Software security, secure programming

Lecture 4: Protecting your code against software vulnerabilities ? (overview)

Master M2 Cybersecurity

Academic Year 2024 - 2025

Preamble

Bad news

several **(widely used !)** programming languages are unsecure . . .

- codes are likely to contain vulnerabilities
- some of them can be exploited by an attacker . . .

Good news

Ther exists some protections to make attacket's life harder !

$\rightarrow$ 3 categories of protections:

- from the programmer (and/or programming language) itself
- from the compiler / interpreter
- from the execution plateform

Outline

Step 0: all the languages are not equal . . .

2 main issues:

1. how much the compiler (and not the developer) is in charge of security ?
2. what about unsecure programs ?
   (exploitable vs (random) crash vs exception raised vs compiler rejected)

- **unsecure languages:** Assembly languages, C, C++
  weakly typed, side-effects, undefined behaviors, explicit pointers, explicit heap management, etc.
  $\Rightarrow$ no memory safety, no type safety . . .
- **reasonably secure languages:** Java, C#, Ada, Python, Rust
  strongly typed, no pointers, garbage collector, $\sim$ type safety, but still some possible unsafe primitives/libraries
- **more secure languages ? :** OCaml, Haskell, Python (?), etc.
  strongly typed, no pointers, garbage collector, no side effects (immutable data)

$\rightarrow$ **Of course:** trade-off between security, expressiveness, execution time, code re-use, etc.

Demo: C, Ada, Java

Step 1: Know the threats . . .

Most language level vulnerabilities are well-known !

CWE (Common Weakness Enumeration) https://cwe.mitre.org/

- a community-developed list of common software security weaknesses
- common language + a measuring stick for software security tools
- a baseline for weakness identification, mitigation, and prevention efforts

Ex: CWE-131 (Incorrect Calculation of Buffer Size)

CVE (Common Vulnerabilities and Exposures) https://cve.mitre.org/

An (exhaustive ?) open list of all the publicly known soft. vulnerabilities
$\rightarrow$ provides a common name & a standardized description
Ex: CVE-2017-12705 (A Heap-Based Buffer Overflow in Advantech WebOP).

CAPEC (Common Attack Pattern Enumeration and Classification)

https://capec.mitre.org/

"A comprehensive dictionary and classification taxonomy of known attacks"
Attack scenario, the attacker perspective (means, gains), possible protections
$\rightarrow$ a "design pattern" of an attack
Ex: CAPEC-100 (Overflow Buffers)

Step 2: and avoid the traps !

- The CERT coding standarts
  `https://www.securecoding.cert.org/`
  - covers several languages: C, C++, Java, etc.
  - rules + examples of non-compliant code + examples of solutions
  - undefined behaviors
  - etc.

- Microsoft banned function calls

- ANSSI recommendations
  - JavaSec, LaFoSec (Ocaml, F#, Scala)
  - Rules for Secure C language software

- Use of secure libraries
  - `Strsafe.h` (Microsoft)
    guarantee null-termination and bound to dest size
  - `libsafe.h` (GNU/Linux)
    no overflow beyond current stack frame
  - etc.

Etc. (a lot of available references about "secure coding" . . .)

CERT coding standarts - Example 1

INT30-C. Ensure that unsigned integer operations do not wrap

Example of non compliant code

```
void func(unsigned int ui_a, unsigned int ui_b) {
       unsigned int usum = ui_a + ui_b;
       /* ... */
}
```

Example of compliant code

```
void func(unsigned int ui_a, unsigned int ui_b) {
  unsigned int usum = ui_a + ui_b;
  if (usum < ui_a) {
    /* Handle error */
  }
  /* ... */
}
```

CERT coding standarts - Example 2

ARR30-C. Do not form or use out-of-bounds pointers or array subscripts

Example of non compliant code

```
char *init_block(size_t block_size, size_t offset,
                 char *data, size_t data_size) {
  char *buffer = malloc(block_size);
  memcpy(buffer + offset, data, data_size);
  return buffer;
```

Example of compliant code

```
char *init_block(size_t block_size, size_t offset,
                 char *data, size_t data_size) {
  char *buffer = malloc(block_size);
  if (NULL == buffer) { /* Handle error */ }
  if (data_size > block_size || block_size - data_size < offset) {
    /* Data won't fit in buffer, handle error */
  }
  memcpy(buffer + offset, data, data_size);
  return buffer;
}
```

Code validation

Several tools can also help to detect code vulnerabilities . . .

