Fuzzing Loop Optimizations in Compilers for C++ and Data-Parallel Languages

Vsevolod Livinskii, University of Utah
Dmitry Babokin, Intel Corporation
John Regehr, University of Utah

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Importance of Testing Loop Optimizations

- Advancements in AI and ML fields
- New architectures with vector operations
- Complexity of loop optimizations
  - SCEV and Polly in LLVM

Summary of Found Bugs

122 new errors in total

42% are wrong code bugs

- 66 bugs in GCC
  - 32 wrong code, 31 ICE, 3 timeouts
- 28 bugs in LLVM
  - 5 wrong code, 5 ICE
- 12 bugs in ISPC
  - 5 wrong code, 7 ICE
- 16 bugs in Intel® oneAPI DPC++ compiler
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- 2 bugs in Intel® SDE
- 2 bugs in Alive2

Research Contribution and Features

- New static Undefined Behavior avoidance for loops
- Target loop optimizations explicitly
- Support multiple C-family languages

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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
```

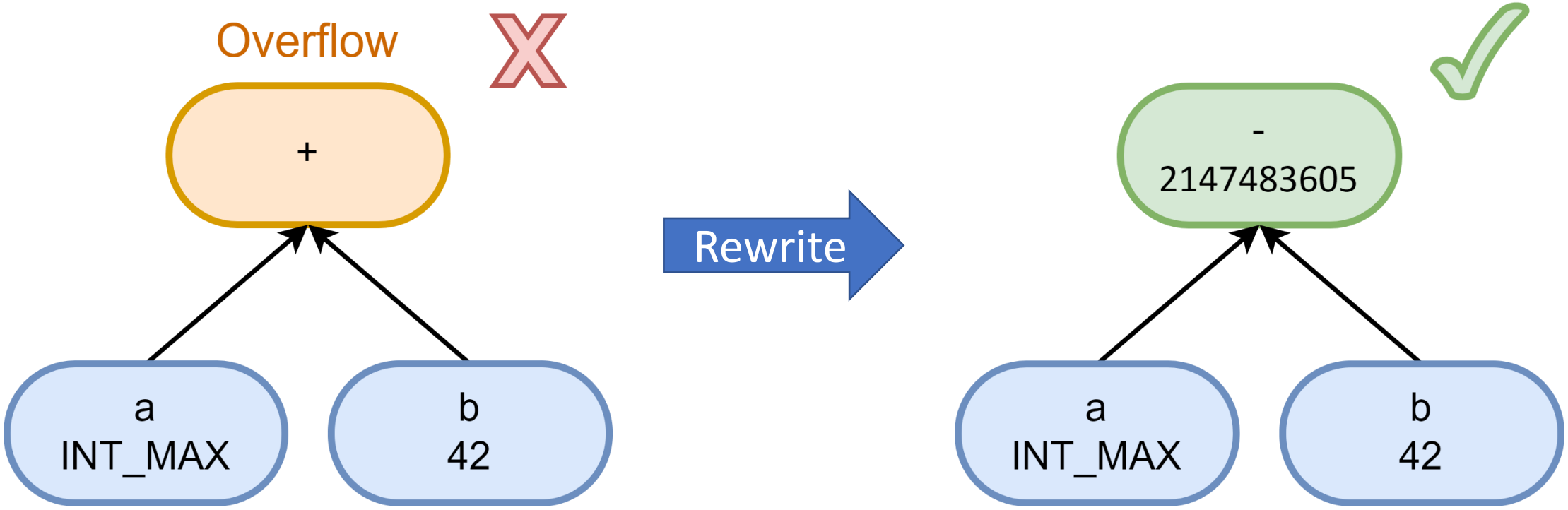
No one!

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;
}
```

UB Avoidance for Loops

i	0	1	2	3
a	5	5	5	5
b	7	7	7	7

```
c[i] = a[i] + b[i];
```

No diversity at runtime!

i	0	1	2	3
a	5	38	5	38
b	7	15	7	15

```
c[i] = a[i] + b[i];
```

UB Avoidance for Loops

i	0	1	2	3
a	5	5	5	5
b	7	7	7	7

```
c[i] = a[i] + b[i];
```

No diversity at runtime!

i	0	1	2	3
a	5	INT_MAX	5	INT_MAX
b	INT_MIN	15	INT_MIN	15

```
c[i] = (i % 2 == zero) ?
       (a[i] + b[i]]) :
       (a[i] - b[i]);
```

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Loop Generation Policies

- Cannot test optimizations that cannot trigger
- A total of 10 Loop Generation Policies
  - 31 fine-grain control parameters
- Not mutually exclusive; compose gracefully
  - Reduction + stencil: `a += (b[i - 1] + b[i] + b[i + 1]) / 3;`

