Buffer overflows

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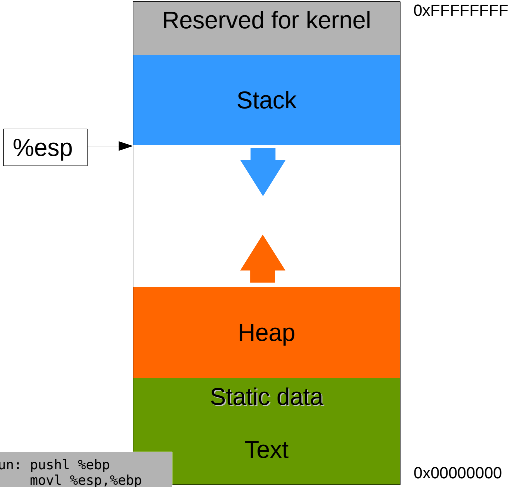
Linux (32-bit) process memory layout (simplified)

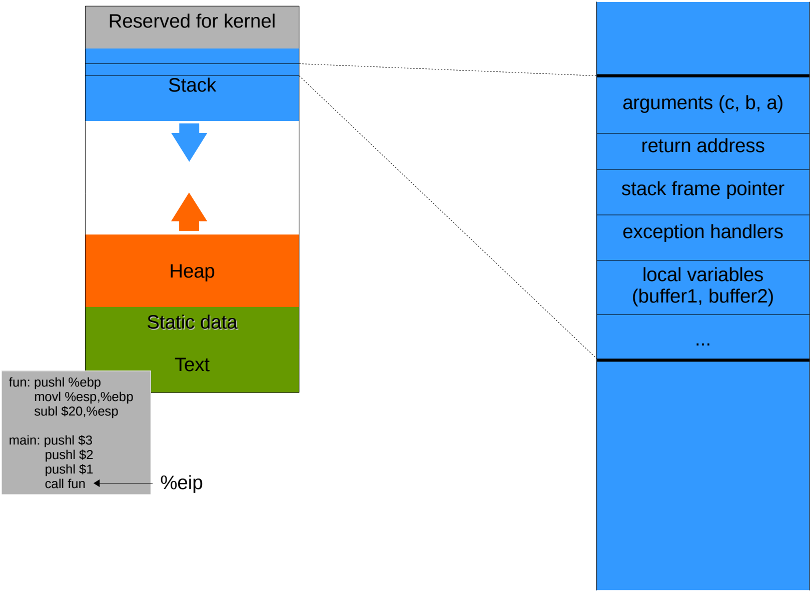



```
void function(int a, int b, int c) {
     char buffer1[5];
     char buffer2[10];
}
void main() {
     function(1,2,3);
}
```

```
fun: pushl %ebp
     movl %esp,%ebp
     subl $20,%esp

main: pushl $3
      pushl $2
      pushl $1
      call fun
```

Stack frame


Reserved for kernel
Stack
Heap
Static data
Text
fun: pushl %ebp
movl %esp,%ebp
subl $20,%esp
main: pushl $3
pushl $2
pushl $1
call fun
%eip
arguments (c, b, a)
return address
stack frame pointer
exception handlers
local variables
(buffer1, buffer2)
...

Stack and functions: Summary

Calling function

1. Push arguments onto the stack (in reverse)
2. Push the return address, i.e., the address of the instruction to run after control returns
3. Jump to the function's address

Called function

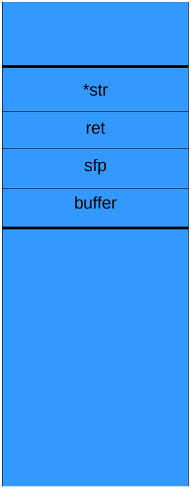
4. Push the old frame pointer onto the stack (%ebp)
5. Set frame pointer (%ebp) to where the end of the stack is right now (%esp)
6. Push local variables onto the stack

Returning function

7. Reset the previous stack frame: %esp = %ebp, %ebp = (%ebp)
8. Jump back to return address: %eip = 4(%esp)

Buffer overflows

```
void function(char *str) {
     char buffer[16];
     strcpy(buffer,str);
}
void main() {
     char large_string[256];
     int i;
     for( i = 0; i < 255; i++)
          large_string[i] = 'A';
function(large_string);
}
```



