IS 2620

Secure Coding in C and C++

Pointer Subterfuge

Lecture 4

Sept 10-17, 2014

Acknowledgement: These slides are based on author Seacord's original presentation

Pointer Subterfuge

- A *pointer* is a variable that contains the address of a function, array element, or other data structure.
- Function pointers can be overwritten to transfer control to attacker-supplied shellcode.
- Data pointers can also be modified to run arbitrary code.
  - attackers can control the address to modify other memory locations.

Data Locations - 1

- For a buffer overflow to overwrite a function/ data pointer the buffer must be
  - allocated in the same segment as the target function/data pointer.
  - at a lower memory address than the target function/data pointer.
  - susceptible to a buffer overflow exploit.

Data Locations - 2

- UNIX executables contain both a data and a BSS segment.
  - The data segment contains all initialized global variables and constants.
  - The Block Started by Symbols (BSS) segment contains all uninitialized global variables.
- Initialized global variables are separated from uninitialized variables.

Data declarations and process memory organization

```
static int GLOBAL_INIT = 1;         /* data segment, global */
static int global_uninit;           /* BSS segment, global */

void main(int argc, char **argv) {  /* stack, local */
  int local_init = 1;               /* stack, local */
  int local_uninit;                 /* stack, local */
  static int local_static_init = 1; /* data seg, local */
  static int local_static_uninit;   /* BSS segment, local*/
  /* storage for buff_ptr is stack, local */
  /* allocated memory is heap, local */
  int *buff_ptr = (int *) malloc(32);
  }
```

Function Pointers - Example Program 1

```
void good_function(const char *str) {...}
void main(int argc, char **argv) {
    static char buff[BUFFSIZE];
    static void (*funcPtr)(const char *str);
    funcPtr = &good_function;
    strncpy(buff, argv[1], strlen(argv[1]));
    (void)(*funcPtr)(argv[2]);
}
```

The static character array buff

funcPtr declared are both uninitialized and stored in the BSS segment.

Function Pointers - Example Program - 2

```
void good_function(const char *str) {...}
void main(int argc, char **argv) {
  static char buff[BUFFSIZE];
  static void (*funcPtr)(const char *str);
  funcPtr = &good_function;
  strncpy(buff, argv[1], strlen(argv[1]));
  (void)(*funcPtr)(argv[2]);
}
```

A buffer overflow occurs when the length of argv[1] exceeds BUFFSIZE.

When the program invokes the function identified by funcPtr, the shellcode is invoked instead of good_function().

Data Pointers

- Used in C and C++ to refer to
  - dynamically allocated structures
  - call-by-reference function arguments
  - arrays
  - other data structures

- Arbitrary Memory Write occurs when an Attacker can control an address to modify other memory locations

Data Pointers - Example Program

```
1. void foo(void * arg, size_t len) {
2.    char buff[100];
3.    long val = ...;
4.    long *ptr = ...;
5.    memcpy(buff, arg, len); //unbounded memory copy
6.    *ptr = val;
7.    ...
8.    return;
9. }
```

- By overflowing the buffer, an attacker can overwrite ptr and val.
- When *ptr = val is evaluated (line 6), an arbitrary memory write is performed.

Modifying the Instruction Pointer

- For an attacker to succeed an exploit needs to modify the value of the instruction pointer to reference the shellcode.

```
void good_function(const char *str) {
  printf("%s", str);
}
int _tmain(int argc, _TCHAR* argv[]) {
  static void (*funcPtr)(const char *str);
  // Function pointer declaration
  funcPtr = &good_function;
  (void)(*funcPtr)("hi ");
  good_function("there!\n");
  return 0;
}
```

Function Pointer Disassembly Example - Program

- (void)(*funcPtr)("hi ");
- **00424178 mov esi, esp**
- **0042417A push offset string "hi" (46802Ch)**
- **0042417F call dword ptr [funcPtr (478400h)]**
- **00424185 add esp, 4**
- **00424188 cmp esi, esp**
- good_function("there!\n");
- **0042418F push offset string "there!\n" (468020h)**
- **00424194 call good_function (422479h)**
- **00424199 add esp, 4**

This address can also be found in the dword ptr [funcPtr

First function call invocation takes place at 0x0042417F. The machine code at this address is ff 15 00 84 47 00

The actual address of good_function() stored at this address is 0x00422479.

