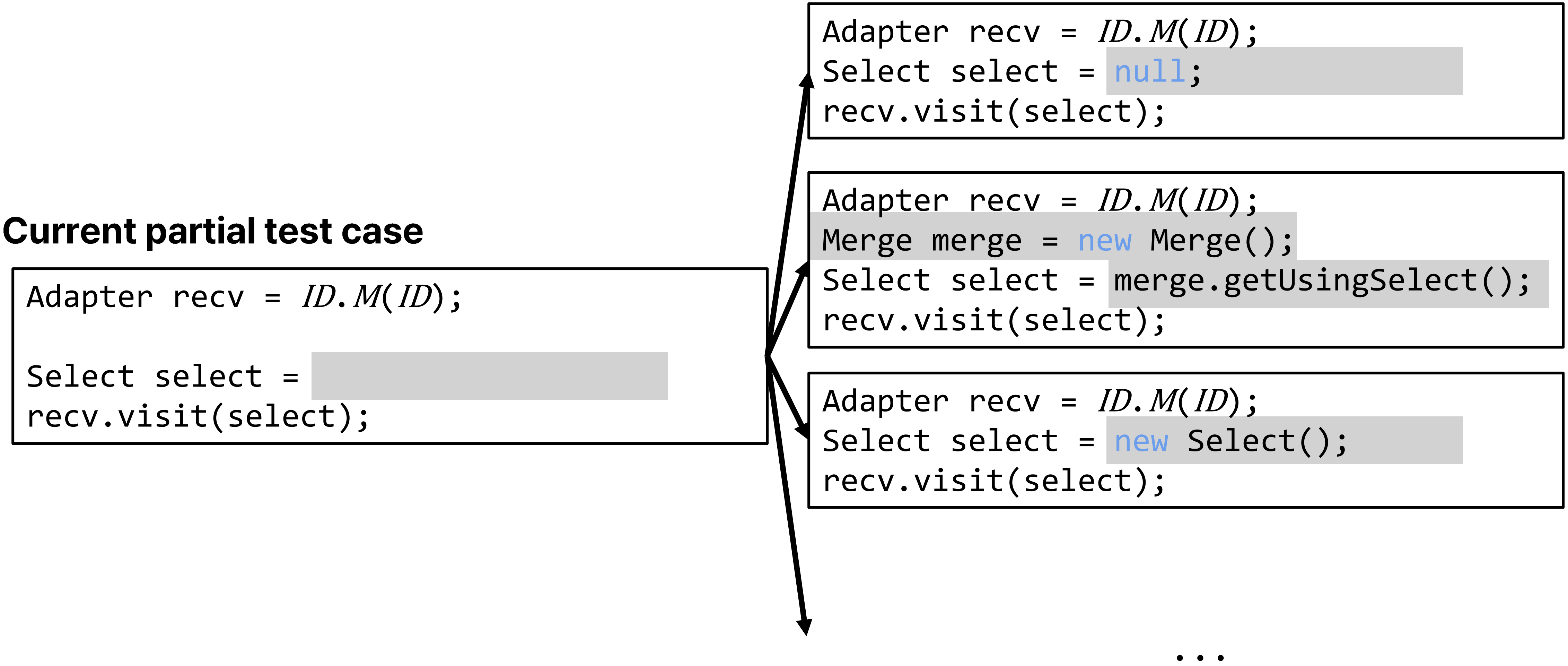
```
Adapter recv = ID.M(ID);
Select select = null;
recv.visit(select);
```

```
Adapter recv = ID.M(ID);
Merge merge = new Merge();
Select select = merge.getUsingSelect();
recv.visit(select);
```

```
Adapter recv = ID.M(ID);
Select select = new Select();
recv.visit(select);
```

Pruning

- Discard partial test cases with identical semantics.



Current partial test case

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Select select = null;
recv.visit(select);
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...

Pruning

- Discard partial test cases with identical semantics.

Current partial test case

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Adapter recv = ID.M(ID);

Select select = 
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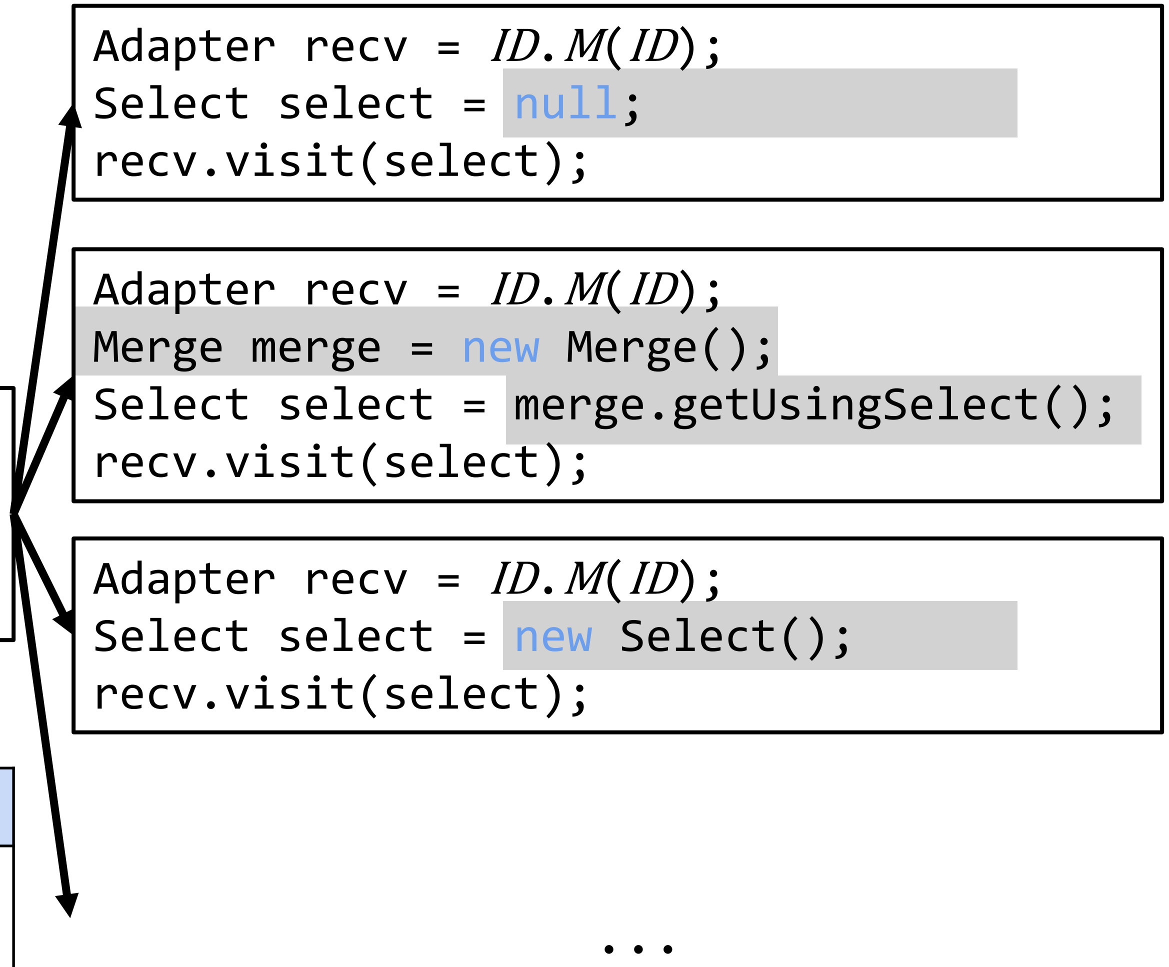
```



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Merge merge = new Merge();
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```

```
Adapter recv = ID.M(ID);
Select select = new Select();
recv.visit(select);
```

...

Method Summaries

Method	Memory
`Merge`	`{ usingSelect ↦ null }`
`getUsingSelect`	`{ ret ↦ usingSelect }`
...	...

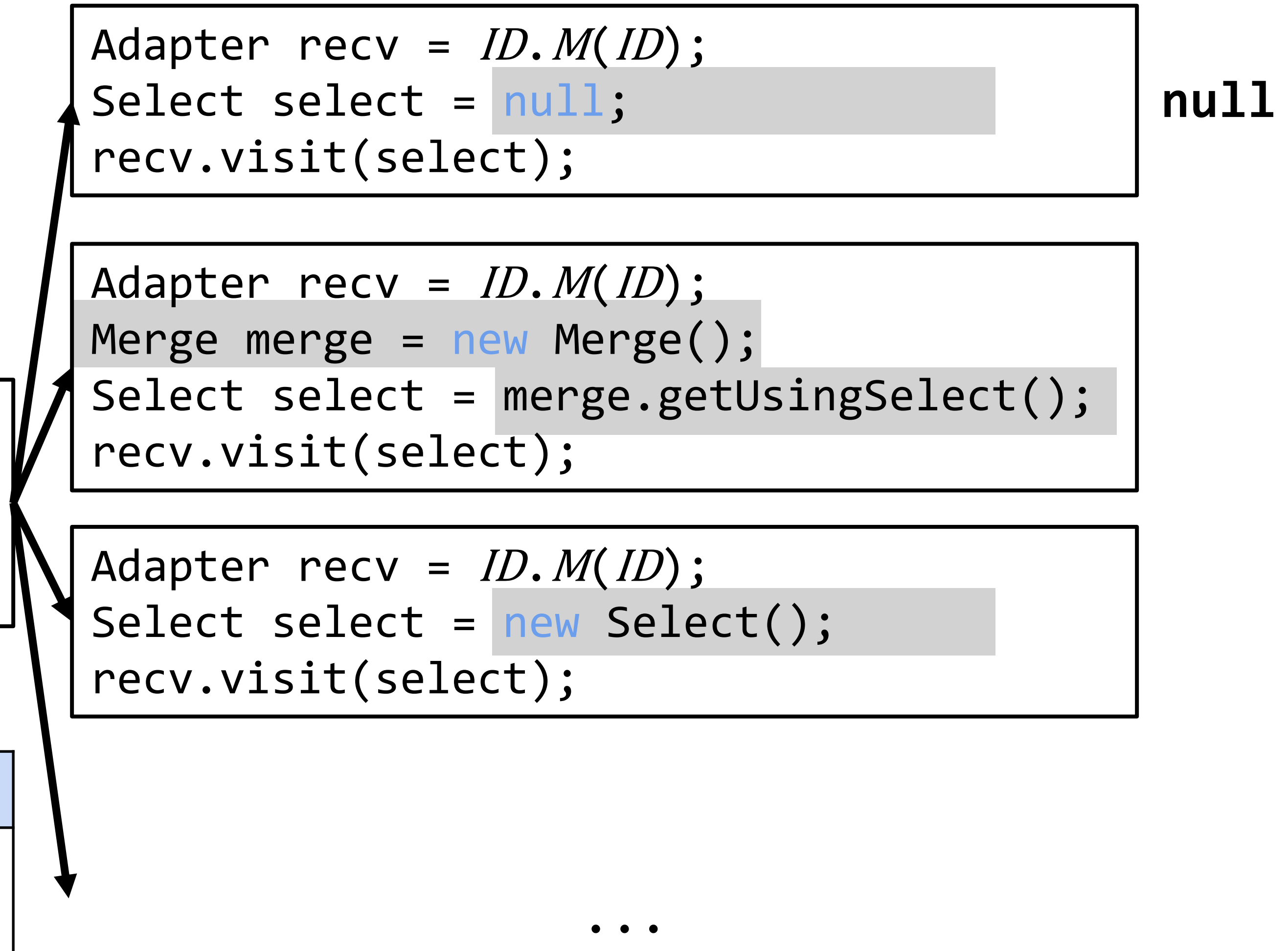
Pruning

- Discard partial test cases with identical semantics.

Current partial test case

```
Adapter recv = ID.M(ID);

Select select = 
recv.visit(select);
```



```
Adapter recv = ID.M(ID);
Select select = null;
recv.visit(select);
```

null

```
Adapter recv = ID.M(ID);
Merge merge = new Merge();
Select select = merge.getUsingSelect();
recv.visit(select);
```

```
Adapter recv = ID.M(ID);
Select select = new Select();
recv.visit(select);
```

...

Method Summaries

Method	Memory
Merge	{ usingSelect ↦ null }
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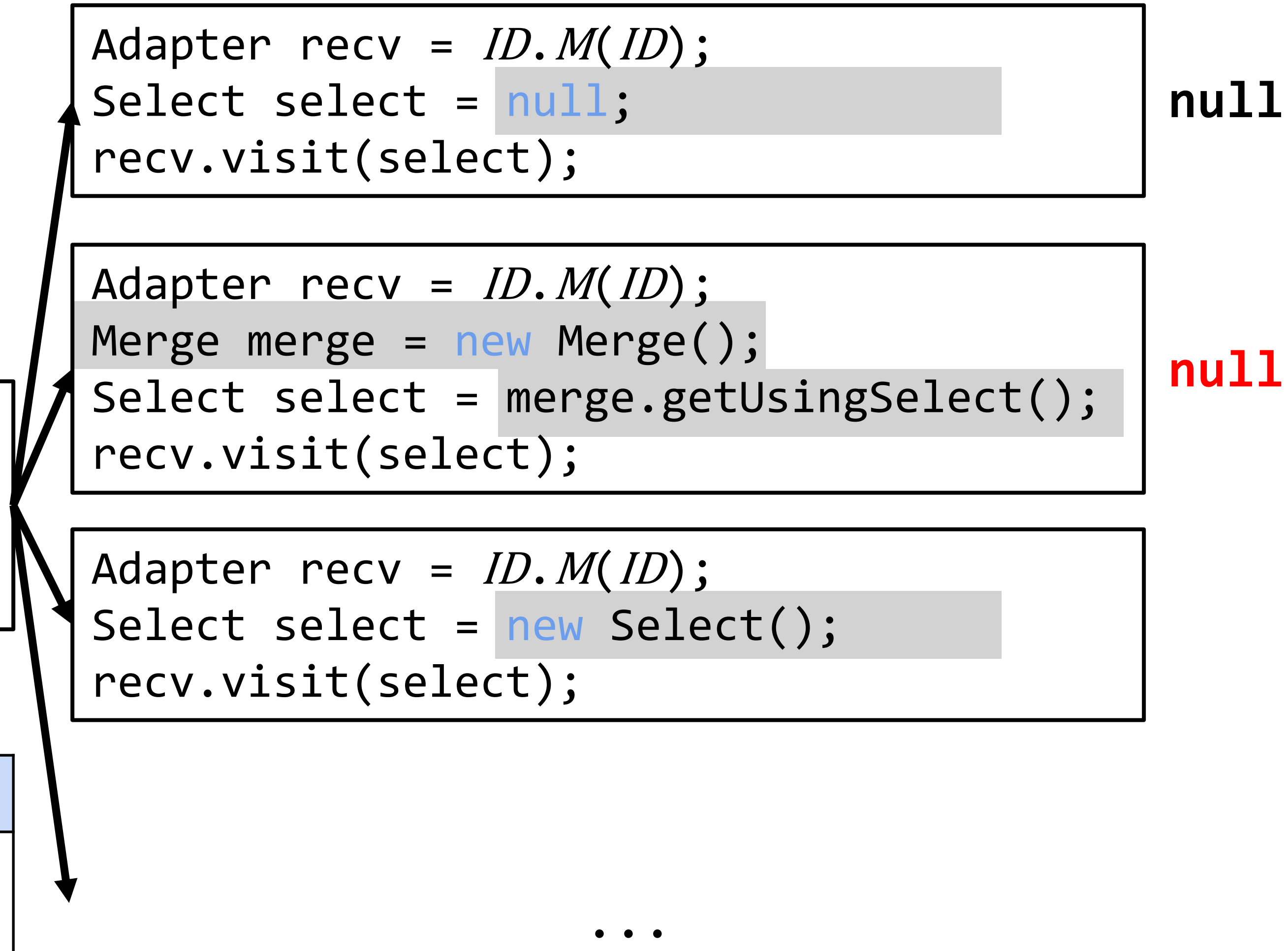

