Promises and pitfalls of sandboxes

“Multiple speed bumps don’t make a wall” (TT)

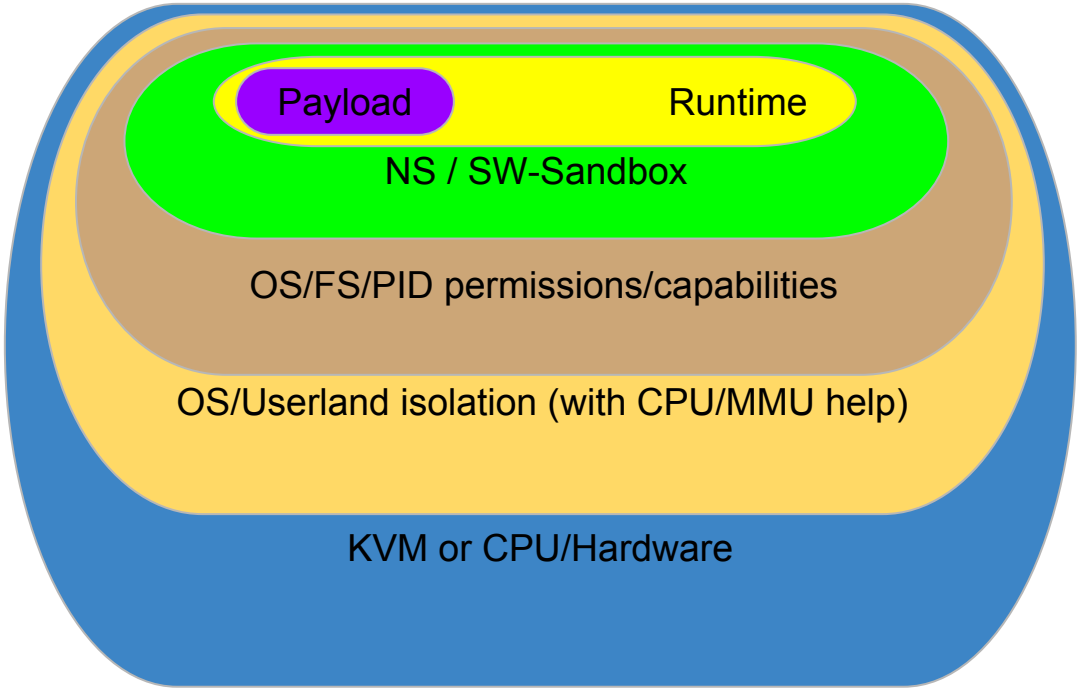
Robert Swiecki (expressing his own opinions here)
Confidence, Kraków 2017

But why?

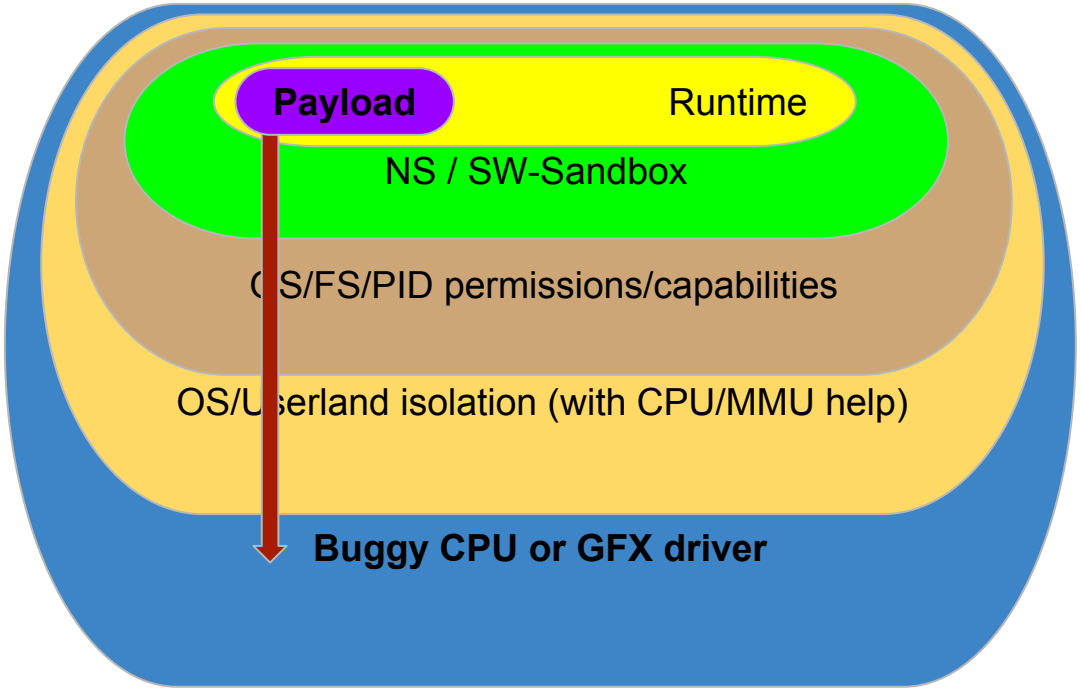
- Known to be broken services containment (e.g. image converters)
- Hardening of services of a relatively good quality (e.g ISC bind)
  - also for resource limitation
  - fuzzing
  - gcc as a service?
- Cloud: VPSes
- IaaS: Infrastructure as a Service
- SaaS: Sandbox as a Service (e.g. hiring pipelines for coders)
- Capture The Flag (CTF) competitions
- Malware research
- Reverse Engineering
- ...

