Overwriting the Exception Handling Cache Pointer - Dwarf Oriented Programming

James Oakley
Electron100 *noSPAM* gmail.com

Rodrigo Rubira Branco (@BSDaemon)
rodrigo *noSPAM* kernelhacking.com

Sergey Bratus (@SergeyBratus)
Sergey *noSPAM* cs.dartmouth.edu

Motivation

- Software exploitation is **not generic** anymore
- There are different exploitation primitives in different contexts
- A modern exploitation technique shows how to take advantage of those primitives
- Targets as written are capable of many more computations that intended. **Exploitation is proof of that**

This Talk in One Minute

- GCC exception handling unwinds stack by running special **bytecode** in a VM; that VM is inside any GCC-built process runtime
- This bytecode is Turing-complete: you can write **any** program in it
- Your non-native binary payload could use it!
- **Memory leak** to set it up + a **write** primitive (then use our *DWARF-only dyn. linker!*)

A Bit of Theory

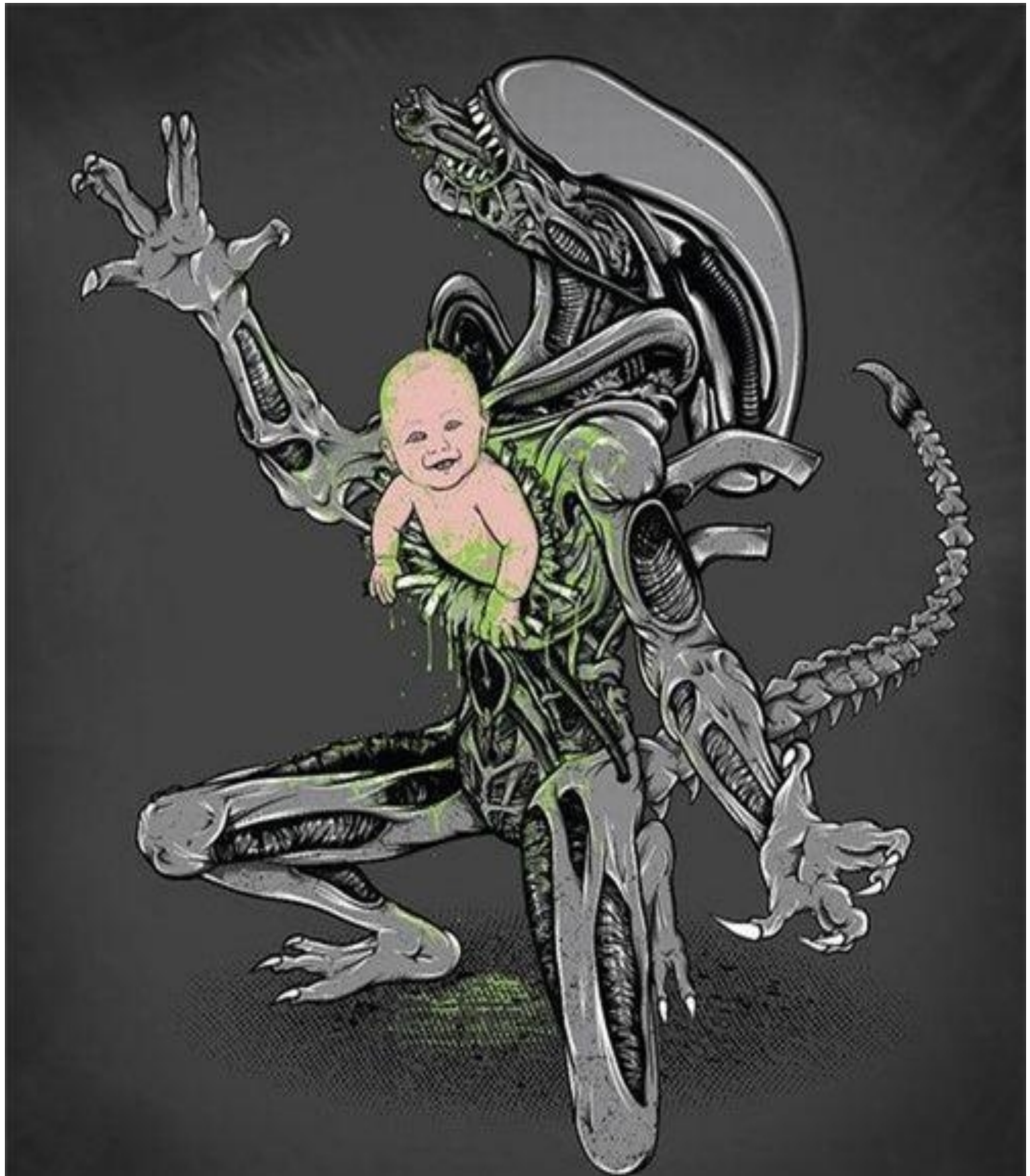
- *Trustworthiness* of a computer system is **what the system can and cannot compute**
  - Can the system decide if an input is invalid/unexpected/malicious & reject it?
  - Will program perform only *expected* computations, or *malicious* ones too?

- ***Exploitation is setting up, instantiating, and programming a <u>weird machine</u>***
  - A part of the target is overwhelmed by crafted input and enters an **unexpected** but **manipulable** state

Software Exploitation

- A part of the target is overwhelmed by crafted input and enters an **unexpected** but **manipulable** state
- **Primitives** are exposed
  - Memory corruption, unexpected control flows, …
  - From a formal model point of view, primitives supply extra state and/or transitions
- A "weird machine" is constructed from primitives
  - A **more powerful**, programmable **execution environment** than intended or expected

Weird Machine is Born!