Loop Sequence and Loop Fusion

```
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];
```

Fuse

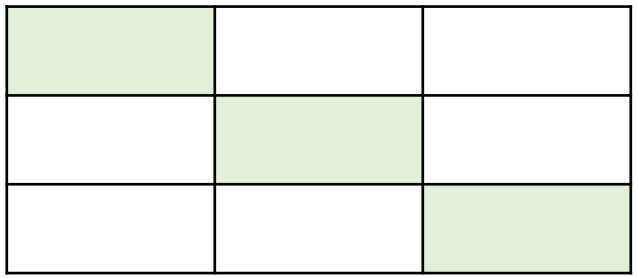
```
for (i=0; i < (d ? e : 10); i++){
    a[i] = c[i] + b[i];
    b[i] = b[i] * c[i];
}
```

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

Array Access Patterns

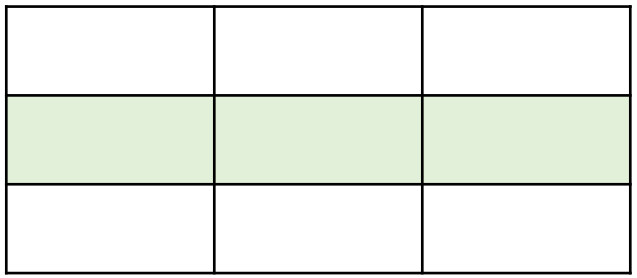
Diagonal

`a[i][i]`



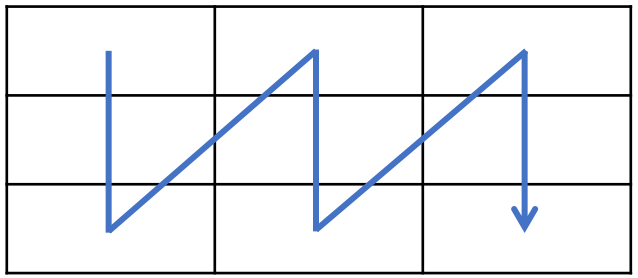
Slice

`a[1][i]`



Column-major

`a[j][i]`



- Relation between loop nest depth and dimensionality
- In-order or not
- Constant, iterator, iterator with offset

Stencils

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

GVN in LLVM forwards values to a subsequent loop iteration

Stencil as a pattern:

- arrays
- dimensions
- stride
- computations

```
.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
```

Generation Policies Composition

```
for (int i = 0; i < a + b; i++) {

      for (int j = 0; j < (c ? d : 10); j++)
            e[i][j] = f[1][j][i] + f[2][i][i];

      for (int k = 0; k < (c ? d : 10); k++)
            g += (h[i][k - 1] + h[i][k] + h[i][k + 1]) / 3;
}
```

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Multi-language Support and IR Lowering

