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AUTOMATIC SECCOMP SYSCALL POLICY GENERATOR

AUTOMATICKÝ GENERÁTOR POLITIKY SYSTÉMOVÉHO VOLÁNÍ

BACHELOR'S THESIS
BAKALÁŘSKÁ PRÁCE

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Bachelor's Thesis Specification

For: **Tamaškovič Marek**
Branch of study: Information Technology
Title: **Automatic Seccomp Syscall Policy Generator**
Category: Algorithms and Data Structures

Instructions for project work:

1. Study the fundamentals of Linux system calls, tools for monitoring syscalls, Berkeley packet filter, and libseccomp. Conduct research on an intermediate representation of syscalls and optimizer of the intermediate representation.
2. Based on the research, design the intermediate representation and provide a design of appropriate optimizer for it.
3. Implement tool which reads output of strace comment and translates it to the intermediate representation. Implement designed optimizer and translator which transforms optimized structure to a seccomp policy.
4. Evaluate implementation of this tool on selected complex programs.

Basic references:

- Paul Moore. Libseccomp. https://github.com/seccomp/libseccomp, 2012. [Online; accessed 2017-11-02]

Requirements for the first semester:
Items 1 and 2.

Detailed formal specifications can be found at http://www.fit.vutbr.cz/info/szz/

The Bachelor's Thesis must define its purpose, describe a current state of the art, introduce the theoretical and technical background relevant to the problems solved, and specify what parts have been used from earlier projects or have been taken over from other sources.

Each student will hand-in printed as well as electronic versions of the technical report, an electronic version of the complete program documentation, program source files, and a functional hardware prototype sample if desired. The information in electronic form will be stored on a standard non-rewritable medium (CD-R, DVD-R, etc.) in formats common at the FIT. In order to allow regular handling, the medium will be securely attached to the printed report.

Supervisor: **Turoňová Lenka, Ing.**, DITS FIT BUT
Beginning of work: November 1, 2017
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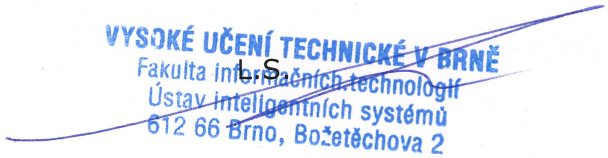

L.S.

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Associate Professor and Head of Department

Abstract

This bachelor's thesis has been developed in collaboration with Red Hat, Inc.

Abstrakt

Do tohoto odstavce bude zapsán výtah (abstrakt) práce v českém (slovenském) jazyce.

Keywords

seccomp, libseccomp, strace, optimizer, clustering, C++, policy generator

Klíčová slova

seccomp, libseccomp, strace, optimalizátor, zhlukovaniem C++, generátor politík

Reference

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Automatic Seccomp Syscall Policy Generator

Declaration

Hereby I declare that this bachelor's thesis was prepared as an original author's work under the supervision of Ms. Ing. Lenka Turoňová (FIT BUT) and by Mr. Bc. Daniek Kopecek (Red Hat, Inc.). The supplementary information was provided by Security Engineering team. All the relevant information sources, which were used during preparation of this thesis, are properly cited and included in the list of references.

.....
Marek Tamaškovič
April 20, 2018

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V této sekci je možno uvést poděkování vedoucímu práce a těm, kteří poskytli odbornou pomoc (externí zadavatel, konzultant, apod.).

Contents

1 Introduction **3**

2 System Calls and Monitoring Tools **4**
2.1 System Calls 4
2.2 Monitoring 5
2.2.1 Strace 5
2.2.2 Ptrace 6
2.2.3 Ftrace 6
2.2.4 Dtrace 7
2.2.5 SystemTap 7
2.2.6 Autrace 7

3 Security Facilities in Linux **9**
3.1 Systrace 9
3.2 Seccomp 9
3.3 Berkeley Packet Filter and Seccomp 10
3.4 Libseccomp 11

4 Solution Design **12**
4.1 Requirements 12
4.2 Architecture 13
4.2.1 Parser 14
4.2.2 Intermediate Data Structure 14
4.2.3 Optimizer 15
4.3 Parsing Expression Grammar 18

5 Development of strace2seccomp **20**
5.1 Input 20
5.1.1 Configure Strace to Produce Expected Input 20
5.1.2 Strace grammar 21
5.2 Class Hierarchy 21
5.3 Output 21
5.4 Used software 21
5.4.1 Compilers 21
5.4.2 LLVM/Clang-tidy 22
5.4.3 AddressSanitizer 22
5.4.4 Git 22
5.4.5 Artistic Style 23

5.4.6 LCOV & GCOV 23
5.5 Usage 23
5.5.1 C/C++ template 23

6 Software Verification **24**
6.1 Module Testing 24
6.1.1 Params Testing 24
6.1.2 StraceParser Testing 24
6.1.3 Algorithms 25
6.1.4 Optimizer 26
6.1.5 Output 26
6.2 System and Acceptance Testing 26
6.2.1 Testing on real app 26
6.2.2 USBGuard 26
6.3 Static analysis 26
6.4 Test Requirements 26
6.5 Results 26

Bibliography **27**

A Comparison of libseccomp and raw BPF filtering **29**
A.1 BPF 29
A.2 libseccomp 30

B other appendix **31**

Chapter 1

Introduction

Nowadays, when malicious code or malware is becoming more and more sophisticated and pressing security risk, it is really needed to control a program behaviour and monitor what the program is doing in a system. Monitoring program behaviour can be done in many ways and one of the easiest ways is to use Intrusion Detection System (IDS). IDS is an out-of-the-box solution which can monitor i.e. where program wrote or read something and it is not allowed. After that, IDS is reporting this violation.

Another way is to monitor and block system calls (syscalls). Monitoring is performed using tools mentioned in the next chapter. The actual blocking can be performed with mandatory access control (MAC) (Apparmor, SELinux), sandboxing (seccomp) or others mechanisms. MAC refers to a type of access control by which the operating system constraints the ability of a subject or initiator to access or generally perform some sort of operation on an object or target. Seccomp is a Linux kernel module which allows a process one-way transition to secure a state where the process can only use four syscalls. When the process tries to call another syscall then one of the four member's sets is terminated with SIGKILL. The set of allowed system calls can be extended using seccomp-bpf. This extension allows filtering system calls using a configurable policy implemented with Berkley Packet Filter (BPF) rules. This last part is an area on which I would like to focus in my thesis.

I aim to design and develop a tool which helps developers using libseccomp and seccomp-bpf. I plan to create policies for a specific program in a format readable by libseccomp or seccomp-bpf.