Exploiting Additional Computations

- Finally we are in our talk line…

- There are many **auxiliary computations** inside a process/runtime that can be used to subvert code execution (and some of then have nothing to do with the original code)

- This isn't like ROP, we are borrowing an existing machine fully (but in unexpected way)

*nix Exception Handling

- Binaries compiled with GCC and that support exception handling have Dwarf bytecode:
  - Describe the stack frame layout
  - Interpreted to unwind the stack after an exception occurs
- The process image includes the Dwarf interpreter (part of the GNU C++ runtime)
- Bytecode can be written to force the interpreter to perform any computation (Turing-Complete), including, but not limited to, setup a library/system call modifying registers such as stack and base pointers -> See James and Sergey previous work on Dwarf Trojans

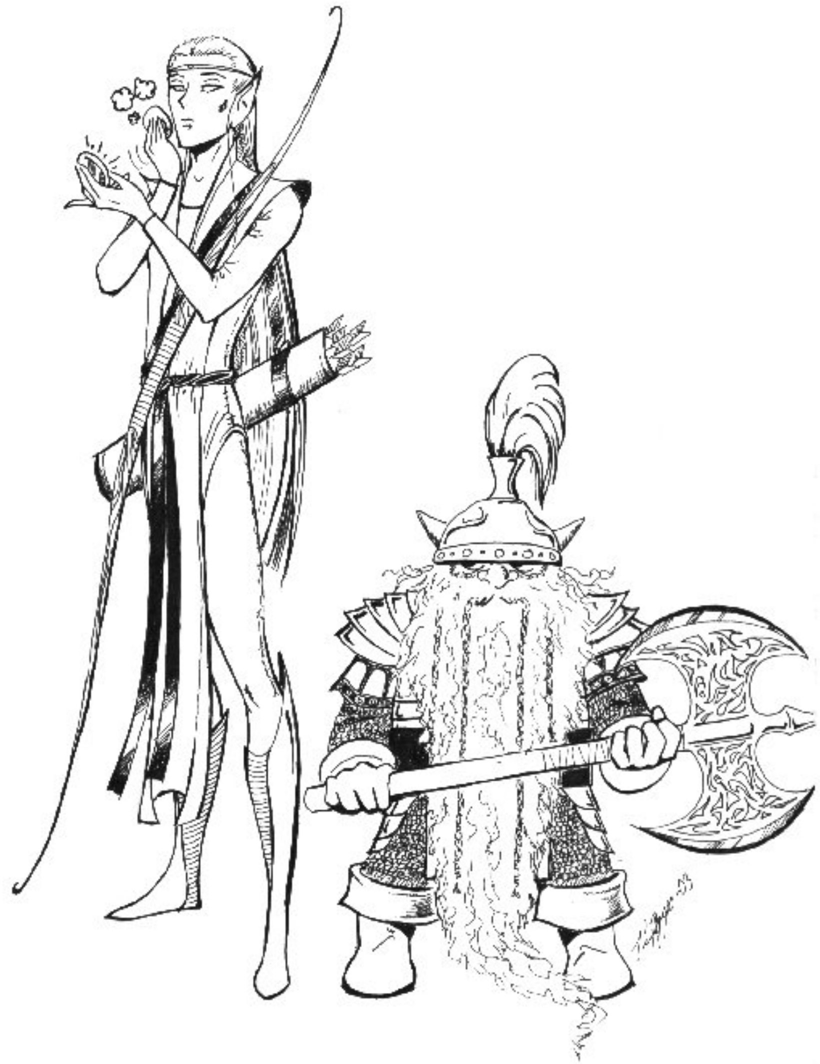
James Oakley and Sergey Bratus

- Proved that Dwarf can replace code creating a Trojan completely using Dwarf bytecode

- Proved that Dwarf is a complete development environment:
  - Can read memory
  - Can compute with values from memory/registers
  - Can influence the flow of execution of a process

ELF layout of process space

ELF Header
Program Headers
.init
.plt
.text
.fini
.eh_frame_hdr
.eh_frame
.gcc_except_table
.dynamic
.got
.data
.symtab
.strtab
Section Headers



Dwarf

- Developed as a debugging format to replace STABS
- Standard: http://dwarfstd.org
- Provide information such as code line, variable types, backtraces, others
- ELF Sections: .debug_info, .debug_line, .debug_frame are defined in the standard
- .debug_frame defines how to unwind the stack (how to restore each entry in the previous call frame)

Linux Exception Handling

- GCC, the Linux Standards Base and the ABI x86_64 adopted a very similar format used in the .debug_frame to describe the stack unwind during an exception: .eh_frame

- It is not exactly the same as dwarf

- It adds pointer encoding and language-specific data

- As usual, the documentation is not perfect:
  - Partially discussed in the Linux Standards Base
  - Partially defined in the ABI
  - Partially implemented in GCC

.eh_frame

- Theoretically it is a table, where for each address in the .text it is describe how to restore the registers to the previous call frame

EIP	CFA	EBP	EBX	EAX	RET
0xf000f000	rsp+16	*(cfa-16)			*(cfa-8)
0xf000f001	rsp+16	*(cfa-16)			*(cfa-8)
0xf000f002	rbp+16	*(cfa-16)		eax=edi	*(cfa-8)
…	…	…	…	…	…
0xf000f00a	rbp+16	*(cfa-16)	*(cfa-24)	eax=edi	*(cfa-8)