Orthogonality/Layering #1

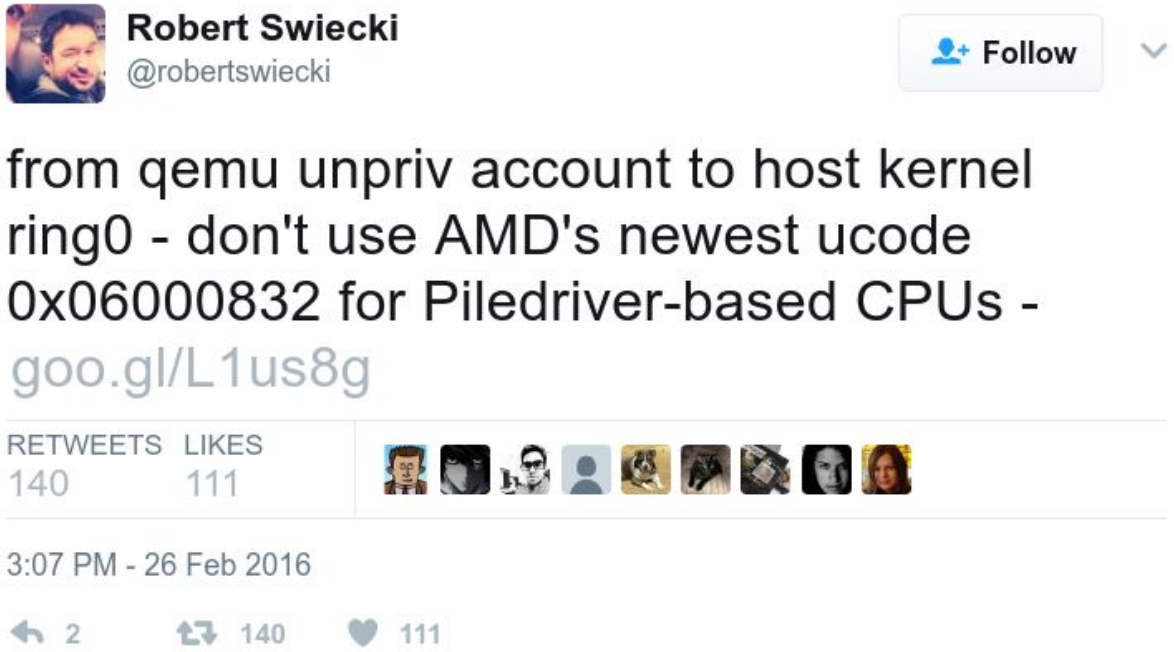
- Layers of defense



Orthogonality/Layering #2



Orthogonality/Layering #3



Runtime hardening

- ASLR/PIE/NX-stack/CFI/Stack-protector/Fortify-Source
  - Good: Typical CPU/mem penalty <5%
  - Bad: By-passable with memory leaks

- ASAN/MSAN/UBSAN
  - Good: Truly effective at finding security problems
  - Bad: Not security features, can even compromise security

```
ASAN_OPTIONS='verbosity=2:log_path=foo' ./setuid
```

Legacy mechanisms (rlimits, cgroups)

- RLimits: Quite basic
  - Can limit VM size of a process, number of open file-descriptors, and a few more things
  - Per-process only, with the exception of RLIMIT_NPROC
- Cgroups: Nicer
  - Per-process, but cumulative resource use and inheritable
  - Confusing design (via multiple /sys files)

Legacy mechanisms (chroot) #1

- Popular during 90’s
  - Good: Easy concept to understand
  - Bad: Only for root (root-equivalent capability), by-passable

```
mkdir("abc", 0755);
chroot("abc");
chdir("../../../../../../../../..");
```

(also: namespaces - `CLONE_NEWUSER|CLONE_NEWNS`)

Legacy mechanisms (chroot) #2

- Doesn’t compartmentalize other aspects of the OS

1. `ptrace(PTRACE_ATTACH, <pid_outside_chroot>, 0, 0);`
2. `process_vm_writev(<pid_outside_chroot>);`
3. `socket(AF_UNIX),`
   `connect(abstract_socket_namespace_to_a_broker)`

Legacy mechanisms (chroot) #3

- Reduces kernel attack surface minimally only (incl. /dev)

- The **FUTEX** test

Linux Kernel Futex Local Privilege Escalation (CVE-2014-3153)

The futex_requeue function in kernel/futex.c in the Linux kernel through 3.14.5 does not ensure that calls have two different futex addresses, which allows local users to gain privileges via a crafted FUTEX_REQUEUE command that facilitates unsafe waiter modification.

Legacy mechanisms (capabilities)

- Interesting idea (power-less root)
- Not really used (with exceptions, like '*ping*')
  - Messy list of capabilities (>60) - require good understanding of interactions within Linux
- Many capabilities are root-equivalent
- Not for regular users (for root only)

```
$ man 7 capabilities
  CAP_SYS_CHROOT
    Use chroot(2)

$ ln /bin/su /tmp/chroot/su
$ chroot /tmp/chroot
$ /su
```

SW/CPU Emulators

- Good: probably no good sides of SW/CPU emulators
- Bad:
  - Slow (faster with JIT)
  - Enormous attack surface: CPU and HW
  - Additional services: Printing interfaces, Network NAT/Bridges
- Truly bad history of security vulnerabilities:
  - Venom CVE-2015-3456
  - Kostya Kortchinsky's printer service flaw VMSA-2015-0004
  - Bugs in VGA, ETH, USB emulation ...

