**Nexpro**

**Making `syscall´ a Privilege not a Right**

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***Abstract***—Browsers, Library OSes, and system emulators rely on sandboxes and in-process isolation to emulate system resources and securely isolate untrusted components. All access to system resources like system calls (syscall) need to be securely mediated by the application. Otherwise system calls may allow untrusted components to evade the emulator or sandbox monitor, and hence, escape and attack the entire application or system. Existing approaches, such as ptrace, require additional context switches between kernel and userspace, which introduce high performance overhead. And, seccomp-bpf supports only limited policies, which restricts its functionality, or it still requires ptrace to provide assistance.

In this paper, we present nexpro, a secure syscall interception mechanism combining Memory Protection Keys (MPK) [1] and Seccomp or Syscall User Dispatch (SUD) [2]. Our approach transforms an application’s **syscall** instruction into a privilege reserved for the trusted monitor within the address space, allowing flexible user defined policy. To execute a syscall, the application must switch contexts via nexpro. It offers better efficiency than secure interception techniques like ptrace, as nexpro can intercept syscalls through binary rewriting securely. Consequently, nexpro ensures the safety, flexibility and efficiency for syscall interception. Notably, it operates without kernel modifications, making it viable on current Linux systems without needing root privileges. Our benchmarks demonstrate improved performance over ptrace in interception overhead while achieving the same security guarantees. When compared to similarly performing firejail, nexpro supports more complex policies and enables the possibility to emulate system resources.

# **I. INTRODUCTION**

System call interception has been widely utilized in various computing domains, ranging from improving system safety and performance to aiding in emulation and debugging. Its widespread use in technologies like containers [3]–[8] and sandbox [9]–[13], which utilize system call interception for security purposes [12]–[14], and in tools such as strace, which are indispensable for debugging and security modeling [6], [7], [12], [15]. System call interception provides security-related applications with protection against jailbreaking through the operating system and allows for complex policies. Furthermore, its application in providing operating systems interface for libOS [16]–[18], emulation purposes [19], [20] or compatibility.

Unfortunately, existing approaches to system call interception often suffer from drawbacks related to security, efficiency, and policy flexibility. Binary-rewrite techniques, developed through tools like syscall intercept [21], e9patch [22], and zpoline [23], provided efficient redirection of programs but could be easily bypassed by jumping to existing syscall instructions, compromising their security effectiveness. To

User

Kernel

app

mon

app

mon

BPF

app

SUD

mon

syscall ptrace seccomp-bpf nexpro

## Fig. 1: Secure Syscall Interception Mechanism

securely intercept syscalls, methods such as ptrace or seccompbpf must be used, as shown in Fig 1. Seccomp-bpf [24] is introduced for security-oriented purposes, but it only allows BPF policy program to access only registers without the ability to preserve context information. Ptrace, when used alone, or in conjunction with seccomp-bpf to offer improved efficiency, but will redirected intercepted system calls to another process, leading to slower performance [25].

eBPF and kprobe require superuser permissions and operate globally. eBPF communicates with the monitor process via shared memory. While ideal for applications like instrumentation, it lacked the flexibility needed for complex scenarios (e.g., check file path). And, kprobe and custom Linux Security Module [26] (LSM) can offer flexible policies, they need to be compiled as kernel modules and loaded, which limits their use in unprivileged applications.

Syscall User Dispatch [2] (SUD) provided a method to limit valid syscall locations, converting all other system calls into signals. However, it was not originally designed for security, allowing its switch bit to be flipped easily, and a jump to the legal syscall can allow bypass of the interception. Jenny and Enclosure, have attempted kernel modifications [14], [27], [28] for securing syscall interception for the in-process monitor. However, these modifications were tailored for specific scenarios rather than for a general use, posing challenges for their inclusion in the kernel [29]. Some modifications still necessitated a switch to the kernel mode and then a switch back [27], adding overhead from the context switches.

Our solution, nexpro, is a trampoline mechanism that ensures efficient and non-bypassable syscall interception. Nexpro divides the application into two parts: a trusted part that performs syscall interception and an untrusted part consisting of the original application. Based on this division, we require that syscall instructions can only be executed by the trusted part, which includes a path that has switched through nexpro. In the untrusted part, syscall instructions are redirected to nexpro for system call processing. This can be achieved by modifying libc or through binary rewriting. The path integrity of nexpro ensures that applications cannot exploit existing syscall instructions through jumping. This is achieved by combining the features of MPK with Seccomp-bpf or SUD to protect and verify the memory containing the path indicator.

We explored various methods to implement nexpro. While SUD requires newer kernel versions, seccomp-bpf relies on randomization for security but can be used on any kernel supporting MPK. All these implementations require no modifications to the kernel and do not rely on global control flow integrity of main applications or ptrace and signals, which cause high performance overhead, while still offering security gains. Our results show that, compared to other methods, nexpro achieves secure interception of system calls with overhead similar to binary rewriting, while also offering flexible policy implementation.