Matrix multiplication

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

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

Limitations

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

Some are research questions; others require more engineering resources

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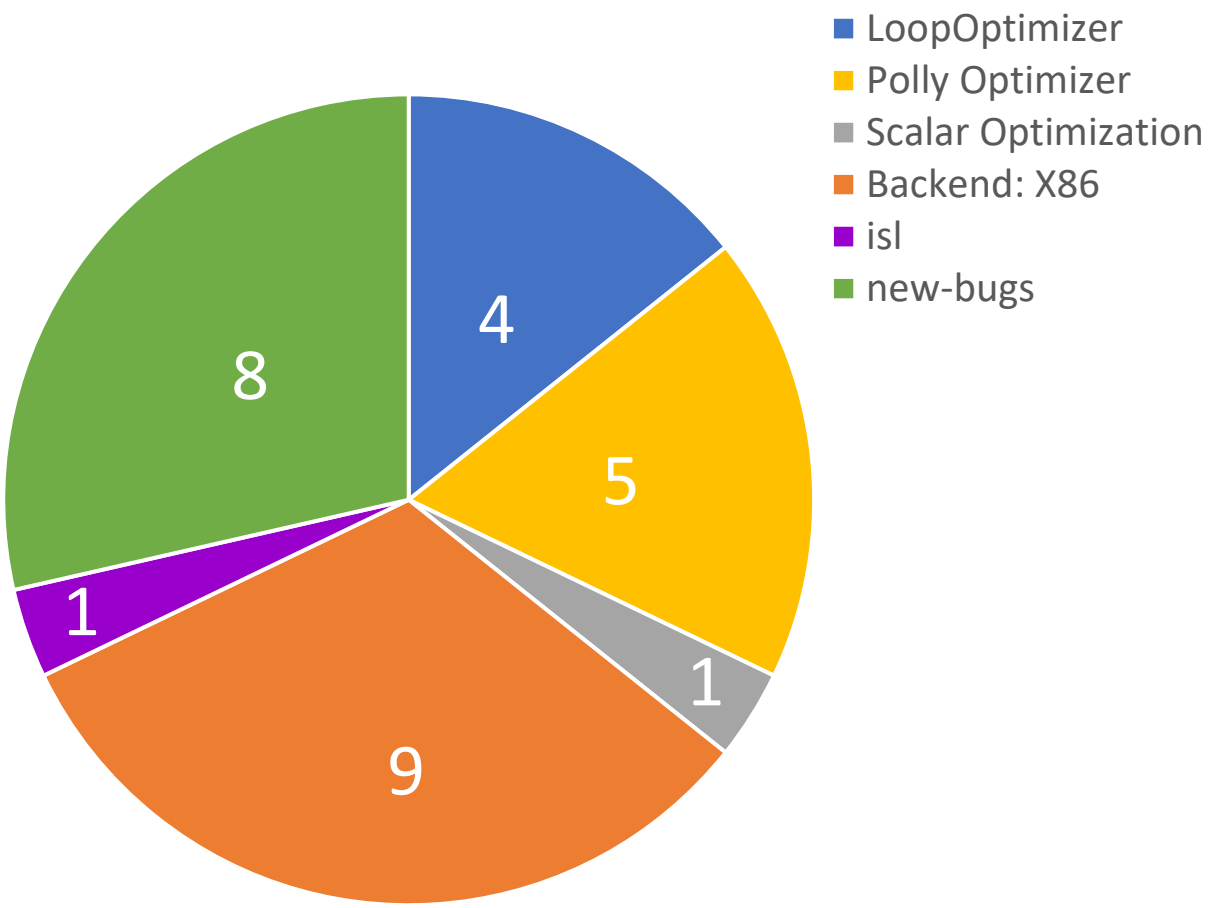
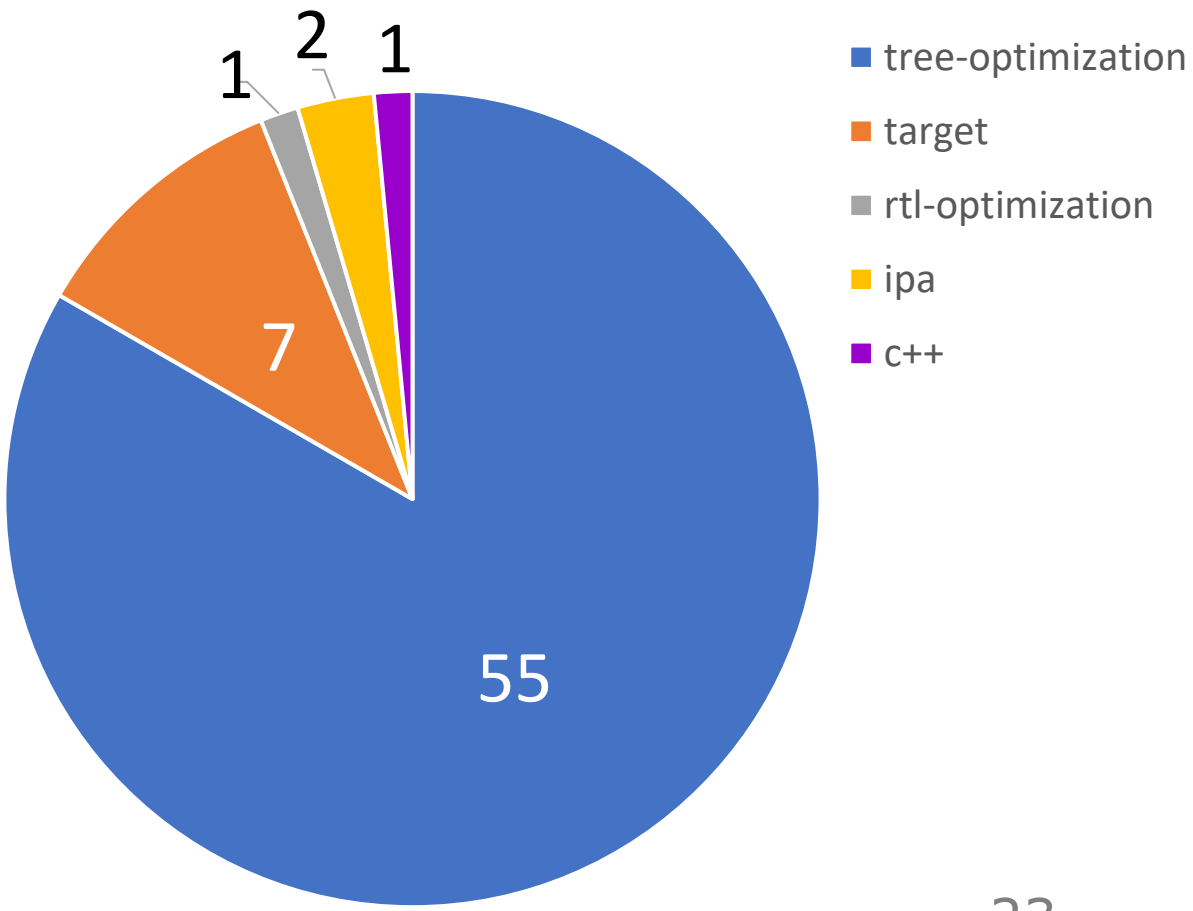
Bugs Distribution by Components