Chapter 2 describes syscalls and how to monitor them. In the chapter Chapter 3 of the thesis, I will illustrate how security facilities in Linux, such as systrace and seccomp, work. After the theoretical part, the design and development of a tool will follow. In conclusion, methodology how this tool was tested is described.

Chapter 2

System Calls and Monitoring Tools

In this chapter, I will describe the term system call and make an overview of tools which can monitor the system calls. We will focus in detail on the strace tool which will be used as an input to my tool. The other applications are described briefly not as detailed as the strace tool.

2.1 System Calls

In computer terminology, the term syscall is a way in which a computer program requests a service of the operating system on which is executed on. In other words, system calls are functions used in the kernel itself. The system call appears to a standard developer as a C function call. This design is typical for monolithic kernels. We can find them on every UNIX system. The system call can be called on Linux/i86 multiple ways. One of them is to call interruption no. `0x80` with value of syscall in register `eax`. The seccond and third one is by calling system calls `syscall()` or `sysenter()` and these syscalls are handled by the kernel in a privileged mode. When a user invokes a system call, an execution flow is as follows:

- Each syscall is vectored through a stub in libc. Some syscalls are more complicated than others because of a variable length of the arguments, but the entry point and the end point of syscall are still the same.
- In libc, the number of the syscall is then set to an `eax` register, and the stack frame is also set up.
- An interrupt number `0x80` is called and transferred to the kernel entry point. The entry point is the same for every system call.
- In the table of interrupts, a pointer to interruption handler is found. After that, the execution of the interrupt handler follows which stores the content of the CPU registers and checks if a valid syscall is called.
- The handler finds the corresponding offset in the table of interrupts `_sys_call_table`, where a pointer to the syscall service is stored.
- Control is transferred to the syscall service.
- Syscall returns a value to the register `EAX` on a 32-bit architecture or `RAX` on a 64-bit architecture.

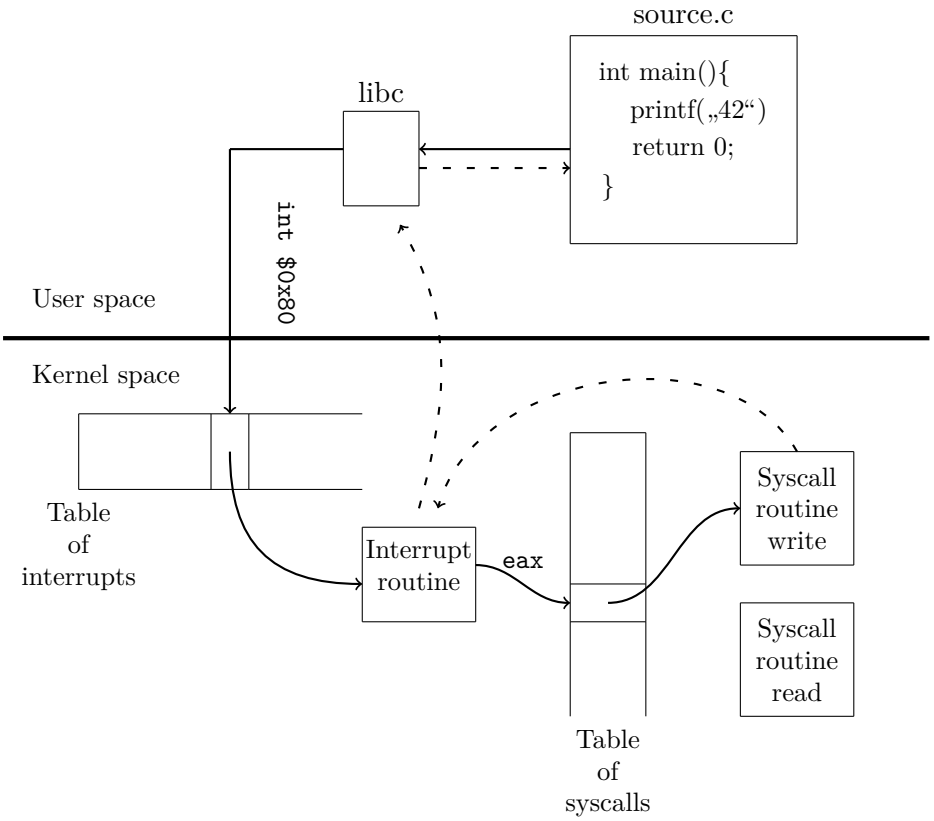

Figure 2.1: Interruption handling in Linux

- At the end of the syscall, `_ret_from_sys_call` is called. This call is done before returning to userspace. It checks if the scheduler should be run, and if so, it calls it.
- Immediately after return from the system call to interrupt handler, `syscallX()` macro checks for a negative return value from the syscall, if so it puts a positive copy of a return value to a global variable `_errno`, for accessing from code like `perror()`.

This procedure is illustrated in Figure 2.1. [23]

2.2 Monitoring

The most used and conventional method for monitoring is tracing, in other words watching what a program is doing during the execution. Tracing involves a specialized logging to record information, useful for debugging, about a program's execution. This can be done in multiple layers, from tracing which lines in the program was executed to individual instructions run on a CPU. Collecting this information can be done with various tools, e.g., strace, ftrace etc.

2.2.1 Strace

Strace [6] is a easy to use diagnostic, instructional and debugging tool. You can monitor every syscall or signal made by the program you are tracking. Using this tool it is possible to log what the observed program demanded from the kernel. The individual recorded

operations can be, e.g., an attempt to open a file or delete a content of CPU caches. This tool also shows arguments for the called syscall and it can show data strcutures with their elements, etc. The developer can perform a fault injection for the specified set of syscalls as well, to simulate the program in faulty test cases. Another feature is that the Strace can trace child processes of the observing program. The log on the output will contain the system calls from the primary process and its child processes.

The main advantage of Strace tool is that it does not need any source codes. The observing program has not to be compiled with extra flags nor object files. Also, it does not matter if the application is statically or dynamically linked. This is useful because we only need to execute the binary. These features are helpful for my tool, but this will be more described in a later chapter. The usage of strace tool is straightforward, i.e., when one wants to run ls with strace he types in a command line:

```
>$ strace ls
```

In this case, strace executes the `ls` command, and on the output, it shows which system calls were called. An example of the strace output is in the next figure.

```
execve(„/usr/bin/ls", [„ls"], 0x7ffd0cf4ba60 /* 59 vars */) = 0
open(„/etc/ld.so.cache", O_RDONLY|O_CLOEXEC) = 3
fstat(3, { st_mode=S_IFREG|0644, st_size=202163, ...}) = 0
mmap(NULL, 202163, PROT_READ, MAP_PRIVATE, 3, 0) = 0x7fd781293000
close(3)
```

2.2.2 Ptrace

Strace is using ptrace [5] system call. Ptrace is used to implement debuggers and other tools for process monitoring. Basically, the strace call ptrace and attach to a tracee (monitored process). When the connection is established the tracee is halted before and after syscall. Now the tracer (strace) can observe and control the execution as well as inspect memory and registers of (tracee). With this information, strace can determine which syscall was called. During the second halt after syscall, the strace can get information of return value from syscall.

