YARPGen: A Compiler Fuzzer for Loop Optimizations and Data-Parallel Languages

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Summary of Found Bugs

120 completely new errors in total

40% are wrong code bugs

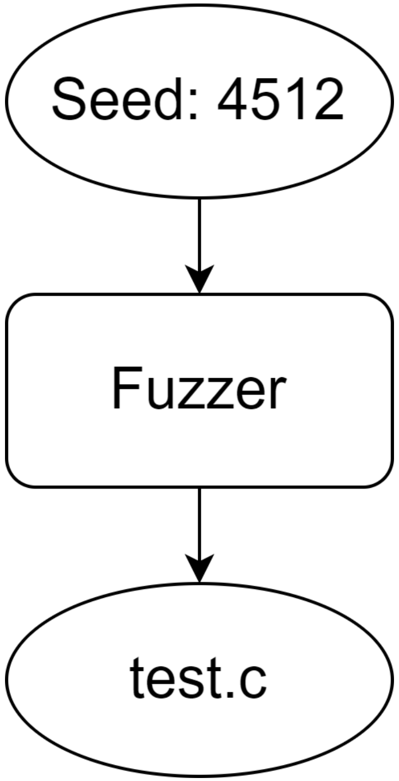
- 27 bugs in LLVM
- 61 bugs in GCC
- 12 bugs in ISPC
- 16 bugs in the DPC++
- 2 bugs in SDE
- 2 bugs in Alive2

YARPGen Features

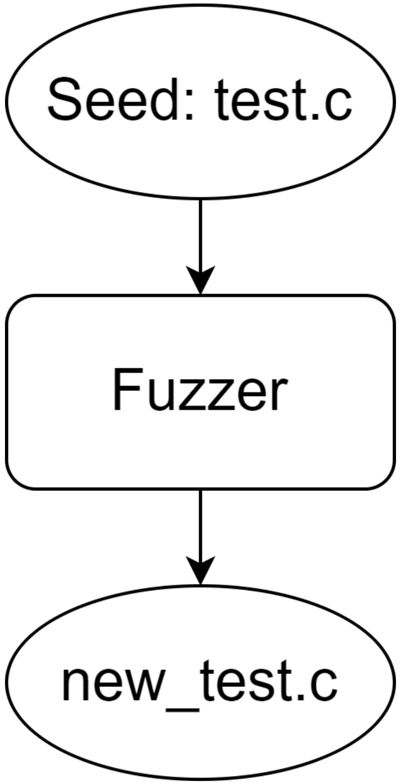
- Detect wrong code bugs
  - Avoid Undefined Behavior statically
- Target optimizations explicitly
- Easily extensible for C-family languages
  - Including compilers for emerging languages
- Easy to use

Fuzzing Approaches

Generative



Mutation-based



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Undefined Behavior (UB)

```
# include <stdio.h>

int main () {
    int x = 1;
    x = x++ + ++x;
    printf ("%d\n", x);
    return 0;
}
```

Who is wrong?

```
>$ icc test.cpp && ./a.out
5
>$ clang++ test.cpp && ./a.out
4
```

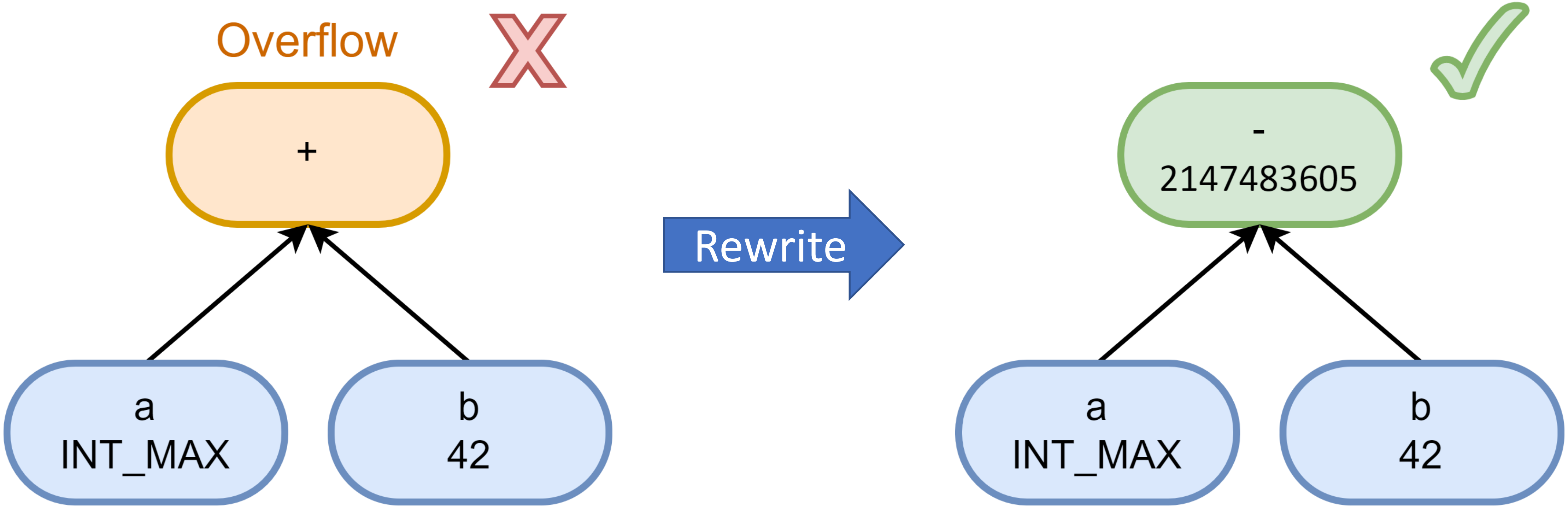
No one!

