

Trusted Reference Monitors for Linux using Intel SGX Enclaves

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Declaration

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Abstract

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Contents

List of Figures	ii
List of Tables	iii
1 Introduction	1
2 Background	3
2.1 Information Flow Control	3
2.1.1 Motivation, History, and <i>Decentralised IFC</i>	4
2.1.2 Security Labels and the Reference Monitor	4
2.1.3 Modelling	5
2.2 Intel® SGX	8
2.2.1 Security Characteristics	9
2.2.2 Architecture and Implementation	9
2.2.3 Enclave Lifecycle	11
2.2.4 Attestation	13
2.2.5 Sealing	15
2.2.6 SGX Versions	16
2.3 Aspects of the <i>Linux</i> Kernel	16
2.3.1 Virtual File System	16
2.3.2 Linux Security Modules	17
3 Related Work	19
3.1 <i>Flume</i> and <i>CamFlow</i>	19
3.1.1 Other IFC Systems	20
3.2 Interoperation between Linux and SGX	21
3.3 Dataflow Protection using SGX	22
4 CITADEL	23
4.1 Motivation	23
4.2 Challenges	24
4.3 The CITADEL IFC Model	27

4.3.1	Reservations	27
4.3.2	Permissible Operations	28
4.3.3	Transient Entities	29
4.4	Implementation	30
4.4.1	Enforcement	31
4.4.2	Policy Components	33
4.4.3	Communication Pathways	36
4.4.4	libcitadel	38
4.4.5	Additional Security Features	40
4.4.6	CITADEL Build System	41
5	Evaluation	43
5.1	Performance	43
5.1.1	Evaluation Environment	44
5.1.2	<i>syscall</i> Microbenchmarks	44
5.1.3	IPC Microbenchmarks	47
5.1.4	NGINX Benchmarks	50
5.2	Security	51
5.2.1	CITADEL TCB	51
5.2.2	IFC Model Implications	53
5.2.3	SGX Vulnerabilities	54
5.3	Use Cases	54
6	Conclusions	57
A	PID Tampering: Proof of Concept	59

List of Figures

2.1	Abstract overview of SGX's protection in an adversarial environment. .	8
2.2	A high-level overview of the SGX hardware and software architecture.	10
2.3	The process of creating and initialising an enclave.	13
4.1	Abstract <i>syscall</i> control flow route. Grey components show the natural Linux design. Green additions highlight the externalised enclave LSM component.	25
4.2	Two possible enclave integration designs.	26
4.3	High level overview of the CITADEL architecture.	30
4.4	Accesses across the taint boundary	31
4.5	Overview of the components inside <code>citadel</code>	34
5.1	Control flow inhabitation for <code>libcitadel</code> 's <code>c_open()</code> function, $n = 100$.	44
5.2	Effective <code>read()/write()</code> bandwidths for both the native Linux kernel and CITADEL.	46
5.3	Effective bandwidths for various types of IPC between <i>2 threads</i> , $n = 200$.	48
5.4	Effective bandwidths for various types of IPC between <i>2 processes</i> , $n = 200$	49

List of Tables

2.1	Overview of the four core IFC events used in § 2.1.3.	6
2.2	Overview of notable SGX x86 instructions in an enclave's lifecycle. . .	14
5.1	libcitadel microbenchmarks	45
5.2	NGINX performance comparinon between native Linux, and both un- tainted and tainted CITADEL, $n = 25$	50

Chapter 1

Introduction

Defending computer systems against malicious programs and enforcing the isolation of protected components has always been exceedingly challenging. A system's *Trusted Computing Base*, or *TCB*, defines the minimal set of components critical to establish and maintain system security and integrity. This traditionally includes, amongst others; the OS kernel; device drivers; device firmware; and the hardware itself. Compromise of a trusted component inside a system's *TCB* is a direct threat to any secure application. One approach to hardening a system's security is to minimise its *TCB*, diminishing its potential *attack surface*.

