Compile Once
Debug Twice

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Co-founder of Backtrace. Building a modern debugging platform for natively compiled software.

AppNexus, Message Systems, GWU HPCL. Scalability, reliability, productivity, multicore, heterogeneous architectures and PGAS.

Concurrency Kit. Advanced synchronization primitives for the research, design and implementation of high-performance concurrent systems.

Introduction

```
(lldb) frame variable
(void *) unused = <variable not available>
(int) n_state = <variable not available>

(uint64_t) a = 0
(uint64_t) j = <variable not available>
```

Introduction

Most people select their compiler based on:

- Availability
- Correctness
- Compilation Speed
- Code Generation Quality

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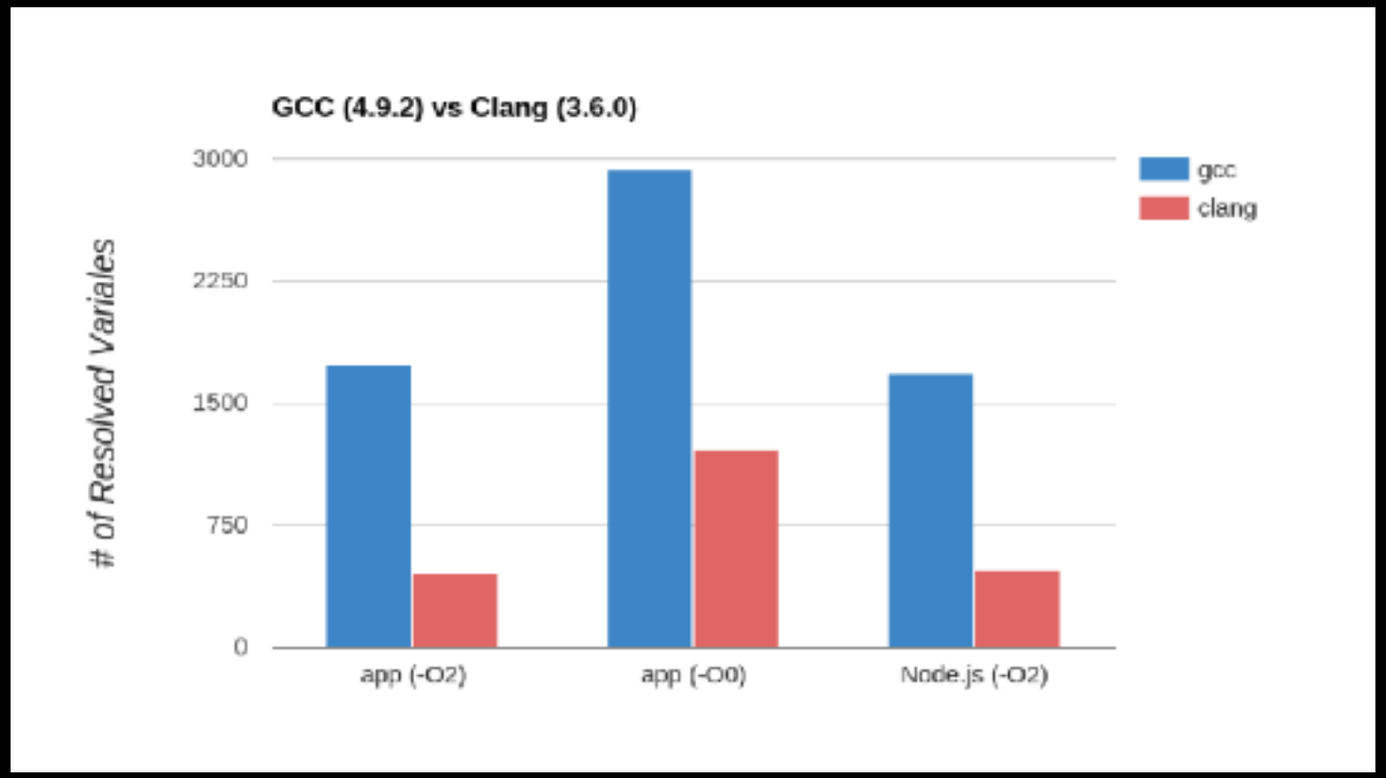
A facet that is commonly ignored is:
Debug Information Quality.

Introduction

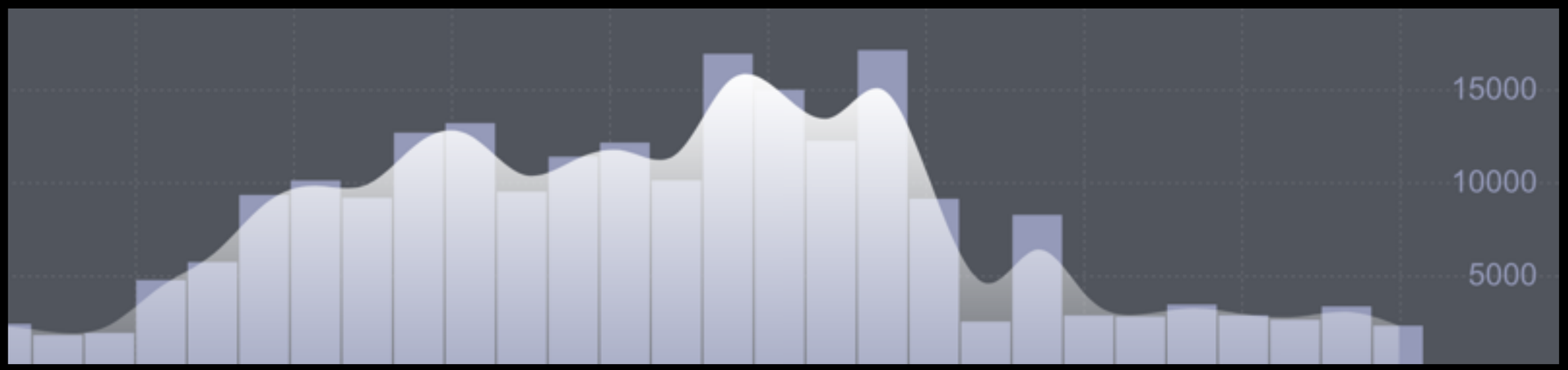
Debug information quality **is not** proportionally related to the quality of the generated executable code and wildly varies from compiler to compiler.



Introduction

Being able to symbolically debug your software effectively directly impacts your ability to resolve many classes of bugs quickly.

Resolution time can be the difference between success and failure.



– “We crash a couple hundred times a day”

Backtrace

Agenda

- An Introduction to Symbolic Debugging
- Optimizations and Debug Information
- A Comparison

Symbolic Debugging

The wc program tells you the number of ‘w’ characters in a file, terribly.

```
static unsigned int
count(char *buffer, size_t n)
{
        unsigned int sum = 0;
        size_t i;

        for (i = 0; i < n; i++)
                sum += buffer[i] == 'w';

       return sum;
}
```

Symbolic Debugging

The program is compiled and linked into an executable file in a format the underlying operating system understands.

