optimuzz

PLDI Seoul 2025

Optimization-Directed Compiler Fuzzing for Continuous Translation Validation

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aws

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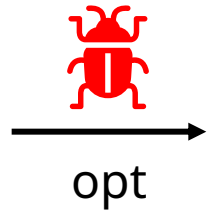
Correctness of Compiler Optimization

- A wrong compiler optimization can silently change the meaning of your code → Miscompilation
- It is crucial to guarantee the correctness of optimization

```
int src(int a, int b) {
    return (a / b) * b;
}
```

src(4, 3) = 3



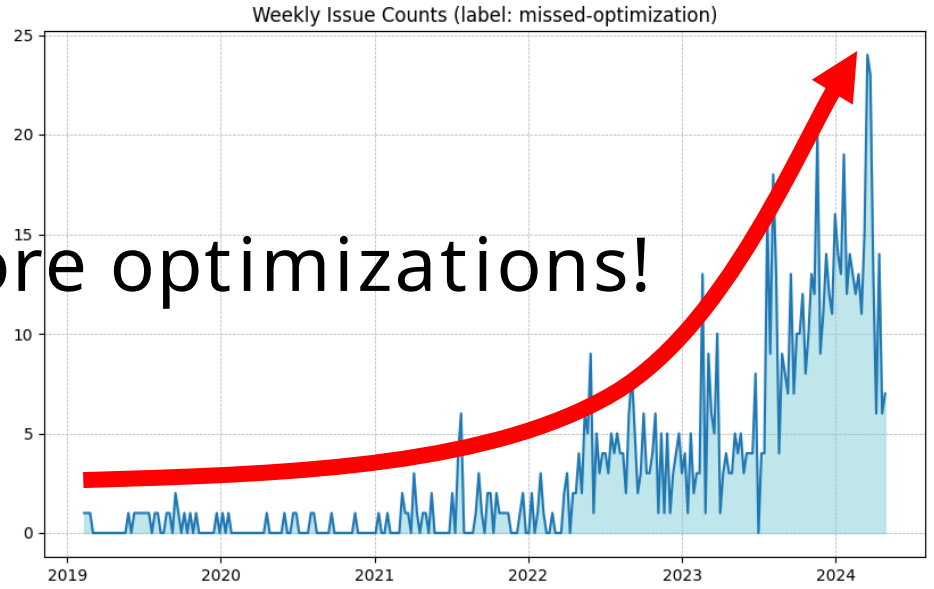

```
int tgt(int a, int b) {
    return a;
}
```

tgt(4, 3) = 4

Challenge: Complexity

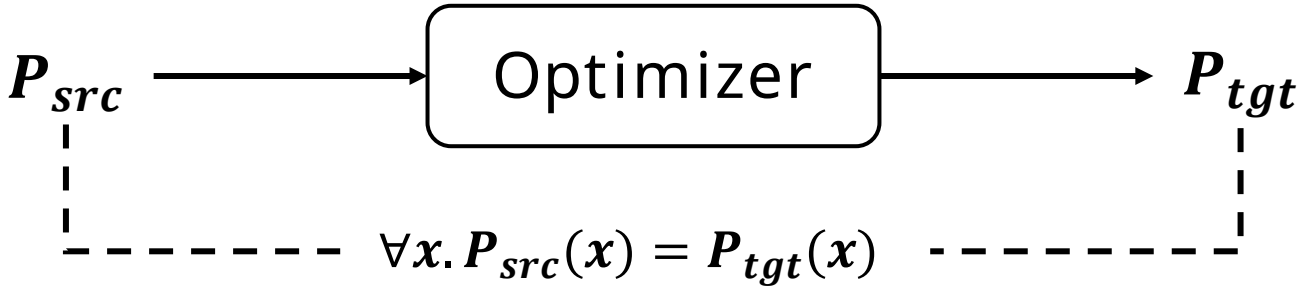
- Real-world Compiler (LLVM)
  - Massive Codebase: > 1.5M LoC
  - Constantly Evolving: > 37,000 commits in 2024

More and more optimizations!



Status Quo: Translation Validation (TV)

- TV checks if the source and target are equivalent (or refinement)
- Common Usage: LLVM optimization updates needs TV checks




```
int src(int a, int b) {
    return (a / b) * b;
}
```