An increasingly common trend is outsourcing a system's physical layer to a foreign party, for example a *cloud provider* — this is beneficial in terms of cost and flexibility, but confuses many security considerations which assume that the physical layer itself can be trusted. This is not guaranteed when the physical layer is a *virtual machine*, inflating the system's *TCB* with an external and transparent software layer, the underlying *hypervisor*.

Trusted Execution Environments, *TEEs*, have been explored by the security community for a very long time as potential protection against this. They generate isolated processing contexts in which an operation can be securely executed irrespective of the rest of the system — one such example is software *enclaves*. *Enclaves* are general-

purpose *TEEs* provided by the CPU, protecting the logic found inside at the architectural level. Intel’s Software Guard Extensions (SGX) is the most prolific example of a *TEE*, affording a *black-box* environment and runtime for arbitrary apps to execute under.

An alternative approach is the use of *Information Flow Control* (IFC) to police system components. Enforced using a *reference monitor*, IFC models permissible data use, manipulating systems at a granular level.

This work aims to explore methods of hardening Linux with an SGX-driven *reference monitor* to track and protect host OS resources using IFC methods. Further, it aims to reason what the future relationship between an OS and the enclaves it hosts should be, and whether complete isolation between them is the natural answer in several common situations.

Contributions

- A prototype implementation of a modular *reference monitor* protected using Intel SGX, empowering IFC techniques to operate with autonomy and protection from the host operating system. Enforcement is achieved using a *Linux Security Module* embedded in the Linux kernel, with an overall *TCB* of only a minimal footprint of the kernel alongside the enclave application.
- A userspace interposition library to near-transparently integrate unmodified applications to fully function under the new restrictions.
- A full port of the *libtomcrypt* cryptography library for use inside an SGX enclave.
- A rigorous investigation of the performance implications of this approach, featuring a lightly-modified version of the *Nginx* production webserver. Worst-case performance shows a 24% decrease in request throughput, with other trials reporting performance parity with native Linux. Additionally we report a median overhead of $43\ \mu s$ (IQR $26 - 72\ \mu s$, $n = 10^6$) per affected *system call* without caching, matching or surpassing similar, non-enclave-based, systems.

Chapter 2

Background

This chapter will cover the topics essential to understanding the rationale and implementation of the design as discussed in § 4. These include; an introduction to *Information Flow Control (IFC)*, the Intel SGX platform, and an overview of key aspects of the Linux kernel relevant to the architecture of the prototype.

2.1 Information Flow Control

IFC regulates how and where data is permitted to move and be transformed in a computer system. [1] This differs from access control, which defines *what* resources may be used by an entity — IFC allows granular control over *how* they may be used once accessed, including restricting propagation between components.

Formally, IFC defines and enforces a non-interference policy between abstract *security contexts*. A simple example is the distinction between *unclassified* and *classified* data — here, information is only allowed to flow *up*, ensuring that an *unclassified* entity does not learn anything marked as *classified*. [2] In general this relationship can be represented as a partial ordering over *security contexts*, formulated as a lattice. [3]

However, practical systems often require dataflow adhering to a more complicated policy set — for example, supporting *declassification*. [4] Work undertaken by Pasquier

et al., [5] the core influence of the IFC model developed in this project, constructs a pliable and efficient *decentralised information flow control (DIFC)* model suitable for provenance enforcement and auditing in the Linux kernel.

2.1.1 Motivation, History, and *Decentralised IFC*

IFC has, in recent years, been increasing in support as a powerful methodology for ensuring granular privacy whilst not unduly restricting access to sensitive information. IFC annotates data records with opaque *labels* referring to their confidentiality or integrity status. Rather than simply restricting access to sensitive data, as an access control mechanism would, IFC tracks data as it propagates — if an entity attempts to move data into an unknown, untrusted, or conflicting *security context* the IFC system prohibits this to prevent improper release.

IFC originated from research conducted in the mid-1970s [3] but has not, as of yet, seen mainstream adoption. A major reason for this is that early schemes were designed around the *multi-level security (MLS)* doctrine set out in the *Orange Book*: [6] this locked IFC to a shallow set of broad labels, mirroring existing institutional segregation (such as *restricted*, *secret*, *top secret*). Policies were managed centrally, something easily applicable in settings with rigorous hierarchies such as the military, but unwieldy in an organisation with manifold security protocols.

