Automatic program generation for detecting vulnerabilities and errors in compilers and interpreters

0368-3500

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Preliminaries

- Students will group in teams of 2-3 students.
- Each group will do one of the projects presented.

Administration

- Workshop meetings will take place **only** on Tuesdays 16-18
  - No meetings (with us) during other hours

- **Attendance** in all meetings is **mandatory**

- Grading: 100% of grade will be given after final project submission.
- Projects will be graded based on:
  - Code correctness and functionality
  - Original and innovative ideas
  - Level of technical difficulty of solution

Administration

- Workshop staff should be contacted by email.
- Please address all emails to all of the staff:
  - Noam Rinetzky - maon@cs.tau.ac.il
  - Nurit Dor - nurit.dor@gmail.com

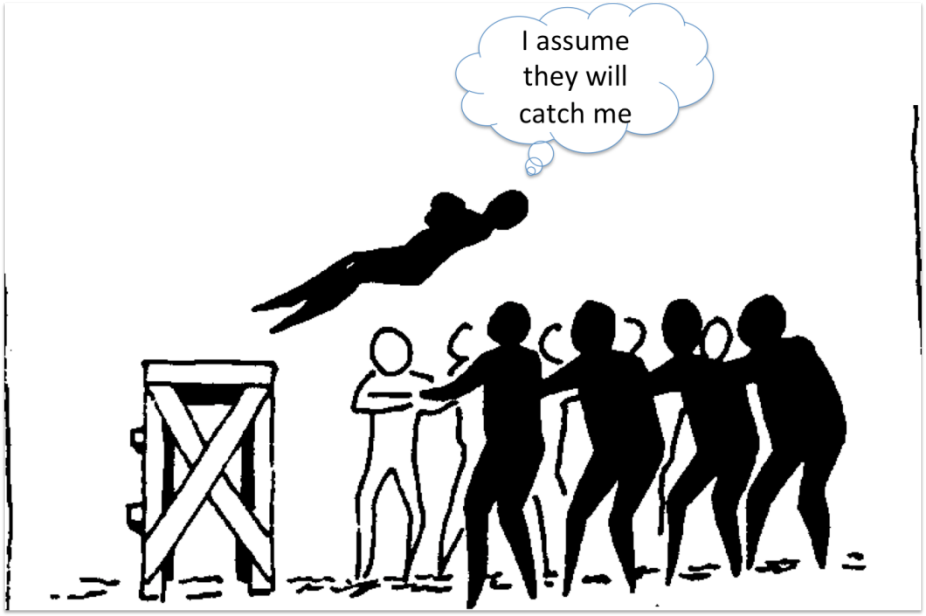
- Follow updates on the workshop website:
  http://www.cs.tau.ac.il/~maon/teaching/2015-2016/workshop/workshop1516b.html

Tentative Schedule

- Meeting 1, 8/03/2016 (today)
  - Project presentation
- Meeting 2, 5/04/2016 (or 12/4)
  - Each group presents its initial design
- Meeting 3, 17/05/2016
  - Progress report – meeting with each group
- Meeting 4, 7/06/2016
  - First phase submission
- Submission: 01/09/2016
- Presentation: ~08/09/2016
  - Each group separately

Automatic program generation for detecting vulnerabilities and errors in compilers and interpreters

Programming Errors



"As soon as we started programming, we found to our surprise that it wasn't as easy to get programs right as we had thought. Debugging had to be discovered. I can remember the exact instant when I realized that a large part of my life from then on was going to be spent in finding mistakes in my own programs."

—Maurice Wilkes,
Inventor of the EDSAC,
1949

Compiler bugs?

- Most programmers treat compiler as a 100% correct program
- Why?
  - Never found a bug in a compiler
    - Even if they do, they don't understand it and solve the problem by "voodoo programming"
  - A compiler is indeed rather thoroughly tested
    - Tens of thousands of testcases
    - Used daily by so many users

Small Example

```
int foo (void) {
   signed char x = 1;
   unsigned char y = 255;
   return x > y;
}
```

- Bug in GCC for Ubuntu compiles this function to return 1

FUZZERS

What is Fuzzing?

- Fuzzing is a testing approach
  - Test cases generated by a program.
  - Software under test in activated on those testcases
  - Monitored at run-time for failures

Naïve Fuzzing

- Miller et al 1990

- Send “random” data to application.
  - Long printable and non-printable characters with and without null byte
- 25-33% of utility programs (emacs, ftp,…) in unix crashed or hanged

Naïve Fuzzing

- Advantages:
  - Amazingly simple
- Disadvantage:
  - inefficient
    - Input often requires structures
      - random inputs are likely to be rejected
    - Inputs that would trigger a crash is a very small fraction, probability of getting lucky may be very low
    - Today's security awareness is much higher

Mutation Based Fuzzing

- Little or no knowledge of the structure of the inputs is assumed
- Anomalies are added to existing valid inputs
- Anomalies may be completely random or follow some heuristics
- Requires little to no set up time
- Dependent on the inputs being modified
- May fail for protocols with checksums, those which depend on challenge response, etc.

Mutation Based Example: PDF Fuzzing

- Google .pdf (lots of results)
- Crawl the results and download lots of PDFs

- Use a mutation fuzzer:
  1. Grab the PDF file
  2. Mutate the file
  3. Send the file to the PDF viewer
  4. Record if it crashed (and the input that crashed it)

Generation Based Fuzzing

- Test cases are generated from some description of the format: RFC, documentation, etc.
- Anomalies are added to each possible spot in the inputs
- Knowledge of protocol should give better results than random fuzzing
- Can take significant time to set up

Example Specification for ZIP file

```
<!--  A.  Local file header -->
  <Block name="LocalFileHeader">
    <String name="lfh_Signature" valueType="hex" value="504b0304" token="true" mut
    <Number name="lfh_Ver" size="16" endian="little" signed="false"/>
    ...
    [truncated for space]
    ...
    <Number name="lfh_CompSize" size="32" endian="little" signed="false">
      <Relation type="size" of="lfh_CompData"/>
    </Number>
    <Number name="lfh_DecompSize" size="32" endian="little" signed="false"/>
    <Number name="lfh_FileNameLen" size="16" endian="little" signed="false">
      <Relation type="size" of="lfh_FileName"/>
    </Number>
    <Number name="lfh_ExtraFldLen" size="16" endian="little" signed="false">
      <Relation type="size" of="lfh_FldName"/>
    </Number>
    <String name="lfh_FileName"/>
    <String name="lfh_FldName"/>
    <!--  B.  File data -->
    <Blob name="lfh_CompData"/>
  </Block>
```

Src: http://www.flinkd.org/2011/07/fuzzing-with-peach-part-1/

Mutation vs Generation

Mutation Based

- Easy to implement, no need to understand the input structure
- General implementation
- Effectiveness is limited by the initial testcases
- Coverage is usually not improved