LLVM (28 bugs)



GCC (66 bugs)



Analysis of Reported Bugs

The most common reasons for bugs are:

- Missed corner-cases
- Use of corrupted information
- Too weak preconditions

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  - Examples: INT_MIN, back-edges
- Use of corrupted information
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The most common reasons for bugs are:

- Missed corner-cases
- Use of corrupted information
  - Analyses are computationally expensive
  - Cache invalidation is hard
- Too weak preconditions

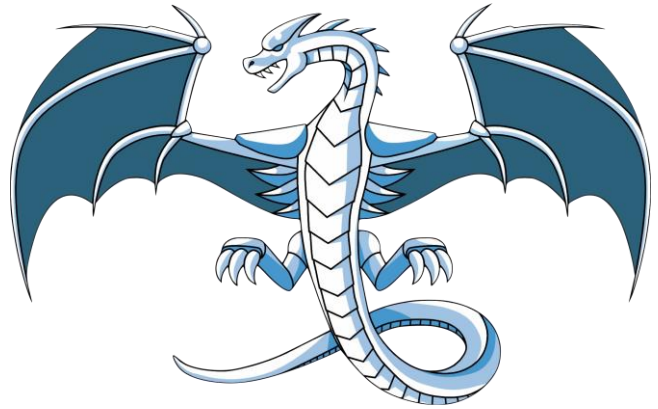
Analysis of Reported Bugs

The most common reasons for bugs are:

- Missed corner-cases
- Use of corrupted information
- Too weak preconditions
  - Examples: vector size or type mismatch, bool is special

