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seL4 API/ABI emulation approaches in Linux

by

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Abstract

This thesis examines different methodologies and designs that aim to realize the idea of emulating seL4 in Linux. This report will mainly focus on reviewing the related projects. The first three are QEMU, Cygwin, and Wine, which provide solutions to run either foreign operating systems or programs targeting the foreign operating systems on a different host operating system. Lastly, the UML project gives an idea of porting the Linux kernel to the userspace. This report also proposes two approaches, the first one is to perform emulation at the sel4 syscall API layer, and the second one is to provide seL4 kernel ABI layer. They all share similar goals but tackle the problem from different perspectives. An analysis in this report will reveal similarities and differences between those techniques. Evaluation approaches and applications will also be proposed at the end to demonstrate the underlying technical solutions and outcomes of this project.

Acknowledgements

The work of this thesis has been inspired by Prof. Gernot Heiser and Axel Heider who encourage me to explore the scope of this project leading to an enhancement in research skills and understanding of emulation technologies. Further support and encouragement have been given by James Nakoda Nugraha who provides me the recommendation, advice, and information about Linux. At last, I would like to thank you, my families and friends, who always support me.

Abbreviations

ABI Application Binary Interface

API Application Programming Interface

ASLR Address Space Layout Randomization

DLL Dynamic-link library

IPC Inter Process Communication

KVM Kernel-based Virtual Machine

OS Operating System

PID Process Identifier

POSIX Portable Operating System Interface

RPC Remote Procedure Call

TCB Trusted Computing Base

UML User-mode Linux

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Chapter 1

Introduction

seL4 provides a very secure environment to run any untrusted applications as separate components on top of it. What's more, it maintains a good performance as well as having a strong isolation guarantee of the applications and the kernel to keep the entire system robust and safe. However, developing seL4 systems is not trivial because of the development ecosystems of seL4. On the other hand, Linux has a much larger and more complete ecosystem than seL4 does, therefore, in this project, we are going to explore some approaches to emulate the entire the seL4 kernel in the Linux environment. The outcome of this project will let us leverage helpful tools such as debuggers in Linux to make developing seL4 systems much easier and faster.

Chapter 2 explains the related projects that have been done before, followed by a detailed explanation of those projects. Chapter 3 states the rough design models and implementation ideas of this project. Chapter 4 explains the success criteria defined for this project and the methods that will be used for the evaluation. Chapter 5 states the plan for the future research project and the timeline for the next semester.

Chapter 2

Background

In the fisrt section, we are going introduce some basics of the design in seL4, then move on to the next section where defines the challenge that we are going to solve in this thesis. Finally, we are going to introduce three related projects, and present how those projects solve the similar problem that we faced in this thesis.

2.1 Overview of seL4

seL4 has been formally verified for correctness ([KEH+09]) and is the fastest microkernel in the world. The componentized system architecture that seL4 implements enforce the isolation between those untrusted components and other trusted components running on top of the kernel. seL4 was born for safety. The fine-grained capability-based access control model carefully manages the access to the hardware resources from the software components.

(TODO: Formal descriptio of seL4!)

2.1.1 Functionalities in seL4

(TODO: Cpabilities)

(TODO: Communication and System calls)

(TODO: Memory Management)

(TODO: Scheduling)

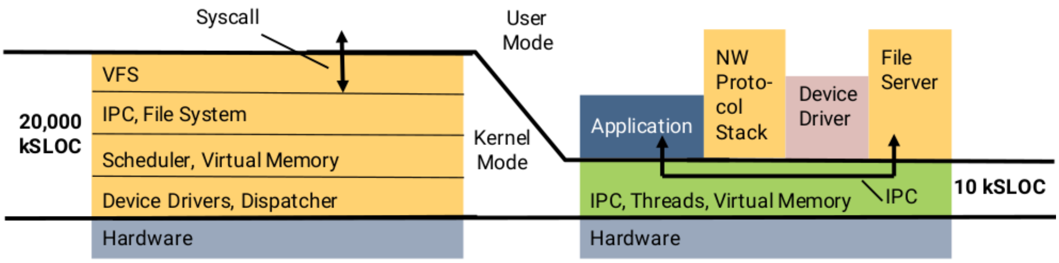
The secure and well design of the seL4 microkernel together with the formal verification ensure the kernel itself is robust and is the ideal foundation to build a secure system on top of it ([KAE+10]). What's more, seL4 is not only secure but also fast. With its performant IPC mechanisms and most advanced mixed critical real-time systems ([LH14]) (TODO: use the new paper), seL4 is capable of handling a wide range of real-world scenarios. However, seL4 is relatively young comparing to other mainstream kernels, such as Linux, and its ecosystem is still growing. For those seL4 developers, there are limited tools that can be used while developing seL4 systems. On the other hand, Linux provides us a powerful developing environment with lots of useful tools. Therefore, the main motivation of this project is to explore some ways to leverage the Linux tools in terms of development to make developing seL4 systems much easier and faster.