Generation based

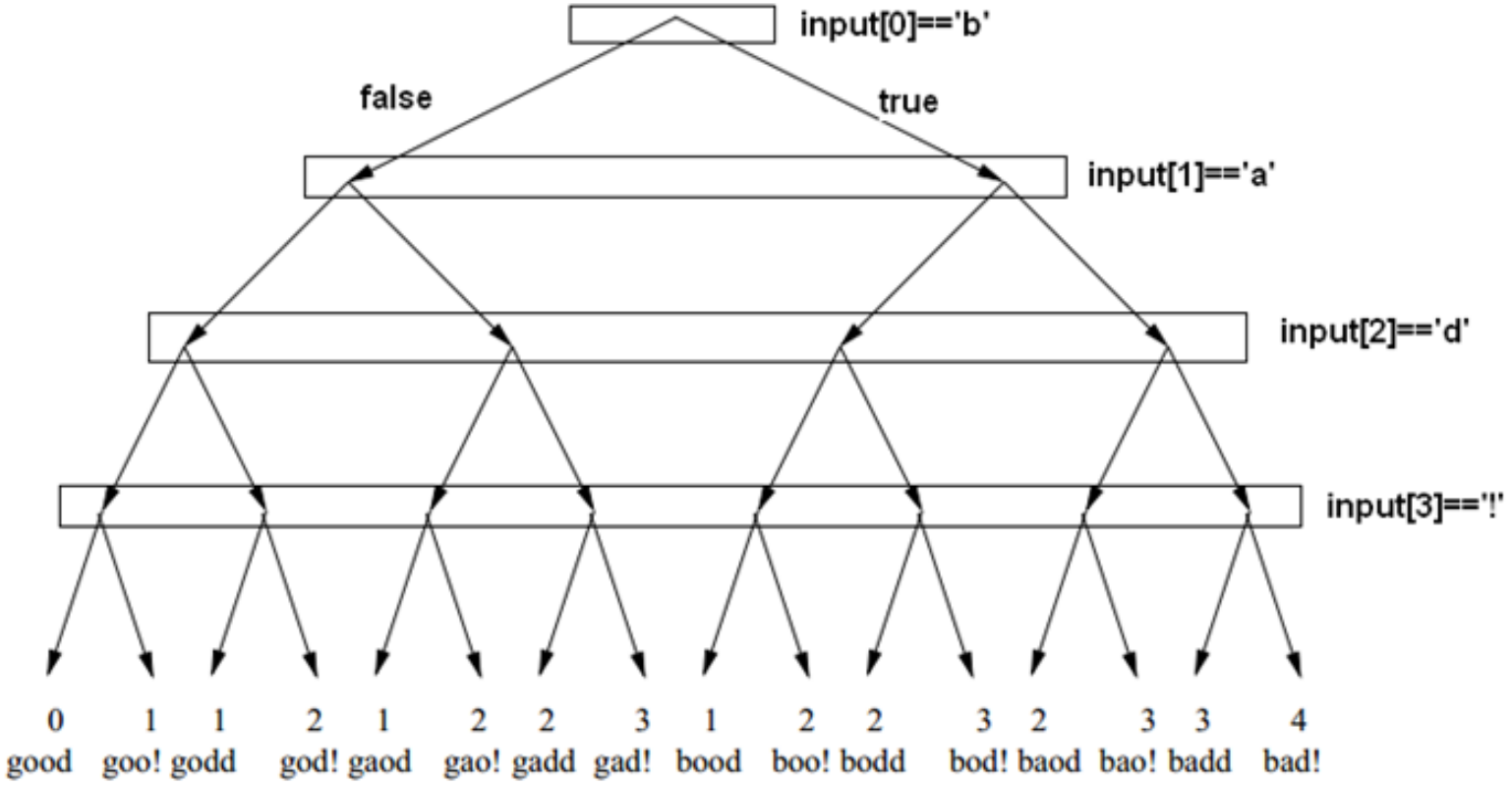
- Can be labor intensive to implement epically for complex input (file formats)
- Implementation for specific input
- Can produce new testcases
- Coverage is usally improved

Constraint Based Fuzzing

- Mutation and generation based fuzzing will probably not reach the crash

```
void test(char *buf)
{
    int n=0;
    if(buf[0] == 'b') n++;
    if(buf[1] == 'a') n++;
    if(buf[2] == 'd') n++;
    if(buf[3] == '!') n++;
    if(n==4) {
        crash();
    }
}
```