```
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Select select = null;
recv.visit(select);
```

```
Adapter recv = ID.M(ID);
Merge merge = new Merge();
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recv.visit(select);
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```
Adapter recv = ID.M(ID);
Select select = new Select();
recv.visit(select);
```

Method Summaries

Method	Memory
Merge	{ usingSelect ↦ null }
getUsingSelect	{ ret ↦ usingSelect }
...	...

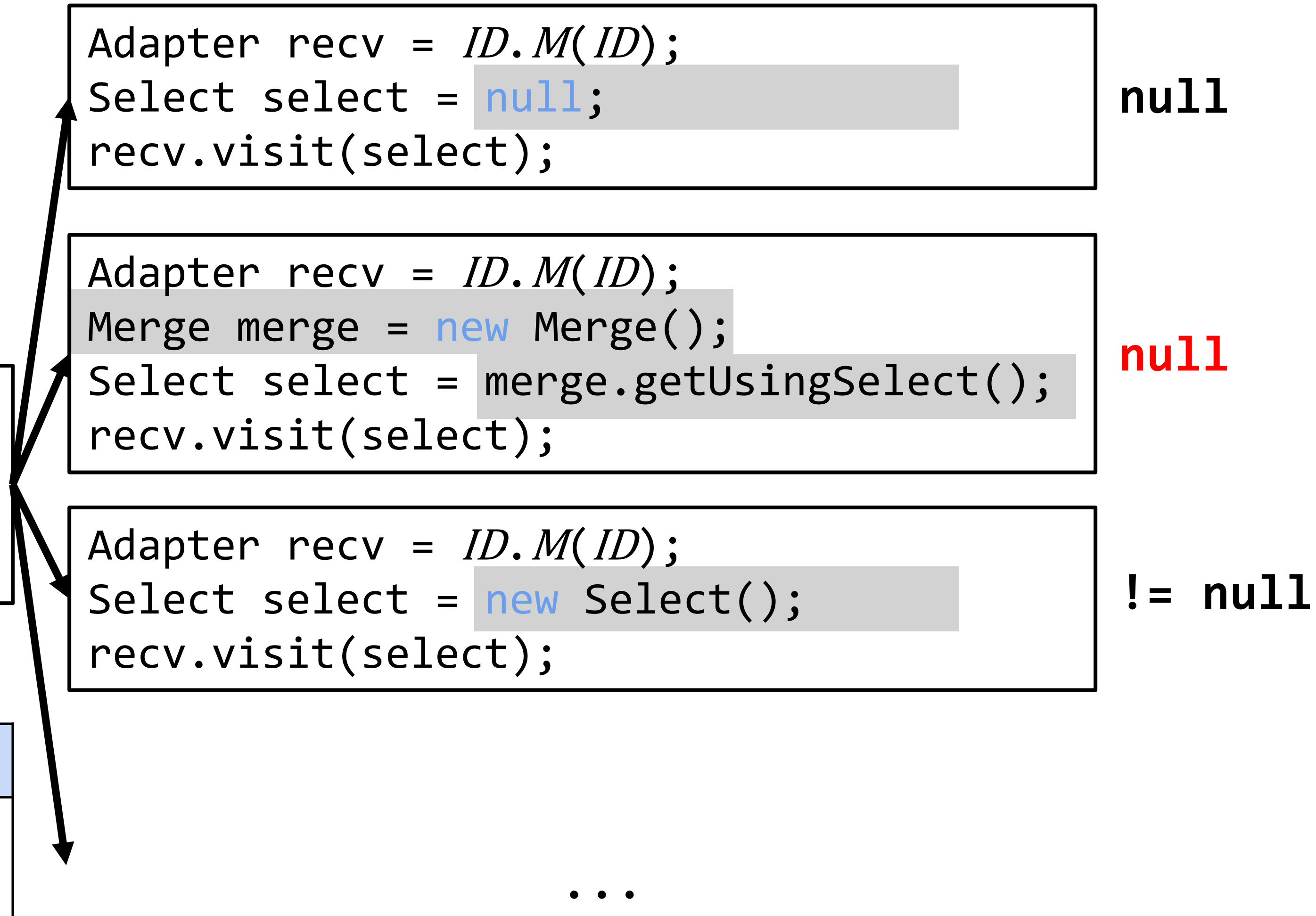
Pruning

- Discard partial test cases with identical semantics.

Current partial test case

```
Adapter recv = ID.M(ID);

Select select = 
recv.visit(select);
```



```
Adapter recv = ID.M(ID);
Select select = null;
recv.visit(select);
```

null

```
Adapter recv = ID.M(ID);
Merge merge = new Merge();
Select select = merge.getUsingSelect();
recv.visit(select);
```

null

```
Adapter recv = ID.M(ID);
Select select = new Select();
recv.visit(select);
```

!= null

...

Method Summaries

Method	Memory
Merge	{ usingSelect ↦ null }
getUsingSelect	{ ret ↦ usingSelect }
...	...

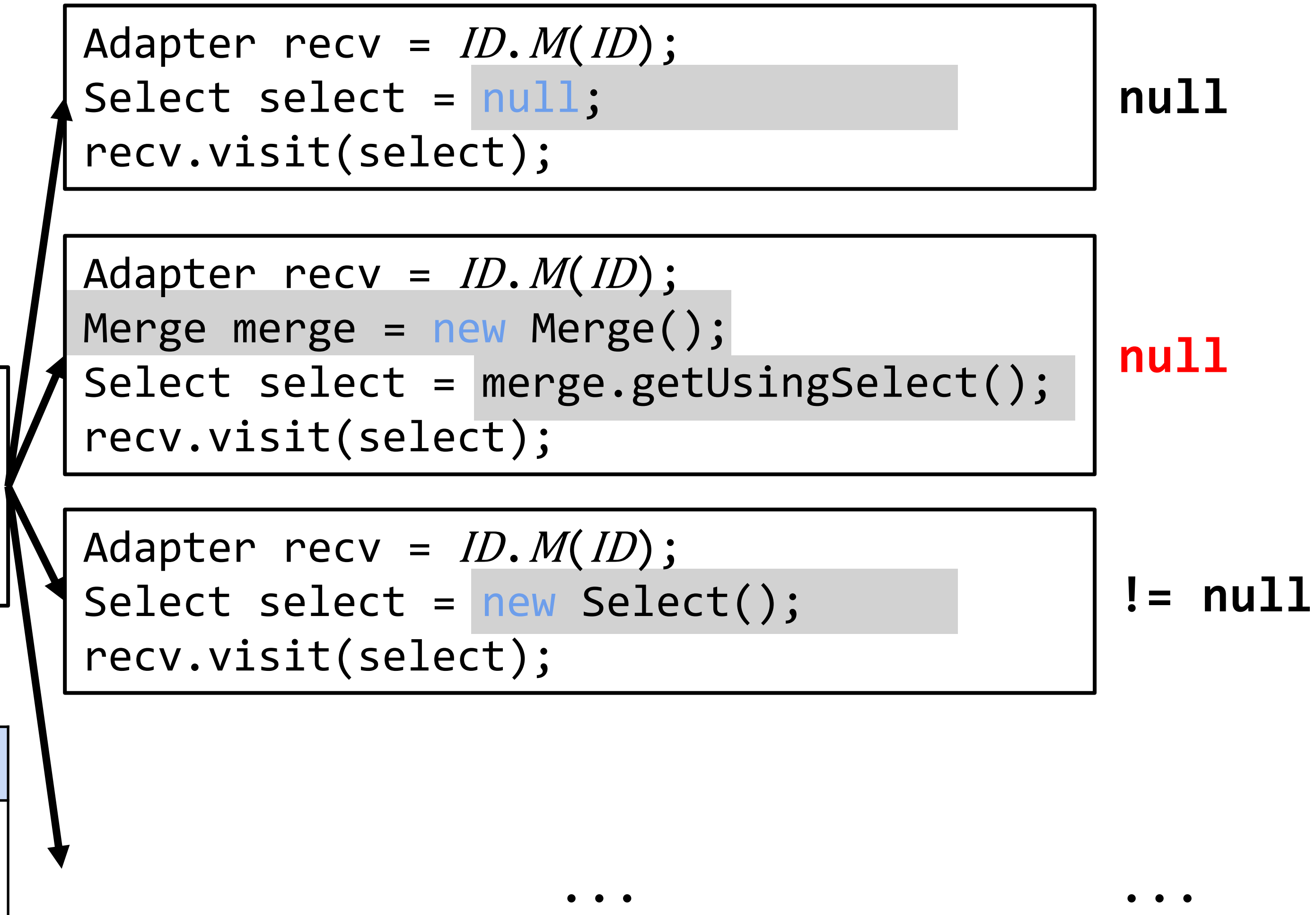
Pruning

- Discard partial test cases with identical semantics.

Current partial test case

```
Adapter recv = ID.M(ID);

Select select = 
recv.visit(select);
```



```
Adapter recv = ID.M(ID);
Select select = null;
recv.visit(select);
```

null

```
Adapter recv = ID.M(ID);
Merge merge = new Merge();
Select select = merge.getUsingSelect();
recv.visit(select);
```

null

```
Adapter recv = ID.M(ID);
Select select = new Select();
recv.visit(select);
```

!= null

...

...

Method Summaries

Method	Memory
Merge	{ usingSelect ↦ null }
getUsingSelect	{ ret ↦ usingSelect }
...	...

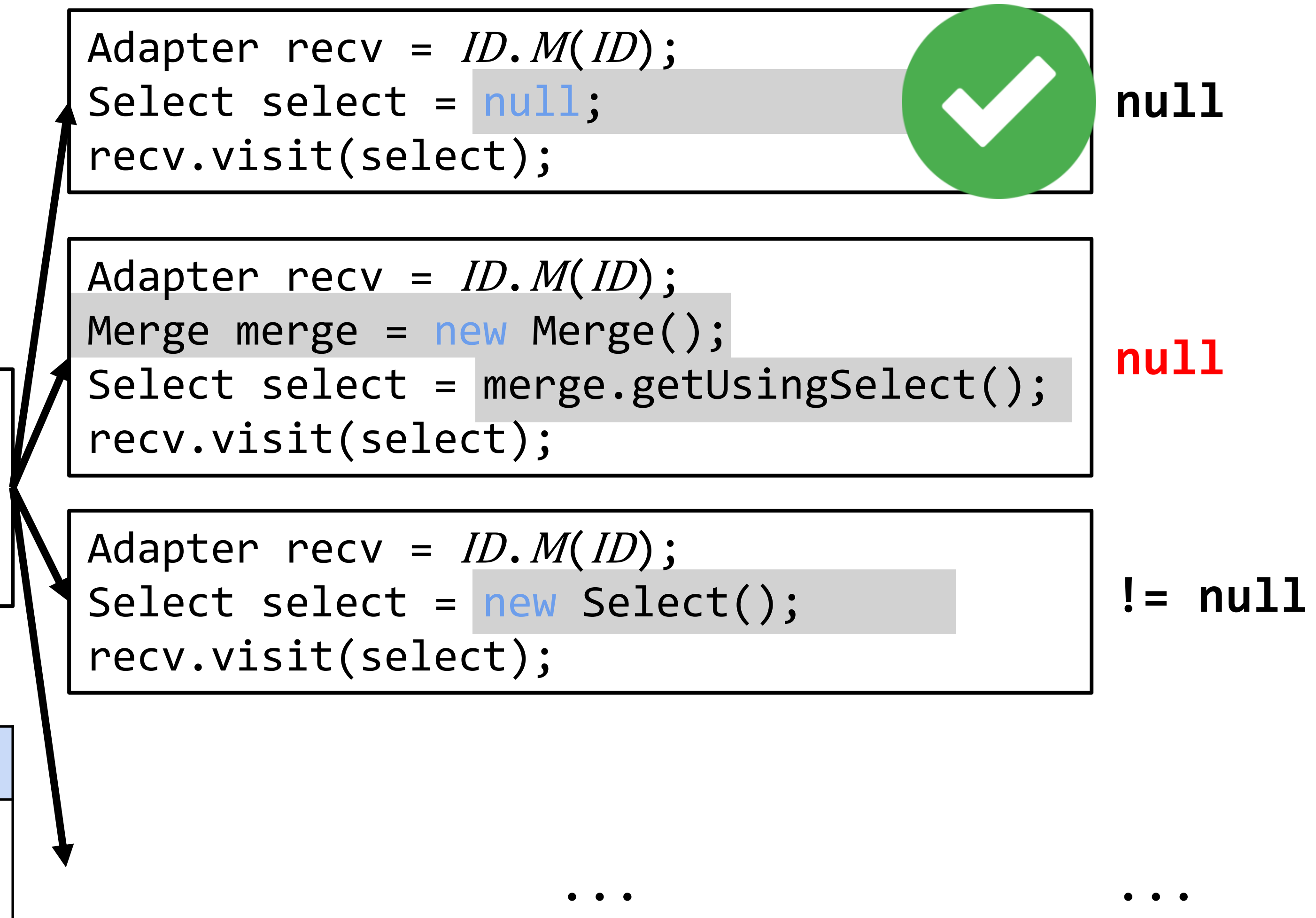
Pruning

- Discard partial test cases with identical semantics.

Current partial test case

```
Adapter recv = ID.M(ID);

