White Paper
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Debugging Buffer Overruns in the FreeBSD* Kernel

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Abstract

This paper provides an overview of the tools and methodology used to resolve memory buffer overruns in FreeBSD* Kernel code, including new features available in the upcoming release of FreeBSD 8.0. Buffer overruns in the heap and stack, and the steps involved in their identification and root cause analysis, are discussed. The paper advocates that the tools presented form part of a unit test strategy for FreeBSD Kernel code.

Contents

Introduction

This paper is intended to help developers identify, root cause, and resolve buffer overruns in the FreeBSD Kernel. Buffer overruns occur when memory is written outside of a buffer's boundaries. They may occur in both stack and heap memory; the tools available to resolve both situations are discussed.

There are many possible root causes for an overrun. They often occur accidentally, most commonly due to a buffer-size miscalculation. Or they occur deliberately, where an attacker seeks to exploit a flaw in system security. This paper presents code examples to help demonstrate solutions for both situations.

User-space tools to diagnose and root cause buffer overruns have been available for some time and are well known. Multi-platform tools such as Rational* Purify* and GNU* Electric Fence* or DUMA* are proven tools for resolving overruns and have become development standards.

Kernel-space tools to diagnose and root cause memory overruns are operating-system dependent. An overrun in Kernel-space is a potential serious threat to system security and stability. Until recently, User-space overruns were considered much easier to diagnose and resolve than those in Kernel-space. Recent FreeBSD releases, however, have brought significant improvement in tools supporting the identification and root cause of buffer overruns in Kernel-space:

- MemGuard*, a tool to determine if buffers are used after being freed, was introduced in FreeBSD 6.0.
- RedZone*, a tool to detect memory overruns on the heap, was introduced in FreeBSD 7.0.
- Stack-Protector*, also known as the Stack-smashing protector, is a feature of the GCC* compiler. It is designed to detect buffer overruns on the stack. It is enabled in the Kernel build process in FreeBSD 8.0 and above.

This paper is divided into two sections. The first demonstrates using RedZone to identify and resolve a buffer overrun in heap memory. The second demonstrates the use of Stack-Protector to stop attackers seeking to exploit a security flaw caused by a buffer overrun on the stack.

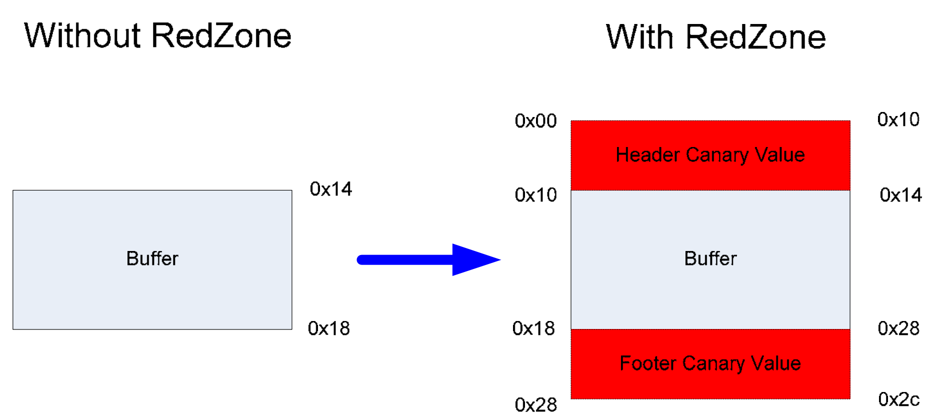
Overruns on the Heap

An overrun on the heap is when heap memory outside of the intended target buffer is overwritten. Overruns on the heap can be notoriously hard to trace in User-space, let alone in Kernel-space. They can often display themselves in subtle ways, minor corruption to strings or strange integer values. They may be evident in one run of a software but not another.

Heap corruption will not necessarily threaten the stability of a system, and can be so subtle in nature that software can be released without heap-corrupting code ever being identified. It will, however, lessen user confidence as the intermittently buggy system behavior continues. It can often be hard to identify a specific bug. Users will report system "weirdness", restarting the software and/or rebooting to resolve the problem. The "weirdness" is explained by buffers in memory being placed next to each other in one execution of software but not another, making bugs hard to reproduce.

The FreeBSD Kernel provides the RedZone* tool to identify heap corruption in Kernel-space. RedZone is a simple but powerful tool. As shown in Figure 1, it works by writing a canary value of 16 bytes above and below each buffer allocated on the heap. The value 0x42 is repeated in each byte of the RedZone canary value. If the value is found to be corrupted at the freeing of a buffer, a message is written to the system log, detailing the corruption along with a stack trace of the allocation and freeing of the buffer.

Figure 1. RedZone* Canary Values

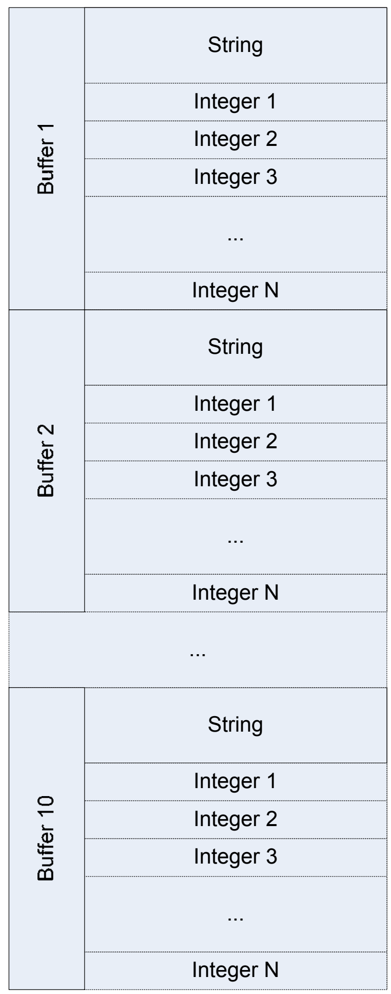


Note: The RedZone canary values are 16 bytes in size, 32 bytes in total as there is a canary value above and below the allocated buffer. Therefore, the memory overhead of using RedZone can be significant if, for example, your driver uses large numbers of small buffers.

About the Sample Code

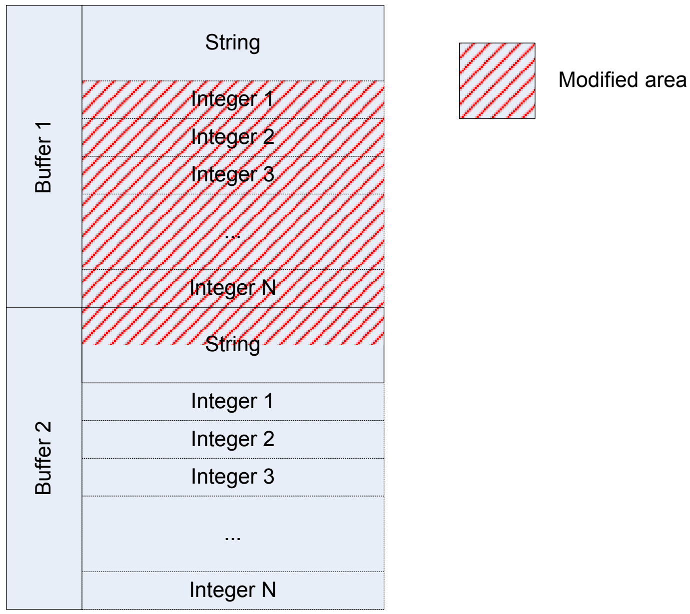
The sample code presented in this section recreates the class of subtle bug discussed above. The sample code is a Kernel module that on initialization creates ten contiguous buffers in memory and starts a Kernel thread. Each buffer contains a string and an array of integers. The string acts as an indicator that will show the corruption; therefore, it is called the “canary string”.

Figure 2. Layout of Structure in Heap Memory



The Kernel thread wakes and sleeps for random amounts of time up to ten seconds. When awakened, the Kernel thread will randomly select one of the buffers and then add one to each integer in the buffer’s integer array. The subtle bug is introduced when the code miscalculates the number of integers in the array. This causes the first four bytes of the buffer occurring next in memory to be treated as an integer; this corrupts the canary string in this buffer.