*a) Contribution:* In our work, we introduce a novel method to make invoking syscall instructions a privilege in user space, ensuring secure interception of all syscall-s from users. Key contributions of our approach include:

* We identify problems in current syscall interception methods, as they fail to simultaneously achieve efficiency, security, and policy flexibility.
* We implemented nexpro based on MPK, Seccomp, and SUD. It allows for secure, efficient, and flexible syscall interception, achieved by transforming syscall into a privilege.
* We implemented secure signal delivery in nexpro, notably without requiring any modifications to the kernel. • We evaluated nexpro in both micro and macro benchmarks. We evaluated the performance of nexpro as a sandbox for nginx and redis. Nexpro offers better performance than traditional sandbox like mbox, while provides more flexible interception policies than firejail.

# **II. MOTIVATION**

1. *The Need for Secure System Call Interception:* In a range of application scenarios, there is a notable need for system call interception that is protected by privileged system call instructions. Privileged system call instructions mean that system calls can no longer be performed in any context; instead, they are restricted to a specific, authorized context. This is particularly relevant in cases such as inprocess monitors, secure environments and sandboxes like mbox and gVisor [30], where the system call must be restricted to protect the integrity of the monitor or the sandbox. These situations highlight the inadequacy of simpler methods like binary rewriting, which are susceptible to being bypassed. To address this, technologies such as ptrace and seccompbpf [24] are employed [9], [10]. They play a crucial role [31] in restricting system calls and assigning the decision-making process to a separate, more secure mechanism. However, the implementation of these technologies can lead to additional performance overhead.

Moreover, various applications that utilize system call interception aim to prevent the bypassing of this protective layer, particularly for maintaining accurate coverage in instrumentation-focused scenarios. This concern leads some systems to adopt solutions like eBPF. However, eBPF’s requirement for privileged loading and its global scope can be inconvenient for applications needing local interception. Additionally, applications like Wine [19], [32], while not predominantly security-oriented, demonstrate the benefits of restricting native system calls to reduce their potential attack surface. While this approach doesn’t ensure complete security, it significantly contributes to creating a more secure and manageable computing environment.

1. *Applications:* With nexpro, sandbox applications can make more decisions within the same process space. This allows sandboxes like mbox [10] to effectively intercept system calls, and to make secure decisions or implement more complex policies without fallback to ptrace. Linux offers many features to aid in sandbox implementation [33], such as LSM framework [26], AppArmor [34], [35], namespaces [36], cgroups [37], SELinux [38], and Landlock [39]. In fact, if the required policies can be implemented through them, the kernel can provide better performance (although not always) and assurances [40], as adopted by modern sandbox implementations like firejail [11]. However, these interfaces cannot offer the same flexibility as interception. They only allow developers to implement policies in a specific way. A simple example is that you cannot use them to implement an application kernel like gVisor [30] and support customized file systems through 9p.

In-process isolation can also benefit from nexpro. For example, current works using MPK for in-process isolation require modifications to the kernel to perform system call interception for multi-threaded or signal supported applications [27], [41], [42]. Using nexpro can eliminate such need, thereby lowering the barrier for using in-process isolation in practice.

# III. THREAT MODEL

Our threat model divides the user space into trusted interceptor program and untrusted user application. The user application contains all user data and code, and can make invoke syscall instructions during execution. Attackers have full control over the untrusted user application, which means they can perform arbitrary reads, writes, or jumps, attempting to alter the running state of the trusted program or exploit existing syscall instructions in both trusted and untrusted’s code.

We employ the same binary scanning as ERIM [43] and to prevent the presence of WRPKRU and XRSTOR instructions, except for in the nexpro trampoline. Compared to the 2-byte syscall instruction, the length of these instructions makes them easier to filter out using binary scanning. Syscall instructions that do not pass through nexpro will be intercepted by SUD or seccomp, even though they can be executed.

We assume that the implementation of the nexpro is bugfree as well as the user-defined interception programs or in-process monitors. We assume that privileged components TABLE I: MPK Permission Assignment

|  |  |  |  |
| --- | --- | --- | --- |
| PKRU | 0 | pkey 1 | 2 |
| $trusted\_pkru | rw | rw | rw |
| $untrusted\_pkru | ro | - | rw |

such as the operating system, hypervisor and hardware are trustworthy, and that nexpro is initially loaded as the application loader.

Side-channel attacks, Rowhammer and Denial of Service (DoS) attacks are out of our scope.

# IV. NEXPRO

## *A. Background*

1. *Syscall User Dispatch:* In a nutshell, SUD is a mechanism recently added to the Linux kernel that allows for the efficient emulation of system calls within only a part of their process [2].

By specifying an offset, length, and selector, SUD permits system calls only from the [offset*,*offset+length) range when the value of \*selector is set to block. Any system calls outside this range trigger a SYSSIG signal. When \*selector is set to allow, SUD temporarily removes the restriction and allows all syscall, a change that can be made without a system call. However, SUD is not a security mechanism in itself, as it only limits the IP of syscall but cannot prevent attackers from jumping to this address or modifying the \*selector value.

