Finding Missed Compiler Optimizations by Differential Testing

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Main takeaways

Does your compiler *always* optimize well?

- compare compilers' outputs to find missed optimizations
- automated toolchain finds minimal test cases
- issues found in GCC, Clang, CompCert:
  - peephole optimizations, dead stores, useless spills, missed instruction selection patterns, missed copy coalescing, ...

Example: missing range analysis

Generated source code:

```
int f(int p, int q) {
 return q + (p % 6) / 9;
}
```

($p \% 6 \in [-5, 5]$,
division truncates to 0)

Clang:

```
movw r2, #43691
movt r2, #10922
smmul r2, r0, r2
add r2, r2, r2, lsr #31
add r2, r2, r2, lsl #1
sub r0, r0, r2, lsl #1
movw r2, #36409
movt r2, #14563
smmul r0, r0, r2
asr r2, r0, #1
add r0, r2, r0, lsr #31
add r0, r0, r1
```

GCC:

```
mov r0, r1
```

https://bugs.llvm.org/show_bug.cgi?id=34517 (fixed)

Example: redundant code

Source code:

```
int fn3(
 double c,
 int *p, int *q)
{
 int i = (int)c;
 *p = i;
 *q = i;
 return i;
}
```

Clang:

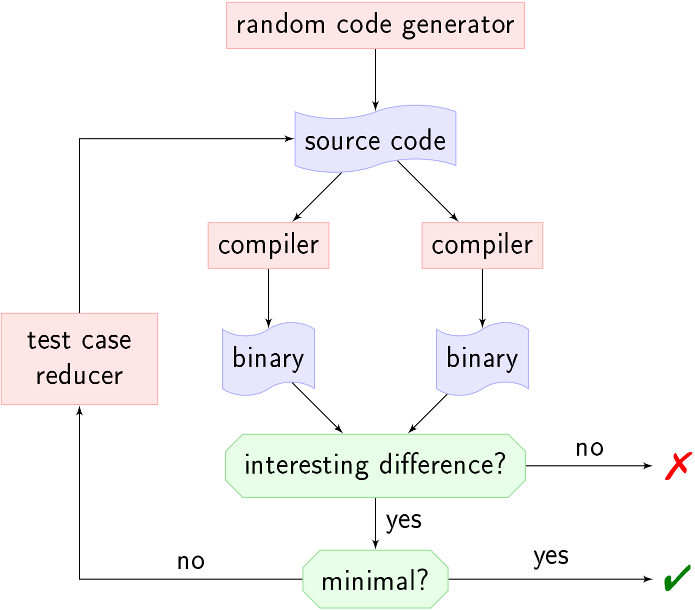
```
vcvt.s32.f64 s2, d0
vstr s2, [r0]
vcvt.s32.f64 s2, d0
vcvt.s32.f64 s0, d0
vmov r0, s0
vstr s2, [r1]
```

GCC:

```
vcvt.s32.f64 s15, d0
vstr.32 s15, [r0]
vmov r0, s15
vstr.32 s15, [r1]
```

https://bugs.llvm.org/show_bug.cgi?id=33199 (fixed)

Randomized differential testing



Randomized differential testing for missed optimizations

random code generator

off-the-shelf tools: Csmith, ldrgen (or many others)

test case reducer

off-the-shelf tool: C-Reduce

interesting difference?

custom tool: `optdiff`

- binary analysis to find optimization differences
- assigns scores to binaries, compares

`optdiff`

- based on `angr` binary analysis framework
  - multi-platform (x86, x86-64, ARM, PowerPC, ...)
  - Python API
- load binary, compute CFG, estimate basic block frequencies w_b

Checkers: local scoring functions $c : \mathit{instruction} \to \mathbb{N}$

Total score: $$s = \sum_{b \in f} w_b \cdot \sum_{i \in b} c(i)$$

Examples: number of instructions, general memory loads/stores, stack loads/stores, function calls, floating-point arithmetic instructions, vector instructions, ...

Checker implementation: instructions

Checkers

- Python functions with @checker decorator
- inspect one instruction at a time

```python
@checker
def instructions(arch, instr):
    """Number of instructions."""
    return 1
```

Checker implementation: loads

```
@checker
def loads(arch, instr):
    """Number of memory loads."""
    op = instr.insn.mnemonic
    if is_arm(arch):
        if op == 'ldrd':                          # load doubleword
            return 2
        elif re.match('ldm.*', op):               # load multiple
            return len(instr.insn.operands)-1
        return bool(re.match('v?ldr.*', op))      # load one word
    ... # other architectures
```

Example: useless spill

Source code:

```
char fn2(
 float p)
{
 char c=(char)p;
 return c;
}
```

Clang:

```
vcvt.u32.f32 s0, s0
vmov r0, s0
```

instruction score: 2
stack load score: 0

GCC:

```
vcvt.u32.f32 s15, s0
sub sp, sp, #8
vstr.32 s15, [sp, #4]
ldrb r0, [sp, #4]
add sp, sp, #8
```

instruction score: 5
stack load score: 1

https://gcc.gnu.org/bugzilla/show_bug.cgi?id=80861
(confirmed, diagnosed)

CompCert: an example

Source code:

```
int fn10(int p1) {
 int a, b, c, d, e, v, f;
 a = 0;
 b = c = 0;
 d = e = p1;
 v = 4;
 f = e * d | a * p1 + b;
 return f;
}
```

CompCert:

```
str r4, [sp, #8]
mov r4, #0
mov r12, #0
mov r1, r0
mov r2, r1
mul r3, r2, r1
mla r2, r4, r0, r12
orr r0, r3, r2
ldr r4, [sp, #8]
```

- dead code `v = 4;` causes spilling
- missed copy coalescing
- missed constant propagation and folding: `a * p1 + b` $= 0$

Undefined behavior: the good

Undefined behavior may be compiled arbitrarily
— do we have to be careful?

Unproblematic cases:

- Clang and GCC treat many cases identically, comparisons OK
- `char f(float p) { return (char) p; }`
  (assume never called with bad values of `p`)
- `x < x + 1` $\rightarrow$ true
  (undefined for `x` signed integer)

Undefined behavior: the bad

Problematic cases:

- unconditional undefined behavior, e. g.,
  `int fn(int a) { int x = 0; return a / x; }`
- infinite loops:
  `while (x) { y = ...; }`
- C-Reduce likes to produce such cases
- no compiler warnings but different 'optimized' code

Workarounds

- static analysis to find UB/nontermination? ineffective ☹
- accept some cases
- don't let random generators produce loops/problematic constructs

Why *randomized* differential testing?

Arguments against random input programs

- examples look artificial
- may not correspond to real-world performance problems

Advantages of random input programs

- unlimited amount of code available
- controlled sublanguage (loop-free, only constructs of interest)
- reducer output looks artificial even for real-world input

Results

Some missed optimizations found

	reported	fixed	other
GCC	6	1	13
Clang	3	3	3
CompCert	3	3	6

- generally treated as low priority by developers
- many duplicates

Causes

- missing/wrong rules or costs
- phase ordering
- weak heuristics

Summary

- compare compilers' outputs to find missed optimizations
- automated toolchain finds minimal test cases
- issues found in GCC, Clang, CompCert

`https://github.com/gergo-/missed-optimizations`

Thank you for your attention

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