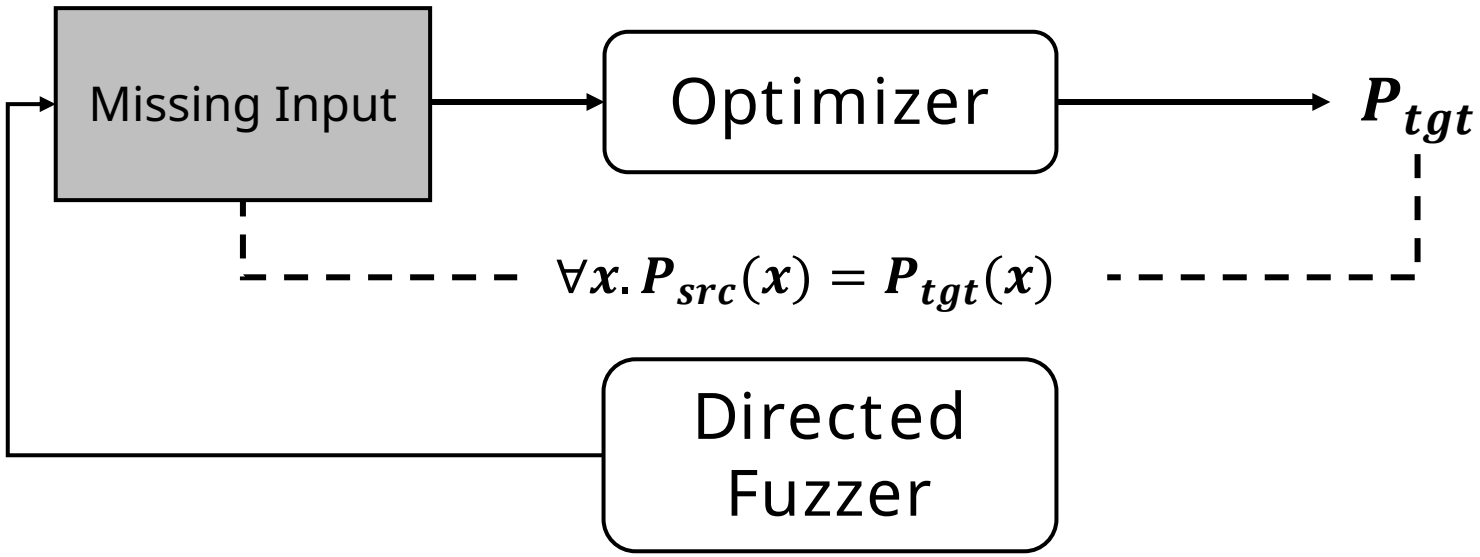
opt

```
int tgt(int a, int b) {
    return a;
}
```

TV: src(4,3) ≠ tgt(4,3)

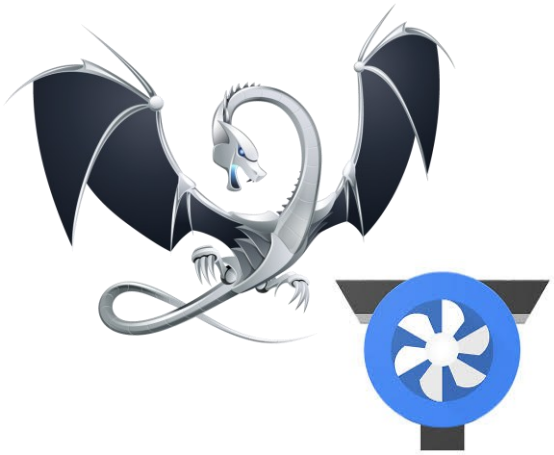
Limitation of TV & Our Solution

- TV needs input programs to detect miscompilation bugs.



Let’s automatically generate input programs!