1. *Seccomp-bpf:* Seccomp-bpf is a security facility in the Linux kernel that allows users to load a BPF program to inspect the parameters of system calls before they are executed. However, this BPF program has limited access to resources; for example, it can only access the values of registers used by the system call, not the memory pointed to by these registers. For instance, seccomp-bpf cannot filter open based on the file’s path. For complex policies, the BPF program can only return RET TRAP or RET TRACE to handle them through signals or a ptrace debugger.

Besides accessing syscall arguments, the BPF program can also access the instruction pointer, which indicates the IP of the syscall instruction. Therefore, seccomp-bpf can offer policies similar to SUD, with less flexibility, such as dynamically enabled or disabled through a selector.

1. *Memory Protection Keys:* MPK allows the switching of the current memory protection state through the WRPKRU instruction in the user space. It operates by marking each memory page with a pkey ranging from 0 to 15. Additionally, the CPU contains a 32-bit PKRU register. For each pkey, PKRU has two bits designated for access (data read) denial (AD) and write denial (WD). During memory access, MPK checks whether the AD and WD bits for the page’s pkey in the PKRU are set, in addition to the usual page protection, to determine if the operation is allowed. In nexpro, we use 3 pkeys, 0 and 1 for the memory used by nexpro and the 2 for user. Their allocation is shown in Table I. $trusted\_pkru refers to a PKRU that allows access and write to both memory.

**~~syscall~~**

**call**

trap

trap:

**mov**

...

**WRPKRU**

**mov**

,

0

\*

Sel

**call**

Intercept

**mov**

,

1

\*

Sel

...

Selector = 1

Kernel\_Entry()

ifSel==0

Normal Syscall

else

Failed Signal

Intercept()

...Handling

**syscall**

...

MPK Protected

Proof

Verify

Source Code

Nexpro

SetSUDSelector

## Fig. 2: **Nexpro Overview**

$untrusted\_pkru refers to a PKRU that permits access and write to user memory, access to nexpro memory with pkey 0 and no access with pkey 1.

In Linux, a new pkey can be created using pkey\_alloc, and the pkey of a page can be changed with mprotect\_pkey.

### B. Design

Overview – Intercepting system calls within the process can reduce the additional performance overhead caused by process switching in methods such as ptrace. At the same time, unlike BPF programs which need to consider kernel security, user programs face fewer restrictions, making complex policies feasible.

To achieve this, nexpro divides the process space into two parts: the untrusted user application and the trusted system call interceptor program. Nexpro’s trampoline acts as a callgate bridging these two, forcing the user application to switch to

the trusted part through nexpro before making system calls. SUD or seccomp is used to verify that the syscall originates from the trusted part. It effectively makes invoking syscall instruction a privilege and ensure the interception of all system calls. Also, nexpro redirects signal handlers, ensuring that the running state of the trusted part is not exposed to the user application through signals. Lastly, nexpro implements system call policies to protect the integrity of MPK.

Nexpro – Nexpro works through the combination of two features to ensure syscall instructions cannot be used by the untrusted part. SUD or Seccomp-bpf is used to prohibit illegal system calls.

Fig 2 demonstrates the basic structure of nexpro when using SUD. The value of \*selector determines if system calls are allowed. After the MPK switch in the nexpro, we set \*selector to 0, allowing the subsequent interception program to make system calls, and restore this value to 1 afterward. This ensures that only programs that have passed through nexpro can make system calls.

With Seccomp-bpf, we use a BPF program to determine whether to allow system calls, based on whether the instruction pointer is within the gadget segment, whose address is within the range of [*sbegin,send*). This region is mapped and protected at the start of the application’s execution and is never unmapped. During the nexpro switch, we randomly put a 3byte gadget syscall;ret within the [*sbegin,send*) range that is not in use, and save the gadget address. We then use this randomized address to make syscall, and upon returning from nexpro, the gadget is reset to int3-s. Unlike SUD, Seccomp-bpf cannot reset different filters for new threads. Therefore, all threads must use the fixed IP or IP range for filtering syscall address. If a fixed address is used, one thread’s nexpro allows another thread to use the same syscall;ret for its system call, regardless of whether it is trusted or untrusted. Our solution allows all syscall instructions within a gadget segment but generates a random address for each interception to prevent other threads from using it.

MPK is used to protect the memory pointed to by the selector or the gadget segment. For the SUD’s selector, we can use pkey 0, which is read-only for the untrusted part, as we only need to ensure that the attacker cannot modify the selector. For the gadget segment, we use pkey 1, which the untrusted part cannot read, to prevent attackers from finding the syscall;ret location.

Signal Handling – Nexpro needs to redirect signals, as the kernel can transfer control to the signal handler at any time, including when running in the trusted part or the nexpro.

When the user program is running in the untrusted part, our handler only needs to give the control back to the user’s signal handler, as the kernel has already correctly pushed the sigframe onto the appropriate position in the user stack. When the user program runs in the trusted part, which means we are processing a syscall interception, we assume that the signal occurred at the time the user requested the syscall. We generate a new sigframe on the user’s stack based on that. And, when returning from nexpro, we return to the user’s signal handler.