Program contains UB

https://godbolt.org/z/dfETYae9T

Static Undefined Behavior Avoidance

Based on concrete value tracking and rewrite rules



"Random testing for C and C++ compilers with YARPGen.“ contains more details

UB Avoidance for Loops

```
var_37 = 20;
var_43 = 99;
…
var_10 = (var_37 / 15) - var_43;
```

```
arr_37[20] = {20, 20, 20, ...};
var_43 = 99;
…
arr_10[0] = (arr_37[0] / 15) - var_43;
```

driver.cpp

```
arr_37[20] = {20, 20, 20, ...};
var_43 = 99;
```

…

test.cpp

```
for (int i = 0; i < 19; ++i) {
  arr_10[i] = (arr_37[i] / 15) - var_43;
}
```

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Generation Policies

- IR elements
  - Loop Nest, Loop Sequence, Stencil, Reduction
- Explicit mechanisms
  - Common Subexpression Buffer, Used Constant Buffer
- Skewed Probability
  - Vectorizable Loops, INT_MAX / INT_MIN

The goal is to generate code that is likely to trigger optimization

Loop Fusion and Loop Sequence

```
for (i=0; i < (d ? e : 10); i++)
      a[i] = c[i] + b[i];

for (j=0; j < (d ? e : 10); j++)
    b[j] = b[j] * c[j];
```

```
for (i=0; i < (d ? e : 10); i++){
    a[i] = c[i] + b[i];
    b[i] = b[i] * c[i];
}
```

- Hard to generate purely at random
- Loop Sequence as first-class IR element for synchronized decisions

Loop Patterns: Stencil

```
for (int i = 1; i < n - 1; ++i)
    out[i] = (in[i - 1] +
              in[i] +
              in[i + 1]) / 3;
```

```
.LBB0_2:
    fadd    d1, d0, d1
    fmov    d2, d0
    ldr     d0, [x9], #8
    fmov    d3, x10
    subs    x8, x8, #1
    fadd    d1, d1, d0
    fmul    d3, d1, d3
    fmov    d1, d2
    str     d3, [x1], #8
    b.ne    .LBB0_2
```

GVN propagates value to next loop iteration

Stencil as a pattern

- arrays
- dimensions
- stride

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Multi-language Support and IR Lowering

Matrix multiplication

$$c_{ij} = \sum_{k=1}^{K} a_{ik} b_{kj}\,; i = 1, \ldots, M\,; j = 1, \ldots, N$$

Multi-language Support and IR Lowering

C++

```
for (int i = 0; i < M; i++)
  for (int j = 0; j < K; j++)
    for (int k = 0; k < N; k++)
      c[i][j] += a[i][k] * b[k][j];
```

ISPC

```
foreach (m = 0 ... M) {
  for (k = 0; k < K; k++) {
    sum = 0.0f;
      for (n = 0; n < N; n++) {
        aValue = a[m*N + n];
        bValue = b[n*K + k];
        sum +=  aValue * bValue;
      }
      c[m*K + k] = sum;
  }
}
```

Multi-language Support and IR Lowering

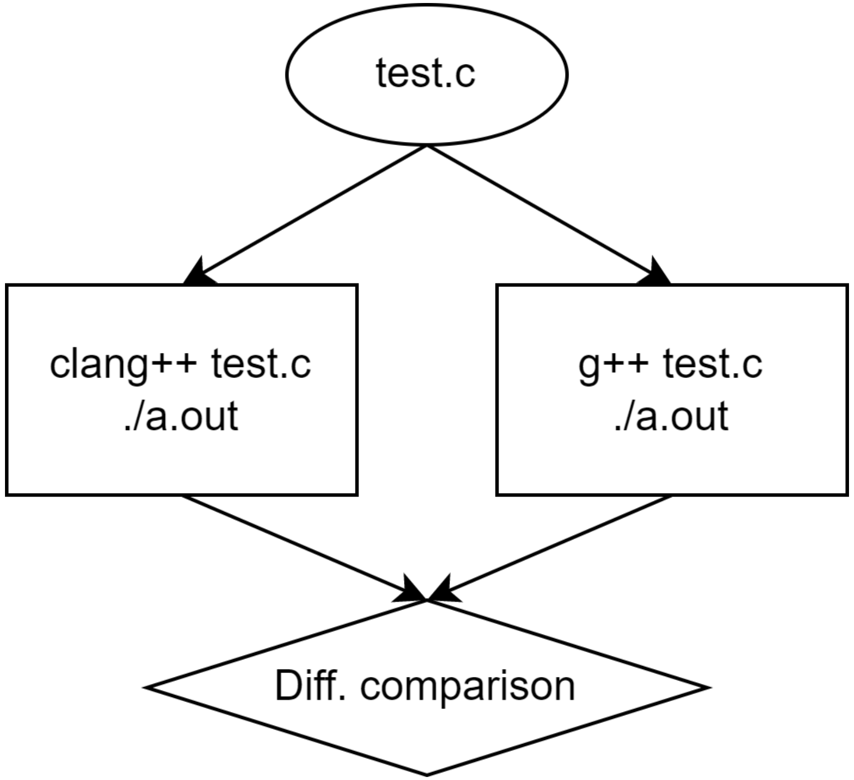
```
Loop #1: i in [0, 10), step 2
  If-then (d):
    a[i] = b[i] ^ d
  Else:
    a[i] = b[i] & d
Loop #2: j in [0, 10), step 2
  c[i] = b[j] + 134
```

```
for (int i = 0; i < 10; i += 2){
  if (d)
    a[i] = b[i] ^ d;
  else
    a[i] = b[i] & d;
}
for (int j = 0; j < 10; j += 2)
  c[i] = b[j] + 134;
```

