Using seccomp to limit the kernel attack surface

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Outline

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2 Introduction and history
3 Seccomp filtering and BPF
4 Constructing seccomp filters
5 BPF programs
6 Further details on seccomp filters
7 Applications, tools, and further information
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Who am I?

- Maintainer of Linux man-pages (since 2004)
  - Documents kernel-user-space + C library APIs
    - ~1000 manual pages
- API review, testing, and documentation
  - API design and design review
  - Lots of testing, lots of bug reports, a few kernel patches
- “Day job”: programmer, trainer, writer
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Goals

- History of seccomp
- Basics of seccomp operation
- Creating and installing BPF filters (AKA “seccomp2”)
  - Mostly: look at hand-coded BPF filter programs, to gain fundamental understanding of how seccomp works
  - Briefly note some productivity aids for coding BPF programs
Introduction and history

- Mechanism to restrict system calls that a process may make
  - Reduces attack surface of kernel
  - A key component for building application sandboxes
- First version in Linux 2.6.12 (2005)
  - Filtering enabled via /proc/PID/seccomp
    - Writing “1” to file places process (irreversibly) in “strict” seccomp mode
- Need CONFIG_SECCOMP
Initially, just one filtering mode ("strict")

- Only permitted system calls are `read()`, `write()`, `_exit()`, and `sigreturn()`
  - Note: `open()` not included (must open files before entering strict mode)
  - `sigreturn()` allows for signal handlers
- Other system calls ⇒ `SIGKILL`
- Designed to sandbox compute-bound programs that deal with untrusted byte code
  - Code perhaps exchanged via pre-created pipe or socket
Introduction and history

Linux 2.6.23 (2007):

- `/proc/PID/seccomp` interface replaced by `prctl()` operations
- `prctl(PR_SET_SECCOMP, arg)` modifies caller’s seccomp mode
  - `SECCOMP_MODE STRICT`: limit syscalls as before
- `prctl(PR_GET_SECCOMP)` returns seccomp mode:
  - `0 ⇒ process is not in seccomp mode`
  - Otherwise?
    - `SIGKILL (!)`
      - `prctl()` is not a permitted system call in “strict” mode
      - Who says kernel developers don’t have a sense of humor?
Linux 3.5 (2012) adds “filter” mode (AKA “seccomp2”)

- `prctl(PR_SET_SECCOMP, SECCOMP_MODE_FILTER, ...)`
- Can control which system calls are permitted,
  - Control based on system call number and argument values
- Choice is controlled by user-defined filter—a BPF “program”
  - Berkeley Packet Filter (later)
- Requires `CONFIG_SECCOMP_FILTER`
- By now used in a range of tools
  - E.g., Chrome browser, OpenSSH, `vsftpd`, Firefox OS, Docker
Linux 3.8 (2013):

- The joke is getting old...
- New `/proc/PID/status` Seccomp field exposes process seccomp mode (as a number)
  
<table>
<thead>
<tr>
<th>Mode Number</th>
<th>Seccomp Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>SECCOMP_MODE_DISABLED</td>
</tr>
<tr>
<td>1</td>
<td>SECCOMP_MODE_STRICT</td>
</tr>
<tr>
<td>2</td>
<td>SECCOMP_MODE_FILTER</td>
</tr>
</tbody>
</table>

- Process can, without fear, read from this file to discover its own seccomp mode
  - But, must have previously obtained a file descriptor...
Introduction and history

Linux 3.17 (2014):

- `seccomp()` system call added
  - (Rather than further multiplexing of `prctl()`)
- Provides superset of `prctl(2)` functionality
  - Can synchronize all threads to same filter tree
    - Useful, e.g., if some threads created by start-up code before application has a chance to install filter(s)
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Seccomp filtering and BPF

- Seccomp filtering available since Linux 3.5
- Allows filtering based on system call number and argument (register) values
  - Pointers are not dereferenced
- Filters expressed using BPF (Berkeley Packet Filter) syntax
- Filters installed using `seccomp()` or `prctl()`
  1. Construct and install BPF filter
  2. `exec()` new program or invoke function inside dynamically loaded shared library (plug-in)
- Once installed, every syscall triggers execution of filter
  - Installed filters can’t be removed
    - Filter == declaration that we don’t trust subsequently executed code
BPF origins

- BPF originally devised (in 1992) for *tcpdump*
  - Monitoring tool to display packets passing over network

- Volume of network traffic is enormous ⇒ must filter for packets of interest

- BPF allows **in-kernel selection of packets**
  - Filtering based on fields in packet header