- CFA (Canonical Frame Address) – Address relative to the call frame
- Each line defines how each part of the code can return to the previous frame

Size Limitations

- Obviously, keep such a table would use more space then the code itself
- That’s why the adoption of bytecode: The table is ‘compressed’, providing everything required to create it when needed
- Portions of the table are created as needed (on-demand)

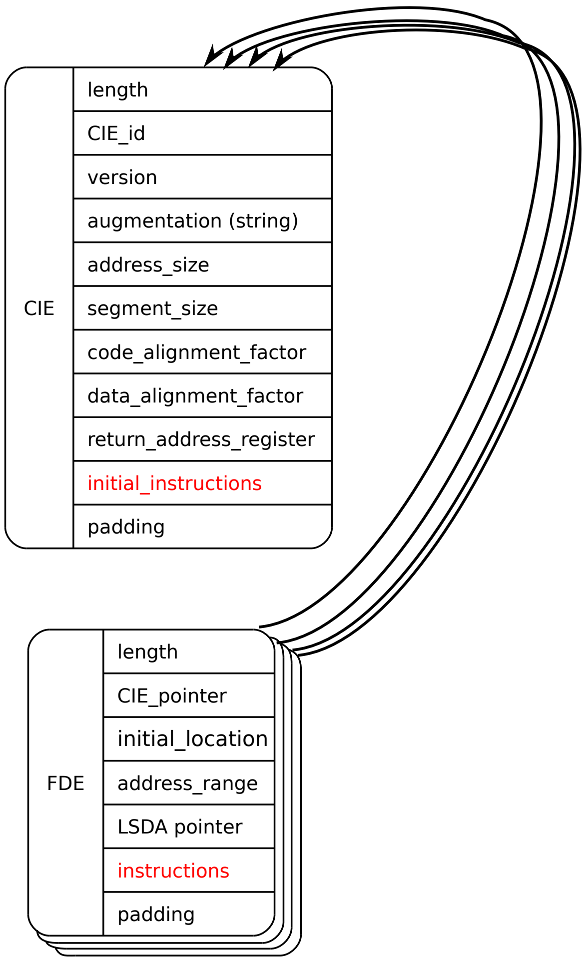
.eh_frame

```
.eh_frame section
    .-----------------------.
    | CFI                   |
    |     .---------------. |
    |     | CIE           | |
    |     '---------------' |
    |     | FDE           | |
    |     |     .-------. | |
    |     |     | *LSDA | | |
    |     |     '-------' | |
    |     '---------------' |
    |     | FDE           | |
    |     |     .-------. | |
    |     |     | *LSDA | | |
    |     |     '-------' | |
    |     '---------------' |
    |     |               | |
    |     | ...           | |
    |     '---------------' |
    |     | FDE           | |
    |     |     .-------. | |
    |     |     | *LSDA | | |
    |     |     '-------' | |
    |     '---------------' |
    '-----------------------'
```

```
CFI = Call Frame Information

CIE = Common Information Entry

FDE = Frame Description Entry

LSDA = Language Specific Data Area
```

"The .eh_frame section shall contain 1 or more Call Frame Information (CFI) records. The number of records present shall be determined by size of the section as contained in the section header. Each CFI record contains a Common Information Entry (CIE) record followed by 1 or more Frame Description Entry (FDE) records. Both CIEs and FDEs shall be aligned to an addressing unit sized boundary”
Linux Standard Base Specification 1.3

FDE x CIE

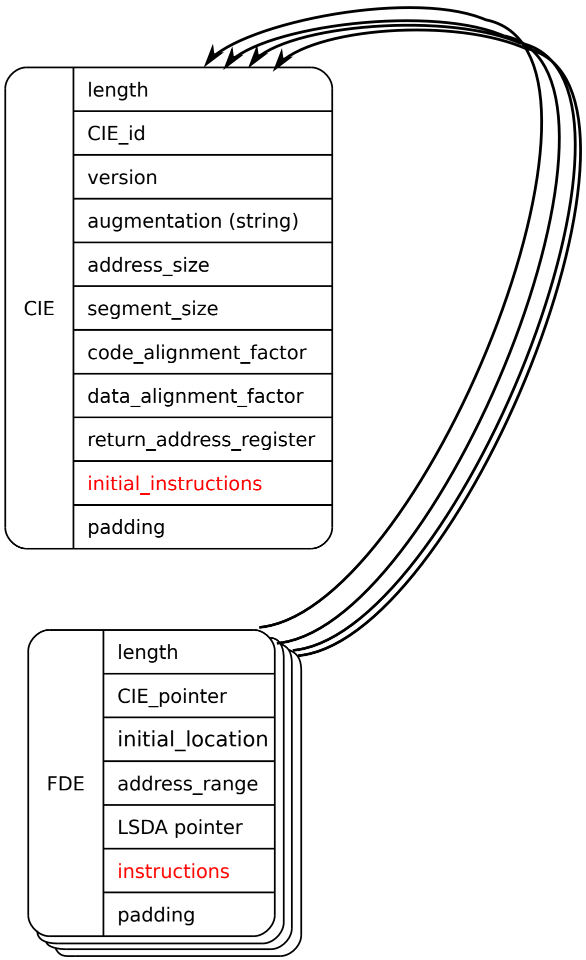


FDE (Frame Description Entry) exists for each logical Instruction block

CIE (Common Information Entry) holds common Information between FDEs

INSTRUCTIONS in FDE hold the DWARF bytecode

FDE x CIE



initial_location/address_range:
Defines for which instructions this FDE applies

augmentation:
Language-specific information

return_address_register:
Entry in a virtual table that defines the .text location to return to (eip)

instructions:
Table rules. Dwarf has a language to describe the table.