Figure 3. Area Modified on the Heap



The sample code prints the canary string of the buffer it is currently acting upon to the system log. In this way, evidence of the memory overrun is visible to the user. This sample code has been tested with FreeBSD 7.2 only.

Executing the Sample Code

The sample code in Appendix A includes two files:

1. Makefile: The makefile for the Kernel module.
2. module.c: The source code for the Kernel module.

Copy the files listed in Appendix A to a directory and build the device driver with the *make* command.

```
image72# make
Warning: Object directory not changed from original /root/stack_smash
cc -O2 -fno-strict-aliasing -pipe  -D_KERNEL -DKLD_MODULE
…
ld -Bshareable  -d -warn-common -o module.ko module.kld
objcopy --strip-debug module.ko
```

Load the module with the *kldload* command.

```
image72# kldload ./module.ko
```

Leave the system for a few minutes and then inspect the system log with the following command:

tail –f /var/log/messages

```
…
image72# tail -f /var/log/messages
Aug 10 04:07:05 bsd72 Kernel: [bad_mod] sleep for 7000 ms
Aug 10 04:07:12 bsd72 Kernel: [fad_mod] sleep for 1000 ms
Aug 10 04:07:13 bsd72 Kernel: [bad_mod] sleep for 7000 ms
Aug 10 04:07:20 bsd72 Kernel: [bad_mod] sleep for 7000 ms
Aug 10 04:07:27 bsd72 Kernel: [fad_mod] sleep for 1000 ms
Aug 10 04:07:28 bsd72 Kernel: [bad_mod] sleep for 3000 ms
Aug 10 04:07:31 bsd72 Kernel: [cad_mod] sleep for 5000 ms
Aug 10 04:07:36 bsd72 Kernel: [bad_mod] sleep for 3000 ms
Aug 10 04:07:39 bsd72 Kernel: [bad_mod] sleep for 3000 ms
Aug 10 04:07:42 bsd72 Kernel: [bad_mod] sleep for 7000 ms
```

The heap memory corruption is clearly visible in the system log, the canary string *bad_mod* has been inadvertently changed to *cad_mod* and *fad_mod*.

Unload the module with the *kldunload* command.

```
image72# kldunload module.ko
```

RedZone* and the Kernel Debugger

This section details using RedZone and the Kernel Debugger to root cause the heap corruption.

Note: If the reader wishes to reproduce the examples below, please note that it may not be possible to do so using a virtual machine. At the time of writing, virtual machines do not support hardware watch points; therefore, hardware watch points may not work in the Kernel Debugger.

Building RedZone and Kernel Debugger

The *Profiling and Debugging the FreeBSD Kernel White Paper* covers the steps required to build and maintain multiple FreeBSD Kernels on the same system. Please see the related link to the paper in the Reference List, and read the paper's section, "The FreeBSD Kernel", for instructions on building the Kernel.

To build a Kernel that supports RedZone and the Kernel Debugger, add the following options to a Kernel profile. As discussed in the in *Profiling and Debugging the FreeBSD Kernel White Paper,* add these options to a custom Kernel profile called *REDZONE.*

```
options KDB
options DDB
options DEBUG_REDZONE
```

After the Kernel has been built, installed, and the system has been rebooted, check to ensure the correct Kernel is being used.

```
image72# uname -a
FreeBSD CRB_168.ir.intel.com 7.0-RELEASE FreeBSD 7.0-RELEASE #0: Mon Nov 10 14:02:42 UTC
2008
root@CRB_168.ir.intel.com:/usr/obj/usr/src/sys/REDZONE  i386
```

Executing the Sample Code

Rebuild the Kernel module with the following command:

make clean && make

```
image72# make clean && make
rm -f export_syms module.ko module.kld module.o
Warning: Object directory not changed from original /root/overflow_detect
cc -O2 -fno-strict-aliasing -pipe  -D_KERNEL -DKLD_MODULE -std=c99 –
…
objcopy --strip-debug module.ko
```

Load the module with the *kldload* command.

```
image72# kldload ./module.ko
```

Leave the system for a few minutes and then inspect the system log with the following command:

```
image72# tail -f /var/log/messages
Aug 10 04:10:54 bsd72 Kernel: [bad_mod] sleep for 5000 ms
Aug 10 04:10:59 bsd72 Kernel: [bad_mod] sleep for 5000 ms
Aug 10 04:11:04 bsd72 Kernel: [bad_mod] sleep for 6000 ms
Aug 10 04:11:10 bsd72 Kernel: [bad_mod] sleep for 7000 ms
Aug 10 04:11:17 bsd72 Kernel: [bad_mod] sleep for 1000 ms
Aug 10 04:11:18 bsd72 Kernel: [bad_mod] sleep for 3000 ms
Aug 10 04:11:21 bsd72 Kernel: [bad_mod] sleep for 2000 ms
Aug 10 04:11:23 bsd72 Kernel: [bad_mod] sleep for 8000 ms
Aug 10 04:11:31 bsd72 Kernel: [bad_mod] sleep for 3000 ms
Aug 10 04:11:34 bsd72 Kernel: [bad_mod] sleep for 8000 ms
```

There is no evidence of memory corruption in the system log. RedZone has padded the buffers with its own canary values; these are now being corrupted instead of the canary string.

When the module is unloaded with the *kldunload* command, RedZone detects the corruption in its canary values and prints stack traces of both the allocation and freeing of the corrupted buffer.

```
image72# kldload ./module.ko
image72# more /var/log/messages
…
Aug 10 04:21:34 bsd72 Kernel: REDZONE: Buffer overflow detected. 1 byte corrupted after
0xc4bb08c0 (64 bytes allocated).
Aug 10 04:21:34 bsd72 Kernel: Allocation backtrace:
Aug 10 04:21:34 bsd72 Kernel: #0 0xc0a1d66a at redzone_setup+0x3a
Aug 10 04:21:34 bsd72 Kernel: #1 0xc07dbeb3 at malloc+0xd3
Aug 10 04:21:34 bsd72 Kernel: #2 0xc4bb68e3 at _alloc+0x33
Aug 10 04:21:34 bsd72 Kernel: #3 0xc4bb69f2 at event_handler+0x12
Aug 10 04:21:34 bsd72 Kernel: #4 0xc07dde87 at module_register_init+0x107
Aug 10 04:21:34 bsd72 Kernel: #5 0xc07d6d4f at linker_load_module+0xa5f
Aug 10 04:21:34 bsd72 Kernel: #6 0xc07d725c at kern_kldload+0xec
Aug 10 04:21:34 bsd72 Kernel: #7 0xc07d7334 at kldload+0x74
Aug 10 04:21:34 bsd72 Kernel: #8 0xc0af7605 at syscall+0x335
Aug 10 04:21:34 bsd72 Kernel: #9 0xc0adbaf0 at Xint0x80_syscall+0x20
Aug 10 04:21:34 bsd72 Kernel: Free backtrace:
Aug 10 04:21:34 bsd72 Kernel: #0 0xc0a1d600 at redzone_check+0x180
Aug 10 04:21:34 bsd72 Kernel: #1 0xc07dbc7a at free+0x1a
Aug 10 04:21:34 bsd72 Kernel: #2 0xc4bb689a at _free+0x2a
Aug 10 04:21:34 bsd72 Kernel: #3 0xc4bb6a25 at event_handler+0x45
Aug 10 04:21:34 bsd72 Kernel: #4 0xc07dda37 at module_unload+0x67
Aug 10 04:21:34 bsd72 Kernel: #5 0xc07d5658 at linker_file_unload+0x1d8
Aug 10 04:21:34 bsd72 Kernel: #6 0xc07d6113 at kern_kldunload+0xe3
Aug 10 04:21:34 bsd72 Kernel: #7 0xc07d619b at kldunloadf+0x2b
Aug 10 04:21:34 bsd72 Kernel: #8 0xc0af7605 at syscall+0x335
Aug 10 04:21:34 bsd72 Kernel: #9 0xc0adbaf0 at Xint0x80_syscall+0x20
```

Trapping the Overrun

RedZone shows its value as a tool to detect and report memory corruption that might otherwise be overlooked. It identifies the code that allocated and freed the corrupted buffer. This is useful, but it doesn't provide insight into why the buffer is being corrupted.