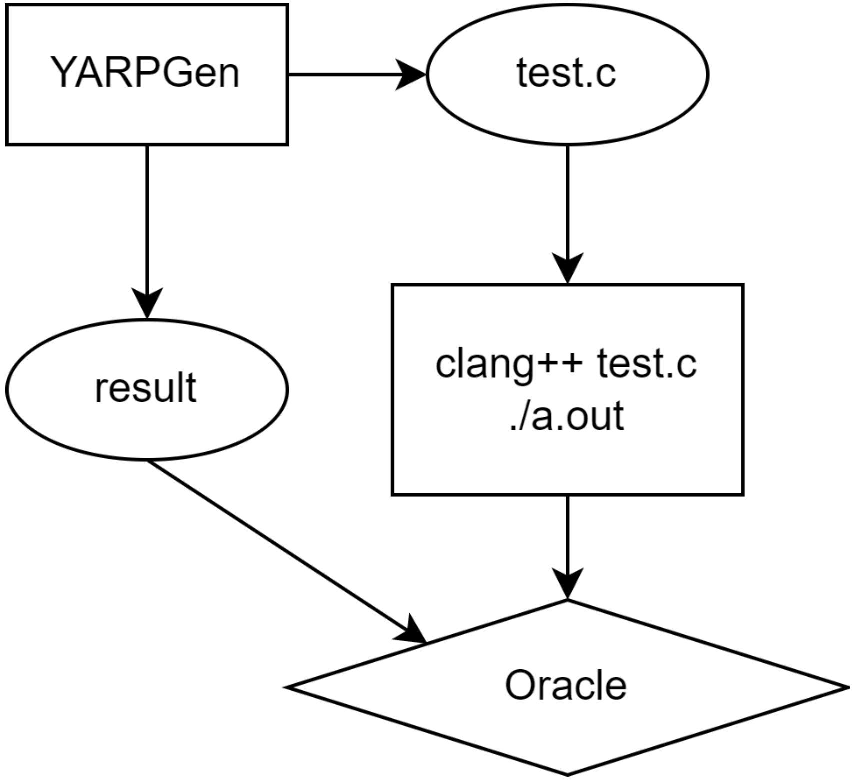
- C-family languages has similar UB rules
- High-level IR is (mostly) independent from target languages
  - contains common information

Test Oracles

Differential testing



Ground truth



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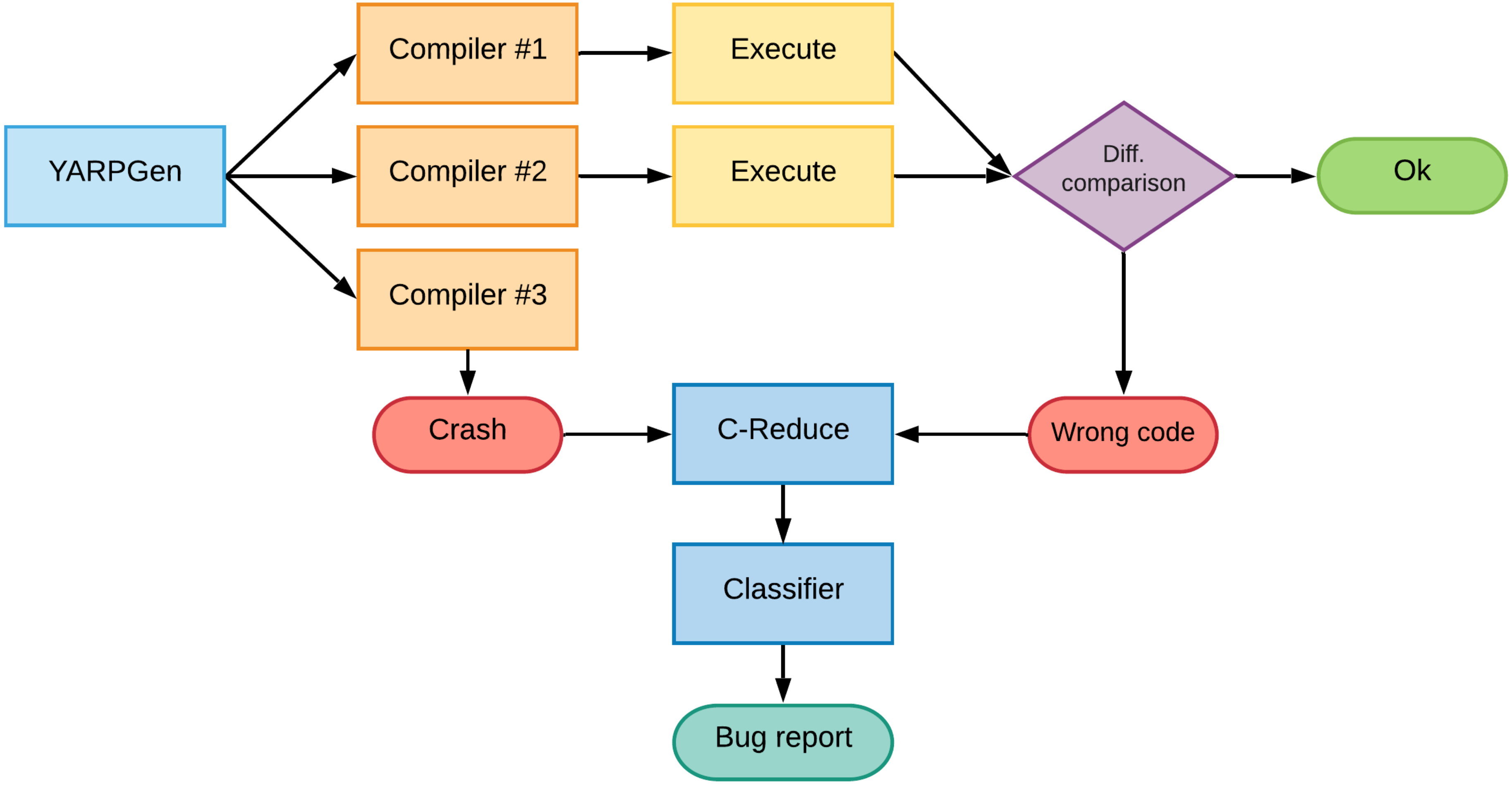
Automated Testing System