- Filtering in kernel more efficient than filtering in user space
  - Unwanted packet are **discarded early**
  - ⇒ Avoids passing **every** packet over kernel-user-space boundary
BPF virtual machine

- BPF defines a **virtual machine** (VM) that can be implemented inside kernel
- VM characteristics:
  - **Simple instruction set**
    - Small set of instructions
    - All instructions are same size
    - Implementation is simple and fast
  - Only **branch-forward** instructions
    - Programs are directed acyclic graphs (DAGs)
  - Easy to verify validity/safety of programs
    - Program completion is guaranteed (DAGs)
    - Simple instruction set ⇒ can verify opcodes and arguments
    - Can detect dead code
    - Can verify that program completes via a “return” instruction
    - BPF filter programs are limited to 4096 instructions
Generalizing BPF

- BPF originally designed to work with network packet headers
- Seccomp 2 developers realized BPF could be generalized to solve different problem: filtering of system calls
  - Same basic task: test-and-branch processing based on content of a small set of memory locations
- Further generalization (“extended BPF”) is ongoing
  - Linux 3.18: adding filters to kernel tracepoints
  - Linux 3.19: adding filters to raw sockets
  - In progress (July 2015): filtering of *perf* events
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Basic features of BPF virtual machine

- Accumulator register
- Data area (data to be operated on)
  - In seccomp context: data area describes system call
- Implicit program counter
  - (Recall: all instructions are same size)
- Instructions contained in structure of this form:

```c
struct sock_filter {
    __u16  code; /* Filter code (opcode) */
    __u8   jt;  /* Jump true */
    __u8  jf;  /* Jump false */
    __u32  k;  /* Generic multiuse field */
};
```

- See `<linux/filter.h>` and `<linux/bpf_common.h>`
BPF instruction set

Instruction set includes:

- Load instructions
- Store instructions
- Jump instructions
- Arithmetic/logic instructions
  - ADD, SUB, MUL, DIV, MOD, NEG
  - OR, AND, XOR, LSH, RSH
- Return instructions
  - Terminate filter processing
  - Report a status telling kernel what to do with syscall
Conditional and unconditional jump instructions provided

Conditional jump instructions consist of
  - **Opcode** specifying condition to be tested
  - **Value** to test against
  - **Two** jump targets
    - \( jt \): target if condition is true
    - \( jf \): target if condition is false

Conditional jump instructions:
  - **JEQ**: jump if equal
  - **JGT**: jump if greater
  - **JGE**: jump if greater or equal
  - **JSET**: bit-wise AND + jump if nonzero result
  - \( jf \) target \( \Rightarrow \) no need for \( JNE, JLT, JLE, and JCLEAR \)
BPF jump instructions

- Targets are expressed as relative offsets in instruction list
  - \( 0 \) \( \Rightarrow \) no jump (execute next instruction)
  - \( \texttt{jt} \) and \( \texttt{jf} \) are 8 bits \( \Rightarrow \) 255 maximum offset for conditional jumps
- Unconditional \( \texttt{JA} \) ("jump always") uses \( k \) as offset, allowing much larger jumps
Seccomp BPF data area

- Seccomp provides data describing syscall to filter program
  - Buffer is read-only
- Format (expressed as C struct):

```c
struct seccomp_data {
    int nr; /* System call number */
    __u32 arch; /* AUDIT_ARCH_* value */
    __u64 instruction_pointer; /* CPU IP */
    __u64 args[6]; /* System call arguments */
};
```
Seccomp BPF data area

```c
struct seccomp_data {
    int nr;          /* System call number */
    __u32 arch;      /* AUDIT_ARCH_* value */
    __u64 instruction_pointer; /* CPU IP */
    __u64 args[6];  /* System call arguments */
};
```

- **nr**: system call number (architecture-dependent)
- **arch**: identifies architecture
  - Constants defined in `<linux/audit.h>`, e.g., `AUDIT_ARCH_X86_64`, `AUDIT_ARCH_I386`, `AUDIT_ARCH_ARM`, etc.
- **instruction_pointer**: CPU instruction pointer
- **args**: system call arguments
  - System calls have maximum of six arguments
  - Number of elements used depends on system call
Building BPF instructions

- Obviously, one can code BPF instructions numerically by hand.
- But, header files define symbolic constants and convenience macros (`BPF_STMT()`, `BPF_JUMP()`) to ease the task.

```c
#define BPF_STMT(code, k) \{
    (unsigned short)(code), 0, 0, k
}\n#define BPF_JUMP(code, k, jt, jf) \{
    (unsigned short)(code), jt, jf, k
}\n```

- (Macros just plug values together to form structure)
Building BPF instructions: examples

- Load architecture number into accumulator