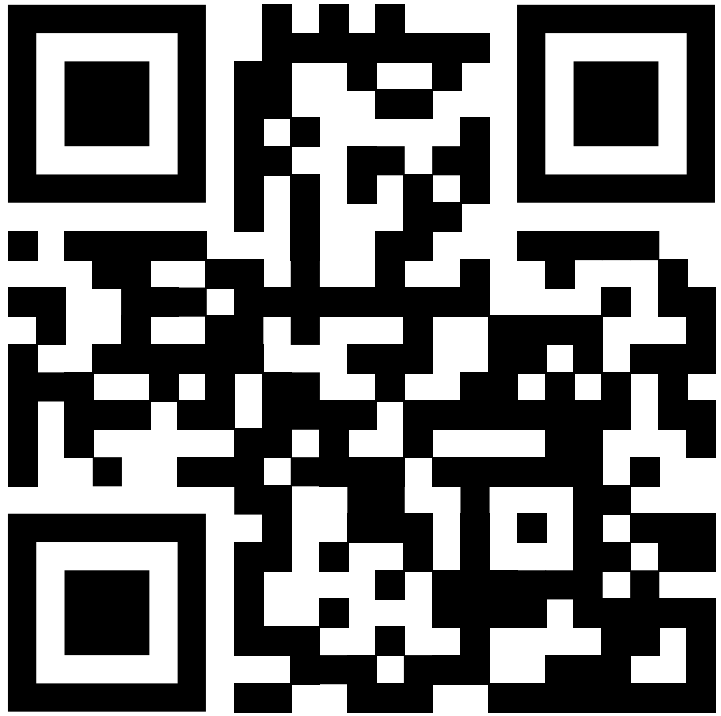
https://github.com/intel/yarpgen

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



Looking for Job

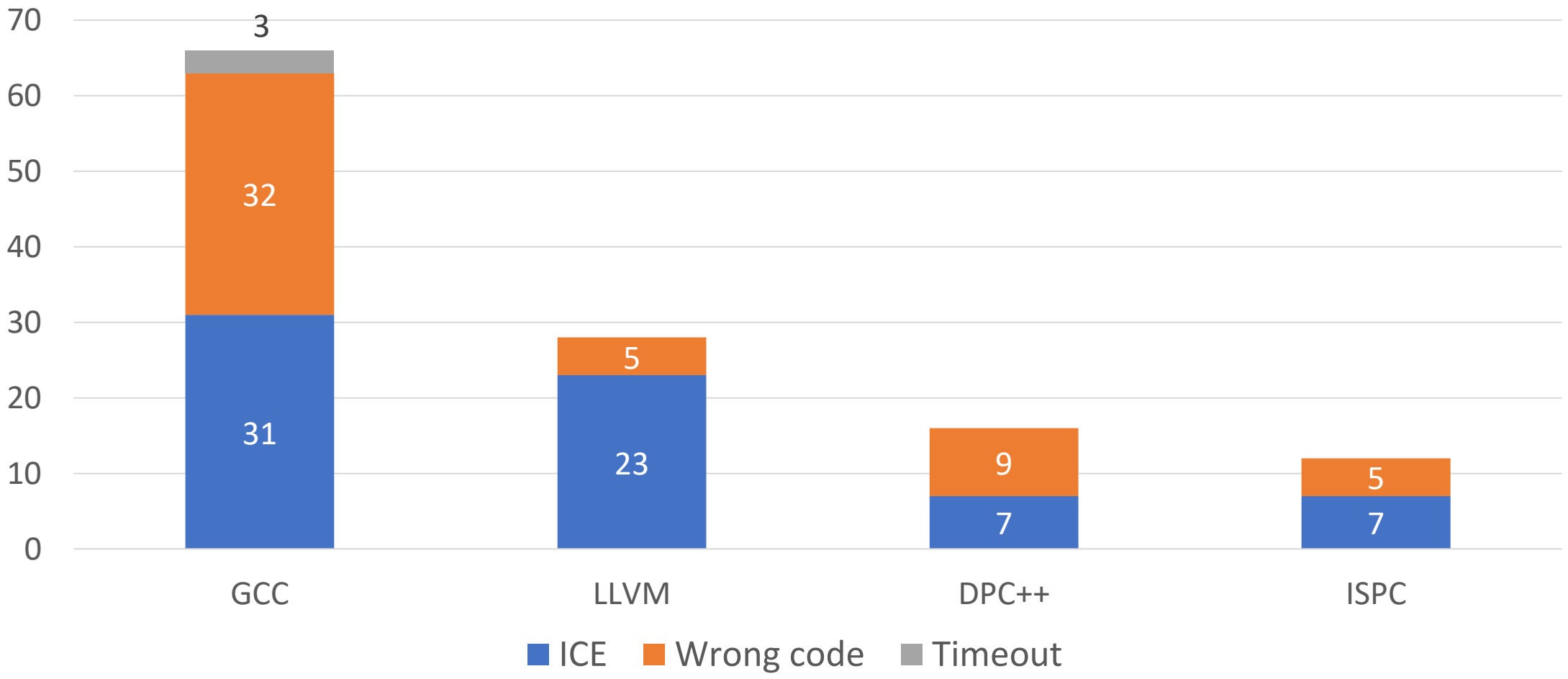
- Expected graduation: Fall 2023
- CV: livinskii.com/#cv
- Email: Vsevolod.Livinskii@gmail.com