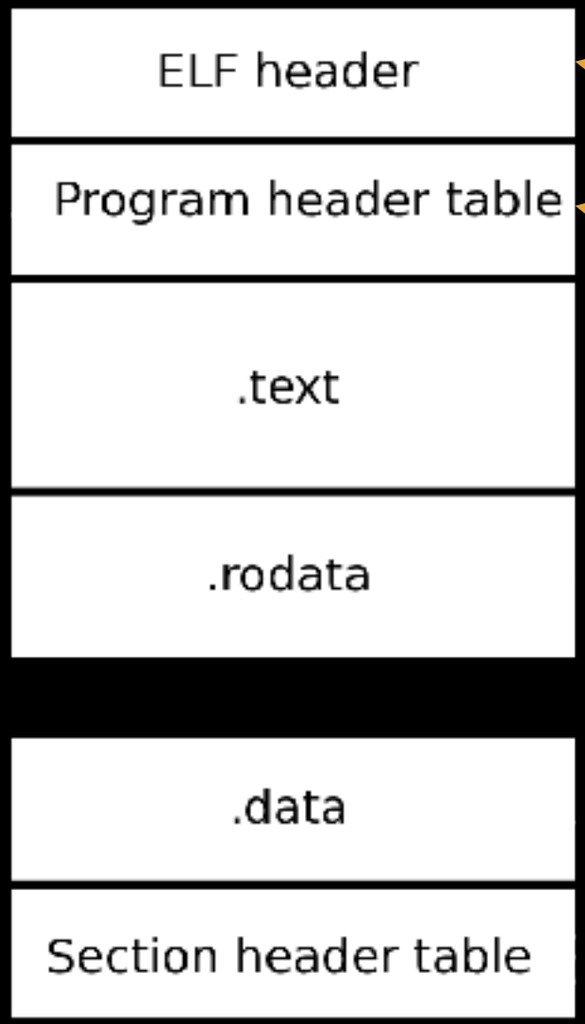
```
$ gcc -o wc wc.c -O2 -ggdb
$ ./wc /etc/passwd
16
```

The executable format consists of various sections that tell the kernel **how** the executable should be loaded as well as **executable code.**

Symbolic Debug

Mention Mach-O and PE.

ELF for **E**xecutable and **L**inking **F**ormat




```
sbahra@broadwell$ readelf -l ./wc

Elf file type is EXEC (Executable file)
Entry point 0x400800
There are 9 program headers, starting at offset 64

Program Headers:
  Type           Offset             VirtAddr           PhysAddr
                 FileSiz            MemSiz              Flags  Align
  PHDR           0x0000000000000040 0x0000000000400040 0x0000000000400040
                 0x00000000000001f8 0x00000000000001f8  R E    8
  INTERP         0x0000000000000238 0x0000000000400238 0x0000000000400238
                 0x000000000000001c 0x000000000000001c  R      1
      [Requesting program interpreter: /lib64/ld-linux-x86-64.so.2]
  LOAD           0x0000000000000000 0x0000000000400000 0x0000000000400000
                 0x0000000000000b24 0x0000000000000b24  R E    200000
  LOAD           0x0000000000000e08 0x0000000000600e08 0x0000000000600e08
                 0x0000000000000270 0x0000000000000288  RW     200000
  DYNAMIC        0x0000000000000e28 0x0000000000600e28 0x0000000000600e28
                 0x00000000000001d0 0x00000000000001d0  RW     8
  NOTE           0x0000000000000254 0x0000000000400254 0x0000000000400254
                 0x0000000000000044 0x0000000000000044  R      4
  GNU_EH_FRAME   0x00000000000009b8 0x00000000004009b8 0x00000000004009b8
                 0x000000000000003c 0x000000000000003c  R      4
  GNU_STACK      0x0000000000000000 0x0000000000000000 0x0000000000000000
                 0x0000000000000000 0x0000000000000000  RW     10
  GNU_RELRO      0x0000000000000e08 0x0000000000600e08 0x0000000000600e08
                 0x00000000000001f8 0x00000000000001f8  R      1
```

Symbolic Debugging

```
static unsigned int
count(char *buffer, size_t n)
{
        unsigned int sum = 0;
        size_t i;

        for (i = 0; i < n; i++)
                sum += buffer[i] == 'w';

        return sum;
}
```

```
Dump of assembler code for function count:
   0x00000000004008b0 <+0>:     push   %rbx
   0x00000000004008b1 <+1>:     lea    0x1000(%rdi),%rdx
   0x00000000004008b8 <+8>:     xor    %ebx,%ebx
   0x00000000004008ba <+10>:    nopw   0x0(%rax,%rax,1)
   0x00000000004008c0 <+16>:    xor    %eax,%eax
   0x00000000004008c2 <+18>:    cmpb   $0x77,(%rdi)
   0x00000000004008c5 <+21>:    sete   %al
   0x00000000004008c8 <+24>:    add    $0x1,%rdi
   0x00000000004008cc <+28>:    add    %eax,%ebx
   0x00000000004008ce <+30>:    cmp    %rdx,%rdi
   0x00000000004008d1 <+33>:    jne    0x4008c0 <count+16>
…
   0x00000000004008d8 <+40>:    mov    %ebx,%eax
   0x00000000004008da <+42>:    pop    %rbx
   0x00000000004008db <+43>:    retq
End of assembler dump.
```

Source is compiled into executable code that interacts with **memory** and a limited set of **registers**.

Symbolic Debugging

A symbolic debugger is able to map the state of registers and memory to a backtrace with variables and type information.

```
sbahra$ bt `pgrep wc`
PID: 8870
---------------------------------------------------------------------------
Thread 8870
  [  0] libc-2.21.so              pause (../sysdeps/unix/syscall-template.S:81)
…
  |  1| wc                        count (wc.c:19)
     buffer = (parameter) reference(0, 0x7ffce7b64e10)
       {char} -><> = string(0x7ffce7b64e10, 32, [root:x:0:0:root:/root:/bin/bash?])
     sum = 0
     i = --
     n = (parameter) 4096
  [  2] wc                        main (wc.c:42)
…
  [  3] libc-2.21.so              __libc_start_main
…
```

Symbolic Debugg

Mention that on Windows, other facilities are available.

The first step is to extract register state to determine the current state of the process.

```
NAME
     ptrace -- process tracing and debugging

SYNOPSIS
     #include <sys/types.h>
     #include <sys/ptrace.h>

     int
     ptrace(int request, pid_t pid, caddr_t addr, int data);
```

Available in various broken ways on Linux and the BSD family of operating systems.