  ```c
  BPF_STMT(BPF_LD | BPF_W | BPF_ABS, (offsetof(struct seccomp_data, arch)))
  ```

- Opcode here is constructed by ORing three values together:
  
  - **BPF_LD**: load
  
  - **BPF_W**: operand size is a word
  
  - **BPF_ABS**: address mode specifying that source of load is data area (containing system call data)

- See `<linux/bpf_common.h>` for definitions of opcode constants

- `offsetof()` generates offset of desired field in data area
Building BPF instructions: examples

- Test value in accumulator

  \[
  \text{BPF\_JUMP(BPF\_JMP | BPF\_JEQ | BPF\_K,}
  \]
  \[
  \phantom{\text{BPF\_JUMP(BPF\_JMP | BPF\_JEQ | BPF\_K,}}
  \text{AUDIT\_ARCH\_X86\_64, 1, 0)}
  \]

  \(\text{BPF\_JMP | BPF\_JEQ}\): jump with test on equality
  \(\text{BPF\_K}\): value to test against is in generic multiuse field \((k)\)
  \(k\) contains value \(\text{AUDIT\_ARCH\_X86\_64}\)
  \(jt\) value is 1, meaning skip one instruction if test is true
  \(jf\) value is 0, meaning skip zero instructions if test is false
  I.e., continue execution at following instruction

- Return value that causes kernel to kill process with \(\text{SIGSYS}\)

  \[
  \text{BPF\_STMT(BPF\_RET | BPF\_K, SECCOMP\_RET\_KILL)}
  \]
Checking the architecture

- Checking architecture value should be first step in any BPF program
- Architecture may support multiple system call conventions
  - E.g. x86 hardware supports x86-64 and i386
  - System call numbers may differ or overlap
Filter return value

- Once a filter is installed, each system call is tested against filter.
- Seccomp filter must return a value to kernel indicating whether system call is permitted.
  - Otherwise `EINVAL` when attempting to install filter.
- Return value is 32 bits, in two parts:
  - Most significant 16 bits (`SECCOMP_RET_ACTION` mask) specify an action to kernel.
  - Least significant 16 bits (`SECCOMP_RET_DATA` mask) specify “data” for return value.
Filter return action component is one of

- **SECCOMP_RET_ALLOW**: system call is executed
- **SECCOMP_RET_KILL**: process is immediately terminated
  - Terminated *as though* process had been killed with **SIGSYS**
- **SECCOMP_RET_ERRNO**: return an error from system call
  - System call is not executed
  - Value in **SECCOMP_RET_DATA** is returned in **errno**
- **SECCOMP_RET_TRACE**: attempt to notify `ptrace()` tracer
  - Gives tracing process a chance to assume control
  - See `seccomp(2)`
- **SECCOMP_RET_TRAP**: process is sent **SIGSYS** signal
  - Can catch this signal; see `seccomp(2)` for more details
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Installing a BPF program

- A process installs a filter for itself using one of:
  - `seccomp(SECCOMP_SET_MODE_FILTER, flags, &fprog)`
    - Only since Linux 3.17
  - `prctl(PR_SET_SECCOMP, SECCOMP_MODE_FILTER, &fprog)`

- `&fprog` is a pointer to a BPF program:

```c
struct sock_fprog {
    unsigned short len; /* Number of instructions */
    struct sock_filter *filter;
        /* Pointer to program
         (array of instructions) */
};
```
Installing a BPF program

To install a filter, one of the following must be true:

- Caller is privileged (CAP_SYS_ADMIN)
- Caller has to set the no_new_privs process attribute:

```c
prctl(PR_SET_NO_NEW_PRIVS, 1);
```

- Causes set-UID/set-GID bit / file capabilities to be ignored on subsequent `execve()` calls
  - Once set, no_new_privs can’t be unset
- Prevents possibility of attacker starting privileged program and manipulating it to misbehave using a seccomp filter
- `! no_new_privs && ! CAP_SYS_ADMIN ⇒ seccomp()` fails with EACCES
Example: seccomp/seccomp_deny_open.c

```c
int main(int argc, char **argv) {
    prctl(PR_SET_NO_NEW_PRIVS, 1, 0, 0, 0);

    install_filter();

    open("/tmp/a", O_RDONLY);

    printf(" We shouldn’t see this message\n");
    exit(EXIT_SUCCESS);
}
```

Program installs a filter that prevents `open()` being called, and then calls `open()`

- Set `no_new_privs` bit
- Install seccomp filter
- Call `open()`
Example: seccomp/seccomp_deny_open.c