Dynamic code analysis

Instruments the code to detect runtime errors (beyond language semantics!)

- invalid memory access (buffer overflow, use-after-free)
- uninitialized variables
- etc.

$\Rightarrow$ No false positive, but runtime overhead ($\sim$ testing)
Tool examples: Purify, Valgrind, AddressSanitizer, etc.

Static code analysis

Infer some (over)-approximation of the program behaviour

- uninitialized variables
- value analysis (e.g., array access out of bounds)
- pointer aliasing
- etc.

$\Rightarrow$ No false negative, but sometimes "inconclusive" . . .
Tool examples: Frama-C, Polyspace, CodeSonar, Fortify, etc.

Dynamic analysis tool example: AddressSanitizer

Google, open-source plugin for clang/gcc (flag `-fsanitize=address`)

Targets

- buffer overflows (within stack, heap, or globals)
- use-after-free (heap), use-after-return (stack)
- memory leaks, ...

Means

- code instrumentation (load/store operations)
- use of redzones around variables memory area
- custom version of `malloc()`
  (redzone insertion, delay re-used of free memory, collect log information)

At work

- $\sim$ 2x slowdown (Valgrind is $\sim$ 20x) and 1.5x-3.x memory overhead
  ($\rightarrow$ ok for tests and/or fuzzing campaigns)
- # (security) bugs found in Chrome, Firefox, MySQL, gcc, etc.

Demo: AdSan

Static analysis example: Frama-C RTE

runtime error annotation pluging for the Frama-C plateform [CEA List]

Targets

potential runtime-errors and undefined behaviors

- invalid memory accesses
- arithmetic overflows on signed and unsigned integers
- invalid casts from float to int, etc.

Means

- **static** enhanced type checking ⇒ potential **false positives**
- lighweight optimizations (e.g., constant folding) to improve precision

At work

- exhibits potential RTE issues at the source level (assert annotations)
- to be **discharged** by hand and/or by other Frama-C plugins (Wp, Eva)

(see `https://frama-c.com/rte.html`)

Demo: Frama-C RTE

Outline

Compilers may help for code protection

Most compilers offer compilation options enforce security

Examples[1]

- stack protection
  - stack layout
  - FORTIFY (enforces the use of safe libraries, e.g., `__strcpy_chk`)
  - canaries (e.g, gcc stack protector)
  - shadow stack for return addresses
  - control-flow integrity (e.g., clang CFI, Java)
  - ...
- pointer protection
  - pointer encryption (PointGuard)
  - smart pointers (C++)
  - ...
- no "undefined behavior"
  e.g., enforce wrap around for unsigned int in C
  (`-fno-strict-overflow`, `-fwrapv`)
- etc.

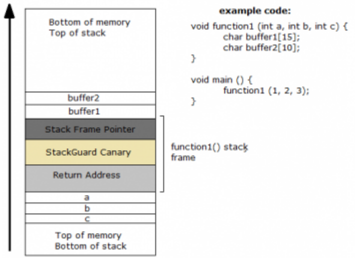
[1] see also `https://blog.quarkslab.com/clang-hardening-cheat-sheet.html` and E. Poll slides on the course web page)

Stack protection example: canaries

↪ gcc StackProtector, Redhat StackGuard, ProPolice, etc.

Principle: compiler generates extra code to:

1. insert a random value on the stack above the return address
2. check it before return and stops the execution if it has changed



Limited to **stack** (≠ heap) and **return** `@` (≠ loc. variables) protection

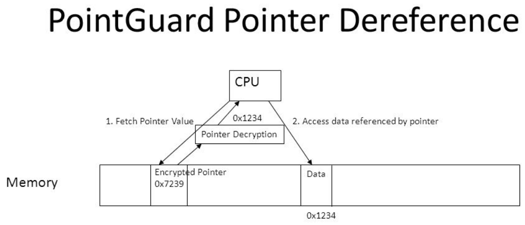
Possibly defeated by information disclosure, non consecutive overflow, etc.