2.2.3 Ftrace

Ftrace [4] is an internal tracer which traces events in the kernel. It is designed for developers to examine kernel events. The main feature of this tool is to measure latencies and find issues that take place outside of the user-space. Ftrace is typically considered as a function tracker, but it is a framework of several different tracing utilities. One neat feature of ftrace is measurement of latency among interrupts, the lag between the time when the task is woken up and time when the task is scheduled in. Another frequent use of ftrace is event tracing. In the kernel, there is a massive amount of static event points that can be enabled with a tracefs file system. The event points provide an interface to observe what is going on in the various parts of the kernel.

2.2.4 Dtrace

DTrace [3, 16] (shortcut for Dynamic Tracing) is a performance analysis and a troubleshooting tool. It is included in various operating systems, such as FreeBSD, Mac OS, Solaris and Linux. This tool instruments all software, not just user-level software but also operating system kernel and device drivers. It supports dynamic tracing which means dynamically patching while running instructions with an instrumentation code. Static tracing is supported as well, but it needs to add tracepoints to the code. DTrace provides a scripting language called 'D' for writing scripts and one-liners. It is similar to C with AWK elements. With this script, you can create filters and summarize data in the kernel before passing to user-space. This design can decrease the overhead in performance of sensitive systems.

For our purposes, DTrace is too complicated to setup or gather the information about syscalls. You need to write some scripts to define which syscalls you want to be informed with and in our use case, we need every system call.

2.2.5 SystemTap

SystemTap [8] is a tracing and probing tool that allows to gather information from probes injected into the kernel. It is similar to Dtrace. It started as a clone of Dtrace because it has uncompatible licence for using in GNU Linux. One of the common thing with Dtrace is that both tools use some type of scripting language. In this case it is named SystemTap. With this language you can specify what happens when some event occurs in the kernel.

SystemTap works as daemon which communicates with a stap program. Stap is a small program that translates the SystemTap script to a kernel module. It is done in a few steps. At first it runs semantic analysis on the script. After that, stap tries to translate it into a C code. The next step is to compile it as a kernel module and load it into the kernel. After load it is working and doing the useful part. When you send a signal to terminate the stap program it will unload the kernel module and stop working.

Similar as Dtrace the SystemTap is too complicated to work as system call monitor and it is not flawless. The Systemtap can not dereference the pointer address in the system call but the strace tool can.

2.2.6 Autrace

The Linux Auditing System helps system administrators to create an audit trail. Every action on workstation or server is logged into a log file. This tool can track security-relevant events, record the events and detect misuses or unauthorised activities by inspecting the audit log. You can also set which actions should or should not be reported.

Audit System is composed of two main parts. The first one *autrace* is a kernel component which intercepts system calls, records events and sends these audit messages to the next part. The second component is an audit daemon working in user space. This part is collecting the information emitted by a kernel component. Emitted data is then stored as entries in a log file. As you can see this tool is not for monitoring one specific program, but it is designed to monitor the whole system. In the output, there is specified who and when executed the syscall, current working directory, uid, gid, etc. Above specified functionality is useful for server administrators but not for our work.

Entry example in a log file:

```
type=SYSCALL msg=audit(1434371271.277:135496):  arch=c000003e syscall=2
success=yes exit=3 a0=7fff0054e929 a1=0 a2=1fffffffffff0000 a3=7fff0054c390
items=1 ppid=6265pid=6266 auid=1000 uid=0 gid=0 euid=0 suid=0 fsuid=0
egid=0 sgid=0 fsgid=0 tty=pts0 ses=113 comm=„cat"
exe=„/usr/bin/cat" key=„sshconfigchange"
```

Chapter 3

Security Facilities in Linux

This chapter describes security facilities in GNU Linux operating system. First we mention an old tool named Systrace [20]. Later we will mention a secure computing module named Seccomp [18]. The next topic will be Berkley Packet Filter (BPF) because it is used in seccomp-bpf. The seccomp-bpf is an extension to basic seccomp. This extension can better describe the behavior of seccomp. In the end, there will be a description of libseccomp which is an easy to use library to the kernel syscall filtering.

3.1 Systrace

Systrace is security facility which limits an application's access to the system. It is similar to a newer tool named seccomp-bpf which will be described later. The restrictions of a program are provided via system call blocking. The policy is generated interactively. Operations not covered by the defined policy raise an alarm. When an alarm is raised the user can refine the current policy. Systrace provides an option to generate policies automatically which can be immediately used in sandboxing (Sandbox is a security mechanism for separating programs, usually in an effort to mitigate system failures or software vulnerabilities from spreading.)[1]. It is not flawless, so it sometimes needs minimal manual post-processing.

This tool provides cybersecurity by providing intrusion prevention. One of the uses is that you run systrace on the server. The systrace monitors all running daemons (daemon is a computer program that runs as a background process, executed on system start up) and can generate a warning when some incident occurs. These alerts can be sent to a system administrator and can provide information what happened.

3.2 Seccomp

A large number of syscalls are exposed to user space of a process. Many of this syscalls are unused for the entire lifetime of the process. This exposes a possibility to misuse some syscalls to corrupt the process itself. A particular subset of applications benefits from a reduced set of syscalls by reducing exposed kernel surface to process. The filtering is done by seccomp. Seccomp filtering provides a means for a process to reduce the set of syscalls available to the process [9].

In most contemporary distribution, a kernel module named Seccomp [18] is enabled. Sec-comp stands for the shortcut of Secure Computing Mode. This module provides one

[1] https://www.wikiwand.com/en/Sandbox_(computer_security)

way transition to a secure mode which restricts a thread to a few system calls `read()`, `write()`, `exit()`, `sigreturn()`. If the thread tries to call another system call then the one from the four-member set, the whole process is terminated with signal `SIGTERM`. The drawback of this solution is that these four system calls are not enough for application to run correctly.

3.3 Berkeley Packet Filter and Seccomp

The seccomp filter mode allows developers to write BPF programs that determine if a given syscall will be allowed or not. That allowance can be based on a system call number or specific syscall argument values. Only the passed values are available, as any pointer are not dereferenced by the BPF. Filters can be installed using `seccomp()` or `prctl()`. The BPF program should be constructed first, then installed in the kernel. After that, every system call triggers the filter code. The installed filter cannot be removed or modified. Another property of applied filter is that the filter is inherited from a parent process to every child process when using `fork(2)` or `exec(2)`.