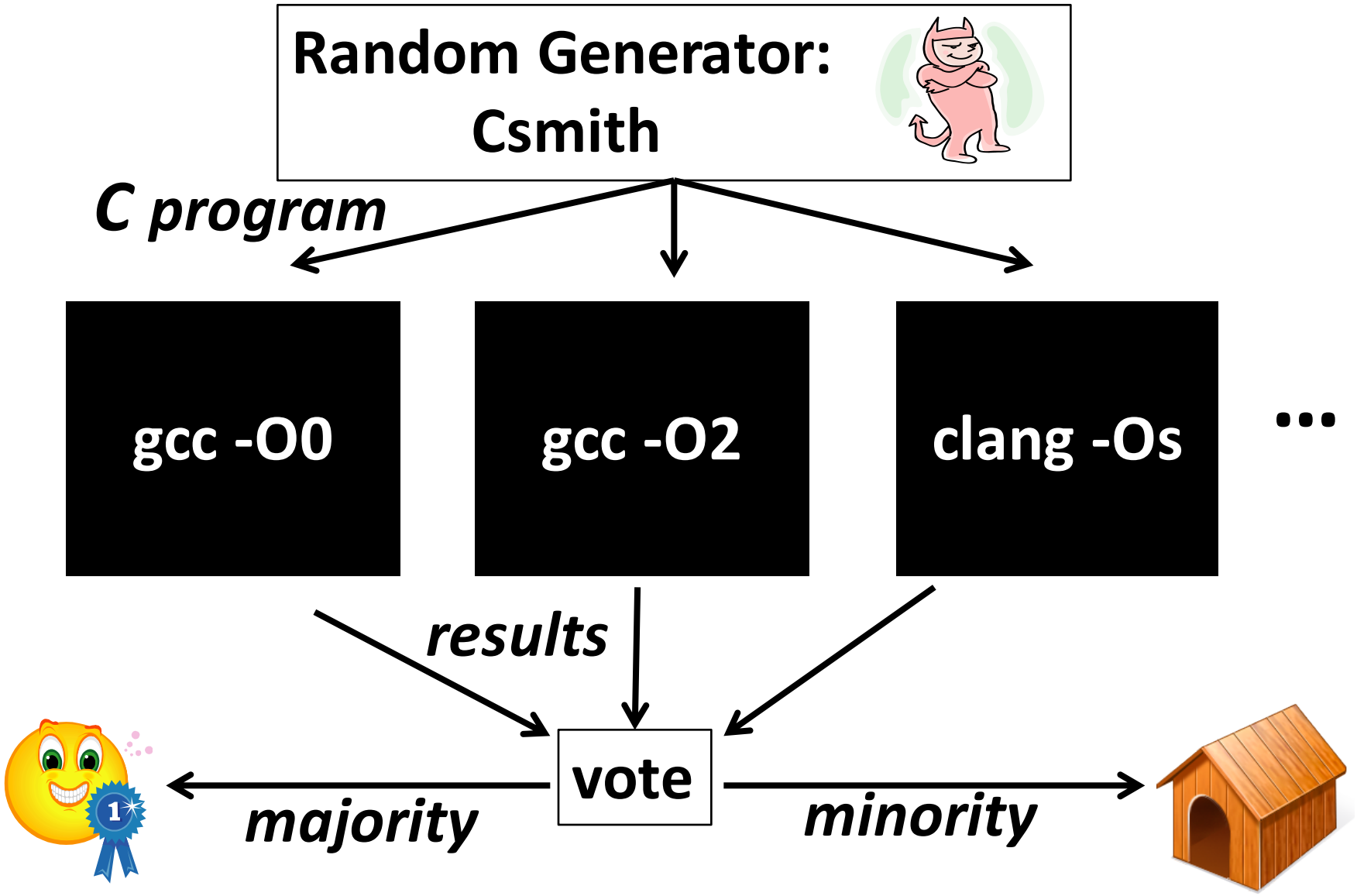
Constraint Based Fuzzing



CSMITH

Csmith

- From the University of Utah
- Csmith is a tool that can generate random C programs
  - Only valid C99 standard


Random Generator:
Csmith
C program
gcc -O0
gcc -O2
clang -Os
...
results
vote
majority
minority

```
#include "csmith.h"
static long __undefined;

/* --- Struct/Union Declarations --- */
/* --- GLOBAL VARIABLES --- */
static int32_t g_7 = 9L;
static int32_t *g_6 = &g_7;
static int64_t g_10 = (-1L);
static const int32_t ** const  volatile g_14[6][5][6] = {{{0, 0, 0, 0, 0, 0}, {0, 0, 0, 0, 0, 0},
static volatile int32_t g_29 = (-6L);/* VOLATILE GLOBAL g_29 */
static int32_t g_30 = 0xDE63B691L;
static uint64_t g_43 = 0xA8FD5F396434D12ELL;
```

```
        int64_t l_464 = (-1L);
lbl_474:
        if ((g_169 & (safe_mul_func_uint8_t_u_u(g_43, (l_431 != 0)))))
        { /* block id: 412 */
            const int32_t *l_432 = 0;
            int32_t *l_434 = &g_30;
            (*l_434) ^= (*g_105);
            for (g_7 = 0; (g_7 <= (-17)); g_7 = safe_sub_func_uint64_t_u_u(g_7, 1))
            { /* block id: 416 */
                const int16_t l_441 = 7L;
                (*l_434) = (safe_add_func_int64_t_s_s((((~(g_30 == (safe_mul_func_uin
                return g_232;
            }
            (*l_434) = (0U | (((safe_mod_func_int32_t_s_s((*l_434), (*l_417))) ^ g_133)
            l_451 = (safe_add_func_int32_t_s_s((*l_434), (safe_mul_func_uint8_t_u_u
        }
```

```
int main (int argc, char* argv[])
{
    int i, j, k;
    int print_hash_value = 0;
    if (argc == 2 && strcmp(argv[1], "1") == 0) print_hash_value = 1;
    platform_main_begin();
    crc32_gentab();
    func_1();
    transparent_crc(g_7, "g_7", print_hash_value);
    transparent_crc(g_10, "g_10", print_hash_value);
    transparent_crc(g_29, "g_29", print_hash_value);
```

```
jxyang@gamow:~/csmith/demo$ ls
jxyang@gamow:~/csmith/demo$ ../src/csmith --bitfields --packed-struct -s 4276401180 > test.c
jxyang@gamow:~/csmith/demo$ ls -l
total 56
-rw-r--r-- 1 jxyang embed 52378 2011-06-07 08:49 test.c
jxyang@gamow:~/csmith/demo$ ~regehr/z/bin/current-gcc -v
Using built-in specs.
COLLECT_GCC=/home/regehr/z/bin/current-gcc
COLLECT_LTO_WRAPPER=/uusoc/exports/scratch/regehr/z/compiler-install/gcc-r174655-install/bin/../libexec/gcc/x86_64
-unknown-linux-gnu/4.7.0/lto-wrapper
Target: x86_64-unknown-linux-gnu
Configured with: ../configure --with-libelf=/usr/local --enable-lto --prefix=/home/regehr/z/compiler-install/gcc-r
174655-install --program-prefix=r174655- --enable-languages=c,c++
Thread model: posix
gcc version 4.7.0 20110605 (experimental) (GCC)
jxyang@gamow:~/csmith/demo$ ~regehr/z/bin/current-gcc -O3 -I../runtime test.c
test.c: In function 'func_1':
test.c:239:27: warning: comparison of distinct pointer types lacks a cast [enabled by default]
test.c: In function 'func_25':
test.c:625:48: warning: comparison of distinct pointer types lacks a cast [enabled by default]
test.c:661:133: warning: comparison of distinct pointer types lacks a cast [enabled by default]
test.c:679:287: warning: comparison of distinct pointer types lacks a cast [enabled by default]
test.c: In function 'main':
test.c:1055:5: internal compiler error: in vect_enhance_data_refs_alignment, at tree-vect-data-refs.c:1551
Please submit a full bug report,
with preprocessed source if appropriate.
See <http://gcc.gnu.org/bugs.html> for instructions.
```