Nexpro performs context switching in stages, which means that intermediate states can also lead to signal distribution. We need to analyze which information is trustworthy in each state in order to handle it correctly.

Signal Return – Nexpro must handle user’s sigreturns, as this system call changes the control flow, affecting nexpro’s action of clearing the selector or syscall gadget upon return. Nexpro reads the sigframe on the user stack and copy the registers. Subsequently, these registers are restored during the return process of nexpro, and we ensure that PKRU is also correctly set to the user’s PKRU.

# **V. IMPLEMENTATION**

Nexpro’s implementation is challenging when considering performance, compatibility, and security. To allow for easy adoption, our implementation requires no kernel modifications.

Our implementation particularly focuses on the following three key goals of Nexpro.

1. Our mechanism needs to be viable in a multi-threaded environment and ensure security.
2. We need to ensure secure handling of signals, which includes signals related to MPK, SUD and Seccomp, as well as preventing signals from affecting the interception process.
3. We need to prevent known MPK-related attack methods from impacting the integrity of nexpro.

## *A. Multithraeding Support*

Nexpro needs to consider the multi-threaded environment because each thread has its own stack, signals, and other running states.

Threading Context Initialization – We create a threading context protected by MPK for each thread and place its address in %gs. We need to do this for each new thread created through clone.

Thread-Independent Syscall Switch – SUD is enabled separately in each thread and sets a different selector address. By changing \*selector, we can disable or enable system calls. Since each thread has a different address, this prevents a system call enabled by one thread from being exploited by another.

Seccomp-bpf does not support modifying filters for each thread, all threads use the same BPF program and hardcoded gadget segment. We adopt a method of syscall addresss randomization, allowing each thread to use an independent syscall;ret address. Before making a system call, each thread generates its own random and unique syscall gadget address, and uses this address to perform the system call. This address quickly becomes invalid, and a different address is used for the next syscall. The memory segment is unreadable (using AD from MPK), so attackers can only guess the address. However, incorrect guesses will trigger int3, thus being detected by nexpro.

## *B. Secure Signal Handling*

Signals from the kernel can interrupt the current execution state at any time, causing uncontrollable changes in the control flow. We need to ensure that these changes do not affect the integrity of nexpro. For example, executing the user’s handler in a trusted state. Additionally, the current version of the kernel cannot correctly deliver signals on sigaltstack. To avoid modifying the kernel, we need to ensure under safe conditions that the address pointed to by %rsp is always writable, which brings additional challenges. Because we will not be able to fully trust the sigframe information from the user stack.

*a) Signal Aware Nexpro:* – Listing 1 shows the simplified nexpro trampoline code which performs MPK and context switching. User registers are saved on the caller’s stack as a trapframe, and these registers are restored when returning from nexpro. We use the WRPKRU + cmp code given in ERIM [43] to ensure the correct PKRU is written, preventing

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| --- |
| nexpro\_trap:  // Push registers to the stack  // Nexpro  // Normal MPK Switch  xor %ecx, %ecx  xor %edx, %edx  mov $trusted\_pkru, %eax  wrpkru // MPK Switched  // Stage 0: PKRU=T, Stack=U, Sel=Block  cmp $trusted\_pkru, %eax  jne \_\_exit  xchg %rsp, %gs:(Scratch)  // Stage 1: PKRU=T, Stack=T, Sel=Block  movl $0, %gs:(Selector)  call syscall\_intercept  movl $1, %gs:(Selector)  xchg %rsp, %gs:(Scratch)  // Stage 2: PKRU=T, Stack=U, Sel=Block  // Normal MPK Switch  xor %ecx, %ecx  xor %edx, %edx  mov $untrusted\_pkru, %eax  wrpkru // MPK Switched  cmp $untrusted\_pkru, %eax  jne \_\_exit  // Stage 3: PKRU=U, Stack=U, Sel=Block  // Registers restor, clear redzone  retn 128 |

## Listing 1: Nexpro Trampoline Code

attackers from jumping to the WRPKRU in nexpro to write their own PKRU values.

To allow the signal delivery during nexpro, we carefully arrange switches of MPK and the stack, ensuring the %rsp is switched only after the target stack is writable. This means that, after switching PKRU to trusted, there will be several instructions executed with %rsp pointing to the user stack. Likewise, before switching %rsp back to untrusted, there are also several instructions where %rsp has already switched back to the user stack. In both scenarios, we cannot trust the registers saved sigframe on the user stack, including %rip and PKRU. Therefore, when return from the signal handler, we need to set PKRU to the untrusted and roll back %rip before the WRPKRU switch.

For signals delivered between Stage 0-Stage 1 in Listing 1, we process it as a user signal, but we can set PKRU to trusted during sigreturn and move %rip to a point after Stage 1. For signals delivered between Stage 1-Stage 2, they are treated as being in the trusted state because %rsp points to the MPKprotected stack. For signals delivered between Stage 2-Stage 3, we can directly set PKRU to untrusted, move %rip to the end of Stage 3, and handle them as signals delivered in the user.