```c
static void install_filter(void) {
    struct sock_filter filter[] = {
        BPF_STMT(BPF_LD | BPF_W | BPF_ABS,
            (offsetof(struct seccomp_data, arch))),
        BPF_JUMP(BPF_JMP | BPF_JEQ | BPF_K,
            AUDIT_ARCH_X86_64, 1, 0),
        BPF_STMT(BPF_RET | BPF_K, SECCOMP_RET_KILL),
        ...
    }
}
```

- Define and initialize array (of structs) containing BPF filter program
- Load architecture into accumulator
- Test if architecture value matches `AUDIT_ARCH_X86_64`
  - True: jump forward one instruction (i.e., skip next instruction)
  - False: skip no instructions
- Kill process on architecture mismatch
Example: seccomp/seccomp_deny_open.c

```c
BPF_STMT(BPF_LD | BPF_W | BPF_ABS,
    (offsetof(struct seccomp_data, nr))),

BPF_JUMP(BPF_JMP | BPF_JEQ | BPF_K, __NR_open,
    1, 0),
BPF_STMT(BPF_RET | BPF_K, SECCOMP_RET_ALLOW),
BPF_STMT(BPF_RET | BPF_K, SECCOMP_RET_KILL)
```
Example: seccomp/seccomp_deny_open.c

```c
struct sock_fprog prog = {
    .len = (unsigned short) (sizeof(filter) / sizeof(filter[0])),
    .filter = filter,
};

seccomp(SECCOMP_SET_MODE_FILTER, 0, &prog);
```

- Construct argument for `seccomp()`
- Install filter
Upon running the program, we see:

```bash
$ ./seccomp_deny_open
Bad system call  # Message printed by shell
$ echo $?          # Display exit status of last command
159
```

- “Bad system call” indicates process was killed by **SIGSYS**
- Exit status of 159 (== 128 + 31) also indicates termination as though killed by **SIGSYS**
  - Exit status of process killed by signal is 128 + `signum`
  - **SIGSYS** is signal number 31 on this architecture
A more sophisticated example

Filter based on *flags* argument of *open()*

- **O_CREAT** specified ⇒ kill process
- **O_WRONLY** or **O_RDWR** specified ⇒ cause *open()* to fail with **ENOTSUP** error
Example: seccomp/seccomp_control_open.c

```c
struct sock_filter filter[] = {
    BPF_STMT(BPF_LD | BPF_W | BPF_ABS,
             (offsetof(struct seccomp_data, arch))),
    BPF_JUMP(BPF_JMP | BPF_JEQ | BPF_K, AUDIT_ARCH_X86_64, 1, 0),
    BPF_STMT(BPF_RET | BPF_K, SECCOMP_RET_KILL),

    BPF_STMT(BPF_LD | BPF_W | BPF_ABS,
             (offsetof(struct seccomp_data, nr))),
    BPF_JUMP(BPF_JMP | BPF_JEQ | BPF_K, __NR_open, 1, 0),
    BPF_STMT(BPF_RET | BPF_K, SECCOMP_RET_ALLOW),
};
```

- Load architecture and test for expected value
- Load system call number
- Test if system call number is `__NR_open`
  - True: skip next instruction
  - False: skip 0 instructions ⇒ permit all other syscalls
Example: seccomp/seccomp_control_open.c

BPF_STMT(BPF_LD | BPF_W | BPF_ABS,
 (offsetof(struct seccomp_data, args[1]))),

BPF_JUMP(BPF_JMP | BPF_JSET | BPF_K, O_CREAT, 0, 1),
BPF_STMT(BPF_RET | BPF_K, SECCOMP_RET_KILL),

- Load second argument of `open()` (flags)
- Test if `O_CREAT` bit is set in flags
  - True: skip 0 instructions ⇒ kill process
  - False: skip 1 instruction
Example: seccomp/seccomp_control_open.c

```c
BPF_JUMP(BPF_JMP | BPF_JSET | BPF_K,
         O_WRONLY | O_RDWR, 0, 1),
BPF_STMT(BPF_RET | BPF_K,
         SECCOMP_RET_ERRNO |
         (ENOTSUP & SECCOMP_RET_DATA)),
BPF_STMT(BPF_RET | BPF_K, SECCOMP_RET_ALLOW)
};
```

- Test if `O_WRONLY` or `O_RDWR` are set in `flags`
  - True: cause `open()` to fail with `ENOTSUP` error in `errno`
  - False: allow `open()` to proceed
Example: seccomp/seccomp_control_open.c