Symbolic Debugging

The **%rip** register tells us the currently executing instruction in a program.

```
Thread 6870
------------------------------------------------------------------------------
 [  0] libc-2.21.so                pause (../sysdeps/unix/syscall-template.S:81)
------------------------------------------------------------------------------
   rax=0xfffffffffffffdfe       rdx=0x7ffce7b65e10       rcx=0x7ff9b15b5b70
                  rbx=0       rsi=0x7ff9b1ad5020       rdi=0x7ffce7b65e10
          rbp=0x10b6010       rsp=0x7ffce7b64df8        r8=0x7ff9b1ad5020
                   r9=0              r10=0x3c1               r11=0x246
           r12=0x4007b0       r13=0x7ffce7b65f10                  r14=0
                  r15=0      rip=0x7ff9b15b5b70                 cs=0x33
                 ss=0x2b                  ds=0                   es=0
                   fs=0                  gs=0           eflags=0x246
```

Symbolic Debugging

The kernel provides a mechanism to determine what the process address space looks like.

```
sbahra@broadwell$ cat /proc/`pgrep wc`/maps
00400000-00401000 r-xp 00000000 08:02 6034972                            /home/sbahra/projects/backtrace/bangbangcon/wc
00600000-00601000 r--p 00000000 08:02 6034972                            /home/sbahra/projects/backtrace/bangbangcon/wc
00601000-00602000 rw-p 00001000 08:02 6034972                            /home/sbahra/projects/backtrace/bangbangcon/wc
010b6000-010d7000 rw-p 00000000 00:00 0                                  [heap]
7ff9b14eb000-7ff9b16ab000 r-xp 00000000 08:02 5246298                    /lib/x86_64-linux-gnu/libc-2.21.so
7ff9b16ab000-7ff9b18ab000 ---p 001c0000 08:02 5246298                    /lib/x86_64-linux-gnu/libc-2.21.so
7ff9b18ab000-7ff9b18af000 r--p 001c0000 08:02 5246298                    /lib/x86_64-linux-gnu/libc-2.21.so
7ff9b18af000-7ff9b18b1000 rw-p 001c4000 08:02 5246298                    /lib/x86_64-linux-gnu/libc-2.21.so
7ff9b18b1000-7ff9b18b5000 rw-p 00000000 00:00 0
7ff9b18b5000-7ff9b18d9000 r-xp 00000000 08:02 5246292                    /lib/x86_64-linux-gnu/ld-2.21.so
7ff9b1ab1000-7ff9b1ab4000 rw-p 00000000 00:00 0
7ff9b1ad5000-7ff9b1ad8000 rw-p 00000000 00:00 0
7ff9b1ad8000-7ff9b1ad9000 r--p 00023000 08:02 5246292                    /lib/x86_64-linux-gnu/ld-2.21.so
7ff9b1ad9000-7ff9b1ada000 rw-p 00024000 08:02 5246292                    /lib/x86_64-linux-gnu/ld-2.21.so
7ff9b1ada000-7ff9b1adb000 rw-p 00000000 00:00 0
7ffce7b48000-7ffce7b69000 rw-p 00000000 00:00 0                          [stack]
7ffce7bf9000-7ffce7bfb000 r--p 00000000 00:00 0                          [vvar]
7ffce7bfb000-7ffce7bfd000 r-xp 00000000 00:00 0                          [vdso]
ffffffffff600000-ffffffffff601000 r-xp 00000000 00:00 0                  [vsyscall]
```

rip=0x7ff9b15b5b70

Symbolic Debugging

ELF objects contain various debug-related sections.

Section	Description
`.debug_line`	Maps memory addresses to line numbers.
`.debug_info`	Type, variable and function information.
`.debug_frame`	Unwinding information by memory address.
`.eh_frame`	Unwinding information by memory address.

These sections and their contents are specified by the **DWARF** format on most UNIX-like systems.

Symbolic Debugging

.debug_line contains a sequence of operations that are executed by a state machine to form a giant matrix.

```
[0x000000dc]  Extended opcode 2: set Address to 0x4008b0
[0x000000e7]  Special opcode 12: advance Address by 0 to 0x4008b0 and Line by 7 to 8
[0x000000e8]  Special opcode 119: advance Address by 8 to 0x4008b8 and Line by 2 to 10
[0x000000e9]  Special opcode 121: advance Address by 8 to 0x4008c0 and Line by 4 to 14
[0x000000ea]  Special opcode 200: advance Address by 14 to 0x4008ce and Line by -1 to 13
[0x000000eb]  Special opcode 78: advance Address by 5 to 0x4008d3 and Line by 3 to 16
[0x000000ec]  Special opcode 77: advance Address by 5 to 0x4008d8 and Line by 2 to 18
[0x000000ed]  Advance PC by 4 to 0x4008dc
[0x000000ef]  Extended opcode 1: End of Sequence

[0x000000f2]  Extended opcode 2: set Address to 0x4006c0
[0x000000fd]  Advance Line by 21 to 22
[0x000000ff]  Copy
[0x00000100]  Special opcode 131: advance Address by 9 to 0x4006c9 and Line by 0 to 22
[0x00000101]  Advance PC by constant 17 to 0x4006da
[0x00000102]  Special opcode 38: advance Address by 2 to 0x4006dc and Line by 5 to 27
[0x00000103]  Extended opcode 4: set Discriminator to 1
[0x00000107]  Set is_stmt to 0
[0x00000108]  Special opcode 75: advance Address by 5 to 0x4006e1 and Line by 0 to 27
```

Symbolic Debugging

.debug_line contains a sequence of operations that are executed by a state machine to form a giant matrix.

Address	Source
0x4000	wc.c:80
0x4008	wc.c:20
0x400d	wc.c:19
0x401a	wc.c:10

Symbolic Debugging

.debug_frame or **.eh_frame** contain a sequence of operations that are executed by a state machine to form a giant matrix of register states.

```
00000090 000000000000002c 00000064 FDE cie=00000030 pc=00000000004006c0..00000000040078d
  DW_CFA_advance_loc: 1 to 00000000004006c1
  DW_CFA_def_cfa_offset: 16
  DW_CFA_offset: r6 (rbp) at cfa-16
  DW_CFA_advance_loc: 1 to 00000000004006c2
  DW_CFA_def_cfa_offset: 24
  DW_CFA_offset: r3 (rbx) at cfa-24
  DW_CFA_advance_loc: 7 to 00000000004006c9
  DW_CFA_def_cfa_offset: 4144
  DW_CFA_advance_loc1: 131 to 000000000040074c
  DW_CFA_remember_state
  DW_CFA_def_cfa_offset: 24
  DW_CFA_advance_loc: 1 to 000000000040074d
  DW_CFA_def_cfa_offset: 16
  DW_CFA_advance_loc: 1 to 000000000040074e
  DW_CFA_def_cfa_offset: 8
  DW_CFA_advance_loc: 1 to 000000000040074f
  DW_CFA_restore_state
```

Symbolic Debug

Mention David Watson's talk about exception handing.