When using SUD, the trampoline switches

%gs:(selector) directly. For seccomp, the syscall gadget used by seccomp need to avoid conflicts between different threads. The switch requires generating a new gadget address, using atomic instructions to check and occupy the position, and finally writing the gadget to the new location.

Secure Signal Handler – When registering a signal, we

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| signal\_entry:  // Kernel set PKRU=0x5555555c  // And mask all signals  mov 1, %gs:(Signal)  xor %ecx, %ecx  xor %edx, %edx  mov $trusted\_pkru, %eax  wrpkru  cmp $trusted\_pkru, %eax  jne \_\_exit  cmp 1, %gs:(Signal)  jne \_\_exit  mov $0, %gs:(Selector)  xchg %rsp, %gs:(SigStack)  call signal\_handler  ret // -> sigreturn to interceptor |

## Listing 2: Signal Entrance Trampoline Code

use signal\_entry from Listing 2 instead of the original sigaction function. We set sa\_mask to ensure that the kernel blocks re-entry into our handler function.

The code in Listing 2 first set %gs:(Signal) before WRPKRU to avoids abuse (jump to) of this entry point by user programs. This is because the kernel automatically sets PKRU during signal delivery, ensuring that %gs:(Signal) can be written to. A user program that abuses the entry point, however, cannot provide the correct PKRU needs for writing to %gs:(Signal).

Our signal\_handler function processes signals related to MPK, and delivers other signals to the user-specified sigaction. At this time, there are two cases:

1. %rsp points to memory on the user stack. In this case, we push a trapframe onto the user’s stack and adjust %gs and %rsp. Then, we fake a system call to sigprocmask to unmask the sigmask. The user’s signal handler will be called after the execution of the faked sigprocmask.
2. %rsp points to memory on a stack protected by MPK. In this scenario, we re-deliver the signal to the user stack, as illustrated in Fig 3, which depicts the stack manipulation of signal re-delivery. This is achieved by pushing a new sigframe onto the user’s stack, copying the contents of the current trapframe into this sigframe, and creating a new trapframe that points to this new sigframe with the real sigaction set as its %rip. Subsequently, we use sigreturn to continue the previous interception. The signal delivery takes place after the interception has concluded.

Distinguishing between these is important, as it determines whether our handler function can trust the information on the signal stack, which includes the %rip and PKRU values where the signal occurred.

sigaltstack could be used to avoid this distinction, thereby distributing all signals to a protected stack. However, it cannot be utilized due to a flaw in the current kernel implementation [44].

For signal returning to the user, we cannot implement it by using a sigreturn system call. This is because to



Old

%rip

OldTrapFrame

SigFrame



%rip

TrapFrame

Scratch

RSP

RSP

USER

Red-Zone

Signal Handler

NewRSP

Copy

New TrapFrame

Red-Zone

1

2

3

4

5

6

7

8

9

10

11

12

13

14

15

16

Stack

Fig. 3: User Stack Manipulation for Signal Re-Delivery during interception

call sigreturn, we need to allow system calls by setting %gs:(Selector) to 0. However, after sigreturn, execution continues as the user, and we do not have the opportunity to reset %gs:(Selector) to 1. Therefore, we have to to emulate a sigreturn. And, we need to copy the registers from the sigframe to the trapframe and perform xrstor without changing the PKRU. Then, the correct switching of PKRU and %gs:(Selector) is achieved through the normal return of nexpro.

It’s noteworthy that kernel may deliver signal during the process of copying the registers to trapframe. In this case, the signal handler cannot use the registers from the trapframe on the stack; instead, it needs to complete the copying of the registers first.

### C. MPK-related Attacks

The impact of system calls on MPK security has been studied priviously [41], [45]. Simply put, the kernel also adheres to MPK restrictions, but some system calls can bypass or change these limitations. On the other hand, other system calls might change the control flow outside of signals, such as rseq. Therefore, we must impose restrictions on them to ensure that nexpro is not affected by their influence.

Syscall Delegation – The nexpro has a trusted PKRU that allows kernel to access all memory. This means we need to check all pointers coming from the user to avoid unwanted access, or alternatively, we can temporarily switch PKRU back to untrusted. We refer to such system calls as delegated syscalls in Listing 3.

To achieve this, we need to switch PKRU back to untrusted and %rsp to a temporary user stack to allow signal delivery during the delegation. %gs:(Delegation) is set and check to prevent attackers from abusing the WRPKRU back to the trusted with a following ret sequence in the end of Listing 3 by jumping to it.

Signals delivered during the delegation process require special handling. The signal handler uses %gs:(Delegation) to determine whether the signal occurred while truly in a

|  |
| --- |
| delegated\_syscall:  mov 1, %gs:(Delegation)  // Provide a user stack  xchg %rsp, %gs:(DeleStack)  xor %ecx, %ecx  xor %edx, %edx  mov $untrusted\_pkru, %eax  wrpkru  cmp $untrusted\_pkru , %eax  jne \_\_exit  syscall  xor %ecx, %ecx  xor %edx, %edx  mov $trusted\_pkru, %eax  wrpkru  cmp $trusted\_pkru , %eax  jne \_\_exit  cmp 1, %gs:(Delegation)  jne \_\_exit  xchg %rsp, %gs:(DeleStack)  mov 0, %gs:(Delegation)  ret |

## Listing 3: System call delegation

trusted state and decides the state after sigreturn based on it. As we can’t trust the registers in the sigframe on the temporary stack, and we need to restart the delegated syscall.