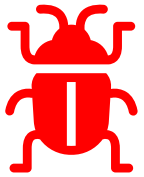
Contributions



First Directed
Compiler Fuzzers
for LLVM and TurboFan

27 vs. 0

27 miscompilation bugs
SOTA compiler fuzzers reproduced 0

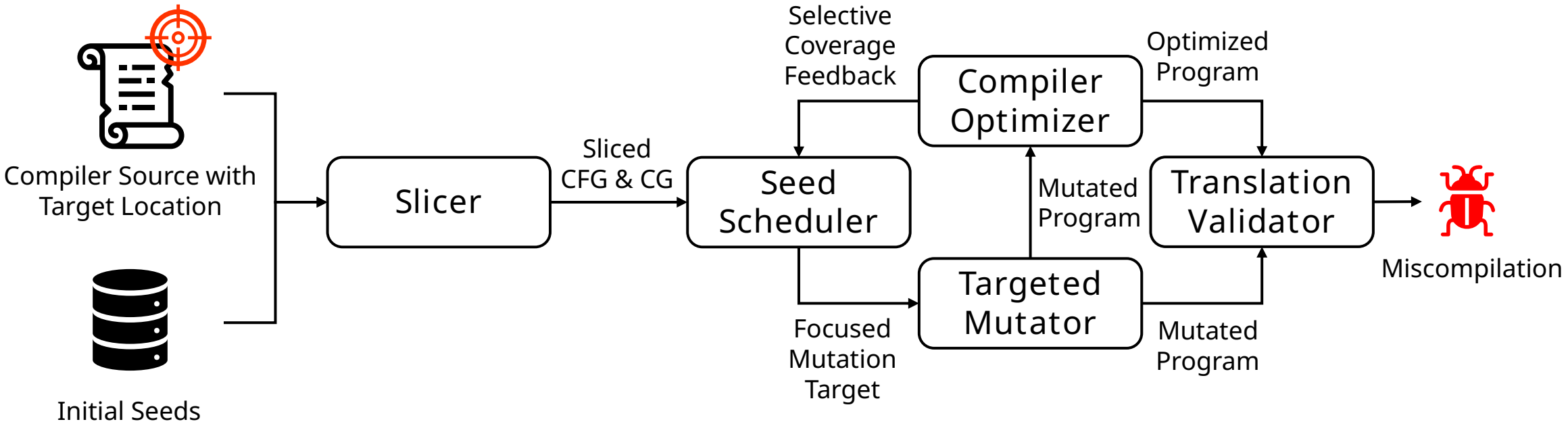


56

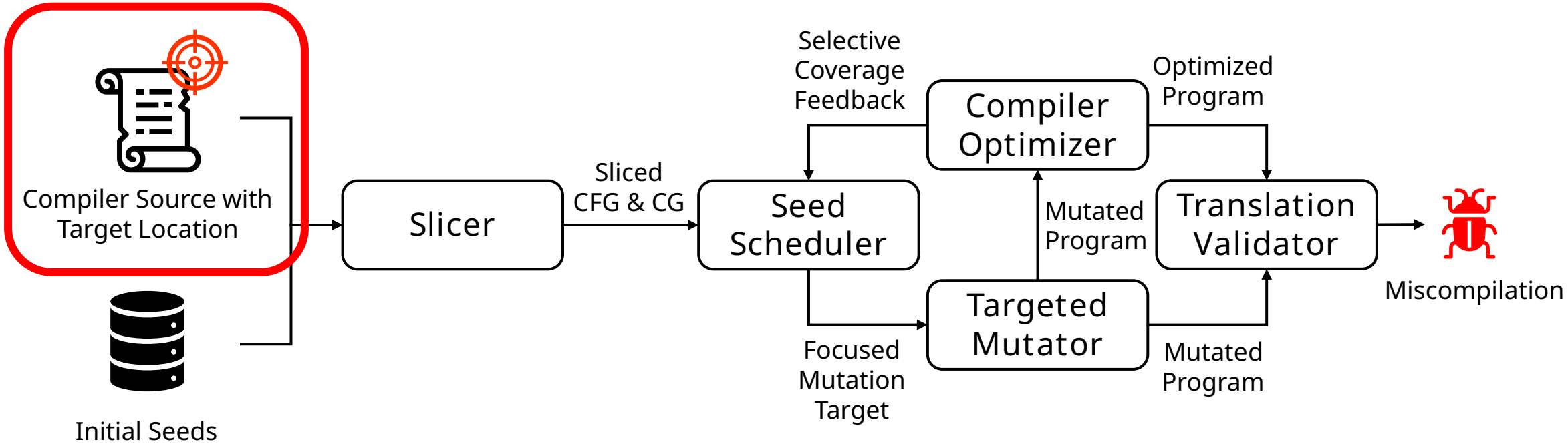
22

56 LLVM bugs reported
22 patched

System Overview



Step 1: Targeting an Optimization



Target Identification

- Optimization: Checks condition + Returns optimized code
- Target Line: Where optimization is triggered and returned

2116921 [InstCombine] Fold select of srem and conditional add

```
+ if (!(match(TrueVal, m_Add(m_Value(RemRes), m_Value(Remainder))) &&
+       match(RemRes, m_SRem(m_Value(Op), m_Specific(Remainder))) &&
+       IC.isKnownToBeAPowerOfTwo(Remainder, /*OrZero*/ true) &&
+       FalseVal == RemRes))
+   return nullptr;
+
+ Value *Add = Builder.CreateAdd(Remainder,
+                                Constant::getAllOnesValue(RemRes->getType()));
+ return BinaryOperator::CreateAnd(Op, Add);
```

Checks Optimization Condition

Target: Returns Optimized Code

Automatic Target Line Collection

- Optimization has a simple pattern
  - Simple String Search: lines of "`return NewInstruction()`"
  - LLM: teach the pattern and analyze the source code

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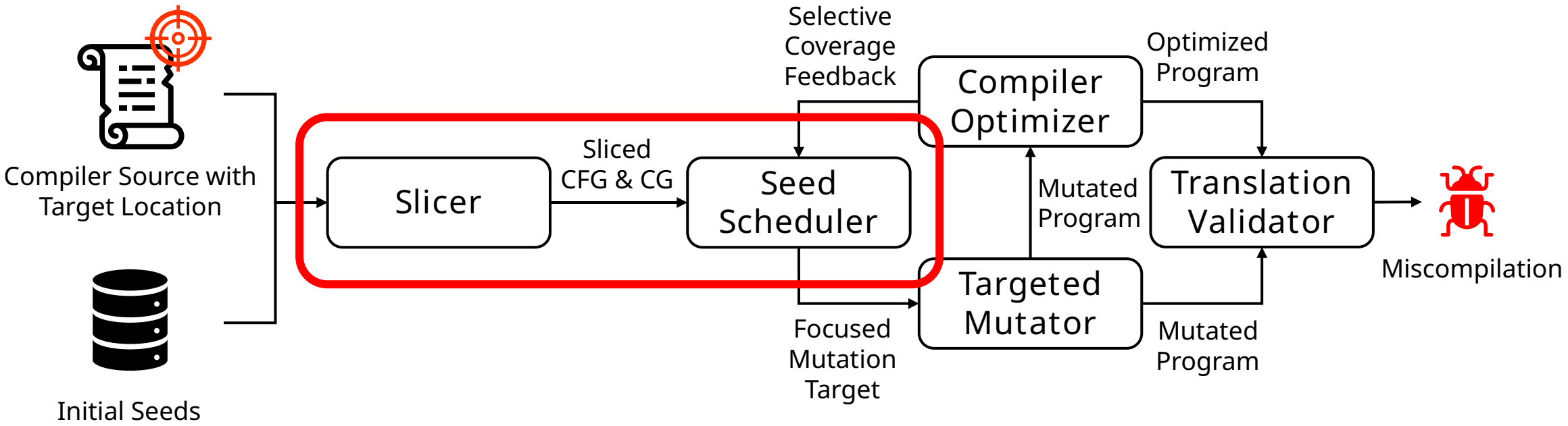
Checks Optimization Condition