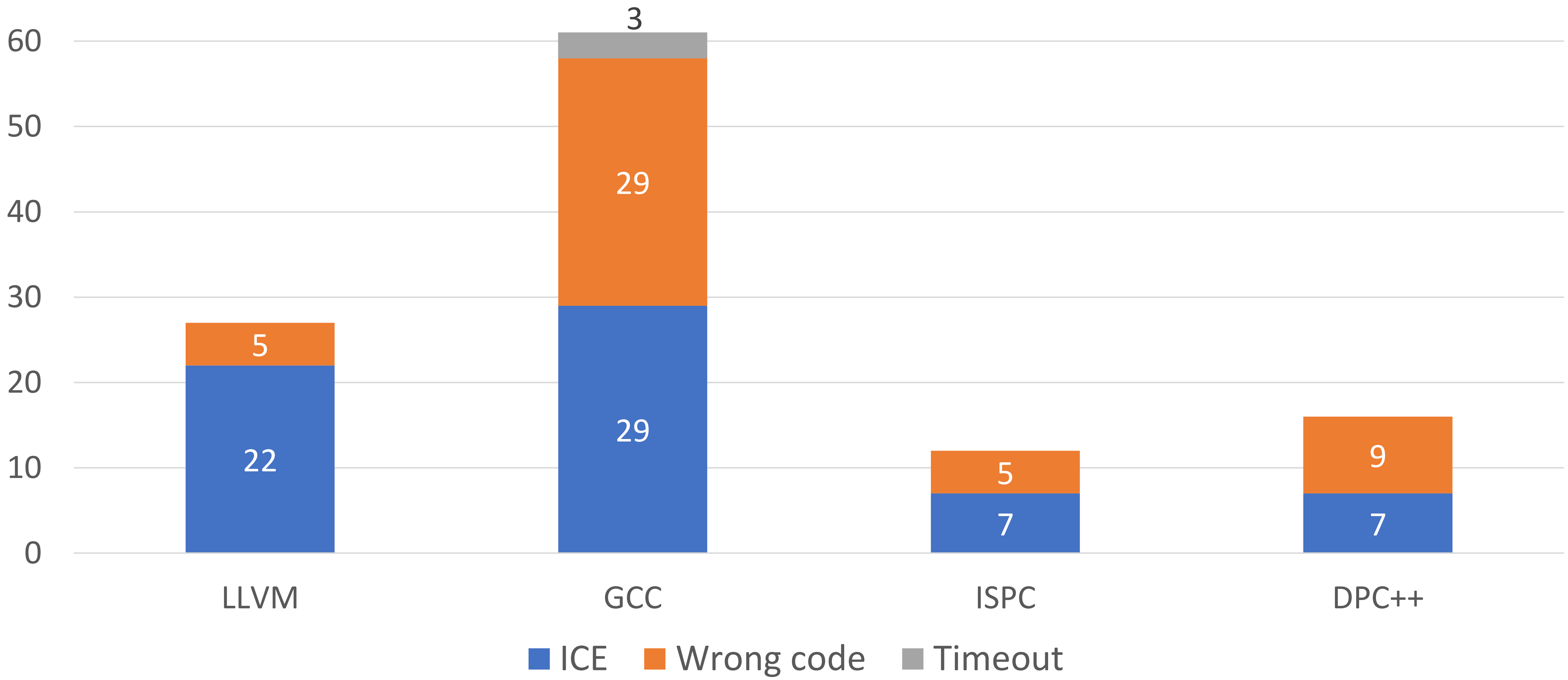


Limitations

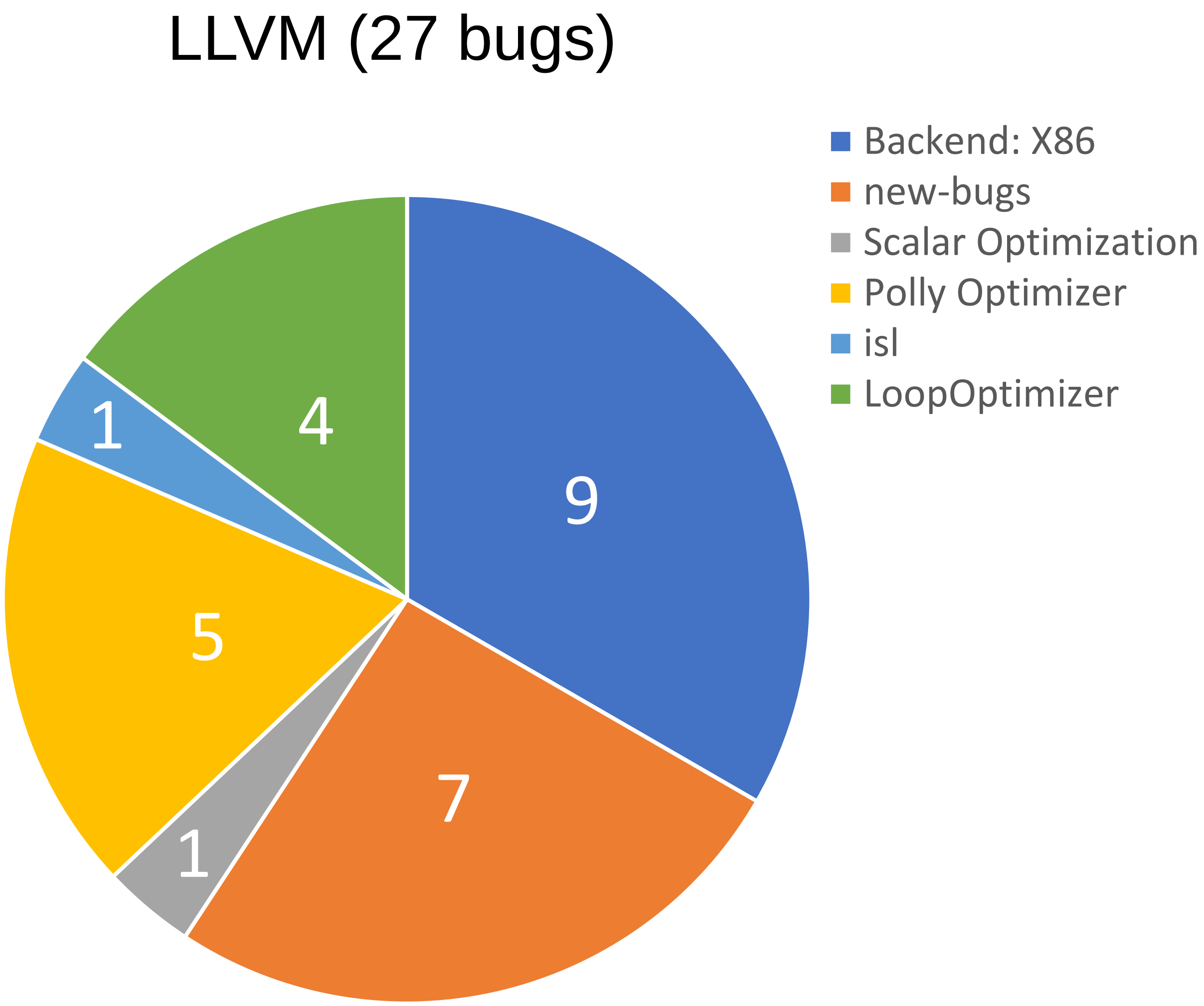
- No floating-point support
- Only stdlib function calls
- Lack of dynamic memory allocation
- …