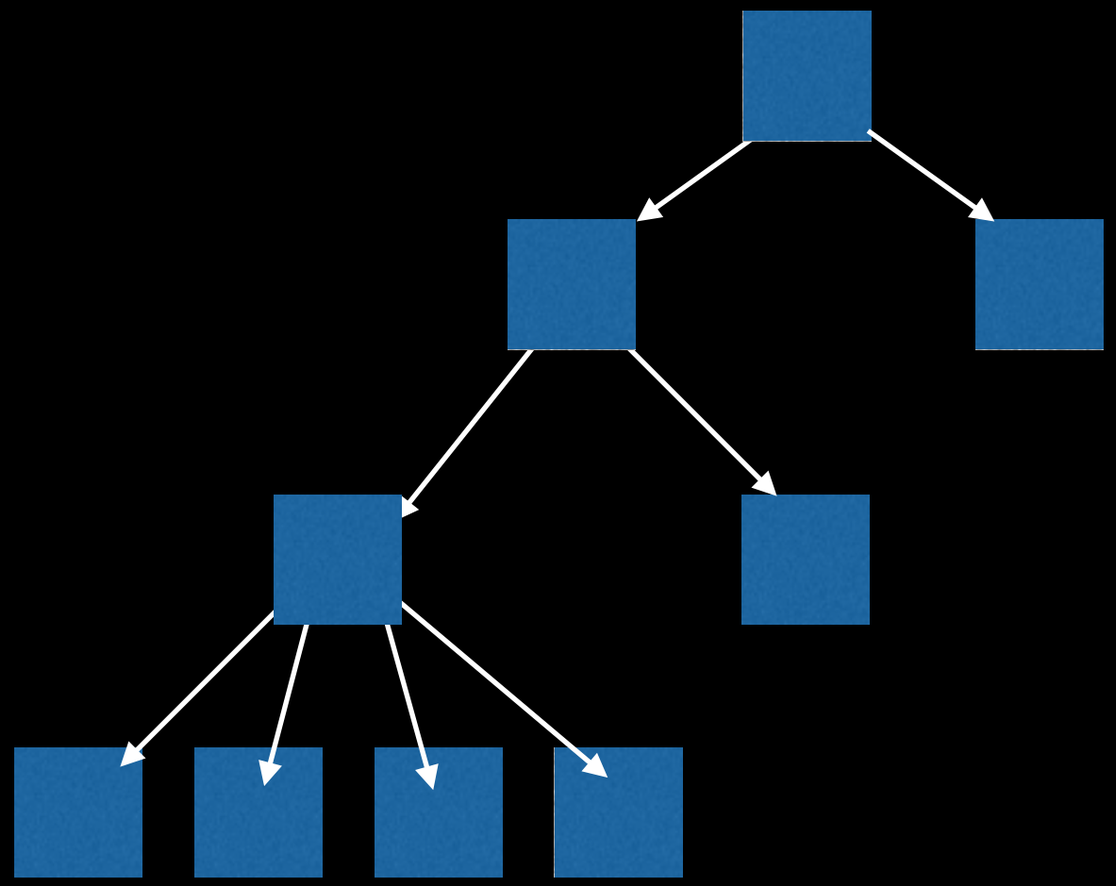
.eh_frame is included in programs that need to do exception unwinding.

.debug_frame or **.eh_frame** contain a sequence of operations that are executed by a state machine to form a giant matrix of register states.

```
000000d0 0000000000000044 000000a4 FDE cie=00000030 pc=4005e0..400645
   LOC           CFA      rbx   rbp   r12   r13   r14   r15   ra
0000000000004005e0 rsp+8    u     u     u     u     u     u     c-8
0000000000004005e2 rsp+16   u     u     u     u     u     c-16  c-8
0000000000004005e4 rsp+24   u     u     u     u     c-24  c-16  c-8
0000000000004005e9 rsp+32   u     u     u     c-32  c-24  c-16  c-8
0000000000004005eb rsp+40   u     u     c-40  c-32  c-24  c-16  c-8
0000000000004005f3 rsp+48   u     c-48  c-40  c-32  c-24  c-16  c-8
0000000000004005fb rsp+56   c-56  c-48  c-40  c-32  c-24  c-16  c-8
000000000040060a rsp+64   c-56  c-48  c-40  c-32  c-24  c-16  c-8
000000000040063a rsp+56   c-56  c-48  c-40  c-32  c-24  c-16  c-8
000000000040063b rsp+48   c-56  c-48  c-40  c-32  c-24  c-16  c-8
000000000040063c rsp+40   c-56  c-48  c-40  c-32  c-24  c-16  c-8
000000000040063e rsp+32   c-56  c-48  c-40  c-32  c-24  c-16  c-8
0000000000400640 rsp+24   c-56  c-48  c-40  c-32  c-24  c-16  c-8
0000000000400642 rsp+16   c-56  c-48  c-40  c-32  c-24  c-16  c-8
```

Symbolic Debugging

.debug_info specifies how the program is structured. It includes **type**, **variable** and other **structural** information.



Symbolic Debugging

DW_TAG_compile_unit
DW_AT_name = wc.c
DW_AT_ranges = A .. B

DW_TAG_subprogram
DW_AT_name = count
DW_AT_type =

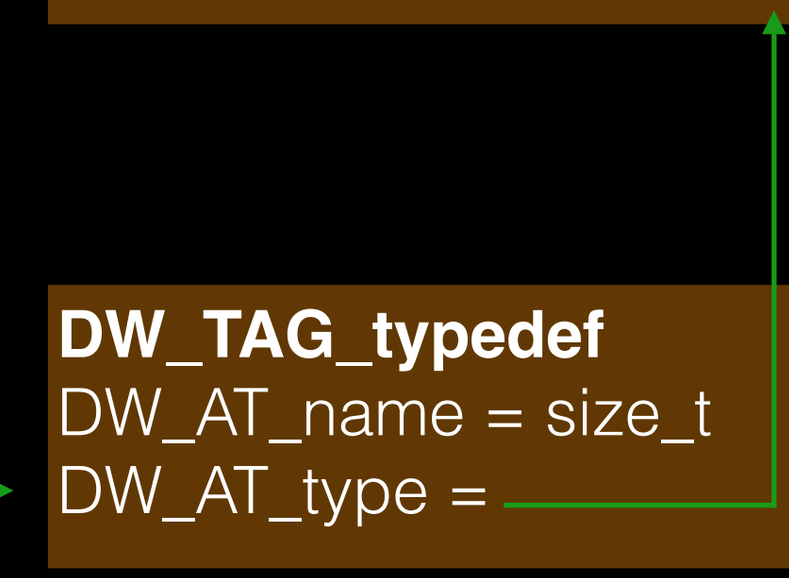
DW_TAG_formal_parameter
DW_AT_name = buffer
DW_AT_type =

DW_TAG_variable
DW_AT_name = **sum**
DW_AT_type =

DW_TAG_variable
DW_AT_name = i
DW_AT_type =

DW_TAG_base_type
DW_AT_byte_size = 8
DW_AT_encoding = unsigned
DW_AT_name = “long unsigned”