Dwarf Instructions

- Works as an assembly language (unexpected computations)
- Turing-Complete Stack-Based Machine
- Can access memory and register values
- Have some limitations:
  - Cannot write to memory (but we can force out-of-order code execution and obtain writes)
  - Cannot call native code
  - Cannot write to registers that are not callee-saved in the ABI (we can write to callee-saved register though)
  - GCC limits the stack to 64 words

Dwarf Programming

- **DW_CFA_set_loc N**
  Next instructions apply to the first N bytes of the function
- **DW_CFA_def_cfa R OFF**
  CFA is calculated starting from register R and offset OFF
- **DW_CFA_offset R OFF**
  Register R is restored from the value in CFA OFF
- **DW_CFA_register R1 R2**
  Register R1 is restored with the contents of R2

And the table is back…

- Each architecture register receives a DWARF equivalent (the mapping is architecture specific)
- Dwarf Instructions define rules for a column or advances to the next line (program location)
- In FDE, lines inherit from instruction lines above them

EIP	CFA	EBP	EBX	EAX	RET
0xf000f000	rsp+16	*(cfa-16)			*(cfa-8)
0xf000f001	rsp+16	*(cfa-16)			*(cfa-8)
0xf000f002	rbp+16	*(cfa-16)		eax=edi	*(cfa-8)
…	…	…	…	…	…
0xf000f00a	rbp+16	*(cfa-16)	*(cfa-24)	eax=edi	*(cfa-8)

Dwarf Expressions

- To not anticipate all unwinding mechanisms of a system, the standard defines flexibility:
  - DW_CFA_expression R EXPRESSION
    R receives the value from the EXPRESSION result
  - DW_CFA_val_expression R EXPRESSION
    R restored to result of EXPRESSION
- Expressions have their own instructions:
  - Constant Values: DW_OP_constu, DW_OP_const8s, etc
  - Arithmetic: DW_OP_plus, DW_OP_mul, DW_OP_and, DW_OP_xor, etc
  - Memory read: DW_OP_deref
  - Register read: DW_OP_bregx
  - Flow Control: DW_OP_le, DW_OP_skip, DW_OP_bra, etc

Katana

Emit a dwarfscript

➢ $e=load "demo"

Loaded ELF "demo"

➢ dwarfscript emit ".eh_frame" $e "demo.dws"

Wrote dwarfscript to demo.dws

Dwarfscript assembler

➢ $ehframe=dwarfscript compile "demo.dws"

➢ replace section $e ".eh_frame" $ehframe[0]

Replaced section ".eh_frame"

➢ save $e "demo_rebuilt"

Saved ELF object to "demo_rebuilt"

➢ !chmod +x demo_rebuilt

So what?

- With Katana you can see and modify unwind tables in an easy way
  - Control the unwinding flow (how the call stack is handled)
  - Avoid an exception handler to execute another one
  - Redirect exceptions
  - Find/solve symbols
  - Calculate relocations

Example

- If function foo is responsible for an exception
  - Change flow to function bar
  - Thru static analysis, we see that bar is at 0x600DF00D
  - In the FDE, we change:

    DW_CFA_offset r16 1
  - To:

    DW_CFA_val_expression r16

    begin EXPRESSION

    DW_OP_constu 0x600DF00D

    dnd EXPRESSION

.gcc_except_table

- So far, redirected only to ‘catch’ blocks
- The .gcc_except_table hold language-specific data (where the exception handlers are)
  - Interpreted by the personality routines
  - We can stop an exception at any time
  - Unlike the .eh_frame, do not have standards
  - There is no documentation, so let’s see the code ;)