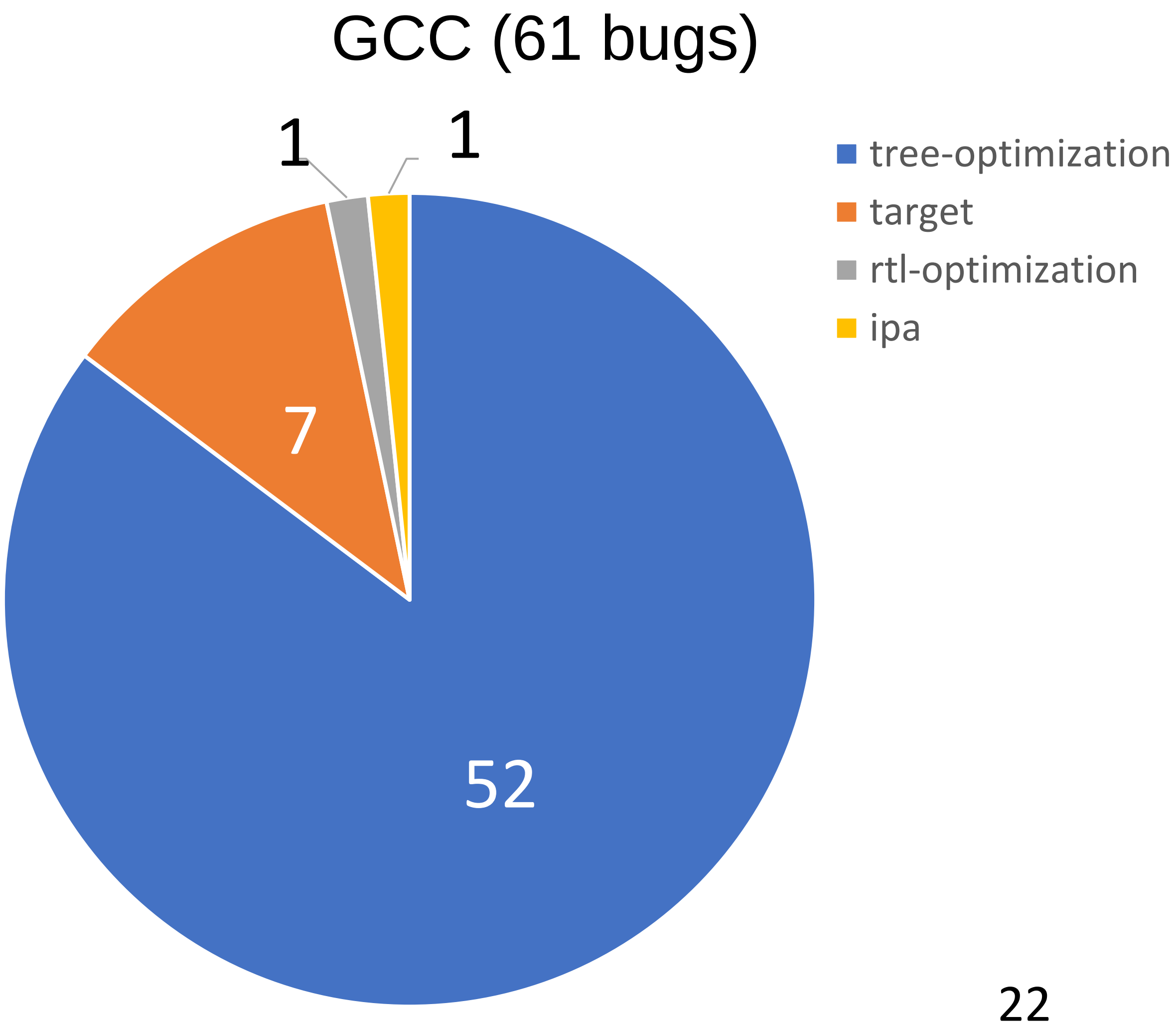
Some are research question; others require more engineering resources

