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SGX-Enabled TREDIS

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SGX-Enabled TREDIS

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ABSTRACT

Intel SGX hardware is a trust-computing base for applications to protect themselves from potentially-malicious OSes or hypervisors. In cloud and other outsourced computing environments, many users and applications could benefit from SGX. However, legacy applications are not prepared to work out-of-the-box on SGX.

Previous research work have already addressed library emulated OSes targeted to execute unmodified applications on SGX, but a belief has emerged that such approaches will not be interesting in terms of performance and TCB size, making in practice that application code modifications or reengineering is always an implicit and better prerequisite for adopting SGX-enabled computing environments.

(HELP) this next paragraph enters the abstract? or just conclusions after it's done?

In this thesis we intend to study existent library OSes approaches and conduct an experimental evaluation by adopting a recent solution of a OS library emulation to be ported on top of SGX, as a fully-featured library OS that can eventually be adopted to rapidly deploy unmodified applications, with overheads comparable to applications modified to use “shim” layers. Our targeted evaluation will be conducted in virtualizing the Redis Key-Value Store, redesigning and implementing it as a SGX-enabled Trusted Key-Value Store (TREDIS).

Keywords: Intel SGX, REDIS, Trusted Execution Environment, Data Protection, Privacy, Dependability ...

RESUMO

O Intel SGX é uma base de computação confiável para que aplicações se protejam de SOs ou Hipervisores potencialmente maliciosos. Em *cloud* ou noutros ambientes de computação garantidos por terceiros, muitos utilizadores e aplicações podem beneficiar do SGX. Trabalhos já realizados que abordaram a emulação de bibliotecas de SOs visaram a execução de aplicações não modificadas sobre SGX, mas surgiu uma convicção de que esse tipo de abordagem não será interessante no que toca à performance ou ao tamanho da base de computação confiável fazendo com que, na prática, tanto modificações como a reengenharia do código de aplicações estejam sempre implícitos e sejam um melhor pré-requisito para adotar ambientes de computação com SGX.

(HELP) this next paragraph enters the abstract? or just conclusions after it's done?

Nesta tese pretendemos estudar as abordagens já existentes de bibliotecas de SOs e conduzir uma avaliação experimental adotando a solução recente de uma emulação de uma biblioteca de SOs para ser usada sobre o SGX, como sendo uma biblioteca completamente caracterizada que possa eventualmente ser adotada para implantar aplicações não modificadas de forma rápida, com *overheads* comparáveis a aplicações modificadas para usar camadas "*shim*". O foco da nossa avaliação consistirá na virtualização da base de dados do tipo Chave-Valor *Redis*, redesenhando e implementando-a como uma base de dados Chave-Valor confiável com permissões SGX (TREDIS).

Palavras-chave: Intel SGX, REDIS, Ambiente de Execução Confiável, Proteção de Dados, Privacidade, Confiabilidade ...

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GLOSSARY

aliquam	tincidunt urna. Nulla ullamcorper vestibulum turpis. Pellentesque cursus luctus mauris.
computer	An electronic device which is capable of receiving information (data) in a particular form and of performing a sequence of operations in accordance with a predetermined but variable set of procedural instructions (program) to produce a result in the form of information or signals.
cras viverra	metus rhoncus sem. Nulla et lectus vestibulum urna fringilla ultrices. Phasellus eu tellus sit amet tortor gravida placerat.
donec nonummy	pellentesque ante. Phasellus adipiscing semper elit. Proin fermentum massa ac quam. Sed diam turpis, molestie vitae, placerat a, molestie nec, leo.
integer sapien	est, iaculis in, pretium quis, viverra ac, nunc. Praesent eget sem vel leo ultrices bibendum. Aenean faucibus.
lorem ipsum	dolor sit amet, consectetur adipiscing elit. Ut purus elit, vestibulum ut, placerat ac, adipiscing vitae, felis. Curabitur dictum gravida mauris.
maecenas lacinia	nam ipsum ligula, eleifend at, accumsan nec, suscipit a, ipsum. Morbi blandit ligula feugiat magna. Nunc eleifend consequat lorem.
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nulla malesuada	porttitor diam. Donec felis erat, congue non, volutpat at, tincidunt tristique, libero. Vivamus viverra fermentum felis.
sed lacinia	nulla vitae enim. Pellentesque tincidunt purus vel magna. Integer non enim. Praesent euismod nunc eu purus. Donec bibendum quam in tellus.

ACRONYMS

CPU	Central Processing Unit
EK	Endorsment Key-pair
EPC	Enclave Page Cache
HSM	Hardware Security Modules
IaaS	Infrastructure as a Service
OS	Operating System
PCR	Platform Configuration Registers
SGX	Intel Software Security Guard Extensions
SSL	Secure Socket Layer
TCB	Trusted Computing Base
TCE	Trusted Computing Environment
TEE	Trusted Execution Environment
TLS	Transport Layer Security
TPM	Trusted Platform Module
VM	Virtual Machine
VMM	Virtual Machine Manager
XOM	eXecute Only Memory

SYMBOLS

*

INTRODUCTION

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1.1 Topic Framework and Motivation

The *novathesis* was originally developed to help MSc and PhD students of the Computer Science and Engineering Department of the Faculty of Sciences and Technology of NOVA University of Lisbon (DI-FCT-NOVA) to write their thesis and dissertations Using \LaTeX . These student can easily cope with \LaTeX by themselves, and the only need some help in the bootstrap process to make their life easier.

However, as the template spread out among the students from other degrees at FCT-NOVA, the demand for an easier-to-use template has grown. And the template in its current shape aims at answering the expectations of those that, although they are not familiar with programming nor with markup languages, so still feel brave enough to give \LaTeX a try and rejoice with the beauty of the texts typeset by this system.

1.2 Objective

It is up to you, the student, to read the FCT and/or NOVA regulations on how to format and submit your MSc or PhD dissertation.

This template is endorsed by the FCT-NOVA and even linked from its web pages, but it is not an official template. This template exists to make your life easier, but in the end of the line you are accountable for both the looks and the contents of the document you submit as your dissertation.

1.3 Expected Contributions

1.4 Document Organization

RELATED WORK

We're currently in a period where we start to depend more and more on allowing remote services to access our data and execute our applications. Cloud computing systems require users to trust them with their data. Therefore these systems need a way to assure data privacy and security, thus gaining users trust.

In this chapter we address existing solutions that are able to protect applications from the OS or hypervisor, regardless the machine where they're running on, thus increasing the level of trust an user can deposit in an execution of an application.

These existing solutions are organized in different sections in the following way: Section 2.1 covers protection against untrusted OSes; Section 2.2 covers TEEs and hardware-enabled approaches; In Section 2.3 we cover, in more detail, hardware-enabled TEE solutions used today. Section 2.4 covers shielded applications and frameworks compatible with Intel-SGX, which is the TEE technology we choose for our approach. Finally, in Section 2.4 we make a critical analysis on the topics previously discussed, while covering their main advantages and disadvantages.