2.2 Challenge

Developing applications targeted for seL4 in Linux is challenging because seL4 as a microkernel has different semantics and OS model based on seL4 comparing with Linux (In figure 2.1).

Linux is a monolithic kernel that provides a wide range of OS services. The drivers, OS components are implemented inside of the kernel. All those OS services execute in kernel mode. While in seL4, to guarantee the strong isolation of different OS components, seL4 itself is just a thin wrapper of the underlying hardware providing minimal critical

(Fixed: fix the bad scaling problem)



Source: "The seL4 Microkernel – An Introduction" (p. 3), by Gernot Heiser, 2020, the seL4 foundation. Copyright under the Creative Commons Attribution-ShareAlike 4.0 International (CC BY-SA 4.0) License.

Figure 2.1: Linux based OS model vs seL4 based OS model.

services of the hardware resources. The OS services are implemented at the user level as separate components. Such design minimizes the TCB.

In a monolithic kernel, the user-level applications request the OS services through the system call interfaces that are exported to the user level. A system call will cause a context switch from the user mode to the kernel mode, and the kernel will serve the OS requests by itself. For example, an I/O request from the user level will trigger the system call and the kernel will dispatch such request to the corresponding handler. In Linux, this might be a handler in the VFS layer. Then the VFS layer handler will find the particular file system handler and finally, it will invoke the driver to perform the I/O. After the system call getting triggered, everything happens in the kernel mode until the requests have been served. However, in the seL4 based OS model, it works differently. First, to clarify the term, we are going to call anything that runs in seL4 user level the "seL4 applications". Also, we distinguish those applications into client applications that request OS services and those server applications that serve the OS services. In the rest of the article, we will use the seL4 applications as the term to make the description easier. When the seL4 client applications request OS services, it will invoke IPC mechanisms provided by the seL4 kernel. (Fixed: description of IPC in seL4) The seL4 IPC is a synchronous method for transmitting small amounts of data and capabilities between seL4 threads. The IPC message passing is the main system call in the seL4, it triggers the context switch to the kernel mode, and the seL4 microkernel will then transport the input to the designated seL4 server application via an exported entry point. Those requests are served by the seL4 server application at the user level. The seL4 client applications and seL4 server applications are isolated components, which ensures the security of the whole system.

As we can see, the main problem here is that seL4 and Linux have different semantics and program flow of serving OS services, the final goal of this project will be providing methods for developing seL4 user-level applications which can either run on Linux or seL4. In other words, we need to provide compatibility between seL4 applications and Linux.

2.3 Related Work

(Fixed: I would expect this to lead off with a discussion on the various abstraction levels we have, and that emulation can happen at each of them)

In this section, we are going to introduce several related projects which provide emulation at different levels from ISA layer to API layer. First, we will present an existing solution to the challenge we stated before, which uses QEMU to provide an ISA-level emulation. Then we will present an API-level emulation project called Cygwin and two ABI-level emulation approaches called Wine and UML.

2.3.1 ISA-level Emulation

The ISA-level emulation provides a way to run an unmodified target binary code, such as applications or even operating systems like Linux or Windows on a host machine, even if the target's binary code is compiled for targeting a different CPU as the host's. One example of performing ISA-level emulation is using QEMU.

QEMU

(Fixed: This whole section is highly confusing, mangling hardware virtualisation with dynamic translation. This needs much better explanation and classification that these are two completely separate operating modes Also, the"more efficient" claim is unsubstantiated Really, this is virtualising at the ISA level, and is just one approach to that)

QEMU is a machine emulator supporting a wide range of ISA and a virtualizer providing us the hardware virtualization feature if the guest's ISA is the same as the host's ISA ([Wik21b]). With those features, we are capable of running the seL4 microkernel on top of the Linux, and from the seL4 user-level applications' view, they are still running on top of the seL4 microkernel.

QEMU is a machine emulator, which means it can use portable dynamic translation to emulate an entire machine, including its processors and peripherals. To convert the guest instruction set into the host instruction set, QEMU will perform two phases. The first phase is the translation and the second phase is the code generation. In the first phase, QEMU splits each target CPU instruction into a few instructions called micro-operations. Each micro-operation is implemented using a small piece of C code that will be compiled by GCC to an object file later. A novel design in QEMU is that QEMU uses dummy code relocations generated by GCC as a place holder with a prefix *__op_param* in the micro-operations, and patches it later when the code generator runs. Because some constants parameters in the target instructions are only known in the runtime. Those relocations can also be references to static data or functions. After that, the *dyngen* will be invoked to generate the dynamic code generator. It will parse the previously generated object file depends on the host operating system's object file format, such as ELF in Linux, to get the symbol table, relocations, and code sections and use that information as the input to generate a dynamic code generator. In the second phase, the dynamic code generator will copy the stream of micro-operations into the host code section and patch the relocations with the runtime parameters. Those relocation patches are host-specific. For optimization, QEMU will maintain a fixed size cache to hold the recently translated blocks of instructions.