DW_TAG_typedef
DW_AT_name = size_t
DW_AT_type =



Symbolic Debugging

DWARF must support all kinds of aggressive compiler optimizations and has a complex expression state machine for expressing variable values.

```
static unsigned int
count(char *buffer, size_t n)
{
        unsigned int sum = 0;
        size_t i;

        for (i = 0; i < n; i++)
                sum += buffer[i] == 'w';

       return sum;
}
```

```
Dump of assembler code for function count:
   0x00000000004008b0 <+0>:     push   %rbx
   0x00000000004008b1 <+1>:     lea    0x1000(%rdi),%rdx
   0x00000000004008b8 <+8>:     xor    %ebx,%ebx
   0x00000000004008ba <+10>:    nopw   0x0(%rax,%rax,1)
   0x00000000004008c0 <+16>:    xor    %eax,%eax
   0x00000000004008c2 <+18>:    cmpb   $0x77,(%rdi)
   0x00000000004008c5 <+21>:    sete   %al
   0x00000000004008c8 <+24>:    add    $0x1,%rdi
   0x00000000004008cc <+28>:    add    %eax,%ebx
   0x00000000004008ce <+30>:    cmp    %rdx,%rdi
   0x00000000004008d1 <+33>:    jne    0x4008c0 <count+16>
…
   0x00000000004008d8 <+40>:    mov    %ebx,%eax
   0x00000000004008da <+42>:    pop    %rbx
   0x00000000004008db <+43>:    retq
End of assembler dump.
```

Symbolic Debugging

```
< 2><0x00000361>      DW_TAG_variable
                        DW_AT_name                  "i"
                        DW_AT_decl_file             0x00000001 /home/sbahra/projects/backtrace/bangbangcon/wc.c
                        DW_AT_decl_line             0x0000000b
                        DW_AT_type                  <0x00000029>
…
< 1><0x0000036b>    DW_TAG_subprogram
                      DW_AT_abstract_origin       <0x00000332>
                      DW_AT_low_pc                0x004008b0
                      DW_AT_high_pc               <offset-from-lowpc>44
…
< 2><0x0000038f>      DW_TAG_variable
                        DW_AT_abstract_origin       <0x00000356>
                        DW_AT_location              <loclist with 3 entries follows>
                    4008b0 4008ba (DW_OP_lit0; DW_OP_stack_value)
                    4008ba 4008cc (DW_OP_breg5 (rdi): 0; DW_OP_breg1 (rdx): 0; DW_OP_minus; DW_OP_plus_uconst: 4096; DW_OP_stack_value)
                    4008cc 4008ce (DW_OP_breg5 (rdi): 0; DW_OP_breg1 (rdx): 0; DW_OP_minus; DW_OP_plus_uconst: 4095; DW_OP_stack_value)
```

```
   0x00000000004008b0 <+0>:     push   %rbx
   0x00000000004008b1 <+1>:     lea    0x1000(%rdi),%rdx
   0x00000000004008c0 <+16>:    xor    %eax,%eax
   0x00000000004008c2 <+18>:    cmpb   $0x77,(%rdi)
   0x00000000004008c5 <+21>:    sete   %al
   0x00000000004008d1 <+33>:    jne    0x4008c0 <count+16>
…
   0x00000000004008d8 <+40>:    mov    %ebx,%eax
   0x00000000004008da <+42>:    pop    %rbx
   0x00000000004008db <+43>:    retq
End of assembler dump.
```

Backtrace

Symbolic Debugging

```
< 2><0x00000361>      DW_TAG_variable
                        DW_AT_name                  "i"
                        DW_AT_decl_file             0x00000001 /home/sbahra/projects/backtrace/bangbangcon/wc.c
                        DW_AT_decl_line             0x0000000b
                        DW_AT_type                  <0x00000029>
…
< 1><0x0000036b>    DW_TAG_subprogram
                      DW_AT_abstract_origin       <0x00000332>
                      DW_AT_low_pc                0x004008b0
                      DW_AT_high_pc               <offset-from-lowpc>44
…
< 2><0x0000038f>      DW_TAG_variable
                        DW_AT_abstract_origin       <0x00000356>
                        DW_AT_location              <loclist with 3 entries follows>
    4008b0 4008ba (DW_OP_lit0; DW_OP_stack_value)
    4008ba 4008cc (DW_OP_breg5 (rdi): 0; DW_OP_breg1 (rdx): 0; DW_OP_minus; DW_OP_plus_uconst: 4096; DW_OP_stack_value)
    4008cc 4008ce (DW_OP_breg5 (rdi): 0; DW_OP_breg1 (rdx): 0; DW_OP_minus; DW_OP_plus_uconst: 4095; DW_OP_stack_value)
```

```
(gdb) info locals
sum = 0
i = <optimized out>
(gdb) break *0x4008cc
Breakpoint 2 at 0x4008cc: file wc.c, line 14.
(gdb) r
14                          sum += buffer[i] == 'w';
(gdb) info locals
sum = 0
i = 0
```

```
Dump of assembler code for function count:
   0x00000000004008b0 <+0>:     push   %rbx
   0x00000000004008b1 <+1>:     lea    0x1000(%rdi),%rdx
   0x00000000004008b8 <+8>:     xor    %ebx,%ebx
   0x00000000004008ba <+10>:    nopw   0x0(%rax,%rax,1)
   0x00000000004008c0 <+16>:    xor    %eax,%eax
   0x00000000004008c2 <+18>:    cmpb   $0x77,(%rdi)
   0x00000000004008c5 <+21>:    sete   %al
   0x00000000004008c8 <+24>:    add    $0x1,%rdi
   0x00000000004008cc <+28>:    add    %eax,%ebx
   0x00000000004008ce <+30>:    cmp    %rdx,%rdi
   0x00000000004008d1 <+33>:    jne    0x4008c0 <count+16>
…
   0x00000000004008d8 <+40>:    mov    %ebx,%eax
   0x00000000004008da <+42>:    pop    %rbx
   0x00000000004008db <+43>:    retq
End of assembler dump.
```