2.1 Protection in untrusted OSes

A lot of applications these days depend on sensitive data to operate. Therefore protecting this data must be taken into account while designing the application. One of the things we have to think about is the size of the TCB, and how to reduce it as much as possible without losing the operability of the system. Typically, the host OS is considered safe and trustworthy, although that is not always the case. A compromised OS can give complete access to sensitive data, if not isolated from the application. That's why this is a major security problem and must be tackled in today's systems.

Approaches like Virtual Ghost, Flicker, MUSHI [39], SeCage [22], InkTag [12], Seg0

[19], grant security by isolating the sensitive data from the untrusted OS either by monitoring the application while it runs, or by enforcing memory isolation by using virtualization.

Virtual Ghost [8] provides application security against untrusted OSes by implementing the idea of ghost memory, which is inaccessible for the OS to read or write, as well as providing trusted services like ghost memory management, key management, and encryption and signing services.

It relies in sandboxing to protect the system from the OS, where a thin layer of abstraction is interposed between the kernel and the hardware. This layer works as a library of functions that the kernel can call directly, without the need of higher privileges being given to it.

Thus, Virtual Ghost protects the system against a direct threat from the OS, without losing significant levels of performance.

Flicker [23] provides secured isolated execution of sensitive code by relying on hardware facilities, such as AMD and Intel commodity processors, to run certain pieces of code in a confined environment, while reducing the TCB to as few as 250 additional lines of code.

When Flicker starts, none of the software already executing can monitor or interfere with it's execution and all traces of it's execution can be eliminated before non-Flicker execution resumes.

Thus, with a small TCB and a good level of isolation during the execution fase, where no data is leaked nor possible to access while inside the confined environment, the system can achieve reliability and security.

MUSHI [39] is designed to deal mainly with multi-level security systems, and provides isolation to individual guest VMs executing in a cloud infrastructure. MUSHI ensures that VMs are instantiated securely and remain that way throughout their life cycle.

It offers: 1- Trusted Execution, where both the kernel and user image, as well as MUSHI itself, are attested upon a VM start using a TPM, and thus defining a trusted initial state; 2- Isolation, where each VM executing on the same machine runs isolated, as a way to guarantee confidentiality and integrity; 3- User Image Confidentiality, by encrypting the user image with a cryptographic key provided by the user itself.

MUSHI guarantees confidentiality and integrity of a VM even during malicious attacks from both inside and outside the cloud environment. It trusts a TCB relatively small, including only the hardware, hardware virtualization, BIOS and System Management Mode, and can be implemented with quite ease using modern commodity hardware containing SMM memory (SMRAM), necessary for the isolation between the host and VM.

SeCage [20] is an approach that aims to protect user-defined secrets from application potential threats and malicious OS through hardware virtualization, thus isolating sensitive code and critical secrets while denying hypervisor intervention during runtime. It's designed to deal with a strong adversary model, assuming that both application and OS

can be compromised, while supporting large-scale software, which usually means a big attack surface. SeCage divides the system in compartments, where secret compartments have all the functions with permissions to access and manipulate those secrets, and a main compartment is responsible to handle the rest of the code.

The main goals of SeCage are to assure confidentiality of user secrets (e.g., cryptographic keys) and to be a practical approach with small overheads for large software systems. To achieve this, it ensures

- Hybrid analysis of secrets - provides a mechanism that prevents secrets from being disclosed during runtime, while not affecting their normal usage. For it, SeCage combines static and dynamic analysis. The first one is used to discover potential functions related to the secrets, while the second one complements the first one, being more precise than the first one. With this, SeCage defines secret compartments, containing a set of secrets and their most common functions. This ensures that only the functions inside a compartment can access that set of secrets.
- Hypervisor protection - isolate each compartment in a completely isolated address space through hardware virtualization, making them inaccessible to the Hypervisor. Only if a function outside a compartment tries to access a secret without permission, it's the Hypervisor job to handle that violation.
- Separating control and data plane - since each compartment needs to communicate with each other, there will eventually be contact with the hypervisor. Therefore, instead of frequent VM exits which cause high overheads, SeCage minimizes hypervisor intervention by only require it to define policies on whether two compartments can communicate (control plane) for as long as they conform to those policies (data plane) SeCage was shown useful protecting large-scale system software from HeartBleed attacks, kernel memory disclosure and rootkit memory scanning, without adding any significant performance overhead to the application.

InkTag [12] is a virtualization-based architecture that protects trusted applications from an untrusted OS, allowing trusted applications to securely use untrusted OS services.

InkTag admits trust in the hypervisor, which is responsible to protect the application code, data, and control flow from the OS, allowing applications to execute in isolation, in a high-assurance process (HAP). Trusted applications can securely and privately share data without interference from the OS or other applications. Each secure application communicates directly with the InkTag hypervisor via hypercalls to detect OS misbehavior.

It introduces a concept called paraverification, which is a technique that simplifies the hypervisor by forcing the untrusted OS to participate in its own verification. As a result, the OS notifies the hypervisor when there is any update to be made to the state, which the hypervisor then checks for correctness. InkTag also ensures virtualization through hardware, which is used to grant isolation, as well as separate secure from insecure data. Access control policies can be specified by each trusted applications to access their secure files, with privacy and integrity of them managed by InkTag through encryption and hashing. Other important aspect of InkTag is recoverability. InkTag is capable of ensuring crash consistency between file data and metadata. Metadata, which consists in

hashed data, is fundamental to guarantee integrity of data therefore, with this consistency granted, InkTag hypervisor can protect the integrity of files even if the system crashes. If for some reason some data is inconsistent, the application must discard it.

Sego [18] is a hypervisor-based system that gives strong privacy and integrity guarantees to trusted applications, even when the guest OS is compromised or hostile, by removing the trust from the OS. Sego verifies OS services, like the file system, instead of replacing them. To protect the application from the untrusted OS, Sego relies on a trusted hypervisor and assumes that hardware always executes hypervisor code correctly. It uses paraverification, where the guest OS communicates its actions and intent to the hypervisor, therefore making this verification of the untrusted OS behavior more efficient and easy.

Figure 2.2: Sego Architecture Overview

Sego executes trusted code in a HAP. After booting the OS, the hypervisor starts the HAP in a way that the HAP itself can verify its own initial code and data, similar to a TPM. Once running, the hypervisor ensures that HAP's registers and trusted address space are isolated from the OS. Everytime the HAP wants to perform a system call, it must inform the hypervisor of its intent, so that the hypervisor can verify OS activity. HAPs use a small library called libsego as a way to handle system calls and get Sego services without having to change their code. Each HAP also contains an untrusted trampoline code, that uses to interact with the OS. This is used as a way to protect HAP control-flow, since it uses this trampoline as the issuer for the system calls, therefore never compromising the HAP itself. Figure 2.2 shows well enough Sego's overall design without going into too much depth, referring which components are included in the TCB and which are not. Context switches are handled by the hypervisor, hiding any information about the HAP from the OS. Sego does not guarantee OS availability. A compromised OS can simply shut down or refuse to schedule processes. However this is easily detected.

drawback of those approaches (inktag, virtghost...) and why aren't enough

————— END OF TO DO —————

2.2 Hardware-Enabled TEE - Trusted Execution Environments

A **TEE** is an abstraction provided by both software and hardware that guarantees isolated execution of specific programs in a machine, including the host **OS**, hypervisor or even system administrators, preventing them from leveraging their privileges. A **TEE** also provides integrity of applications running inside it, along with confidentiality of their assets.