Function Pointer Disassembly Example - Program

- `(void)(*funcPtr)("hi ");`
- **`00424178 mov esi, esp`**
- **`0042417A push offset string "hi" (46802Ch)`**
- **`0042417F call dword ptr [funcPtr (478400h)]`**
- **`00424185 add  esp, 4`**
- **`00424188 cmp  esi, esp`**

- `good_function("there!\n");`
- **`0042418F push offset string "there!\n" (468020h)`**
- **`00424194 call good_function (422479h)`**
- **`00424199 add  esp, 4`**

The second, static call to good_function() takes place at 0x00424194. The machine code at this location is e8 e0 e2 ff ff.

Function Pointer Disassembly Analysis - 1

- call Goodfunction(..)
  - indicates a near call with a displacement relative to the next instruction.
  - The displacement is a negative number, which means that good_function() appears at a lower address
  - The invocations of good_function() provide examples of call instructions that can and cannot be attacked

Function pointer disassembly analysis - 2

- The static invocation uses an *immediate* value as relative displacement,
  - this displacement cannot be overwritten because it is in the code segment.
- The invocation through the function pointer uses an *indirect* reference,
  - the address in the referenced location can be overwritten.
- These indirect function references can be exploited to transfer control to arbitrary code.

Global Offset Table - 1

- Windows and Linux use a similar mechanism for linking and transferring control to library functions.
  - Linux solution is exploitable
  - Windows version is not

- The default binary format on Linux, Solaris 2.x, and SVR4 is called the executable and linking format (ELF).

- ELF was originally developed and published by UNIX System Laboratories (USL) as part of the application binary interface (ABI).

- The ELF standard was adopted by the Tool Interface Standards committee (TIS) as a portable object file format for a variety of IA-32 operating systems.

Global Offset Table - 2

- The process space of any ELF binary includes a section called the global offset table (GOT).
  - The GOT holds the absolute addresses,
  - Provides ability to share, the program text.
    - essential for the dynamic linking process to work.
- Every library function used by a program has an entry in the GOT that contains the address of the actual function.
  - Before the program uses a function for the first time, the entry contains the address of the runtime linker (RTL).
  - If the function is called by the program, control is passed to the RTL and the function’s real address is resolved and inserted into the GOT.
  - Subsequent calls invoke the function directly through the GOT entry without involving the RTL

Global Offset Table - 3

- The address of a GOT entry is fixed in the ELF executable.
- The GOT entry is at the same address for any executable process image.

- The location of the GOT entry for a function can be found using the objdump

- An attacker can overwrite a GOT entry for a function with the address of shellcode using an arbitrary memory write.

  - Control is transferred to the shellcode when the program subsequently invokes the function corresponding to the compromised GOT entry.

Global Offset Table Example

```
% objdump --dynamic-reloc test-prog
format:     file format elf32-i386

DYNAMIC RELOCATION RECORDS
OFFSET    TYPE                      VALUE
08049bc0 R_386_GLOB_DAT     __gmon_start__
08049ba8 R_386_JUMP_SLOT    __libc_start_main
08049bac R_386_JUMP_SLOT          strcat
08049bb0 R_386_JUMP_SLOT          printf
08049bb4 R_386_JUMP_SLOT           exit
08049bb8 R_386_JUMP_SLOT          sprintf
08049bbc R_386_JUMP_SL
```

The offsets specified for each R_386_JUMP_SLOT relocation record contain the address of the specified function (or the RTL linking function)

The .dtors Section

- Another function pointer attack is to overwrite function pointers in the .dtors section for executables generated by GCC
- GNU C allows a programmer to declare attributes about functions by specifying the __attribute__ keyword followed by an attribute specification inside double parentheses
- Attribute specifications include constructor and destructor.
- The constructor attribute specifies that the function is called before main()
- The destructor attribute specifies that the function is called after main() has completed or exit() has been called.