Bugs Distribution by Kind



Bugs Distribution by Components





Fixed Bugs

- LLVM
    - 70% fixed
        - 18 fixed, 7 new, 1 resolved, 1 confirmed

- GCC
    - 95% fixed
        - 58 fixed, 3 assigned

Test Example

```
/* LoopNest 2 */
for (short i_2 = ((((int) ((short) var_6))) - (181))/*0*/; i_2 < ((((int)
((short) ((((bool) (signed char)4)) && (((bool) ((((((bool) var_2)) ||
(((bool) 3431126726U)))) ? (((unsigned int) ((int) std::max((((unsigned
short) (signed char)-39)), ((unsigned short)63238))))) : (((((bool) arr_2
[i_0] [i_0])) ? (((unsigned int) ((int) (unsigned short)2297))) :
(var_1)))))))))) + (13))/*14*/; i_2 += ((((int) ((short) var_9))) +
(20186))/*3*/) {
  #pragma clang loop vectorize(enable)
  for (long long int i_3 = 0LL/*0*/; i_3 < ((((long long int) var_7)) -
(3048972888LL))/*18*/; i_3 += 2LL/*2*/) {
      arr_15[i_3] = ((int) ((((((unsigned long long int) ((3243476438U) <<
(((int) arr_5 [i_0 / 5]))))) & (((((bool) var_2)) ? (var_8) : (((unsigned
long long int) ((int) arr_12 [i_0] [i_1] [i_2] [i_1] [i_1] [i_1]))))))) <<
(((((int) arr_10 [i_0] [i_1 + 1] [i_2])) << (((int) arr_5 [i_2 / 14]))))));
      arr_16[i_2][i_1] = ((unsigned short) ((unsigned char) ((((int)
arr_10 [i_3] [i_1] [i_2])) & (((int) arr_12 [i_2] [i_1] [i_1 - 3] [i_2]
[i_2] [i_3])))));
```

LLVM Bug #51677

```
void test() {
#pragma clang loop vectorize_predicate(enable)
  for (char a = 4; a < var_3; a++) {
    arr_13[a] = arr_12[a - 3];
    var_23 = arr_12[a - 1];
  }
}
```

```
>$ clang++ -O0 -march=skx func.cpp driver.cpp && sde -skx -- ./a.out
1
>$ clang++ -O1 -march=skx func.cpp driver.cpp && sde -skx -- ./a.out
0
```

https://github.com/intel/yarpgen

Paper in submission, available upon request

Special thanks to Intel and
LLVM developers,
who fix reported bugs!

Looking for Job

- Expected graduation: end of Spring 2023
- CV: livinskii.com/#cv
- Email: Vsevolod.Livinskii@gmail.com

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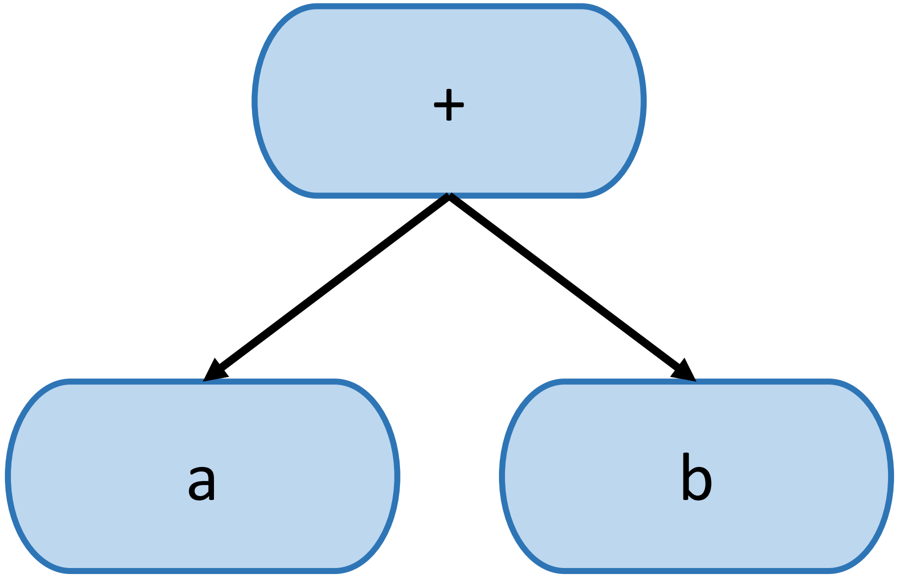
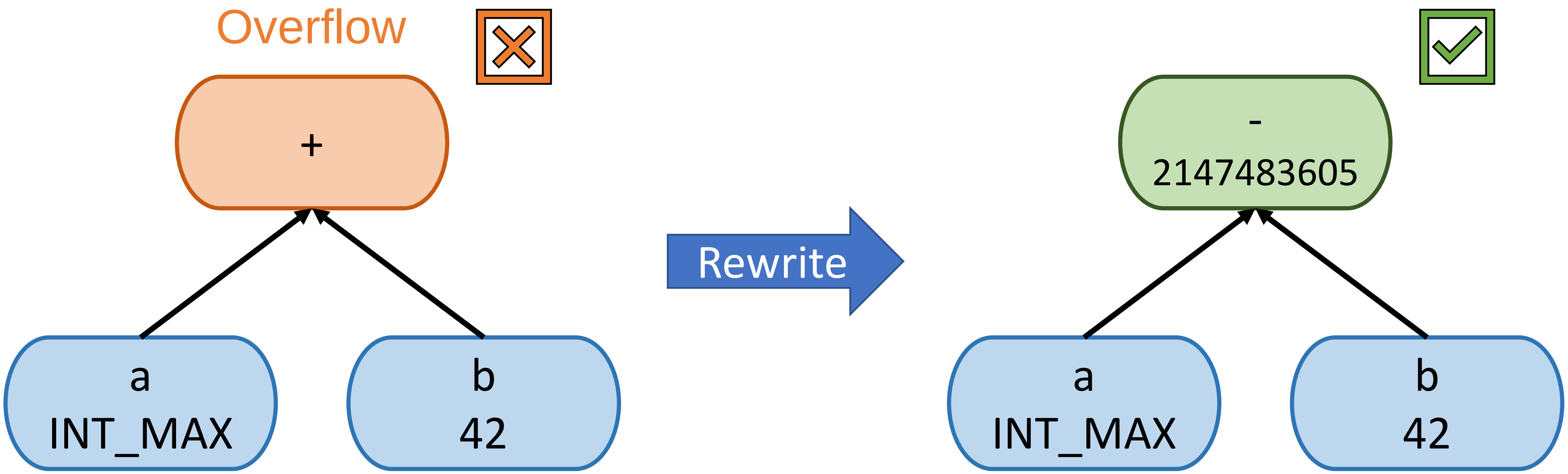
Backup slides