The first attempts to implement a **TEE** on a cloud system consisted of combining a hypervisor with isolation properties and a **TPM**.

A **TPM** [11] consists of a hardware chip, called microcontroller, that aims to create a trustable platform, through encryption and authenticated boot, and make sure it remains trustworthy, through remote attestation. It provides cryptographic functions that can't be

modified, and a private key (Endorsement Key) that is unique to every [TPM](#) made, working as an identifier for each [TPM](#).

However, [TPMs](#) have several problems when applied to the cloud due to being designed with the intention to offer security to a single machine. It is not flexible enough to guarantee that anyone can get the encrypted data from a different node. Thus, a distributed environment would not be the best kind of environment for a [TPM](#) to work on.

The current best practice for protecting secrets in a cloud system uses [HSMs](#).

[HSM](#) [2] are physical components whose main function is to provide and store cryptographic keys used to encrypt/decrypt data inside a system. [HSMs](#) can also perform cryptographic operations (e.g. encryption, hashing, etc.) as well as authenticate through verification of digital signatures and accelerate [SSL](#) connections [30], by relieving the servers from some of the workload caused by operations involving cryptography.

Thus, the system can protect critical secrets, such as cryptographic keys, and support a range of cryptographic functions.

With that in mind, new hardware-enabled solutions were developed to be more flexible and cloud friendly than the [TPM](#), or to incorporate the advantages of [HSM](#) to the system. We'll dive into technologies like ARM TrustZone, Intel SGX, AMD-SEV, and others, in the following section.

2.3 Hardware-Enabled TEE Solutions

The idea of using hardware to provide trusted execution environments started appearing as a way to deal with piracy, with examples like TCPA [37] and Microsoft's Palladium being the most known ones. By making use of hardware, it was possible to encrypt data (DVD's, for example) that could only be decrypted by a specific hardware, making it impossible to copy.

Although this approaches were effective back in the day, both of them place their trust in the hardware, not trusting the [OS](#) entirely. Thus, since any application does not trust the [OS](#), it does not trust the application to properly use its resources either. Therefore, some of the protection aspects of the [OS](#) must be moved into the hardware, as well as changing the interface between the [OS](#) and the application so it supports the hardware security features.

[XOM](#), described in the next subsection, was developed as a way to deal with these changes that were required to use this idea of trusted computing in a better way.

2.3.1 XOM

[XOM](#) [20], which stands for eXecute Only Memory, is a processor architecture that is able to provide copy protection and tamper-resistance functions, good for enabling code to run in untrusted platforms, deployment of trusted clients in distributed systems like

banking transactions, online gaming and electronic voting, but also fundamental to deal with piracy back in the day it was published.

The main idea is to only trust the processor to protect the code and data, thus not trusting the main memory nor any software, including the host OS. However, this idea of only trusting hardware has some implications for OSes design. This happens due to the fact that sharing hardware resources between multiple users is a hard job, specially without trusting any software. It is usually easier to have this policies performed by the OS. Therefore, not trusting the software entirely can sometimes be a drawback.

For XOM architecture to be used, it is required a specific OS (XOMOS). XOMOS runs on hardware that supports tamper-resistant software, and is adapted to manage hardware resources for applications that do not trust it.

XOM offers protection against attackers who may have physical access to the hardware itself, as well as main memory protection, if compromised. For it, the XOM processor encrypts the values in memory and stores the hash of those values in memory as well. It then only accepts encrypted values from memory if followed by a valid respective hash.

2.3.2 ARM TrustZone

ARM Trust Zone [27] are hardware security extentions offered by ARM application processors with the same finality as Intel SGX, create isolated environments where software can execute in a secured and trustable way.

To accomplish this, ARM processors implement two virtual processors backed by hardware access control, where the software stack can switch between two states called secure world (SW) and normal world (NW). The first one has higher priviledges than the second one, therefore it can access NWs copies of registers, but not the other way around. SW is also responsible of protecting running processes in the CPU, while providing secured access to peripherals. Each world acts like a runtime environment and has it's own set of resources. This resources can be partioned between the two worlds or just assigned to one of them, depending on the ARM chip specs.

For the context switch between worlds, ARM processors implement a secured mode called Secure Monitor, where there's a special register responsable of determine if the processor runs code in SW or NW.

Most ARM processors also offer memory curtaining. This consists on the Secure Monitor allocating physical addresses of memory specifically to the SW, making this region of memory inaccessible to the rest of the system.

By default, the system boots always in SW so it can provision the runtime environment before any untrusted code start to run. It eventually transitions to NW where untrusted code can start to be executed.

2.3.3 AMD-SEV

AMD Secure Encrypted Virtualization (SEV) is the AMD approach to provide a TEE, integrated with virtualization. It's a technology focused primarily on cloud computing environments, specifically in public IaaS, as its main goal is to reduce trust from higher privileged parties (VMMs or OS), so that they can not influence the execution on the other "smaller" parties (VMs).

To achieve this, AMD grants encryption of memory through a technology called Secure Memory Encryption (SEM), or through TransparentSEM (TSEM) if the system runs a legacy OS or hypervisor with no need for any software modifications. After the data is encrypted, SEV integrates it with AMD virtualization architecture to support encrypted VMs. By doing this, every VM is now protected from his own hypervisor (VMM), unabling its access to the decrypted data. Although incapable of accessing the VM, the VMM is still responsible of controlling each VM's resources. [9]

Thus, AMD provides confidentiality of data by removing trust from the VMM, and creates an isolated environment for the VM to run, where only the VM and the processor can be trusted. However it does not provide integrity of data, allowing replaying attacks to take place, and has a considerably large TCB, since the OS of each VM is trusted. [25]

2.3.4 Sanctum

Just like SGX, the main objective of Sanctum is to offer strong isolation of software modules, although following a different approach focused in avoiding unnecessary complexity, thus granting a simple security analysis. To make this possible, Sanctum [7], which typically runs in a RISC-V processor, combines minimal and minimally invasive hardware modifications with a trusted software security monitor that is receptive to analysis and does not perform cryptographic operations using keys.

This minimality idea consists on reusing and slightly modifying existing well-understood mechanisms, while not modifying CPU building blocks, only adding hardware to the interfaces between blocks, causing Sanctum to be adaptable to other processors in addition to RISC-V.

Sanctum is a pratical approach that shows that a strong software isolation is achievable with a small set of minimally invasive hardware changes, causing reasonably low overhead. This approach provides strong security guarantees dealing with side-channel attacks, such as cache timing and passive address translation attacks.