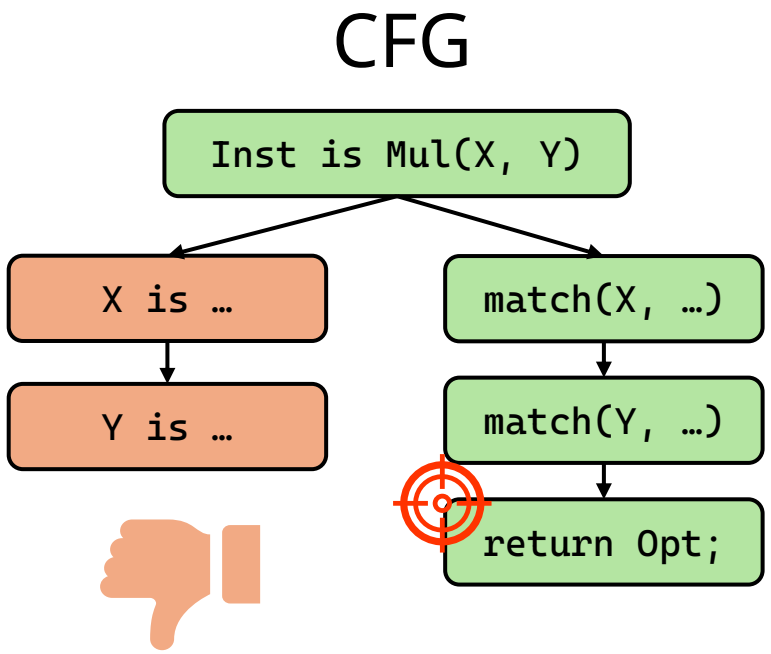
Target: Returns Optimized Code

Step 2: Guided Search Strategy



Slicer: Selective Coverage Feedback

- Coverage feedback guides the fuzzer
- Only relevant program locations → Efficiency



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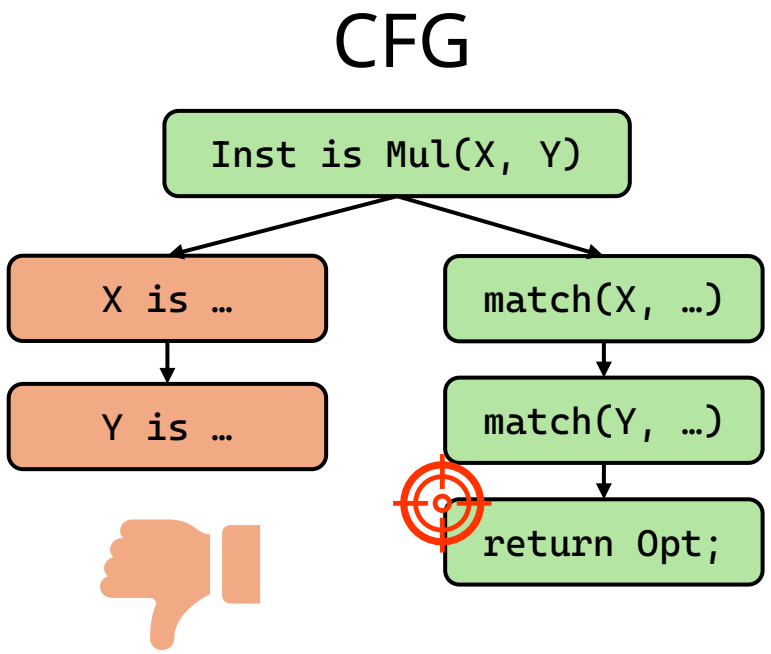
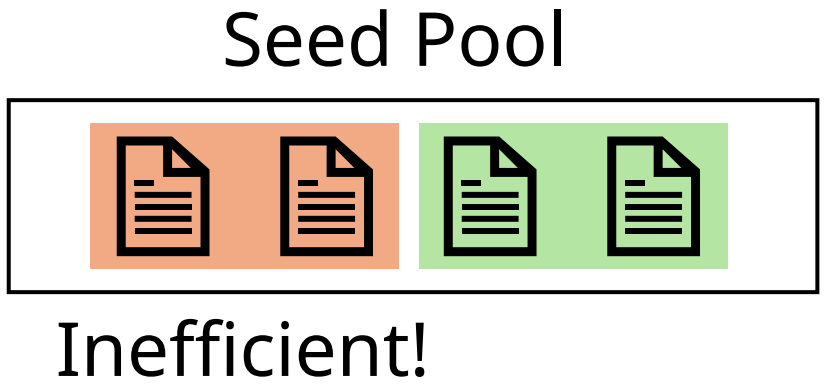
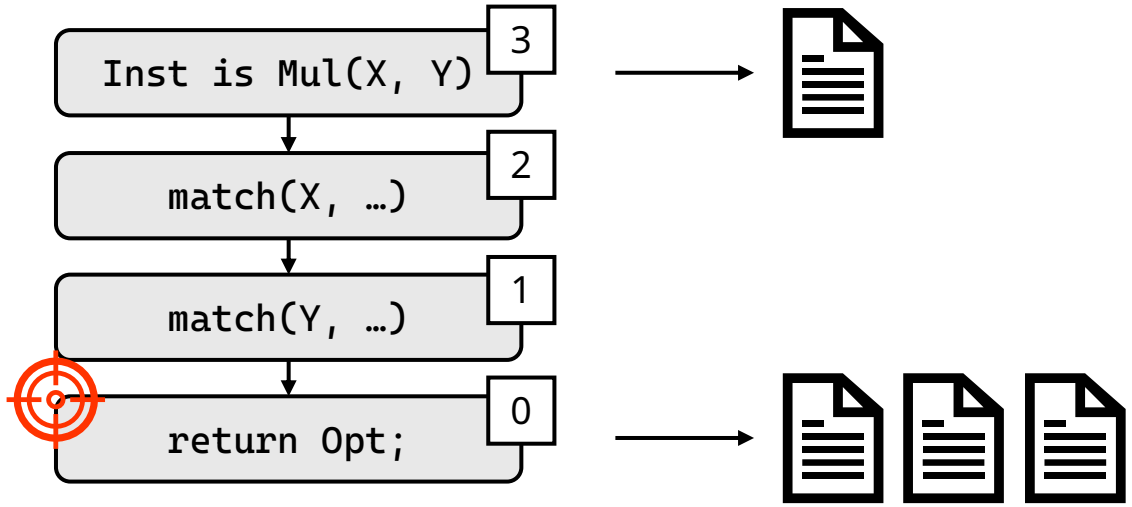