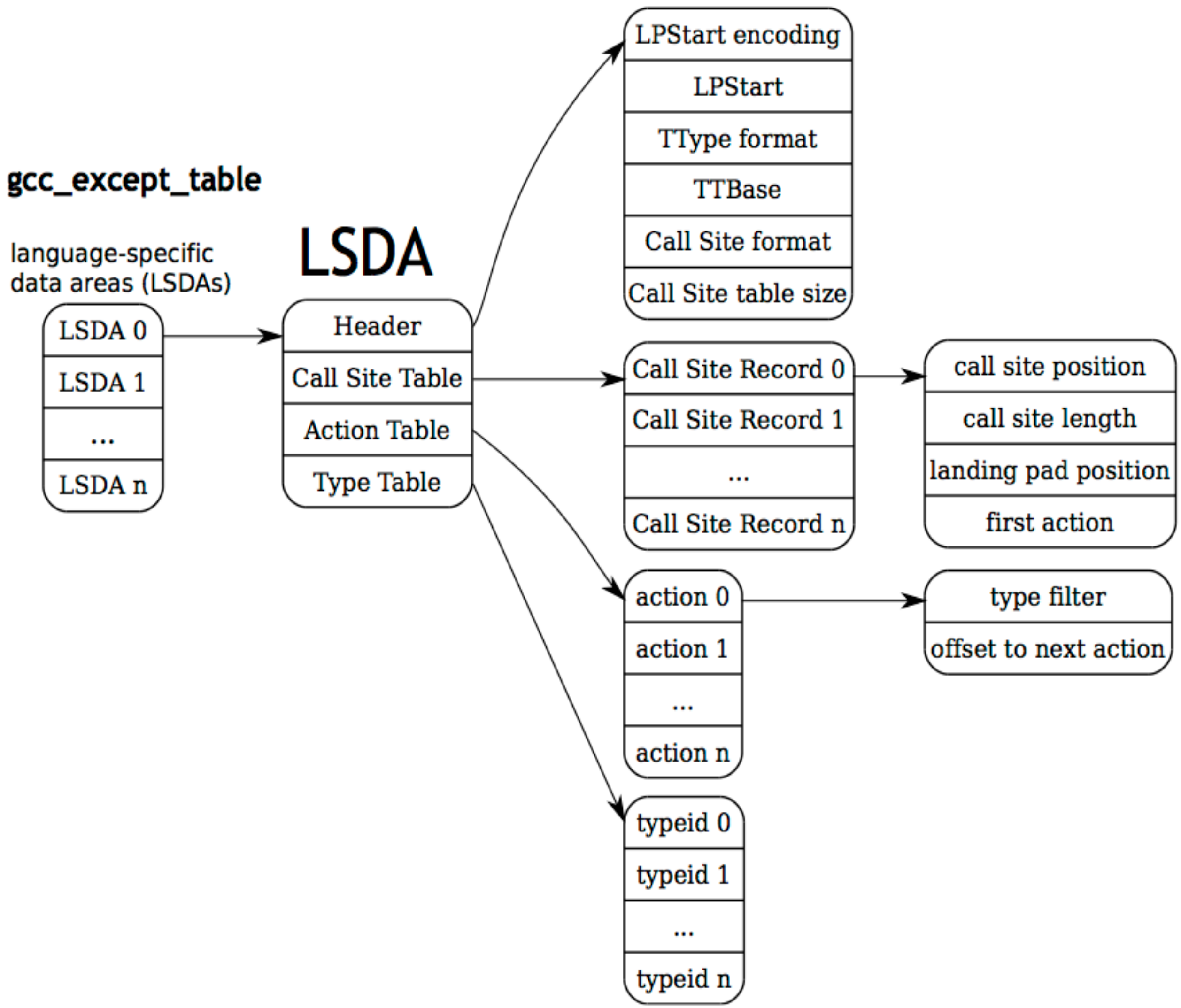
Assembly

- While compiling a program using GCC, do:

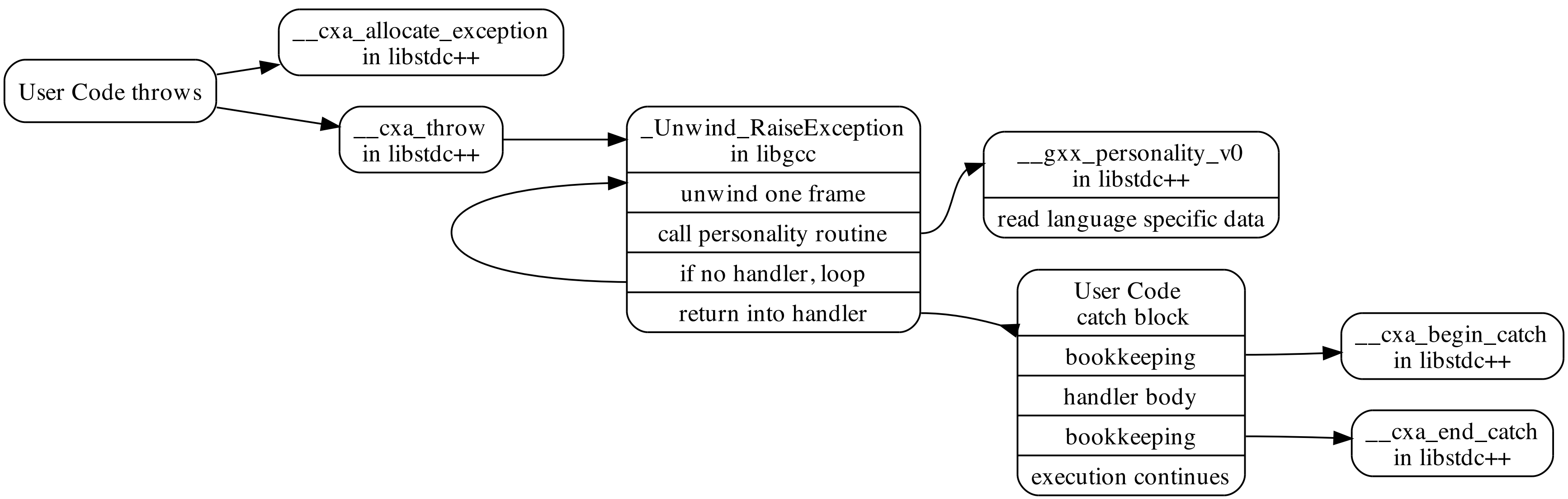
  --save-temps –fverbose-asm –dA

```
        .section .gcc_except_table,"a",@progbits
        .align 4
 .LLSDA963:
        .byte 0xff # @LPStart format (omit)
        .byte 0x3 # @TType format (udata4)
        .uleb128.LLSDATT963−.LLSDATTD963 # @TType base offset
.LLSDATTD963:
        .byte 0x1 # call−site format (uleb128)
        .uleb128 .LLSDACSE963−.LLSDACSB963 # Call−site table length
.LLSDACSB963:
        .uleb128 .LEHB0−.LFB963 # region 0 start .uleb128 .LEHE0−.LEHB0 #
length .uleb128 .L6−.LFB963 # landing pad .uleb128 0x1 # action
        .uleb128 .LEHB1−.LFB963 # region 1 start .uleb128 .LEHE1−.LEHB1 #
length .uleb128 0x0 # landing pad
        .uleb128 0x0 # action
        .uleb128 .LEHB2−.LFB963 # region 2 start .uleb128 .LEHE2−.LEHB2 #
length .uleb128 .L7−.LFB963 # landing pad .uleb128 0x0 # action
.LLSDACSE963:
        .byte 0x1 # Action record table .byte 0x0
        .align 4
        .long _ZTIi
```