The majority of recent research has advocated *decentralised information flow control (DIFC)*, introduced by Myers and Liskov. [7, 8, 9] DIFC is more granular than schemes adhering to the *MLS* model, for example, creating two distinct *security contexts* for two files in the same folder. Policies are *discretionary*, allowing users to specify and modify the enforced policies for assets they own.

2.1.2 Security Labels and the Reference Monitor

A DIFC system relies on *tags* and *labels* to annotate the entities it tracks. Let \mathcal{T} be a large set of opaque tokens, or *tags*. An individual tag alone does not carry any particular meaning, but is used as an abstract identifier for an entity's *security context*. A *label*, $l \subseteq \mathcal{T}$, is a collection of tags that are concretely attached to assets, such as files;

these form a lattice under the subset-relation partial order. For each process a there are two labels, one for secrecy, a_s , and one for integrity, a_i . For a tag t , $t \in a_s$ implies, conservatively, that process a has seen information associated with tag t . Likewise, $t \in a_i$ indicates that every input to a has been endorsed for an integrity level marked with t .

Walkthrough — Secrecy Enforcement In a typical environment, a user can only convince themselves that a text editor is safe to use if they, or someone they trust, audits the program’s source code. With DIFC however, it is possible to reason that if the system can provide the following four guarantees, it cannot leak sensitive data without the user’s permission.

1. If a process a read a file with a secrecy tag t , then $t \in a_s$.
2. $t \in a_s$ implies that a cannot communicate with another process, b , where $t \notin b_s$.
3. a cannot remove t from a_s without permission.
4. $t \in a_s$ restricts a ’s access to an uncontrolled medium, such as a network.

The heart of an IFC implementation is its *reference monitor*, which tracks the labelling for each process, granting or rejecting permission to execute an operation before it is executed by the OS. Contrasting solutions handle this process differently: *Flume*, [10] for example, implements a full system interposition layer, forcing all *syscalls* to pass through its userspace *reference monitor* before reaching the OS, whereas *CamFlow* [5] embeds its *reference monitor* in the kernel itself. In all schemes, however, this trusted component is responsible for both policy and enforcement. This project focusses on this implementation.

2.1.3 Modelling

In centralised IFC schemes, the *reference monitor* is the only entity capable of creating, changing, and assigning tags. However DIFC gives *all* processes the ability to create and modify tags for entities they own; thus they alone have the right to declassify them.

Notation	Explanation
$A \rightarrow B$	Rule α ; a permissible information flow between entity A and entity B .
$A \Rightarrow B$	Rule β ; a creation flow, initialising B from A as its parent.
$A \rightsquigarrow A'$	Rule γ ; a context change, with A modifying its security context in accordance with its capabilities.
$A \xrightarrow{t_x^\pm} B$	Rule δ ; privilege delegation, with A passing a capability t_x^\pm to B .

Table 2.1: Overview of the four core IFC events used in § 2.1.3.

Notation As the model we build in § 4 is closest in spirit to *CamFlow*, we use the same notation (as summarised in Table 2.1).

Enforcing Safe Flows (α) , below, describes the conditions in which a flow can be considered *safe*. The recipient must be *at least as privileged* as the originator and cannot accept information graded below its own integrity status. Here \preceq denotes any applicable preorder relation; this context uses inclusion (\subseteq). If a flow is *impermissible* it is denoted as $A \nrightarrow B$.

$$A \rightarrow B \iff A_s \preceq B_s \wedge B_i \preceq A_i \quad (\alpha)$$

Information produced within a *security context* may only flow within the same context or a related *subcontext*.

Entity Creation Correct initialisation of a new object’s *security context* is shown in (β) . Logically it must be held at the same level as the environment creating it. For example, when a process creates a new file, this must subject to the same tainting as the original process.

$$A \Rightarrow B \implies A_s = B_s \wedge A_i = B_i \quad (\beta)$$

Vocational Label Management The core mantra of the *decentralised* aspect of *DIFC* is that processes are responsible for policies governing their assets. Therefore, a process's labelling must be dynamic. Generally, entities are sorted into two distinct categories;

- *Active* (processes), with *mutable* security contexts.
- *Passive* (files, pipes, sockets, etc.), which merely act as data vessels for *active* entities.