2.3.5 Intel-SGX

Intel Software Security Guard Extensions (SGX) are a set of instructions built in Intel CPUs, that allow programmers to create TEEs, called enclaves. Enclaves are isolation containers that create an isolated environment where sensitive code can be stored and executed inside, ensuring integrity and confidentiality to it. By doing so, it reduces the

TCB in a way that most of the system software, apart from the enclaves and the CPU, is considered not trusted.

Enclaves are mapped into private regions of memory, where only the CPU has access to, reducing the TCB to only the enclave and the CPU itself. Due to this restrictions, not even the most common system libraries can be accessed inside the enclave, since the OS is not considered trusted.

A system that incorporates SGX under its architecture is divided in two: a trusted component being the enclave, and an untrusted component being the rest of the system. The untrusted one requests the launch of the enclave, where the CPU then manages to allocate the enclave in a private region of memory, made available only to that particular enclave. This portion of memory is kept encrypted in volatile memory, being only decrypted by the CPU if the responsible enclave requests it [4].

Although isolation is the main objective of SGX, it still allows a way for both untrusted and trusted parties to communicate. This is made possible by the functions ECALL and OCALL. ECALLs are used for an untrusted component to call for trusted code in a secured way - the enclave copies the pointers to that specific code into a buffer, which is then made visible for the untrusted component, ensuring that the untrusted party can't know the real memory address inside the enclave. To communicate the other way around the enclave calls for an OCALL, where the enclave is temporarily exited, executing then the untrusted function needed. After that, the enclave is re-entered. OCALLs are mainly used by the enclave to access the network or to deal with I/O disk access.

2.4 SGX-Enabled Frameworks and Shielded Applications

The need for cloud computing is constantly growing in modern applications. It is a cost-effective and practical solution to run large distributed applications, however the fact that it requires users to trust the cloud provider with their code and data creates some trust concerns for developers.

Although the usage of TEEs aim to tackle this problem by running and storing sensitive data on a isolated environment, protecting that data from unauthorized access. To accomplish this, the main approach is to divide the application into trusted and untrusted parts, reducing the TCB as much as possible as a way to reduce security breaches.

In the next sections we'll discuss frameworks that can accomplish solutions to the problem described above, by working with Intel-SGX as the TEE provider, as a way to complement its regular execution.

2.4.1 Shielded protected applications in untrusted Clouds

As said previously, cloud computing is becoming more and more adopted in today's systems. Therefore, by being a such popular technology, it is a must that their users data remains confidential. However, today's cloud systems are build using a classical

hierarchical security model that aims to protect only the cloud provider's code from untrusted code (user's virtual machine), while doing nothing in terms of protecting the users data. Hereupon, the users of a cloud platform must trust the provider's software entirely, as well as the provider's staff (i.e. system administrators or anyone with physical access to the hardware).

Several approaches were developed as a way to deal with this potential problem, by implementing the notion of shielded execution for applications running in the cloud.

This concept consists on running server applications in the cloud inside of an isolated compartment. The cloud provider is limited to offering only raw resources (computing power, storage and networking) to the compartment, without being able to access any of the users data, except the one being transmitted over the network.

Assuring a shielded execution of an application fundamentally means that both confidentiality and integrity of the data and code running are granted, and that if the application executes, it behaves just as it is expected. As for the provider, it retains control of the resources, and may protect itself from a malicious guest [3].

2.4.2 SCONE

Container-based virtualization has become quite popular for offering better performance properties than the use of VMs, however it offers weaker isolation guarantees, therefore less security. That's why we observe that containers usually execute network services (i.e. Redis). These are systems that don't need as much system calls as the other services, since they can do a lot via networking, thus keeping a small TCB for increased security.

SCONE [1] is a mechanism for Linux containers that increases the confidentiality and integrity of services running inside them by making use of Intel-SGX.

SCONE increases the security of the system while trying to keep the performance levels reasonable. It does it by: (1) keeping the size of the container's TCB as small as possible, by linking a (small) library inside the enclave to a standard C library interface exposed to container processes. The system calls are executed outside the enclave, and networking is protected by TLS. (2) maximizes the time threads spend inside the enclave by supporting user-level threading and asynchronous system calls, thus allowing a thread outside the enclave to execute system calls without the need for enclave threads to exit. This increases the performance since major performance losses are caused by enclave threads entering/exiting, due to the costs of encrypting/decrypting the data.

2.4.3 Haven

Haven is the first system to achieve shielded execution of unmodified legacy applications for a commodity OS (Windows) and hardware, achieving mutual distrust with the entire host software stack.

It leverages Intel-SGX to protect against privileged code and physical attacks, but also against the challenge of executing unmodified legacy binaries while protecting them from an untrusted host.

Instead of shielding only specific parts of applications and data by placing them inside enclaves, Haven aims to protect entire unmodified applications, written without any knowledge of SGX.

However, there may be problems with this approach. Executing entire chunks of legacy binary code inside an SGX enclave pushes the limits of SGX, and while the code to be protected was written assuming that the OS executing the code would run it properly, this may not be the case. The OS may be malicious. For this latest problem, the so called "Iago attack", Haven uses a library OS adapted from Drawbridge [26], running inside an SGX enclave.

By combining with a remote attestation mechanism, Haven is able to guarantee to the user end-to-end security without the need of trusting the provider.

Although this approach may need a substantial TCB size (LibOS quite large), all this code is inside the enclave, which makes it under user's control.

That's the main goal of Haven: give the user trust by granting confidentiality and integrity of their data when moving an application from a private area to a public cloud.

2.4.4 OpenSGX

OpenSGX [16] was developed as a way to help with the access to TEE software technologies, since these type of technologies were only available for a selected group of researchers. It was made available as an open source platform, and by providing TEE and OS emulation, it contributed a lot for expanding the possibility of research in this area, as well as promoting the development of SGX applications.

OpenSGX emulates the hardware components of Intel-SGX and its ecosystem, including OS interfaces and user library, as a way to run enclave programs. To emulate Intel-SGX at instruction-level, OpenSGX extended an open-source emulator, QEMU. Its practical properties result due to six components working with each other: (1) Hardware emulation module: SGX emulation, by providing SGX instructions, data structures, EPC and its access protection, and SGX processor key; (2) OS emulation: since some SGX instructions are privileged (should be executed by the kernel), OpenSGX defines new system calls to perform SGX operations, such as dynamic memory allocation and enclave provisioning; (3) Enclave loader: enclave must be properly loaded to EPC; (4) User library: provides a library (sgxlib) with a useful set of functions to be used inside and outside the enclave; (5) Debugging support; (6) Performance monitoring: allow users to collect performance statistics about enclave programs.