Ptrace #1

- Debugging interface, not a security one
- Good: Surprisingly effective (starting with *systrace* by N.Provos)
- Bad:
  - slow -> context switches
  - full of security bugs itself
  - messy, inconsistent behavior between different kernel versions

```
pid: syscall(syscall_no, arg0, arg1, ...)
ptracer: ptrace(PTRACE_SYSCALL, pid, 0, 0);
another process/thread: kill(pid, SIGKILL)
```

Ptrace #2

Ptracer

```
bool is_entry;

for (;;) {
 int pid = wait(&status);
 …
 if (WIFSTOPPED(status) &&
  WSTOPSIG(status) == SIGTRAP) {
   is_entry = !is_entry;
   if (is_entry) {
    check_syscall();
   }
  }
}
```

Tracee

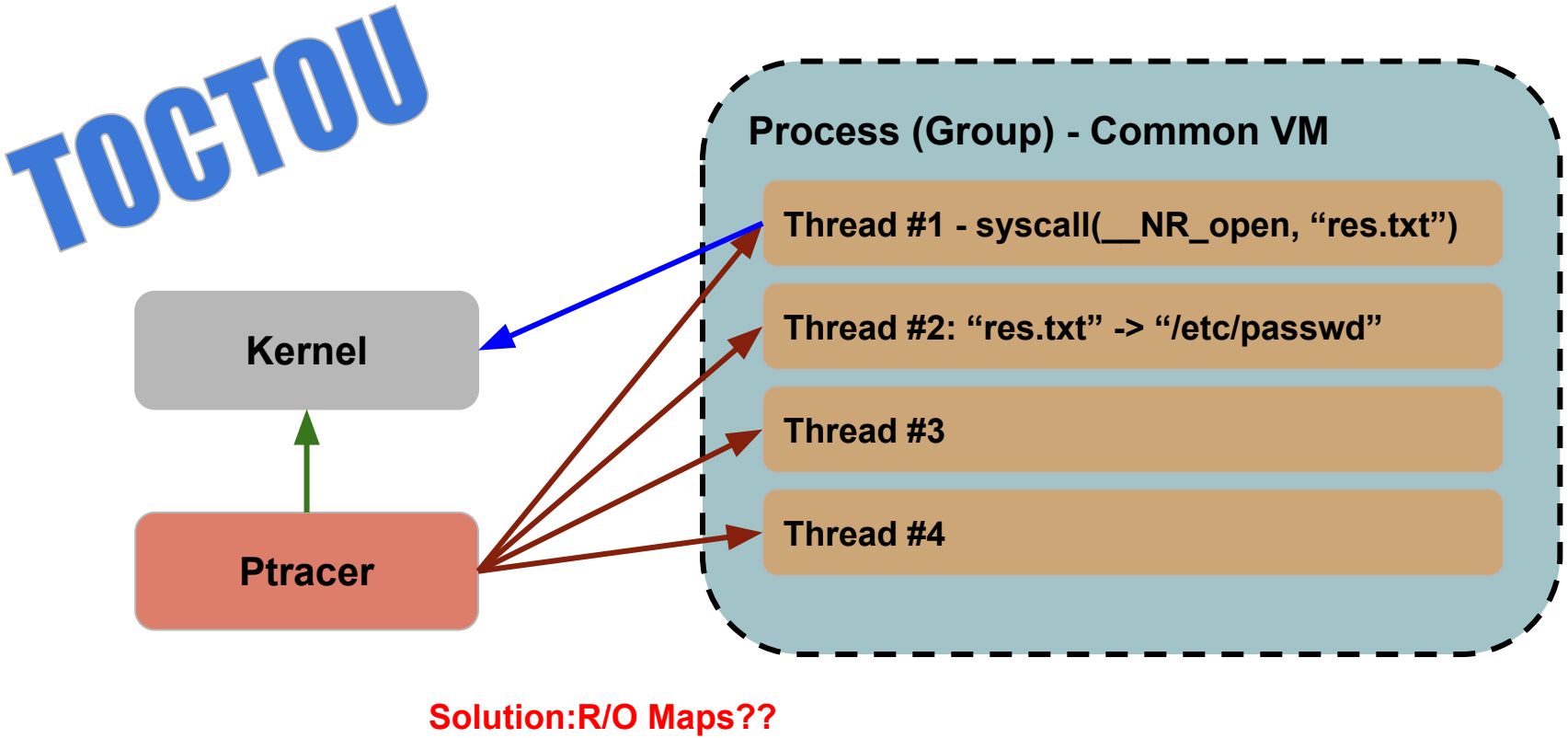
```
int main() {
    syscall1();
    asm("int3");
    syscall2();
}
```

rt_sigreturn changes orig_eax to -1

Since Linux 2.4.6

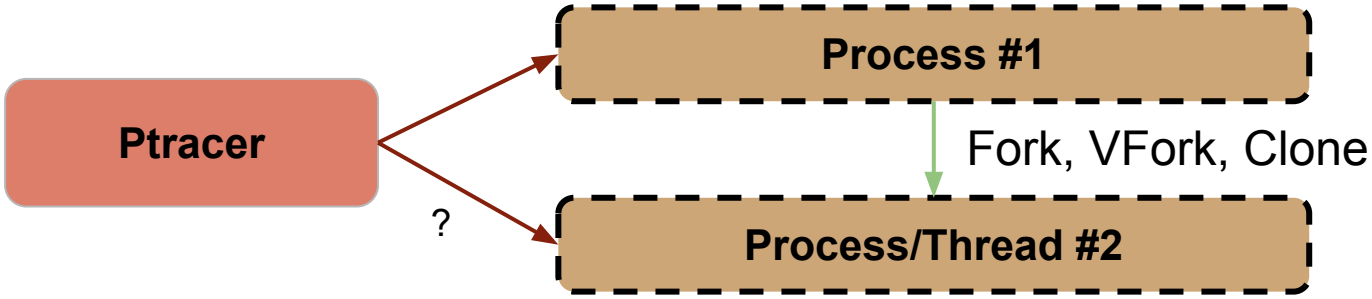
PTRACE_O_TRACESYSGOOD

Ptrace #3



Solution:R/O Maps??

