Secure Software Development

Countermeasures: Exploitation Prevention & Privilege Minimization

Daniel Gruss, Vedad Hadzic, Lukas Maar, Martin Schwarzl, Marcel Nageler

02.12.2022

Winter 2022/23, www.iaik.tugraz.at

Table of contents

Attacker's perspective

- Vulnerability discovery ☑
- Exploitation ☑
- Privilege elevation ☑

Defender's perspective

- Vulnerability prevention ☑
- Exploit prevention (today)
- Privilege minimization (today/next time)

Attacker's perspective

Vulnerability discovery

- buffer/integer overflow, use-after-free, format strings, type confusion

Exploitation

- Data corruption, shellcode, code reuse, ROP, return-to-libc

Privilege elevation

- exploit suid binaries, kernel exploits, crack root PW hash ;)

Defender's perspective

Vulnerability prevention

- Code quality, memory safety, type safety, error handling ...

Exploit prevention

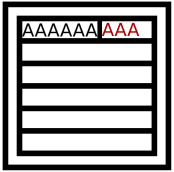
- Compiler/runtime defenses, hardware defenses

Privilege minimization

- System call filtering, sandboxing, virtualization

- Attacker triggered a vulnerability
  - Part 1: Can we prevent exploitation? → Exploit Prevention
- Attacker gained arbitrary code execution
  - Part 2: Can we prevent further damage? → Privilege Minimization
- Defenses must be cheap!

Stack Buffer Overflows



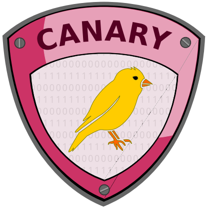

```c
void printName(char* buffer) {
  char name[16];
  strcpy(name, buffer);
  printf("Hello %s\n", name);
}

int main(int argc, char* argv[]) {
  if(argc > 1) printName(argv[1]);
  return 0;
}
```

- Observation 1: Buffer overflows are mostly linear
  - Cannot hit arbitrary memory, unlike format string vulnerabilities
- Observation 2: Attackers typically overwrite code pointer (return address)
- How can we detect linear buffer overflows?

CANARY

"This means something but I can't remember what!"

- If the mine canary is dead, get out immediately



Idea: Introduce a canary on the stack that signals a hazard

- Hazard = corrupted return address

Implementation

- Simple compiler extension
- Function prologue: push a random value (the canary), after the return address
- Linear buffer overflow can only overwrite return address when also overwriting canary
- Function epilogue: check if canary is valid (unmodified) before doing `retq`

Stack Canary II

Stack

return address
saved EBP
canary
...

```
<func>:
  Setup stack frame
  PUSH canary
  [...]
  ; check canary
  RET

<main>:
  [...]
  CALL func
  [...]
```

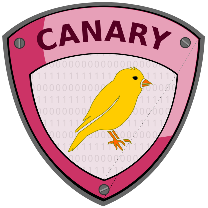
```
#include <stdio.h>
#include <string.h>

void printName(char* buffer) {
  char name[16];
  strcpy(name, buffer);
  printf("Hello %s\n", name);
}

int main(int argc, char* argv[]) {
  if(argc > 1) printName(argv[1]);
  return 0;
}
```

```
% gcc -o stack -fno-stack-protector stack.c
% ./stack AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
Hello AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
[1]    12345 segmentation fault (core dumped)  ./stack
```

```
% gcc -o stack -fstack-protector stack.c
% ./stack AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
Hello AAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAAA
*** stack smashing detected ***: ./stack terminated
```

```
% objdump -d stack
00000000004005d6 <printName>:
  // function prologue
  ...
  4005e2: mov    %fs:0x28,%rax    // load canary value
  4005eb: mov    %rax,-0x8(%rbp) // store canary on stack
  4005ef: xor    %eax,%eax
  ...
  // function epilogue
  40061b: mov    -0x8(%rbp),%rax // load canary from stack
  40061f: xor    %fs:0x28,%rax    // compare
  400628: je     40062f <printName+0x59>
  40062a: callq  4004a0 <__stack_chk_fail@plt>
  40062f: leaveq
  400630: retq
```

Stack Canary Summary

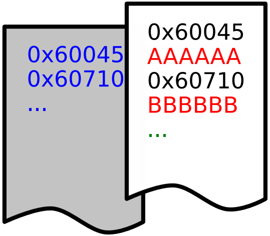


Properties

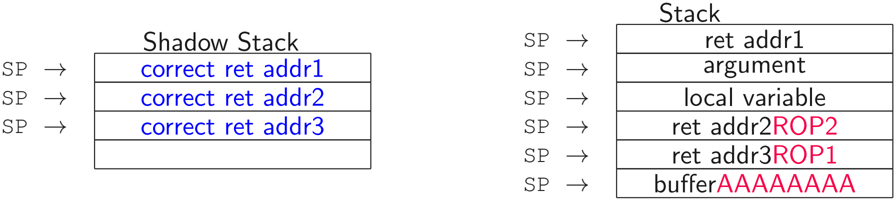
- Detects linear stack buffer overflows corrupting return address
- Does not detect
  - overflowing one buffer into the other
  - overflowing co-located variables
  - arbitrary write access, e.g. `buffer[input] = input2;`
  - format string vulnerabilities ...
- Probabilistic defense
  - Ineffective if attacker can guess or leak the canary value
- Animal welfare compatible (no bird has to die ;)

If we push/pop a canary for each return address, why not just duplicate return addresses instead?