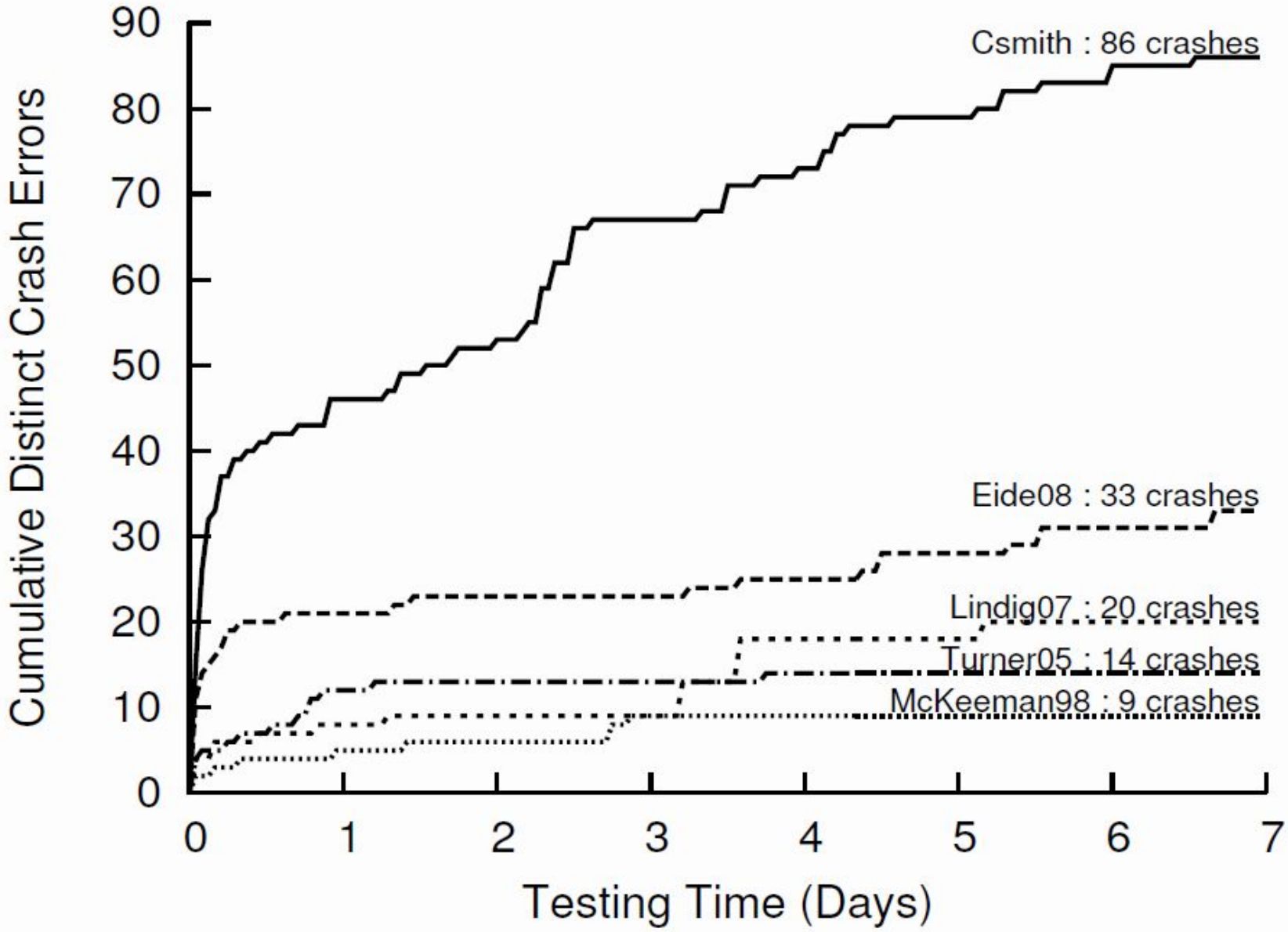
Why Csmith Works

• **Unambiguous**: avoid undefined or unspecified behaviors that create ambiguous meanings of a program

Integer undefined behavior	**Use of dangling pointer**
Use without initialization	**Null pointer dereference**
Unspecified evaluation order	**OOB array access**

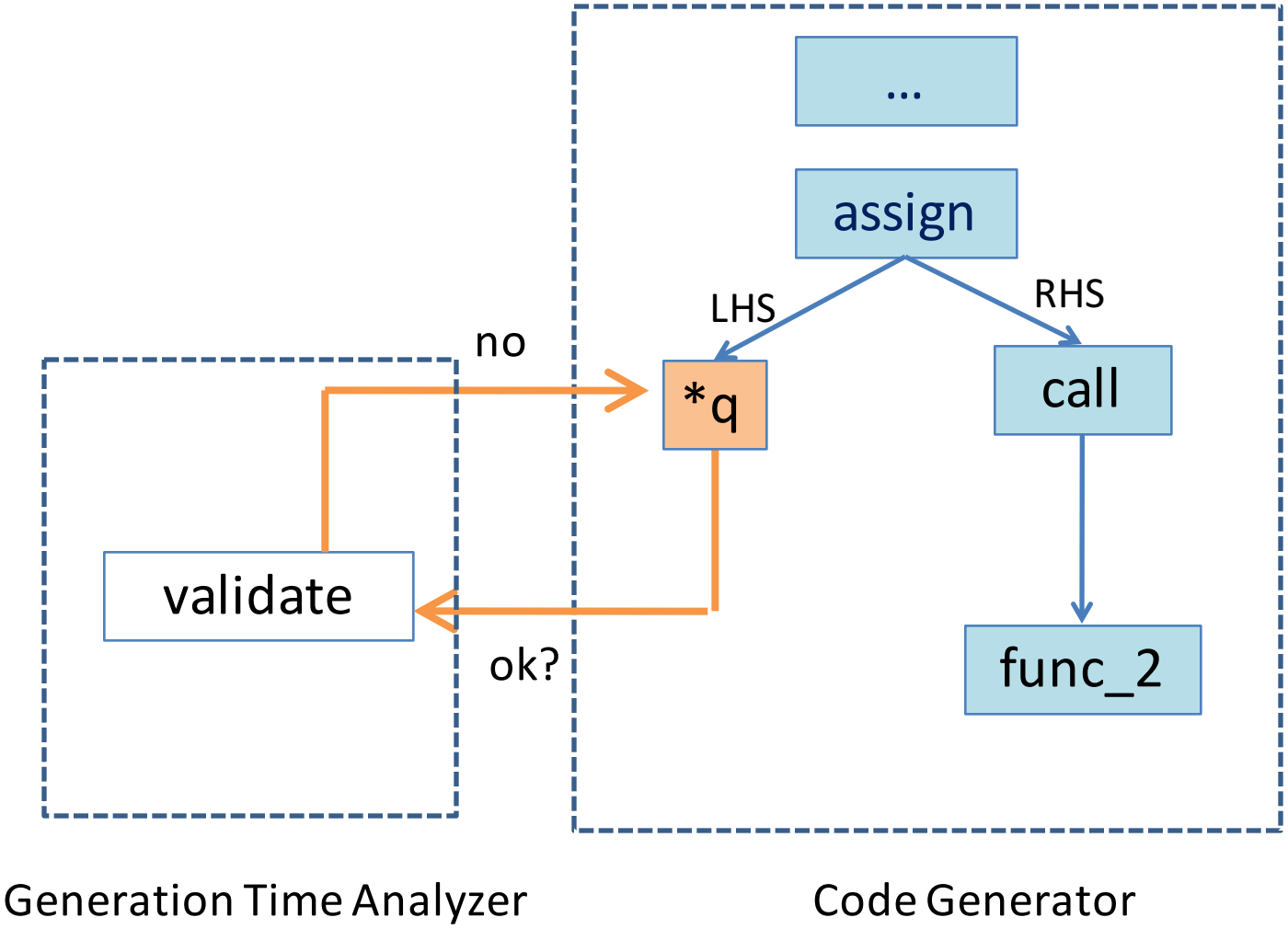
• **Expressiveness**: support most commonly used C features