Select select = 
recv.visit(select);
```



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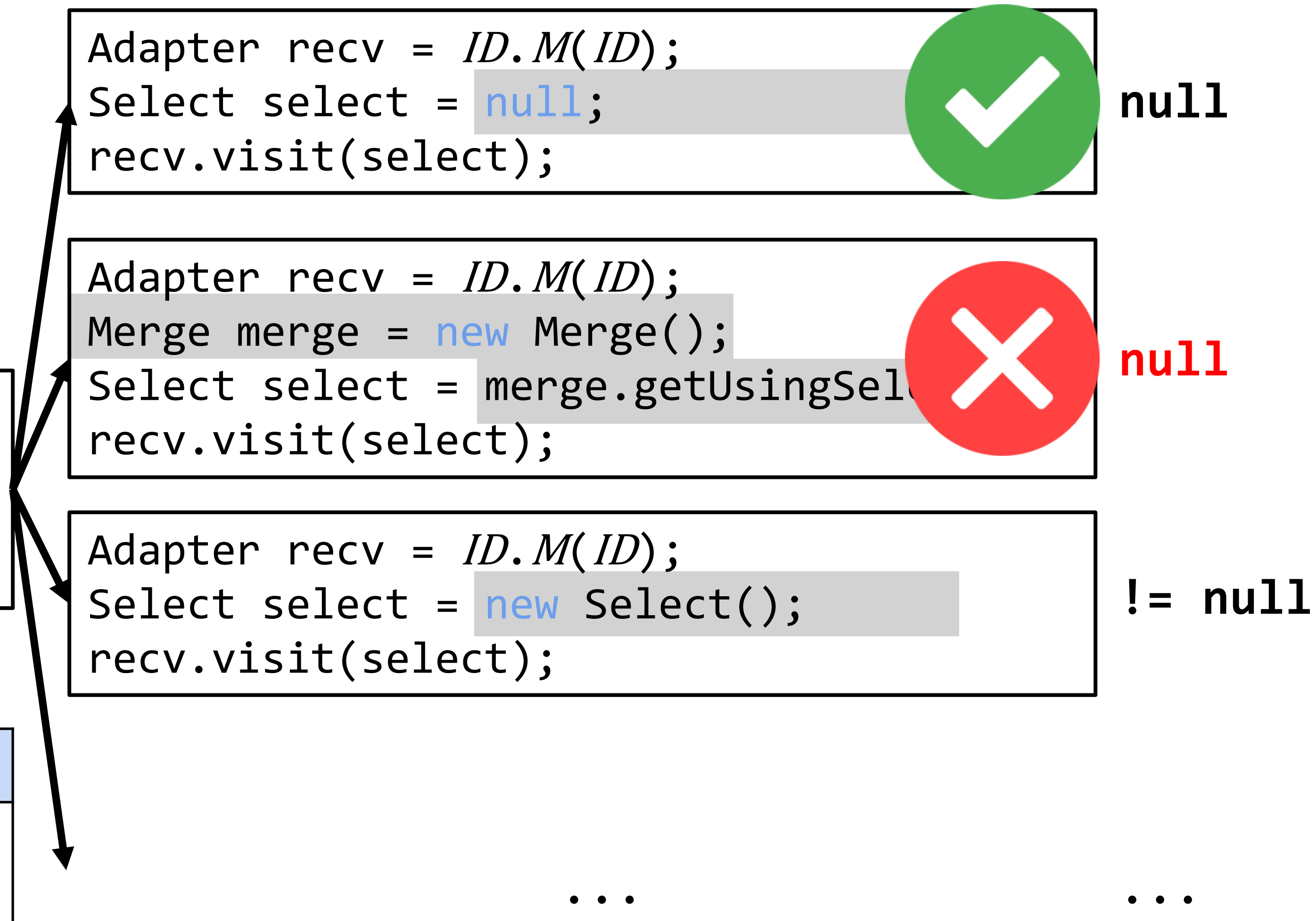

```
Adapter recv = ID.M(ID);
Select select = null;
recv.visit(select);
```

✓ null

```
Adapter recv = ID.M(ID);
Merge merge = new Merge();
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```

✗ null

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!= null

...

...

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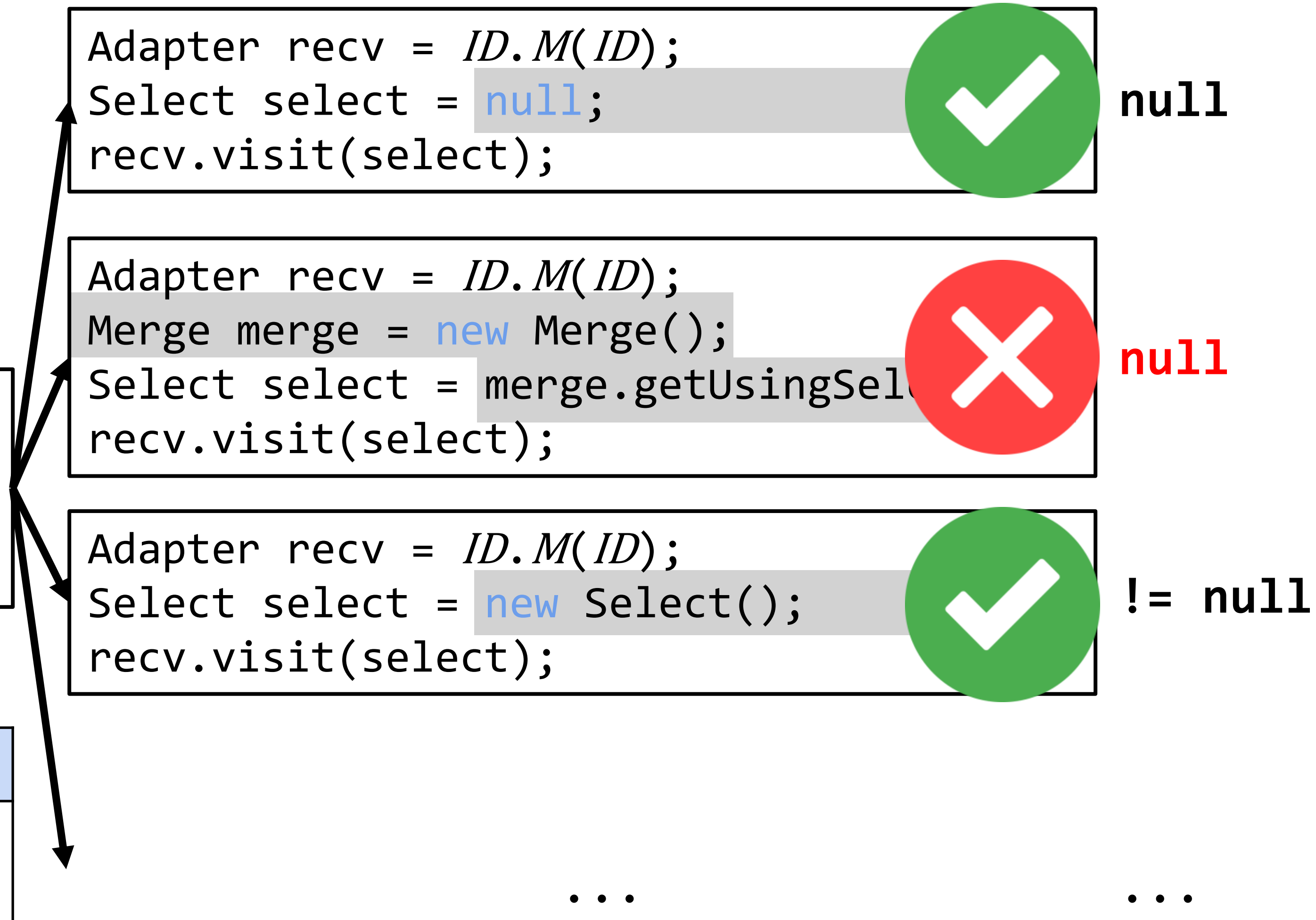

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Select select = null;
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✓ null

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```

✗ null

```
Adapter recv = ID.M(ID);
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recv.visit(select);
```

✓ != null

... ...

Prioritization

Prioritization

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Error Conditions

Object	Condition
`select.itemsList`	`== null`
`this.visitor`	`!= null`
`select`	`!= null`

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recv.visit(select);
```

. . .

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👎

```
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👍

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```

...

Error Conditions

Object	Condition
`select.itemsList`	`== null`
`this.visitor`	`!= null`
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Example

```java
public class Adapter {
  private Visitor visitor;

  public void setVisitor(Visitor visitor) {
    this.visitor = visitor;
  }

  public void visit(Select select) {
    if (visitor != null) {
      ItemsList itemsList = select.getItemsList();
      for (Item item: itemsList) { // Target location
        ...
}

public class Select {
  private List <Item> itemsList;

  public List <Item> getItemsList() { return itemsList; }
}

public class Merge {
  private Select usingSelect;

  public Select getUsingSelect() { return usingSelect; }
}
```

```java
public void test() {
  Adapter recv = new Adapter();
  Visitor visitor = new Visitor();
  recv.setVisitor(visitor);
  Select select = new Select();
  recv.visit(select);
}
```

Exception reproduced in **39 seconds**.

Evaluation: Known Bug Reproduction

Evaluation: Known Bug Reproduction

Benchmarks

Evaluation: Known Bug Reproduction

Benchmarks

- 198 Java programs (1 target exception per program).

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Task

Evaluation: Known Bug Reproduction

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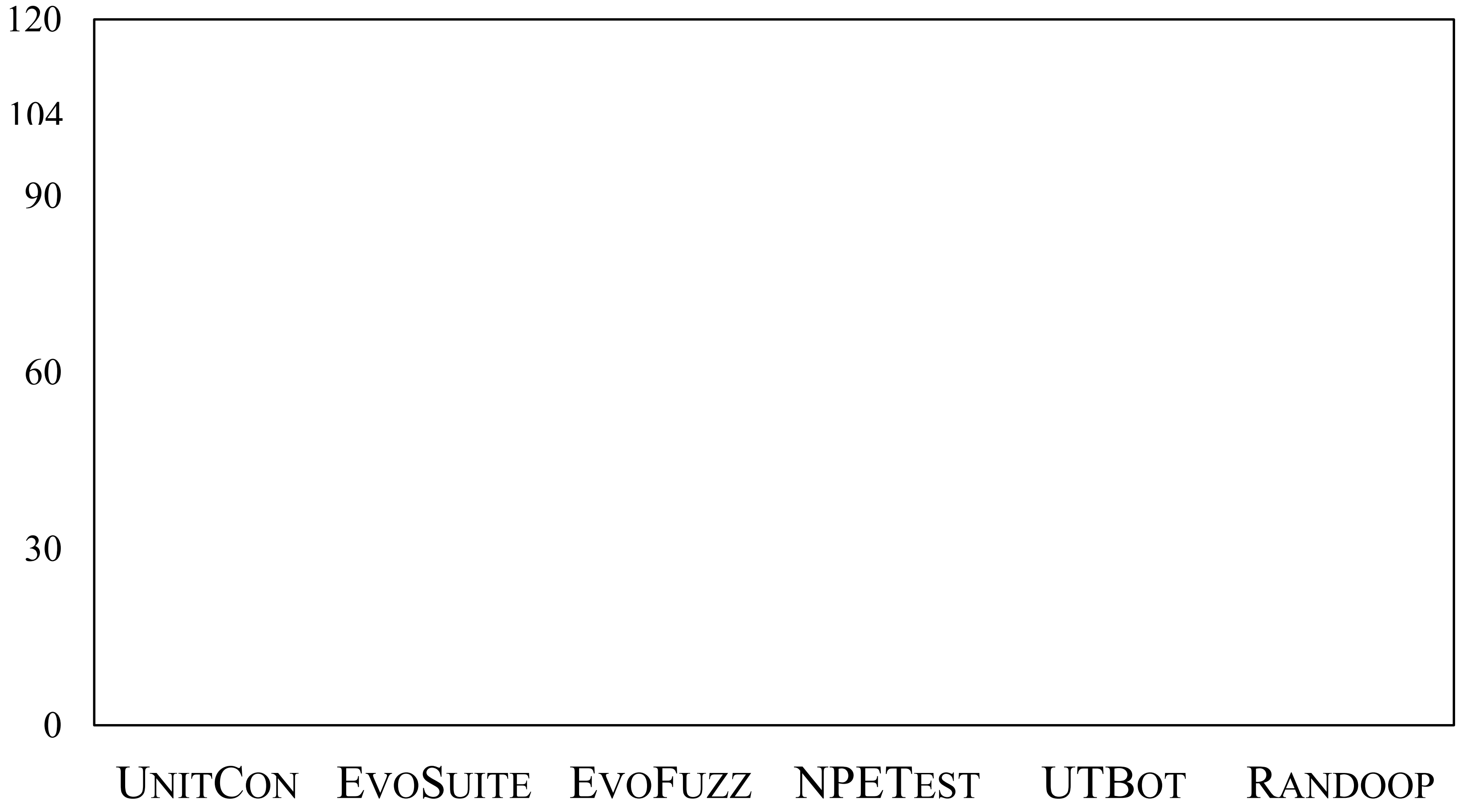
Task

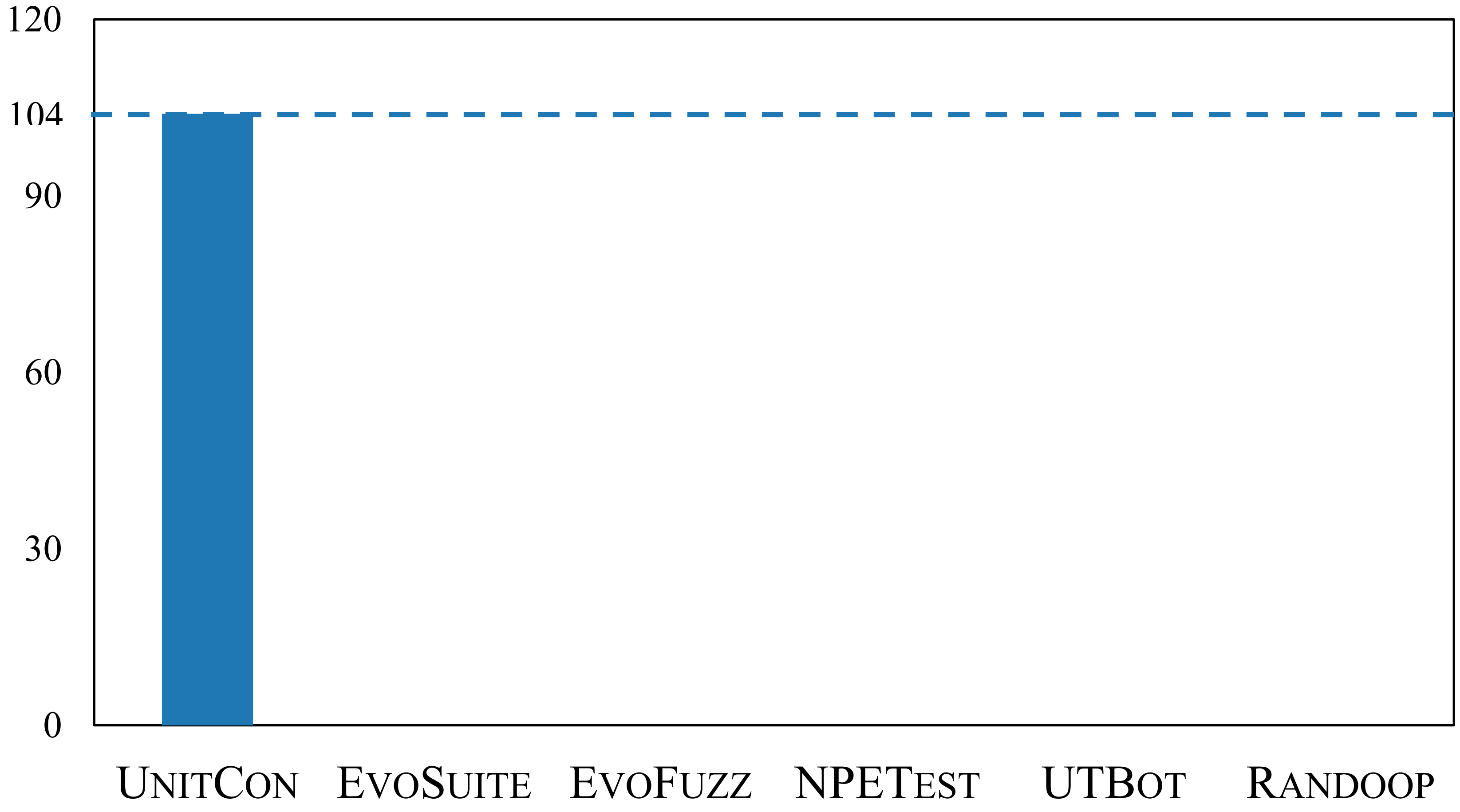
- 10 minutes time limit per 1 target exception.