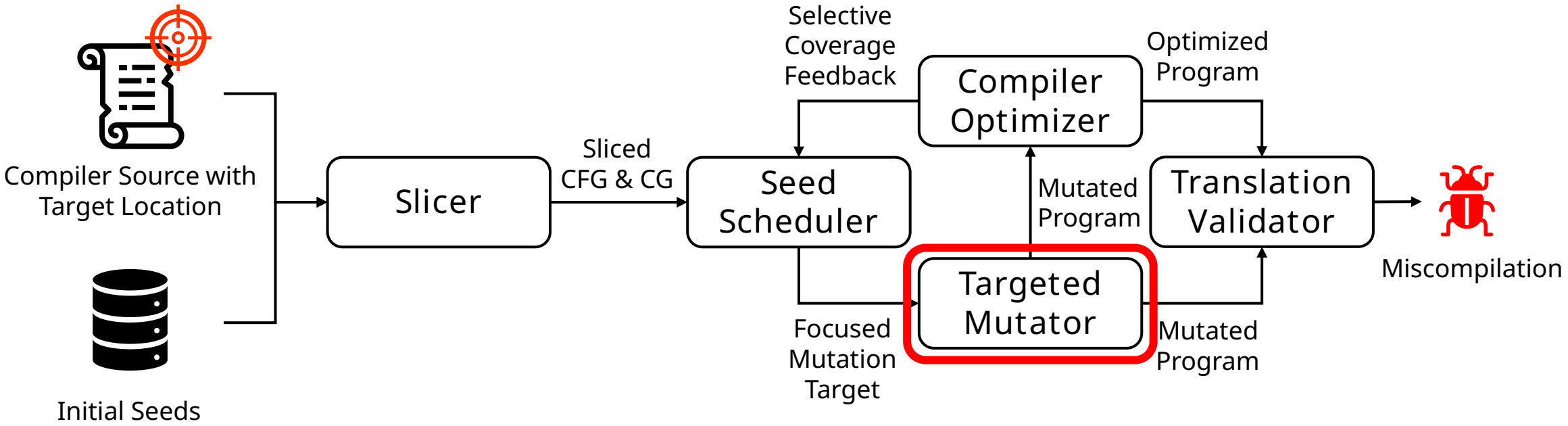


Seed Scheduler: Distance Metric

- Assign “distance-to-target” values to nodes in the sliced CFG
- Closer seed → Generate more mutated programs!

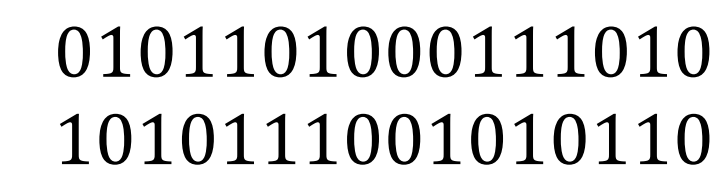


Step 3: Targeted Mutation Strategy



Program as an Input

- Conventional Fuzzing: Bitstream Input
  - Hard to analyze the structure of an input
- Compiler Fuzzing: Program Input
  - Input has useful structures such as CFG, DUG, …



Conventional Fuzzing

```
define i8 @f(i8 %x, i8 %c) {
  %2 = shl 1, %c
  %3 = mul %x, %2
  ret i8 %3
}
```