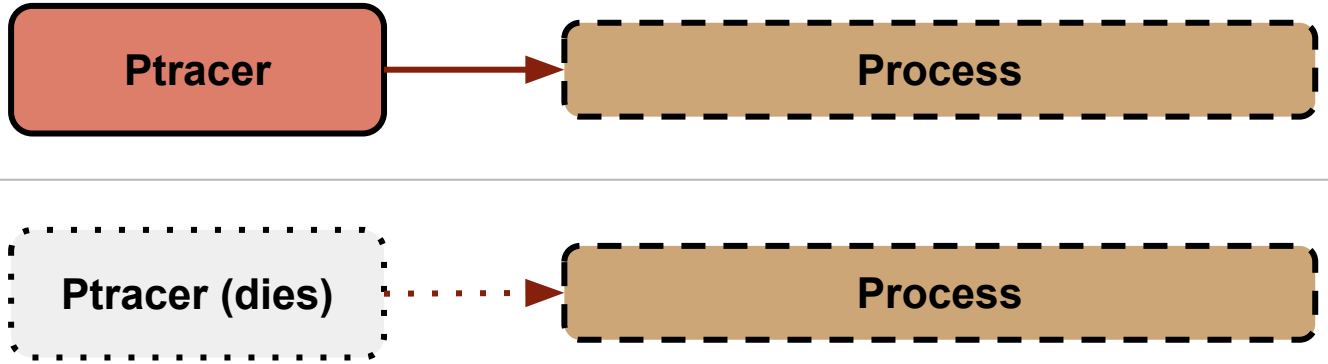
Ptrace #4



1. Modify **`fork/vfork`** -> **`clone(CLONE_TRACE)`**
2. **`PTRACE_O_TRACEFORK,PTRACE_O_TRACEVFORK,PTRACE_O_TRACECLONE`** (v. 2.5)

… unless **`clone(CLONE_UNTRACED)`** is used -> remove the flag, or invoke the syscall violation procedure

Ptrace #5



- If ptracer dies -> no more sandboxing
- Since v.3.8 -> **`PTRACE_O_EXITKILL`**

- Multitude of other problems
  - Unclear SIGSTOP semantics (thread stop, thread group stop)
  - Spurious SIGTRAP events
  - Emulation of process stop state (**`PTRACE_LISTEN`**)
  - ...

Ptrace #6

- Different syscall tables (e.g. i386 vs x86-64)

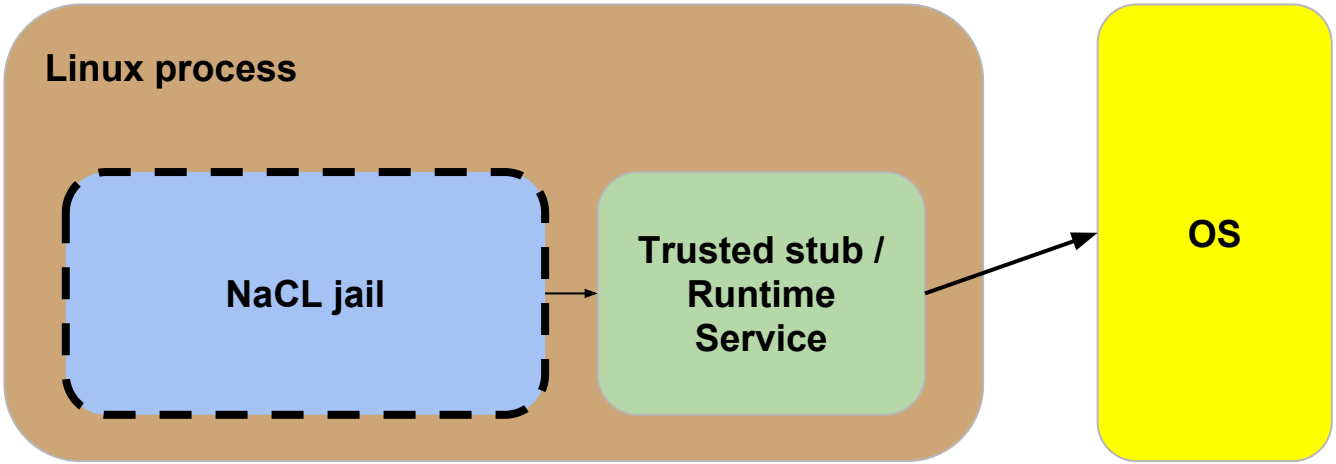
```
#define __NR_restart_syscall 0
#define __NR_exit            1
#define __NR_fork            2
```

```
#define __NR_read       0
#define __NR_write      1
#define __NR_close      2
```

- No easy way to differentiate between 32/64-bit syscall tables from *ptrace()*
    - return value from ptrace(PTRACE_GETREGSET) returns info about bitness of the **process bitness**, and not about the syscall table used
    - it's possible to fetch syscall-inducing instruction (**int 0x80** vs **syscall** vs **sysenter**) but **TOCTOU**.
    - Checking the **CS** segment register might be inconclusive

Native Client (NaCL) #1

- Based on the Russ Cox' and Bryan Ford's idea from **vx32**
- User-level sandboxing, makes use of custom ELF loader/verifier and CPU segmentation (`modify_ldt()` on i386) and large mappings (non i386)



Native Client (NaCL) #2

- limited subset of x86-32, x86-64 and ARM
- SFI - Software Fault Isolation, DFI/CFI - Data/Control Flow Integrity
- naclcall, nacljmp, naclret
- Possible to change CFI (func ptrs), but not to escape the jail