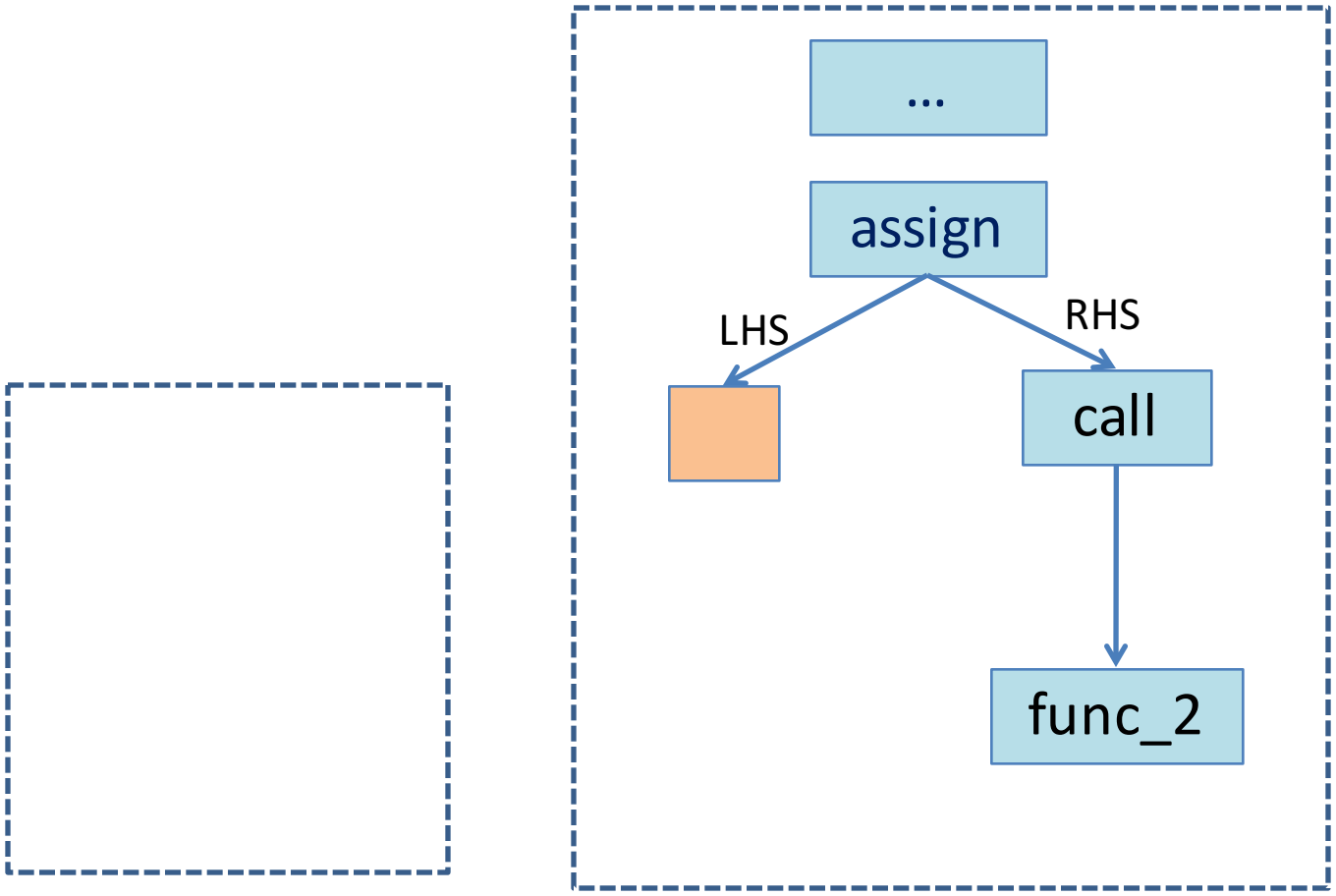
Integer operations	**Const and volatile**
Loops (with break/continue)	**Structs and Bitfields**
Conditionals	**Pointers and arrays**
Function calls	**Goto**