A BPF language came in 1992 for a program called tcpdump which is a monitoring tool for network packets. The volume of packet can be colossal, so it makes the transfer to user-space expensive. The BPF provides a way to do filtering in the kernel and the user space only handles those packets which is interested in.

The seccomp filter developers realised that they wanted very similar task. After that, the BPF was generalized to allow system call filtering. After the update, there is a tiny BPF virtual machine in the kernel space that interprets the BPF instructions.

The next update of BPF was to eBPF which stands for extended BPF. This update was released in Linux Kernel 3.18 for tracepoints later in 3.19 for raw sockets and in 4.1 for performance monitors. The eBPF brought the performance improvements and new capabilities.

The eBPF virtual machine is widely used in the kernel for various filtering:

- eXpress Data Path (XDP) *is a high performance, programmable network data path in the Linux Kernel*
- Traffic control,
- Sockets,
- Firewalling $xpf\_bpfmodule$,
- Tracing,
- Tracepoints,
- kprobe *dynamic tracing of a kernel function call*,
- cgroups.

eBPF - Specification The eBPF virtual machine has a 64-bit RISC architecture designed for one to one mapping to 64-bit CPUs. Instructions are similar to classic BPF for simple conversion to eBPF. The old format had registers A and X instead of current 11 registers, grouped by function as described below [22].

- R0 exit value for eBPF
- R1 - R5 function call arguments to in-kernel functions
- R6 - R9 callee-saved registers preserved by in-kernel functions
- R10 stack frame pointer (read only)

So far 87 internal BPF instructions were implemented. Opcode field has a room for new instructions. Some of them may use 16/24/32 byte encoding.

Same as the original BPF (the new format runs within controlled environment) is deterministic and the kernel can easily prove that. The safety of a program can be verified in two steps. First step does depth-first-search to forbid loops and CFG[2] validations. The second step starts from first instruction and descends all possible paths in CFG. It simulates execution of every instruction and examines the state of registers and a stack [22].

eBPF - Instruction Encoding An eBPF program is a sequence of 64-bit instructions. All eBPF instructions use the same design of instruction encoding which is shown in Figure 3.1. As you can see in the figure, there are 5 parts that are opcode (operation code), dst (destination), src (source), offset, immediate [22].

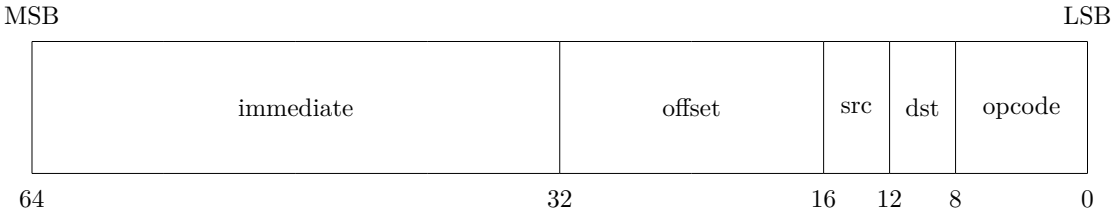

Figure 3.1: eBPF instruction encoding

3.4 Libseccomp

Libseccomp [19] is easy to use library which provides a platform-independent interface to the Linux Kernel's syscall filtering. The libseccomp API is designed to abstract an user from underlying BPF based syscall filtering and present a more conventional function-call based filtering interface. The interface should be more familiar to and quickly adopted by application developers. The comparison of libseccomp and raw BPF filter is shown in Appendix A.1 and A.2.

The library accept on input a set of rules which are later transformed into a eBPF format used in seccomp. One of the advantages of a libseccomp is that you can write a function call based filter. This filter is then translated to eBPF and after that it is loaded into seccomp as filter. This method is not transitive from function call filter to eBPF. There are some differences but they are on so small-scale they can be ignored.

Another advantages of seccomp is that it has a permissive mode in which every syscall violation is reported to the user. This feature can be helpful if you want to obtain information which syscalls was called. This use case is really similar to the syscall monitoring. But it is really tough to depend on this output because it is in development.

[2]Control flow graph

Chapter 4

Solution Design

This chapter will describe the technical part of the thesis. We will discuss requirements and particular parts, its architecture and issues, we have to deal with.

4.1 Requirements

We will require from the application to fulfill the following requirements:

1. Application will have only CLI[1].
2. The application will be implemented in C++17 [11].
3. Application will be designed with consideration of good OOP.
4. Application will consist of these main parts:
   (a) parser
   (b) optimizer
   (c) policy generator
   (d) logger
5. Parser will be implemented using PEG[2] [7] design.
6. Optimizer will have at least three optimizing methods:
   (a) strict - without use of advanced methods,
   (b) minimax - possibility to count an interval interval between minimum and maximum value found in a set of arguments,
   (c) advanced - combination of above methods.
7. Policy will be generated with libseccomp [19] syntax as C language [13] code.

[1] Command Line Interface
[2] Parsing Expression Grammar

4.2 Architecture

The architecture of this application is based on architectural patterns. In this case *Pipe-and-Filter* [14] architectural pattern was used. This pattern best fits our problem. A big inspiration came from compilers. They are very similar to this application. They break down the processing required for input into separate components (or filters), each performing a single task. By normalization the format of the data that each component produces, this component can be arranged as a pipeline. The pattern is good for possibility of changing or adding components and reduces duplicit code. But in this case this pattern is slightly modified. The data in pipeline is processed as whole batch.

The similar components with compilers are: parser, optimizer, output generator. As you can see the component is dependent on a component before. They have got parser, optimizer, output generator as well and every component is dependent on a component before. There are two main cases as shown in Figure 4.1.

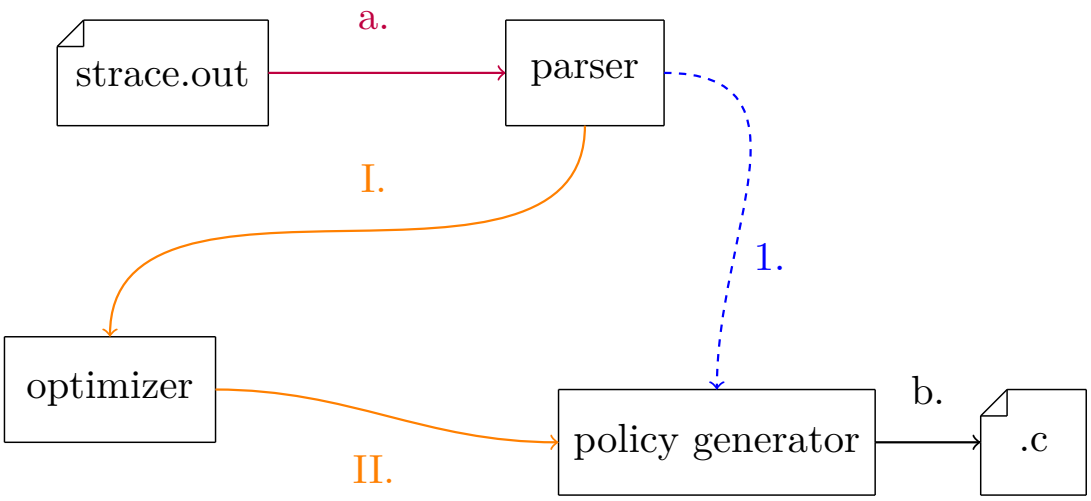

Figure 4.1: Architecture of strace2seccomp

Without Optimizer In this case, optimizer is not in the pipeline, a raw input is translated into libseccomp commands. This pipeline is shown in Figure 4.1 *(path: a., 1., b. in Figure 4.1)*. There are no optimizations when optimizer is turned off.