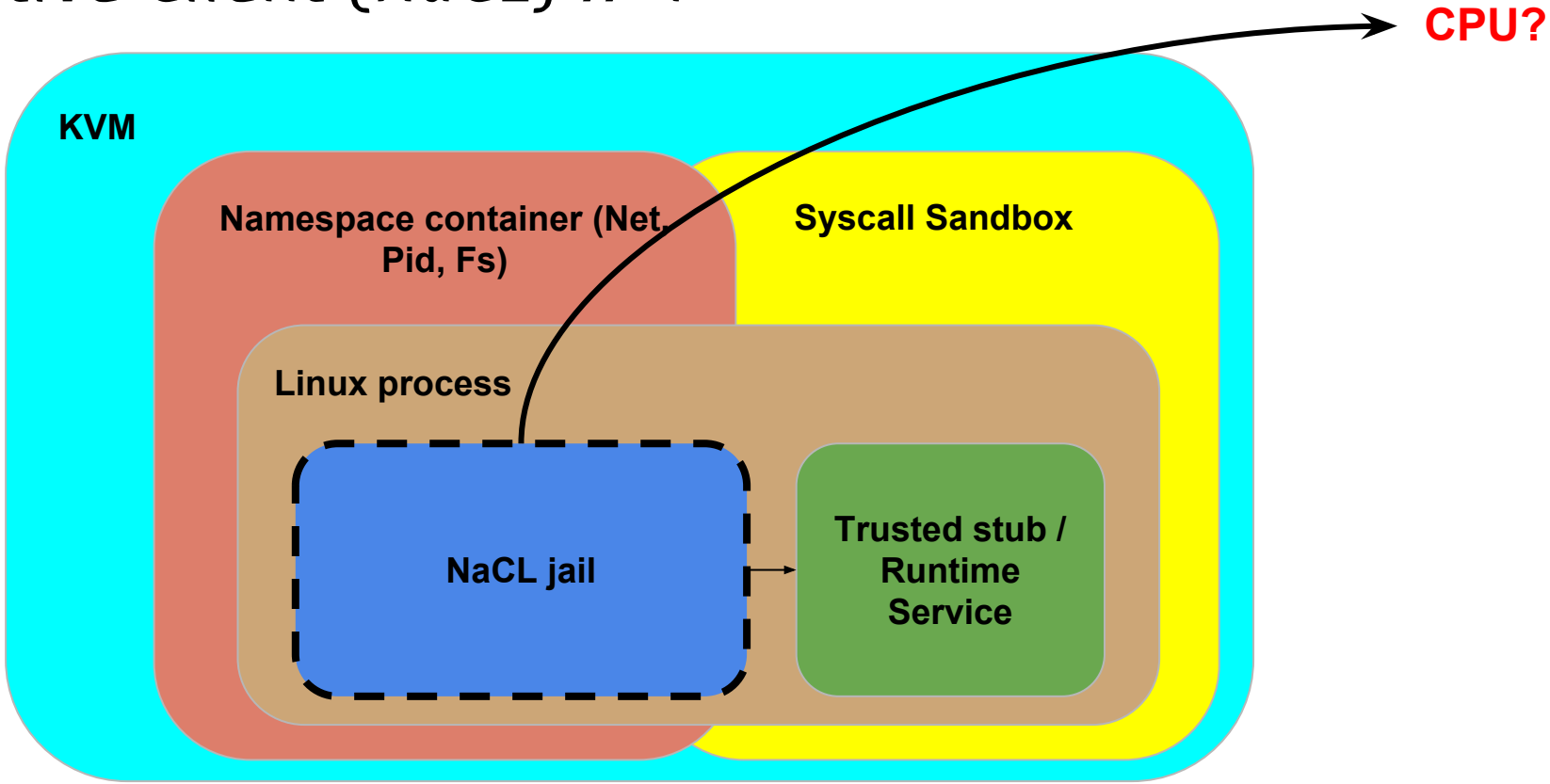
```
nacljmp eax          ->     and eax,0xffffffe0
                            jmp eax
```

```
nacljmp %eXX,%rZP    ->     and $-32,%eXX
                            add %rZP,%rXX
                            jmp *%rXX
```

Native Client (NaCL) #3

- Good
  - Quite effective & rather fast (5-10% slow-down)
  - Based on CPU instruction whitelists
  - Statically pre-verified
  - Ability to apply an external syscall sandbox (e.g. ptrace or seccomp-bpf based)
- Bad
  - Writing safe trusted stubs (trampolines) requires great deal of work and attention
  - The whole process is not very straightforward (custom compilers/SDK/gdb)
  - Depends on perfect implementation of white-listed CPU instructions (CPU errata)
  - Lots of restrictions
    - No dynamic/self-modifying/JIT code
    - No assembler inlines
    - No direct access to syscalls/FS/Net