```c
int main(int argc, char **argv) {
    prctl(PR_SET_NO_NEW_PRIVS, 1, 0, 0, 0);
    install_filter();

    if (open("/tmp/a", O_RDONLY) == -1)
        perror("open1");
    if (open("/tmp/a", O_WRONLY) == -1)
        perror("open2");
    if (open("/tmp/a", O_RDWR) == -1)
        perror("open3");
    if (open("/tmp/a", O_CREAT | O_RDWR, 0600) == -1)
        perror("open4");

    exit(EXIT_SUCCESS);
}
```

- Test `open()` calls with various flags
Example: seccomp/seccomp_control_open.c

```
$ ./seccomp_control_open
open2: Operation not supported
open3: Operation not supported
Bad system call
$ echo $?  
159
```

- First `open()` succeeded
- Second and third `open()` calls failed
  - Kernel produced **ENOTSUP** error for call
- Fourth `open()` call caused process to be killed
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Installing multiple filters

- If existing filters permit `prctl()` or `seccomp()`, further filters can be installed
- **All** filters are always executed, in **reverse order** of registration
- Each filter yields a return value
- Value returned to kernel is first seen action of highest priority (along with accompanying data)
  - `SECCOMP_RET_KILL` (highest priority)
  - `SECCOMP_RET_TRAP`
  - `SECCOMP_RET_ERRNO`
  - `SECCOMP_RET_TRACE`
  - `SECCOMP_RET_ALLOW` (lowest priority)
fork() and execve() semantics

- If seccomp filters permit \texttt{fork()} or \texttt{clone()}, then child inherits parents filters
- If seccomp filters permit \texttt{execve()}, then filters are preserved across \texttt{execve()}
Cost of filtering, construction of filters

- Installed BPF filter(s) are executed for every system call
  - ⇒ there’s a performance cost

Example on x86-64:
- Use our “deny open” seccomp filter
  - Requires 6 BPF instructions / permitted syscall
- Call `getppid()` repeatedly (one of cheapest syscalls)
- +25% execution time (with JIT compiler disabled)
  - (Looks relatively high because `getppid()` is a cheap syscall)

- Obviously, order of filtering rules can affect performance
  - Construct filters so that most common cases yield shortest execution paths
  - If handling many different system calls, binary chop techniques can give $O(\log N)$ performance
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Applications

Possible applications:

- Building sandboxed environments
  - Whitelisting usually safer than blacklisting
  - Default treatment: block all system calls
  - Then allow only a limited set of syscall / argument combinations

- Various examples mentioned earlier

- Failure-mode testing
  - Place application in environment where unusual / unexpected failures occur
  - Blacklist certain syscalls / argument combinations to generate failures
Tools: **libseccomp**

- High-level API for kernel creating seccomp filters
  - [https://github.com/seccomp/libseccomp](https://github.com/seccomp/libseccomp)
  - Initial release: 2012

- Simplifies various aspects of building filters
  - Eliminates tedious/error-prone tasks such as changing branch instruction counts when instructions are inserted
  - Abstract architecture-dependent details out of filter creation
  - Can output generated code in binary (for seccomp filtering) or human-readable form ("pseudofilter code")
  - Don’t have full control of generated code, but can give hints about which system calls to prioritize in generated code

- [http://lwn.net/Articles/494252/](http://lwn.net/Articles/494252/)

- Fully documented with man pages that contain examples (!)
Other tools

- **bpfc** (BPF compiler)
  - Compiles assembler-like BPF programs to byte code
  - Part of *netsniff-ng* project ([http://netsniff-ng.org/](http://netsniff-ng.org/))

- LLVM has an eBPF back end (merged Jan 2015)
  - eBPF support for seccomp is planned
  - Compiles subset of C to BPF
    - C dialect; does not provide: loops, global variables, FP numbers, vararg functions, passing structs as args...
    - Examples in kernel source: *samples/bpf/*_kern.c
  - GCC patches exist, but not (yet?) merged upstream
Other tools

- In-kernel JIT (just-in-time) compiler
  - Compiles BPF binary to native machine code at load time
    - Execution speed up of 2x to 3x (or better, in some cases)
  - Disabled by default; enable by writing “1” to 
    `/proc/sys/net/core/bpf_jit_enable`
  - See `bpf(2)` man page
Resources

- Kernel source files:
  Documentation/prctl/seccomp_filter.txt,
  Documentation/networking/filter.txt

- http://outflux.net/teach-seccomp/
  - Shows handy trick for discovering which of an application’s system calls don’t pass filtering

- `seccomp(2)` man page

- “Seccomp sandboxes and memcached example”
  - blog.viraptor.info/post/seccomp-sandboxes-and-memcached-example-part-1
  - blog.viraptor.info/post/seccomp-sandboxes-and-memcached-example-part-2
Thanks!

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