The .dtors Section - Example Program

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

static void create(void)
     __attribute__ ((constructor));
static void destroy(void)
     __attribute__ ((destructor));

int main(int argc, char *argv[]) {
  printf("create: %p.\n", create);
  printf("destroy: %p.\n", destroy);
  exit(EXIT_SUCCESS);
}

void create(void) {
  printf("create called.\n");
}

void destroy(void) {
  printf("destroy called.\n");
}
```

```
create called.
create: 0x80483a0.
```

```
destroy: 0x80483b8.
destroy called.
```

The .dtors Section - 1

- Constructors and destructors are stored in the .ctors and .dtors sections in the generated ELF executable image.
- Both sections have the following layout:
  - `0xffffffff {function-address} 0x00000000`

- The .ctors and .dtors sections are mapped into the process address space and are writable by default.
- Constructors have not been used in exploits because they are called before the main program.

- The focus is on destructors and the .dtors section.
- The contents of the .dtors section in the executable image can be examined with the objdump command

The .dtors Section - 2

- An attacker can transfer control to arbitrary code by overwriting the address of the function pointer in the .dtors section.
- If the target binary is readable by an attacker, an attacker can find the exact position to overwrite by analyzing the ELF image.
- The .dtors section is present even if no destructor is specified.
- The .dtors section consists of the head and tail tag with no function addresses between.
- It is still possible to transfer control by overwriting the tail tag 0x00000000 with the address of the shellcode.

The .dtors Section - 3

- For an attacker,.dtors section has advantages over other targets:
  - .dtors is always present and mapped into memory.
  - It is difficult to find a location to inject the shellcode onto so that it remains in memory after main() has exited.
  - The .dtors target only exists in programs that have been compiled and linked with GCC.

Virtual Pointers - 1

- A virtual function is a function member of a class, declared using the virtual keyword.

- Functions may be overridden by a function of the same name in a derived class.

- A pointer to a derived class object may be assigned to a base class pointer, and the function called through the pointer.

- Without virtual functions, the base class function is called because it is associated with the static type of the pointer.
- When using virtual functions, the derived class function is called because it is associated with the dynamic type of the object

Virtual Pointers - Example Program- 1

```
class a {
  public:
    void f(void) {
      cout << "base f" << endl;
    };

    virtual void g(void) {
      cout << "base g" << endl;
    };
};

class b: public a {
  public:
    void f(void) {
      cout << "derived f" << endl;
    };

    void g(void) {
      cout << "derived g" << endl;
    };
};

int _tmain(int argc, _TCHAR* argv[])
  a *my_b = new b();
  my_b->f();
  my_b->g();
  return
```

Class a is defined as the base class and contains a regular function f() and a virtual function g().

Class b is derived from a and overrides both functions.

A pointer my_b to the base class is declared in main() but assigned to an object of the derived class b.

Virtual Pointers - Example Program- 1