Native Client (NaCL) #4



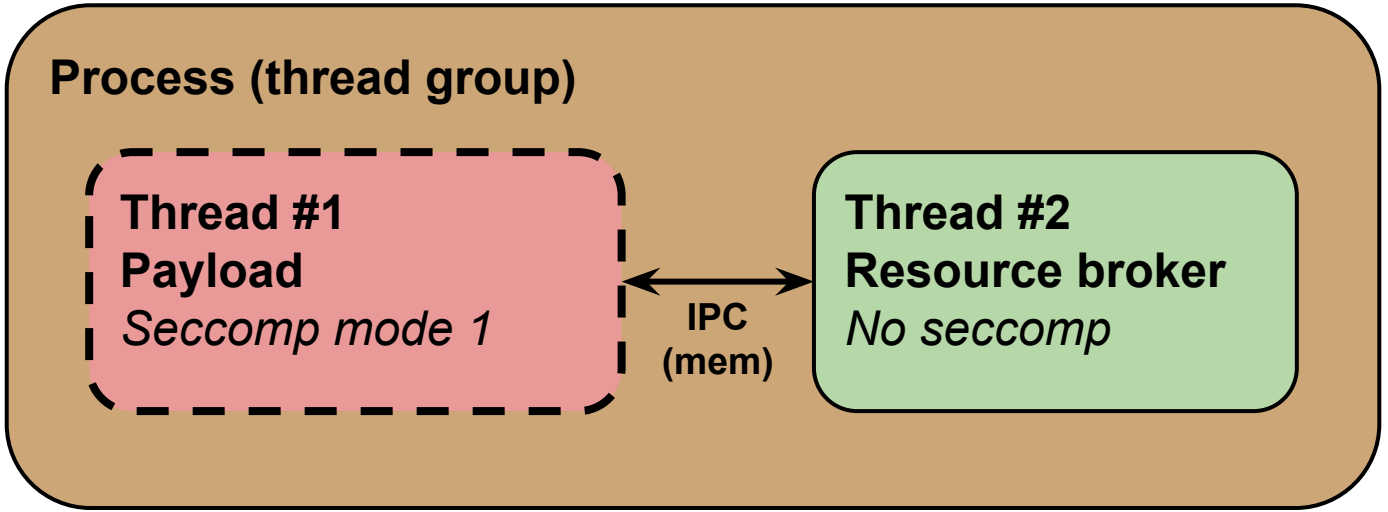
Seccomp (v1) #1

read write exit sigreturn

- Neat idea, but turned out to be immensely hard to work with
- Required brokers for resources, but nothing can be done for memory management
- Chromium Legacy Seccomp Sandbox
  - One of the most complex implementations out there

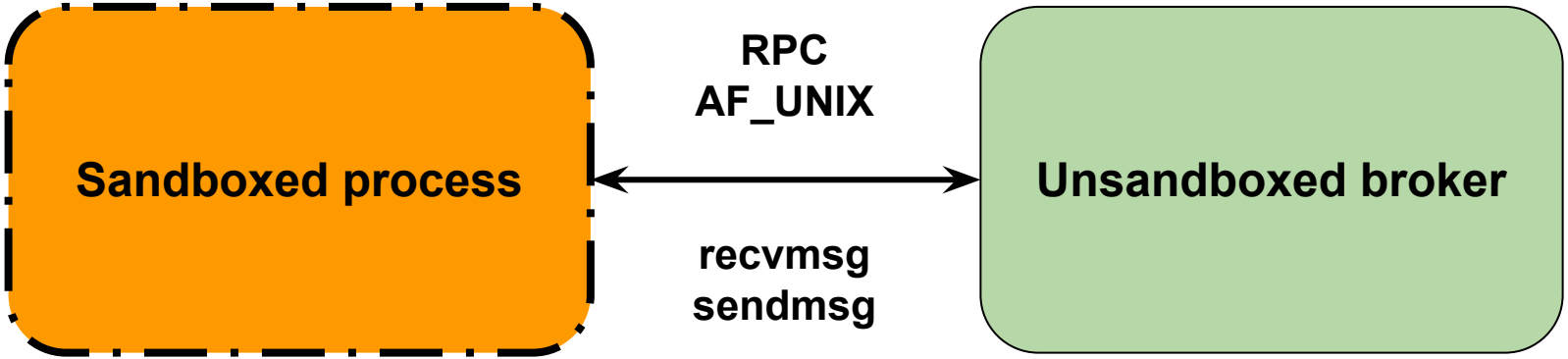
Seccomp (v1) #2

One-process Seccomp-v1 Sandbox



Resource brokering

Resources are File-Descriptors *(with exceptions)*
ptrace/seccomp-bpf (but not seccomp v1)



Seccomp-bpf #1

- There were a few ideas about pushing syscall evaluators into kernel before (e.g. in the perf's subsystem - ftrace)
- Authors came up with two ideas:
  - Reusing BPF - Berkeley Packet Filter(s) VM
  - Letting the userland to create the full evaluator operating on a simple struct

```
struct seccomp_data {
    int nr;
    __u32 arch;                    /* NO PID and TID!!! */
    __u64 instruction_pointer;
    __u64 args[6];
};
```

Seccomp-bpf #2

```
SECCOMP_RET_KILL    /* kill the task immediately */
SECCOMP_RET_TRAP    /* disallow and force a SIGSYS */
SECCOMP_RET_ERRNO   /* returns an errno */
SECCOMP_RET_TRACE   /* pass to a tracer or disallow */
SECCOMP_RET_ALLOW   /* allow */
```

- **`SECCOMP_RET_TRACE`** – no tracer → syscall disallowed
- If multiple filters - all evaluated, and the “worst” return value wins
- No loops!

Seccomp-bpf #3

```
struct sock_filter {
    uint16_t code;  /* the opcode */
    uint8_t jt;     /* if true: jump displacement */
    uint8_t jf;     /* if false: jump displacement */
    uint32_t k;     /* immediate operand */
};
```

```
/* load the syscall number */
BPF_STMT(BPF_LD+BPF_W+BPF_ABS, offsetof(struct seccomp_data, nr)),
/* allow read() */
BPF_JUMP(BPF_JMP+BPF_JEQ+BPF_K, SYS_read, 0, 1),
BPF_STMT(BPF_RET+BPF_K, SECCOMP_RET_ALLOW)
/* deny anything else */
BPF_STMT(BPF_RET+BPF_K, SECCOMP_RET_KILL)
```

Seccomp-bpf #4

```
VALIDATE_ARCHITECTURE,

LOAD_SYSCALL_NR,
SYSCALL(__NR_exit, ALLOW),
SYSCALL(__NR_exit_group, ALLOW),
SYSCALL(__NR_write, JUMP(&l,
write_fd)),
SYSCALL(__NR_read, JUMP(&l,
read)),
DENY,

LABEL(&l, read),
ARG(0),
...
```

```
...
JNE(STDIN_FILENO, DENY),
ARG(1),
JNE(buf, DENY),

ARG(2),
JGE(sizeof(buf), DENY),
ALLOW,

LABEL(&l, write_fd),
ARG(0),
JEQ(STDOUT_FILENO, JUMP(&l, w_buf)),
JEQ(STDERR_FILENO, JUMP(&l, w_buf)),
DENY,
```