`http://wiki.osdev.org/Stack_Smashing_Protector` Demo: -fstack-protector

Pointer protection

↪ Memory safety enforcement and attack prevention

- smart pointers: ⇝ temporal memory safety
  ADT including pointer facilities + memory management (garbage collection)
  Ex: C++ template with unique/shared/weak pointers
- fat pointers: ⇝ spatial memory safety
  extra meta-data to store memory cells base+bounds (**Ex:** C SoftBound)
- ciphered pointers: ⇝ pointer integrity



Control-Flow Integrity (CFI)

The main idea

→ Ensure that the **actual** pgm control-flow is the one **intended** by the pgmer

several means:

- pre-compute all possible flows (CFG) and insert rutime-checks in the binary code
  pb: function pointers, dynamic calls (virtual functions), etc.
- simpler version: focus only on the call graph
  protect function calls and returns, possible over-approximations
- execution overhead: 20% - 40% ?

More details in Abadi et al. paper:
Control-Flow Integrity Principles, Implementations, and Applications
https://users.soe.ucsc.edu/~abadi/Papers/cfi-tissec-revised.pdf

CFI in practice (`gcc`, `clang`)

↪ focus on **Call Graph** . . .

Forward edges

↪ to enforce the validity of call statements
targets **virtual** and/or `indirect` function calls
Examples:

- C++ virtual functions, dynamic binding
- function pointers (`int *f(void)`)

check at runtime that the function type is the expected one

Backward edges

↪ to enforce the validity of return statements use a (software) shadow stack
to save a copy of return addresses
(located at random position, and protected against overflows)

see `https://blog.quarkslab.com/clang-hardening-cheat-sheet.html`

Outline

- Programmer's level protections
- Compilers level protections
- Plateform level protections
- Bonus

Some more generic protections from the execution plateform

General purposes operating systems (Linux, Windows, etc.)

- Memory layout randomization (ASLR, KASLR)
  attacker needs to know precise memory addresses
  - make this address random (and changing at each execution)
  - no (easy) way to guess the current layout on a remote machine ...
  - randomized regions includes code, stack, heap and shared libraries
- Non executable memory zone (NX, W $\ominus$ X, DEP)
  basic attacks $\Rightarrow$ execute code from the data zone
  distinguish between:
  - memory for the code (eXecutable, not Writeable)
  - memory for the data (Writable, not eXecutable)

  Example: make the execution stack non executable ...

Rks:

- exists other dedicated protections for specific plateforms:
  e.g., JavaCard, Android, embedded systems, ...
- exists also hardware level protections:
  e.g., Intel SGC, ARM TrustZone, HW pointer protections, etc.

Defeating the ASLR ?

- some sections may not be be randomized
  (requires **Position Independent Executable**)

- On a 32 bits machine, brute force may be effective, e.g
  - heap spraying = filling the heap witth # copies of the payload
  - overwritting the LSB of a pointer

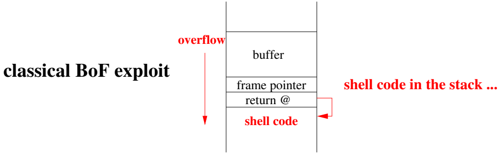
- Information leaks may help to fully disclose address information

$\Rightarrow$ needs to chain several (exploitable) vulns ...

Stronger counter-measures ?

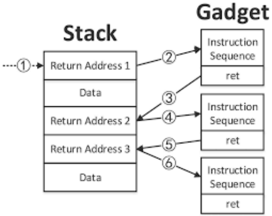
$\rightarrow$ encrypt the data stored in memory

Defeating the DEP ?



Do not store shellcode in the stack . . . use existing code instructions instead !

- return-to-libc: redirect the control-flow towards library code
- return oriented programming (ROP)
  payload = sequence of return-terminated instructions (gadgets)



- gadget programming is "turing complete"
- ∃ tools for gagdget extraction (ROPgadget, ROPium, etc.)
- ∃ ROP variants:
  COP (call-oriented programming), JOP (jump-oriented programming)

Rks: may also ∃ library calls allowing to make the stack executable . . .

Preventing ROP, COP, JOP ?

- preventing ROP:
  - count the number of `RET` instructions at runtime
  - use a **shadow stack** to duplicate return addresses
- preventing JOP and COP:
  use a new machine instruction to "tag" valid jump/call destinations
  e.g.: Intel CET (Control-Flow Enforcement Technology)

```
                ...
                CALL 0xabcdef
                ...
0xabcdef:
                ENDBRANCH  // tag a valid jum/call des
                ...
                RET
```

→ no (easy) way to jump in the middle of a function . . .