Arithmetic Expression Tree

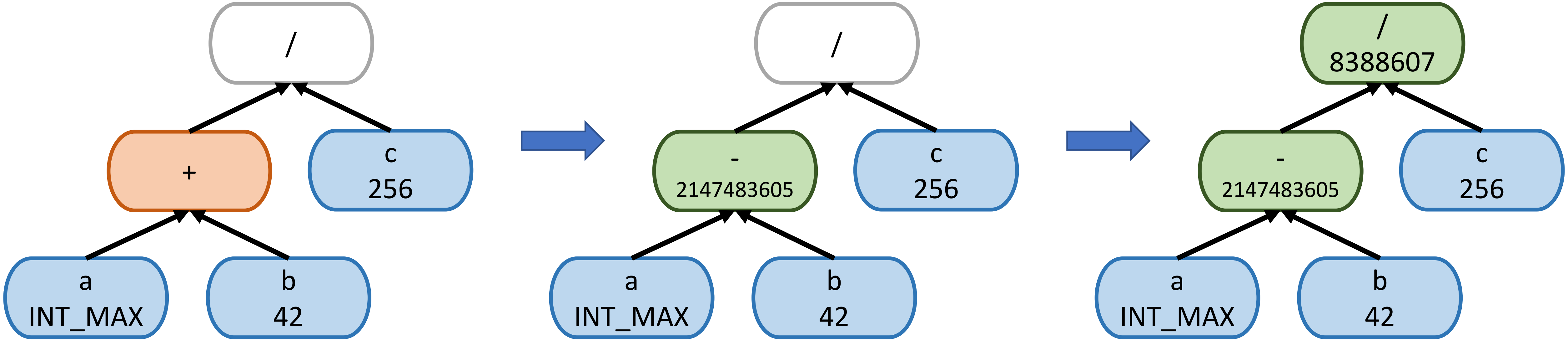


Orange fuzzer: Nagai E., Hashimoto A., Ishiura N. Reinforcing random testing of arithmetic optimization of C compilers by scaling up size and number of expressions, 2014