Seccomp-bpf #5

- Kafel (config language)

```
#define mysyscall -1
POLICY sample {
 ALLOW {
  kill(pid, sig) {
   pid == 1 && sig == SIGKILL
  }
  mysyscall(arg1, myarg2) {
       arg1 == 42 &&
       myarg2 != 42
  }
 }
}
USE sample DEFAULT KILL
```

- Chromium BPF-DSL (C++ API)

```
EvaluateSyscall(int sysno) const OVERRIDE
{
 if (sysno == __NR_socketpair) {
  const Arg<int> domain(0), type(1)
    return If(domain == AF_UNIX &&
    (type == SOCK_STREAM ||
     type == SOCK_DGRAM), Error(EPERM)).
     Else(Error(EINVAL));
  }
  return Allow();
}
```

Seccomp-bpf #6

- Implementers tend to forget to check the (syscall) architecture in use

```
struct sock_filter filter[] = {
        VALIDATE_ARCHITECTURE,
```

- Seccomp-bpf cannot check user-land arguments (FS paths, connect())
  - Use ptrace() or namespaces

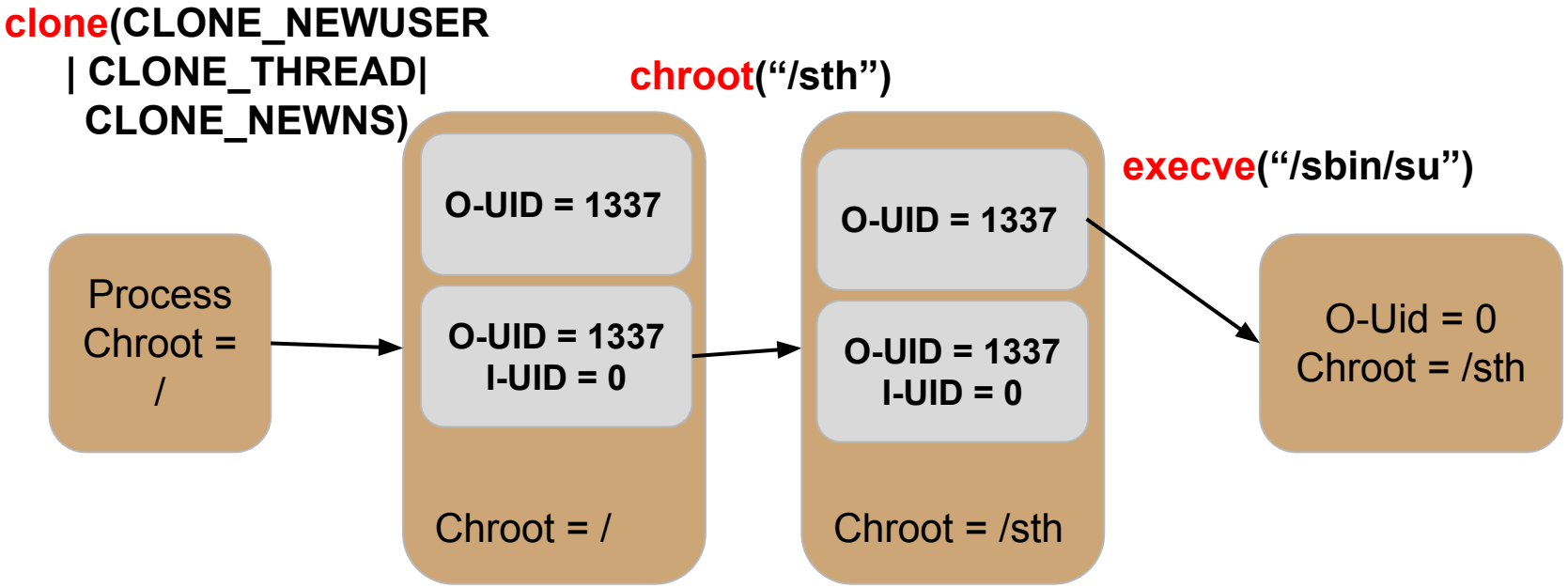
```
syscall(__NR_open, "/etc/passwd", O_RDONLY);
```

- Decompiled seccomp-bpf code is *rather unreadable* (for verification)
- Syscalls vary between architectures (no "*one policy for all*"), OpenSSH

Namespaces #1

- Concept borrowed from Plan9 (*from outer space*)
- Some aspects of the OS can be unshared from other processes
  - Uids, Hostname, Fs tree, Net context, Pid tree, Cgroups…
- Since ~3.16 it's possible, with **CLONE_NEWUSER**, to unshare context for an unprivileged user
  - This enable huge attack surface, many priv-esc's in the past
    - Access to raw sockets for various protocols
    - Ability to mount some filesystems (bugs in overlayfs)
    - Chroot escape trick?
    - Quite complex semantics wrt clone flag exclusion (e.g. no **CLONE_THREAD|CLONE_NEWNS**)
  - Can be disabled with kernel patches