Shadow Stack

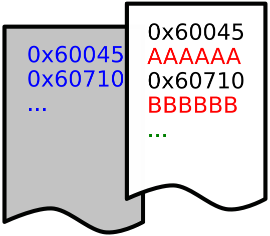


- Idea: duplicate return address on separate stack
- Implementation: compiler extension similar to canaries
  - Prologue: push return address also on shadow stack
  - Epilogue: verify return address before doing `retq`



- Shadow stack duplicates all return addresses
- Attacker injects ROP chain
- Program crashes because of shadow stack mismatch

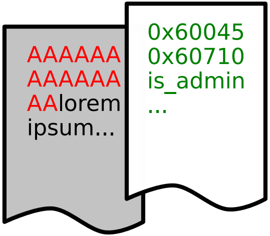
Shadow Stack Summary



☆ Properties

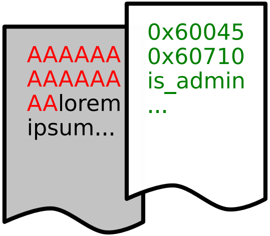
- Detect if buffer overflow corrupts return address
- Does not prevent
  - attacks not affecting return addresses
  - attacks on shadow stack

? Why duplicate at all if we assume shadow stack is secure?



- Inverse idea: store unsafe buffers on separate stack
  - Safe stack only contains return addresses and sensible variables that cannot overflow
- Implementation: compiler extension similar to shadow stack

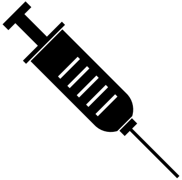
Safe Stack Summary



- Properties
  - Buffer overflow cannot corrupt return addresses / safe variables
  - Does not prevent
    - overflowing one unsafe buffer into the other
    - format string vulnerabilities ...
    - attacks on safe stack
- Why not protect shadow/safe stack in hardware?
  - Control-Flow Enforcement Technology (CET) for Intel (and AMD)

Code Injection Attacks

Recap: Shellcode



- Exploit buffer overflow
- Inject custom code that spawns a shell → Shellcode
- Corrupt code pointer to execute shellcode

Data Execution Prevention

Data Execution Prevention (DEP) $\approx$ Write-Xor-Execute (W$\oplus$X)

Observation: Von-Neumann CPUs mix code and data memory

- This allows code injection into data memory

Idea 1: make data memory non-executable

Idea 2: make code memory non-writable

Implementation

- Set writable memory to non-executable, e.g.: stack, heap, data, ...
- Usually done by the program loader (using `mmap`, `mprotect`)
- Hardware support in the page tables
  - Intel: XD-bit, AMD: NX-bit, ARM: XN-bit

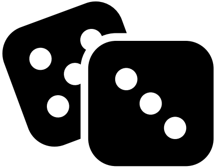
```c
#include <stdio.h>
#include <string.h>

char code[] = "\x31\xc0\x48\xbb\xd1\x9d\x96\x91\xd0\x8c\x97\xff\x48\xf7\xdb\x53\
    x54\x5f\x99\x52\x57\x54\x5e\xb0\x3b\x0f\x05";

int main()
{
    printf("len:%d bytes\n", strlen(code));
    (*(void(*)()) code)();
    return 0;
}
```

```
% gdb ./shellcode
(gdb) run
Starting program: /home/shellcode
len:27 bytes

Program received signal SIGSEGV, Segmentation fault.
0x0000000000601040 in code ()
```

```
% execstack -s ./shellcode
% gdb ./shellcode
(gdb) run
Starting program: /home/shellcode
len:27 bytes
process 9494 is executing new program: /bin/dash
$
```

- Properties of DEP/W⊕X
  - Prevents code injection attacks
  - Does not prevent code reuse attacks (since no code is injected)
  - No runtime overhead
  - Requires hardware support
- How to protect just-in-time (JIT) compiled code? JIT compiler needs to modify code at runtime ...

Code Reuse Attacks



- Observation: Many exploits need knowledge of addresses (ROP, ret2libc ...)
- Idea: randomize program to make exploit development (much) more difficult
- General properties
  - Probabilistic defense
    - Can be broken by information leakage (e.g., via side channels)
    - How big is the entropy?