To determine the root cause of the overrun, the hardware watch-point feature in the Kernel Debugger can be used to trap the actual instruction overwriting the RedZone canary value. To demonstrate this feature, uncomment line 89 in the sample module and rebuild.

```
…
if(i >= top_index && i < (top_index + COOKIE_NUM))
{
    pBuffer[e] = alloc_buf[i];
    bzero( pBuffer[e],COOKIE_SIZE);
       strcpy(pBuffer[e]->canary_string, module_name);
       e++;

       //printf("RZFooter: 0x%.08x\n",((int) alloc_buf[i]) + COOKIE_SIZE); ← Line 89
}
…
```

The RedZone footer is the RedZone canary value that occurs immediately following a buffer in memory (please see Figure 1). Once the module has finished building, load the module. The memory address of the RedZone footer for each of the buffers used by the module is printed to the system log.

```
image72#  make clean && make
…
image72# kldload ./module.ko
image72# tail –f /var/log/messages
Aug 10 05:13:09 bsd72 Kernel: RZFooter: 0xc4bb00c0
Aug 10 05:13:09 bsd72 Kernel: RZFooter: 0xc4bb01c0
…
Aug 10 05:13:09 bsd72 Kernel: RZFooter: 0xc4bb09c0
Aug 10 05:13:09 bsd72 Kernel: [bad_mod] sleep for 8000 ms
```

Now it is a simple matter of setting a hardware watch to monitor for writes in a RedZone footer, and then letting the module execute until the watch is tripped. A hardware watch is a hardware-backed mechanism that allows reads and writes to a given memory address to be trapped by a debugger. On Intel® Architecture Processors, hardware watch points use the debug registers to trap memory writes.

The Kernel debugger prompt is activated with the following command:

sysctl debug.kdb.enter=1

Set a hardware watch with the following command:

hwatch address, size of structure to watch

Confirm the watch has been set with the following command:

show watches

```
image72# sysctl debug.kdb.enter=1
debug.kdb.enter:K DOB: enter: sysctl debug.kdb.enter
[thread pid 1045 tid 100068 ]
Stopped at      kdb_enter_why+0x3a:     movl    $0,kdb_why
db> hwatch 0xc4bb00c0,4
db> show watches
No watchpoints set

hardware watchpoints:
  watch    status        type  len     address
  -----  --------  ----------  ---  ----------
  0      enabled        write    4  0xc4bb00c0
  1      disabled
  2      disabled
  3      disabled

debug register values:
  dr0 0xc4a4b0c0
  dr1 0x00000000
  dr2 0x00000000
  dr3 0x00000000
  dr4 0xffff0ff0
  dr5 0x000d0402
  dr6 0xffff0ff0
  dr7 0x000d0402
```

Once the hardware watch point has been set, return the system to an executing state with the *cont* command;

```
db> cont
 -> 0
image72#
```

When the hardware watch point is tripped, generate a backtrace with the *bt* command to trace the cause of the overrun.

```
image72#
[bad_mod] sleep for 5000 ms
[thread pid 857 tid 100052 ]
Stopped at      _thread+0x47:   addl    $0x1,%ecx
db> bt
Tracing pid 857 tid 100052 td 0xc47bf8c0
_thread(c4c15bc0,c3e86d38,c3e86d2c,c0823ddf,c47bf8c0,...) at _thread+0x47
fork_exit(c4c14730,c4c15bc0,c3e86d38) at fork_exit+0x99
fork_trampoline() at fork_trampoline+0x8
--- trap 0, eip = 0, esp = 0xc3e86d70, ebp = 0 ---
```

If you are satisfied that you have located the cause of the buffer overrun, delete the watch with the following command:

dhwatch address, size of structure to watch

Confirm the watch has been deleted with the following command:

show watches

```
db> dhwatch 0xc4bb00c0,4
db> show watches
No watchpoints set

hardware watchpoints:
  watch    status        type  len     address
  -----  --------  ----------  ---  ----------
  0      disabled
  1      disabled
  2      disabled
  3      disabled

debug register values:
  dr0 0x00000000
  dr1 0x00000000
  dr2 0x00000000
  dr3 0x00000000
  dr4 0xffff0ff1
  dr5 0x00000400
  dr6 0xffff0ff1
  dr7 0x00000400
```

Conclusion

The RedZone heap overrun detection mechanism is an effective way to ensure that heap memory is not being inadvertently corrupted during development. The tool has a low overhead in terms of additional memory usage and performance penalty, and as such can be easily integrated into an automated unit testing framework. The system log can be easily inspected to determine if an overrun has occurred during testing.

Overruns on the Stack

An overrun on the stack is when stack memory outside of expected boundaries is accidentally or deliberately overwritten. Overruns on the stack introduced during development are more obvious than those previously described on the heap, as they are more likely to create system instability. They will, therefore, rarely escape unit testing. When an overrun occurs, stack pointers saved on the stack are quickly corrupted, causing the Kernel to become unstable and the system quickly crashes.

Trickier to find and patch are stack overruns caused by a security attack. These occur when an attacker seeks to exploit a security flaw in code that is executing with privileges greater than the attacker's own session. The attacker's intention is to cause the privileged code to jump to a set of instructions that will compromise the system. The Kernel is therefore a target for this kind of attack.

Tools to identify stack overruns in the Kernel, during Kernel code testing or for security audit purposes, have been lacking for some time. The FreeBSD 8.0 Kernel introduces a stack-overrun protection mechanism called *stack-protector* into the Kernel. As yet, there does not appear to be a mechanism at either compile or run time to disable the protection.

The sample code for this section, a poorly protected character device driver, demonstrates using a stack-overrun to compromise security. The driver reads a password from User-space through a character device. If the password matches a hardcoded value, a "virtual" lock is unlocked. An attacker's objective in this case is to cause the driver to unlock the "virtual" lock without supplying the correct password.

The driver is demonstrated without stack-overrun protection on FreeBSD 7.2, and with stack overrun protection on FreeBSD 8.0. The character device driver code is based on Murray Stokely's code from the *FreeBSD Architecture Handbook**. Stokely's code is an excellent example of a secure character device driver correctly checking buffer sizes before copying.

Note: If the reader wishes to reproduce the examples below, using a virtual machine is recommended to limit system damage.

About the Sample Code

The code for the character device driver is listed in the file *module.c* in Appendix B. The main logic of the driver is contained within the *test_password* function. The *test_password* function copies a buffer from User-space to Kernel-space and then tests if the copied buffer matches a hardcoded password string. If the strings match, the *unlock* function is called.

The attacker's objective is to exploit the code's failure to ensure that the buffer passed from User-space is not greater in size than the Kernel-space buffer. By passing a buffer greater in size, the attacker can overwrite the stack beyond the buffer. The attacker's target is the *Return Instruction Pointer*; this is the stack value that records the instruction to jump to on function return, that is, an address within a function's parent function. If the attacker can overwrite this value, the attacker can cause the *unlock* function to be called on return, without supplying the correct password.