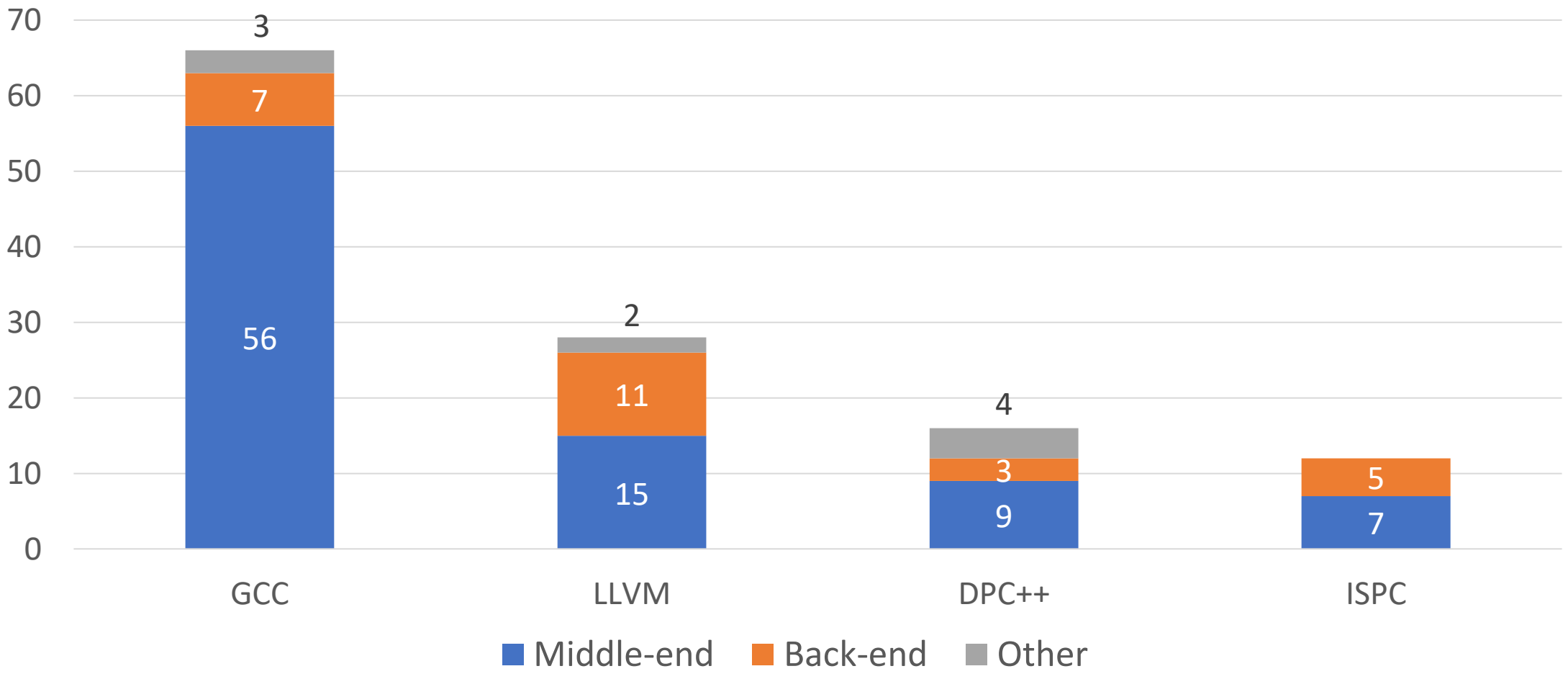
https://github.com/intel/yarpgen

Backup slides

Bugs Distribution by Kind



Bugs Distribution by Component



Loop Optimizations Coverage

- 238 loop-related optimization counters in LLVM

Test suite + SPEC® CPU2017	YARPGen with GP	YARPGen without GP
80	72	71

- With GP 71 is better, 1 is the same, none is worse
  - Geomean ratio is 9.14

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];
  }
}
```