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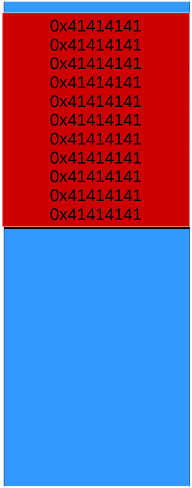
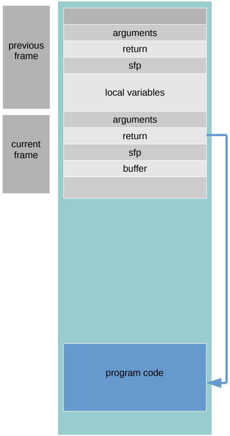
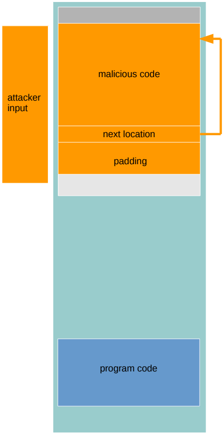


`strcpy(src,dest)` does not check that `dest` is bigger than `src`

The return address is now `0x41414141`

Control hijacking





A buffer overflow can change the flow of execution of the program:

- load malicious code into memory
- make %eip point to it

Shellcode injection

Goal: "spawn a shell" - will give the attacker general access to the system

```
#include stdio.h
void main() {
char *name[2];
name[0] = "/bin/sh";
name[1] = NULL;
execve(name[0], name, NULL);
}
```

C code

```
"\x31\xc0"
"\x50"
"\x68" "//sh"
"\x68" "/bin"
"\x89\xe3"
"\x50"
...
```

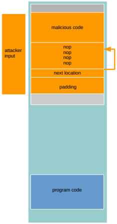
Machine code
(part of attacker's input)

- must inject the machine code instructions (code ready to run)
- the code cannot contain any zero bytes (`printf`, `gets`, `strcpy` will stop copying)
- can't use the loader (we're injecting)

The return address

Challenge: find the address of the injected malicious code?

- If code accessible: we know how far is the overflowed variable from the saved %ebp
- If code not accessible: try different possibilities!
  In a 32 bits memory space, there are 2^{32} possibilities
- NOP sled
  - guess approximate stack state when the function is called
  - insert many NOPs before Shell Code



Reference

Aleph One. Smashing The Stack For Fun And Profit.
http://phrack.org/issues/49/14.html#article

Buffer overflow opportunities

Unsafe libc functions

```
strcpy (char *dest, const char *src)

strcat (char *dest, const char *src)

gets (char *s)

scanf (const char *format, ...)

...
```

Do not check bounds of buffers they manipulate!!

Arithmetic overflows

- Limitation related to the representation of integers in memory
- In 32 bits architectures, signed integers are expresses in two's compliment notation
  - $0x00000000$ - $0x7ffffff$: positive numbers 0 - $(2^{31} - 1)$
  - $0x80000000$ - $0xffffffff$: negative numbers $(-2^{31} + 1)$ - (-1)
- In 32 bits architectures, unsigned integers are only positive numbers $0x00000000$ - $0xffffffff$.
  Once the highest unsigned integer is reached, the next sequential integer wraps around zero.

```
# include <stdio.h>
int main(void){
  unsigned int num = 0xffffffff;
  printf(``num + 1 = 0x%x\n'', num + 1);
  return 0;
}
```

The output of this program is: $\text{num} + 1 = 0x0$

Integer overflows

[Blexim] Basic Integer Overflows http://phrack.org/issues/60/10.html#article

Attempt to store a value in an integer which is greater than the maximum value the integer can hold
⟶ the value will be truncated

Ariane 5 rocket launch explosion due to integer overflow

Arithmetic overflow exploit (1)

- Stack-based buffer overflow due to arithmetic overflow:

```
int catvars(char *buf1, char *buf2,
                  unsigned int len1, unsigned int len2){
  char mybuf[256];
  if((len1 + len2) > 256){
    return -1;
  }
  memcpy(mybuf, buf1, len1);
  memcpy(mybuf + len1, buf2, len2);
  do_some_stuff(mybuf);
  return 0;
}
```

Arithmetic overflow exploit (1)