Active entities may modify their labelling iff they have the capability to add or remove specific tags. The set $A_s^+ \subseteq \mathcal{T}$ lists all the tags that entity A has the ability to add to its security labelling, while $A_s^- \subseteq \mathcal{T}$ holds all the tags A has the ability to remove from its labelling. These sets are modified either during creation or in receipt of a delegated capability from a peer. The sets $A_i^\pm \subseteq \mathcal{T}$ also exist, performing the same function for integrity labels. (γ) describes this process formally.

$$\left\{ \begin{array}{ll} A'_x \leftarrow A_x \cup \{t\} & \text{if } t \in A_x^+ \\ A'_x \leftarrow A_x \setminus \{t\} & \text{if } t \in A_x^- \end{array} \right\} \implies A \rightsquigarrow A' \quad (\gamma)$$

A notable restriction is that processes need to be aware of the IFC constraints imposed on them and how to interact with the system to manage their labels.

Capability Lifecycle and Delegation As defined by (β) , an entity automatically inherits the labelling of its creator: however without any capabilities ($A_s^\pm, A_i^\pm = \emptyset$). This raises the need for *capability delegation* (δ) . A capability held by A , t_x^\pm , where $t \in A_x^\pm$, is permitted to be transferred to B to act on its behalf.

$$A \xrightarrow{t_x^\pm} B \text{ only if } t \in A_x^\pm \quad (\delta)$$

Delegation is vital for web servers, for example. To transmit another entity's information over an untrusted socket the server must have permission to *declassify* it — i.e. it must hold f_s^- , where f is the secrecy label of the information to transmit.¹

¹The server process, W , must have $W_i = \emptyset$ as it holds a connection to an untrusted socket. Thus the integrity clause in (α) will not interfere.

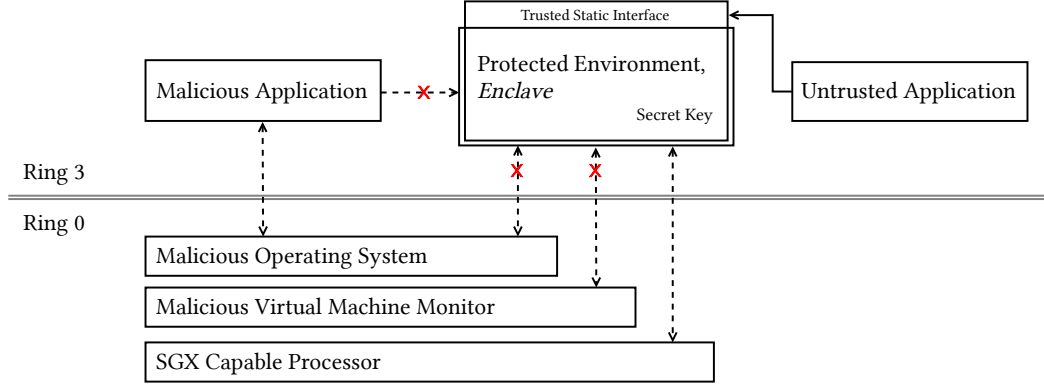


Figure 2.1: Abstract overview of SGX’s protection in an adversarial environment.

2.2 Intel® SGX

Intel’s Software Guard Extensions, SGX, was first announced and detailed in 2013. [11, 12, 13, 14] It’s whitepapers described a novel approach to *trusted computing*, creating in-CPU containers with dedicated protected memory pools. These regions, called *enclaves*, cannot be read from or written to by an unauthorised party due to fundamental protection mechanisms provided by the x86 architecture, even if running in *Ring 0*² (Figure 2.1). *Enclaves* guarantee both integrity and secrecy to the application running inside it, even in the presence of a malicious host.