Layout


gcc_except_table
language-specific
data areas (LSDAs)
LSDA 0
LSDA 1
...
LSDA n
LSDA
Header
Call Site Table
Action Table
Type Table
LPStart encoding
LPStart
TType format
TTBase
Call Site format
Call Site table size
Call Site Record 0
Call Site Record 1
...
Call Site Record n
call site position
call site length
landing pad position
first action
action 0
action 1
...
action n
type filter
offset to next action
typeid 0
typeid 1
...
typeid n

Exception Handling Flow



Exceptions are not asynchronous

- Functions that call throw() just call:
  - __cxa_allocate_exception() -> To allocate space using malloc (or buffers in the .bss if malloc fails – gcc-xxx/libstd++v3/libsupc++/eh_alloc.:84)
  - And then __cxa_throw() -> That will go thru the frames until a handler for the exception is found

Proving (assembly)

```
Dump of assembler code for function main:
   ...
   <+9>:     mov    $0x4,%edi                # std::size_t thrown_size

   # Allocates a new "__cxa_refcounted_exception" followed by 4 bytes; we
   # do a "throw(1)", 1 being an "int" occupies 4 bytes.
   <+14>:    callq  0x400930 <__cxa_allocate_exception@plt>
   ...
   <+25>:    mov    $0x0,%edx                # void (*dest) (void *)
   <+30>:    mov    $0x6013c0,%esi           # std::type_info *tinfo
   <+35>:    mov    %rax,%rdi                # void *obj
   <+38>:    callq  0x400940 <__cxa_throw@plt>
```

__cxa_allocate_exception()

- Returns a pointer to a
  - struct __cxa_refcounted_exception, which helds a reference to an object __cxa_exception
- __cxa_throw() is then executed to:
  - Initialize the current context (register values)
  - Iterate in the stack until it finds the exception handler

What We've Shown Before

- Ret-into-libc
- Used the dynamic-linker already in Dwarf to find execvpe
- Used Dwarf to prepare the stack
- In less than 200 bytes and less than 20 words in the stack (showing that a 64-stack word limitation is not an obstacle)
- Started in an offset of execvpe where they can control the Dwarf registers (and not in the function beginning)

What else can be done?

- Old GCC had both, the .eh_frame and the .gcc_except_table as +W
- Well…
  - Libgcc/libstdc++ need to find those areas in memory, right?
  - The program header, GNU_EH_FRAME contains the .eh_frame location (dl_iterate_phdr is the function that finds it)
  - Libgcc caches the value!

Fake EH

- If we can overwrite the cached value, we are able to control the exceptions and leverage everything already explained
- Libgcc does not export symbols, so we need to find an heuristic/reverse to find what to overwrite

Caching

- The pointer caching is done in: unwind-dw2-fde-glibc.c:

```
#define FRAME_HDR_CACHE_SIZE 8
...
static struct frame_hdr_cache_element
{
  _Unwind_Ptr pc_low;
  _Unwind_Ptr pc_high;
  _Unwind_Ptr load_base;
  const ElfW(Phdr) *p_eh_frame_hdr;
  const ElfW(Phdr) *p_dynamic;
  struct frame_hdr_cache_element *link;
} frame_hdr_cache[FRAME_HDR_CACHE_SIZE];
```

Caching

- 8 cache entries for the frame header
  - Uses a Least Used Replacement Algorithm (_Unwind_IteratePhdr_Callback())
  - Most recently used is the head of the list

- In the test environment, the frame_hdr_cache was at 0x6e0 bytes from the offset of the writable data segment of libgcc

- This is the aforementioned array, with 48 bytes in size

- The executable itself is the 3rd element of the array (the first two are the libgcc and libstdc++)

- The offset for the writable data segment of libgcc can be found in this way (based in what we know):
  - 0x6e0+48*2=0x740

- The entry p_eh_frame_hdr that we want to overwrite is at 24 bytes of this structure.