ASLR

- Randomize the memory layout
  - Attacker cannot guess location of libc, stack, heap ...
- Implementation
  - At program startup move various segments to a random position
    - Stack, heap, shared memory
    - Shared libraries
    - Main executable (optional)
  - Randomization done by operating system (e.g., on `mmap`)
    - Linux `/proc/sys/kernel/randomize_va_space`

ASLR on Stack and Heap

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

int main() {
  int x;
  printf("Stack: %p\n", &x);
  printf("Heap:  %p\n", malloc(10));
  return 0;
}
```

```
% ./aslr
Stack: 0x7ffcc2666e74
Heap:  0x1dd9420
% ./aslr
Stack: 0x7ffcbf0c1ae4
Heap:  0x124b420
```

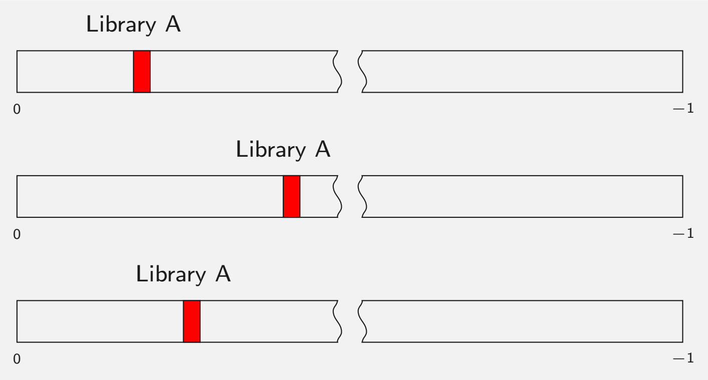
ASLR on Stack, Heap, Libraries

```
% cat /proc/self/maps
00400000-0040c000 r-xp 00000000 fd:00 395191             /bin/cat
0060b000-0060c000 r--p 0000b000 fd:00 395191             /bin/cat
0060c000-0060d000 rw-p 0000c000 fd:00 395191             /bin/cat
00b0c000-00b2d000 rw-p 00000000 00:00 0                  [heap]
7efcbb558000-7efcbb87e000 r--p 00000000 fd:00 11534857   /usr/lib/locale/locale-archive
7efcbb87e000-7efcbba3e000 r-xp 00000000 fd:00 4587769    /lib/x86_64-linux-gnu/libc-2.23.so
7efcbba3e000-7efcbbc3e000 ---p 001c0000 fd:00 4587769    /lib/x86_64-linux-gnu/libc-2.23.so
7efcbbc3e000-7efcbbc42000 r--p 001c0000 fd:00 4587769    /lib/x86_64-linux-gnu/libc-2.23.so
7efcbbc42000-7efcbbc44000 rw-p 001c4000 fd:00 4587769    /lib/x86_64-linux-gnu/libc-2.23.so
7efcbbc44000-7efcbbc48000 rw-p 00000000 00:00 0
7efcbbc48000-7efcbbc6e000 r-xp 00000000 fd:00 4588089    /lib/x86_64-linux-gnu/ld-2.23.so
7efcbbe38000-7efcbbe3b000 rw-p 00000000 00:00 0
7efcbbe4b000-7efcbbe6d000 rw-p 00000000 00:00 0
7efcbbe6d000-7efcbbe6e000 r--p 00025000 fd:00 4588089    /lib/x86_64-linux-gnu/ld-2.23.so
7efcbbe6e000-7efcbbe6f000 rw-p 00026000 fd:00 4588089    /lib/x86_64-linux-gnu/ld-2.23.so
7efcbbe6f000-7efcbbe70000 rw-p 00000000 00:00 0
7ffff84c6000-7ffff84e7000 rw-p 00000000 00:00 0          [stack]
7ffff8536000-7ffff8538000 r--p 00000000 00:00 0          [vvar]
7ffff8538000-7ffff853a000 r-xp 00000000 00:00 0          [vdso]
ffffffffff600000-ffffffffff601000 r-xp 00000000 00:00 0 [vsyscall]
```

ASLR on Stack, Heap, Libraries

```
% cat /proc/self/maps
00400000-0040c000 r-xp 00000000 fd:00 395191            /bin/cat
0060b000-0060c000 r--p 0000b000 fd:00 395191            /bin/cat
0060c000-0060d000 rw-p 0000c000 fd:00 395191            /bin/cat
00799000-007ba000 rw-p 00000000 00:00 0                 [heap]
7fec1f08d000-7fec1f3b3000 r--p 00000000 fd:00 11534857  /usr/lib/locale/locale-archive
7fec1f3b3000-7fec1f573000 r-xp 00000000 fd:00 4587769   /lib/x86_64-linux-gnu/libc-2.23.so
7fec1f573000-7fec1f773000 ---p 001c0000 fd:00 4587769   /lib/x86_64-linux-gnu/libc-2.23.so
7fec1f773000-7fec1f777000 r--p 001c0000 fd:00 4587769   /lib/x86_64-linux-gnu/libc-2.23.so
7fec1f777000-7fec1f779000 rw-p 001c4000 fd:00 4587769   /lib/x86_64-linux-gnu/libc-2.23.so
7fec1f779000-7fec1f77d000 rw-p 00000000 00:00 0
7fec1f77d000-7fec1f7a3000 r-xp 00000000 fd:00 4588089   /lib/x86_64-linux-gnu/ld-2.23.so
7fec1f96d000-7fec1f970000 rw-p 00000000 00:00 0
7fec1f980000-7fec1f9a2000 rw-p 00000000 00:00 0
7fec1f9a2000-7fec1f9a3000 r--p 00025000 fd:00 4588089   /lib/x86_64-linux-gnu/ld-2.23.so
7fec1f9a3000-7fec1f9a4000 rw-p 00026000 fd:00 4588089   /lib/x86_64-linux-gnu/ld-2.23.so
7fec1f9a4000-7fec1f9a5000 rw-p 00000000 00:00 0
7ffeffa30000-7ffeffa51000 rw-p 00000000 00:00 0         [stack]
7ffeffa7f000-7ffeffa81000 r--p 00000000 00:00 0         [vvar]
7ffeffa81000-7ffeffa83000 r-xp 00000000 00:00 0         [vdso]
ffffffffff600000-ffffffffff601000 r-xp 00000000 00:00 0 [vsyscall]
```

ASLR on Shared Libraries



- Same library code is randomized to different addresses at each program start

❓ How does randomized code remain functional?

- Within a module
  - Compiler replaces absolute addresses with (rip-)relative addresses
  - Code can be executed from virtually any offset
  - Shared libraries: compile flags `-fpic`, `-fPIC`
  - Executable: compile flags `-fpie`, `-fPIE`
- Across modules
  - Runtime linker resolves addresses via:
  - Global Offset Table (GOT) for arbitrary addresses
  - Procedure Linkage Table (PLT) for function calls