Motivation At a high-level SGX aims to achieve security for sensitive applications by shielding them and their resources against tampering, and to guarantee an enclave’s integrity to end-users; this is achieved using attestation and measurement (described in § 2.2.4). One use cases [15, 16, 17] is in cloud computing, where users are forced to trust an outside party with their data and business logic. By distributing encrypted, yet executable, containers targetted at a single, unique SGX core, users can be assured that their information is safe, regardless of virtualisation. Only the provisioned CPU is able to decrypt and execute the enclave, strictly in accordance with the restrictions of the SGX platform.

2.2.1 Security Characteristics

At its heart SGX is designed to be *trustworthy*; this is achieved in several ways, including robust enclave provisioning, sealing and attestation. Intel summarises SGX’s protections [12, 18] as follows;

- Memory is secured against observation and modification from outside the enclave, using an in-die *Memory Encryption Engine (MEE)*, [19] with a secret that rotates on every boot. This protection notably works against host hypervisors, other enclaves, and anything running in supervisor mode.
- Enclaves can *attest to*, or prove, their identity to a challenger with the help of a permanent hardware security key for asymmetric encryption.
- Software calls are proxied to prepare and transfer control in and out of an enclave. Arguments are securely marshalled according to a static enclave definition.
- SGX does not defend against reverse engineering or side-channel attacks: [20] mitigating this is the developer’s responsibility.

2.2.2 Architecture and Implementation

The SGX platform comprises several interlocking parts (Figure 2.2), building on the core extended x86 instruction set. Information here as reported by [14, 21].

2.2.2.1 Hardware

Enclaves’ state is stored securely in *Processor Reserved Memory, PRM*, a set of pages in system memory presided over by the *MEE*. *PRM* consists of two data structures; the *Enclave Page Cache (EPC)* and the *Enclave Page Cache Map (EPCM)*.

An enclave is defined by its *SGX Enclave Control Structure, SECS* — generated when an enclave is created and stored in a dedicated entry in the *EPC*. A *SECS* holds important metadata including; the enclave’s (system-)global identifier, its measurement hash (*MRENCLAVE*, § 2.2.4) and its memory usage.

²Linux uses two of x86’s four protection *rings* — 0 for the kernel, and 3 for userspace.

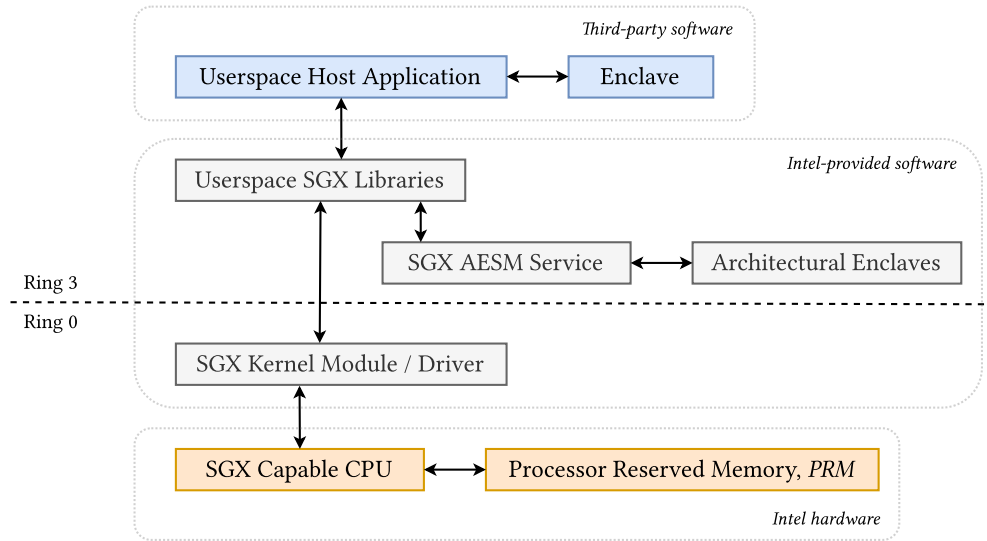


Figure 2.2: A high-level overview of the SGX hardware and software architecture.