Exploiting

- To simplify the exploitation, it is interesting to align the structures in known offsets/ controlled offsets:
  - .eh_frame in the example aligned to start exactly at 0x50 bytes from the start of the .eh_frame_hdr
  - .gcc_except_table aligned to start exactly at 0x200 bytes from the start of the .eh_frame

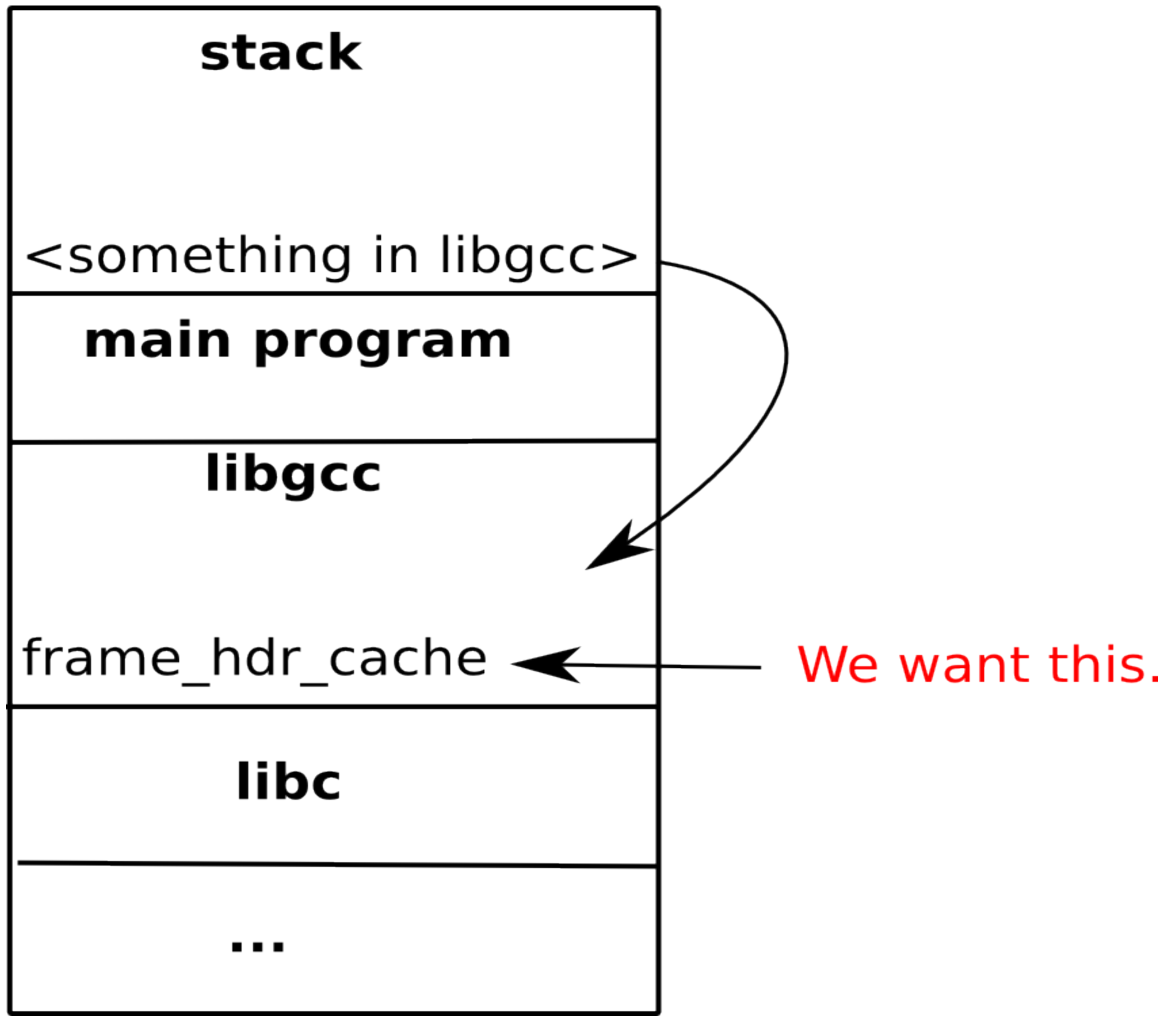
Memleak

- We need the value of EBP, so we going to use a memleak. It can be achieved in different ways, depending on the target program (e.g.: overwriting parameters to printf-like functions, or if the vulnerability is a format string, which is our sample case)

- To calculate the EBP_PREVIOUS we use %llx (format string), so we use 4 bytes of space in the buffer and advance the stack pointer in 8 bytes (so the premise for exploiting the sample program is to manage to leak the EBP):

```
...
#to get the value of ebp_previous
instr=r"%llx%llx%llx%llx%llx%llx%llx%llx%llx%llx%llx%llx%llx%llx%llx%llx%llx%llx%llx%llx%llx%llx%llx%llx
%llx%llx%x%x"
proc.sendline(instr)
proc.expect("unknown command: [0-9a-f]* ([0-9a-f]*).*")
ebp_previous=int(proc.match.group(1),16)
info("\nfound ebp_previous = 0x%x" % ebp_previous)
```

Memleak



stack
<something in libgcc>
main program
libgcc
frame_hdr_cache
We want this.
libc
...