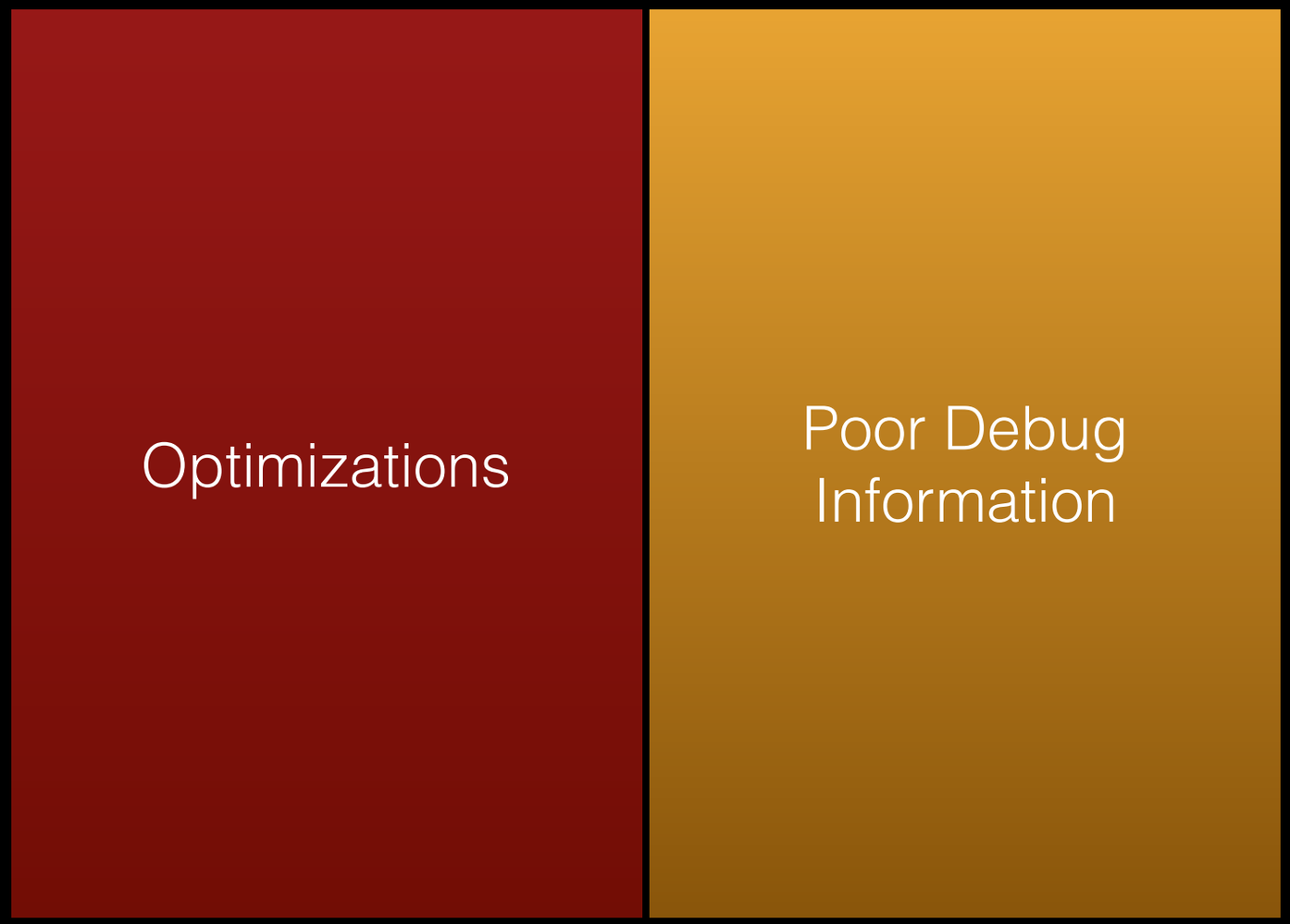
Backtrace

Symbolic Debugging

DWARF is designed to support aggressive compiler optimizations.

So why is my debugger not unwinding correctly or missing crucial information such as variable values?

Symbolic Debugging



Debug Information Quality

Though a debugger may show a value as optimized output, it may just be a side-effect of bad DWARF being emitted.

```
(gdb) info locals
sum = 0
i = <optimized out>
(gdb) break *0x4008cc
Breakpoint 2 at 0x4008cc: file wc.c, line 14.
(gdb) r
14                      sum += buffer[i] == 'w';
(gdb) info locals
sum = 0
i = 0
```

```
Dump of assembler code for function count:
   0x00000000004008b0 <+0>:     push   %rbx
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   0x00000000004008c0 <+16>:    xor    %eax,%eax
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   0x00000000004008ce <+30>:    cmp    %rdx,%rdi
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…
   0x00000000004008d8 <+40>:    mov    %ebx,%eax
   0x00000000004008da <+42>:    pop    %rbx
   0x00000000004008db <+43>:    retq
End of assembler dump.
```

Debug Information Quality

This program stores a loop counter into the same variable UINT64_MAX times.

```
int
main(void)
{
        uint64_t limit;
        uint64_t vr_index;
        uint64_t vr_ac = 0;

        VOLATILE_STORE(&limit, UINT64_MAX);
        for (vr_index = 0; vr_index < limit; vr_index++)
                VOLATILE_STORE(&vr_ac, vr_index);

        pause();
        return vr_ac;
}
```

Debug Information Quality

Different compilers emit DWARF at varying levels of **quality** and **accuracy.**

GCC	clang
Thread 11237 [1] induction_00 main limit = 18446744073709551615 vr_index = 6676766858 vr_ac = 6676766857	[1] induction_00 main vr_ac = 0 vr_index = 0 limit = -- [optimized out]
CORRECT	**INVALID DATA**

Optimizations

Let’s review optimizations that will impact availability of debug information.

Variables and Optimization

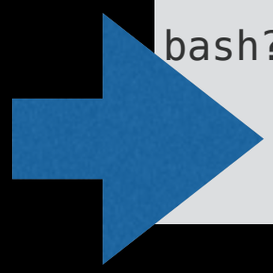
Unfortunately, things do **actually** get optimized out.

```
static unsigned int
count(char *buffer, size_t n)
{
        unsigned int sum = 0;
        size_t i;

        for (i = 0; i < n; i++)
                sum += buffer[i] == 'w';

       return sum;
}
```

```
 [  1] wc.gcc                          count.constprop.0
     buffer = (parameter) reference(0, 0x7ffe8ef83ac0)
       {char} -><> = string(0x7ffe8ef83ac0, 32, [root:x:0:0:root:/root:/bin/
bash?])
     sum = 0
     i = --
     n = (parameter) 4096
```



Variables and Optimization

Unfortunately, things do **actually** get optimized out.

```
static unsigned int
count(char *buffer, size_t n)
{
        unsigned int sum = 0;
        char *end = buffer + n;

        do {
                sum += *buffer == 'w';
        } while (++buffer != end);

       return sum;
}
```

i is optimized out by **induction variable elimination.**

Variables and Optimization

A good compiler is able to express optimized out constants in debug information.

```
int
main(void)
{
        const int x = 3931;

        return x;
}
```

```
Dump of assembler code for function main:
   0x0000000000400400 <+0>:     mov    $0xf5b,%eax
   0x0000000000400405 <+5>:     retq
```

x is optimized out by **constant value propagation**.

Variables and Optimization

A good compiler is able to express optimized out constants in debug information.

```
< 2><0x000002a3>      DW_TAG_variable
                        DW_AT_name                  "x"
                        DW_AT_decl_file             0x00000001 /home/sbahra/
lol.c
                        DW_AT_decl_line             0x00000006
                        DW_AT_type                  <0x000002af>
                        DW_AT_const_value           3931
```

x is optimized out by **constant value propagation**.