```c
#include <stdio.h>

int main() {
  printf("Hi\n");
}
```

```
% gcc -o main -static main.c
% objdump -d main
00000000004009ae <main>:
  4009ae: 55                    push   %rbp
  4009af: 48 89 e5              mov    %rsp,%rbp
  4009b2: bf a4 11 4a 00        mov    $0x4a11a4,%edi    # Address of Hi
  4009b7: e8 24 f2 00 00        callq  40fbe0 <_IO_puts> # Direct call
  4009bc: b8 00 00 00 00        mov    $0x0,%eax
  4009c1: 5d                    pop    %rbp
  4009c2: c3                    retq
```

```c
#include <stdio.h>

int main() {
  printf("Hi\n");
}
```

```
% gcc -o main -fPIE main.c
% objdump -d main
0000000000000526 <main>:
     526: 55                    push   %rbp
     527: 48 89 e5              mov    %rsp,%rbp
     52a: 48 8d 3d 93 00 00 00  lea    0x93(%rip),%rdi   # Address of Hi
     531: e8 ca fe ff ff        callq  400 <puts@plt> # PLT
     536: b8 00 00 00 00        mov    $0x0,%eax
     53b: 5d                    pop    %rbp
     53c: c3                    retq
```

Address Space Layout Randomization (ASLR) Summary

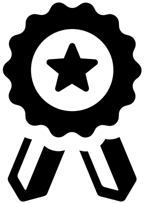
Properties

- Cheap
- Make exploit development hard
- Does not prevent exploitation within a module
- Requires operating system support
- ASLR on code requires position independence
- Quite limited entropy on 32-bit systems → brute-force
- Information leak breaks ASLR

How to protect ASLR against information leakage?

- Execute-only memory (non-readable)

Challenge #8 - Selective ASLR

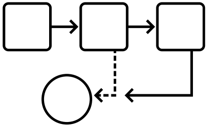


Change the randomization of the code segment

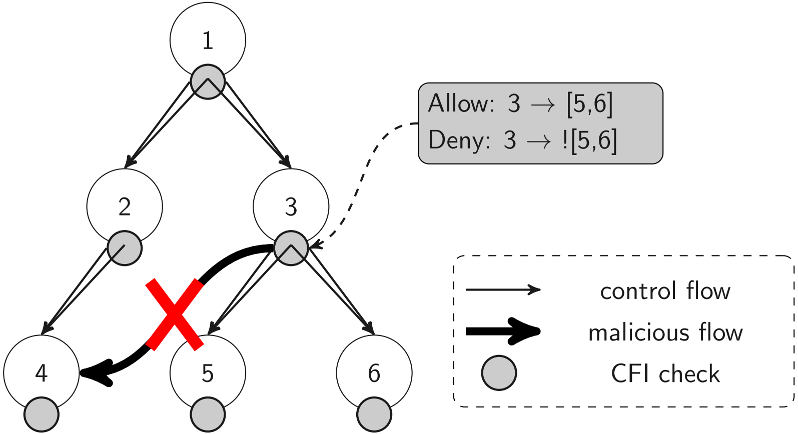
- You should generate two binaries with ASLR enabled
- One binary should have randomization for stack, heap, and code
- The other binary should only have randomization for stack and heap, but not for code
- Both binaries must run for at least 5 seconds (e.g., `sleep(5);` before return) but not longer than 10 seconds
- Upload your binaries at `https://challenges.sasectf.student.iaik.tugraz.at/aslr/index.php`
- If it is correct, you will get the flag
- Test system is Ubuntu 20.04.1 LTS, kernel 4.19.0-11

CFI

Control Flow Integrity (CFI)

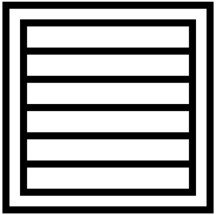


- Observation: most attacks corrupt code pointers
- Idea: specifically protect code pointers
  - CFI: Program must stay inside control flow graph (CFG)
  - Attacker cannot (arbitrarily) change control flow
  - Prevent ROP and maybe ret2libc
- Code pointers everywhere
  - Return addresses
  - Function pointers
  - C++ vtables
  - GOT entries
  - Signal handlers
- We need to protect all of them!

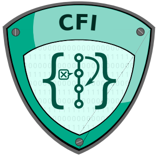

1
2
3
4
5
6
Allow: 3 → [5,6]
Deny: 3 → ![5,6]
control flow
malicious flow
CFI check

- CFI on backward edges
  - Return addresses shall only point to the real caller
  - Solved via shadow stack / safe stack
- CFI on forward edges
  - GOT entries shall only contain legitimate pointers
  - Function pointers shall only call legitimate functions
  - C++ vtable shall only call legitimate members
  - ❓ How to determine *legitimate* targets?

Global Offset Table (GOT) Protection

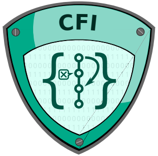


- Observation: only runtime linker populates GOT
  - Any other GOT manipulation is either an accident or an attack
- Idea: Make GOT read-only
- Implementation
  - Linker populates *all* GOT entries at program start → slowdown
  - Compiler flag `-Wl,-z,relro` "relocations read-only"



What are **legitimate targets** for an indirect function call? Possible answers:

- A1: **any** function
  - Simple but imprecise
  - Attacker can invoke arbitrary functions without violating CFI
- A2: functions with the **same signature** as the function pointer
  - Better, prevents some type confusion attacks
- A3: only functions which **could be assigned** to the function pointer
  - Even better, still a bit imprecise
- A4: only the function which is **actually assigned** to the function pointer
  - Fully precise, more expensive
  - Code pointer integrity



Examples for Hardware/Software CFI mechanisms

- A1: **any** function is valid
  - Hardware CFI: Control-Flow Enforcement Technology (CET)
- A2: functions with the **same signature** are valid
  - Software CFI: clang `-fsanitize=cfi`
  - Hardware CFI: Arm Pointer Authentication

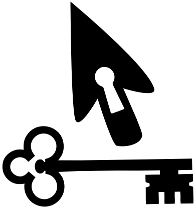
- Every function entry marked with `endbr64` instruction
- Call instructions only succeed towards `endbr64` instructions
- Supported by future Intel and AMD CPUs