Namespaces #2

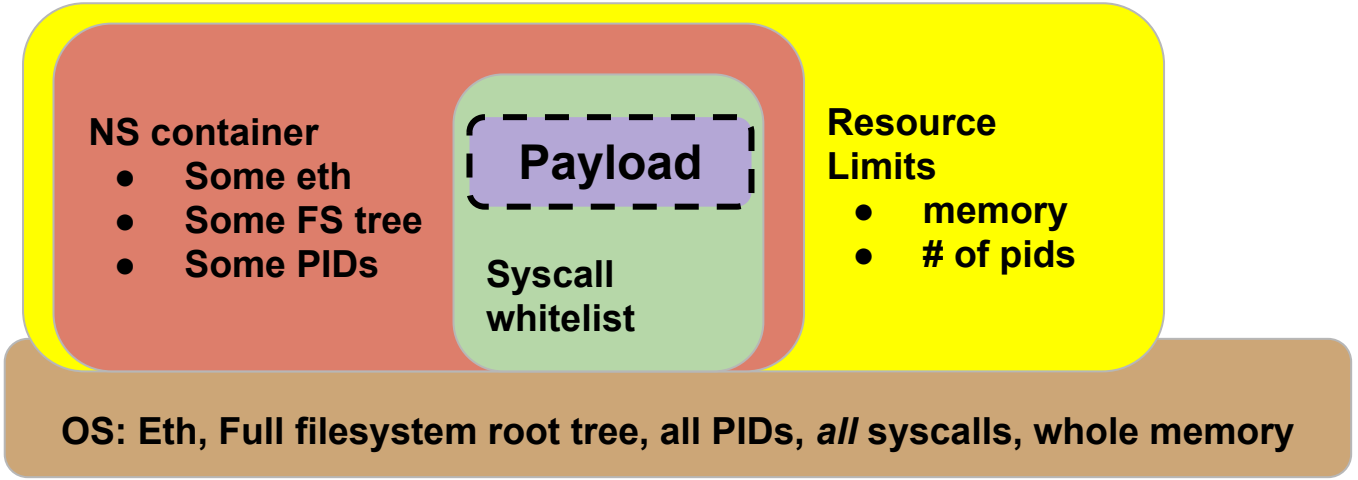


Namespaces #3

- It shrinks the kernel attack surface (**the *futex* problem**) minimally only
- It expands this attack surface in some other places
  - Can be avoided by careful setup of namespaces
    i. Enable namespaces
    ii. Setup chroot, hostname, net etc.
    iii. Drop capabilities
    iv. Somehow block **CLONE_NEWUSER** (can be by **chrooting**)
    v. Run sandboxed process
  - firejail, nsjail, minijail0, docker/lxc

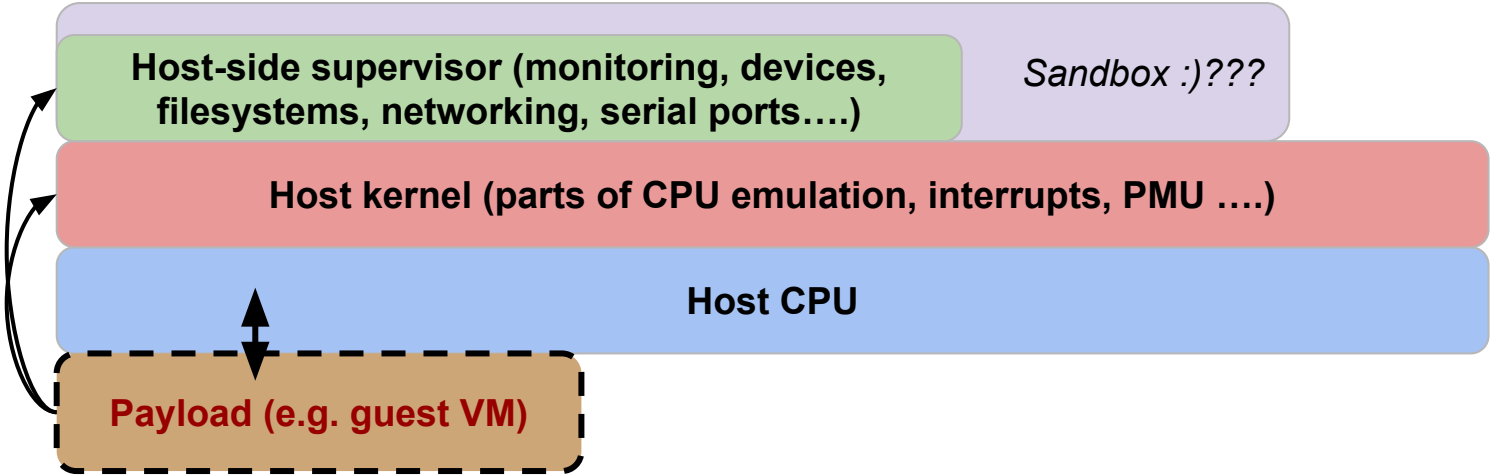
Namespaces + Syscall whitelist + resource limits

- Eg: NS + Seccomp-bpf + Cgroups



KVM

- Direct access to a subset of CPU instructions
  - Many still need to be emulated (attack surface!!)
- If devices or services (printing servers) are simulated (some can be exposed directly via IOMMU) → attack surface!!



Others: Xen, Capsicum, LSM

- Xen
  - Creation of domains: privileged (Dom**0**) and unprivileged (Dom**U**)
  - Personal opinion: usage declining bc of KVM in Linux
  - Problems: attack surface - non trivial IO API exposed by the Dom**0**
- Capsicum
  - Working motto: *“Practical capabilities for UNIX”*
  - Resources as file-descriptors
  - Linux implementation: LSM + Seccomp-bpf
- LSM
  - Yama, AppArmor, SELinux
  - Typically try to limit access to resources (e.g. filesystem paths)
  - Protection of the kernel attack surface doesn’t seem to be priority (the *futex* problem)

The futex test

Technology	Futex test
rlimits, cgroups, chroot, capabilities	**FAILS**
ptrace syscall whitelist	**PASSES**
seccomp	**PASSES**
seccomp-bpf	**PASSES**
NaCL	**PASSES**
LSM	**FAILS**
Capsicum	**FAILS**
KVM / SW Emulators	N/A

Conclusions

- Many features shouldn’t be called sandboxes these days
  - chroot, rlimits, capabilities
- Attack surface is what matters
- Not every protection/hardening method is a layer (or, a strong layer)
- There’s no golden bullet: practically all sandboxing Linux kernel facilities or external projects suffer from non trivial flaws, or hard to overcome practical problems (e.g. NaCL)
- Combination of a few of those features (if these are solving independent problems) might actually produce something useful (effective)
- Creating safe and functional sandboxes for Linux is a truly non-trivial job, where corner-cases are common

Q&A