```
int _tmain(int argc, _TCHAR* argv[]) {
  a *my_b = new b();
  my_b->f();
  my_b->g();
  return
```

A pointer my_b to the base class is declared in main() but assigned to an object of the derived class b.

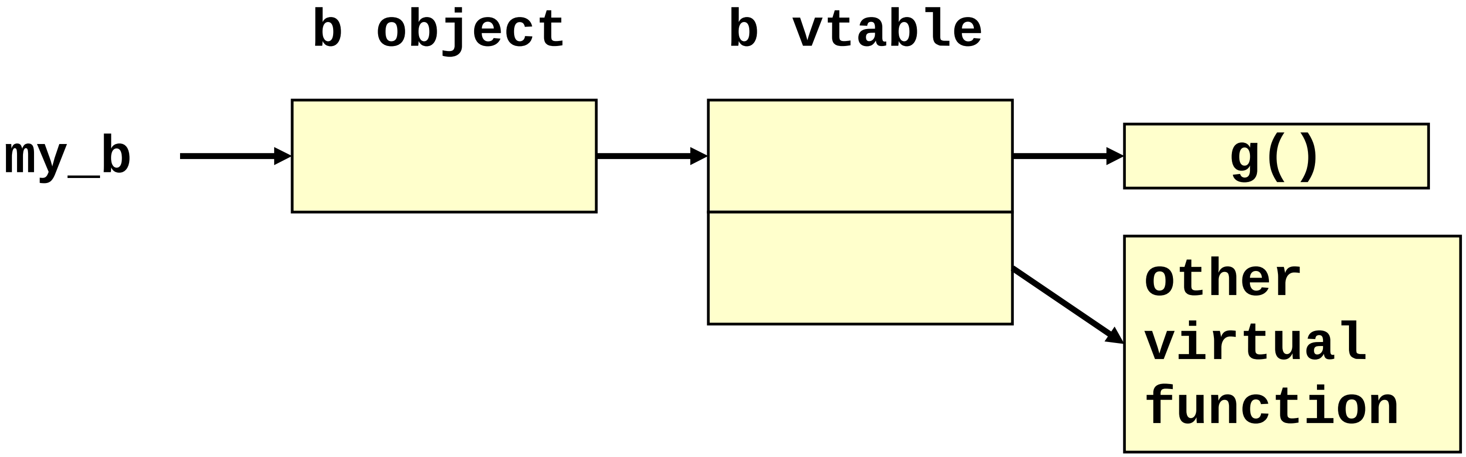
When the virtual function my_b->g() is called on the function g() associated with b (the derived class) is called

When the non-virtual function my_b->f() is called on the function f() associated with a (the base class) is called.

Virtual Pointers - 2

- Most C++ compilers implement virtual functions using a virtual function table (VTBL).
- The VTBL is an array of function pointers that is used at runtime for dispatching virtual function calls.
- Each individual object points to the VTBL via a virtual pointer (VPTR) in the object’s header.
- The VTBL contains pointers to each implementation of a virtual function.

VTBL Runtime Representation



Virtual Pointers - 3

- It is possible to overwrite function pointers in the VTBL or to change the VPTR to point to another arbitrary VTBL.
- This can be accomplished by an arbitrary memory write or by a buffer overflow directly into an object.
- The buffer overwrites the VPTR and VTBL of the object and allows the attacker to cause function pointers to execute arbitrary code.

The atexit() and on_exit() Functions - 1

- The atexit() function is a general utility function defined in C99.
- The atexit() function registers a function to be called without arguments at normal program termination.
- C99 requires that the implementation support the registration of at least 32 functions.
- The on_exit() function from SunOS performs a similar function.
- This function is also present in libc4, libc5, and glibc

The atexit() and on_exit() – Example Program

```
char *glob;

void test(void) {
  printf("%s", glob);
}

void main(void) {
  atexit(test);
 glob = "Exiting.\n";
}
```

The atexit() and on_exit() Functions - 2

- The atexit() function works by adding a specified function to an array of existing functions to be called on exit.

- When exit() is called, it invokes each function in the array in last in, first out (LIFO) order.

- Because both atexit() and exit() need to access this array, it is allocated as a global symbol (__atexit on *bsd and __exit_funcs on Linux)

Debug session of atexit program using gdb - 1

```
(gdb) b main
Breakpoint 1 at 0x80483f6: file atexit.c, line 6.
(gdb) r
Starting program: /home/rcs/book/dtors/atexit