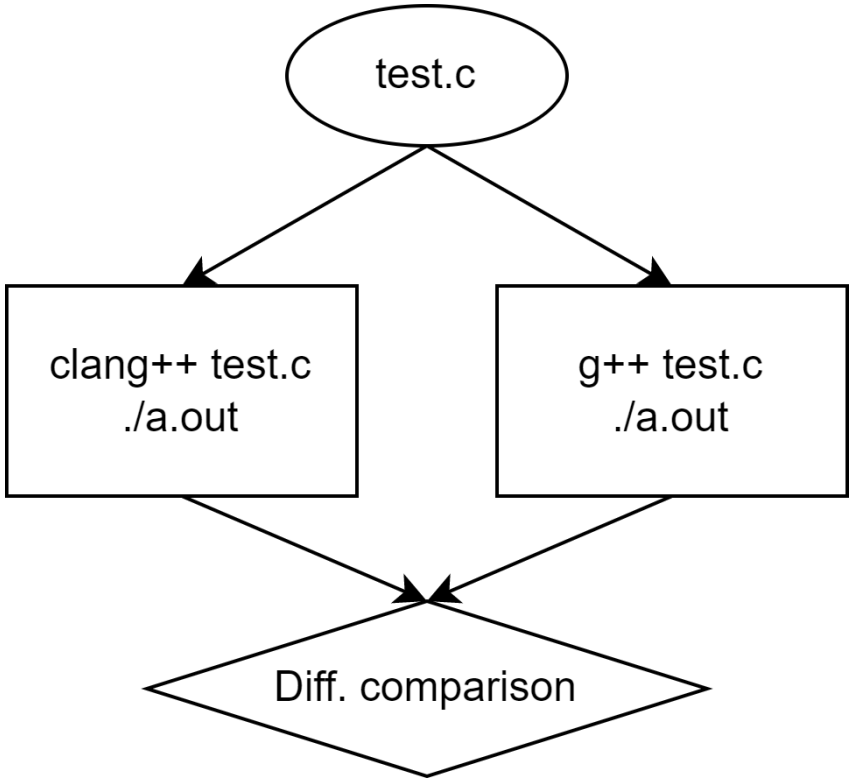
```
>$ clang++ -O0 -march=skx func.cpp driver.cpp && sde -skx -- ./a.out
1
>$ clang++ -O1 -march=skx func.cpp driver.cpp && sde -skx -- ./a.out
0
```

GCC Bug #102920

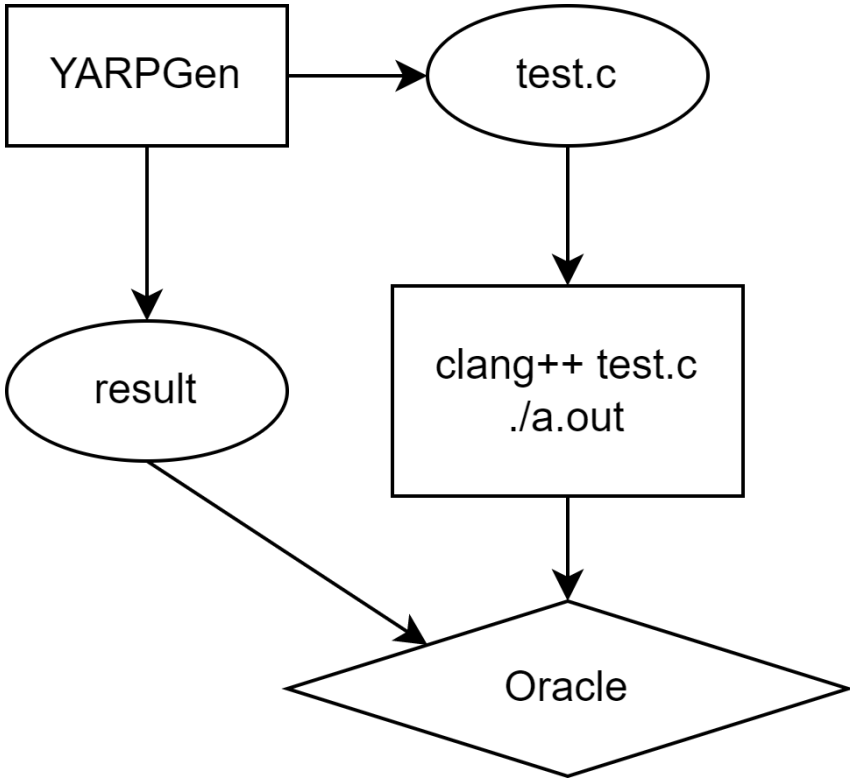
```
void test (unsigned short a, unsigned short b, long long c) {
  for (char i = 0; i < (char)c; i += 5) {
    if (!b)
      var_120 = a;
    else
      var_123 = a;
    }
}
>$ g++ -O3 small.cpp && ./a.out
0