It is flexible in that QEMU can emulate CPUs via dynamic binary translation allowing binary code written for a given ISA to be executed on another ISA, such as running ARM binary on x86. However, the entire system emulation introduces a massive performance overhead. Therefore, QEMU leverages the hardware virtualization extensions, such as Intel VT-x or AMD-v, which are supported by modern processors to overcome this issue. These technologies directly map a slice of the physical CPU to the virtual CPU. Hence, the instructions of the virtual CPU can directly execute on the physical CPU slice. In Linux, QEMU allows using the KVM as an accelerator to use physical CPU virtualization extensions. However, since KVM is a driver for the physical CPU capabilities, this approach is very tightly associated with the CPU architecture. It means that the benefits of hardware acceleration will be available only if the target system emulated uses the same ISA as the host's and the host processor supports hardware virtualization feature. Otherwise, it won't work.

Although QEMU is an existing solution to emulate the seL4 system in Linux at the ISA layer, it's not an optimal option for emulating a high-performance microkernel like seL4 because of the overhead of hardware virtualization or machine emulation. In the former case, if the guest system such as our seL4 performs a privilege instruction, then it will trigger a world switching to the host, and such overhead is not negligible. In the latter case, if the seL4 system is compiled for targeting a different ISA as our host ISA, then the QEMU will have to perform a full machine emulation and translate the ISA into the host's ISA, which introduces significant overhead. Moreover, though QEMU provides its debugging interfaces to debug the guest system. However, the design goal of QEMU focuses on low-level machine emulation. It's helpful to inspect each instruction's execution of the CPU, but it's hard to use from a high-level seL4 developers' perspective. Because the debugger is not OS aware, the guest OS's context switch might confuse the debugger and lead to a breakpoint missing or a wrong variable value issue. In the following sections, we will introduce other approaches performing emulation at different layers, and then propose approaches used in this thesis to tackle the problem that we stated before in chapter 3.

2.3.2 API-level Emulation

As we mentioned before, the ISA-level emulation involves emulating the emtire machine or using virtualization technologies, which introduces non-negligible overhead. In this section, we will introduce a project which performs emulation approach at the API layer to provide compatibility between two differnt systems.

Cygwin

The Cygwin is a compatibility layer that allows Unix-like applications to run on top of Windows ([Wik21a]). This is achieved by introducing a DLL called cygwin1.dll which acts as an emulation layer providing substantial POSIX system call functionalities providing a Unix semantics. With Cygwin, users can access several standard Unix utilities such as bash, etc.

(TODO: diagram of the architecture) Cygwin began development in 1995 at Cygnus Solutions. In the project, developers provided interfaces called Cygwin API to add the missing Unix-like functionalities in Win32 API, such as fork, signals, select, etc ([Cyg]). Cygwin will not magically make any Unix-like application's binary code runnable on top Windows directly. Executing those Unix-ike applications require the recompilation of the application. The source code can be compiled under the Cygwin and linked with the shared library which implements the POSIX system call semantics using the Win32 APIs and native NT APIs. After executing the application, the Cygwin DLL will be loaded into the application's test region so that it has full access to the whole process. Next, shared memory is created containing the instances of the resources that the shared library can access. Therefore, the OS resources such as file descriptors can be tracked. Besides such shared memory regions, each process also has its resource bookkeeping structures, such as signal masks, PID, etc.

Cygwin has several nice designs to implement the POSIX features in Windows. For example, it handles signals by starting a separate thread from the library for only signal handling purposes. This thread waits for the Windows event used to pass signals to the process, and scan through its signal bitmask to handle the signals appropriately. However such thread resides in the same address space as the executing program, the signal sending function for sending a signal to other processes is wrapped with a mutex, and the signal sending function which sends the signal to itself is wrapped by separate semaphore or event pair to avoid them being interrupted.

Another example is the implementation of sockets. They are mapped on top of the Winsock. But Unix domain socket is not provided in Windows, so Cygwin implements it with the local IPv4 as the address family. Besides, Cygwin provides the Winsock initialization on the fly, as the Winsock requires to be initialized before the socket function is called. For implementing the POSIX select, Cygwin implements the polling of file handles besides socket type handles by sorting the file descriptors into different types and creating a thread for each type of the file descriptors present to poll those file descriptors with Win32 API. Such a design is because the Winsock only works on socket type file descriptors.

(Fixed: mention somtimes the implementation of the emulation can be complex because of the poor mapping between two systems.)

The API layer emulation requires to utilize the host systems' functionalities, but it's hard to find an appropriate functions provided by the host systems sometimes. For example, in Unix-like systems, the $fork()$ system call provides a way to create a child process that copies the parent's address space, but there are no appropriate process creation functions in Windows which can be mapped on top of it, so the implementation of $fork()$ in Cygwin is relatively complex.