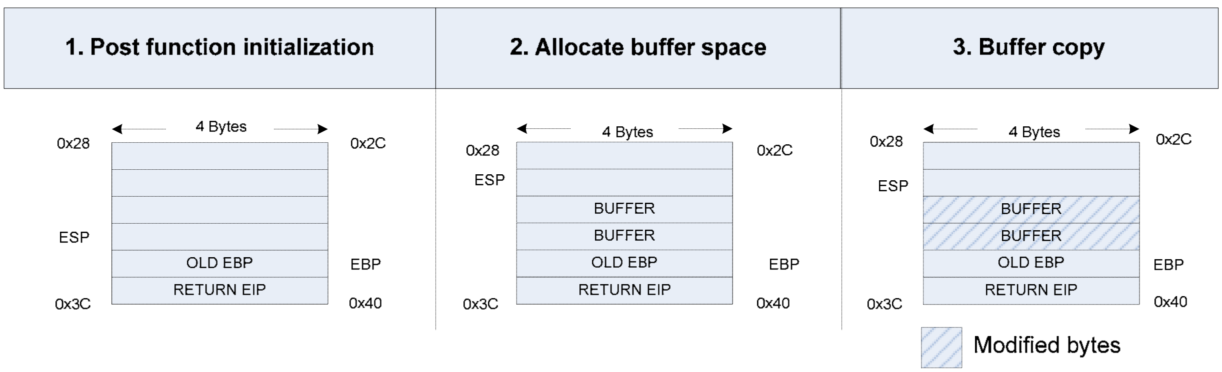
FreeBSD 7.2

This section details how an attacker would attempt to exploit the sample code on FreeBSD 7.2

Compromising the Stack

The following examples have been simplified to omit details not relevant to buffer overruns on the stack. Figure 4 shows the normal operation of the stack in the *test_password* function.

Figure 4. Normal Stack Operation



When the *test_password* function is called from *ulock_write*:

1. The *call* instruction, in the function *ulock_write* pushes the return address (RETURN EIP) onto the stack, execution then starts in the function *test_password*. The return address is the address of the instruction that will execute when the *test_password* function has returned. It is usually the address of the instruction immediately following the *call* instruction in the function *ulock_write*, *ulock_write's* stack base pointer (OLD EBP) is then also pushed onto stack.

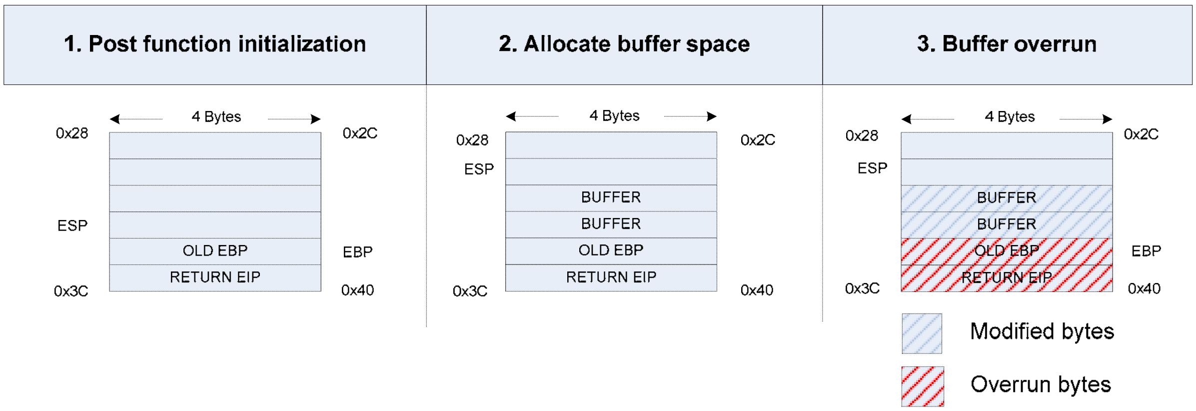
2. A further eight bytes is then created on the stack for the Kernel-space buffer (2 x BUFFER). This is the Kernel-space buffer, to which the User-space buffer will be copied.

3. The buffer is then copied from User-space to Kernel-space, overwriting the space allocated for the buffer on the stack.

In this case, when the *test_password* function returns, control correctly passes back to *ulock_write*.

Figure 5 shows the operation of the stack when an attacker has passed a User-space buffer greater in size than the receiving Kernel-space buffer.

Figure 5. Compromised Stack Operation



When the *test_password* function is called from *ulock_write*:

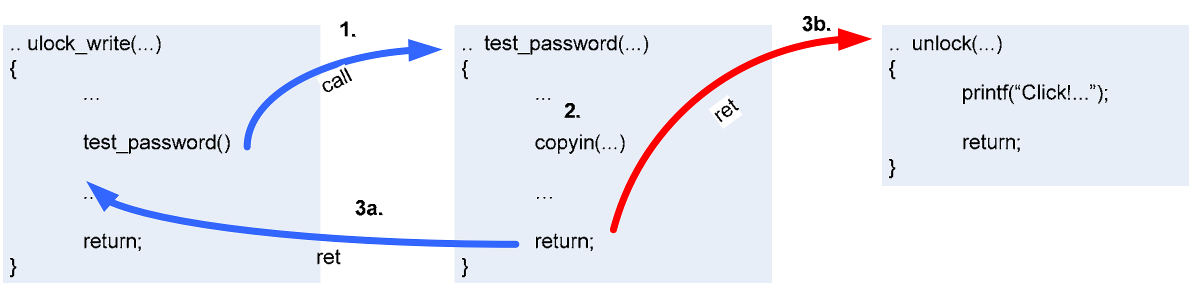
1. and 2. per previous example.

3. The code overruns the Kernel-space buffer, overwriting *ulock_write*'s base stack pointer (OLD EBP) and the address of the instruction to execute on return (RETURN EIP).

The attacker has succeeded in overwriting the Return Instruction Pointer (RETURN EIP) such that when the *test_password* function returns (that is, the *ret* instruction executes), the unlock function will be called.

Figure 6 shows both code flows discussed (normal and compromised stack operations).

Figure 6. Code Flow



1. *ulock_write* function calls the *test_password* function.
2. The *copyin* function copies the buffer from User-space to Kernel-space.
3. When the *test_password* function returns:

a. In the case of normal stack operation, control returns to the *ulock_write* function.

b. In the case of compromised operation, control is passed to the *unlock* function.

In the sample code, system behavior after the *unlock* function returns is unpredictable as the stack has been irreparably corrupted by the attacker. In compromising the system, the attacker has overwritten *ulock_write*'s base stack pointer with a dummy value. This means that when execution eventually continues in *ulock_write,* a corrupted stack state is restored, yielding unpredictable results. A clever attacker might be able to substitute valid values for *unlock_write*'s base stack pointer.

Executing the Sample Code

As has been stated, FreeBSD 7.2 does not include stack overrun protection. An attacker can therefore compromise the sample code using the method described in the previous section.

The sample code in Appendix B; includes three files:

1. Makefile: The makefile for the character device driver.
2. module.c: The source code for the character device driver.
3. hack.c: A User-space program to hack the character device driver.

Copy the files listed in Appendix B to a directory and build the character device driver with the *make* command.

```
image72# make
Warning: Object directory not changed from original /root/stack_smash
cc -O2 -fno-strict-aliasing -pipe  -D_KERNEL -DKLD_MODULE
…
ld -Bshareable  -d -warn-common -o module.ko module.kld
objcopy --strip-debug module.ko
```

Load the module with the *kldload* command.

```
image72# kldload ./module.ko
```

To test the driver to ensure normal operation, try passing the driver an incorrect password.

```
image72# echo -n pa1sword > /dev/ulock
image72# dmesg | tail -n 1
testing password
…
```

The *testing password* text indicates that the *ulock_write* function did execute, but the absence of a subsequent *Click* indicates an incorrect password. Try passing the driver the correct password.

```
image72# echo -n password > /dev/ulock
image72# dmesg | tail -n 2
testing password
Click, lock has been opened!
```

In this case, the correct password was passed and the lock was opened. Now build the User-space program to hack the character device driver.

```
image72# gcc -O2 hack.c -o hack
```

Inspect the source file *hack.c* and you will see that the memory written to the character driver does not contain the correct password. The data structure is shown below.

```
unsigned int crack_data[8] =
        {
            0xFFFFFFFF,
            0xFFFFFFFF,
            0xFFFFFFFF,
            0xFFFFFFFF,
            0xFFFFFFFF,
            0xFFFFFFFF,
            0x5b0,
            0x67d
        };
```

Ignore the first six unsigned integers; as these contain dummy values (they should contain the password). The final two values are the most important:

- The second to last value, shown above as 0x5b0, is the instruction address to be jumped to when *test_password* returns (in this case, the *unlock* function).
- The last value, shown above as 0x67d, is the instruction address to be jumped to when *unlock* returns. In this case, the goal is to return to an instruction address in *unlock_write* function.