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                 unsigned int len1, unsigned int len2){
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  }
  memcpy(mybuf, buf1, len1);
  memcpy(mybuf + len1, buf2, len2);
  do_some_stuff(mybuf);
  return 0;
}
```

Check can be bypassed by using suitable values for `len1` **and** `len2`**:** `len1 = 0x104`, `len2 = 0xfffffffc`, `len1+len2 = 0x100` (decimal 256)

Arithmetic overflow exploit (2)

- Heap-based buffer overflow due to arithmetic overflow:
  - Memory **dynamically** allocated will persist across multiple function calls.
  - This memory is allocated on the **heap** segment.
  - Heap-based buffer overflows are more complex, and require understanding garbage collection and heap implementation.

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```
int myfunction(int *array, int len){
  int *myarray, i;
  myarray = malloc(len * sizeof(int));
  if(myarray == NULL){
    return -1;
  }
  for(i = 0; i < len; i++){
    myarray[i] = array[i];
  }
  return myarray;
}
```

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  }
  for(i = 0; i < len; i++){
    myarray[i] = array[i];
  }
  return myarray;
}
```

Can allocate a size 0 buffer for `myarray` **by using suitable value for** `len`**:** `len = 1073741824` , `sizeof(int) = 4`, `len*sizeof(int) = 0`

Format strings

[Ref] scut/team teso. Exploiting Format String Vulnerabilities

- A format function takes a variable number of arguments, from which one is the so called format string

  Examples: `fprintf`, `printf`, ..., `syslog`, ...

Format strings

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- A format function takes a variable number of arguments, from which one is the so called format string

  Examples: `fprintf`, `printf`, ..., `syslog`, ...

- The behaviour of the format function is controlled by the format string. The function retrieves the parameters requested by the format string from the stack

  Example: `printf(fmt_str,` $\texttt{arg}_1$`, ...,` $\texttt{arg}_n$`);`

...
$\texttt{arg}_n$
...
$\texttt{arg}_1$
`&fmt_str`
`ret`
`sfp`
...

Example: printf

```
printf(``Num %d has no address, num %d has:%08x\n'', i, a,&a);
```

...	
<&a>	address of variable a
<a>	value of variable a
<i>	value of variable i
&fmt_str	address of the format string
ret	
sfp	
...	

Exploiting format strings

- If an attacker is able to provide the format string to a format function, a format string vulnerability is present

```
int vulnerable_print(char *user) {
  printf(user);
}

int safe_print(char *user){
  printf ("%s", user);
}
```

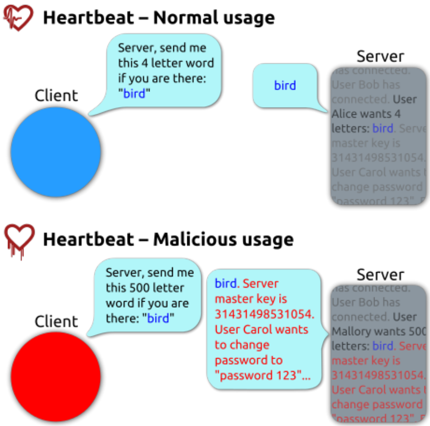
Format strings exploits

- We can view the stack memory at any location
  - walk up stack until target pointer found
  - `printf (``%08x.%08x.%08x.%08x.%08x|%s|'');`
  - A vulnerable program could leak information such as passwords, sessions, or crypto keys
- We can write to any memory location
  - `printf(``hello %n'', &temp)` – writes '6' into temp
  - `printf(``hello%08x.%08x.%08x.%08x.%n'')`

More buffer overflow opportunities

- Exception handlers
- Function pointers
- Double free
- ...

TLS Heartbleed



TLS Heartbleed

Then, OpenSSL will uncomplainingly copy 65535 bytes from your request packet, even though you didn't send across that many bytes:

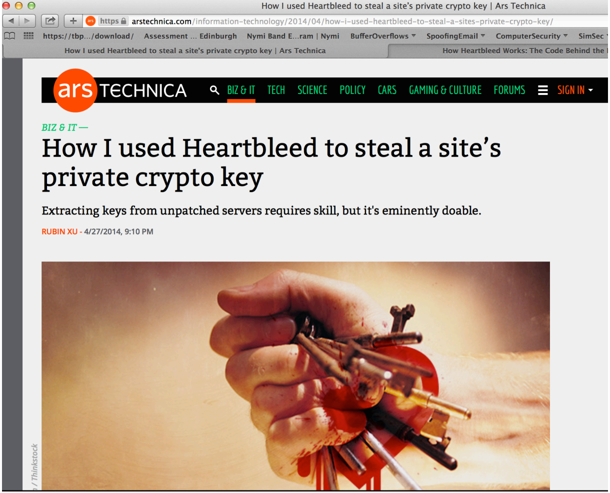
```
/* Allocate memory for the response, size is 1 byte
 * message type, plus 2 bytes payload length, plus
 * payload, plus padding
 */
buffer = OPENSSL_malloc(1 + 2 + payload + padding);
bp = buffer;