Implementing $fork()$ semantics in Windows requiring to copy all of the executable binary and all the DLLs loaded statically or dynamically to be identical as to when the parent process has started or loaded a DLL. This can be problematic as Windows allows the binaries to be renamed to even removed to the recycle bin while the binary is executing, which means they can reside in a different directory or have a different file name. However, an executing process has to access to the binary files via the original filenames to fork its child processes. The solution to this problem is that Cygwin will try to create a private directory that contains the hardlink to the original files and remove it when no process is using it. When the parent process wants to fork a child process, it will first initialize a space in Cygwin process table for the child and create a suspended child process using Win32 CreateProcess system call.

After that, the parent process will use setjump to save the context and set a pointer to the current context in the Cygwin shared memory, and fill the child process's .data and .bss section with its own address space. Next, the parent process will block on a mutex and the child process will run and use the longjump to jump to the saved jump buffer. Then child process will release the mutex that the parent is blocked on and waits for another mutex. The parent process will copy its stack and heap into the child process space then release the mutex that the child is blocking on and return from the fork call. Finally, the child process will wake up and recreates any memory-mapped areas that passed to it and return from the fork call. However, such implementation is not perfectly reliable as in Windows, Windows implements the ASLR starting from Vista, which means the stack, heap, text, and other regions may be placed in different places in each process. This behavior interferes with the POSIX fork's semantic that is the child process has the same address space as the parent process. In that case, Cygwin will try to compensate the movable memory regions at the wrong place but can't do anything with those unmovable regions such as the memory heap.

In summary, adding compatibility at the API layer can solve most of the problems when attempting to run applications from foreign systems. While the downside is that, apparently this will only work when the user of Cygwin can obtain the source code of the application. Meanwhile, it's very difficult to implement every POSIX system call in Windows correctly due to the huge difference between the internal design and the semantics.

Even though Cygwin is used to make Unix-like applications compatible with the Windows environment, we can still leverage the nice idea that Cygwin uses. To emulate seL4 in Linux we can link applications to a specific library that remaps the system calls with the underlying host's system calls.

2.3.3 ABI-level Emulation

In the previous section, we have introduced Cygwinwhich is an API-compatible solution for providing compatibility between Windows and Linux. However, the downside is that it's not binary compatible as we have to obtain the source code first and recompile it. In that case, if we can't obtain the source code or the application that we want to emulate directly invokes functions via a foreign system's ABI, then it's impossible to perform the emulation. Hence, in this section, we will introduce two ABI-level emulations which are binary compatible.

Wine

(TODO: Need to be improved, add more internals related to Wine)

First example that provides the compatibility layer to run Windows applications in Unix-like operating systems is called Wine ([Wik21c]). However, Wine doesn't emulate the internal Windows logic like a virtual machine or an emulator. Instead, it directly translates the Windows ABI into POSIX-compliant calls. Besides, Wine also provides various Windows services through Wineserver as well as other Windows components. In Wine's architecture, it implements Windows's ABI entirely in the user space, rather than a kernel module.

A system call from a Windows application usually invokes a particular DLL library, which in turn invokes the user-mode GDI/user32 libraries, and then finally invokes the system calls via Win32 subsystem. However, since the architecture of Windows OS is a hybrid model of monolithic kernel combined with the microkernel, some OS services run as separate processes, so applications need to invoke RPCs to communicate the user-mode services. In that case, this is somehow similar to how seL4 applications request OS services. Although Wine implements the Wineserver to provide services that are provided by the Windows kernel, as well as other OS functionalities, it's impossible to implement all the aspects of the Windows kernel as well as to use native Windows drivers due to the internal architecture of Wine.

In Wine's architecture, the critical libraries are implemented using shared libraries and loaded dynamically at runtime, while in the seL4 system, all the binary codes are statically linked. So we can't imitate Wine's architecture and implementation. However, with a similar idea as the Wine project, we can still target the emulation layer of seL4 applications at the kernel ABI layer to achieve binary compatibility.

User-mode Linux

(TODO: This whole section suffers from being written bottom-up (or bottom-down?) rather than to-down. There's no big-picture view, no abstractions, just a collection of seemingly random detail. Iris totally impenetrable by someone who doesn't have a lot of OS Ann's Linux background)

UML is an old project used to port a Linux kernel to the userspace. This can be helpful to the system developers as it provides a nice way to develop and debug the kernel as well as to make several interesting applications possible for Linux ([Dik06]).

In UML's architecture, it treats Linux as a platform to which the kernel can be ported. All the implementation fully leverages the Linux system calls without any modification of the host kernel. And all the user-level code can run natively on the processors without any instruction emulation overhead. The implementation creates a separate thread that uses the *ptrace*() system call to trace all the other threads running in UML.

(TODO: explain the how to the tracing thread control the context switch)

System Call

(TODO: Diagram) Since the transition between user mode and the kernel mode is controlled by the tracing thread, it will intercept all the signals and system calls that the running process issues and then transit from the user mode to the kernel mode and continue executing the particular process without tracing it. (TODO: add constraint that this happens in the emulated mode) The distinction of the user mode and the kernel mode is whether the process is being traced by the tracing thread. After changing the register which contains the syscall number into the syscall number for *getpid*() and restoring a previously saved thread registers state, the tracing thread will invoke the syscall handler to accomplish the syscall request, then finally return the process to the user mode.