Comparison to Baselines

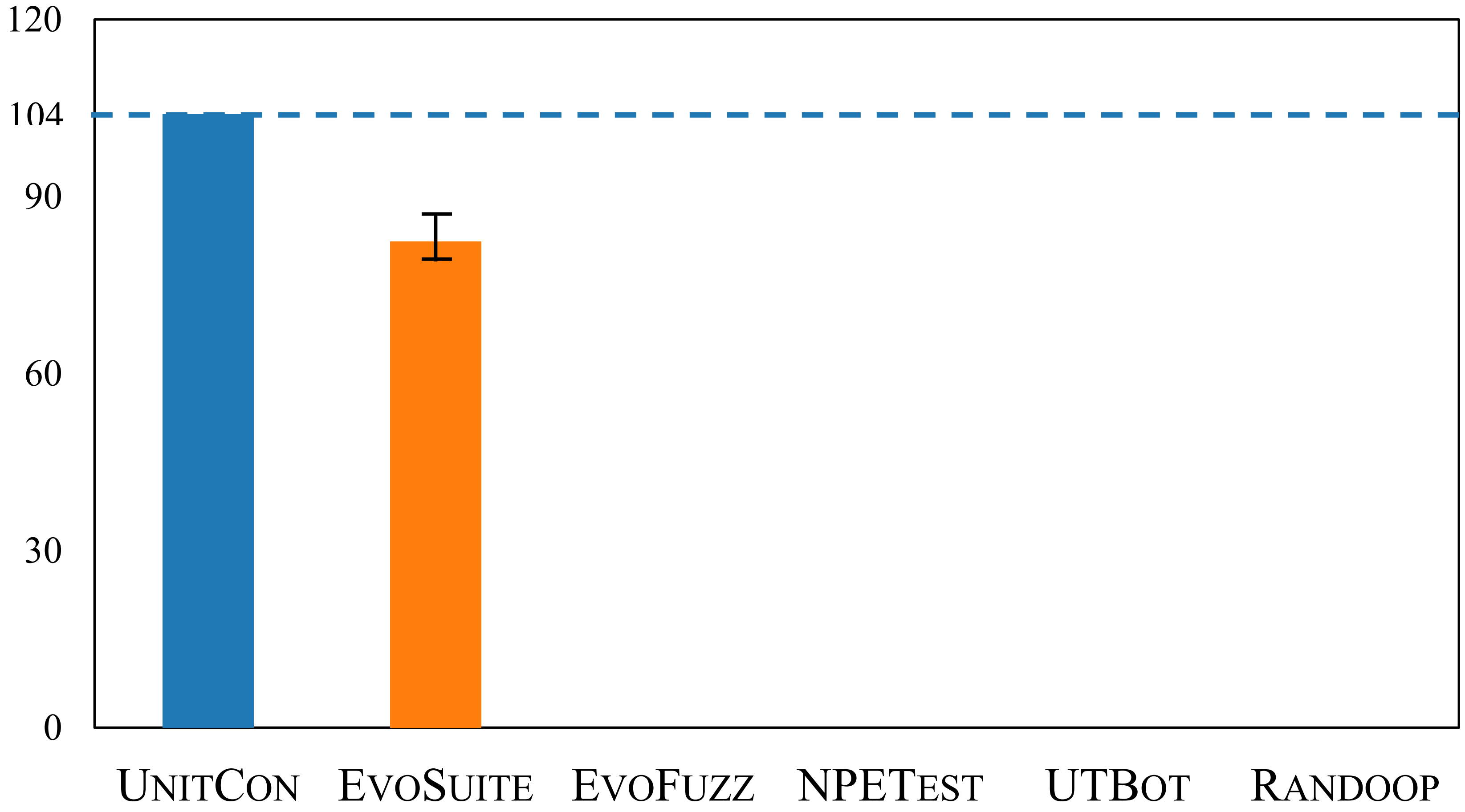
Comparison to Baselines



Comparison to Baselines



Comparison to Baselines



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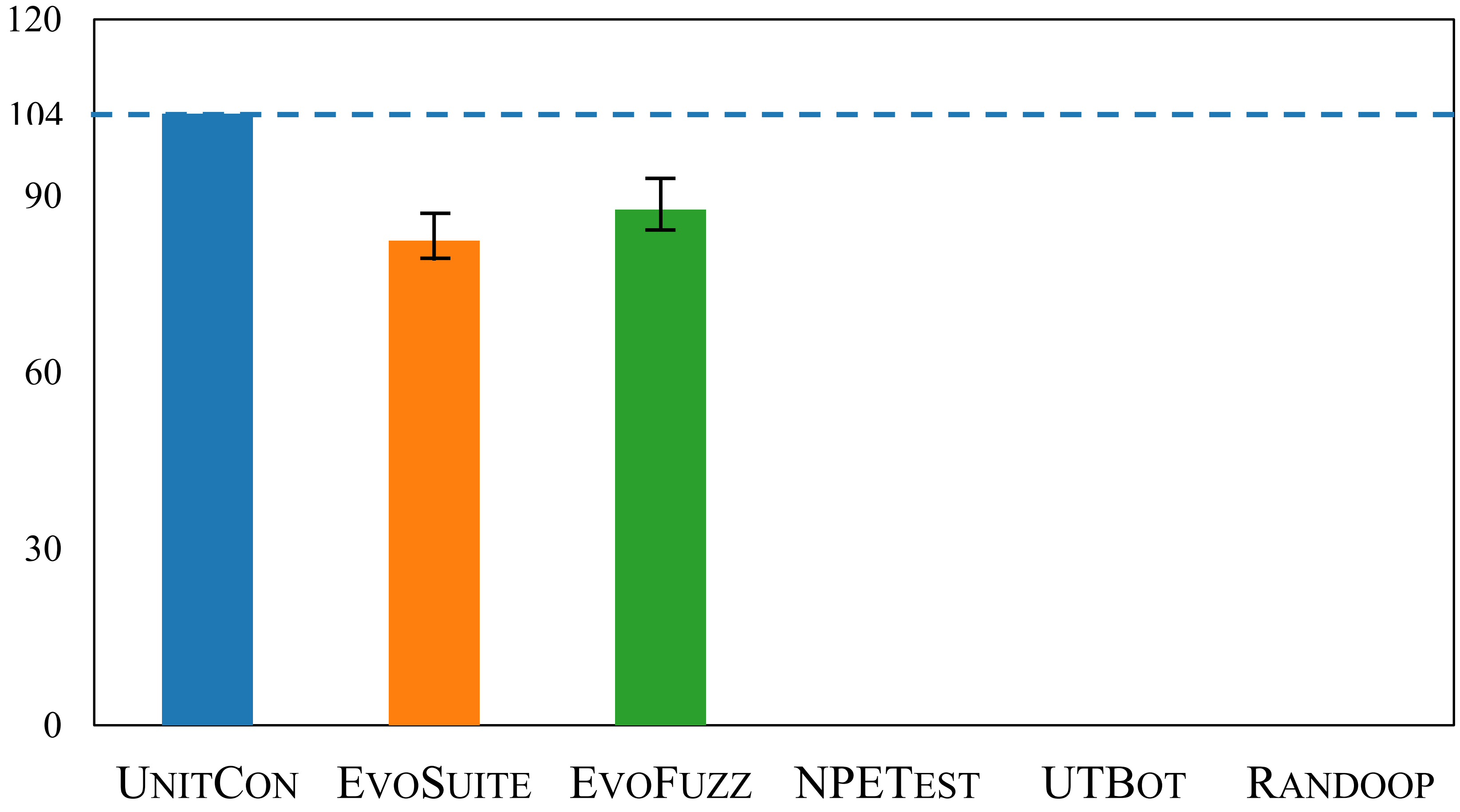

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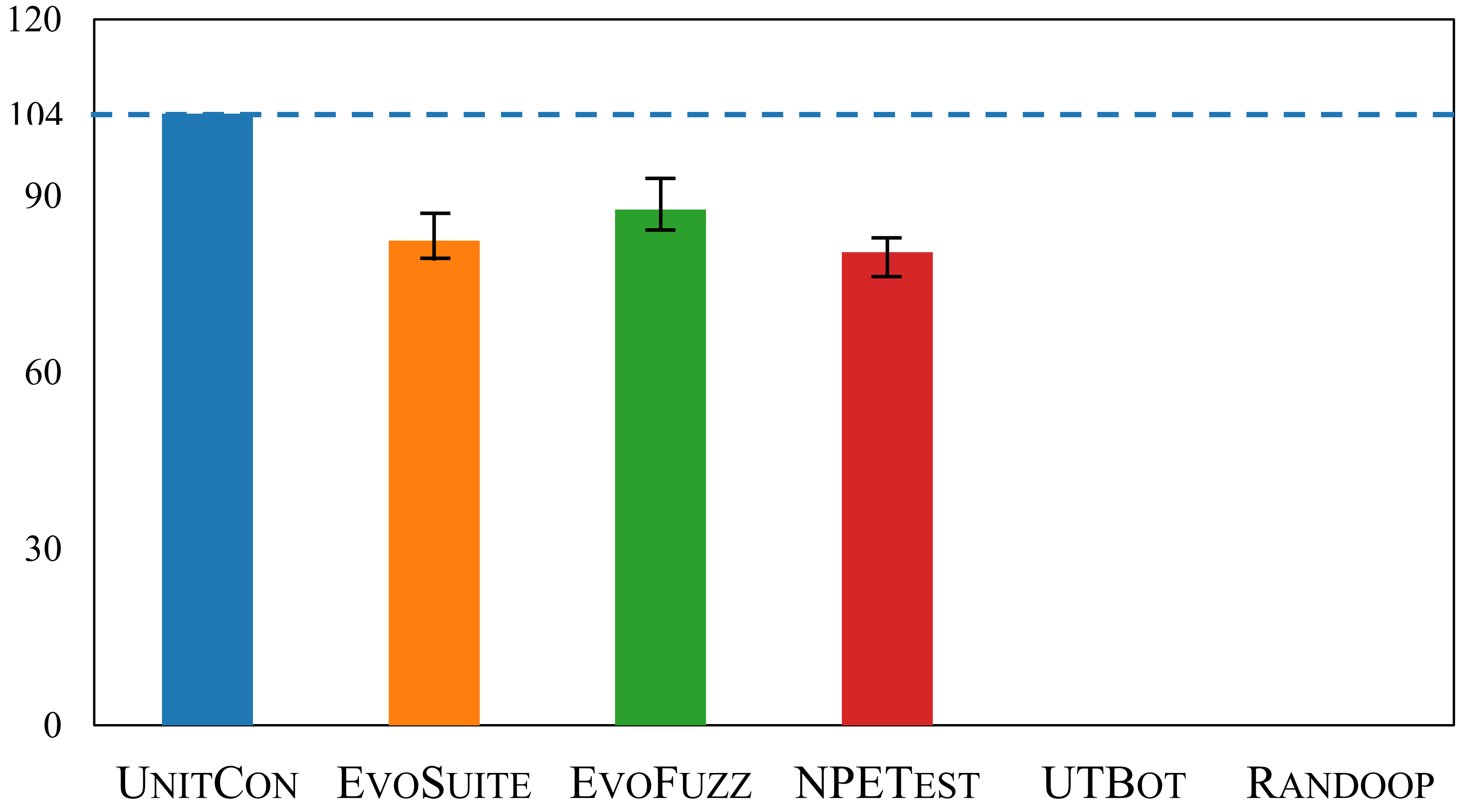