These two addresses can vary depending on the compiler, compiler version, and compiler optimizations used to build the Kernel module. They are obtained by dumping the assembly of the module with the *objdump –S* command.

```
image72# objdump -S module.ko | more
…
000005b0 <unlock>:
 5b0:   55                      push   %ebp
 5b1:   89 e5                   mov    %esp,%ebp
 5b3:   83 ec 04                sub    $0x4,%esp
```

The first address, 0x5b0, is the address of the unlock function shown above in red.

```
00000650 <ulock_write>:
 650:   55                      push   %ebp
 651:   89 e5                   mov    %esp,%ebp
…
 678:   e8 53 ff ff ff          call   5d0 <test_password>
 67d:   c7 04 24 cd 06 00 00    movl   $0x6cd,(%esp)
…
```

The second address is the address of the instruction *after* the *call* to the *test_password* function inside the *ulock_write* function shown above in red. If the instruction addresses in your *module.c* are different than those shown above, you may need to edit these values in *hack.c* and recompile.

There is one final obstacle to surmount before the character device driver is cracked. When *module.ko* is loaded using the *kldload* command, the module is loaded at an offset in memory. This means that instruction addresses within the module change by the offset. This offset can be obtained by using the *kldstat* command:

```
image72# kldload ./module.ko
image72# kldstat
Id Refs Address    Size     Name
 1    4 0xc0400000 9fab28   Kernel
 2    1 0xc0dfb000 6a45c    acpi.ko
 3    1 0xc2977000 2000     module
```

In the above example, the module is loaded at the address 0xc2977000 shown in red. Adding this address to the instruction addresses obtained with objdump calculates the actual addresses of the instructions in memory.

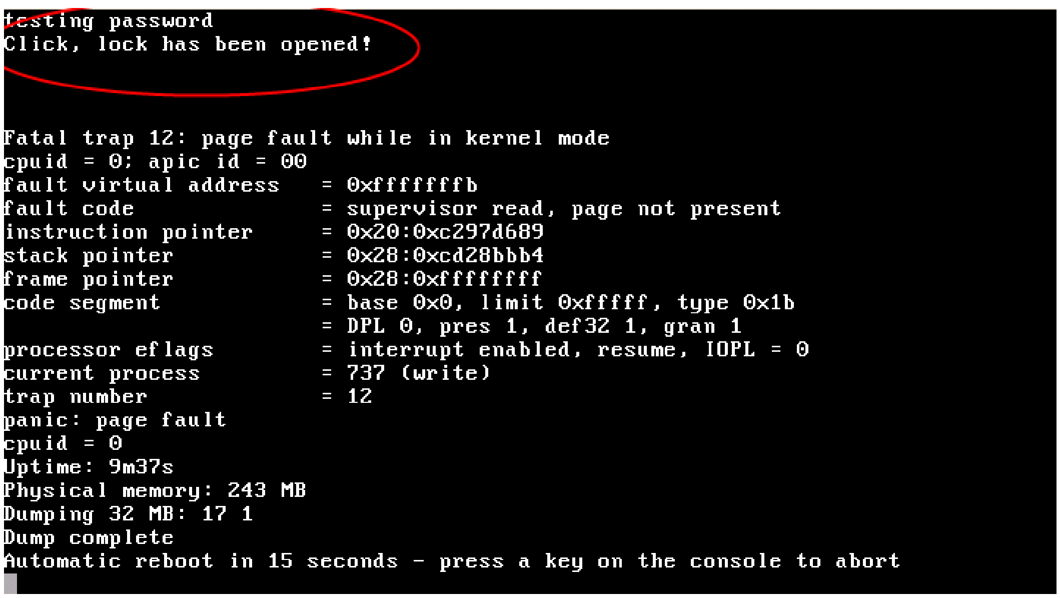
<actual instruction address> = *<module address>* + *<instruction address>*

The hack software performs this calculation when the address of the module is passed to it.

```
image72# ./hack
Enter Module Load Offset :- 0xc2977000
```

Figure 7 shows the system console of a FreeBSD 7.2 system after the hack software has been executed. The lock has been opened without supplying the correct password.

Figure 7. FreeBSD 7.2 System Console after Hack has Executed



FreeBSD 8.0

This section details how an attacker would attempt to exploit the sample code on FreeBSD 8.0.

GCC Stack-Protector

FreeBSD 8.0 includes stack overrun protection; therefore, an attacker cannot compromise the driver using the steps described for FreeBSD 7.2.

Build the sample code on FreeBSD 8.0 and you will notice the new *fstack-protector* parameter is passed to GCC. The new parameter causes extra code to be inserted into the start and end of each function to check that the stack has not been compromised during the execution of the function.

```
image80# make
Warning: Object directory not changed from original /root/stack_smash
cc -O2 -pipe -fno-strict-aliasing -Werror -D_KERNEL -DKLD_MODULE -nostdinc   -I. -I@ -
I@/contrib/altq -finline-limit=8000 --param inline-unit-growth=100 --param large-function-
growth=1000 -fno-common  -mno-align-long-strings -mpreferred-stack-boundary=2  -mno-mmx -
mno-3dnow -mno-sse -mno-sse2 -mno-sse3 -ffreestanding -fstack-protector -std=iso9899:1999
-fstack-protector -Wall -Wredundant-decls -Wnested-externs -Wstrict-prototypes  -Wmissing-
prototypes -Wpointer-arith -Winline -Wcast-qual  -Wundef -Wno-pointer-sign -fformat-
extensions -c module.c
ld  -d -warn-common -r -d -o module.kld module.o
:> export_syms
awk -f /sys/conf/kmod_syms.awk module.kld  export_syms | xargs -J% objcopy % module.kld
```

To see how the GCC Stack-Protector works, change the build parameters such that GCC outputs assembly instead of an executable. Unfortunately the assembly produced by *objdump –S* omits key instructions. To generate the assembly, execute the following commands:

```
image80# setenv CFLAGS "-S"
image80# make
…
<build fails>
…
image80# unset CFLAGS
```

The above commands generate a *module.s* file that contains the assembly generated by GCC. List the contents of the file with the *more* command and find the start and the end of the *test_password* function:

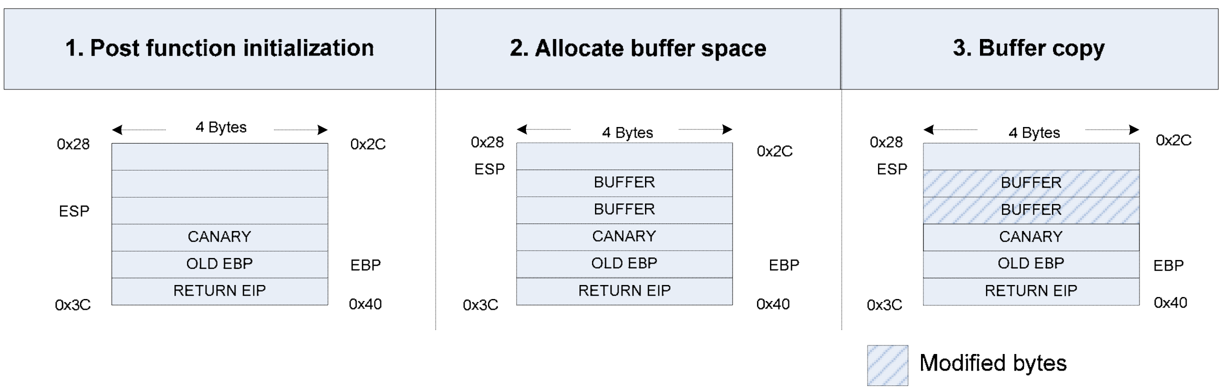
```
…
test_password:
        pushl   %ebp
        movl    %esp, %ebp
        subl    $36, %esp
        movl    8(%ebp), %eax
        movl    %eax, -16(%ebp)
        movl    12(%ebp), %eax
        movl    %eax, -20(%ebp)
        movl    16(%ebp), %eax
        movl    %eax, -24(%ebp)
        movl    __stack_chk_guard, %eax
        movl    %eax, -4(%ebp)
…
.L16:
        movl    -16(%ebp), %eax
        movl    $0, (%eax)
        movl    -4(%ebp), %eax
        xorl    __stack_chk_guard, %eax
        je      .L19
        call    __stack_chk_fail
.L19:
        leave
        ret
        .size   test_password, .-test_password
        .p2align 4,,15
        .type   memset, @function
```

GCC has inserted the additional code (shown in red) that causes a canary value to be written to the stack during the initialization of a function, and for the value to be checked just before a function returns. The stack-protector canary value is inserted between the return instruction pointer (*RETURN EIP)* and any variables on the stack; this means that a buffer overrun attack targeted at overwriting the return instruction pointer will also overwrite the canary value. If the canary value check fails, a message warning the system administrator is displayed and the system is shut down (or launches the Kernel Debugger if available).