HW protection examples: CET and PAC

Intel CET (Control-flow Enforcement Technology)

Shadow stack (not readable/writable by softare)
+
Indirect branch tracking

uses `endbranch` label to mark legitimate branch targets, $\sim$ nop on old CPUs

ARM PAC (Pointer AuthentiCation)

- unused bit addresses in 64 bits architecture
  $\hookrightarrow$ can be used to store some pointer authentication value
  (assigned before writting in memory and verified before each use)
- new instructions to sign and authenticate
  cryptp algo = QUARMA, 128 bit key + some “context value”
- subsumes canaries (return address is protected), enforces CFI (indirect calls)
- Available on iOS

Outline

Programmer's level protections

Compilers level protections

Plateform level protections

Bonus

Bonus: retrieving the stack layout

Stack layout of the following code ?

```
int main() {
   int x;
   int T[10];
   char i;
   T[i]=x;
}
```

1. print variable addresses: need to re-compile, not reliable . . .
   ```
   printf("%x",&x); printf("%x",&i);
   printf("%x",&(T[0]);
   ```
2. use a debugger (ex: `gdb`): need to re-compile, not reliable . . .
   ↪ set a breakpoint (`b main`), execute (`run`), print addresses (`p &i`)
3. disassemble the executable code (`objdump -S`, idaPro, Ghidra, etc.)
   ↪get variable offset w.r.t frame pointer `rpb` on (x86_64)

Bonus: summary of memory-related exploits

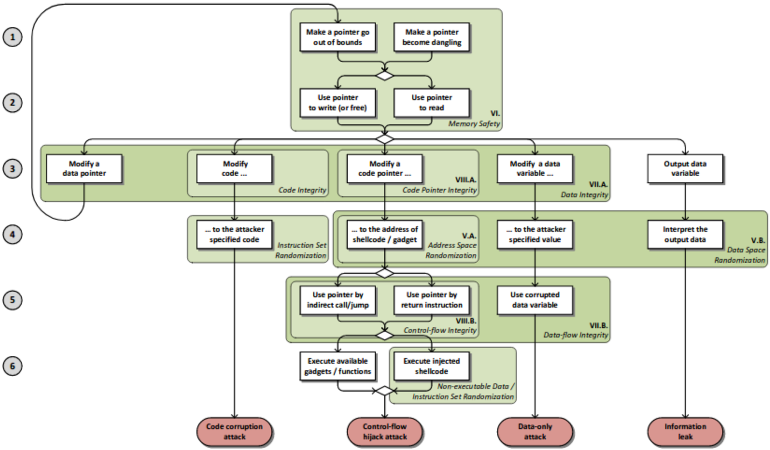


Figure 1. Attack model demonstrating four exploit types and policies mitigating the attacks in different stages

(from “SoK: Eternal War in Memory” Laszlo Szekeres et al., Oakland 13)

Some exploits defeating ASLR + DEP using ROP

CVE ID	Software	Vulnerability	Address leakage	User scripting
CVE-2011-0609	Adobe Flash	JIT type confusion	Read an IEEE-754 number	ActionScript
CVE-2012-0003	Windows Multimedia Library (affecting IE)	Heap buffer overflow	Read a string after overwriting its length	JavaScript
CVE-2011-4130	ProFTPD	Use-after-free	Overwrite the "226 Transfer Complete" message	none
CVE-2012-0469	Mozilla Firefox	Use-after-free	Read a string after overwriting its length	JavaScript
CVE-2012-1889	Microsoft Windows XML Core Services (affecting IE)	Uninitialized pointer	Read as a RGB color	JavaScript
CVE-2012-1876	Internet Explorer 9/10 (Pwn2Own 2012)	Heap buffer overflow	Read a string after overwriting its length	JavaScript

Table I
EXPLOITS THAT DEFEAT BOTH DEP AND ASLR USING ROP AND INFORMATION LEAKS

(from "SoK: Eternal War in Memory" Laszlo Szekeres et al., Oakland 13)

A more recent detailed example:

Exploiting CVE-2018-5093 on Firefox 56 and 57 (part 1 and part 2)

Conclusion

- $\exists$ numerous protections to avoid / mitigate vulnerability exploitations
- several protection levels
  code, verification tools, compilers, plateforms
- they allow to "(partially) mitigate" most known programming languages weaknesses (e.g., C/C++)
- they still require programmers skills and concerns
- even if they make attackers life harder . . .
- . . . they can still be bypassed !

$\rightarrow$ an endless game between "attackers" and "defenders" !