Syscall Intercrption – In our current implementation, we rewrite the syscalls in the libraries to call to syscall trap. This could be done with other binary-write based syscall interception. In this case, we only need to change their interception entry point to nexpro. Regardless of the approach used, both SUD and Seccomp can prevent unauthorized syscalls, thereby enforcing the subsequent policy.

Necessary System Call Security Policy – We need to restrict the functionality of several system calls: a) the target address and pkey during system calls that change page permissions, such as mprotect, mmap, munmap, pkey\_alloc, pkey\_free etc.; b) thread context initialization during the clone system call; c) rewrite the functionality of system calls that involve signals; d) rseq, userfaultfd, process\_vm\_\*, prctl, arch\_prctl, set\_thread\_area, ptrace, seccomp, modify\_ldt, and instructions related to shared memory. All these system calls may circumvent MPK protections, modify %gs, or they might affect the integrity of the control flow. In addition, we rely on ERIM’s binary scanning to ensure that there are no WRPKRU or XRSTOR instructions in the code during mmap and mprotect and limit the use of exec by ensuring the interceptor is still loaded in the target program.

# **VI. EVALUATION**

## *A. Environment Setups*

Our evaluation platform uses an Intel i7-1165G7 @ 2.80GHz with Turbo Boost disabled, 16GB of memory, Ubuntu 20.10, and kernel version 5.9 (with SUD patch [46]). Our experiments rely on Nginx [47] 1.18.0 , Redis [48] 6.2.6, ApacheBench [49] 2.3, mbox [10] a131424 and firejail [11]

0.9.73 for benchmarking.

Mbox is a classic sandbox that uses ptrace and seccomp for system call interception, while firejail employs kernel features namespaces and LSM for isolation offering the least observable performance overhead, but unfortunately failing to provide flexible enough access permission policies to support system call emulators like gVisor. We provide this baseline as a goal post to identify the least overhead nexpro could possibly have in a sandbox application.

We have two implementations of nexpro: one using the newer system call SUD, which we denote as nex-sud, and another using Seccomp-bpf with randomized syscall gadget addresses, denoted as nex-rand.

## *B. Security Evaluation*

In this section, we will discuss the security aspects of the different components involved in nexpro, including the trampoline, signals, multi-threading, and the attack surfaces introduced by MPK, as well as the necessary security policies to mitigate them.

1. *Nexpro:* We need to ensure that Nexpro does not lead to the leakage of MPK privileges. The only indirect jump in our trampoline is ret. Which means We only need to ensure that the MPK state is always untrusted before ret, which is achieved through ERIM [43]’s WRPKRU + cmp. If an attacker jumps to WRPKRU with an abnormal target PKRU value, this will be captured by the following cmp instruction and jump to an int3 instruction to terminate the process.
2. *Randomization:* Using randomization does not guarantee the security of syscall. We improve this by filling the memory segment with int3 and limiting the maximum number of threads allowed to exist. Attackers have only one chance to find the syscall instruction. The success rate is *n/size*, where *n* is the maximum number of active threads, and *size* is the length of the syscall segment. Some applications use thread pools to determine the maximum number of threads, which allows us to define the necessary size of the syscall segment based on this number. Other applications may have more threads, requiring an increase in the segment size accordingly.
3. *Signal:* Signals interrupt execution, and the state prior to the signal is saved on the stack pointed to by %rsp. Our principle is that if the memory pointed to by %rsp belongs to the trusted segment, we consider its content trustworthy, allowing us to return to the previous state via sigreturn. If %rsp points to untrusted memory, which often means the interruption occurred during the execution of user code, we simply need to return to the relevant handler. Special cases include during nexpro switching and syscall delegation.

In these instances, the untrusted sigframe stores the trusted PKRU, but we cannot trust the saved %rip value. For nexpro, we need to discuss the different stages of the current switch, as the stack switch occurs immediately after the MPK switch. We just need to ensure that both these steps are fully executed to establish a correct environment for the trusted program’s execution. The situation when returning from nexpro is similar. For delegation, we establish trust through TABLE II: Security analysis of the known MPK attakcs

|  |  |
| --- | --- |
| Attacks | Mitigation |
| Change page permissions [45] | Limited mprotect |
| Bypass MPK with syscall [45] | Limited syscall-s and  syscall delegation |
| Change PKRU with Instructions [45] | Ban WRPKRU and xrstor |
| Modify Executable Page [41], [45] | No shared memory for  executable-only page |
| Utilize debug and seccomp APIs [45] | Ban syscall-s |
| Signal Context Attack [45] | Trust sigcontext only when  %rsp is safe |
| Hijack Control-flow with Signal [45] | Redirected signal handler |
| Change PKRU using sigreturn [45] | Emulated sigreturn |
| Abuse Nexpro’s Signal Handler Entry | Set %gs:(Signal) flags before WRPKRU |
| Other Control-flow hijacks | Ban syscall-s |