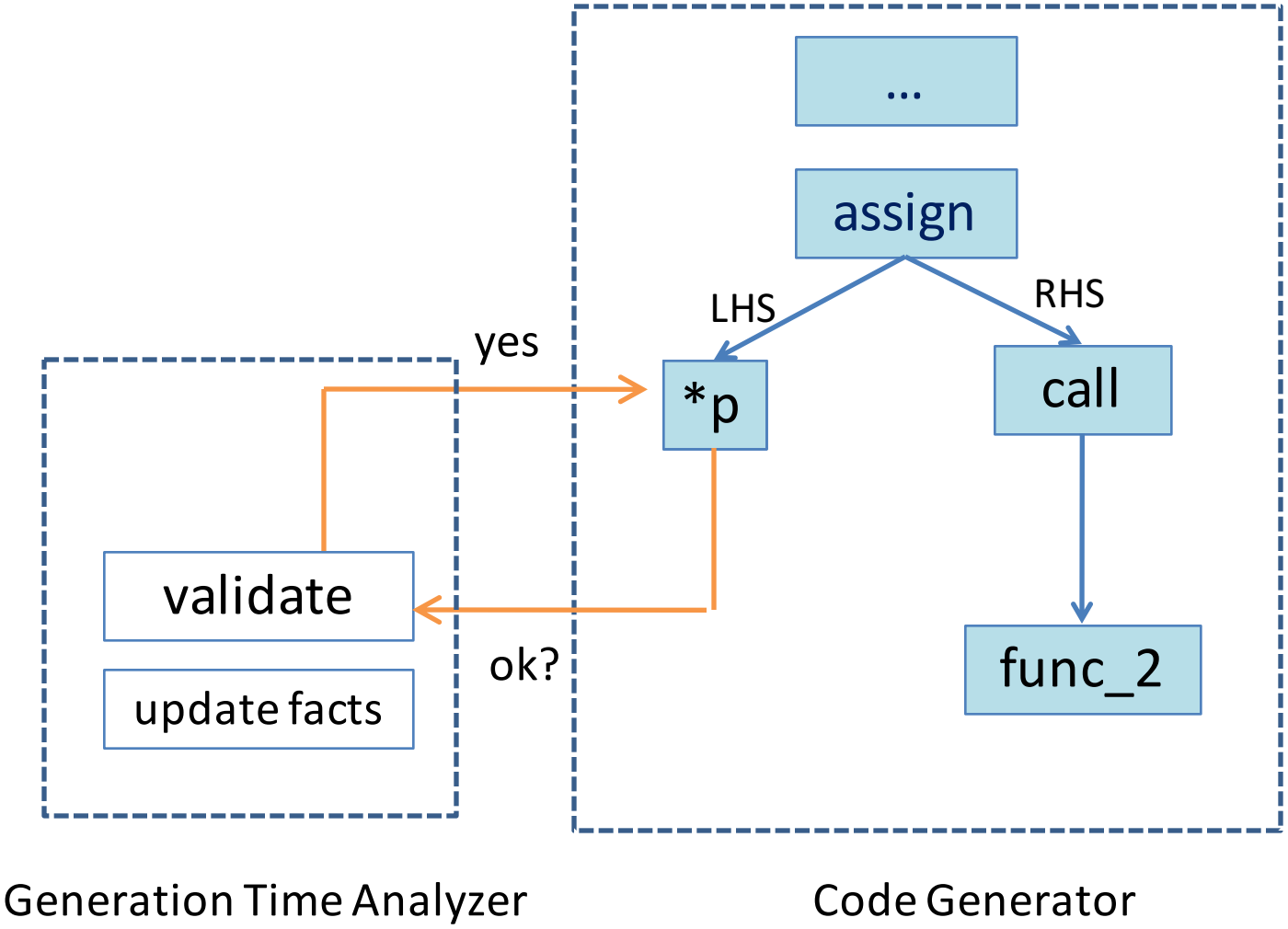

Cumulative Distinct Crash Errors
90
80
70
60
50
40
30
20
10
0
0
1
2
3
4
5
6
7
Testing Time (Days)
Csmith : 86 crashes
Eide08 : 33 crashes
Lindig07 : 20 crashes
Turner05 : 14 crashes
McKeeman98 : 9 crashes

Avoiding Undefined/unspecified Behaviors

Problem	Generation Time Solution	Run Time Solution
Integer undefined behaviors	• Constant folding/propagation • Algebraic simplification	Safe math wrappers
Use without initialization	explicit initializers	
OOB array access	Force index within range	Take modulus
Null pointer dereference	Inter-procedural points-to analysis	
Use of dangling pointers	Inter-procedural points-to analysis	
Unspecified evaluation order	Inter-procedural effect analysis	


...
assign
LHS
RHS
no
*q
call
validate
ok?
func_2
Generation Time Analyzer
Code Generator


...
assign
LHS
RHS
call
func_2
Generation Time Analyzer
Code Generator


...
assign
LHS
RHS
yes
*p
call
validate
update facts
ok?
func_2
Generation Time Analyzer
Code Generator

- From March, 2008 to present:

Compiler	Bugs reported (fixed)
GCC	104 (86)
LLVM	228 (221)
Others (Compcert, icc, armcc, tcc, cil, suncc, open64, etc)	50
Total	382

Accounts for 1% total valid GCC bugs reported in the same period

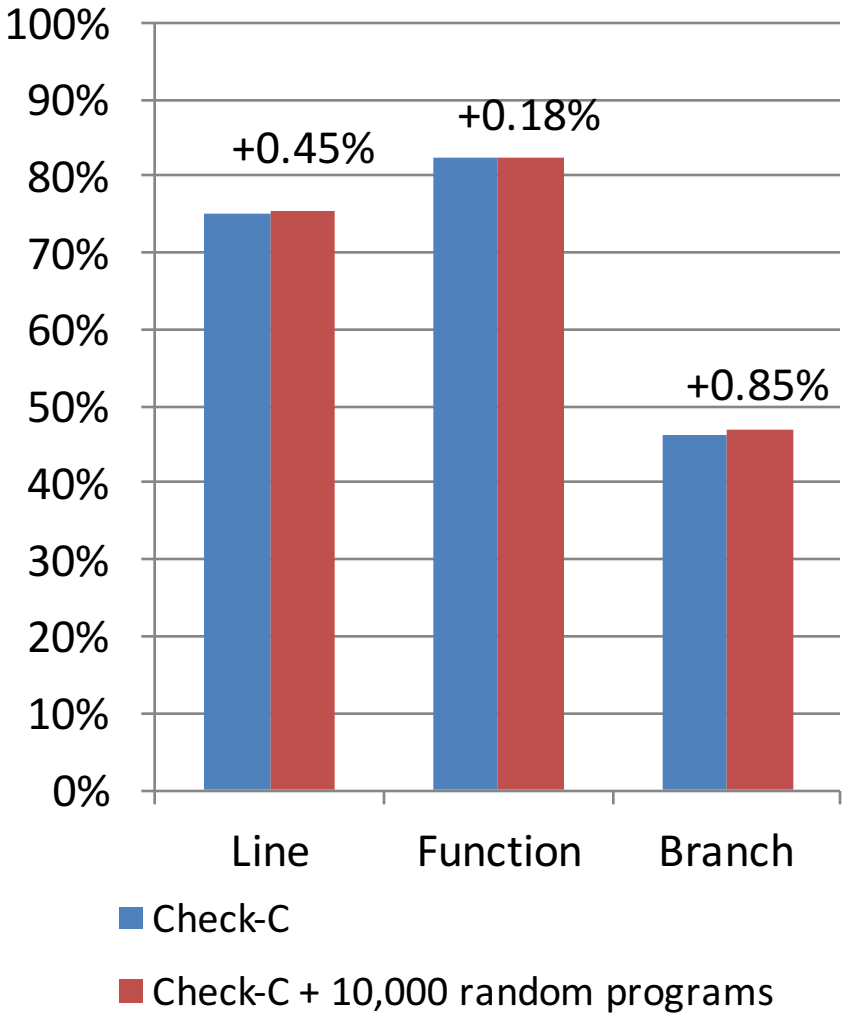
Accounts for 3.5% total valid LLVM bugs reported in the same period

- Do they matter?
  - 25 priority 1 bugs for GCC
  - 8 of reported bugs were re-reported by others

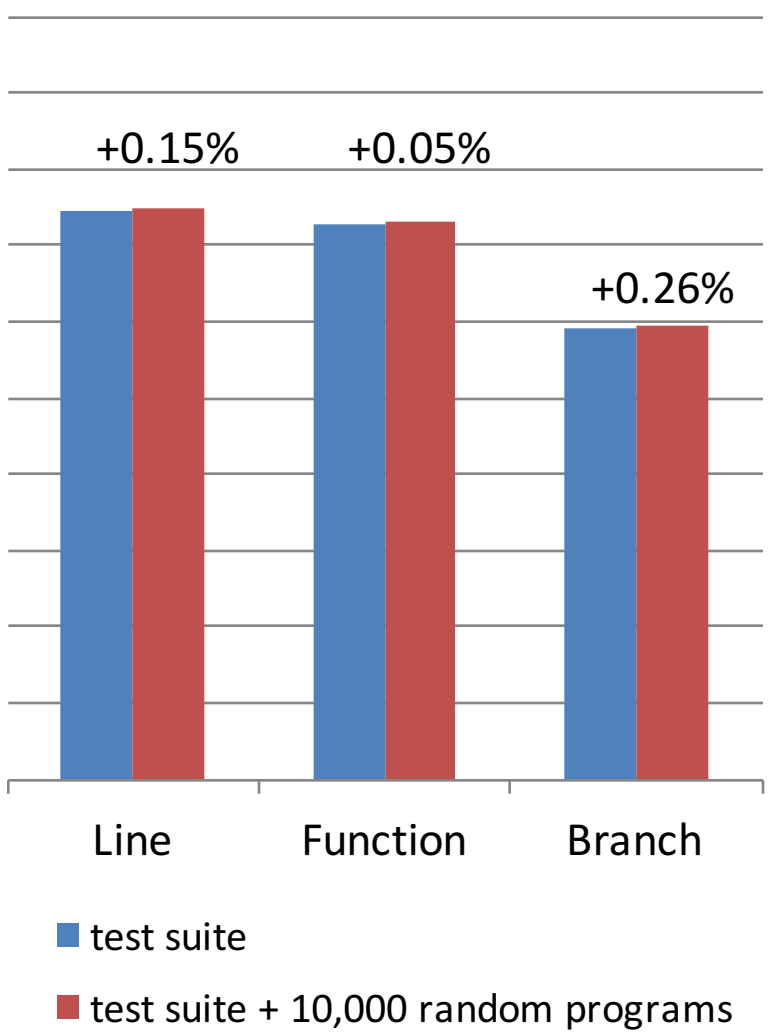
Bug Dist. Across Compiler Stages

	GCC	LLVM
Front end	1	11
Middle end	71	93
Back end	28	78
Unclassified	4	46
Total	104	228