The *EPCM* provides an index into the *EPC*: it stores access control information, ownership and validity indicators, and a marker for a page’s designated use — this is not accessible from software.

PRM pages are only successfully resolved if the CPU is in enclave mode and the *EPCM* corroborates the enclave’s ownership of the region; invalid requests are presented with an unused page from generic system memory. Direct Memory Access to *PRM* is always rejected.

The *EPC* is managed by the system’s hypervisor or OS as typical memory, but it must use SGX-specific instructions. This is to appease the *MEE*, which is responsible for ensuring the integrity and confidentiality of this process, encrypting and decrypting pages as they cross the *PRM* boundary. An SGX driver, *isgx*, is required to allow userspace applications to use the platform and create/manage enclaves.

2.2.2.2 Userspace Services

Starting an enclave requires a *launch token* to be retrieved from Intel’s *Launch Enclave*; this checks the signature and identity of the enclave to ensure it is valid. Ac-

cess to the *Launch Enclave* and other architectural enclaves is provided by the AESM³ service; the userspace SGX libraries facilitate the communication mechanism. Other architectural enclaves include;

- The *Provisioning Enclave* — this verifies the authenticity of the platform and retrieves an enclave’s *attestation key* from the *Intel Provisioning Service*’s servers.
- The *Quoting Enclave* — this provides trust in the identity of the SGX environment and enclave being attested, by converting the locally generated *attestation key* to a remotely-verifiable *quote*.

2.2.2.3 Third-party enclaves

Enclaves are always accompanied by a host application which acts as its untrusted counterpart. The host application calls the SGX SDK to build an enclave on its behalf using an enclave image, packaged as a standard shared library (`enclave.so`) and returns its *global identifier*. Control is passed from the host application to the enclave by invoking an enclave function via an *ECALL*. Execution flow can temporarily leave the enclave if it calls one of the host application’s functions via an *OCALL*. Execution naturally leaves enclave-mode when an *ECALL* terminates. Both *ECALLs* and *OCALLs* are defined statically in the enclave’s interface definition (`enclave.edl`), and the necessary glue code is generated by the SGX SDK’s build toolchain at compile time; this ensures calls crossing the enclave boundary are marshalled safely and correctly.

2.2.3 Enclave Lifecycle

SGX instructions can be separated into two distinct groups; privileged and unprivileged. These, alongside a description of the function they perform, are enumerated in Table 2.2.⁴ The following description of the process of creating an enclave is illustrated in Figure 2.3.

Preparing an enclave To begin, the host application needs to initiate the creation process via a component with *ring 0* privilege — we use *isgx*, the SGX driver. *isgx*

³Application Enclave Services Manager

⁴A handful of instructions not relevant to the explanation given here are omitted.

allocates the requisite number of pages to run the enclave $\langle 1 \rangle$;⁵ this is tracked by the driver’s internal state $\langle 2 \rangle$.

The application next calls ECREATE with the metadata of the enclave to be loaded $\langle 3 \rangle$; the *MEE* checks that the pages being claimed are vacant and populates the *SECS* page $\langle 4 \rangle$. Once complete the application prepares the remaining *EPC* pages using EADD $\langle 5 \rangle$ and loads the enclave’s code and data $\langle 6 \rangle$.

Next the enclave is measured — EEXTEND is called $\langle 7 \rangle$, triggering the *MEE* to update the measurement hash in the *SECS* to mirror the current state of the enclave’s memory $\langle 8 \rangle$. After, the *EPC* memory finalised using EINIT $\langle 9 \rangle$: this operation requires the application to retrieve the EINITTOKEN from the *Launch Enclave*, locking the execution of the measured enclave to currently assigned processor core. Notably, pages cannot be added after EINIT,⁶ and an enclave cannot be attested to or entered before it. To conclude, the *SECS* is updated with the enclave’s final hash $\langle 10 \rangle$.

Stepping into the enclave OAfter creation, an enclave may be invoked using the EENTER instruction; this can only jump to points explicitly defined in the enclave’s interface definition, and switches the CPU core to enclave mode. SGX uses a flag in the CPU core’s *Thread Control Block* to prevent any other logical core following the current one into the enclave.