Heuristics

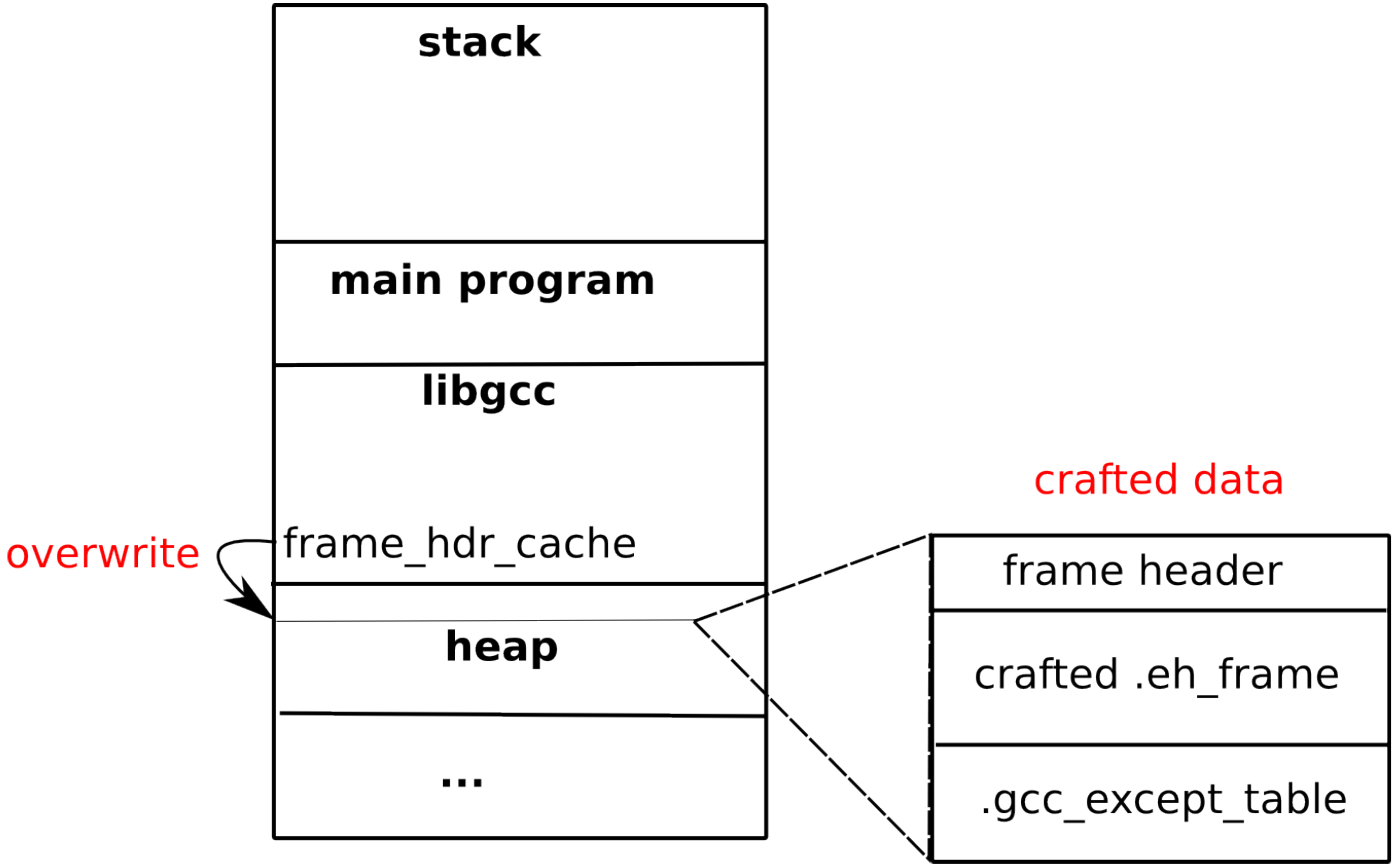
- We know the size of the previous frame (disassembling), so we are capable of calculate the EBP of our frame:
  - ebp=ebp_previous-PREV_FRAME_SIZE

- With our frame address, we can calculate the address of libgcc, since we know the offsets:
  - libgcc_reveal_location=ebp-LIBGCC_REVEAL_EBP_OFFSET;

More Heuristics

- The value that reveals the .text location of the libgcc is at 0xffffc798 (discovered in the previous slide), and it is 0x679 above ESP and 0x750 above EBP
- The libgcc base is calculated using the previously revealed address and masking the 3 low nibbles. We also use a fixed value to adjust the result (found thru disassembly):
  - libgcc_base=(libgcc_revealed & 0xFFFFF000) - LIBGCC_REVEAL_ADJUST
- The separation between .text and .data segments in libgcc is 0x19000 (x86):
  - libgcc_data_base=libgcc_base+LIBGCC_DATA_OFFSET

Overwriting the Frame Header Cache



Finalizing

- Finally, we find the frame_hdr_cache and the respective p_eh_frame_hdr from the libgcc_data_base, as previously described:
  - frame_hdr_cache=libgcc_data_base +CACHE_LIBGCC_OFFSET
  - p_eh_frame_hdr=frame_hdr_cache +CACHE_ENTRY_SIZE*PREVIOUS_CACHE_ENTRIES +OFFSET_IN_CACHE_ENTRY

In the demo case

- The Dwarf payload is injected in the dictionary been readed by the target program (instead of using a shellcode). We find the pointers, overwrite the caching target address and the desired catch block is executed.

- With all the values, we redirect the execution:
  - Function doWork throws an exception
  - We redirect it to I_am_never_called

Other possibilities

- If you have a Write N you can overwrite the .eh_frame entirely (if it is +W, what is not normal in new systems)
- You can overwrite the .eh_frame using a shellcode
- You can use a stagered ret-into-lib to remap the .eh_frame as +W and then overwrite it

THE END! Really!?

http://katana.nongnu.org
https://github.com/rrbranco/defcon2012

James Oakley (Electron)
Electron100 *noSPAM* gmail.com

Rodrigo Rubira Branco (@BSDaemon)
rodrigo *noSPAM* kernelhacking.com

Sergey Bratus (Sbratus)
Sergey *noSPAM* cs.dartmouth.edu