## TABLE III: CPU Cycles for Syscall Interaction

|  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- |
| Mechanism | getpid | read | write | mmap | open | close |
| syscall | 215 | 289 | 242 | 801 | 2435 | 824 |
| sec-bpf | 281 | 366 | 303 | 868 | 2661 | 940 |
| sud-bypass | 297 | 375 | 324 | 917 | 2526 | 1006 |
| sud-signal | 5201 | 5403 | 5128 | 7583 | 12398 | 5319 |
| ptrace | 33072 | 34230 | 34402 | 36184 | 38103 | 35867 |
| mbox | 343 | 445 | 376 | 40258 | 42628 | 999 |
| firejail | 368 | 462 | 392 | 1003 | 2857 | 1077 |
| nex-sud | 457 | 539 | 484 | 2741 | 3385 | 1081 |
| nex-rand | 462 | 549 | 500 | 2705 | 3582 | 1157 |

%gs:(Delegation), and we do not use any register values from the sigframe.

The entry point of the signal handler sets the

%gs:(Signal) using defualt PKRU from the kernel, ensures that the signal is from the kernel and not forged and abused by a user program.

*d) MPK:* The security of MPK is affected by the presence of instructions like WRPKRU in the code, signals and by system calls, for which we use binary scanning and related security system call policies, respectively. These measures can mitigate the known MPK attacks listed in Table II.

### C. Syscall Interaction Overhead

We evaluated the overhead of secure system call interception using nex-sud and nex-rand, comparing them with other

baseline

ptrace

mbox

firejail

nex\_sud

nex\_rand

Mechanism

0

5000

10000

15000

20000

25000

cycles

Signal Registeraion

Signal Delivery

Signal Return

## Fig. 4: Cycles on signal register, deliver and return

syscall interception mechanism. We use rdtsc to measure the overhead of system calls before and after executing syscall\_trap Because system calls only constitute a small part of an application, their overhead tends to be obscured in the macro benchmarks. Such analysis helps in understanding the true overhead of the syscall interception. We selected the syscalls in Table III to cover different operating costs of nexpro. getpid is the fastest and the overhead of syscall interception is significant. read and write a 4k page on /dev/null have medium cost, but nexpro has no additional policy for them. mmap and open are slow, and nexpro needs to perform extra checks, thus resulting in more cycles added. close is also slow, but nexpro does not need to check it, result in lower overhead than open. Nexpro makes changes in signal delivery, we also evaluated its overhead. We trigger signal delivery through the kill system call and evaluate the overhead of signal delivery by recording the current rdtsc before executing the kill, when the signal handler is invoked, and upon returning to the end of the kill.

In Table III, syscall is the baseline. sec-bpf shows the cycles consumed when using a seccomp policy that only allows this system calls. sud-bypass indicates the cycles consumed when SUD is enabled but all system calls are allowed. sud-signal denotes the consumed cycles when intercepting system calls with a signal and executing them. ptrace represents the cycles consumed when intercepting all system calls using ptrace.

For most system calls, the context switch in nexpro combined with the use of SUD or seccomp results in a total overhead of approximately 250 cycles. This fixed cost is from the trampoline. When using syscall delegation, it consumes an additional 60 cycles. In some cases, nexpro requires more system calls; for example, with mmap, nexpro needs an additional mprotect to set the page’s pkey. For open, nexpro requires stat to check if /proc/self/mem is opened. Therefore, the overhead in these cases is higher. Overall, nexpro is 10*x* ∼ 72*x* times faster than their competitions offering the same functionality and security. And only 1*.*0*x* ∼ 2*.*7*x* times slower than the less flexible alternatives.

Fig 4 compares the cycles consumed for the signal. Due to the re-delivery, nexpro requires more cycles to deliver signals. Surprisingly, handling sigreturn in userspace and not relying on the kernel in nexpro regains some of the performance reducing the overall overhead. As a result, for a single signal delivery, both ptrace and mbox have an overhead of *>* 300%, while nex-sud and nex-rand have overhead of 17*.*8% and 25*.*6%, respectively. Firejail has an overhead of about ∼ 1% which is close to seccomp only. This is because both cannot change the behavior of system calls, but only filters out illegal onces.