```
% objdump -d main
0000000000001149 <test>:
    1149:  f3 0f 1e fa     endbr64
    114d:  55              push    %rbp
    114e:  48 89 e5        mov     %rsp,%rbp
    ...

0000000000001160 <test2>:
    1160:  f3 0f 1e fa     endbr64
    1164:  55              push    %rbp
    1165:  48 89 e5        mov     %rsp,%rbp
    ...
```

```cpp
#include <iostream>

class A {
  public: virtual const char* name() { return "A"; };
};
class B {
  public:  const char* name() { return "B"; };
  private: virtual const char* secret() { return "secret"; };
};

int main() {
  A* a = new A();
  std::cout << a->name() << std::endl;
  B* b = new B();
  std::cout << b->name() << std::endl;

  a = (A*)b; // type confusion vulnerability
  std::cout << a->name() << std::endl;
}
```

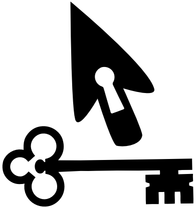
```
% ./test
A
B
secret
```

```
% clang++ -flto -fsanitize=cfi -fvisibility=hidden \
  -fno-sanitize-trap=all tc.cpp -o tc
% ./tc
A
B
tc.cpp:21:9: runtime error: control flow integrity check for
type 'A' failed during cast to unrelated type
(vtable address 0x00000042bd40)
0x00000042bd40: note: vtable is of type 'B'
00 00 00 00  d0 4b 42 00 00 00 00 00  01 1b 03 3b cc 11 00
             ^
```



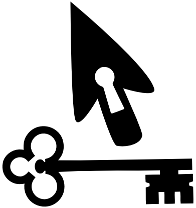
ARMv8.3 hardware-based pointer authentication

- Observation: 64-bit architectures do not use all bits
  - E.g. 48-bit virtual address space → 16 bits unused
- Idea: repurpose bits for cryptograhpically authenticating pointers
- Implementation
  - Compiler secures a pointer with special `PAC` instructions
  - Hardware computes cryptographic MAC
  - Hardware stores parts of the MAC in unused pointer bits
  - Before dereferencing (calling) a pointer, AUT instruction authenticates
  - Hardware invalidates pointer or faults on authentication failure



MAC algorithm has three inputs

- Pointer value
- Secret (process-dependent) key
- User-defined *context*
- *Context* can be used to distinguish
    - Function signatures
    - Types of data pointers
    - Stack frames
    - ...



☆ Properties

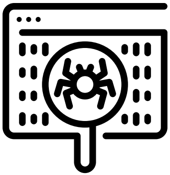
- Cryptographically-enforced CFI
- Effectiveness depends on additional *context* input
  - Precision: if *context* is zero, attacker can exchange all authenticated pointers (Similar to Intel CET)
  - Security: If attacker can control *context* → forge arbitrary pointers
- Authentication code (MAC) is truncated to upper pointer bits
  - Imprecision, allows brute-force/collision attacks

Properties

- CFI: attacker cannot escape control flow graph (CFG)
  - Defeats ROP
  - Still allows more or less code reuse within the CFG
  - Depending on precision of forward edges, attacker can substitute valid pointers
- CFI does not prevent data-only attacks
  - E.g., is_admin flag, loop counters, syscall arguments?

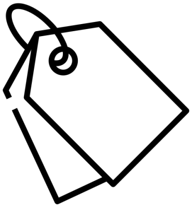
Memory Safety

Memory Safety

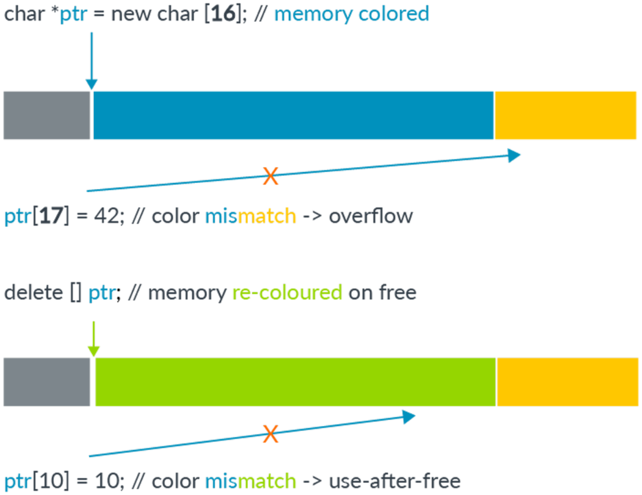


- Observation: Most attacks due to a memory safety vulnerability
- Idea: Prevent exploitation of memory safety vulnerability
