Secure Software Development

Countermeasures: Privilege Minimization

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05.12.2020

Winter 2020/21, www.iaik.tugraz.at

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Recap: Defense In Depth

Attacker's perspective

- Vulnerability discovery ☑
- Exploitation ☑
- Privilege elevation ☑

Defender's perspective

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

Recap: Defense In Depth

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
  - admin flag, spawn a shell, cat flag.txt, gain persistence

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

Recap: What if Vulnerability Prevention Fails?

- 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
  - Our enemy: arbitrary code execution

Privilege Minimization

- What is *arbitrary code execution*?
  - Let's try to define it from an attacker's perspective
  - Attacker can choose which code to execute
  - Attacker obtains feedback (results, output, side-channels ...)
    - Stronger but not strictly necessary
  - Attacker can adapt the code based on the feedback and repeat
    - Even stronger but not strictly necessary
- What does *arbitrary* mean?
  - Any statement from a given language
  - Native x86, Bytecode, JavaScript, WebAssembly ...

❓ Is arbitrary code execution always bad?

- Well, it depends on the use case

☹ Attacker: run arbitrary malicious payloads

☺ Browser: run responsive Websites → arbitrary JavaScript

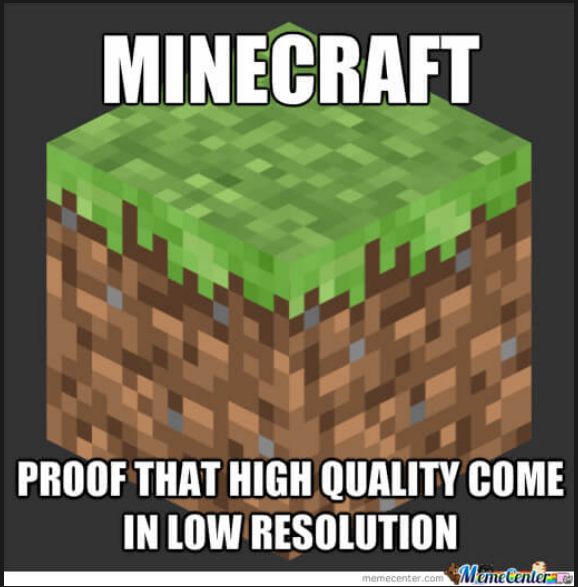
☺ Browser: run WebApps → arbitrary WebAssembly

☺ Android: run Apps → arbitrary Dalvik Bytecode

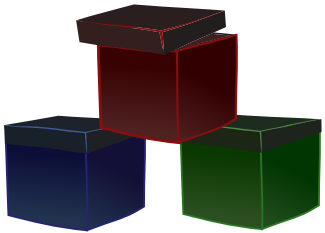
☺ Cloud computing: run a kernel → arbitrary native x86 instructions

- If properly confined, arbitrary code execution is secure
  - Browser: Website/Webapp shall not be able to compromise other tabs or the browser process
  - Android: App shall not be able to compromise other Apps or the kernel
  - Cloud computing: Customer shall not be able to attack other customers or the cloud hypervisor
- Goal: **privilege minimization**
  - Same privilege isolation (e.g., App vs. App)
  - Cross-privilege isolation (e.g., App vs. kernel)

Think inside boxes ...

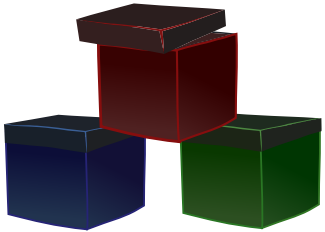


Privilege Minimization Overview



- Everything is a box
  - Make boxes as small as possible (Compartmentalization)
  - A box shall have minimal permission (Isolation)
  - "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

Privilege Minimization Techniques



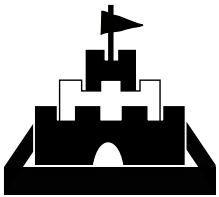
Isolation techniques

- In-process Sandboxing
- Process Sandboxing
- Virtualization
- Enclaves

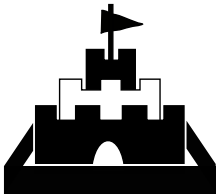
In-process Sandboxing


ME AFTER ESCAPING
THE SANDBOX
imgflip.com

In-process Sandboxing

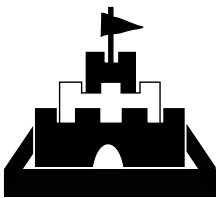


- Goal: confine parts of an application
  - E.g., dangerous plugins, libraries, user-provided code ...
- Idea: Software-generated sandbox via
  - Interpretation
  - Compilation
  - (Binary rewriting)



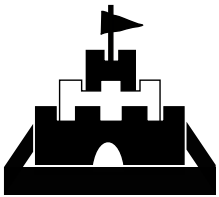
- Dangerous code is not executed natively but interpreted
  - E.g., Java, JavaScript, WebAssembly, Lua, Python, Berkeley Packet Filter (BPF) ...
- Interpreter
  - executes code of "virtual machine" by evaluating e.g., bytecode
  - provides hooks (callbacks) to do e.g., system calls
  - restricts functionality by refusing access to sensitive resources
    - Memory of the interpreter or the runtime
    - System calls
  - is an implicit sandbox

In-process Sandboxing: Interpretation II

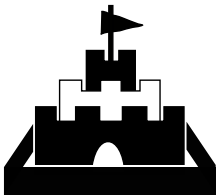


- Properties
  - Interpreter can enforce very powerful and flexible policies
  - Interpreted language typically abstracts away dangerous behavior (e.g., pointer dereference)
  - Slow
  - Vulnerability in interpreter is fatal
    - Prefer simple, restricted languages
- Example: Berkeley Packet Filters (BPF)
  - Interpreter runs in the kernel!
  - Use cases: network packet filtering, system call filtering
  - Very restricted instructions; not even turing complete