In Figure ?? we see an overall example of this framework, where a regular program (Wrapper) and a secured program (Enclave Program) both run as a single process in the same virtual address space. Due to the fact that Intel-SGX uses privilege instructions to

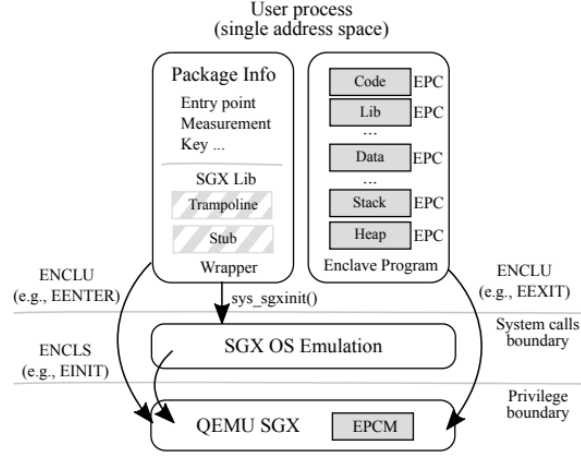


Figure 2.1: Overview design of OpenSGX framework and memory state of an active enclave program

setup enclaves, the requests from the Wrapper program are handled by the OpenSGX set of system calls.

OpenSGX was proven capable of running nontrivial applications and promotes the implementation and evaluation of new ideas. By being the first open-source framework to emulate a SGX environment, it was shown to be fundamental to the growth in the TEE area.

2.4.5 Panoply

Panoply [34] is a system that works as a bridge between SGX-native abstractions and standard OS abstractions, required by most commodity Linux applications. It divides a system into multiple components, called micro-containers (or "micron"), and runs each one of them inside its own enclave. However, when microns communicate with each other, their communication goes through a channel under the OS control. Thus, Panoply design goals are focused on supporting OS abstractions with a low TCB, while also securing inter-enclave communications.

Panoply's design consists of a set of runtime libraries (shim library included) and a build toolchain that helps developers to prepare microns. With this, a programmer can assign annotations to functions to specify which micron should execute a specific function. If not assigned any annotation, a function will be designated to a default micron, who shall execute it. Inter-micron flow integrity is also provided during this stage.

Upon a micron start, Panoply gives it a micron-id which will be used for all further interactions with other microns. It will use this id as a way to assure that only authorized microns can send/receive messages. To extend this inter-micron interaction security, Panoply also provides authenticated encryption of every message, makes use of unique

sequence numbers, and acknowledgement messages are sent for every inter-enclave communication. Thus, Panoply can protect microns from silent aborts, replaying, or tampering attacks.

Unlike many other SGX-based frameworks, Panoply supports unlimited multi-threading and forking. Multi-threading in a way that, if a micron reaches its maximum concurrent thread limit, a new micron is launched and all shared memory operations are safely performed. Forking is achieved by replicating a parent micron's data and sending it to the child, over a secure communication.

2.4.6 VC3

Verifiable Confidential Cloud Computing (VC3) [31] is a framework that achieves confidentiality and integrity of data, as well as verifiability of execution of code with good performance through MapReduce [10] techniques. It uses Intel SGX processors as a building block and runs on unmodified Hadoop [35]. In VC3 users implement MapReduce jobs, compile and encrypt them, thus obtaining a private enclave code E^- . They then join it with a small portion of public code E^+ , that implements the protocols for key exchange and job execution. Users then upload the resulting binary code to the cloud, where enclaves containing both E^- and E^+ are initialized by an untrusted framework F .

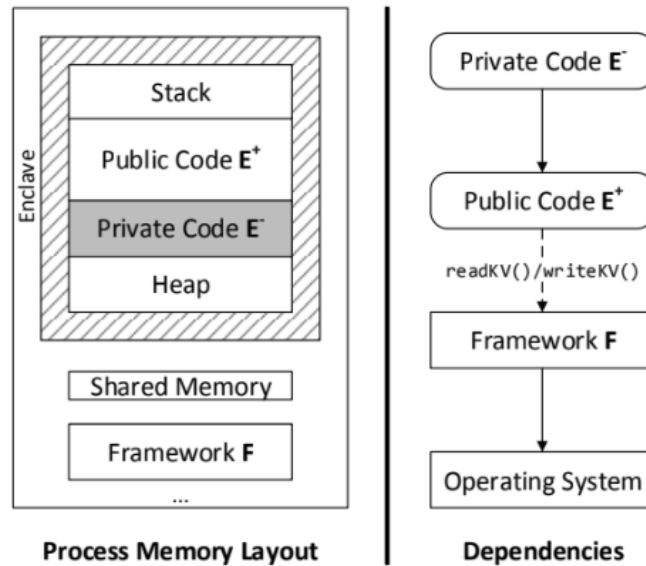


Figure 2.2: VC3 memory design model on the left, component dependencies on the right

A MapReduce begins with a key exchange between the user and the E^+ code running in the enclave. After this, E^+ can proceed to decrypt E^- and process the encrypted data. VC3 isolates this processing from the OS by keeping an interface between the E^+ layer and the outside of the enclave. This interface consists of basically two functions: `readKV()` and `writeKV()`, for reading a key-value pair on Hadoop or write it, respectively. Also, the data inside of the enclave is passed to the outside, more specifically from E^+ to the

untrusted F, by using a virtual address space shared by both. With VC3, both E- and the user data are always encrypted while in the cloud, except when processed by the trusted processor, while allowing Hadoop to manage the execution of VC3 jobs. Map and reduce nodes are seen as regular worker node to Hadoop, therefore Hadoop can provide its normal scheduling and fault-tolerance mechanisms, as well as load balancing. VC3 accomplishes this keeping Hadoop, the OS and the hypervisor out of the TCB.

2.4.7 Protected Zookeeper

ZooKeeper [13] is a replicated synchronization service for distributed systems with eventual consistency. However, ZooKeeper does not guarantee privacy of data stored inside of it by default.

Protected ZooKeeper [6] is an approach that eliminates this privacy concerns, by placing an additional layer between the client and the ZooKeeper, referred as ZooKeeper Privacy Proxy (ZPP). ZPP is a layer responsible for the encryption of all sensitive information, during a communication between a client and the ZooKeeper. Clients communicate with the proxy via a SSL connection, where the packets are encrypted by an individual session key. Here, ZPP acts like a normal ZooKeeper replica to the client. After receiving the packets from the client, ZPP extracts the sensitive data, encrypts it with a mechanism that allows the data to be decrypted by the proxy later on, and forwards the encrypted packet to a ZooKeeper replica where it can be stored with integrity ensured.

ZPP runs inside a TEE, located in the cloud, allowing it to store encryption keys and process plaintext data safely. As a result, even if the attacker is the cloud provider itself, the integrity of the data will still be granted since the attacker won't be able to access or alter anything running inside the TEE.

ZPP also retains all original ZooKeeper functionality, and does not affect ZooKeeper's internal behaviour. Therefore adapting existing ZooKeeper applications to this concept of ZPP it's easily done.

This approach allows applications in the cloud to use ZooKeeper without privacy concerns at the cost of a small decrease of throughput.