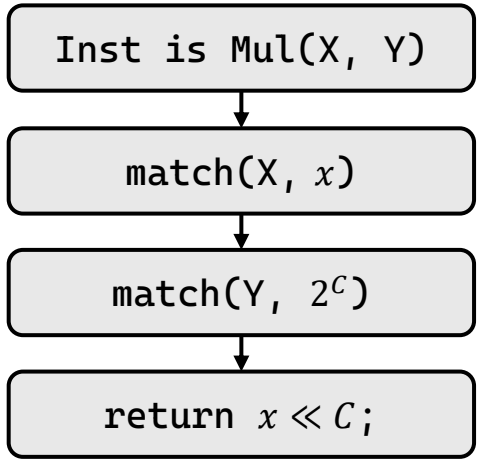
Compiler Fuzzing

Def-Use in Optimization Rules

- Optimization typically checks def-use relation of a program.

$$x \times 2^C \Rightarrow x \ll C$$

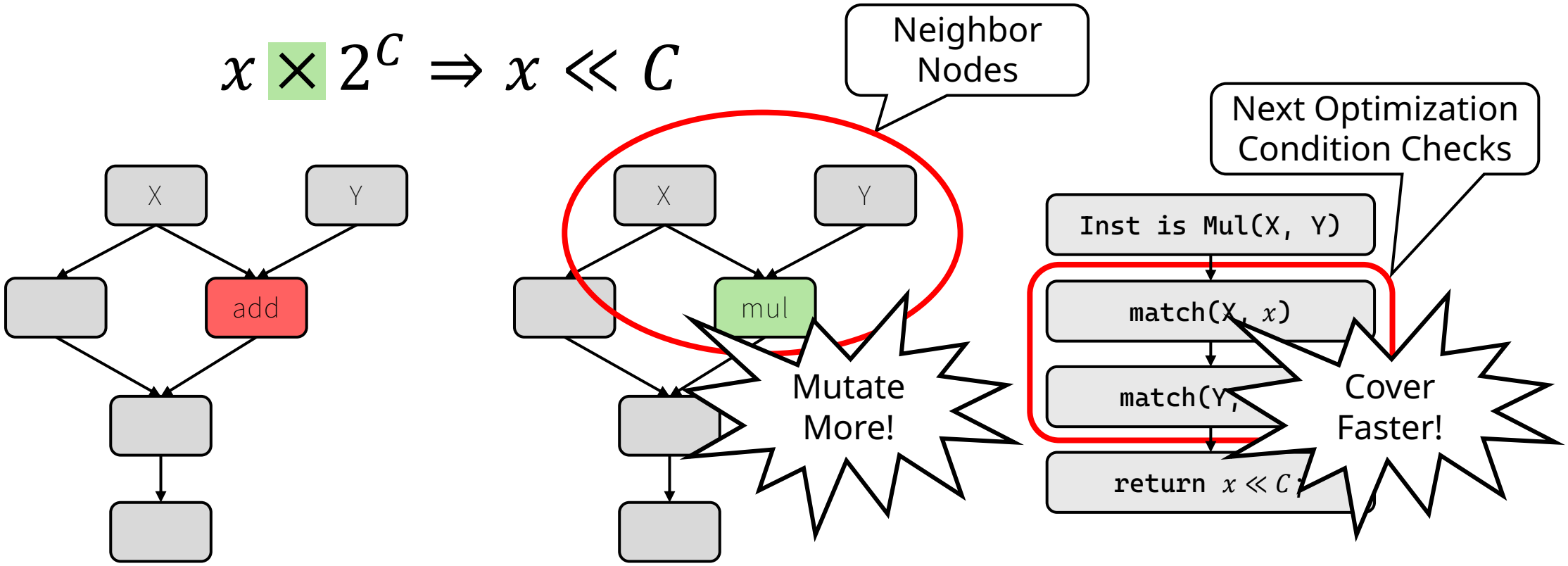
Optimization Rule



CFG

Finding Next Mutation Targets

$$x \times 2^C \Rightarrow x \ll C$$



Input Program

Mutated Program

CFG

Effectiveness Evaluation

- Optimuzz Framework: Fuzzer + Translation Validator (TV)

Compiler	LLVM
Fuzzer	Our Own
TV	Alive2 (PLDI ’17)

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Benchmark	24 Known Bugs
Baselines	FLUX (ASE’ 23) Alive-Mutate (CGO, 24)

Effectiveness Evaluation

- Optimuzz Framework: Fuzzer + Translation Validator (TV)

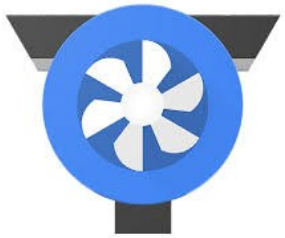
Compiler	LLVM	TurboFan
Fuzzer	Our Own	Fuzzilli + Our Strategies
TV	Alive2 (PLDI ’17)	TurboTV (ICSE ’24)
Benchmark	24 Known Bugs	6 Known Bugs
Baselines	FLUX (ASE’ 23) Alive-Mutate (CGO, 24)	Fuzzilli (As Is)

Effectivess of Optimuzz

- Optimuzz performs significantly better than SOTA fuzzers.