Interrupts and exceptions can be served to the enclave, just as with any other application. Control, however, is not immediately passed over to the defined handler. Instead the enclave’s current state is saved and cleared to prevent leaking. The *Asynchronous Enclave Exit* routine is then invoked and enclave mode disabled. Execution post-interruption is restarted with ERESUME. Once an enclave finishes execution, all registers are erased and EEXIT called. Enclaves are terminated using the EREMOVE command; all claimed *EPC* pages are marked as invalid and the *SECS* page deleted.

A significant restriction of the SGX architecture is that enclaves cannot be entered from *ring 0*; [22] the required instructions are simply not available. Thus all host ap-

⁵These numbers correspond to events in Figure 2.3.

⁶This is only strictly true in SGXv1, as explained in § 2.2.6.

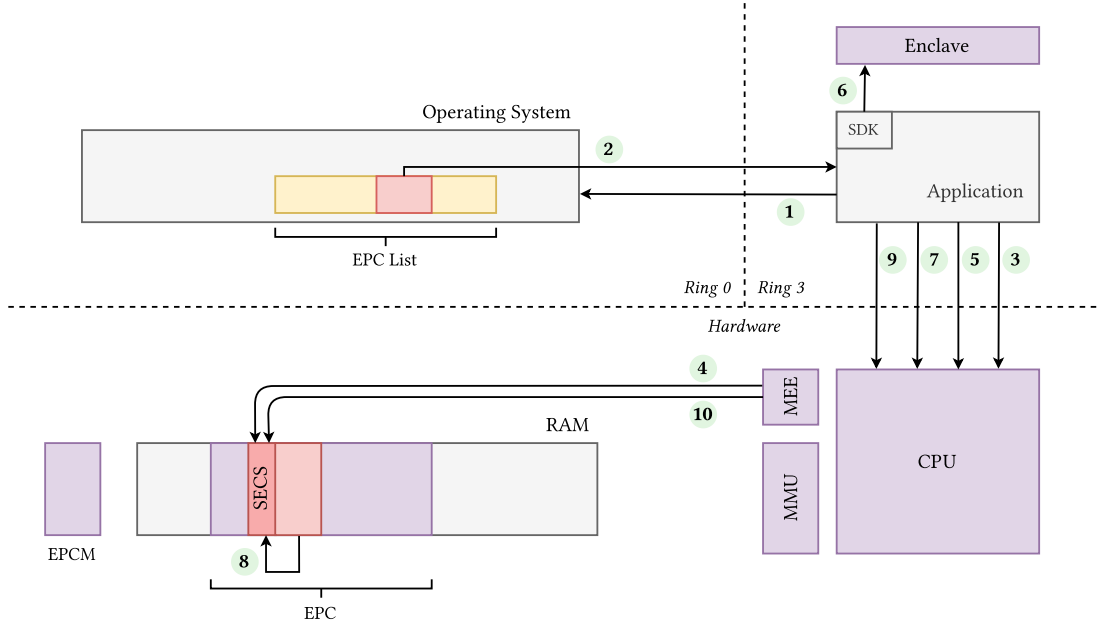


Figure 2.3: The process of creating and initialising an enclave; details given in § 2.2.3. Purple components belong to the SGX platform.

plications must run in userspace, making interoperation with the kernel challenging, as discussed in § 4.2.

2.2.4 Attestation

An essential feature of the *trusted computing* model SGX creates is attestation, the process of verifying both the authenticity and integrity of components cryptographically. SGX achieves by creating two *signing identifiers* per enclave; MRENCLAVE and MRSIGNER. [13, 23]

MRENCLAVE acts as a unique identifier for enclave's contents. It is generated by hashing the instructions and data passed when creating the enclave with ECREATE, EADD, and EEXTEND; the value is finalised and stored in the SECS on EINIT. This value depends on the exact content and ordering of the enclave's EPC pages. As long as the enclave's source remains the same, so will its MRENCLAVE.