The main problem of not using a optimizer is not proper working system call filter. There is a possibility that any minor change in system call parameters can results into a program termination. In complex program, there is no way to be definitely sure wheather every syscall was caught. That can be a big problem in programs which use seccomp. That is the main reason why this option is not recommended.

However there are some users which, may not want to optimize the strace. The reason for not running the optimizer is that their application does not have variable parameteres in system calls. Every syscall is the same on any running instance of the application. Attentive reader may notice that this option can be used only in small applications which has some limited functionality.

The main disadvantage of this solution is that it is too robust to place it in a code and is very strict. It can kill a program even in a false positive case when user changes some of the parameters that was not covered in strace input files.

With Optimizer In this case when optimizer is turned on *(path: a., I., II., b. in Figure 4.1)*, we can specify which type of optimization we want. As mentioned in Section 4.1, there are two optimization variants. Those variants can be switched with runtime arguments in CLI.

The pitfalls of this case is allowing program to continue even in inappropriate circumstances. Invalid circumstances can be defined as a bad syscall argument treated as a valid. It can happen when you allow a set of arguments for specific syscall. This is not secure however it is more suitable for work than the case without optimizer.

You can minimize these pitfalls by providing a lot of strace input files. The best case is when you provide strace files from every major complex test case (with big prime path coverage).

4.2.1 Parser

The parser is crucial part of the whole application because it will put everything in an IR (intermediate representation). Input to the parser is a output from the `Strace` tool. The output was described in Section 2.2.1 and correct configuration of strace to generate valid ouptut for `strace2seccomp` will be described in Section 5.1.1. As you can see the output is in a structured form and has an unambiguous syntax which means that no error should occur during the parsing part. When syntax error occurs, the program should inform where the error is located in the input file. Next step should be a proper exit. Parser should have an option to identify all errors in the input file which can be helpful for identifying more errors on once. Another feature is that the parser can print structured parsed data.

4.2.2 Intermediate Data Structure

One of the main parts of strace2seccomp is intermediate data structure (IDS) in which the individual system calls are stored. The main idea of this abstract data type (ADT) is to be simple, readable with smallest redundancy possible. This can be done only with good abstraction and good design.

IDS is represented as a tree structure. In this structure, there are different information about syscall represented on a different level in the tree. The root node has child elements which represent an individual system calls. In this case, we are naming these nodes as a system call node (SCD). In SCD, information about a system call number is stored and it have multiple children. The n-th level represents the n-th argument of a specific system call. The whole system call (including arguments) can be read as a path from the root node to the leaf node. The IDS representation is shown in Figure 4.2.

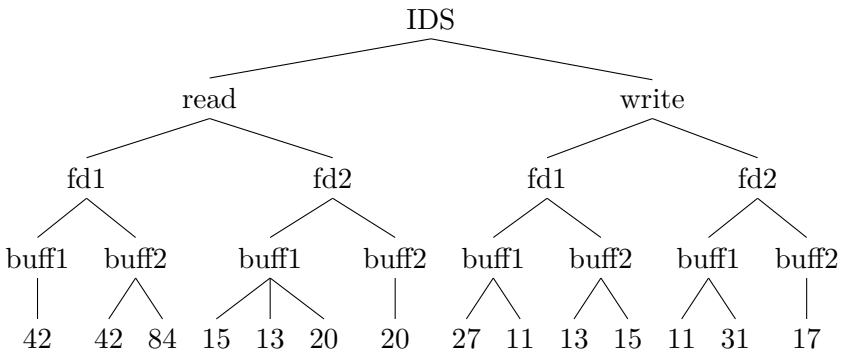

Figure 4.2: Visualized IDS as a tree

4.2.3 Optimizer

Optimizer is the main part of this tool. This part will reduce the intermediate data structure (IDS). There are three approaches of reducing IDS (strict, advanced, minmax).

Strict optimization is defined as 1:1 to strace input file. It means that it will interpret every record in strace as a strict rule. So only that one case is only possible to run. Every minor change in system call will kill the process.

Algorithm 1: Weak optimization

```
   Input: intermediate data structure IDS
   Output: list of rules rules
 1 foreach syscall sc in the IDS do
 2 |   foreach argument arg in the syscall sc do
 3 |   |   num_arg ← get_num_args(p);
 4 |   |   for lvl ← 0 to num_arg do
 5 |   |   |   intervals.append(get_minmax(arg, lvl));
 6 |   |   end
 7 |   |   rules.append(sc, intervals);
 8 |   end
 9 end
```

Minmax optimization is the most basic one of this set of optimizations. The main idea is to find minimum and maximum for each argument of each syscall. The model uses a simple tecniques to find extremes on every position of the system call. Firstly it serialize the arguments from n-th position. Then the serialization is looked for extremes.

So the abstracted algoritm follows as this:

1. Serialize n-th argument position of a system call.
2. Search for extremes in serialization
3. increment n
4. if n is bigger than number of arguments in syscall then exit.
5. go to number 1.

Algorithm 2: Weak optimization

```
Input: intermediate data structure IDS
Output: list of rules rules
foreach syscall sc in the IDS do
    foreach argument arg in the syscall sc do
        num_arg ← get_num_args(p);
        for lvl ← 0 to num_arg do
            intervals.append(get_minmax(arg, lvl));
        end
        rules.append(sc, intervals);
    end
end
```

Clustering is learning algoritm from family of unsupervised machine learning. It is a bunch of numerous operation focused on decomposition of informations. When we decompose information then we can clasify it by clasificators. One of them is clustering. Clustering has many definitions, e.g. in book about data minig from Carlo Vercellis is clustering defined as "*clustering models is to subdivide the records of a dataset into homogeneous groups of observations, called clusters , so that observations belonging to one group are similar to one another and dissimilar from observations included in other groups.*". [2]

The goal of this method is to find subsets (clusters) in given set. Cluster is defined by Paolo S. R. Diniz and group as "*In describing a cluster, most researchers consider internal homogeneity and external separation, i.e., patterns in the same cluster should be similar to each other, while patterns in different clusters should not. Similarities and dissimilarities both should have the potential to be examined in a clear and meaningful way.*". [15]

The clasification of raw data can be done in mulitple ways. Some basic methods are:

- partitioning,
- hierarchical,
- density based clustering,
- fuzzy clustering,
- DBSCAN clustering, (this is interesting for us),
- Model-based clustering.