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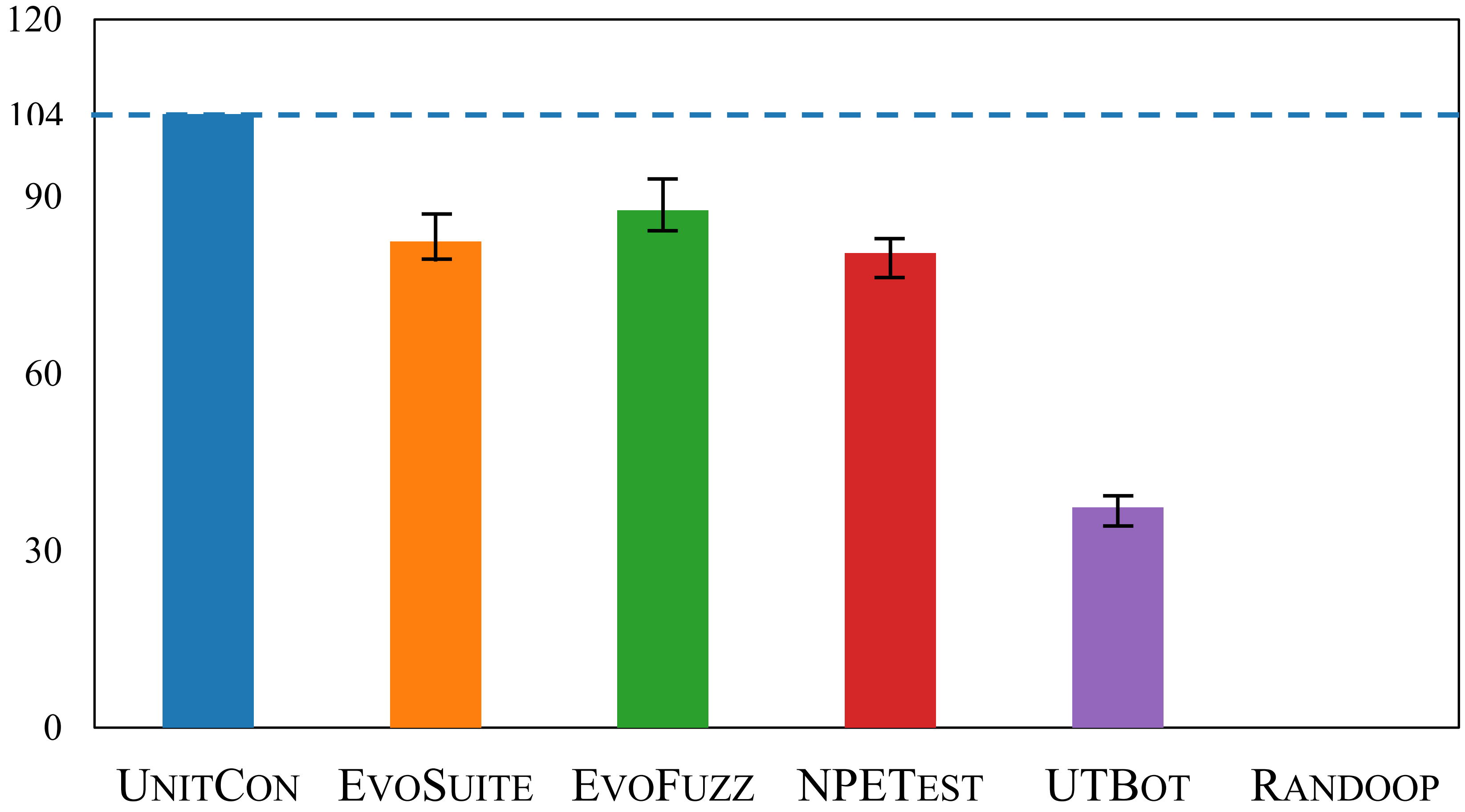

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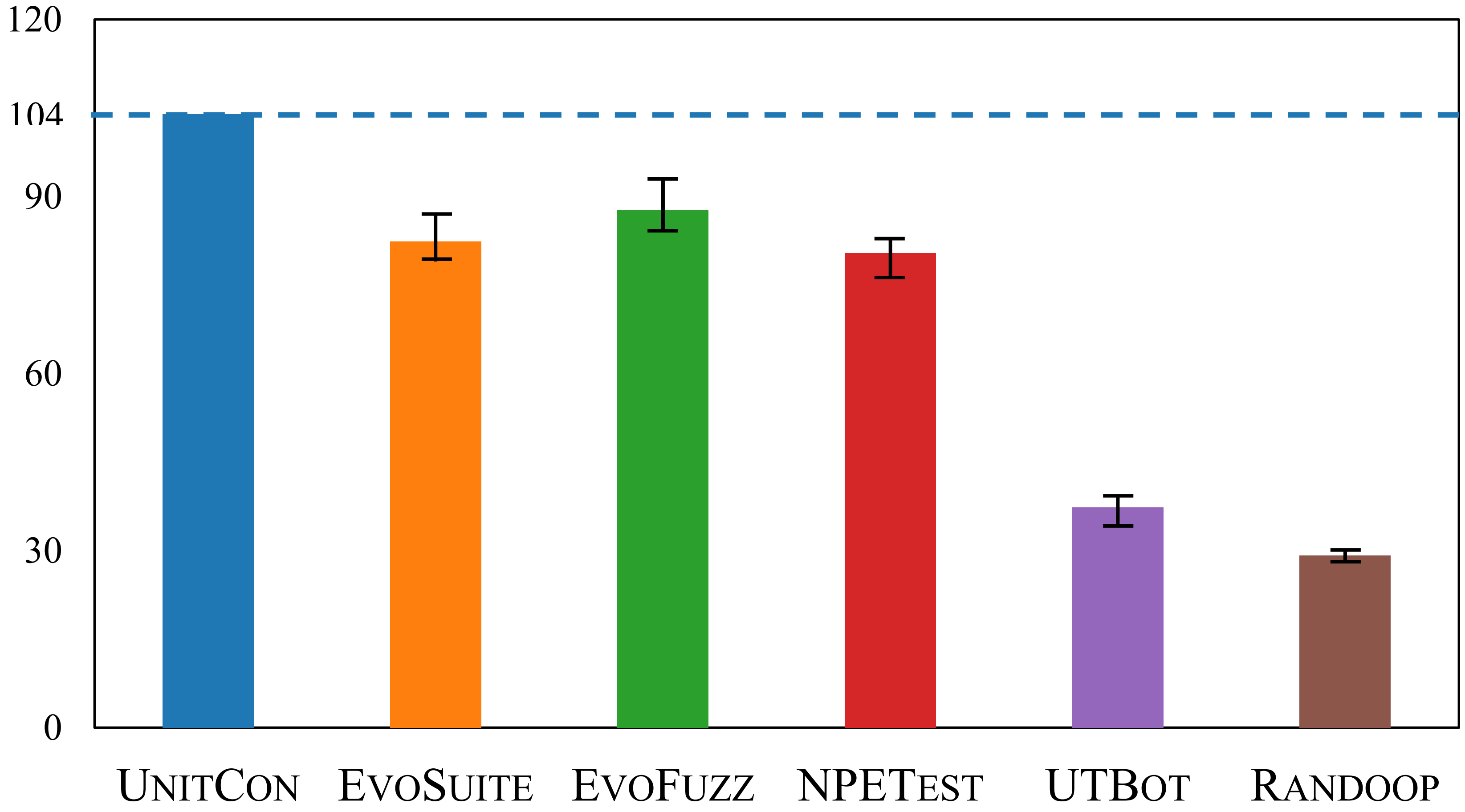
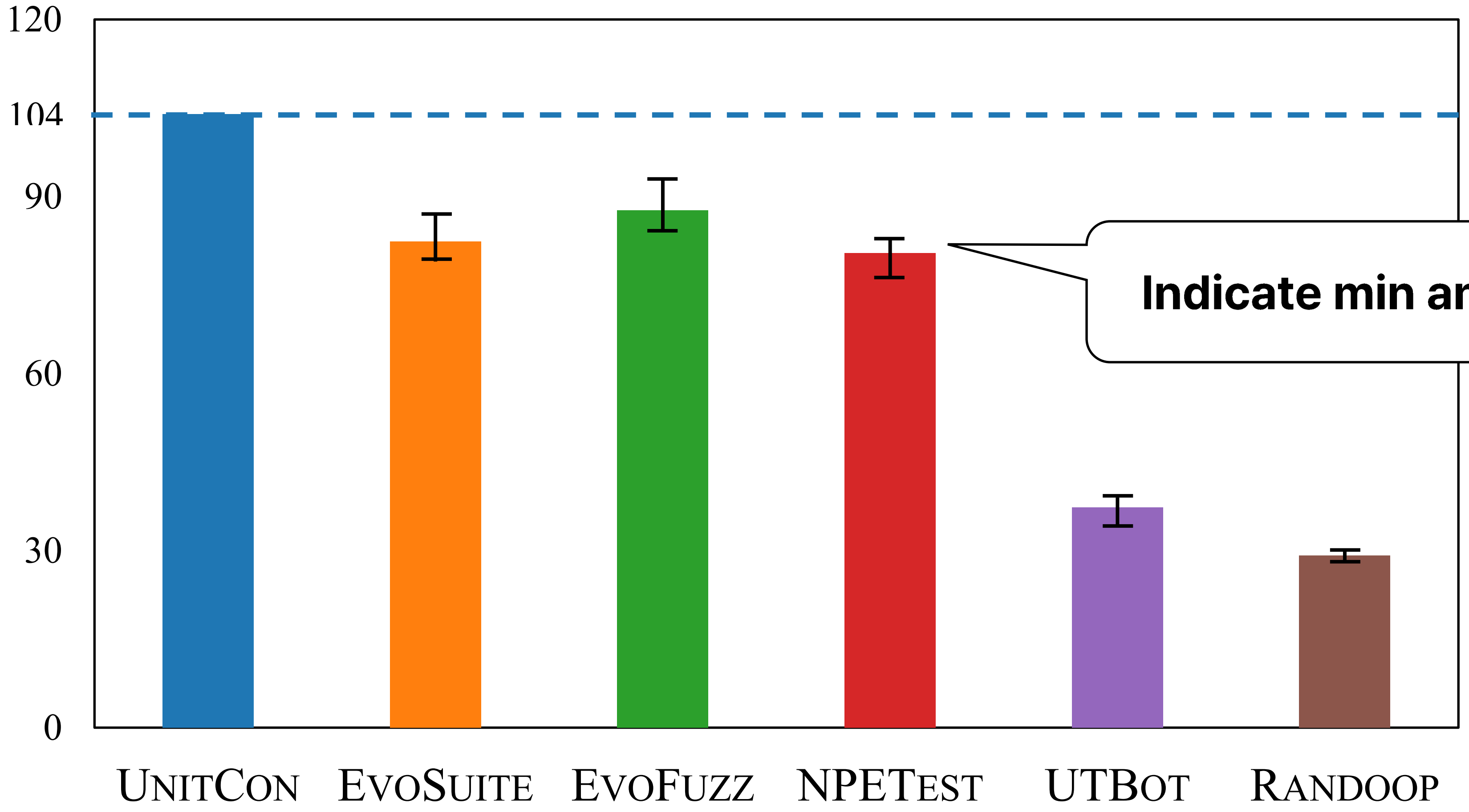