23 vs. 0

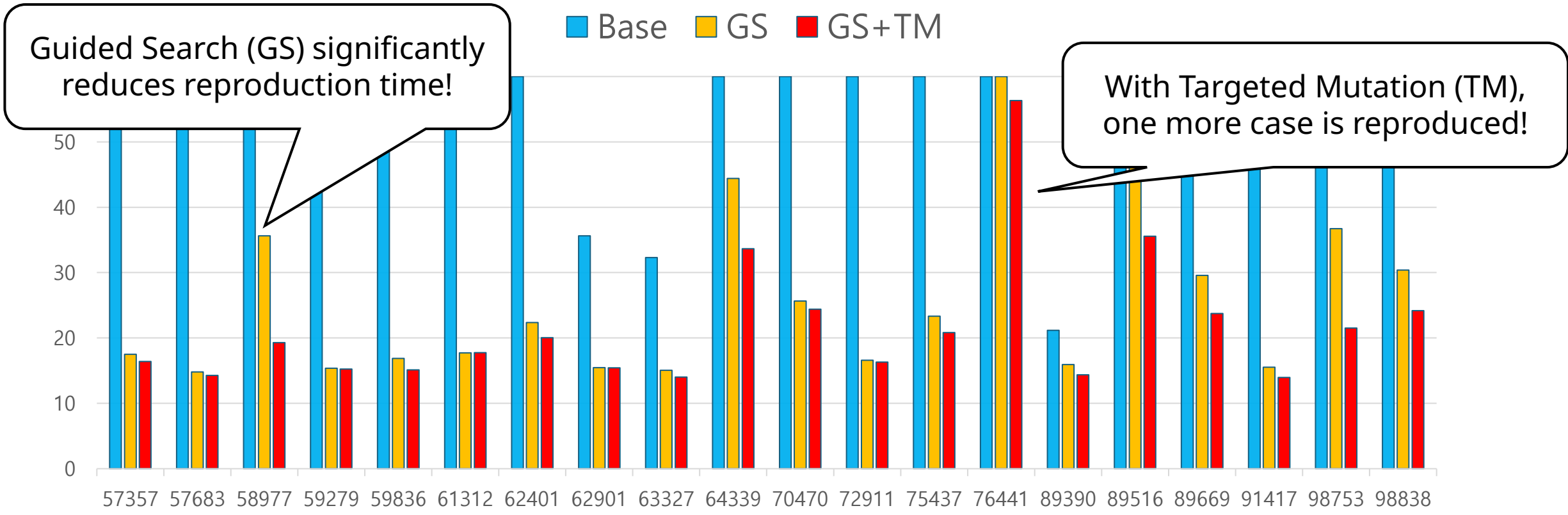
⌛ ~ 1 Hour



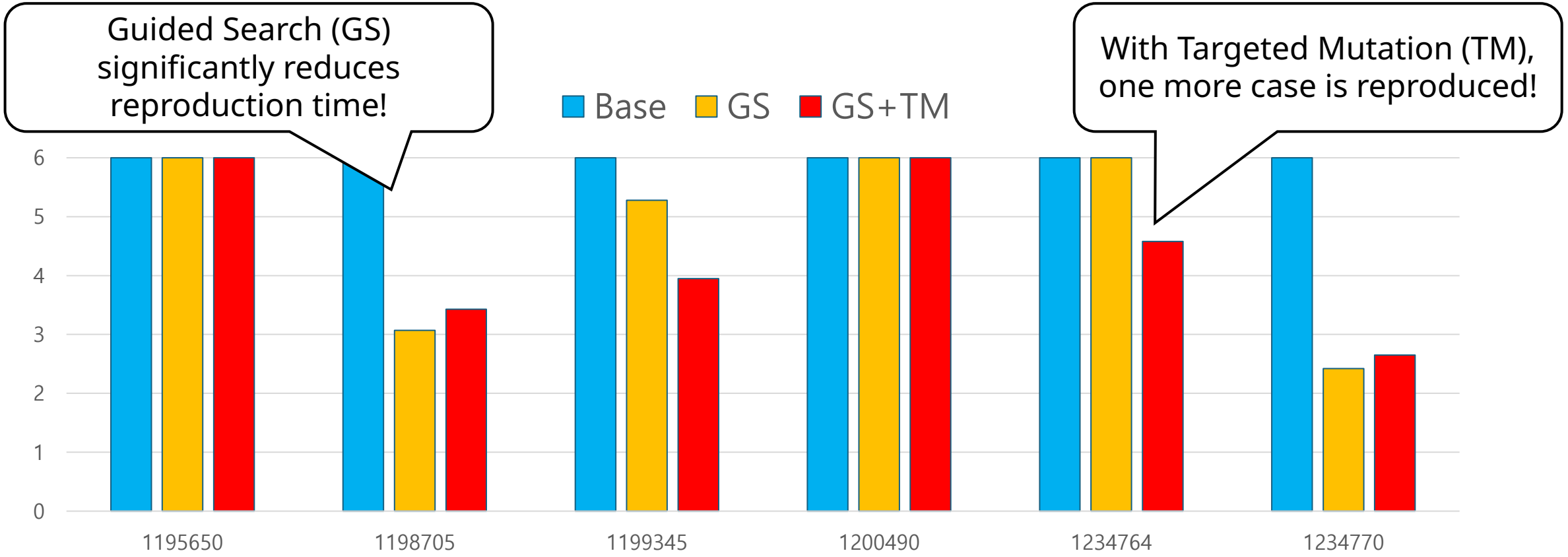
4 vs. 0

⌛ ~ 6 Hour

Each Strategy's Impact on LLVM



Each Strategy's Impact on TurboFan



LLVM Bug Finding

- Optimuzz is effective to find unknown miscompilations
- Continuous Mode: for targets in each LLVM update
- Batch Mode: for all targets in the latest version of LLVM