Variables and Optimization

Things involving more than one pass will confuse some compilers.

```
int
main(void)
{
        static unsigned int vr_value = 42;
        unsigned int vr_return = vr_value;

        pause();
        return vr_return;
}
```

```
(lldb) frame variable
(unsigned int) vr_value = <no location, value may have been optimized out>
```

Apple LLVM version 9.0.0 (clang-900.0.37)

Variables and Optimization

Things involving more than one pass will confuse some compilers.

```
0x00000043:         TAG_variable [3]
                     AT_name( "vr_value" )
                     AT_type( {0x0000005b} ( unsigned int ) )
                     AT_decl_file( "/Users/sbahra/Projects/cdqs/src/constant_00.c" )
                     AT_decl_line( 6 )

0x0000004e:         TAG_variable [4]
                     AT_const_value( 0x0000002a )
                     AT_name( "vr_return" )
                     AT_decl_file( "/Users/sbahra/Projects/cdqs/src/constant_00.c" )
                     AT_decl_line( 7 )
                     AT_type( {0x0000005b} ( unsigned int ) )
```

Apple LLVM version 9.0.0 (clang-900.0.37)

Variables and Optimization

GCC is able to handle transforming debug information along with passes.

```
int
main(void)
{
        static unsigned int vr_value = 42;
        unsigned int vr_return = vr_value;

        pause();
        return vr_return;
}
```

```
(gdb) p vr_return
$1 = 42
(gdb) p vr_value
$2 = 42
```

gcc (Ubuntu 4.8.4-2ubuntu1~14.04.3) 4.8.4

Variables and Optimization

But, it still gets some things wrong.

```
< 2><0x0000004a>      DW_TAG_variable
                        DW_AT_name                  "vr_value"
                        DW_AT_decl_file             0x00000001 /home/sbahra/cs.c
                        DW_AT_decl_line             0x00000004
                        DW_AT_type                  <0x00000088>
                        DW_AT_const_value           42
< 2><0x00000056>      DW_TAG_variable
                        DW_AT_name                  "vr_return"
                        DW_AT_decl_file             0x00000001 /home/sbahra/cs.c
                        DW_AT_decl_line             0x00000005
                        DW_AT_type                  <0x0000008d>
                        DW_AT_const_value           42
```

Variables and Optimization

But, it still gets some things wrong.

```
(gdb) ptype vr_value
type = const unsigned int
```

Apple LLVM version 9.0.0 (clang-900.0.37)

```
(gdb) ptype vr_value
type = unsigned int
```

gcc (Ubuntu 4.8.4-2ubuntu1~14.04.3) 4.8.4

Both GCC and clang get the type information wrong for vr_value.

Variables and Optimization

Certain constructs are simply unresolvable, even with optimizations turned off.

```
int
main(void)
{
        int value;

        struct {
                int apple  : 2;
                int orange : 4;
                int tomato : 5;
        } x;

        ck_pr_store_int(&value, 1);
        x.apple = value;
        x.orange = value;
        x.tomato = value;
        pause();
        return x.apple;
}
```

```
(lldb) frame variable x
((anonymous struct)) x = <no location, value
```

Apple LLVM version 9.0.0 (clang-900.0.37)

```
(gdb) p x
$1 = {apple = 1, orange = 1, tomato = 1}
```

gcc (Ubuntu 4.8.4-2ubuntu1~14.04.3) 4.8.4

Variables and Optimization

Other constructs are inaccurate or incomplete, with optimizations turned on.

```
static int vla_length = 3;

int
main(void)
{
        int vla[vla_length];

        vla[0] = 1;
        vla[1] = 1;
        vla[2] = 1;
        pause();
        return vla[0];
}
```

```
(lldb) frame variable vla
(int []) vla = <no location, value may have b
```

Apple LLVM version 9.0.0 (clang-900.0.37)

```
(gdb) p vla
$3 = <optimized out>
```

gcc (Ubuntu 4.8.4-2ubuntu1~14.04.3) 4.8.4

Variables and Opti n

Live variable analysis

Unfortunately, things are **actually** non-recoverable.

```
int
main(int argc, const char **argv)
{

    VOLATILE_LOAD(argv);
    pause();
    return 0;
}
```

```
[  1] spill_00     main (spill_00.c:9)
  argc = -- [optimized out]
  argv = -- [optimized out]
```

Registers are **extremely fast**. The compiler's **register allocator** tries to optimally allocate registers for variables.

Variables and Optimization

Since **arg** is never used once pause is invoked, the compiler doesn't **spill** it from the register it lived in.

```
int
main(int argc, const char **argv)
{

    pause();
    VOLATILE_LOAD(argv);
    return 0;
}
```

```
 argc = -- [optimized out]
 argv = (parameter) reference(0, 0x7ffe022232c8)
   {pointer(const char)} -><> = reference(0x7ffe022232c8, 0x7ffe02224433)
       {const char} -><> = string(0x7ffe02224433, 10, [./spill_00])
```

Variables and Opti n

The platform **ABI** determines whic
must be saved across function call es
spilling said register if used.

```
+       * According to the DWARF
specification: The default rule for all
+       * columns before interpretation
of the initial instructions is the
+       * undefined rule. However, an
ABI authoring body or a compilation
+       * system authoring body may
specify an alternate default value for
any
+       * or all columns.
```

```
000000d0 0000000000000044 000000a4 FDE cie=00000030 pc=4005e0..400645
   LOC           CFA      rbx   rbp   r12   r13   r14   r15   ra
0000000000004005e0 rsp+8    u     u     u     u     u     u     c-8
0000000000004005e2 rsp+16   u     u     u     u     u     c-16  c-8
0000000000004005e4 rsp+24   u     u     u     u     c-24  c-16  c-8
0000000000004005e9 rsp+32   u     u     u     c-32  c-24  c-16  c-8
0000000000004005eb rsp+40   u     u     c-40  c-32  c-24  c-16  c-8
0000000000004005f3 rsp+48   u     c-48  c-40  c-32  c-24  c-16  c-8
0000000000004005fb rsp+56   c-56  c-48  c-40  c-32  c-24  c-16  c-8
000000000040060a rsp+64   c-56  c-48  c-40  c-32  c-24  c-16  c-8
000000000040063a rsp+56   c-56  c-48  c-40  c-32  c-24  c-16  c-8
000000000040063b rsp+48   c-56  c-48  c-40  c-32  c-24  c-16  c-8
000000000040063c rsp+40   c-56  c-48  c-40  c-32  c-24  c-16  c-8
000000000040063e rsp+32   c-56  c-48  c-40  c-32  c-24  c-16  c-8
0000000000400640 rsp+24   c-56  c-48  c-40  c-32  c-24  c-16  c-8
0000000000400642 rsp+16   c-56  c-48  c-40  c-32  c-24  c-16  c-8
```

Variables and Optimization

Different compilers and debuggers have different semantics for register value propagation in unwinding state machine.

```
(lldb) frame select 1
frame #1: 0x00007fffc5f5eb72 libsystem_c.dylib`nanosleep + 199
libsystem_c.dylib`nanosleep:
    0x7fffc5f5eb72 <+199>: testl  %eax, %eax
    0x7fffc5f5eb74 <+201>: jns    0x7fffc5f5eb3d            ; <+146>
    0x7fffc5f5eb76 <+203>: callq  0x7fffc5f644e4            ; symbol stub for: __error
    0x7fffc5f5eb7b <+208>: cmpl   $0x3c, (%rax)
(lldb) register read
General Purpose Registers:
       rbx = 0x0000000000000000
       rbp = 0x00007fff5fbff690
       rsp = 0x00007fff5fbff660
       r12 = 0x0000000000000000
       r13 = 0x00007fffceda1a20  __stderrp
       r14 = 0x00007fff5fbff6a8
       r15 = 0x00007fff5fbff6b8
       rip = 0x00007fffc5f5eb72  libsystem_c.dylib`nanosleep + 199
13 registers were unavailable.
```