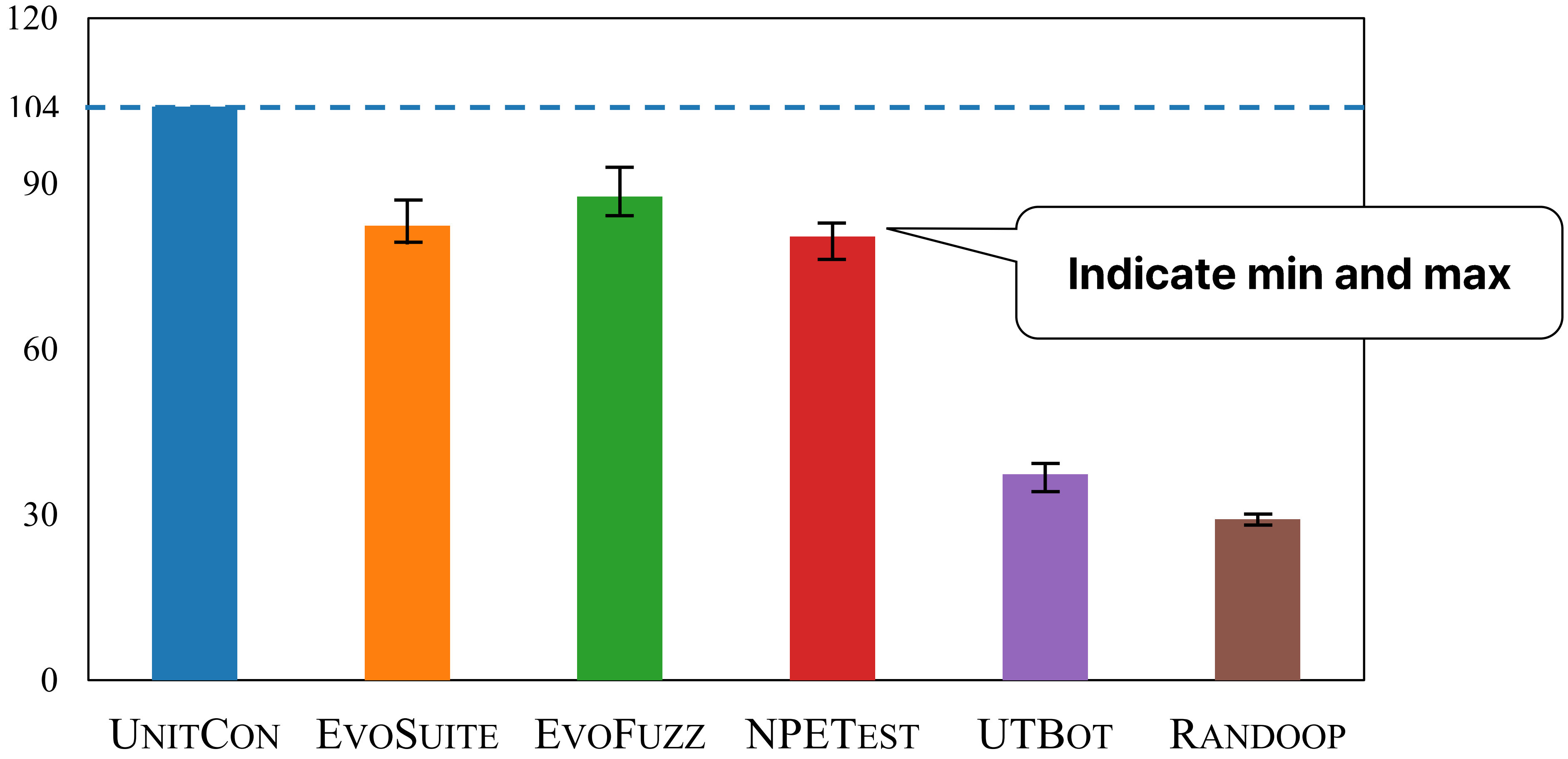
Comparison to Baselines



Indicate min and max

Comparison to Baselines

- **<span>1.2 – 3.6 x</span> more success than baselines.**



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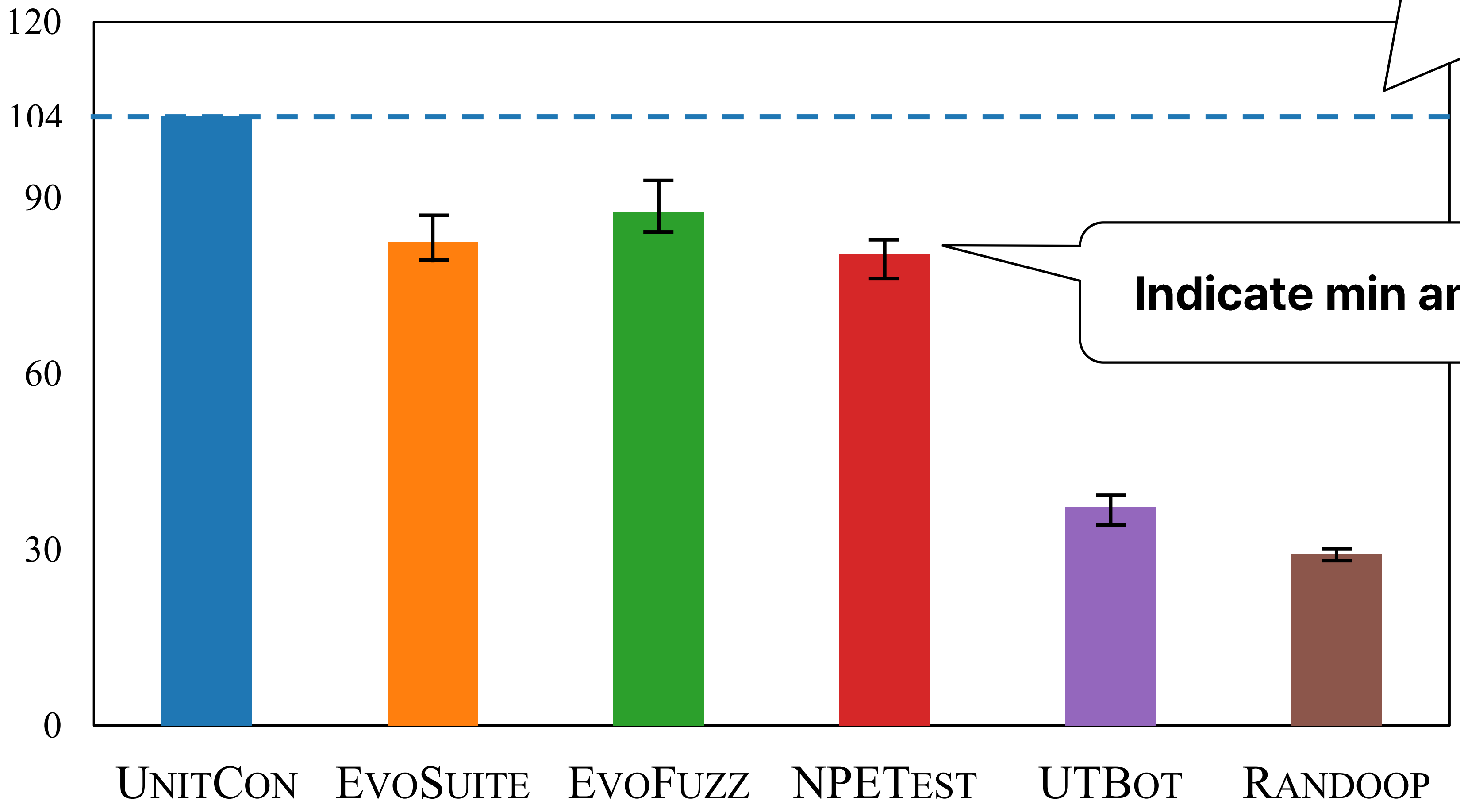
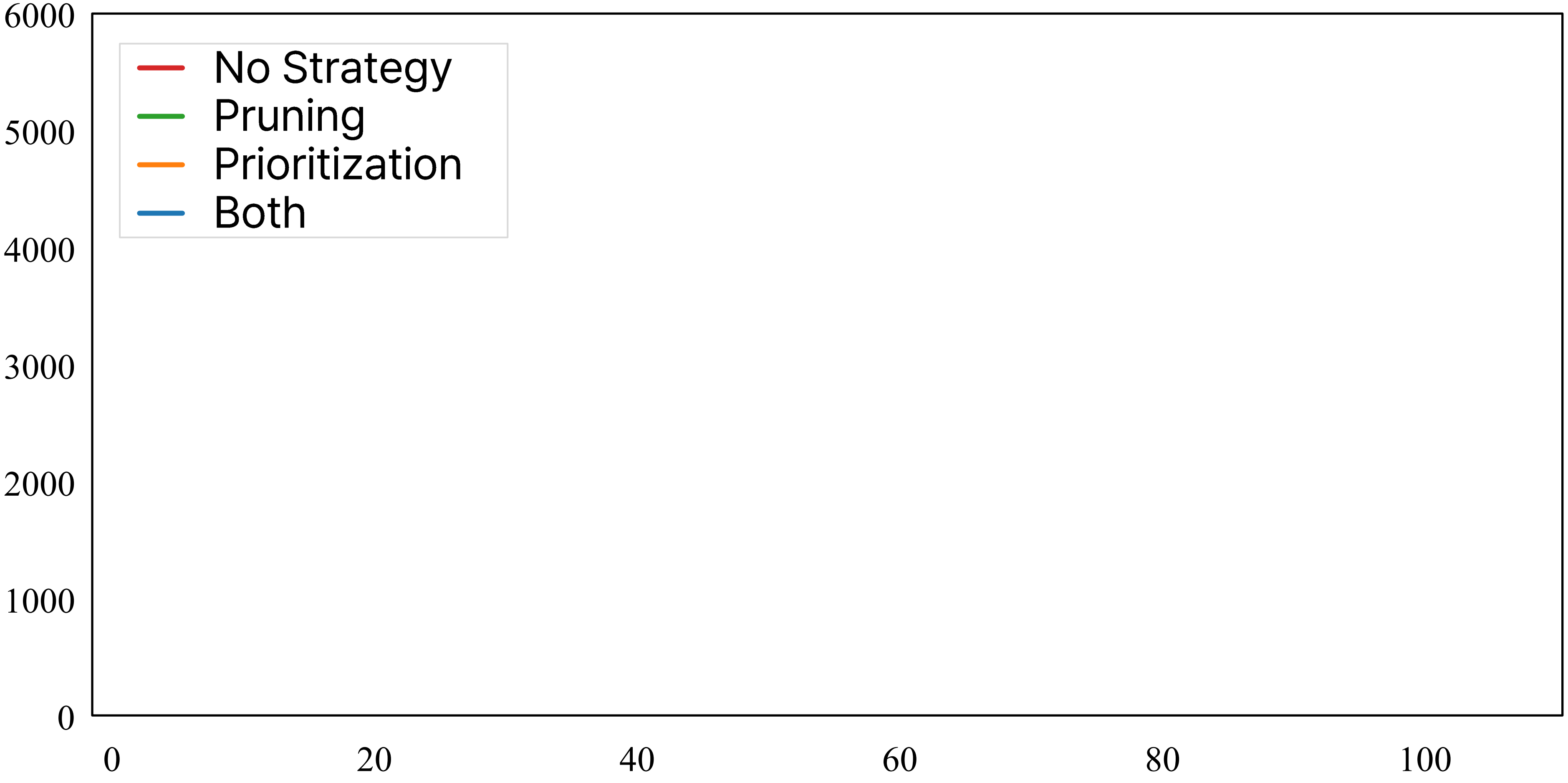


Deterministically outperform baselines.

Indicate min and max

Impact of Each Strategy



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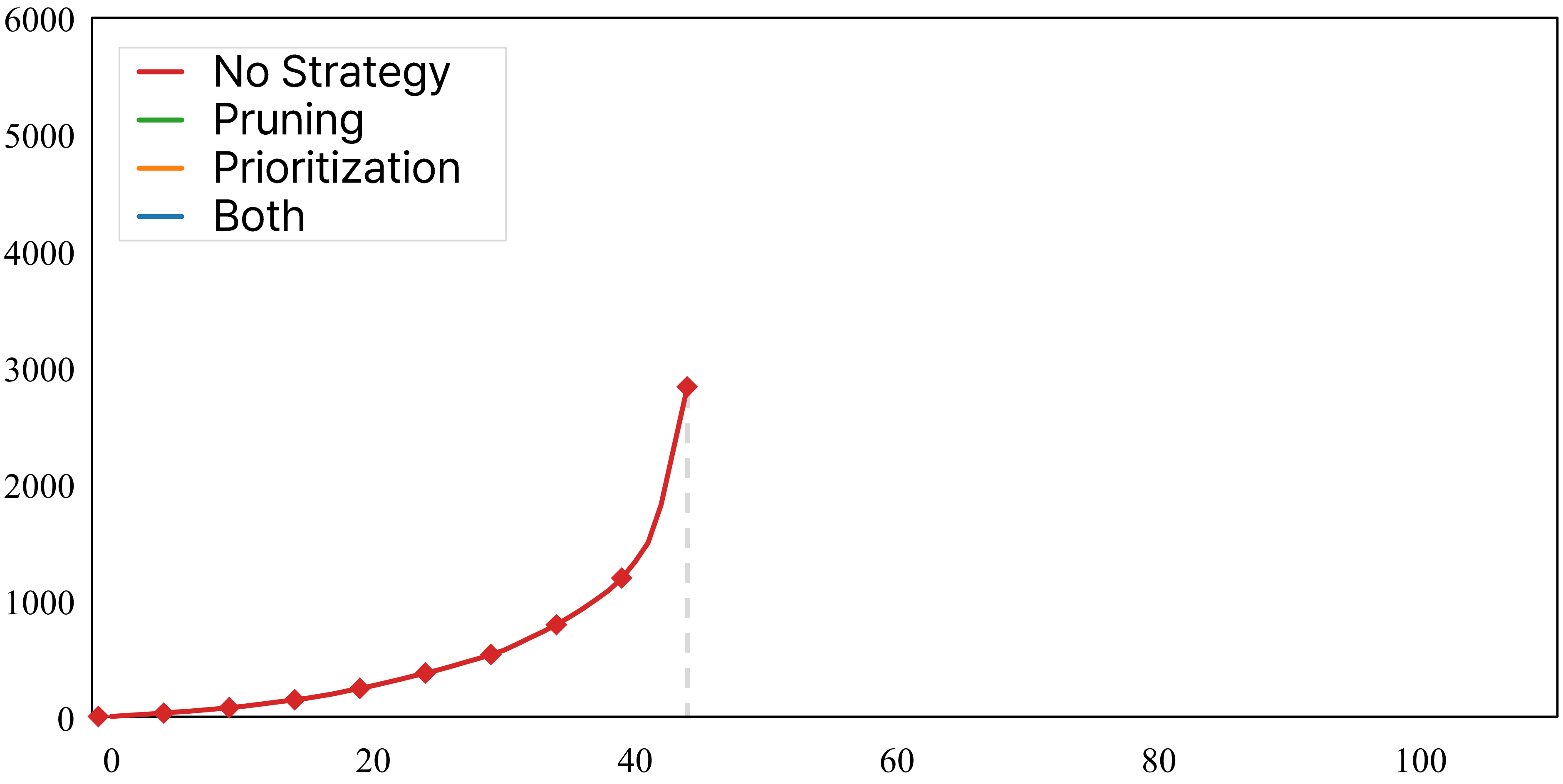

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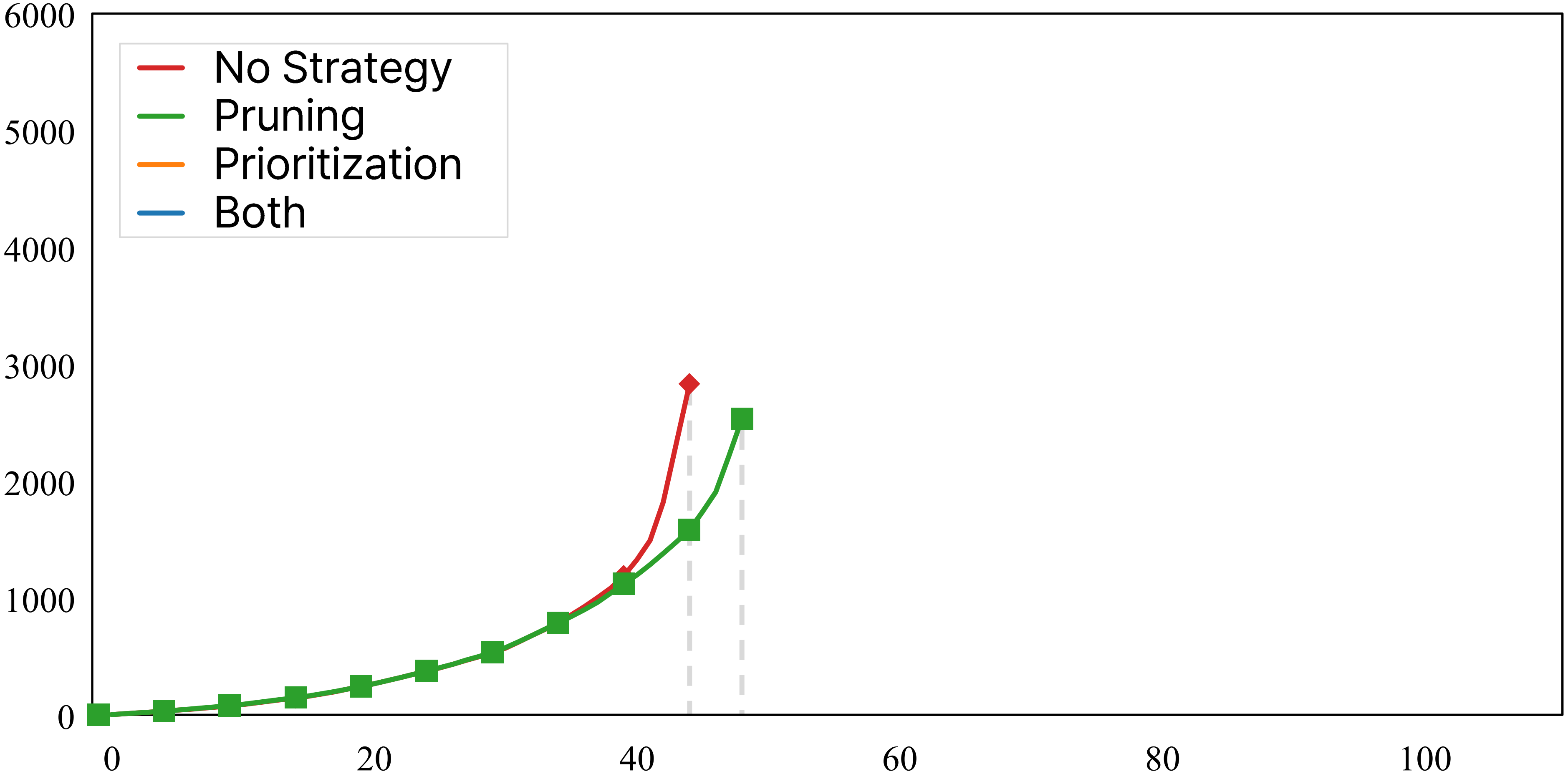