Trap and Fault

(TODO: Diagram) UML not only virtualizes system calls but also implements several other Linux OS services and functionalities. For example, to handle the processor traps or faults, it implements those with signals and installs handlers for each. Once the tracing thread captures the signals that the process received, it will switch to the kernel mode and continue executing the process in the handler.

For the memory fault, UML implements with the $SIGSEGV$ and invokes the handler to figure out whether the fault was because of legal access to an unmapped page or illegal memory access.

Interrupt

(TODO: Explain what those signals are. As the reader won't know)

UML also implements external interrupts and timer interrupts using $SIGIO$ and $SIGALARM$ or $SIGVTALARM$ depending on whether the interrupted process is idling or not. For the external interrupts, it uses *select* to check which file descriptor has received input then invokes the IRQ handler. For the timer interrupt, UML also treats it similarly to treating the external interrupt and invokes the particular IRQ handler.

Scheduling

(TODO: explain it well instead of just mention as an overview)

For process scheduling, UML implements scheduling processes by stoping an outgoing one and running an ingoing one as each process has its thread belongs to it. Since each process has its own address space, UML also manages the page mapping of each process as well as the *SIGIO* queued in each process.

Virtual memory

In UML, the kernel and process's virtual memory is implemented as a physical memory-sized file mapping into their address spaces. However, some regions in the address space will be reserved by placing kernel code and data which is unusable.

Host filesystem access

UML also implements a virtual file system called *hostfs* which translates the directly into the functions in the host's *libc*. Hence, it provides direct access to the host filesystem.

UML was a nice project showing a novel way to use Linux interfaces to implement itself, also it demonstrated that porting a kernel in the userspace can be beneficial to both kernel and application development.

From this project's perspective, UML gives us the hint of how to leverage *ptrace* to intercept the system call from the process being traced as well as how to simulate the kernel in the userspace.

Chapter 3

Approach

At this stage, we are going to purpose a software development approach to tackle the problem. Running seL4 applications in Linux requires introducing an extra compatibility layer between the application and the Linux OS. Hence we are going to purpose two approaches to achieve this. The API layer emulation approach and the ABI layer emulation approach.

3.1 API Layer Emulation Approach

In the original seL4 system, a userland seL4 client application can request OS services from another seL4 server application which also runs in the userland through IPC mechanisms provided by the seL4 kernel. The seL4 system call library provides those IPC interfaces.

(Fixed: How does this related to the background?)

However, if those seL4 userland applications run on top of Linux OS, then directly using the original seL4 system call libraries will not work due to the different semantics between seL4 and Linux. To solve that problem, Cygwin gives a good idea. In Cygwin, it replaces the original system call libraries with a custom implementation to achieve compatibility between POSIX and Windows. Hence, we can provide a custom system call library that exports the same interfaces as the original seL4 system call libraries to seL4 userland applications, but we will use Linux IPC mechanisms as a replacement instead of invoking the seL4 IPC directly.

3.1.1 Design Model

Figure 3.1 shows the model of the API layer emulation approach.

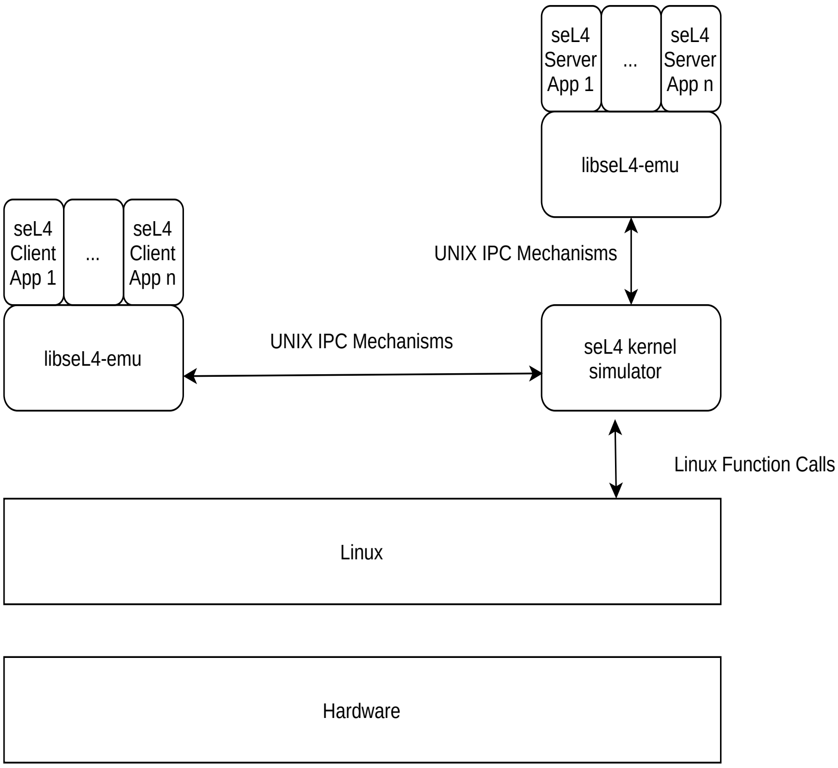


Figure 3.1: The model of API layer emulation approach

In general we need to develop two components in this model.