2.4.8 Ryoan

Ryoan [14] consists on a distributed sandbox that allows users to protect the execution of their data. This is achieved with the help of Intel SGX [15] [24] enclaves, creating sandbox instances that protect data from untrusted software while also preventing leaks of data, which is a weakness of enclaves caused by side channel attacks. Ryoan does not include any privileged software (e.g. OS and hypervisor) in its TCB, while trusting only the hardware (SGX enclave) to assure secrecy and integrity of the data.

It's main goal is to prevent leakage of secret data. This is done by preventing modules from sending sensitive data over their communications if outside the system boundaries,

as well as eliminating stores to unprotected memory and system calls, made possible by the use of a trusted sandbox Native Client (NaCl).

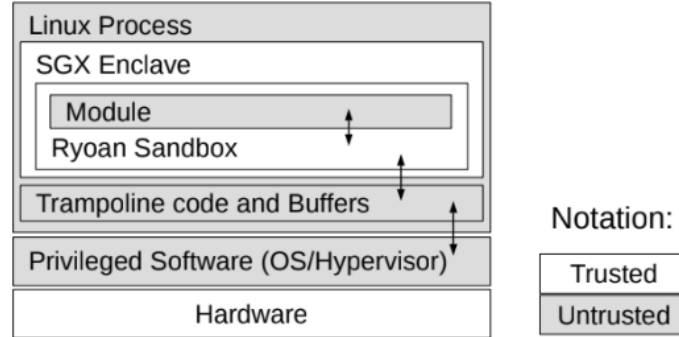


Figure 2.3: Instance of Ryoan running on a single machine

Ryoan’s approach consists on confining the untrusted application in a NaCl, responsible of controlling system calls, I/O channels and data sizes. This NaCl sandbox is implemented inside the enclave, and can communicate with other instances of the NaCl, forming a distributed sandbox between users and different service providers. Inside the sandbox, the untrusted application can execute safely on secret data. The NaCl sandbox uses a load time code to ensure that the module can not do anything it shouldn’t, thus violating the sandbox. To handle faults, exceptions or errors inside the NaCl sandbox, Ryoan uses an unprotected trampoline code, that can enter the enclave and read the information about the fault so it can handle it.

2.4.9 Opaque

Opaque [40] is a distributed data analytics platform that guarantee encryption, secure computation and integrity to a wide range of queries. Therefore, instead of being implemented in the application layer or the execution layer as this kind of security approaches usually are, Opaque is implemented in the query optimization layer.

It is implemented with minimal modifications on Spark SQL, and uses Intel SGX technology as a way to grant confidentiality and integrity of the data. However, the use of enclaves can still be threatened by access pattern leakage that can occur at memory-level, when a malicious OS infers information about encrypted data just by monitoring memory page accesses, and at network-level, when network traffic reveals information about encrypted data.

Opaque hides access patterns in the system by using distributed oblivious relational operators and optimizes these by implementing new query planning techniques. It can be executed in three modes

- encryption mode: provides data encryption and authentication, while granting correct execution.

- oblivious mode: provides oblivious execution, protecting against access pattern leakage.
- oblivious pad mode: extends the oblivious mode by adding prevention of size leakage.

Opaque is an approach that is able to grant oblivious execution 3 times faster than other specialized oblivious protocols.

2.4.10 Graphene-SGX

The usage of Intel SGX, and similar technologies, have proven to add a great sense of privacy to the storage and execution of data in applications. However this technologies impose restrictions (e.g., disallowing system calls inside the enclave) that require the applications to be changed so they can benefit from this extra layer of security.

Graphene-SGX [38] came to help circumvent those restrictions, while still assure security to the data. It is a library OS that aims to reproduce system calls, respecting security concerns, so that unmodified applications can use them to keep executing normally without interacting directly with the OS or hypervisor.

By using a library OS, the system is expected to lose performance and, since a new layer of software was added, to increase the size of the TCB. Although these assumptions are true, they are quite often exaggerated. Graphene-SGX's performance goes from matching a Linux process to less than 2x in most executions of single-processes. Graphene-SGX has also shown some great results comparing it to other similar approaches that use shim layers, such as SCONE [1] and Panoply [34], where it shows to be performancewise similar to SCONE and faster 5-10 percent than Panoply, while adding 54k lines of code to the TCB comparing to SCONE's 97k and Panoply 20k.

Graphene's main goal is to run unmodified applications on SGX quickly. Thus, whilst the size of the TCB is not the smallest comparing to the other approaches, developers can reduce the TCB as needed as a way to reach a more optimal solution.

Graphene-SGX also supports application partitioning, enabling it to run small pieces of one application in multiple enclaves. This can be useful, for instance, to applications with different privilege levels while still increasing the security of the application.

2.4.11 Other approaches

TO DO

Talk about S-NFV - (ler versao july2019 tese antiga)

Talk about hotNets

END OF TO DO

2.4.11.1 SGX-Enabled Network Protocols and Services

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M.-W. Shih, M. Kumar, T. Kim, and A. Gavrilovska. S-NFV: Securing NFV states by using SGX. In Proceedings of the ACM International Workshop on Security in Software Defined Networks and Network Function Virtualization (SDN-NFV Security), pages 45–48. ACM, 2016.

S. Kim, Y. Shin, J. Ha, T. Kim, and D. Han. A first step towards leveraging commodity trusted execution environments for network applications. In Proceedings of the 14th ACM Workshop on Hot Topics in Networks (HotNets), page 7. ACM, 2015.

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2.4.11.2 Trusted Cloud-Based System Administration

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2.4.11.3 SGX-enabled Virtualization

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2.4.11.4 SGX-Enabled Linux Containers

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<https://www.cise.ufl.edu/butler/pubs/codaspy19.pdf>

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2.4.11.5 SGX-Enabled Searchable Encryption

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2.4.11.6 ShieldStore

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<https://dl.acm.org/citation.cfm?id=3303951>

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2.4.11.7 EnclaveDB

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<https://ieeexplore.ieee.org/document/8418608>

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2.5 Summary and Discussion

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ShieldStore vs EnclaveDB

Graphene

Dissertation Approach

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2.6 Trusted Computing Environments

We're currently in a period where we start to depend more and more on allowing remote services access our data and execute our applications. Cloud computing systems require users to trust them their data. Therefore these systems need a way to assure data privacy and security, thus gaining users trust. That's were Trusted Computing Environments come in handy. A [TCE](#) is a concept that came to grant integrity and confidentiality to systems by forcing a certain machine to behave an expected way, while denying any unwanted access to the data while decrypted. This way, even if the system does not run in a trusted machine, it can be expected that it will execute as it should.

[TCEs](#) protect the system against components that, in an ideal world, should always be trusted, like the host OS or even system admins, due to the privileges they've got. As a result, and since these components can also be malicious, [TCEs](#) prevent them from abusing their privileges, thus ensuring the normal execution of the system.

In the following subsections we'll see how to achieve this properties, what hardware technologies can be used to do it and also how each one of them works.