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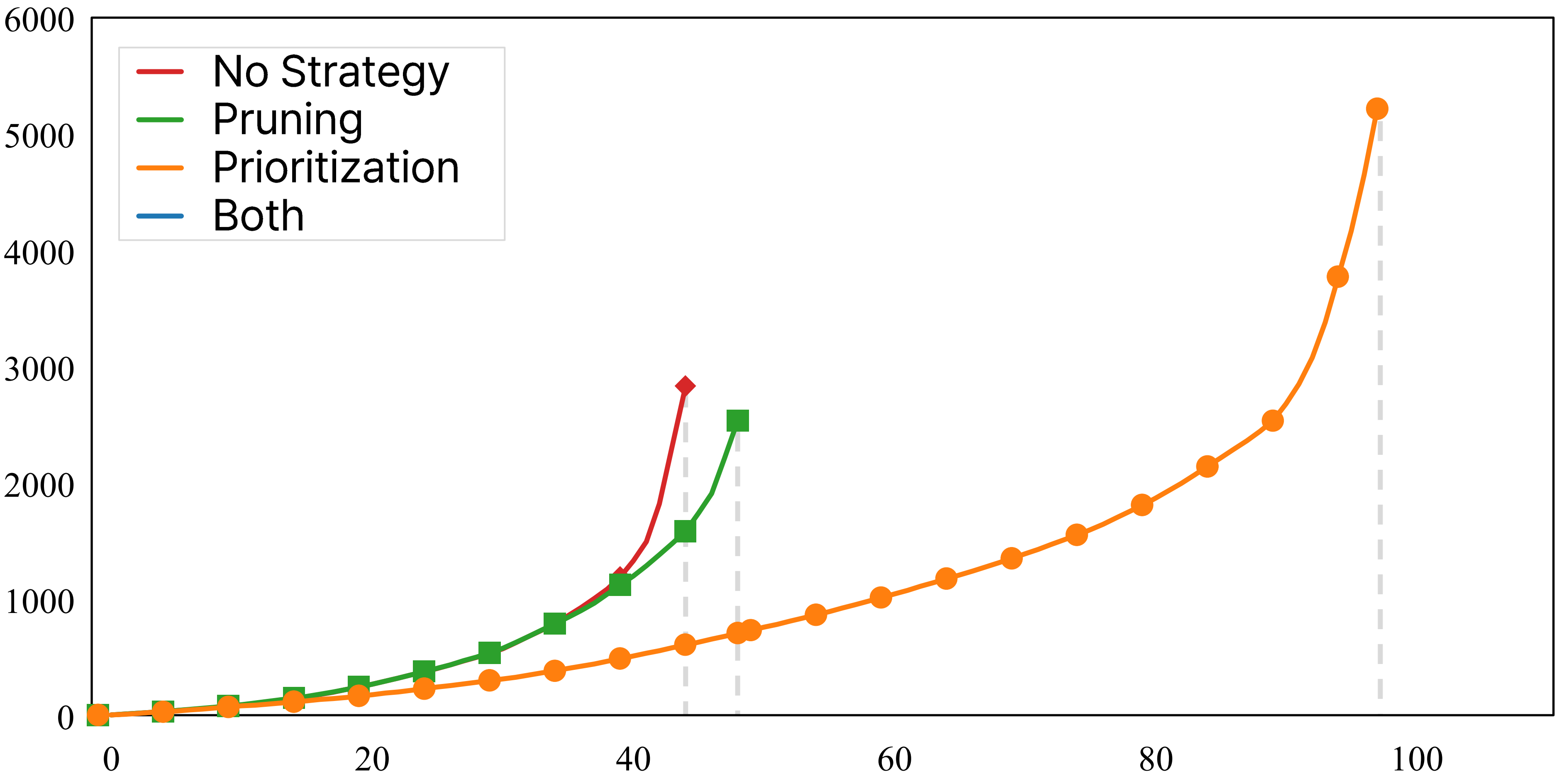
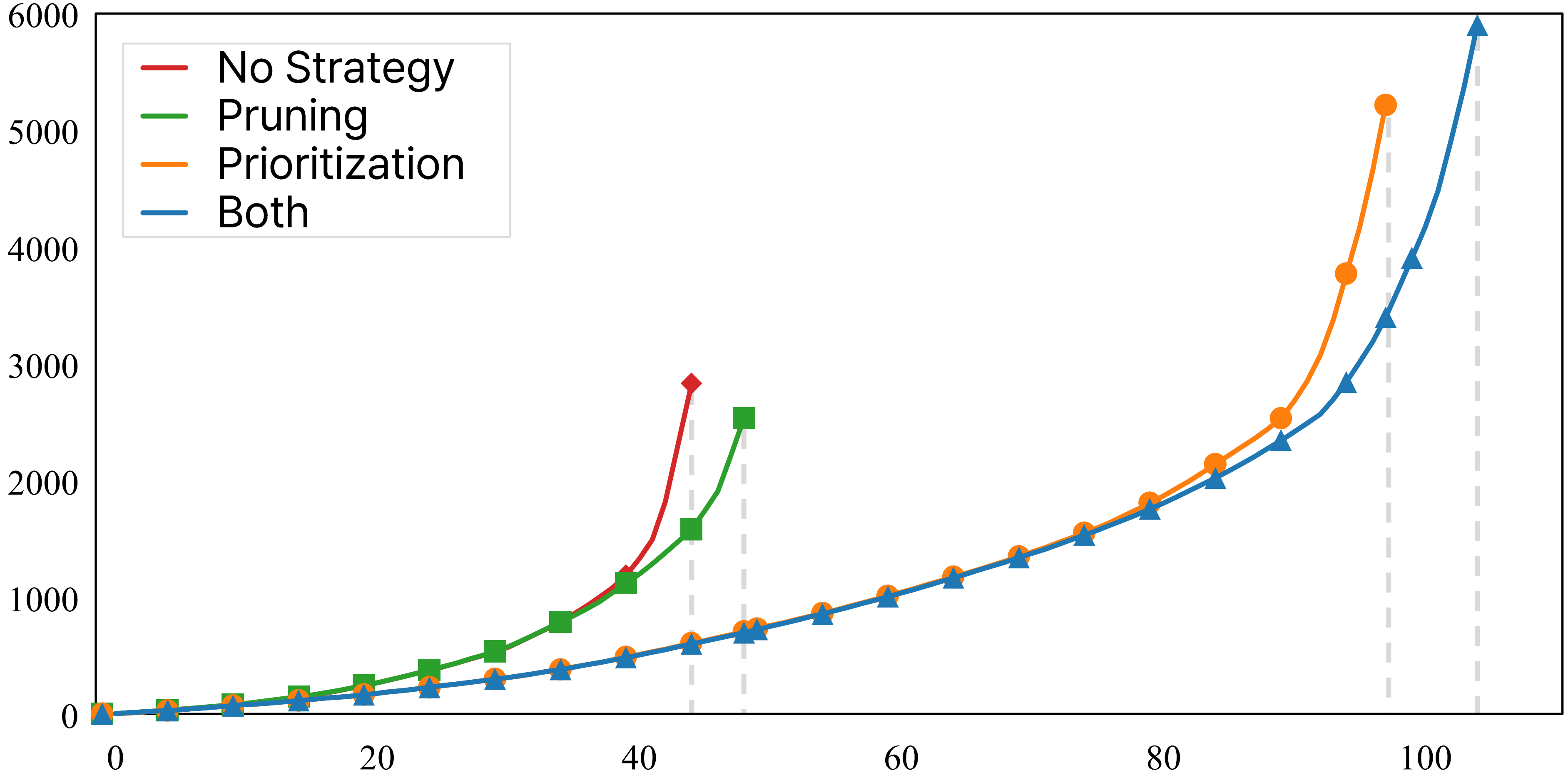
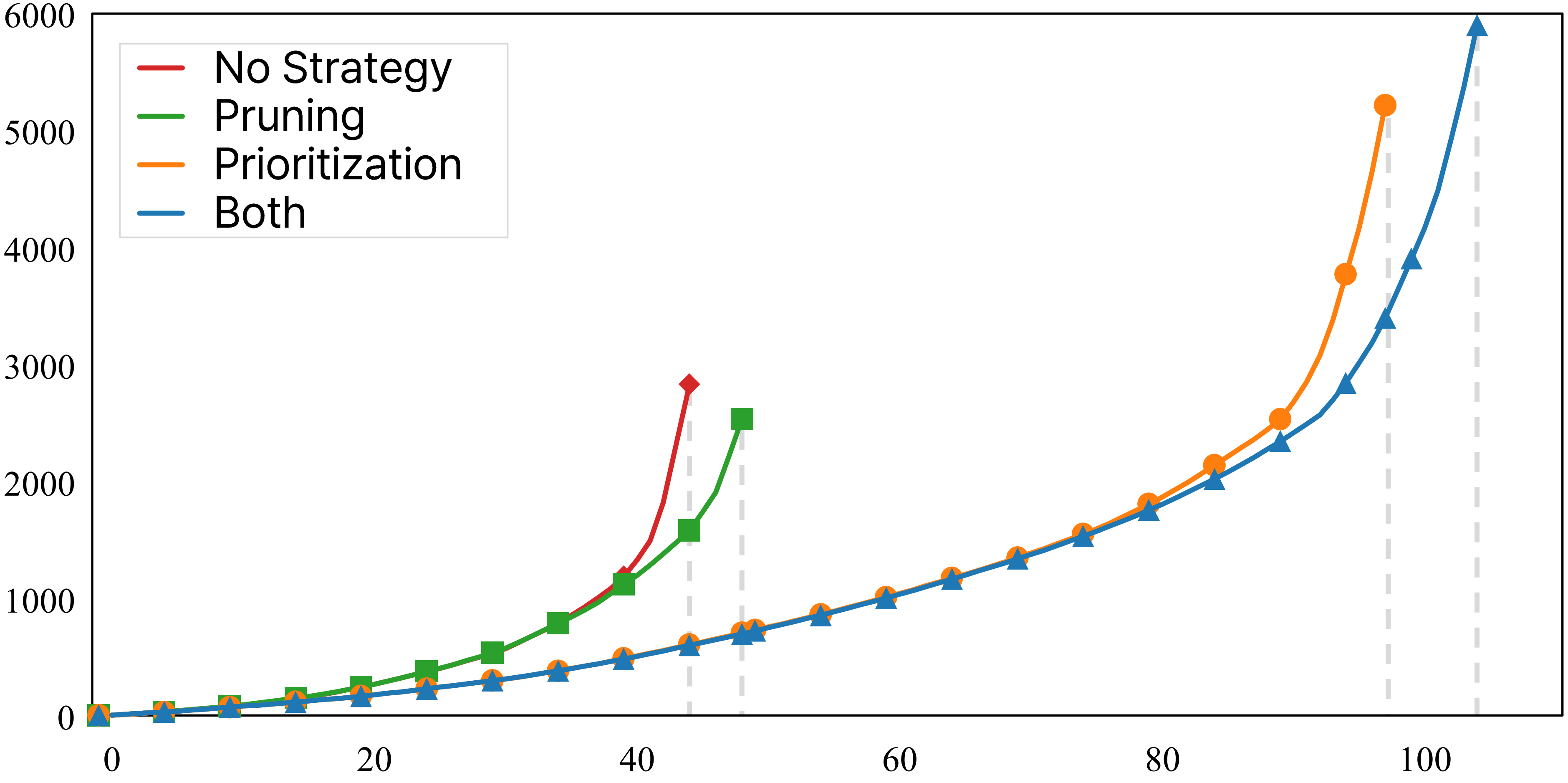


Impact of Each Strategy



Impact of Each Strategy

- **Using both strategies yields the best performance.**

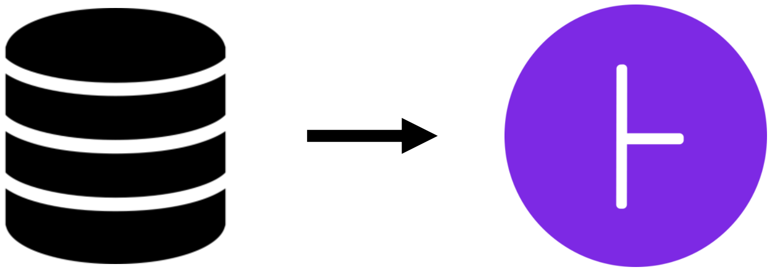


Find New Bugs

Find New Bugs

51 Java programs
(e.g., Apache, Kubernetes)

Find New Bugs



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Static Analysis
(Facebook Infer)

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4,290 NPE alarms

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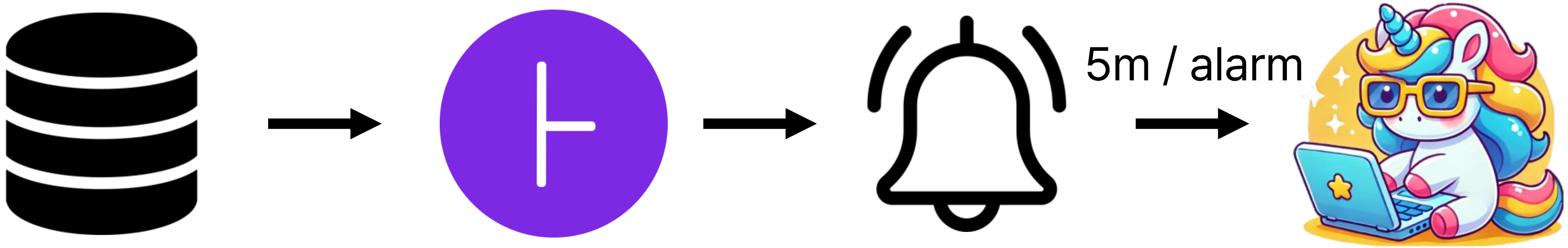

5m / alarm

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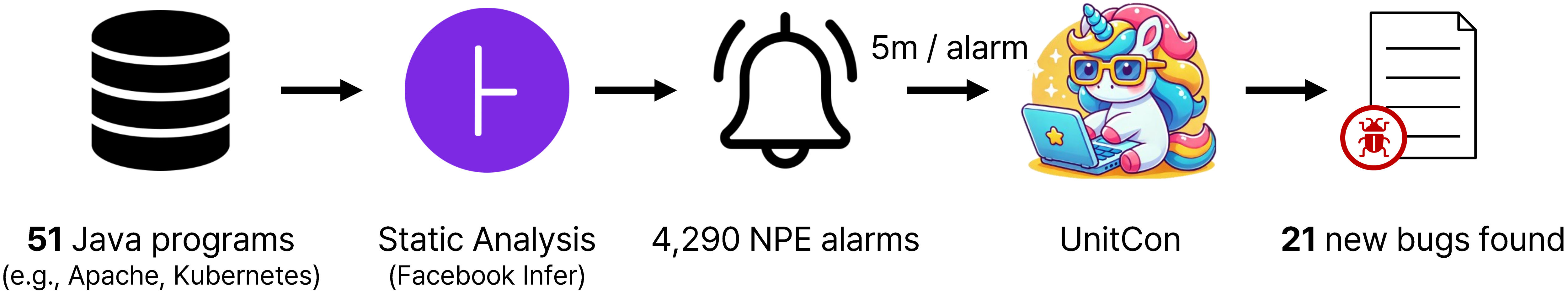
UnitCon

Find New Bugs



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UnitCon

21 new bugs found

Summary

Webpage & Artifact

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Webpage & Artifact

- **UnitCon: Synthesizing targeted unit tests for Java runtime exceptions.**

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- Key Idea: Guided Search via Abstract Semantics

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    - Discard partial test cases with identical semantics.