LLVM Bug Finding: Continuous Mode

- 8 bugs from LLVM GitHub commits

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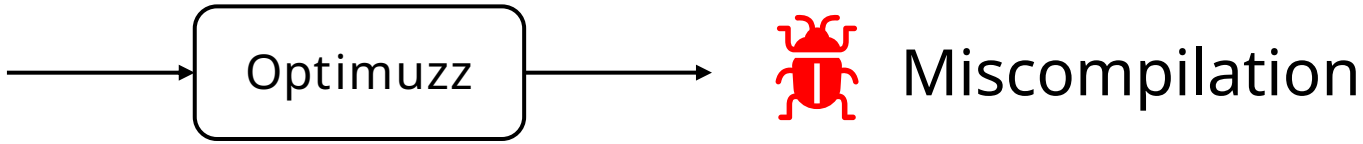
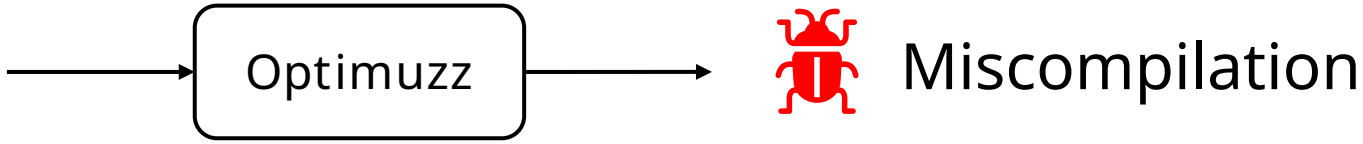


Miscompilation

e710a5 [InstCombine] Fold fneg/fabs patterns

```
+ if ( ... )
+   return Opt;
```

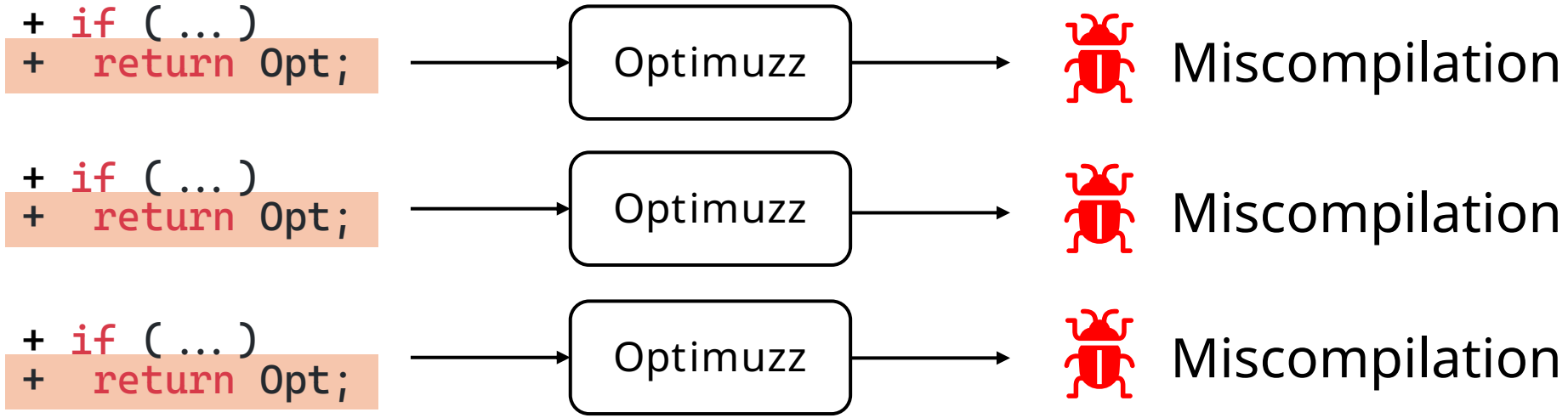


Miscompilation

LLVM Bug Finding: Batch Mode

- 48 bugs from the latest version of LLVM codebase

llvm/lib/Transforms/InstCombine/InstCombineSelect.cpp



Summary

- First Directed Compiler Fuzzing for Continuous TV
- The Guided Search Strategy
  - Selective Coverage Feedback
  - Distance Metric
- The Targeted Mutation Strategy
  - Effectively Finding Next Mutation Targets
- Real World Impacts
  - 56 bugs reported to LLVM, 22 patched

Visit Our Website!

Appendix

Other than InstCombine

- Optimuzz works for optimizations other than InstCombine
- It leverages the condition check and return structure. The structure is observed generally in compiler source codes.

Mode	Optimization Pass					
	InstCombine	InstSimplify	Correlated Propagation	SLP Vectorization	GVN	Vector Combine
Cont	4	0	3	0	0	1
Batch	39	2	0	4	2	1
Total	56					

Target-Hit Ratio (LLVM, %)