2.6.1 TPM – Trusted Platform Modules

A [TPM](#) [11], proposed by the Trusted Computing Group (TCG), is a hardware chip called microcontroller that aims to create a trustable platform and make sure it remains trustworthy.

The microcontroller is identified by an Endorsment Key-pair, which is unique for every [TPM](#) and signed by the manufacturer. It also has a Storage Root Key (SRK) that is used to protect other keys and data inside the [TPM](#). This chip is usually found in the motherboard of most machines nowadays, and it's mainly responsible for providing and storing cryptographic keys that can be used by the system to grant data integrity and confidentiality, as well as provide persistent and volatile memory to store these keys [28].

[TPMs](#) can also be complemented with software technologies to achieve better results constructing a trusted platform.

As said before, the main objective of a **TPM** is to create the idea of a trusted platform. This will be provided by three main services: Encryption, Authenticated Boot and Attestation. The first one is used for pretty much every aspect related with security and privacy. The Authenticated boot consists in booting the OS in stages, as a way of keeping track of which code is trustable through the usage of **PCR**, that store the trusted software hashes. As for the Attestation, we'll see in the next subsection.

2.6.2 TPM – Enabled Software Attestation

TPMs enable the use of Remote attestation, which is the capability of one system to determine if other system can be trusted to run a particular piece of software as expected or not. An example can be seen in Figure 2.4.

This is made possible by having a trusted configuration of state as reference, provided by the **PCRs** defined in the boot sequence, followed by a remote system that proceeds to challenge the trusted platform (containing the **TPM**) with a nonce.

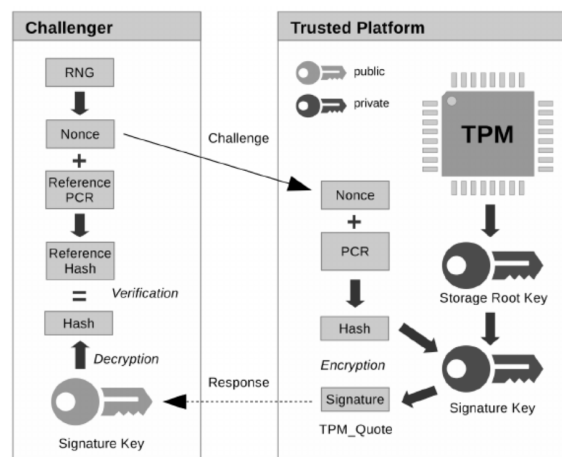


Figure 2.4: Remote Attestation process

Then the platform creates a message with the nonce received previously and the existing configuration and calculates an hash value for that message. With an Attestation Identity Key (AIK), the message is then signed and sent back to the remote system, which then proceeds to decrypt the message with the **EK** public part, that then compares the result with the hash of the nonce plus the configuration it had at the beginning of the challenge.

If the hashes match, the remote system can then identify the **TPM** platform as a trusted platform.

2.6.3 HSM – Hardware Security Modules

HSM [2] are physical components whose main function is to provide and store cryptographic keys used to encrypt/decrypt data inside a system. **HSMs** can also perform cryptographic operations (e.g. encryption, hashing, etc.) as well as authenticate through

verification of digital signatures and accelerate [SSL](#) connections [30], by relieving the servers from some of the workload caused by operations involving cryptography.

These modules are used mainly in large environment systems (e.g. large distributed systems) where there are a lot of machines communicating with each other, therefore creating a more needed sense of security. The inclusion of these modules in these big systems is actually a good idea since [HSMs](#) can also help servers relieve the workload caused by cryptographic operations. However [HSMs](#) do not quite guarantee the idea of absolute security, but increment the cost of attacking the system.

Although [HSMs](#) grant some extra level of security to a system, there's some drawbacks. One of them is the cost, where to buy one [HSM](#) the price varies depending on the sophistication of the security, plus the cost of maintenance makes it even more expensive. Another disadvantage is the difficulty to update a software module that is already running in a functional [HSM](#).

2.6.4 Trusted Execution Environments

A Trusted Execution Environment is an abstraction provided by both software and hardware that guarantees isolated execution of specific programs from all the other programs running on the same machine [4], including the host OS, hypervisor or even system administrators, preventing them from leveraging their privileges and thus take advantage of the system. A [TEE](#) also grants secured storage of sensitive data, as well as remote attestation to make sure a given program runs as expected on a remote [TEE](#).

For a user to communicate with his program running inside an isolated environment, a key-exchange between the [TEE](#) and the user takes place. This way it is ensured both integrity and confidentiality of data during further communications.

This [TEE](#) abstraction can be achieved either by using a virtual machine monitor or by running security critical software (from whole applications to little segments of code) under protection mechanisms provided by hardware [5].

In the next chapters we will be looking into more depth about this hardware protection providers, that are capable of creating trusted and isolated environments in the systems nowadays.

2.6.5 Discussion

Although all the approaches discussed before aim to offer better levels of security to applications, it's possible to find some differences between them.

Between the hardware-only approaches TPM and [HSM](#), while [TPM](#) is a "fixed" module, since it's typically on the motherboard, [HSM](#) is a more flexible approach and can be added to the system after, either as an I/O device or via network. Also [HSM](#) is more optimized to be used at the network level, and it's mainly used by banks to perform encryption of user data, while [TPM](#) is more suited to deal with encryption of local files.

Adding to this, we also discussed hardware and software approaches. From the four technologies, [SGX](#) is the one that proven to be the most reliable for our work. Comparing to ARM Trust Zone, while both really popular in today's systems, [SGX](#) supports remote attestation while ARM's approach does not. AMD SEV does not provide protection against replaying attacks, and though it's capable of running whole [VMs](#), it does not support remote attestation, much like ARM's approach. It's also less used by the community than [SGX](#). Sanctum offers a feature that [SGX](#) does not offer, which is protection against side-channel attacks. Although the fact that Sactum's implementation was focused on dealing with software attacks resulted in a minimal design for it's enclaves, thus being more susceptible to physical attacks. Also adding the fact that it's the less used approach from all four and it targeted RISC-V processors, made [SGX](#) a better option.

Although [SGX](#) does not protect an application from side-channel attacks, it ensures hardware integrity and confidentiality of data, adding the fact that it has proven to be capable of running unmodified applications, by using recently developed frameworks.

2.7 TEE/SGX Enabled Protection Against Untrusted OSes

A lot of applications these days depend on sensitive data to operate therefore protecting these data must be taken into account while designing the application.

One of the things we have to think about is the size of the [TCB](#), and how to reduce it as much as possible without losing the operability of the system. Typically, the host [OS](#) is considered safe, trustworthy, although that is not always the case. A compromised [OS](#) can give complete access to this sensitive data, regardless of how well designed the application is. That's why this is a major security problem and must be tackled in today's systems.

In the following subsections will be discussed how to achieve security for this particular problem, how to remove the OS from our TCB without losing functionality of the system, preferably without any major drawbacks in the system's performance. Thus we'll introduce some software techniques that can increase the security of an application against that threat.