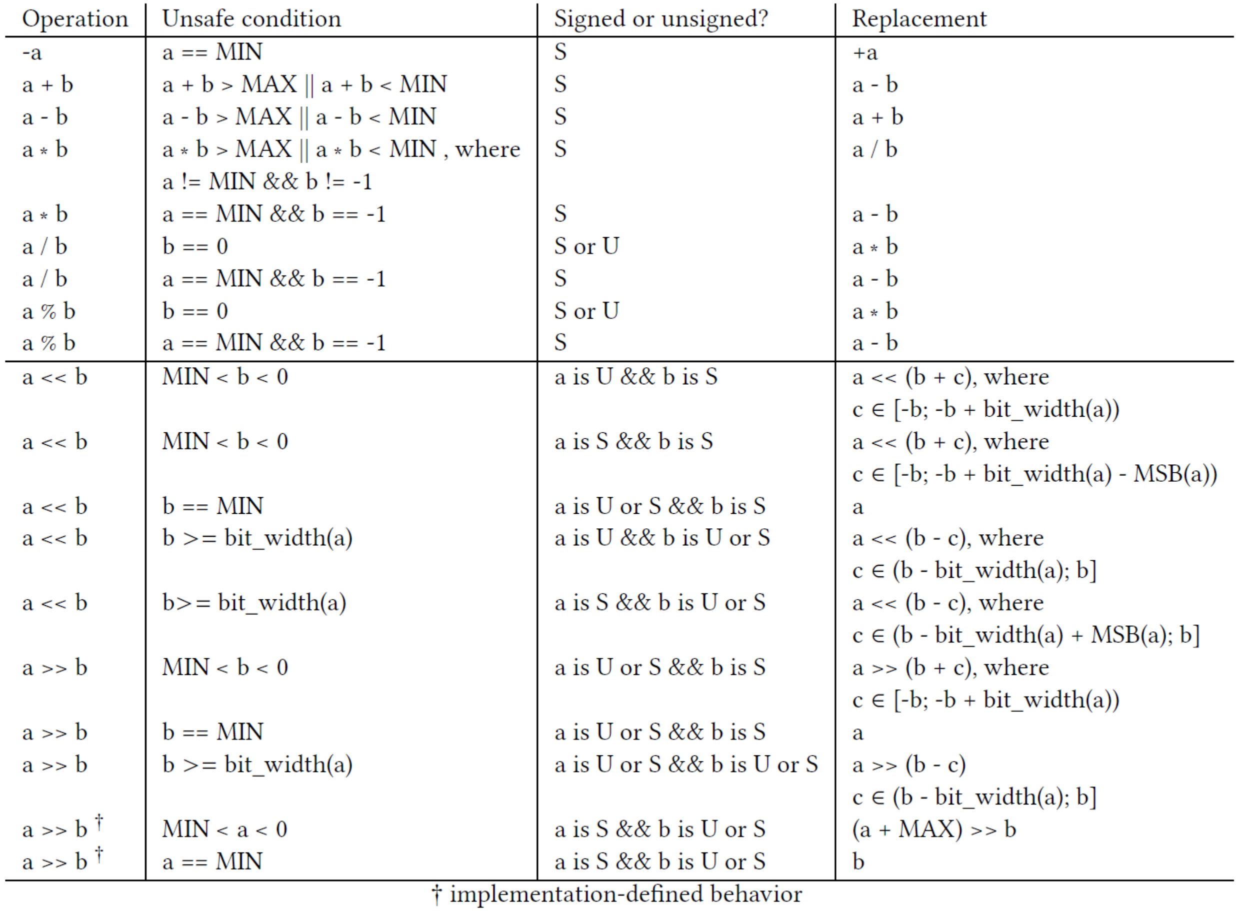
Undefined Behavior Avoidance



Undefined Behavior Avoidance



Rewrite Rules



Operation	Unsafe condition	Signed or unsigned?	Replacement
-a	a == MIN	S	+a
a + b	a + b > MAX || a + b < MIN	S	a - b
a - b	a - b > MAX || a - b < MIN	S	a + b
a * b	a * b > MAX || a * b < MIN , where a != MIN && b != -1	S	a / b
a * b	a == MIN && b == -1	S	a - b
a / b	b == 0	S or U	a * b
a / b	a == MIN && b == -1	S	a - b
a % b	b == 0	S or U	a * b
a % b	a == MIN && b == -1	S	a - b
a << b	MIN < b < 0	a is U && b is S	a << (b + c), where c ∈ [-b; -b + bit_width(a))
a << b	MIN < b < 0	a is S && b is S	a << (b + c), where c ∈ [-b; -b + bit_width(a) - MSB(a))
a << b	b == MIN	a is U or S && b is S	a
a << b	b >= bit_width(a)	a is U && b is U or S	a << (b - c), where c ∈ (b - bit_width(a); b]
a << b	b>= bit_width(a)	a is S && b is U or S	a << (b - c), where c ∈ (b - bit_width(a) + MSB(a); b]
a >> b	MIN < b < 0	a is U or S && b is S	a >> (b + c), where c ∈ [-b; -b + bit_width(a))
a >> b	b == MIN	a is U or S && b is S	a
a >> b	b >= bit_width(a)	a is U or S && b is U or S	a >> (b - c) c ∈ (b - bit_width(a); b]
a >> b †	MIN < a < 0	a is S && b is U or S	(a + MAX) >> b
a >> b †	a == MIN	a is S && b is U or S	b

† implementation-defined behavior

Generative Fuzzers for C

	Csmith	Orange	Quest
UB avoidance mechanism	Static analysis + wrapper functions	Static analysis	Limited subset of C
Specialization	Universal	Arithmetic expressions	Calling conventions
Oracle	Differential testing	Build-in assertions	Ground truth

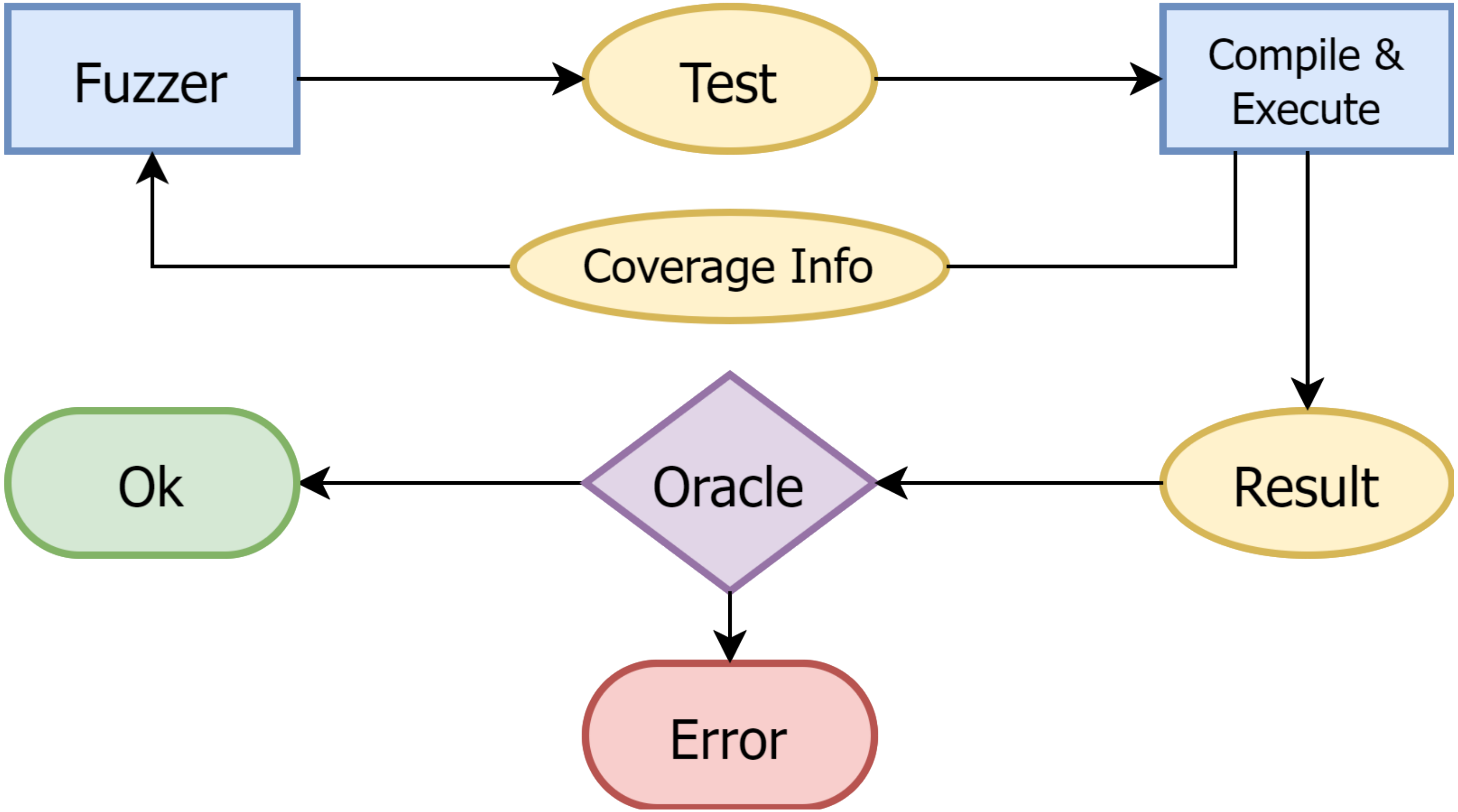
Example of a Missed Bug (GCC #105189)

- Triggered with –O1
- Survived for almost 4 years
    - Introduced on July 23rd 2018
    - Detected on April 6th 2022

```
int foo() {
  return -1;
}

int main() {
  int c = foo() >= 0U && 1;
  if (c != 1)
   abort ();
}
```

Coverage-Guided Fuzzing


Fuzzer
Test
Compile & Execute
Coverage Info
Ok
Oracle
Result
Error