Breakpoint 1, main (argc=1, argv=0xbfffe744) at atexit.c:6
6 atexit(test);
(gdb) next
7 glob = "Exiting.\n";
(gdb) x/12x __exit_funcs
0x42130ee0 <init>:    0x00000000 0x00000003 0x00000004 0x4000c660
0x42130ef0 <init+16>: 0x00000000 0x00000000 0x00000004 0x0804844c
0x42130f00 <init+32>: 0x00000000 0x00000000 0x00000004 0x080483c8
(gdb) x/4x 0x4000c660
0x4000c660 <_dl_fini>: 0x57e58955 0x5ce85356 0x81000054 0x0091c1c3
(gdb) x/3x 0x0804844c
0x804844c <__libc_csu_fini>: 0x53e58955 0x9510b850 x102d0804
(gdb) x/8x 0x080483c8
0x80483c8 <test>: 0x83e58955 0xec8308ec 0x2035ff08 0x68080496
```

Debug session of atexit program using gdb - 2

- Three functions have been registered _dl_fini(), __libc_csu_fini(), test().
- It is possible to transfer control to arbitrary code with an arbitrary memory write or a buffer overflow directly into the __exit_funcs structure.
- The _dl_fini() and __libc_csu_fini() functions are present even when the vulnerable program does not explicitly call the atexit() function.

The longjmp() Function

- C99 defines the setjmp() macro, longjmp() function, and jmp_buf type, which can be used to bypass the normal function call and return discipline.

- The setjmp() macro saves its calling environment for later use by the longjmp() function.

- The longjmp() function restores the environment saved by the most recent invocation of the setjmp() macro.

The longjmp() Function- Example Program - 1

```
#include <setjmp.h>
jmp_buf buf;
void g(int n);
void h(int n);
int n = 6;

void f(void) {
  setjmp(buf);
  g(n);
}

void g(int n) {
  h(n);
}

void h(int n){
  longjmp(buf, 2);
}
```

The longjmp() Function Example Program- 2

```
 1. typedef int __jmp_buf[6];

 2. #define JB_BX 0
 3. #define JB_SI 1
 4. #define JB_DI 2
 5. #define JB_BP 3
 6. #define JB_SP 4
 7. #define JB_PC 5
 8. #define JB_SIZE 24

 9. typedef struct __jmp_buf_tag
    {
10.   __jmp_buf __jmpbuf;
11.   int __mask_was_saved;
12.   __sigset_t __saved_mask;
13. } jmp_buf[1]
```

- The jmp_buf structure (lines 9-13) contains three fields.
- The calling environment is stored in __jmpbuf (declared on line 1).
- The __jmp_buf type is an integer array containing six elements.
- The #define statements indicate which values are stored in each array element.
- The base pointer (BP) is stored in __jmp_buf[3],
- The program counter (PC) is stored in __jmp_buf[5]

The longjmp() Function Example Program- 3

```
longjmp(env, i)
1. movl i, %eax /* return i */
2. movl env.__jmpbuf[JB_BP], %ebp
3. movl env.__jmpbuf[JB_SP], %esp
4. jmp (env.__jmpbuf[JB_PC])
```

The movl instruction on line 2 restores the BP

The movl instruction on line 3 restores the stack pointer (SP).

Line 4 transfers control to the stored PC

The longjmp() Function

- The longjmp() function can be exploited by overwriting the value of the PC in the jmp_buf buffer with the start of the shellcode.

- This can be accomplished with an arbitrary memory write or by a buffer overflow directly into a jmp_buf structure

Mitigation Strategies

- The best way to prevent pointer subterfuge is to eliminate the vulnerabilities that allow memory to be improperly overwritten.
  - Pointer subterfuge can occur as a result of
    - Overwriting data pointers
    - Common errors managing dynamic memory
    - Format string vulnerabilities
- Eliminating these sources of vulnerabilities is the best way to eliminate pointer subterfuge.

W^X

- One way to limit the exposure from some of these targets is to reduce the privileges of the vulnerable processes.
  - The policy called “W xor X” or “W^X” states that a memory segment may be writable or executable, but not both.
  - It is not clear how this policy can be effectively enforced to prevent overwriting targets such as atexit() that need to be both writable at runtime and executable.