2.7.1 Virtual Ghost

2.7.2 Flicker

2.7.3 MUSHI

2.7.4 SeCage

2.7.5 InkTag

2.7.6 Sego

2.7.7 Other approaches

There are also other approaches that tackle the same problem of trusting the OS, making it impossible for the execution of an application to be compromised by a malicious OS, such as

- Hardware-assisted Data-Flow Isolation (HDFI) [36] - data isolation mechanism running on top of RISC-V that uses machine instructions and hardware to enforce isolation, by virtually extending each memory unit with an additional tag that is defined by data-flow. It grants stack protection, standard library enhancement, kernel data protection, virtual function table protection, code pointer protection and information leak prevention. It's easy to use and imposes low performance overhead, while improving security.
- Secure Channel between Rich Execution Environment and Trusted Execution Environment (SeCReT) [17] - it is a framework that is focused in securing the communications between the Rich Execution Environments (REE) and the TEE built in ARM TrustZone, to add to the idea of isolation from the OS. It enables legitimate processes to use a session key in the REE, which is regarded as unsafe. To protect the key, SeCReT verifies the code's integrity and control-flow of the process every time a switch between user mode and kernel mode takes place. SeCReT's key-protection mechanism is only activated during the runtime of the process that has permission to access TrustZone, so it minimizes the performance overhead.

2.7.8 Discussion

Another conclusion about the differences of the approaches.

//TODO

Virtual Ghost - performs well compared to previous approaches; it outperforms InkTag on five out of seven of the LMBench microbenchmarks with improvements between 1.3x and 14.3x. For network downloads, Virtual Ghost experiences a 45files and nearly no reduction in bandwidth for large files and web traffic. An application we modified to use ghost memory shows a maximum additional overhead of 5to the Virtual Ghost

protections. We also demonstrate Virtual Ghost’s efficacy by showing how it defeats sophisticated rootkit attacks.

Protection against untrusted OSes.

Virtual Ghost [20] uses both compile-time and run-time monitoring to protect an application from a potentially-compromised OS, but requires recompilation of the guest OS and application.

Flicker [40], MUSHI [56], SeCage [37], InkTag [21], and Sego [32] protect applications from untrusted OS using SMM mode or virtualization to enforce memory isolation between the OS and a trusted application.

Trustlite, isolate software on low-cost embedded devices using a Memory Protection Unit.

Minibox built a 2-way sandbox for x86 by separating the Native Client (NaCl) [55] sandbox into modules for sandboxing and service runtime to support application execution and use Trustvisor [39] to protect the piece of application logic from the untrusted OS.

Secret builds a secure channel to authenticate the application in the Untrusted area isolated by the ARM TrustZone technology.

HDFI extend each memory unit with an additional tag to enforce fine-grained isolation at machine word granularity in the HDFI system.

2.8 SGX-Frameworks and Application Support

2.8.1 Network services protection approaches

Security and privacy have become one of the main concerns for both users and developers, therefore software technologies, like TLS and even anonymous networks like Tor, have become quite popular. At the same time, hardware approaches capable of providing TEEs (e.g. Intel-SGX) have also made contributions to help with this concerns. As these technologies are being adapted by applications, it’s also believed that they can have a significant impact on networking security, since they can be used, for instance, to solve policy privacy issues in inter-domain routing, thus protecting ISPs policies.

In [18] it’s shown that leveraging hardware protection of TEEs can grant benefits, such as simplify the overall design of the application, as well as securely introduce in-network functionality into TLS sessions. The same paper also presents a possible approach to reach security and privacy on a network level, by building a prototype on top of OpenSGX, that shows that SGX-enabled applications have modest performance losses compared to one with no SGX support, while significantly improving it’s security and privacy.

Also at the networking security level, the usage of Network Function Virtualization (NFV) architecture by applications nowadays imply the creation of internal state as a way to allow complex cross-packet and cross-flow analysis. These states contain sensitive

information, like IP addresses, user details and cached content (e.g. profile pictures), therefore should be a priority to ensure their protection from potential threats.

To tackle this vulnerability, S-NFV has proven to be a valid approach. S-NFV provides a secure framework for NFV applications, securing NFV states by using Intel-SGX. S-NFV divides the NFV application in two: S-NFV enclave and S-NFV host. The enclave is responsible to store the states and state processing code, while the host deals with the rest.

In [33] by implementing the S-NFV approach with Snort [29] on top of OpenSGX was concluded that this SGX-enabled approach results in bigger overheads (aprox. 11x for gets and 9x for sets) than an SGX-disabled Snort application, at the cost of extra security.

2.8.2 Application-level protection approaches

There are software approaches that allow unmodified applications to execute while offering security from potentially malicious OSes, achieved by isolating sensitive data from the rest.

In addition to Graphene-SGX 2.4.10, approaches like Haven [3], Scone [1] and Panoply [34] offer system support, by ensure a secured way for the application to make system calls, such as implementing a library OS or a standard library, inside the enclave. Haven runs an entire library OS (LibOS) inside the enclave, resulting on a very large TCB. Scone uses sandboxing as a way to reduce TCB size due to the LibOS approach. Panoply provides the abstraction of micro-container (micron), having only to import specific micron-libraries instead of the whole LibOS, resulting in a shorter increase of the TCB size.

Although capable of ensuring unmodified applications a way of running on top of SGX, the increase of the TCB size has been seen as a possible vulnerability. Thus new approaches more focused on this TCB size problem, like Glamdring [21] and SGX-Shield [32], have been developed lately by the community as possible alternatives to the above ones.

2.8.3 Discussion

Haven [15] showed that a library OS could run unmodified applications on SGX,

thin “shim” layers, like SCONE [14] and Panoply [49] wrap an API layer such as the system call table.

SGX frameworks and applications.

VC3 [45] runs MapReduce jobs in SGX enclaves.

Bren-ner et al. [17] run cluster services in ZooKeeper in an enclave, and transparently encrypt data in transit between enclaves.

Ryoan [22] sandboxes a piece of un-trusted code in the enclave to process secret data while preventing the loaded code from leaking secret data.

Opaque [57] uses an SGX-protected layer on the Spark framework to generate oblivious relational operators that hide the access patterns of distributed queries.

The *novathesis* class can be customized with the options listed below.

2.9 Related work analysis and rational

In this section we will provide some additional considerations about some of the customizations available as class options.

ELABORATION WORK DIRECTIONS

This Chapter aims at exemplifying how to do common stuff with \LaTeX . We also show some stuff which is not that common! ;)

Please, use these examples as a starting point, but you should always consider using the *Big Oracle* (aka, [Google](#), your best friend) to search for additional information or alternative ways for achieving similar results.

3.1 Materialization of objectives and contributions

3.2 System Model and Reference Architecture

3.3 Prototyping effort

3.4 Prototype Validation and Experimental Assessment

3.5 Open issues

ELABORATION PLAN

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