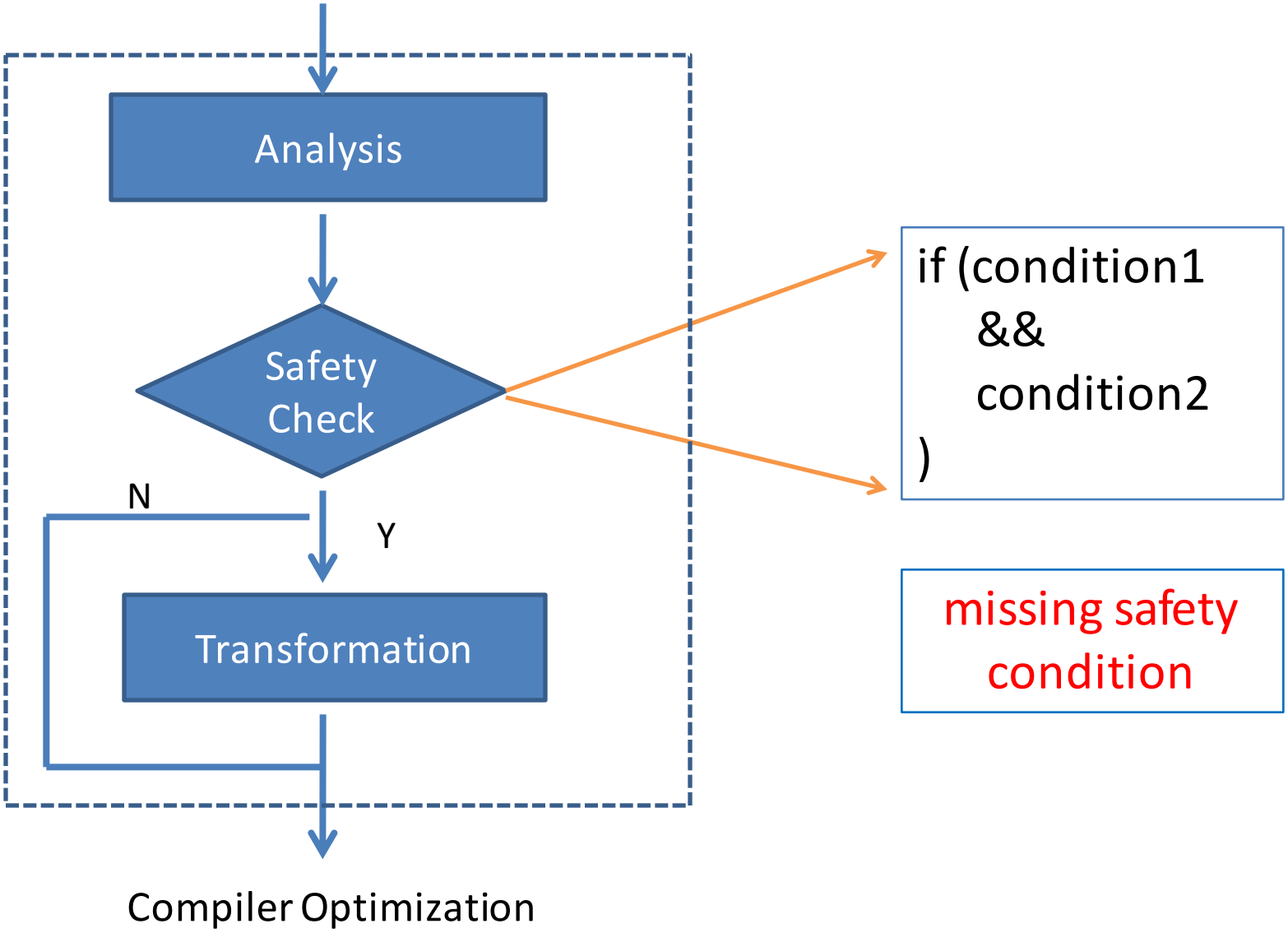
Coverage of GCC



Coverage of LLVM/Clang



Common Compiler Bug Pattern



Optimization Bug

```
void foo (void) {
    int x;
    for (x = 0; x < 5; x++) {
        if (x) continue;
        if (x) break;
    }
    printf ("%d", x);
}
```

- Bug in LLVM in
  scalar evolution analysis computed
  x is 1 after the loop executed

UNDEFINED BEHAVIOR

Example

```
int foo(int a)
{
    return (a+1) > a;
}
```

```
foo: movl $1, %eax
        ret
```

Undefined Behavior

- Executing an erroneous operation
- The program may :
  - fail to compile
  - execute incorrectly
  - crash
  - do exactly what the programmer intended

Undefined Behavior - challenges

- Programmers are not aware of all undefined behavior
- Code may be compiled for a different environment with a different compiler
  - Which undefined behavior are different?

PROJECT IDEAS

1. Add features that are not supported by Csmith
   - C++ constructs
   - Heap allocation
   - Recursive
   - String Operation
   - Use of common libraries
2. Generate programs that takes input
   - Use another fuzzer (constraint-based) to generate inputs to the generated program
3. Generate programs with undefined behavior
   - Automatically understand them
   - Use reduce testcase tools
4. Enhance Csmith by incorporating other fuzzing techniques (mutation, genetic)
5. Apply approach for different languages
6. ….Your idea…

JFuzzer

- Test javascript engines
  - SpiderMonkey (Mozilla)
  - Rhino (Mozilla)
  - NodeJS (Wrapper for Google's V8)
  - Nashrom (Oracle→ Open Source)
  - Dyn.JS

JFuzzer

- AST-based program generation
  - Tweaking : Avoid calling undefined functions, disabling this
- Comparing outputs
  - Global variables at the end
  - Flow of control

JFuzzer

- Results: 5% of the input programs led to different results
- Bugs:
  - Dead code elimination
  - Conditional definitions
  - !2^k, k=32,…,52 is false except in Dyn.JS
  - …

AVR-GCC

- Use fuzzing to find bugs in AVR-GCC, a version of GCC for ATMEL microcontrollers, most popularly Arduino.
- Compile the code on different platforms and with different optimizations to find bugs without relying on known test results
- Characterize the bugs

Features

Csmith is used to generate expressive programs that are small enough to fit on Arduino.