Compromising the Stack

The following examples have been simplified to omit details not relevant to stack overruns. Figure 8 shows the normal operation of the stack in the *test_password* function with the canary value.

Figure 8. Normal Stack Operation



When the *test_password* function is called from *ulock_write*;

1. The *call* instruction in the function *ulock_write* pushes the return address (RETURN EIP) onto the stack; execution then starts in the function *test_password*. The return address is the address of the instruction that will execute when the *test_password* function has returned. It is usually the address of the instruction immediately following the *call* instruction in function *ulock_write*; *ulock_write's* stack base pointer (OLD EBP) is then also pushed onto the stack.

   The canary value (CANARY) is then pushed onto the stack below *ulock_write's* base stack pointer.

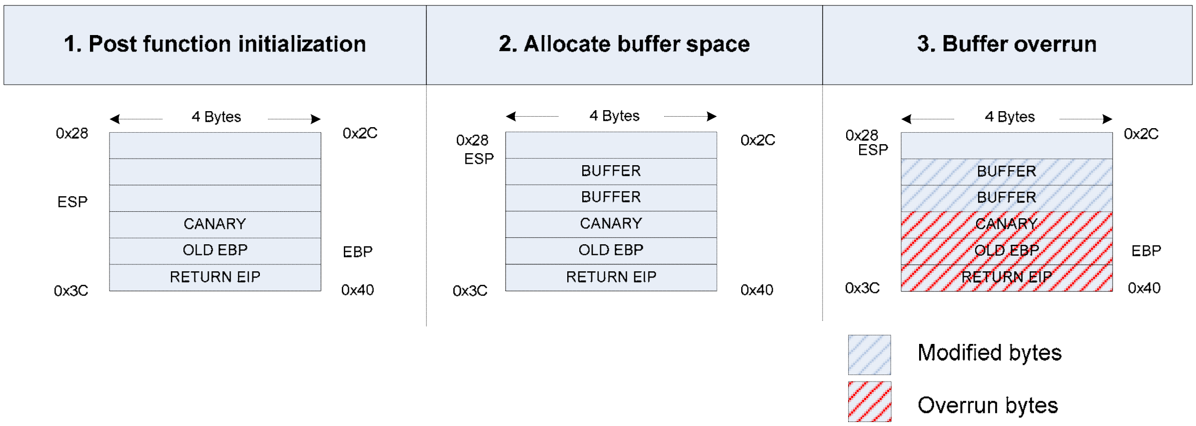
2. A further eight bytes is then created on the stack for the Kernel-space buffer (2 x BUFFER). This is the Kernel-space buffer, to which the User-space buffer will be copied.

3. The buffer is then copied from User-space to Kernel-space, overwriting the space allocated for the buffer on the stack.

In this case, when the *test_password* function returns, control correctly passes back to *ulock_write*.

Figure 9 shows the operation of the stack when an attacker has passed a User-space buffer greater in size than the receiving Kernel-space buffer.

Figure 9. Compromised Stack Operation



When the *test_password* function is called;

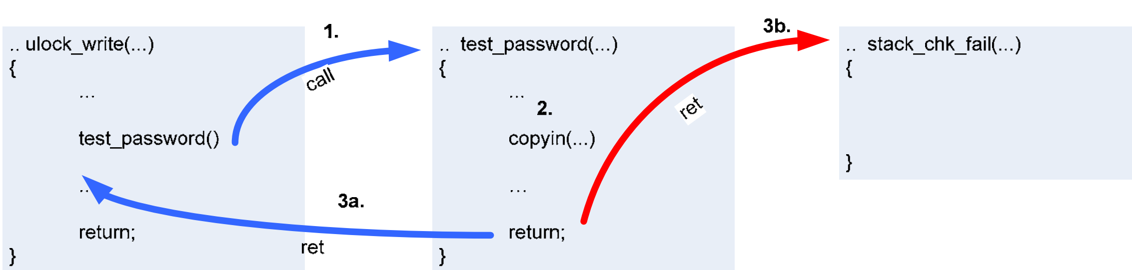
1. and 2. as per previous example.

3. The code overruns the Kernel-space buffer, overwriting the stack canary value (CANARY), *ulock_write's* base stack pointer (OLD EBP), and the address of the instruction to execute on return (RETURN EIP).

The attacker has succeeded in overwriting the Return Instruction Pointer (RETURN EIP), but has also inadvertently overwritten the canary value (CANARY), such that when the *test_password* function returns, the canary value check will fail and *stack_chk_fail* will be called.

Figure 10 shows both code flows discussed (normal and compromised stack operations).

Figure 10. Code Flow



1. *ulock_write* function calls the *test_password* function.

2. The *copyin* function copies the buffer from User-space to Kernel-space.

3. When the *test_password* function returns.

    a. In the case of <u>normal</u> stack operation, control returns to the *ulock_write* function.

    b. In the case of <u>compromised</u> operation, the *stack_chk_fail* function is called and the system will display a message alerting the system administrator to the stack overflow.

Executing the Sample Code

As described in the FreeBSD 7.2 section, build the sample code with the make command.

```
image80# make
…
```

Because a different version of FreeBSD is being used, with a different compiler and so on, all of the offsets can be expected to change. Use the *objdump –S* command to determine the correct offsets for the *unlock function* and the *Return Instruction Pointer.*

```
image80# objdump –S module.ko
…
00000620 <unlock>:
 620:   55                      push   %ebp
 621:   89 e5                   mov    %esp,%ebp
 623:   83 ec 04                sub    $0x4,%esp
 626:   c7 04 24 14 07 00 00    movl   $0x714,(%esp)
…
00000640 <test_password>:
 640:   55                      push   %ebp
 641:   89 e5                   mov    %esp,%ebp
 643:   83 ec 24                sub    $0x24,%esp
 646:   89 5d f4                mov    %ebx,0xfffffff4(%ebp)
…
000006d0 <ulock_write>:
 6d0:   55                      push   %ebp
 6d1:   89 e5                   mov    %esp,%ebp
 6d3:   83 ec 08                sub    $0x8,%esp
 6d6:   c7 04 24 3b 07 00 00    movl   $0x73b,(%esp)
 6dd:   c7 45 fc ff ff ff ff    movl   $0xffffffff,0xfffffffc(%ebp)
 6e4:   e8 fc ff ff ff          call   6e5 <ulock_write+0x15>
 6e9:   8b 55 10                mov    0x10(%ebp),%edx
 6ec:   8d 45 fc                lea    0xfffffffc(%ebp),%eax
 6ef:   8b 4d 0c                mov    0xc(%ebp),%ecx
 6f2:   89 14 24                mov    %edx,(%esp)
 6f5:   8b 55 08                mov    0x8(%ebp),%edx
 6f8:   e8 43 ff ff ff          call   640 <test_password>
 6fd:   c7 04 24 4d 07 00 00    movl   $0x74d,(%esp)
…
```

As expected, the two offsets (shown in red above) have changed. In addition, there is now an extra four bytes between the Kernel-space buffer and the *Return Instruction Pointer* to hold the canary value.

To illustrate this, FreeBSD 8.0 creates 36 bytes of stack space for the *test_complete function*, shown in red above. FreeBSD 7.2 creates 32 bytes of stack space for the *test_complete function*, shown in Figure 11.