  - Preventing invalid memory access
  - ARM Memory Tagging Extention (MTE)

Memory Tagging Extention

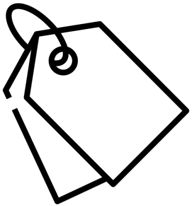


- On allocation
  - e.g., `char *ptr = malloc(8);`
  - Tag memory object
  - Store tag in pointer
- On access
  - Check whether memory object is tagged with the stored tag of the pointer
  - If correct → Access
  - If not correct → Fault

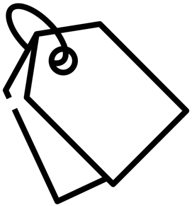


☆ Security claims

- Prevents spatial memory violations
- Prevents temporal memory violations



- Tag size of MTE
  - 4 bits
  - 16 distinct tags
- Tag storage
  - Pointer
    - Only 48 bits used of virtual address
    - Store 4 bit tag in unused bits
  - Memory object
    - In memory
    - 3.125 % memory overhead with 4 bit tag size
    - Two memory lookups for dereferencing a pointer



- Given 16 tags, what how likely is it to detect an arbitrary memory access or a use-after-free?
  - On random re-coloring
  - $\left(1 - \frac{1}{2^4}\right) \cdot 100 = 93.75\,\%$
- Increase tag size to 8 bits?
  - Detection propability increases to $\left(1 - \frac{1}{2^8}\right) \cdot 100 \approx 99.6\,\%$
  - Memory overhead increases to 6.25 %
  - Currently only 4 bit supported

Attacker's perspective

- Vulnerability discovery ☑
- Exploitation ☑
- Privilege elevation ☑

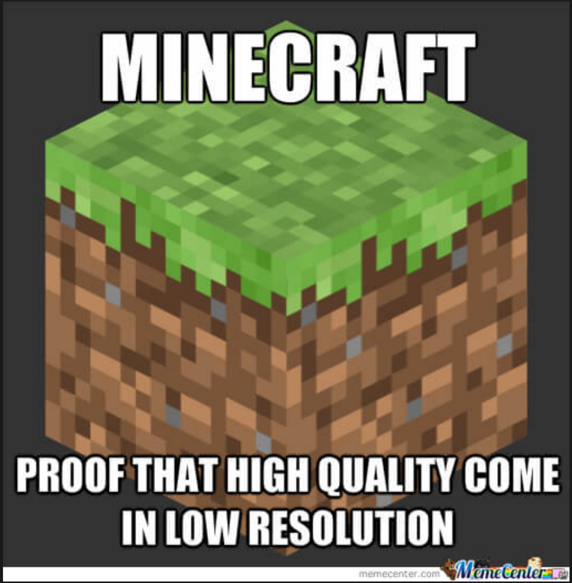
Defender's perspective

- Vulnerability prevention ☑
- Exploit prevention ☑
- Privilege minimization (today)

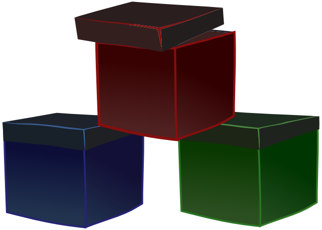
Privilege Minimization

How to minimize the impact of Arbitrary Code Execution

Think inside boxes ...



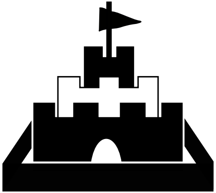
Privilege Minimization Overview



- Everything is a box
  - "Principle of least privileges"
- Compartmentalization
  - Break large boxes into smaller boxes
  - Virtual machines, processes, libraries, functions ...
  - Mostly manual effort
- Isolation
  - Isolate boxes from each other
  - Safeguard all interfaces
    - File permissions, network firewall ... system calls

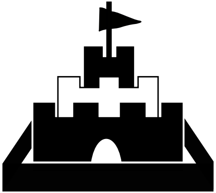
In-process Sandboxing


ME AFTER ESCAPING
THE SANDBOX
imgflip.com



- Goal: confine parts of an application
  - E.g., dangerous plugins, libraries, user-provided code ...
- Language-level
- Microkernels/libOSes
- Hardware-Enforced

In-process Sandboxing



- Dangerous code is not executed natively but interpreted
  - E.g., Java, JavaScript, WebAssembly, Lua, Python, Berkeley Packet Filter (BPF) ...
- Microkernel:
  - Kernel implemented in user space, e.g., , CubicleOS, FlexOS, UniK
- Hardware-enforced: Protection keys

Process Sandboxing

SECCOMP

- Observation: Most programs do not need most system calls
  - E.g., fork, exec, prctl ...
- Idea: block unnecessary system calls
- Implementation
  - Program installs seccomp filters on startup
  - Seccomp supports small *Berkeley Packet Filter (BPF) programs*
  - Kernel does the filtering (e.g., executes the BPF program) on every system call
  - On a filter violation: deny syscall, send signal, kill program ...

Seccomp Example I