In-process Sandboxing: Compilation I



- Dangerous code is compiled to **confined native code**
  - Control-flow confinement, similar to CFI: Attacker cannot jump outside the sandbox
  - Data confinement: Attacker cannot access memory outside the sandbox
- Variant 1: Compiler **introduces checks** to confine execution
  - Example: JavaScript Just-in-Time compiler



- Variant 2: Compiler **masks** all **memory accesses**
  - Simple logical `AND` operation clears upper pointer bits
  - Sandbox can never access upper part of virtual memory
  - Also called *"Software Fault Isolation"* (SFI)
  - Example: Google Native Client (NaCl)
- Properties
  - Much faster than interpretation
  - Requires DEP (W⊕X) to prevent bypassing the checks

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 ~ %
```

Seccomp Example III

```c
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);                          // blacklist everything
  seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(rt_sigreturn), 0);   // whitelist
  seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(exit), 0);           // whitelist
  seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(exit_group), 0);     // whitelist
  seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(read), 0);           // whitelist
  seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(write), 0);          // whitelist
  seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(dup2), 2,            // whitelist
                   SCMP_A0(SCMP_CMP_EQ, 1), SCMP_A1(SCMP_CMP_EQ, 2)); // whitelist
  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!

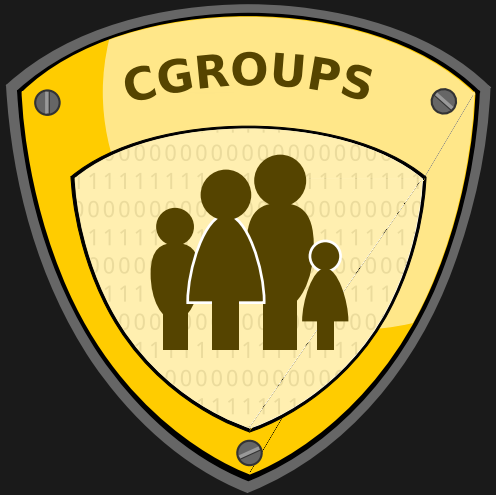
→ Very convenient to use :)

- 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/`

- 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

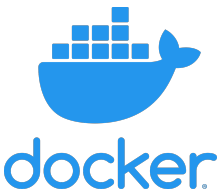

CGROUPS

Control groups (cgroups)

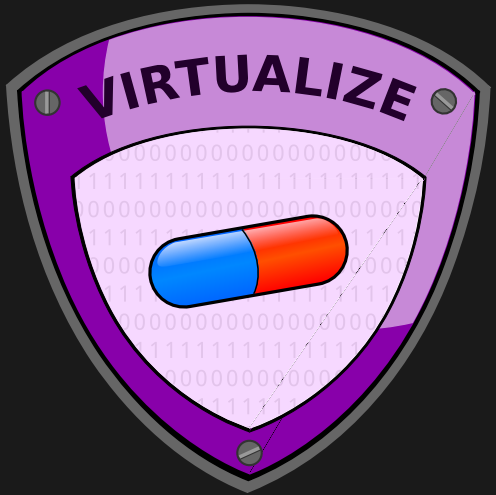
- Idea: Manage resource usage of a group of processes (and all its children)
  - Memory, CPU time, networking, disk I/O ...
  - Set limits / priorities
- Properties
  - Can prevent some Denial-of-Service (DoS) attacks
  - Cannot prevent privilege escalation


NAMESPACES

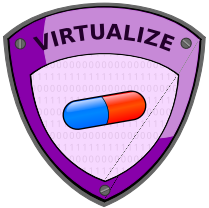
- Idea: Namespace hides (virtualizes) resources from processes
  - Various namespaces: `mnt`, `pid`, `net`, `ipc`, `uts` (hostname), `user`
  - How? Namespace translates resource identifiers
- Examples:
  - Inside namespace: `uid=0(root)`, `path=/f.txt`
  - Outside namepsace: `uid=1000(ssd)`, `path=/home/ssd/f.txt`



- Idea: combine 'em all: Docker containers
  - See also Linux Containers (LXC)
- Docker automagically
  - creates namespaces and cgroups
  - configures seccomp
- Properties
  - Virtualization of software resources (files, processes, users ...)
  - Enforced via kernel
  - Fast
  - Limited to compatible kernels
  - Security depends on proper configuration
    - E.g., privileged vs. unprivileged containers
  - Kernel is shared between containers and host
- What if one container compromises the host kernel?


VIRTUALIZE

Full System Virtualization



- 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
  - See other courses ...
- What if VM compromises hypervisor?
- Is there an end to this recursive problem?

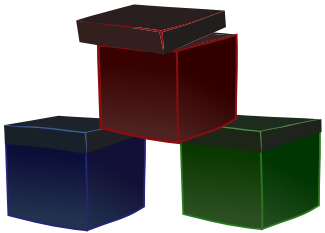

ENCLAVES

- 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 Software Guard Extensions (SGX)

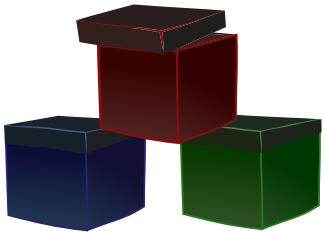
- Properties
  - Enclaves protect a piece of secure code / data
  - Enclaves cannot sandbox untrusted code
  - Can be (mis)used for Digital Rights Management (DRM), hiding malware
- Are we (too) secure now?

Summary & Outlook

Privilege Minimization Overview



- 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

Save The Date: SSD Christmas Special

- Friday, 18 December, afternoon
- Online show
- Betting that ... you'd get surprised!

Questions?