### D. Applications Benchmarks

In this section, we use nexpro to implement an application sandbox, thereby isolating NGINX and Redis. We

baseline

nex-sud

nex-rand

mbox

firejail

Mechenism

0

10000

20000

30000

40000

Request per Second

Ternsfer Size

0

k

4

k

64

k

## Fig. 5: NGINX Benchmark [max. std. *<* 1*.*34%]

forbid most of the unused system calls and limit file system interactions. We compared our results with mbox and firejail. NGINX Server – We evaluated a sandboxed NGINX server. The size of the request affects load characteristics, so we tested with file sizes of 0k, 4k, and 64k. All tests were run locally with NGINX workers set to 1. HTTP requests are initiated using ab with a concurrency level of 64. We use the request per second to calculate the overhead. The results of the evaluation are shown in Fig 5. In the case of using SUD, the maximum overhead caused by nexpro is 5*.*3%. When using randomized seccomp, the maximum overhead is 2*.*8%. Firejail, implemented as a namespace sandbox, has an overhead of only 0*.*7%. In comparison, mbox, which uses seccomp and ptrace, has an average overhead of 40%. In summary, nexpro offers a syscall-based sandbox with low overhead and opens up possibilities for other policies.

Redis Database – We use the redis-benchmark for benchmark, and Fig 6 reports the results in requests per second. We used a concurrency level of 64. The test cases were GET, LPUSH, and LPOP, each with different workload. The GET involves a simple key/value return, while LPUSH and LPOP involve operations on a list. As mbox could not run Redis, only firejail is evaluated. The LPOP has the highest overhead, with nex-sud, nex-rand having overheads of 6*.*1%, 7*.*1%, respectively. Firejail’s maximum overhead is 0*.*8%, benefiting similarly from using only the sandboxing support provided by the kernel.

In conclusion, nexpro provides nearly efficiency as firejail and enhances policy flexibility, enabling applications like gVisor and LibOSes, while significantly reducing overhead compared to seccomp based mbox.

VII. KNOWN LIMITATION io uring [50] and vDSO – Not all system calls are based on syscall. That is the case for io uring and vDSO. They cannot be intercepted even for seccomp. Generally, they do not pose a security issue, but if necessary, disable vDSO and intercept the registration of io uring, especially considering that the performance gains from io uring are not clear [51]. rseq – Nexpro needs to ensure that interrupts are controllable like signal, but rseq causes interrupts and its target

baseline

nex-sud

nex-rand

firejail

Mechenism

0

25000

50000

75000

100000

125000

Request per Second

Testcase

GET

LPUSH

LPOP

## Fig. 6: Redis Benchmark [max. std. *<* 3*.*50%]

address is not decide by the syscall. We need to disable this system call. This is not a problem as rseq is not widely used.

ptrace and remote memory apis – ptrace can be used to debug child processes, thereby compromising the integrity of nexpro in the child process, and therefore needs to be disabled. APIs related to remote memory access bypass the page protection, which circumvents MPK, thus need to be disabled.

libc modification – Currently, nexpro provides system call compatibility by modifying libc. For applications that do not use libc, it is necessary to modify the corresponding libraries to allow them to make system calls via syscall\_trap, such as in the case of Golang. Alternatively, binary modification techniques, such as zpoline, can be used to improve compatibility in these situations.

# **VIII. RELATED WORK**

System Call Interception – System Call Interception involves binary rewriting [21]–[23], [52], [53], ptrace, seccomp, modifying libc [16], [43], and etc [54]. Binary rewriting and modifying libc are inherently insecure and often require additional safeguards, such as seccomp, to mitigate risks like the subtle removal of risky syscall instructions embedded within other operations. Alternatively, ptrace is a usual method for system call interception but incurs significant performance overhead. In contrast, nexpro uses binary rewriting or modifying libc purely for compatibility with existing applications, securing system calls through mechanisms like seccomp and SUD, which can be integrated with these modifications.

Sandboxes – Sandboxes are used to prevent applications from performing illegal operations [9]–[11], [55]–[62]. It requires inspection and filtering of the application’s system calls. LSM and namespaces are commonly used for sandboxing such as firejail [11] in which the kernel limits syscalls policies efficiently [9], [11], offers better performance [40], [63]. However, the limited and inflexible policies cannot be used for applications like gVisor [30] or other LibOSes. For such techniques, ptrace or in-process isoaltion is the only alternative.

In-process Isolation – MPK and other hardware extensions [1], [64], [65],improve the performance of in-process isolation, it’s use has become popular in research prototypes [27], [28], [41], [43], [66]–[73]. Due to MPK’s limitations [41], [45], they also need to restrict system calls. Previous work required modifications to the kernel and are unable to fully and securely support signals [27], [41], thus limiting their usability and scope of application. Nexpro can be used as part of an in-process monitor to enhance their security and compatibility.

Control-flow Integrity and Software Fault Isolation – Enforcing CFI [74]–[89] or SFI [59]–[62], [90]–[94] can also help intercept system calls, by restricting syscall instructions to a specific range. And, they can thus ensures syscall-s are not abused. But, both incur significant overhead compared to efficient hardware in-process isolation techniques due to tracking stack context and/or poor backward compatibility requiring recompilation.

# **IX. CONCLUSION**

This paper presents nexpro, a mechanism that utilizes MPK, Seccomp and SUD to make syscall a privilege.

It allows for exhaustive, safe, and low-overhead system call interception without requiring to modify the kernel. It can be used with other binary rewriting tools to enhance their security. Nexpro provides secure and reliable support for system call policies in tools such as sandboxes, in-process monitors, and operating system emulation.

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