>$ g++ -O2 small.cpp && ./a.out
42
```

Test Oracles

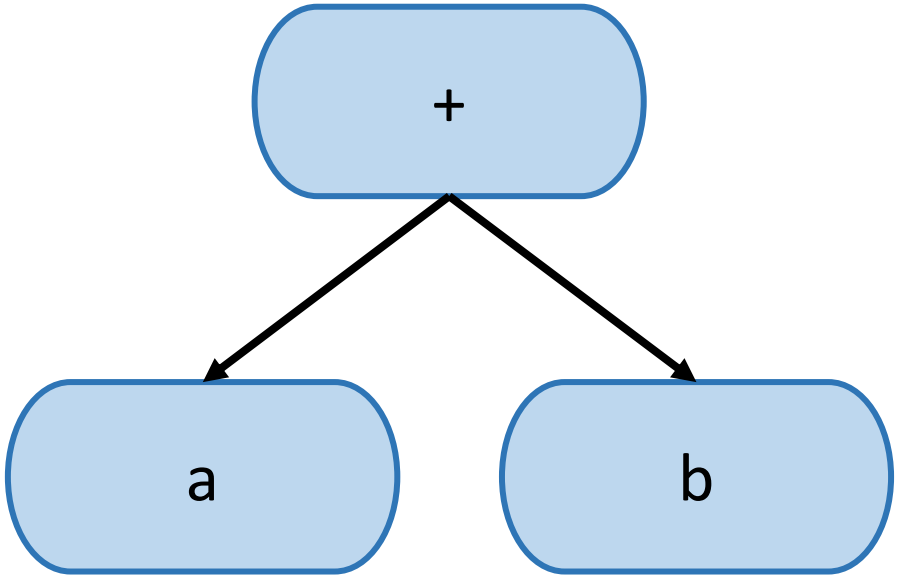
Differential testing



Ground truth

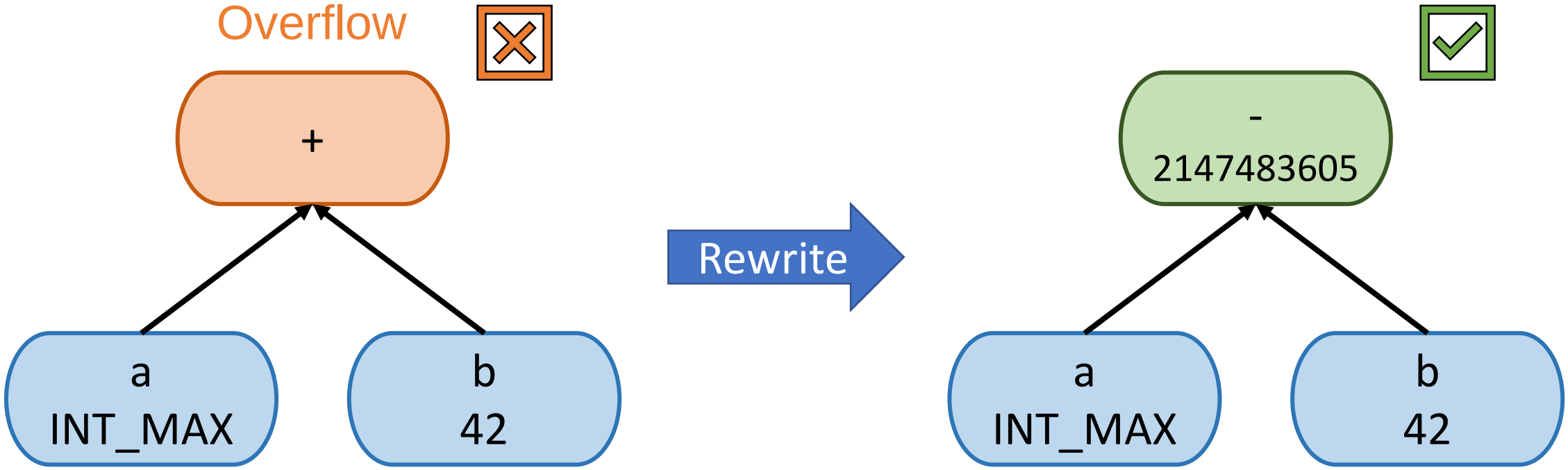


Arithmetic Expression Tree

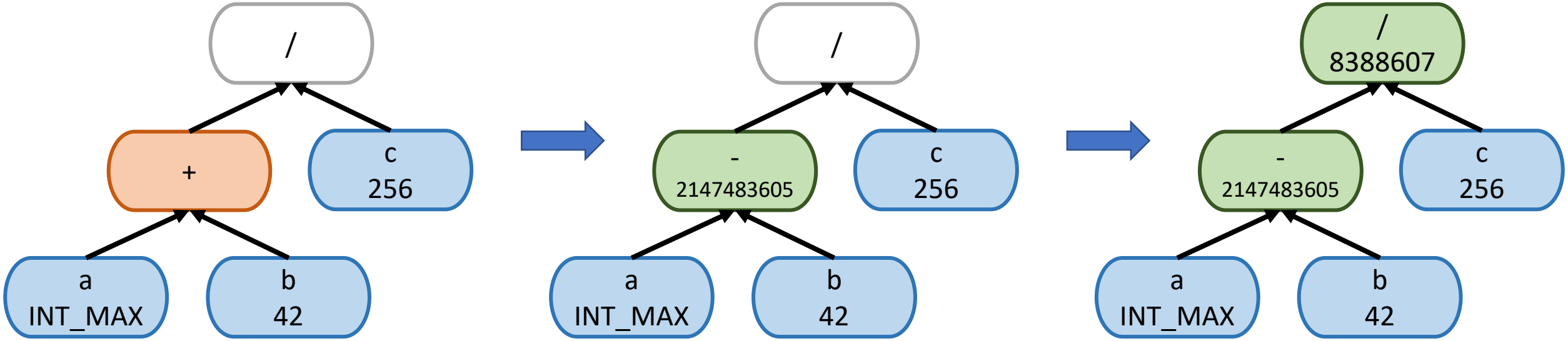


Orange fuzzer: Nagai E., Hashimoto A., Ishiura N. Reinforcing random testing of arithmetic optimization of C compilers by scaling up size and number of expressions, 2014

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