Figure 11. Growing the Stack

Growing the stack on FreeBSD 7.2

```
00000520 <test_password>:
 520:   55                      push   %ebp
 521:   89 e5                   mov    %esp,%ebp
 523:   83 ec 24                sub    $0x20,%esp
```

Growing the stack on FreeBSD 8.0

```
00000640 <test_password>:
 640:   55                      push   %ebp
 641:   89 e5                   mov    %esp,%ebp
 643:   83 ec 24                sub    $0x24,%esp ← Extra 4 bytes is the canary
```

In addition to updating the instruction offsets, the hack software must be updated to also overwrite the canary value. The *crack_data* data structure is shown below, updated with the new offsets and an extra four bytes to overwrite the canary value.

```
unsigned int crack_data[9] =
        {
            0xFFFFFFFF,
            0xFFFFFFFF,
            0xFFFFFFFF,
            0xFFFFFFFF,
            0xFFFFFFFF,
            0xFFFFFFFF,
            0xFFFFFFFF,
            0x620,
            0x6fd
        };
```

Now build the hack software.

```
image80# gcc -O2 hack.c -o hack
```

Load the module and find the modules offset in memory.

```
image80# kldload ./module.ko
image80# kldstat
Id Refs Address    Size     Name
 1    3 0xc0400000 cbabc8   Kernel
 2    1 0xc25d5000 2000     module.ko
```

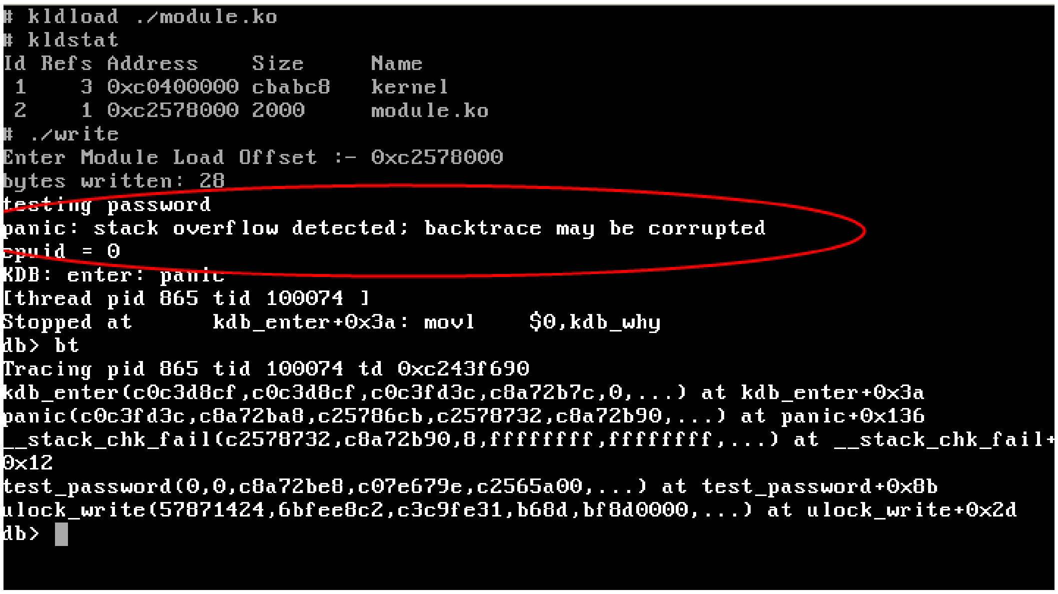
Execute the hack and enter the module's load offset.

```
image80# ./hack
Enter Module Load Offset :- 0xc25d5000
```

The stack overrun is automatically detected at the exit of the *test_password* function and the Kernel Debugger is automatically launched (please see Figure 12). From the

Kernel Debugger prompt the *bt* (backtrace) command can be issued to trace the source of the buffer overrun.

Figure 12. Stack Overflow Detected



```
# kldload ./module.ko
# kldstat
Id Refs Address    Size     Name
 1    3 0xc0400000 cbabc8   kernel
 2    1 0xc2578000 2000     module.ko
# ./write
Enter Module Load Offset :- 0xc2578000
bytes written: 28
testing password
panic: stack overflow detected; backtrace may be corrupted
cpuid = 0
KDB: enter: panic
[thread pid 865 tid 100074 ]
Stopped at      kdb_enter+0x3a: movl    $0,kdb_why
db> bt
Tracing pid 865 tid 100074 td 0xc243f690
kdb_enter(c0c3d8cf,c0c3d8cf,c0c3fd3c,c8a72b7c,0,...) at kdb_enter+0x3a
panic(c0c3fd3c,c8a72ba8,c25786cb,c2578732,c8a72b90,...) at panic+0x136
__stack_chk_fail(c2578732,c8a72b90,8,ffffffff,ffffffff,...) at __stack_chk_fail+
0x12
test_password(0,0,c8a72be8,c07e679e,c2565a00,...) at test_password+0x8b
ulock_write(57871424,6bfee8c2,c3c9fe31,b68d,bf8d0000,...) at ulock_write+0x2d
db>
```

Conclusion

The addition of stack overflow protection to the Kernel in FreeBSD 8.0 is both valuable as an improvement to system security and as an aid in Kernel development. However, the overall effects of this protection on system performance remains to be seen.

Conclusion

Utilities such as RedZone and GCC Stack-Protector can help FreeBSD Kernel developers determine potential buffer overruns early in the development process — when the root cause is far less difficult to identify. Kernel Developers should be familiar with these tools and consider using them in their unit-test processes.

Buffer overruns have a tendency to be overlooked and misdiagnosed, and are frequently attributed to system gremlins by application engineers. They are considered some of the most difficult bugs to resolve, and Kernel coding is often regarded as one of the toughest development environments. Hopefully this paper has demonstrated that Kernel buffer overruns are now easily identified and resolved.

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Appendix A

Makefile

```
# Note: It is important to make sure you include the <bsd.kmod.mk> makefile after
declaring the KMOD and SRCS variables.

# Declare Name of Kernel module
KMOD    =  module

# Enumerate Source files for Kernel module
SRCS    =  module.c

# Include Kernel module makefile
.include <bsd.kmod.mk>
```