```c
#include <stdio.h>         /* printf */
#include <sys/prctl.h>     /* prctl */
#include <linux/seccomp.h> /* seccomp's constants */
#include <unistd.h>        /* dup2: just for test */

int main() {
  printf("step 1: unrestricted\n");
  prctl(PR_SET_SECCOMP, SECCOMP_MODE_STRICT); // Enable filtering
  printf("step 2: only 'read', 'write', '_exit' and 'sigreturn' syscalls\n");
  dup2(1, 2); // redirect stderr to stdout
  printf("step 3: !! YOU SHOULD NOT SEE ME !!\n");
  return 0;
}
```

https://blog.yadutaf.fr/2014/05/29/introduction-to-seccomp-bpf-linux-syscall-filter/

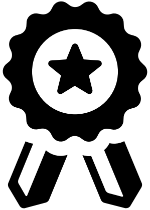
Seccomp Example II

```
dgruss@t460sdg ~ % gcc seccomp.c
dgruss@t460sdg ~ % ./a.out
step 1: unrestricted
step 2: only 'read', 'write', '_exit' and 'sigreturn' syscalls
[1]    19622 killed     ./a.out
137 dgruss@t460sdg ~ %
```

```
int main() {
  printf("step 1: init\n");
  prctl(PR_SET_NO_NEW_PRIVS, 1);
  prctl(PR_SET_DUMPABLE, 0);     // ptrace on this process / childs is not allowed
  scmp_filter_ctx ctx;
  ctx = seccomp_init(SCMP_ACT_KILL);                         // Denylist everything
  seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(rt_sigreturn), 0);   // Allowlist
  seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(exit), 0);           // Allowlist
  seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(exit_group), 0);     // Allowlist
  seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(read), 0);           // Allowlist
  seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(write), 0);          // Allowlist
  seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(dup2), 2,            // Allowlist
                   SCMP_A0(SCMP_CMP_EQ, 1), SCMP_A1(SCMP_CMP_EQ, 2)); // Allowlist
  seccomp_load(ctx);
  printf("step 2: only 'write' and dup2(1, 2) syscalls\n");
  dup2(1, 2);    // redirect stderr to stdout
  printf("step 3: stderr redirected to stdout\n");
  dup2(2, 42);   // redirect stderr to stdout
}
```

Seccomp Example IV