Advanced optimization is defined as combination of both strict and weak optimizations. In some specific cases it will use only the exact values and in other cases it will use weak optimizations. This combination should be more strict than the weak optimization and weaker than the strict optimization.

In this case is used DBSCAN clustering method[21]. The model introduced by DBSCAN uses a simple minimum denisty level estimation. It defines a treshold fot the number of neighbors (minPts) within the radius ϵ. Objects with more than treshold neighbors within ϵ are treated as core points. The intention of DBSCAN is to find all areas, which satisfy at least the minimum density separated by areas with lower density (noise). Every point in ϵ radius is part of the same cluster as a core point. If any neighbour is again a core

point, their neighbourhoods are transitively included to a core point. This is very simple and basic algorithm as you can see later in this section. The strength and weakness of DBSCAN clustering is that it does not require a number of output clusters.

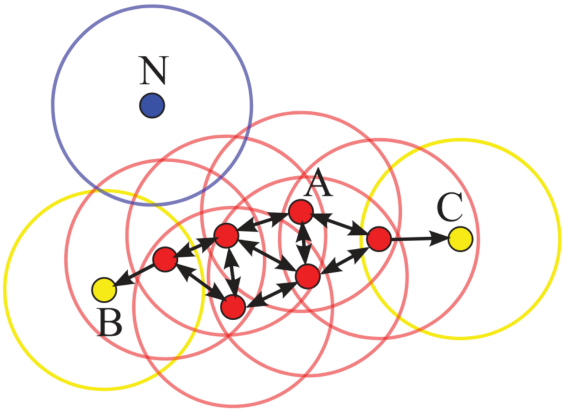

Figure 4.3: Illustration of DBSCAN cluster model

Figure 4.4 illustrates the model DBSCAN. In this illustration are defined parameters:

- minPts is 4
- *epsilon* is indicated by circles

In this picture you can see multiple points and four of them named A, B, C, N. Arrows indicate direct density reachability. Points A, B, C are density connected and B, C points are border points. N is not density reachable (it is not in any ϵ radius). Any point as N is considered as noise point.

The abstracted algorithm is:

1. find neighbors in ϵ radius of every point, and find core points with more that minimum neigthnours (minPts)
2. find connected core points on the graph and merge them into clusters.
3. assign every non-core point to a core point if that non-core point is in ϵ radius of that core-point else assign it to noise.

The whole algorithm is:

ALGORITHM 1: Pseudocode of Original Sequential DBSCAN Algorithm

```
Input: DB: Database
Input: ε: Radius
Input: minPts: Density threshold
Input: dist: Distance function
Data: label: Point labels, initially undefined
foreach point p in database DB do                          // Iterate over every point
    if label(p) ≠ undefined then continue                  // Skip processed points
    Neighbors N ← RangeQuery(DB, dist, p, ε)               // Find initial neighbors
    if |N| < minPts then                                   // Non-core points are noise
        label(p) ← Noise
        continue
    c ← next cluster label                                 // Start a new cluster
    label(p) ← c
    Seed set S ← N \ {p}                                   // Expand neighborhood
    foreach q in S do
        if label(q) = Noise then label(q) ← c
        if label(q) ≠ undefined then continue
        Neighbors N ← RangeQuery(DB, dist, q, ε)
        label(q) ← c
        if |N| < minPts then continue                      // Core-point check
        S ← S ∪ N
```

Figure 4.4: Illustration of DBSCAN cluster model

4.3 Parsing Expression Grammar

Parsing expression grammar was introduced by Ford in 2004. PEG is a type of analytic formal grammar which describes a formal language in terms of a set of rules for recognizing strings in the language. This type of grammar is really similar to a top-down parsing languages. As well it looks very similar to context-free grammars.

Parser that parses the PEG is named a packrat parser. Packrat parser can be easily constructed for any language described by an LL(k) or LR(k) grammar, as well as for many languages that require unlimited lookahead and therefore are not LR. Packrat parsers are also much simpler to construct than bottom-up LR parsers, making it practical to build them by hand. It can directly and efficiently implement common disambiguation rules such as *longest-match*, *followed-by*, and *not-followed-by*, which are difficult to express unambiguously in a context-free grammar or implement in conventional linear-time. Finally, both lexical and hierarchical analysis can be seamlessly integrated into a single unified packrat parser.

The main disadvantage of packrat parsing is memory consumption. The worst case asymptotic computational complexity is very similar to the conventional algorithms (linear in the size of the input).

The one of the many problems with right to left parsing algorithm is that it computes many results that are never needed. Other inconvenience is that we must carefully determine the order in which the results for a particular column are computed. *Packrat parsing* is

a lazy derivation of a tabular algorithm that solves both of these problems. It computes results only when they are needed, in the same order as the original recursive descent parser would. [10]

Additive	←	Multititve '+' Additive | Multitive
Multitive	←	Primary '*' Multitive | Primary
Primary	←	'(' Additive ')' | Decimal
Decimal	←	'0' | . . . | '9'

Table 4.1: Example of a grammar for a trivial language

Chapter 5

Development of strace2seccomp

5.1 Input

As an input was used output from strace tool. As I mentioned earlier strace tool was chosen because it is easy to use system call monitoring tool. It can monitor what observed program demanded from kernel. With strace tool it is possible to trace child processes. The main advantage of strace tool is that is doesn't need any of the source code files, program has not to be compiled with extra flags or withount any library or it does not have to be statically linked.

5.1.1 Configure Strace to Produce Expected Input

The output from strace tool has to be normalised before procesing with strace2seccomp. The normalization is done by providing a few runtime arguments to strace tool. Example:

```
$ strace -s 0 -xx -yy -o dataset -ff nautilus
```

I would like to describe what they are doing in the first place.[6]

-s is a string size. We are setting a string size to zero because the libseccomp does not have the ability to work with strings. It does not know how long is the string or if it is really a string. By this option the filenames are not affected. They are printed in full length.

-xx this option will switch the format of strings to hexadecimal format. It is much easier to parse strings in this format. It affects the filename as well. This option is used because sometimes can occure a non ascii (UTF–8) character in filename.

-f trace children processes.