1. An seL4 emulation library
2. An seL4 kernel simulator

The seL4 emulation library is a compatibility layer named libseL4-emu in the figure which can be linked to other seL4 applications. Therefore, the seL4 applications will invoke the emulated seL4 system calls instead of the real original seL4 system calls. And the libseL4-emu library will dispatch those system call requests to the seL4 kernel simulator.

The seL4 kernel simulator runs at the user level on top of Linux. Hence the dispatching processes can be implemented using Linux IPC mechanisms, such as UDS or shared memory. The seL4 kernel simulator mainly provides the real seL4 semantics and management of capability space, IPC mechanisms, scheduling context management, etc.

In this model, all the seL4 applications and the seL4 kernel simulator are just regular Linux processes running at the user level. And the seL4 applications act as clients, communicating with the server which is our seL4 kernel simulator.

3.1.2 Advantages and Disadvantages

The API layer emulation approach has several advantages. First of all, it is relatively easy to implement regarding the complexity of implementation.

(Fixed: explain why the performance should be good? Comparing to Virtualization/ Emulation? VM exit/ VM$_{e}nter, IPCheavy/light? ContextSwitchesinthisapproachedrequires4traps,$

Secondly, since simulating the seL4 IPC mechanisms uses Linux IPC mechanisms won't introduce too much overhead, the performance should be relatively good compared to fully emulating a machine using QEMU. But it's hard to give an intuitive result of comparing this approach with the hardware virtualization approach using QEMU without further detailed measurement. Although the hardware virtualization will introduce the overhead due to the word switch, the API layer emulation approach will require at least four context switches between the seL4 client application, the seL4 kernel simulator, and the seL4 server application.

Whatsmore, this approach is ISA independent. In the model, all the seL4 applications and the seL4 kernel simulator run at the user level, and the seL4 system call emulation layer provides the interfaces. From the perspective of seL4 applications, everything below the system call emulation library is abstracted away. Ideally, those applications shouldn't notice that they are no longer running on top of the real seL4 kernel, and Linux provides the functions to emulate the seL4 system calls and seL4 kernel. The interactions with hardware are abstracted away by Linux. Therefore, this approach focuses on implementing the correct semantics of the real seL4 kernel.

However, the main disadvantage of the API layer emulation is that it is not binary compatible. It is because that the emulation will work only if the seL4 applications are linked with the seL4 system call emulation library. Hence, we have to obtain the source code of the application first and recompile the source with the emulation library every time we want to use the emulation.

3.2 ABI Layer Emulation Approach

(FIxed: relation to the background review)

In the former approach, we have introduced the API layer emulation, which is not binary compatible, while in this approach, we are going purpose a method to achieve binary compatibility. However, the main challenge is redirecting the system calls issued by the seL4 applications without modifying the source code. Both Wine and UML projects introduce different approaches of providing compatibility at the ABI layer to achieve such a goal. But in Wine's architecture, the system call libraries are implemented as a shared library, while the seL4 build system uses a statically linked method. Therefore, we will implement the ABI layer emulation approach using the idea given by the UML project, which is using the $Ptrace()$ system call in Linux.

3.2.1 Design Model

Figure 3.2 shows the model of the ABI layer emulation approach.

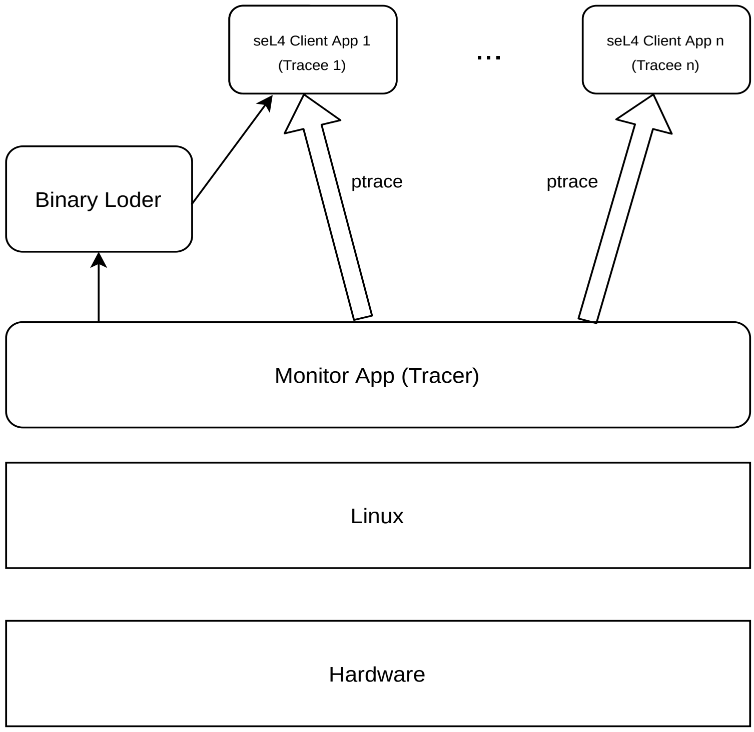


Figure 3.2: The model of ABI layer emulation approach

In the figure, mainly we have two components:

1. An seL4 application monitor

2. An seL4 application binary loader

In the rest of the article, we will call the seL4 application monitor the *monitor*, and the seL4 application binary loader the *binary loader* for simplicity. The main challenge in this approach is that since the seL4 application is an unmodified binary code, hence it will invoke the real seL4 system calls. In that case, we have to redirect the system calls and observe what is the seL4 application requesting then serve the system call by ourselves according to the real seL4 semantics. To achieve this goal, we are going to use the *ptrace*() system call in Linux.

ptrace() allows a tracer process to observe and control the execution of the other process. The "tracee" process can be attached to the "tracer" process, so that the "tracer" can modify the "tracee" process's memory, registers, etc. Also, the *ptarce*() semantics allow us to establish a one-to-many relationship, which means we can have several "tracees", but can only have one "tracer". In this approach, we can leverage such a feature to intercept the system call invocation from the seL4 applications.

(TODO: Why the loader is requireed and what does the loader do?)

In the model described above, the monitor acts as our "tracer", and the seL4 applications are our "tracees". The monitor is also a seL4 kernel simulator providing the same seL4 semantics and kernel mechanisms as the real seL4 kernel does. The emulation starts from the monitor forks a binary loader process that can load the seL4 application's ELF file into the memory and set up the appropriate memory regions for it. Next, the binary loader will block and notify the monitor that the initialization has finished. The monitor can use *ptrace*() to control the seL4 application. Finally, the seL4 application can continue executing after the *ptrace*() process finishes. Now, every time the seL4 application invokes a seL4 system call, the monitor will be notified and suspend the execution of the seL4 application, then the monitor will inspect the system calls requests and do appropriate actions to serve them.

3.2.2 Advantages and Disadvantages

The main advantage of this approach is that the kernel ABI approach is binary compatible. As long as, we obtain the binary code of the seL4 applications that we would like to emulate, no recompilation is required. However, using the ABI layer emulation will introduce overhead. This is because every time the seL4 application invokes a seL4 system call. The monitor will use *ptrace*() to intercept it and modify the arguments, return value if necessary, and the *ptrace*() itself is a system call, which requires trapping into the kernel. The trade-off here is leading to a penalty of the performance. Besides, *ptrace*() is usually used to implement the Linux debuggers, and it only allows on "tracer" to exist at any time. Therefore, we have to provide our own debugging interfaces in some way, which can introduce implementation complexity.

3.3 Comparison Between API and ABI Layer Emulation

Table 3.1 listed the trade-offs of implementing the API and the ABI layer emulation approaches. The API layer approach is relatively easier to implement as we don't need to develop the binary loader and the debugging interfaces. The API layer emulation can fully leverage the native Linux debugging tools such as GDB, LLDB, etc. In terms of portability, the API layer approach is ISA compatible as all the implementation is at the seL4 system call library level and doesn't involve the ISA dependent code. However, the API layer approach doesn't achieve binary compatibility as it requires recompiling the source code to work, while the ABI layer emulation approach is fully binary as we intercept the system calls using *ptrace*().

Last but not least, in terms of the performance, the API layer approach should be better than the ABI layer approach due to the internal implementation. As mentioned before, intercepting system calls and modifying the system calls' arguments or return values require extra context switches to the Linux kernel, which introduces overhead.

Table 3.1: Comparison between API and ABI layer emulation

Approach	Implementation Complexity	Potability	Binary Compatibility	Debugging Support	Kernel IPC Performance
Syscall Library API emulation	Intermediate	Good, as the solution is ISA potable	No	Can use native Linux debugging tools	First
Kernel ABI emulation	Hard	No, if the ABI of the application is different from the host's, it won't work	Yes	Extra debugging interface required	Second

(Fixed: why ABI emulation approach is ISA independent, It is not as the ELF file will be different, in this project targeting to x86)

Chapter 4

Evaluation

In this chapter, we will purpose some evaluation approaches regarding to both API layer emulation and ABI layer emulation approaches. Despite the fact that the real implementation and the benchmark haven't been finished yet we can still set up some criteria in terms of the implementation in both a qualitative aspect and a quantitative aspect.

4.1 Qualitative Evaluation

One way to evaluate whether the implementation of the emulation approaches is successful or not is to test the emulation framework with some existing seL4 applications. In this project, we are going to use applications from the following source:

(Fixed: better layout, put description in each paragraph)

4.1.1 seL4 tutorials

The seL4 tutorials contain several trivial seL4 applications used for demonstration and education purposes.

Those applications mainly focus on demonstrating seL4 features and API usage including printing "Hello World", simple IPC message passing, setting up runnable threads in seL4 userland, etc. Those applications can be used to use to test each of the emulated seL4 features separately.