```
dgruss@t460sdg ~ % gcc seccomp.c -lseccomp && ./a.out
step 1: init
step 2: only 'write' and dup2(1, 2) syscalls
step 3: stderr redirected to stdout
[1]    23312 invalid system call  ./a.out
159 dgruss@t460sdg ~ %
```



Write a secure wrapper binary

- Usage: `./secwrap <command>`
- The wrapper shall start the program specified by `<command>`
- Anything `<command>` does may not be allowed to create new processes!

→ Very convenient to use :)

- Upload your wrapper binary at `https://challenges.sasectf.student.iaik.tugraz.at/secwrap/index.php`
- If it is correct, you will get the flag
- Test system is Ubuntu 20.04.1 LTS, kernel 4.19.0-11

- Sandbox process runs dangerous code
- Monitor process interacts with sandbox via IPC
  - Minimal filter: only allow required IPC system calls
- Example: Google *sandbox2*

  `https://developers.google.com/sandboxed-api/`

Seccomp Summary

Properties

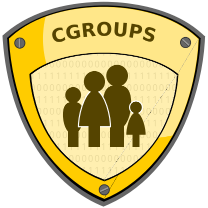
- Protect system call interface
- Filters can only be specialized but not tightened
  - Attacker cannot manipulate/unload existing filters
- Filter: simple arithmetic operations on system call arguments
  - Enhanced filtering is impossible
  - E.g., checking for strings, sanitizing paths, dereferencing pointers

How do we know which system calls are needed by libc functions such as `pthread_create` ? Implementation defined!

How can we virtualize resources?

Virtualization

CGROUPS



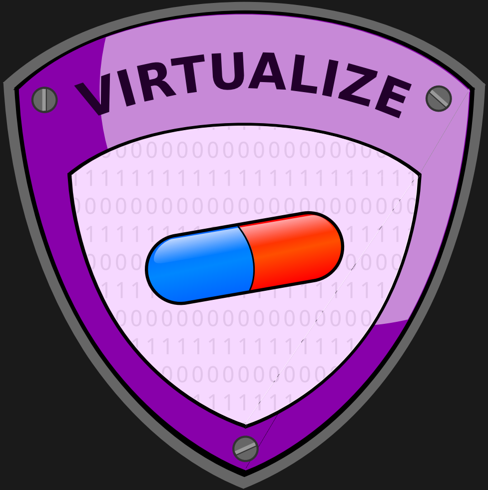
- Idea: Manage resource usage of a group of processes (and all its children)
  - Memory, CPU time, networking, disk I/O ...
  - Set limits / priorities
- Properties
  - Can prevent some Denial-of-Service (DoS) attacks
  - Cannot prevent privilege escalation

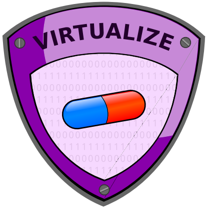

NAMESPACES

- Idea: Namespace hides (virtualizes) resources from processes
    - Various namespaces: `mnt`, `pid`, `net`, `ipc`, `uts` (hostname), `user`
    - How? Namespace translates resource identifiers
- Examples:
    - Inside namespace: `uid=0(root), path=/f.txt`
    - Outside namepsace: `uid=1000(ssd), path=/home/ssd/f.txt`

- Idea: combine 'em all: Docker containers
  - See also Linux Containers (LXC)
- Docker automatically
  - creates namespaces and cgroups
  - configures seccomp
- Properties
  - Fast
  - Security depends on proper configuration
  - Kernel is shared between containers and host
- What if one container compromises the host kernel?

GVisor/Kata to harden Docker containers


VIRTUALIZE



Idea: fake the entire system

- Virtualization of hardware resources (memory, CPU, peripherals ...)
- System runs many isolated virtual machines

Implementation

- Managed by hypervisor
  - Xen, VMware, VirtualBox, Hyper-V, Qemu ...
- Typically hardware-accelerated
- CloudOS in the summer term

What if VM compromises hypervisor?

Is there an end to this recursive problem?


ENCLAVES

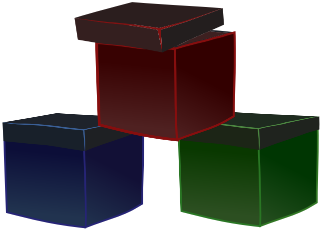
- Observation: Sandboxes follow hierarchical ring model
  - Higher rings (kernel space) have strictly higher privileges
  - Lower rings (user space) need to fully trust higher rings
  - Vulnerability in higher ring is fatal
- Idea: build a reverse sandbox: Enclaves
  - Only trust enclave code (and hardware)
  - Distrust all non-enclave code
    - Host application, kernel, hypervisor
  - Example: Intel SGX/TDX, AMD-SEV, ARM Trustzone

☆ Properties

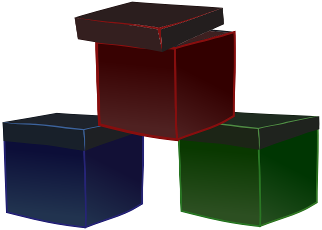
- Enclaves protect a piece of secure code / data
- Enclaves cannot sandbox untrusted code
- Can be (mis)used for Digital Rights Management (DRM), hiding malware

? Are we (too) secure now?

Summary & Outlook



- Everything is a box
  - **Compartmentalization**: Make boxes as small as possible
  - **Isolation**: A box shall have minimal permission
  - "Principle of least privileges"



Isolation techniques

- In-process Sandboxing
  - Interpretation
  - Compilation
- Process Sandboxing
  - Seccomp
- Virtualization
  - Docker container = seccomp + control groups + namespaces
  - Full system virtualization
- Enclaves

Summary

Attacker's perspective

- Vulnerability discovery ☑
- Exploitation ☑
- Privilege elevation ☑

Defender's perspective

- Vulnerability prevention ☑
- Exploit prevention ☑
- Privilege minimization ☑

Questions?


OUR DEVICES ARE NOW 100% SECURE.
HOW DID YOU DO THAT?
I TURNED THEM ALL OFF.
© D.Fletcher for CloudTweaks.com