-yy will print protocol specific information associated with socket file descriptor. It is here for future enhancements of strace2seccomp tool.

-o is used for specifying the output file.

-ff is helpfull when you are tracing a multiprocess program. In this case it will create a multiple files in format NAME.PID where NAME is a provided filename in option `-o` and PID is a process id.

5.1.2 Strace grammar

Strace produces structured output. Simplified version in extended Backus–Naur form (eBNF)[12] you can see in Figure 5.1.

$$
\begin{aligned}
\langle \text{grammar} \rangle &\models \langle \text{system\_call} \rangle \mid \langle \text{signal} \rangle \mid \langle \text{exit\_line} \rangle \\
\langle \text{system\_call} \rangle &\models \langle \text{sc\_name} \rangle \texttt{"("} \{\langle \text{argument} \rangle\} \texttt{")"} \texttt{"="} \langle \text{digit} \rangle \\
\langle \text{signal} \rangle &\models \texttt{"+++ killed with"} \langle \text{signal\_name} \rangle \texttt{"+++"} \\
\langle \text{exit\_line} \rangle &\models \texttt{"+++ exited with"} \langle \text{digit} \rangle \texttt{"+++"}
\end{aligned}
$$

Figure 5.1: Strace output grammar in eBNF

As you can see the grammar is composed of main parts that are *system_call*, *signal* and *exit_line*. For us are interesting the first one (*system_call*). The system call is composed of a name of syscall, arguments and return code. The argument can occur in a sequence and it is made of som atomic types (value, constant, structure, array, string, address and there can be find comments as well). The string is in program represented as a place in memory but strace can dereference this address and show it in analysis.

5.2 Class Hierarchy

5.3 Output

The strace2seccomp tool is generating a source code for C/C++. In the source code is used seccomp library to provide system call blocking. ?

5.4 Used software

In this section I want to mention which software I used to develop strace2seccomp tool.

5.4.1 Compilers

In this project I used two compilers. The reason is simple. Every compiler can detect another set of errors and warnings during the compilation. And at the time of doing project one of the reason of compiling with two compilers was to compare the execution times with an optimizations turned on.

In the project was used `libc++` and `libc++ ABI` from LLVM project. The reason for using implementation from LLVM project was that in the GNU implementation was a bug which affected a C++17 functionality.[1].

GNU Compiler Collection is a part of the GNU project. It aims to improve compiler used in the GNU ecosystem. GCC[2] uses an open development environment. It includes

[1] https://bugs.debian.org/cgi-bin/bugreport.cgi?bug=877838
[2] https://gcc.gnu.org/

front ends for C, C++, Objective-C, Go etc. as well as libraries for these languages. It was firstly written for GNU operating system[3] The compiler collection is released under the GPL license, other components e.g. as runtime libraries are distributed under various free licenses.

LLVM/Clang The goal of Clang[4] project is to provide a new C based language front-end (C, C++, Objective-C,) for the LLVM[5] compiler. It is released under NCSA Open Source Licence. Clang is designed to be highly compatible with GCC. It supports most of the GCC compilation flags and unofficial language extensions[6].

5.4.2 LLVM/Clang-tidy

is clang-based "linter" tool[7]. Its purpose is to diagnose and fix typical programming errors, like interface misuse, style violation, or bugs that can be deduced via static analysis. clang-tidy diagnostics are designed to assert cote that has invalid coding standard or is otherwise problematic. It has options to diasable some false positive warnings (e.g. `\\NOLINT`).

5.4.3 AddressSanitizer

(ASan)[8] is a memory error detector for C/C++ developed by Google. ASan is a very fast and the average slowdown of the instrumented program is ~2x. The tool consist of a runtime library which replaces the `malloc` function and compiler module (currently as LLVM pass). The tool supports multiple architectures e.g. (x86, x86_64, ARM, ARM_64, MIPS, PowerPC64, etc.). It is part of the both compilers mentioned above in Subsection 5.4.1.

Usage of ASan is very straightforward. You have to add only:

```
-fsanitize=address -fno-omit-frame-pointer
```

The first parameter turns on the ASan and the second one print a nicer stack trace in error messages. It is adviced by developers to use optimization e.g. `-O1`, to get reasonable performance.

5.4.4 Git

The Git[9] is a source code manager (SCM). It stand out of the group of SCMs by its branching model. Git allows and encourage you to have multiple local or remote branches that can be entirely independent. This provides features like:

- Context Switching
- Feature Based Workflow
- Role-based Codelines

[3] https://www.gnu.org/gnu/thegnuproject.html
[4] https://clang.llvm.org/
[5] http://www.llvm.org/
[6] https://clang.llvm.org/docs/LanguageExtensions.html
[7] http://clang.llvm.org/extra/clang-tidy/
[8] https://github.com/google/sanitizers/wiki/AddressSanitizer
[9] https://git-scm.com/about

- Disposable Experimentation

Other benefit of Git it is doing nearly all operations locally. This gives the tool huge speed advantage. Git was built to work with Linux kernel, that means it can effectively handle large repositories. The st2se used repository hosting on GitHub.

5.4.5 Artistic Style

Astyle[10] is source code formatter and beautifuller. Works with C, C++ Objective-C, C# and Java programming languages. The motivation to use this tool is to has uniform code style. Some of the editors by default insert spaces instead of tabs when pressing key. Other editors have the abillity to insert space before tab lines to ”pretty up” the code (Emacs). The solution to this problem is to use Artistic Style formatter. It can normalise the source code by rules defined in configuration file provided by developer of the project.

5.4.6 LCOV & GCOV

LCOV[11] is an extension to GCOV, a GNU tool which can determine what parts of a program was executed while running particular testcase. It can provide information about how many times was that part of program executed. LCOV implements to GCOV following additional functionality:

- HTML based output with coverage rates indicated by specific color i.e. (green is 100% and red is 0% coverage).
- Support for large projects. It allows you to browse over overview pages that shows coverage data by providing: directory view, file view and source code view.

LCOW was designed like Git to support Linux kernel, but works as well on standard user space applications.

5.5 Usage

How to run the st2se tool

5.5.1 C/C++ template

Add it in appendix.

[10] http://astyle.sourceforge.net/
[11] http://ltp.sourceforge.net/coverage/lcov.php

Chapter 6

Software Verification

This chapter will describe activities used to assure quality control of the developed tool. First, I want to introduce on which aspects we will focus. One of the aspects is *module testing*. The main purpose of module testing is to detect errors in submodules, in communication among them, in passing data through data structures. Another aspect of verification is *system testing* merged with *acceptance testing*. In this type of testing we will check if the strace2seccomp tool has valid architectural design. Next aspect which will be checked is *static analysis*. Static analysis is type of testing which does not requires run the program but requires a source code of the tool. The static analyzer will analyse the source codes with different heuristics and produces a analysis of detected errors.