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Webpage & Artifact

- **UnitCon: Synthesizing targeted unit tests for Java runtime exceptions.**
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Webpage & Artifact

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- **Key Idea: Guided Search via Abstract Semantics**
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  - **Deterministically** reproduces up to **3.6 X** more target errors than baselines.

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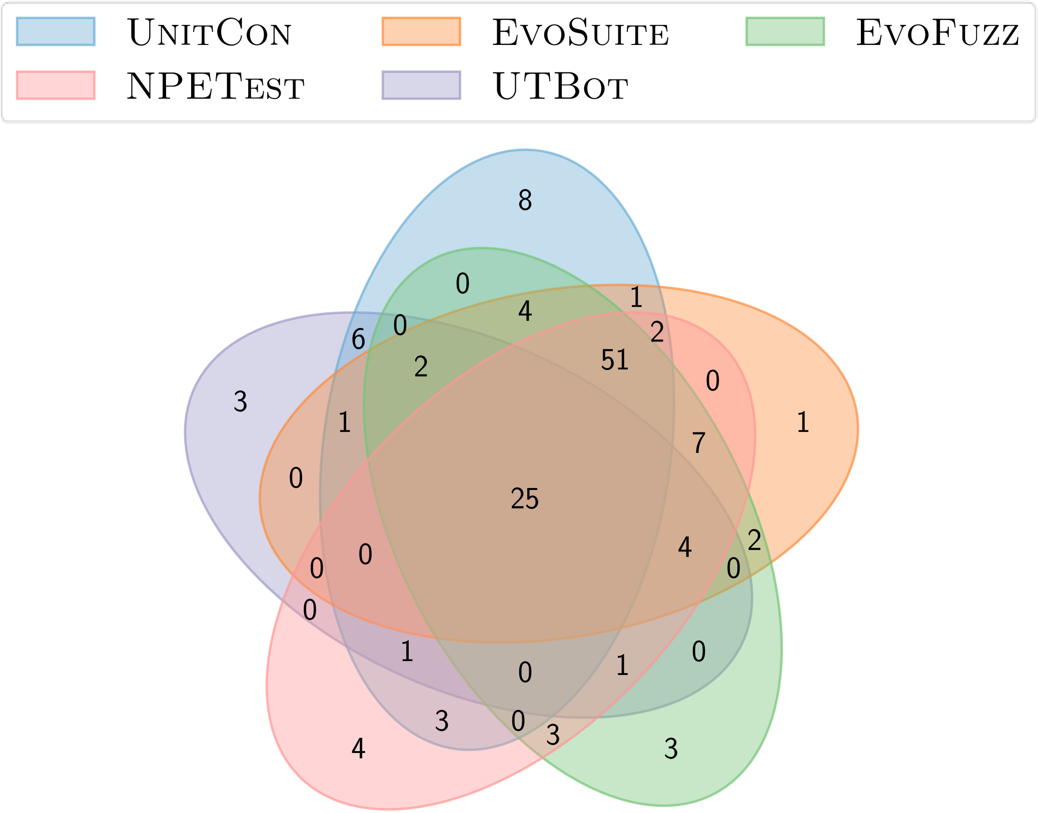
  - **Deterministically** reproduces up to **3.6 X** more target errors than baselines.
  - Found **21** new bugs.

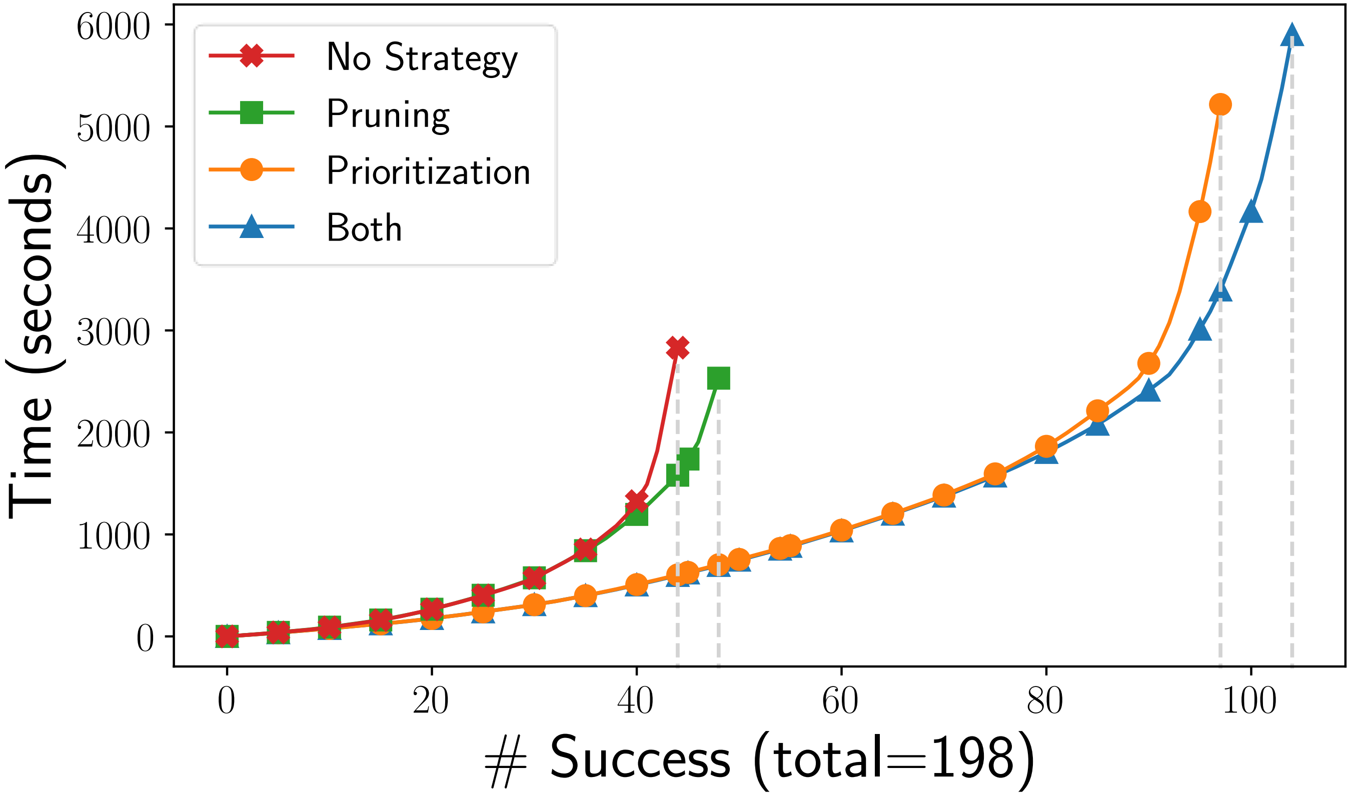
Relationship of Successful Cases Between Tools



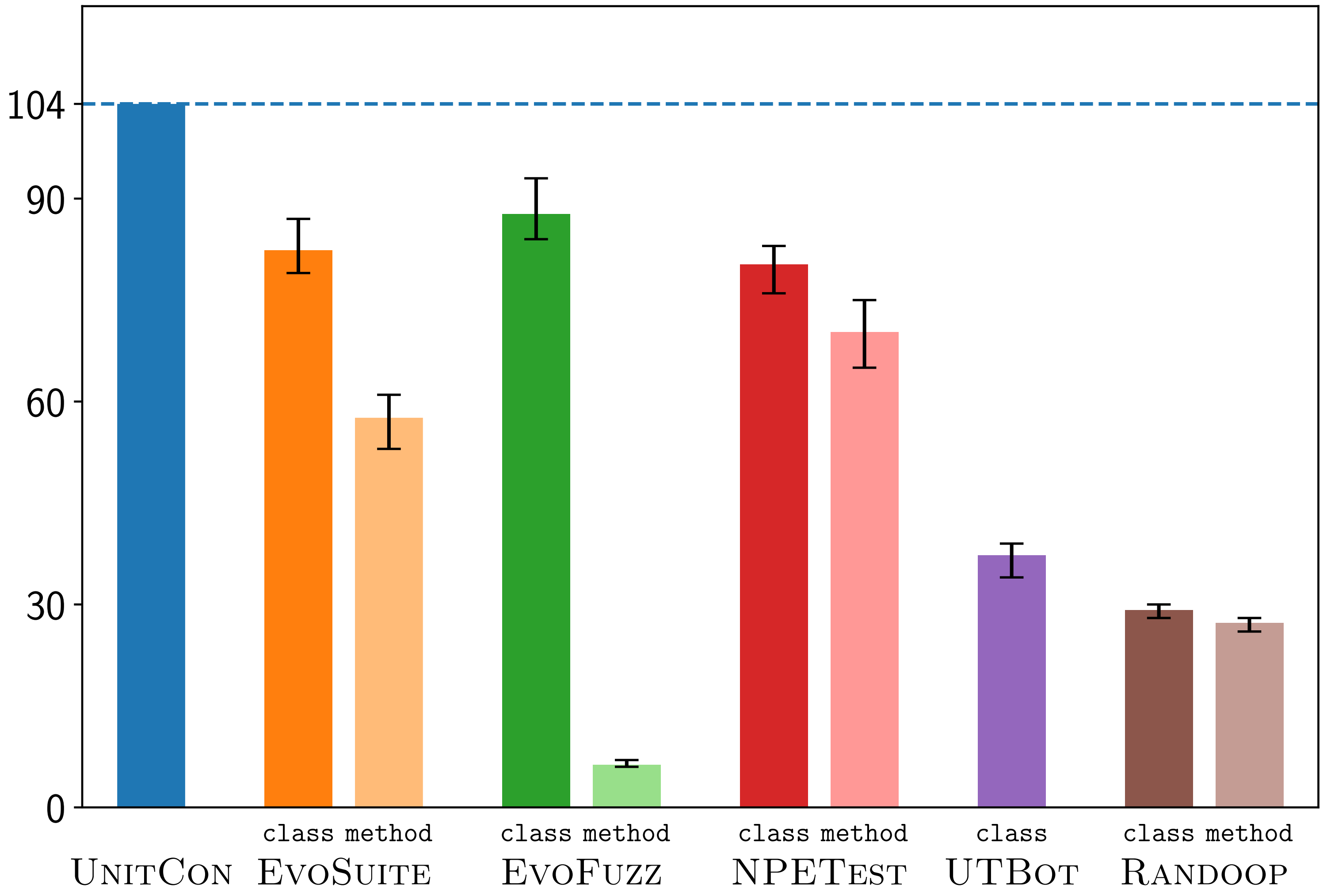
- Each tool has unique strengths.
- UnitCon uniquely reproduced the most errors.

Impact of UnitCon's Strategies

- Pruning conservatively reduces the search space.
- Make time-consuming explorations feasible.



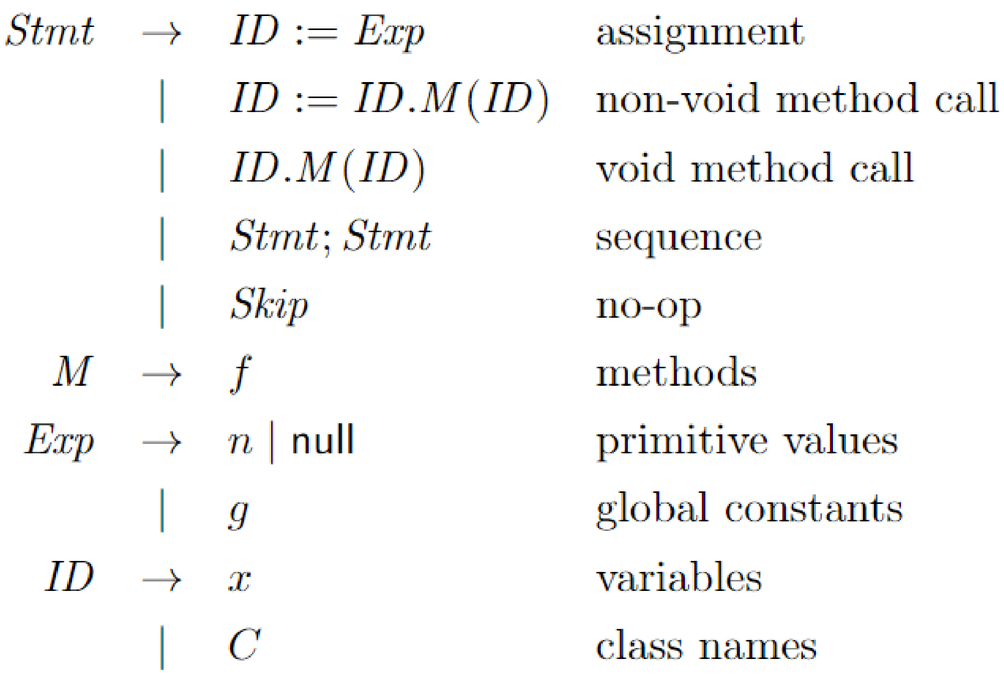
Options of baselines



Characteristics of Infer

- Under-approximate.
- Path-sensitive analyzer.
  - handle up to K (e.g., 5) distinct paths per method.
- Indirect calls are handled imprecisely.
  - e.g., overriding, abstract class

Domain-Specific Language



$$\begin{array}{rcll}
\mathit{Stmt} & \rightarrow & \mathit{ID} := \mathit{Exp} & \text{assignment} \\
 & \mid & \mathit{ID} := \mathit{ID}.M(\mathit{ID}) & \text{non-void method call} \\
 & \mid & \mathit{ID}.M(\mathit{ID}) & \text{void method call} \\
 & \mid & \mathit{Stmt}; \mathit{Stmt} & \text{sequence} \\
 & \mid & \mathit{Skip} & \text{no-op} \\
M & \rightarrow & f & \text{methods} \\
\mathit{Exp} & \rightarrow & n \mid \textsf{null} & \text{primitive values} \\
 & \mid & g & \text{global constants} \\
\mathit{ID} & \rightarrow & x & \text{variables} \\
 & \mid & C & \text{class names}
\end{array}$$

- Define a DSL to support Java at the source-code level in a simple yet powerful way.

Limitation of UnitCon

- No special limitations tied to specific types of bugs.
- However, it struggles with cases that require **strings** or **numbers** not already present in the program.
    - UnitCon’s goal: **deterministically** synthesizing the test cases.

Reliance on Static Analysis

9 NPE alarms

21 new bugs found

- Found the new bugs that the static analyzer was unable to find.
- Program analysis vs. Program synthesis