module.c

```
#include <sys/param.h>
#include <sys/module.h>
#include <sys/Kernel.h>
#include <sys/malloc.h>
#include <sys/endian.h>
#include <sys/libkern.h>
#include <sys/kthread.h>
#include <vm/vm_param.h>
#include <sys/proc.h>

#define COOKIE_SIZE 64
#define COOKIE_NUM  10
#define ALLOC_NUM   1000

MALLOC_DEFINE(swap_mem, "bswap_mem", "bswap_mem");

uint8_t bContinue = TRUE;
const char module_name[] = "bad_mod\0";
const char thread_name[] = "bad_thread";
#define  num_ints (COOKIE_SIZE-sizeof(module_name))/sizeof(uint32_t)
struct proc *pProc = NULL;

struct _cookie
{
        char            canary_string[sizeof(module_name)];
        uint32_t        ints[num_ints];
};

struct _cookie *pBuffer[COOKIE_NUM];

void _thread(void *pParam);
void _alloc(void);
int _start_thread(struct proc **ppProc);
void _wait_4_thread(struct proc *pProc);
void _free(void);


static int
cookie_cmp(const void *p1, const void *p2)
{
        const uint32_t u1 = *((const uint32_t *) p1);
```

```
        const uint32_t u2 = *((const uint32_t *) p2);

        if (u1 > u2)
                return (1);
        else if (u1 < u2)
                return (-1);
        else
                return (0);
}

void _alloc()
{
        struct _cookie *alloc_buf[ALLOC_NUM];
        uint32_t        top_distance = 0xFFFFFFFF;
        uint32_t        cur_distance = 0;
        uint32_t        top_index = 0;

        for(int i=0; i < ALLOC_NUM; i++)
                alloc_buf[i] = malloc(COOKIE_SIZE, swap_mem, 0);

        //sort in order of memory address
        qsort(alloc_buf, ALLOC_NUM, sizeof(struct _cookie *), cookie_cmp);

        /*
         * find the most virtually contiguous memory available,
         * reduces probability of damage to the system,
         * usually works, you may need to tweak
         */

for(int i=0; i < ALLOC_NUM - COOKIE_NUM; i++)
        {
                cur_distance = (uint32_t) alloc_buf[i + COOKIE_NUM] - (uint32_t)
 alloc_buf[i];
                if(cur_distance < top_distance)
                {
                        top_index = i;
                        top_distance = cur_distance;
                }
        }

        for(int i=0, e=0; i < ALLOC_NUM; i++)
        {
                if(i >= top_index && i < (top_index + COOKIE_NUM))
                {
                        pBuffer[e] = alloc_buf[i];
                        bzero( pBuffer[e],COOKIE_SIZE);
                        strcpy(pBuffer[e]->canary_string, module_name);
                        e++;

                        //printf("RZFooter: 0x%.08x\n",
                           ((int) alloc_buf[i]) + COOKIE_SIZE);
                }
                 else
                {
                        free(alloc_buf[i],swap_mem);
                }
        }

}

void _free()
{
        for(int i=0; i < COOKIE_NUM; i++)
```

```
                free(pBuffer[i],swap_mem);
}

int _start_thread(struct proc **ppProc)
{
        return kthread_create(_thread, pBuffer, ppProc,
                0, 0, thread_name);
}

void _wait_4_thread(struct proc *pProc)
{
        tsleep(pProc, curthread->td_priority , "sleep", 0);
}

void _thread(void *pParam)
{
        while(bContinue)
        {
                uint32_t cookie_and_wait =
                        (arc4random() % COOKIE_NUM);

                //don't swap uncharted memory
                if(cookie_and_wait == (COOKIE_NUM-1)) continue;

                //we will only ever go one int over!!!!
                for(int i=0; i <= num_ints; i++)
                        pBuffer[cookie_and_wait]->ints[i]++;

                if(!cookie_and_wait) continue;

                printf("[%.*s] sleep for %d ms\n",
                        sizeof(module_name),
                        pBuffer[cookie_and_wait]->canary_string ,
                        cookie_and_wait * 1000);
                pause("sleep", cookie_and_wait * 1000);
        }

        kthread_exit(KERN_SUCCESS);
}


/* The function called at load/unload. */
static int event_handler(struct module *module, int event, void *arg) {
        int e = 0; /* Error, 0 for normal return status */
        switch (event) {
        case MOD_LOAD:
                _alloc();
                _start_thread(&pProc);
                break;
        case MOD_UNLOAD:
                bContinue=FALSE;
                _wait_4_thread(pProc);
                _free();
                break;
        default:
                e = EOPNOTSUPP; /* Error, Operation Not Supported */
                break;
        }
        return(e);
}

/* The second argument of DECLARE_MODULE. */
static moduledata_t mod_conf = {
```

```
    "mod",    /* module name */
     event_handler,  /* event handler */
     NULL            /* extra data */
};

DECLARE_MODULE(mod, mod_conf, SI_SUB_DRIVERS, SI_ORDER_MIDDLE);
```

Appendix B

Makefile

```
# Note: It is important to make sure you include the <bsd.kmod.mk> makefile after
declaring the KMOD and SRCS variables.

# Declare Name of Kernel module
KMOD    =  module

# Enumerate Source files for Kernel module
SRCS    =  module.c

# Include Kernel module makefile
.include <bsd.kmod.mk>
```

module.c

```
#include <sys/types.h>
#include <sys/module.h>
#include <sys/systm.h>
#include <sys/errno.h>
#include <sys/param.h>
#include <sys/Kernel.h>
#include <sys/conf.h>
#include <sys/uio.h>

/* Function prototypes */
static d_open_t      ulock_open;
static d_close_t     ulock_close;
static d_read_t      ulock_read;
static d_write_t     ulock_write;

#define noinline __attribute__((noinline))

static void noinline unlock(void);

static void noinline
test_password(int *retval, struct cdev *dev, struct uio *uio, int ioflag);


/* Character device entry points */
static struct cdevsw ulock_cdevsw = {
    .d_version = D_VERSION,
    .d_open = ulock_open,
    .d_close = ulock_close,
    .d_read = ulock_read,
    .d_write = ulock_write,
    .d_name = "ulock",
};
```

```
/* vars */
static struct cdev *ulock_dev;

#define MAX_PASSWORD_LEN 8
#define PASSWORD      "password"
#define byte    unsigned char

/*
 * This function is called by the kld[un]load(2) system calls to
 * determine what actions to take when a module is loaded or unloaded.
 */

static int
ulock_loader(struct module *m, int what, void *arg)
{
    int err = 0;

    switch (what) {
    case MOD_LOAD:                /* kldload */
        ulock_dev = make_dev(&ulock_cdevsw,
            0,
            UID_ROOT,
            GID_WHEEL,
            0600,
            "ulock");
        break;
    case MOD_UNLOAD:
        destroy_dev(ulock_dev);
        break;
    default:
        err = EOPNOTSUPP;
        break;
    }
    return(err);
}

static int
ulock_open(struct cdev *dev, int oflags, int devtype, struct thread *p)
{
    return(0);
}

static int
ulock_close(struct cdev *dev, int fflag, int devtype, struct thread *p)
{
    return(0);
}

/*
 * The read function just takes the buf that was saved via
 * echo_write() and returns it to userland for accessing.
 * uio(9)
 */

static int
ulock_read(struct cdev *dev, struct uio *uio, int ioflag)
{
    return(0);
}

static int
ulock_write(struct cdev *dev, struct uio *uio, int ioflag)
```

```
{
    int ret = 0xFFFFFFFF;

    printf("testing password\n");

    /* trivial change in parameters to stop compiler from optimising out
        the test_password call */
    test_password(&ret, dev, uio, ioflag);

    printf("Made it back, Woo hoo!\n");

    return ret;
}

static void noinline
test_password(int* pret, struct cdev *dev, struct uio *uio, int ioflag)
{
    char password[MAX_PASSWORD_LEN];

    /* Copy the password string from user memory to Kernel memory
    neglecting to check the length of the string
    */
    memset(password, 0 , MAX_PASSWORD_LEN);

    copyin(uio->uio_iov->iov_base, ((void *)password),
        uio->uio_iov->iov_len);

   if(strncmp(PASSWORD,password,sizeof(PASSWORD) - 1) == 0)
    {
        unlock();//open the trival lock
    }

     *pret = 0;
}

static void noinline
unlock(void)
{
    printf("Click, lock has been opened!\n");
}

DEV_MODULE(ulock,ulock_loader,NULL);
```

hack.c

```
#include <stdio.h>

int main(int argc, char *argv[])
{
    unsigned int        crack_data[8] =
        {
            0xFFFFFFFF,
            0xFFFFFFFF,
            0xFFFFFFFF,
            0xFFFFFFFF,
            0xFFFFFFFF,
            0xFFFFFFFF,
            0x5b0,
            0x67d
        };
    char            buffer[9];
    int             bytes = 0;
    unsigned int    load_addr = 0;
```

```
    FILE *          fd = 0;

    fd = fopen("/dev/ulock","w+");

    printf("Enter Module Load Offset :- 0x",fd);
    fgets(buffer, 9, stdin);
    sscanf(buffer, "%x", &load_addr);

    crack_data[6]+=load_addr;
    crack_data[7]+=load_addr;

    bytes =  fwrite(&crack_data, sizeof(crack_data), 1, fd);

    printf("bytes written: %d\n", bytes * sizeof(crack_data));

    fclose(fd);

    return (0);
}
```

§

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Terminology

ACPI	Advanced Configuration and Power Interface
BSD	Berkeley Software Distribution
GCC	GNU Compiler Collection
KDB	Kernel Debugger
Canary Value	A value used to indicate a buffer overrun has occurred.

About FreeBSD

FreeBSD is an advanced operating system for x86- (including Intel® Pentium® and Athlon*) and AMD64-compatible (including Opteron*, Athlon 64*, and EM64T*), ARM, IA-64, PowerPC*, PC-98* and UltraSPARC* architectures. It is derived from BSD, the version of UNIX* developed at the University of California, Berkeley. More information on the FreeBSD Operating System is available at FreeBSD.org.