6.1 Module Testing

Module testing is part of whole quality control process. This testing can provide us how functional are particular components and if they meet the requirements. Table 6.1 shows us the description of module's test suits.

Module / Component	**Test descriptiom**
Params	Validity of recognized runtime arguments
StraceParser	Syntax testing, validity of parsed data, correct error handling

Table 6.1: Test plan

6.1.1 Params Testing

about using params class in custom test set and manualy check if the correct flags was ommited.

6.1.2 StraceParser Testing

StraceParser module is responsible for parsing the strace output and translates it to intermediate data structure. Testing of this module can be done with various techniques. First one which is used is fuzzy testing or fuzzing described in section above 6.1.2. AFL fuzzer was used in the process.

Fuzzing

The term fuzzing was first used by professor Barton Miller who used fuzzing to test robustness of UNIX applications in 1989 [24, 17]. Fuzzing is a testing method which generates an unexpected input on tested software and then is observing if the software crashes. The whole process is typicaly automated or semiautomated that involves repeatedly manipulating and supplying input data to targeted program. Some modern fuzzers (programs that generates a stochastic input), record every crash or halt of a tested program. The stochastic data are in most cases invalid to observer how application handles invalid states and boundary conditions. „The name comes from modern applications tendency to fail due to random input caused by line noise on 'fuzzy' telephon lines.“[24, 1] In other literature fuzzing can be named by these terms:

- Negative testing
- Syntax testing
- Dirty testing
- Rubustness testing
- Protocol mutation
- Fault injection

Fuzzers can be divided into two groups:

- **Generation-based** fuzzers creates test suite from scratch by modeling the target grammar.
- **Mutation-based** fuzzers needs an (in)valid input file. The file is mutated by various techniques. The mutation can be e.g. bitflip, byte change, duplicate or swap some chunks in the input file. The mutated test case is then provided to a tested program.
- AFL write sometihong about every fuzzer you mentioned
- Bunny the Fuzzer
- Hongfuzz
- Radamsa
- oss-fuzz

Fuzzing results

Show some results from afl.

Grammar testing

If you got time write grammar tester. or find one .. dunno

6.1.3 Algorithms

How should we test if algorithms?

6.1.4 Optimizer

how should we test this adapter?

6.1.5 Output

Testing correctness of a Output generator

- C/C++
- Go

6.2 System and Acceptance Testing

6.2.1 Testing on real app

6.2.2 USBGuard

6.3 Static analysis

Any bugs?

6.4 Test Requirements

6.5 Results

Which bugs have you found.

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Appendix A

Comparison of libseccomp and raw BPF filtering

A.1 BPF

```
1 int myapp_seccomp_raw_start(void)
2 {
3 struct sock_filter filter[] = {
4   BPF_STMT(BPF_LD+BPF_W+BPF_ABS, 4),
5   BPF_STMT(BPF_JMP+BPF_JEQ+BPF_K, AUDIT_ARCH_X86_64, 0x00, 0x12),
6   BPF_STMT(BPF_LD+BPF_W+BPF_ABS, 0),
7   BPF_STMT(BPF_JMP+BPF_JGE+BPF_K, 0x40000000, 0x10, 0x00),
8   BPF_STMT(BPF_JMP+BPF_JEQ+BPF_K, __NR_open , 0x0e, 0x00),
9   BPF_STMT(BPF_JMP+BPF_JEQ+BPF_K, __NR_close, 0x0d, 0x00),
10  BPF_STMT(BPF_JMP+BPF_JEQ+BPF_K, __NR_read, 0x00, 0x0d),
11  BPF_STMT(BPF_LD+BPF_W+BPF_ABS, 20),
12  BPF_STMT(BPF_JMP+BPF_JEQ+BPF_K, 0, 0x00, 0x0b),
13  BPF_STMT(BPF_LD+BPF_W+BPF_ABS, 16),
14  BPF_STMT(BPF_JMP+BPF_JEQ+BPF_K, 0, 0x00, 0x09),
15  BPF_STMT(BPF_LD+BPF_W+BPF_ABS, 28),
16  BPF_STMT(BPF_JMP+BPF_JEQ+BPF_K, 0, 0x00, 0x02),
17  BPF_STMT(BPF_LD+BPF_W+BPF_ABS, 24),
18  BPF_STMT(BPF_JMP+BPF_JEQ+BPF_K, 0, 0x05, 0x00),
19  BPF_STMT(BPF_LD+BPF_W+BPF_ABS, 36),
20  BPF_STMT(BPF_JMP+BPF_JEQ+BPF_K, (SSIZE_MAX >> 32), 0x00, 0x02),
21  BPF_STMT(BPF_LD+BPF_W+BPF_ABS, 32),
22  BPF_STMT(BPF_JMP+BPF_JEQ+BPF_K, (SSIZE_MAX & 0xffffffff), 0x01, 0x00),
23  BPF_STMT(BPF_RET+BPF_K, SECCOMP_RET_ALLOW),
24  BPF_STMT(BPF_RET+BPF_K, SECCOMP_RET_KILL),
25 };
26 struct sock_fprog prog = {
27   .len = (unsigned short)(sizeof(filter)/sizeof(filter[0])),
28   .filter = filter,
29 };
30 if (prctl(PR_SET_NO_NEW_PRIVS, 1, 0, 0, 0) < 0)
31   return -errno;
32 if (prctl(PR_SET_SECCOMP, SECCOMP_MODE_FILTER, &prog) < 0)
33   return -errno;
34 return 0;
35 }
```

Listing A.1: Using raw BPF filtering

A.2 libseccomp

```
1 int myapp_libseccomp_start(void)
2 {
3   int rc;
4   scmp_filter_ctx ctx;
5   ctx = seccomp_init(SCMP_ACT_KILL);
6
7   if (ctx == NULL)
8     return -ENOMEM;
9
10  rc = seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(open), 0);
11
12  if (rc < 0)
13    goto out;
14
15  rc = seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(close), 0);
16
17  if (rc < 0)
18    goto out;
19
20  rc = seccomp_rule_add(ctx, SCMP_ACT_ALLOW, SCMP_SYS(read), 3, SCMP_A0(
      SCMP_CMP_EQ, STDIN_FILENO), SCMP_A1(SCMP_CMP_NE, 0x0),SCMP_A2(SCMP_CMP_LT,
       SSIZE_MAX));
21
22  if (rc < 0)
23    goto out;
24
25  rc = seccomp_load(ctx);
26
27 out:
28  seccomp_release(ctx);
29  return rc;
30 }
```

Listing A.2: Using simpler libseccomp wrapper

Appendix B

other appendix