4.1.2 seL4Test

The seL4Test (Fixed: naming) contains several unit tests that focus on low-level kernel APIs. As those tests were used to prove the correctness of the implementation of the real seL4 kernel and some seL4 helper libraries. Therefore, we can use those tests to evaluate the implementation of the seL4 kernel simulator. However, since the seL4 kernel simulator fully running in the Linux userspace, it doesn't have the access to the hardware and performs privilege options. We don't expect the kernel simulator can pass all of the tests. We will focus more on testing critical functionalities, such as the IPC mechanisms, cspace management. vspace management and scheduling, etc, and skip those tests that are not quite important to the emulation project or those are complex or even impossible to emulate correctly such as cache tests, multicore tests, etc.

4.1.3 Simple operating system project

The simple operating system is a simple multitasking operating system running on the seL4 kernel which has an interactive shell, and several subsystems including I/O, memory management, process management, etc. Since it has a relatively complex structure and more comprehensive functionalities implemented with seL4 semantics. Hence, emulating it using the emulation approach can be a nice way to both verify and demonstrate the emulation approaches function well.

Table 4.1: Expected success criteria

	syscall API emulation (A1)	kernel ABI emulation (A2)
On the emulated hardware by QEMU (B1)	A1 should be significantly faster than B1 because no hardware emulation is involved	A2 should be significantly faster than B1 but slower than A1 due to syscall interception
Native hardware running seL4 (B2)	A1 should be less than an OoM slower than B2 because seL4 is highly optimized	A2 should be significantly slower than B2 due to syscall interception

4.2 Quantitative Evaluation

From the qualitative perspective, we are going to evaluate the two approaches via microbenchmark and macrobenchmark. Table 4.1 is the expected quantitative benchmarking outcome.

4.2.1 Microbenchmark

(TODO: I would have hoped for more analysis here. These costs can be estimated, at least with the help of some very simple micro benchmarking of Linux syscalls -¿ define the base line performance in Linux and seL4)

The microbenchmark mainly focuses on evaluating the performance of each emulated system call. We can measure the number of system calls that the seL4 application invokes per second. The higher the result, the better the performance. Besides, to make the result more representative, we should measure the result several times and make a statistical analysis.

The ideal expectation is listed in the table 4.1. In general, we expect the API emulation approach will not introduce too much overhead, and the result should be slower compared to the result of running the same application on the native seL4 kernel. In the worst case, the overhead upper bound shouldn't exceed an order of magnitude. While comparing to the result of using ABI layer emulation, hardware virtualization, or emulation approach, the API layer emulation should be faster. This is because, in the API layer approach, all the real seL4 system calls are emulated, which can save some of the overhead of trapping into the kernel.

On the other hand, the ABI layer emulation approach should be faster than using any hardware emulation or virtualization, but slower than the API layer emulation approach, because intercepting system calls will introduce relatively high overhead.

4.2.2 Macrobenchmark

The macrobenchmark can be commenced under two circumstances and the result will be the measurement of the total system calls' elapsed time. On one hand, we can simulate a situation with a heavy system call workload. The result can emphasize the expectation that using either API or ABI layer emulation approach will not introduce unacceptable overhead. On the other hand, we are going to simulate another situation with a low system call workload, the result emphasizes that using API or ABI emulation approach is more performant than using hardware virtualization or emulation approaches such as QEMU.

Chapter 5

Project Plan

So far the work of this project has been done is the background research of the related projects as well as construct the basic solution model in a theoretical aspect. This report summarizes the related projects' ideas that can be borrowed in this project. QEMU is an existing solution for emulating the entire foreign system. While Cygwin and Wine project give the idea that we can avoid hardware virtualization of emulation to execute applications that target foreign systems by adding an extra compatibility layer at API or ABI layer. And the final project UML introduced an approach to port Linux kernel into Linux user space and intercept the system calls from the userspace by using *ptrace*(). With those ideas, we purposed the implementation of the project using the API layer emulation approach by modifying the system call libraries and using the ABI layer emulation approach by using *ptrace*() system calls in Linux. The design and implementation details are not yet finalized at this stage. It's only a rough prototype that could potentially work.

5.0.1 Timeline

Below is the timeline for future thesis research work.

1. Port the seL4 kernel to the Linux userspace, and implement the basic framework

for the API. This will take roughly 2 weeks, and will be done during the break of the term 21T1

2. Refine the emulation framework, complete seL4's critical kernel functionalities, and pinpoint parts that are hard to emulate. At this stage, the emulation framework should be mostly functional. The plan is to achieve this stage before week3 in term 21T2.

3. Evaluate the API emulation framework using the methods listed in this report and modify the implementation if necessary. We should complete evaluating the API emulation approach two weeks before the week5 of the term 21T2.

4. Depending on the time left in the term 21T2. The next stage will be either implementing the ABI emulation approach or refining the theoretical part of the ABI emulation approach and adding details of implementation in the Thesis Report as future work.

5. Preparing for the final demonstration and the presentation.

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