Test avr-gcc intensively by using all available optimizations and by comparing the result with gcc on x86. Handle machine word size differences correctly.

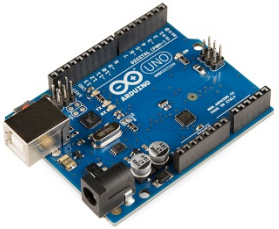
Features

Execute microcontroller code on both the simulator and the real hardware to locate possible simulator bugs as well

A debugger was written to assist with bug characterization, which locates the first line of code that assigns a different value across platforms and optimizations

Challenges & Solutions

- print x86/Arduino
- Limited space on at328p chip
- 32bit vs 8bit
- Debugging



Challenges & Solutions

- Example:

```
{
uint32_t x;
int y;
x+=y;
}
```

```
{
uint32_t x;
int y;
x+=print17(y,3);
}

uint32_t print17(uint32_t x, int line_number);
```

- make sure that the function parameter type and the return type match the type of the l-value in the assignment to keep the behavior unchanged according to the C99 language standard

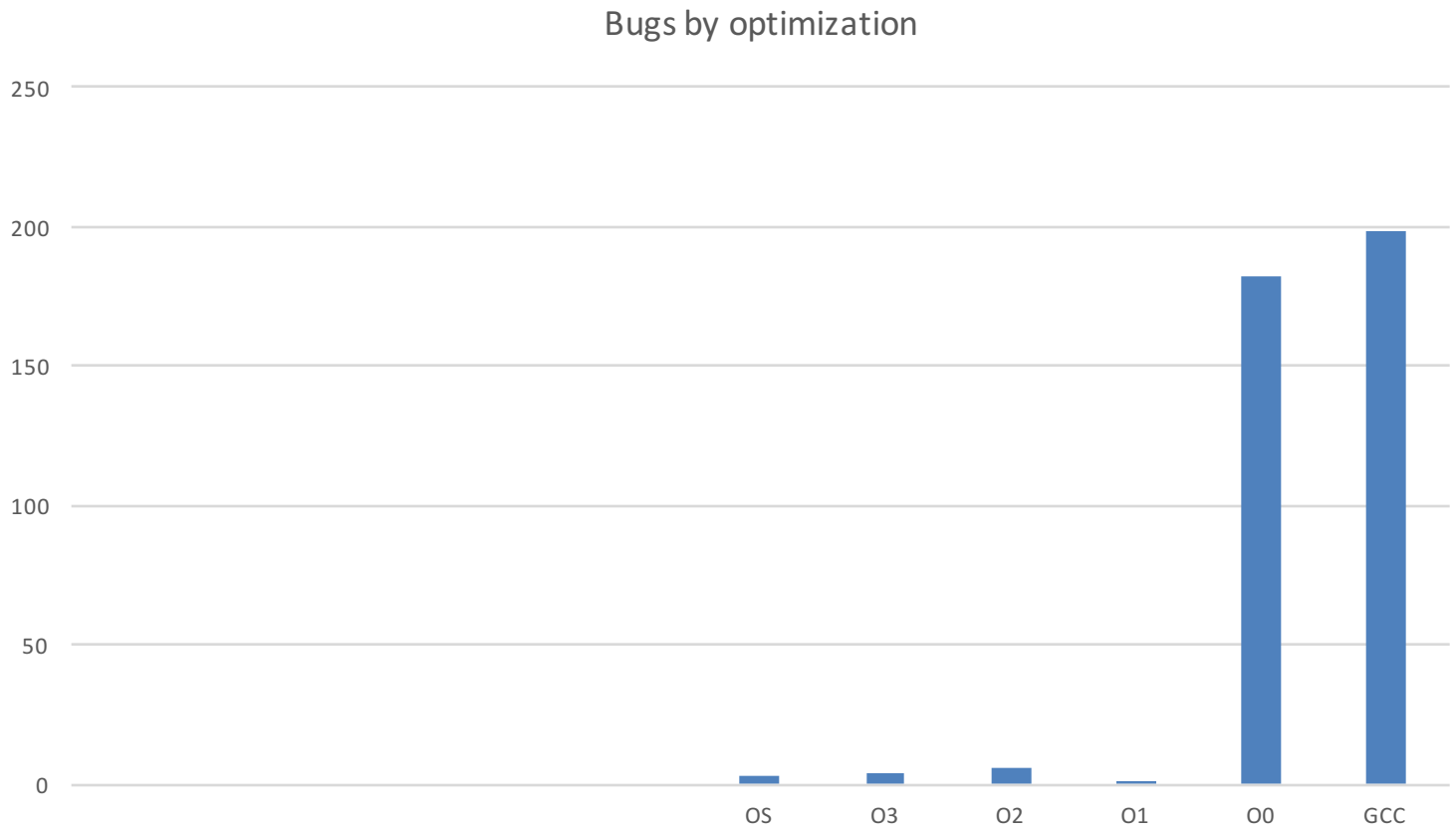
Challenges & Solutions

- Given the large complexity of test cases, optimizations and different machines, we built scripts to generate test programs, automatically compile them for x86 or arduino using the various optimizations available, run the results on a pc or on a simulator and sort the results

Results & Statistics

Optimization	Bug count
GCC	198
O0	182
O1	1
O2	6
O3	4
Os	3

Results & Statistics



Results & Statistics

A total of 9310 test programs were generated, of which 394 contained compiler bugs, about **4%**

Results & Statistics – Bug Demo #1

16 bit arithmetic bug: 0x4000 * 0x2 is 0x8000 or 1000 0000 0000 0000 (b)
which is correct when compiled for x86, but with avr the result is 0x7fff
or 01111 1111 1111 1111 (b)
as seen in the following code:

```
platform_main_end((int16_t)0x4000 * (int16_t)0x2L, 1);
```

Results & Statistics – Bug Demo #2 A Csmith issue with undefined behavior

32 bit shift bug: a 32 bit shift results in different values when shifted by a constant or by a value stored in a variable. Seen in avr, not seen in gcc. Csmith shouldn't generate such code at all, because this behavior is undefined

example code:

```
int32_t x = 32L;
platform_main_end(0x1L << 32L, 1); // this is zero
platform_main_end(0x1L << x, 1); // this should be zero, but is 1 on avr
```

RESOURCES

- Fuzzer survey

  https://fuzzinginfo.files.wordpress.com/2012/05/dsto-tn-1043-pr.pdf
- Csmith

  Website: https://embed.cs.utah.edu/csmith/

  paper: http://www.cs.utah.edu/~regehr/papers/pldi11-preprint.pdf
- Undefined behavior
  - http://blog.regehr.org/archives/213