/* Enter response type, length and copy payload */
*bp++ = TLS1_HB_RESPONSE;
s2n(payload, bp);
memcpy(bp, pl, payload);
bp += payload;
/* Random padding */
RAND_pseudo_bytes(bp, padding);

r = dtls1_write_bytes(s, TLS1_RT_HEARTBEAT, buffer, 3 + payload +
```

That means OpenSSL runs off the end of your data and scoops up whatever else is next to it in memory at the other end of the connection, for a potential data leakage of approximately 64KB each time you send a malformed heartbeat request.

TLS Heartbleed



Defenses against buffer overflows:

making exploitation hard

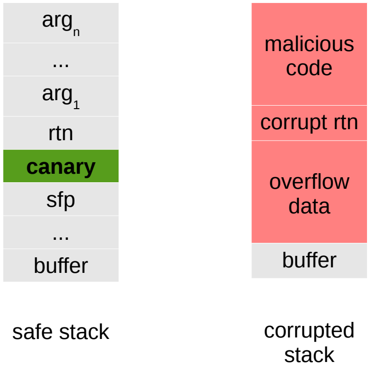
Use safe C libraries

Size-bounded analogues of unsafe libc functions.

- `size_t strlcpy(char *destination, const char *source, size_t size);`
- `size_t strlcat(char *destination, const char *source, size_t size);`
- `char *fgets(char *str, int n, FILE *stream);`
- `int sscanf(const char *str, const char *format, ...);`
- ...

Stack canaries

- detect a stack buffer overflow before execution of malicious code
- place a small integer (canary) just before the stack return pointer
- to overwrite the return pointer the canary value must also be overwritten
- the canary is checked to make sure it has not changed before a routine uses the return pointer on the stack



Canary values

[Ref] Cowan & al. StackGuard: Automatic Adaptive Detection and Prevention of Buffer-Overflow Attacks. In Proceedings of the 7th USENIX Security Symposium, 1998

1. Terminator canaries (CR, LF, NUL (i.e., 0), -1): `scanf` etc. do not allow these values

2. Random canaries
   - Write a new random value at each process start
   - Save the real value somewhere in memory
   - Must write-protect the stored value

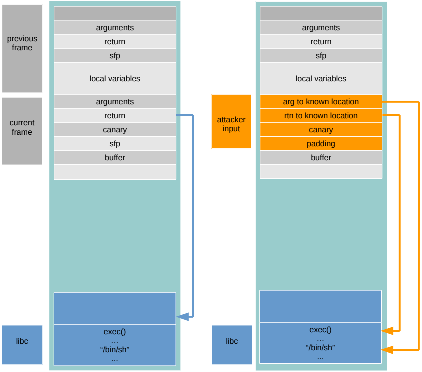
3. Random XOR canaries
   - Same as random canaries
   - But store canary XOR some control info, instead

Make stack and heap non executable

- **Goal:** even if the canary is bypassed, the malicious code loaded cannot be executed

Make stack and heap non executable

- **Goal:** even if the canary is bypassed, the malicious code loaded cannot be executed
- **But:** vulnerable to `return-to-libc` attack!!
  - the `libc` library is linked to most C programs
  - `libc` provides useful calls for an attacker



Address space layout randomization

- **Idea:** place standard libraries to random locations in memory
  $\longrightarrow$ for each program, `exec()` is situated at a different location
  $\longrightarrow$ the attacker cannot directly point to `exec()`

- Supported by most operating systems (Linux, Windows, MAC OS, Android, iOS, ...)

But ultimately

- Hackers have and will develop more complicated ways of exploiting buffer overflows.
- It all boils down to the programmer.
- The most important preventive measure is: **safe programming**
- Whenever a program copies user-supplied input into a buffer ensure that the program does not copy more data than the buffer can hold

Take away message

OSes may have features to reduce the risks of BOs, but the best way to guarantee safety is to remove these vulnerabilities from application code.