Variables and Optimization

Different compilers and debuggers have different semantics for register value propagation in unwinding state machine.

```
(gdb) frame 1
#1  […]
(gdb) info reg
rax            0xfffffffffffffffc       -4
rbx            0x0      0
rcx            0x7f0c75c5d693   139691492234899
rdx            0x2000   8192
rsi            0xbffbe0 12581856
rdi            0x9      9
rbp            0xbff960 0xbff960
rsp            0x7ffd11a7d290   0x7ffd11a7d290
r8             0x1b58   7000
r9             0x67ff410        109048848
r10            0xffffffff       4294967295
r11            0x293    659
r12            0xbffbec 12581868
r13            0xbffbe0 12581856
r14            0xbffbec 12581868
r15            0x0      0
rip            0x423930 0x423930 <cr_io_enter+48>
eflags         0x293    [ CF AF SF IF ]
```

Variables and Optimization

Inlining and tail call optimization in particular, will lead to invalid debug information.

```
int
factorial(int ac, int n)
{

        if (--n == 1) { // 3 * 2 * 1 has occurred if we entered here
                pause();
                return ac;
        }

        return factorial(ac * n, n);
}

int
main(void)
{

        return factorial(3, 3);
}
```

Variables and Optimization

Inlining and tail call optimization in particular, will lead to invalid debug information.

GCC	clang

`| 1| constant_03 factorial`
`n = (parameter) 1`
`ac = (parameter) 3`
	`| 1| constant_03 factorial`
	`ac = (parameter) 3`
	`n = (parameter) 2`

INVALID DATA	**INVALID DATA**

Variables and Optimization

Inlining and tail call optimization in particular, will lead to invalid debug information.

```
0x0000003d:         TAG_formal_parameter [3]
                     AT_location( 0x00000000
                        0x0000000100000d00 - 0x0000000100000d08: rdi
                        0x0000000100000d08 - 0x0000000100000d79: rbx
                        0x0000000100000daf - 0x0000000100000db1: rbx
                        0x0000000100000eb3 - 0x0000000100000eba: rbx )
                     AT_abstract_origin( {0x0000005c}"ac" )

0x00000046:         TAG_formal_parameter [3]
                     AT_location( 0x0000005c
                        0x0000000100000d00 - 0x0000000100000d06: rsi
                        0x0000000100000d0b - 0x0000000100000eb5: rax )
                     AT_abstract_origin( {0x00000067}"n" )
```

Call stack and Optimizations

Frames might disappear in the presence of **tail call optimization.**

```
Thread 8163
  [  0] libc-2.21.so  pause
  [  1] chain         three
  [  2] chain         two
  [  3] chain         one
  [  4] chain         main
```

```
Thread 8224
  [  0] libc-2.21.so  pause
  [  1] chain         three
  [  2] chain         main
```

Tail calls are disambiguated by **call sites** and some times a debugger will only be able to extract the inner-most tail call in a chain.

Call stack and Optimizations

Frames might disappear in the presence of **tail call optimization.**

```
main:
  callq one
  …
one:
  callq two
  …
two:
  callq three
  …
three:
  retq
```

```
main:
  callq one
  …
one:
  jmp two
  …
two:
  jmp three
  …
three:
  retq
```

Call stack and Optimizations

Frames might disappear in the presence of **tail call optimization.**

```
Thread 8163
  [  0] libc-2.21.so  pause
  [  1] chain         three
  [  2] chain         two
  [  3] chain         one
  [  4] chain         main
```

```
Thread 8224
  [  0] libc-2.21.so  pause
  [  1] chain         three
  [  2] chain         main
```

Tail calls are disambiguated by **call sites** and some times a debugger will only be able to extract the inner-most tail call in a chain.

Call stack and Optimizations

Your callstack can be **erroneous** with basic block commoning.

```
static void
function(const char *string)
{

    ck_pr_load_ptr(&string);
    pause();
    return;
}

static int
f(int x)
{

    if (x == 1) {
        function("a");
    } else if (x == 2) {
        function("b");
    }

    return 0;
}
```

f(“a”)	| 2| cbe_00	f (cbe_00.c:21)
f(“b”)	| 2| cbe_00	f (cbe_00.c:21)

Due to this optimization, the calls into this function are combined to a single instruction.

Call stack and Optimizations

Adjacent loads and stores can be hoisted, leading to inaccurate line number information.

```
int
main(void)
{
        struct {
                char one;
                char two;
                char three;
                char four;
        } hoist;

        hoist.one = 1;
        hoist.two = 2;
        hoist.three = 3;
        hoist.four = 4;

        pause();
        ck_pr_rfo(&hoist);
        return 0;
}
```

```
movl   $0x4030201, -0x8(%rbp)    ; imm = 0x4030201
callq  0x100000f94               ; symbol stub for:
```

```
struct {
  char pad[4094];
  char one;
  char two;
  char three;
  char four;
} hoist;
```

Call stack and Optimizations

NULL pointer checks can can be deleted.

```
Thread A {
   if (X != NULL)
     do(X);

   signal(B);
   if (X != NULL)
      do(X);
}
```

Make sure to use stdatomic or volatile for use-cases that demand them.

Next Time…

http://backtrace.io/blog

@0xF390

How do we measure debuggability?
How do we defeat the optimizer?
How do we marry DWARF with tracing?
…or horror stories so you can avoid creating your own.

Symbolic Debugging

Some debuggers rely on system-facilities such as **thread_db** to crawl internal thread data structures. These data structures are **easily corruptible.**

```
PID: 11756
------------------------------------------------------------------------------
Thread 11756
  [  0] libpthread-2.21.so        pthread_join (pthread_join.c:90)
  [  1] crash                     crash_environment_create (crash.c:374)
  [  2] crash                     main (crash.c:570)
  [  3] libc-2.21.so              __libc_start_main
```

Symbolic Debugging

Some debuggers rely on system-facilities such as **thread_db** to crawl internal thread data structures. These data structures are **easily corruptible.**

```
PID: 11756
--------------------------------------------------------------------------------
Thread 11756
  [  0] libpthread-2.21.so        pthread_join (pthread_join.c:90)
  [  1] crash                     crash_environment_create (crash.c:374)
  [  2] crash                     main (crash.c:570)
  [  3] libc-2.21.so              __libc_start_main

Thread 11757
  [  0] libpthread-2.21.so        __libc_pause (../sysdeps/unix/syscall-template.S:81)
  |  1| crash                     inlined (crash.c:104)
  [  2] crash                     crash_signal (crash.c:433)
  [  3] libpthread-2.21.so        0x7f527f8f7d10 (../sysdeps/pthread/funlockfile.c:29)
* [  4] crash                     scenario_smash_fault (smash.c:16)
        ----------------------------------------------------------------
        Signal: [11] SIGSEGV (segmentation violation)
        Reason: SEGV_ACCERR (invalid permissions for object)
        Faulting address: 0x7f527f215000
        ----------------------------------------------------------------
  [  5]  0x4141414141414141
```

Backtrace