Execution Mode	Instruction	Function
Ring 0	ECREATE	Generate and copy the <i>SECS</i> structure to a new page in the <i>EPC</i> , initialising a new enclave.
	EADD	Add a new <i>EPC</i> page for the current enclave; this is used to load initial code and data.
	EEXTEND	Updates the enclave's measurement during attestation; modifies the <i>SECS</i> .
	EINIT	The terminal instruction in an enclave's initialisation, finalising its attributes and measurement.
	EREMOVE	Permanently remove a page from the <i>EPC</i> ; usually invoked during enclave destruction.
Ring 3	EENTER	Transfer control from the host application to a pre-determined location in an enclave.
	ERESUME	Re-enter the enclave after an interrupt/exception and resume execution.
	EEXIT	Restore the original operating mode at the location <i>EENTER</i> was triggered and flush the TLB.
	EGETKEY	Access platform cryptography keys required for attestation and sealing.
	EREPORT	Generate a <i>report</i> for an enclave's <i>attestation key</i> for an attestation process.

Table 2.2: Overview of notable SGX x86 instructions in an enclave's lifecycle. [22]

MRSIGNER, also known as the enclave’s *Sealing Identity*, is generated during the enclave build process — all production enclaves need to be signed using an RSA key provided by the compiling user (the *Sealing Authority*). The public key from this pair is stored in *SIGSTRUCT*, the *Enclave Signature Structure*. During an enclave’s launch its signed compile-time MRENCLAVE value (held in *SIGSTRUCT*) is decrypted and cross-referenced with a freshly-computed runtime MRENCLAVE value to detect tampering. MRSIGNER is the same for all enclaves signed by the same *Sealing Authority*.

Local Attestation Two enclaves resident on the same system are able to attest their identities to each other using their MRENCLAVE and MRSIGNER values; this usually precedes the establishment of a shared secret (using a variant of *Diffie-Hellman* backed by the platform’s master SGX key) for confidential communication between them.

Remote Attestation The Intel specification also provides a workflow for an enclave to attest its identity to a remote party. The system’s *Quoting Enclave* verifies an enclave’s local *quote* and creates a digital signature of it using the CPU’s permanent hardware SGX private key. Through the use of an *Intel Enhanced Privacy Identifier (EPID)* [24] this process can be carried out anonymously; it relies on information encoded in the CPU during the manufacturing process. The *Provisioning Enclave* assists in this process, especially as production enclaves are required to attest with Intel’s provisioning service [23] before executing. Remote attestation is not explicitly required in this project, hence will not be covered in any further detail.

2.2.5 Sealing

Sealing is the encryption of data using a key unique to the generating enclave on a particular platform. SGX offers two policies for deriving the encryption key based on the platform’s *Root Sealing Key* — relative to the current enclave (MRENCLAVE) or the current enclave’s *Sealing Authority* (MRSIGNER). These serve many use cases, including allowing state to persist through enclave upgrades.

2.2.6 SGX Versions

There are currently two versions of SGX available — the details given here relate to *v1* as this project will be compatible with both. *v2* offers a number of improvements on which this project does not rely, including: (a) dynamic memory management, (b) eased production enclave restrictions (‘Flexible Launch Control’), (c) increased PRM size support, and (d) support for virtualisation.

2.3 Aspects of the *Linux* Kernel

Linux needs little introduction. First created in 1991 as an open-source alternative to UNIX, it now powers over 90% of *the cloud* and 85% of smartphones. With almost 25,000 contributors to the kernel, it is immensely complex, with numerous interlocking parts. This section shall provide a brief overview of a small subset of them to support the information given in § 4.

2.3.1 Virtual File System

Linux represents almost every component as a file, including sockets, terminals, and driver interfaces. The VFS is the transparent layer that provides this abstraction, routing requests to the correct underlying implementation. This virtual interface relies on the following mechanisms.

Superblocks The *superblock* attached to an entity represents the characteristics and properties of the filesystem in which it sits. An important marker held in the superblock is its *magic value*; this predefined code⁷ indicates the underlying implementation the filesystem belongs to.

Inodes The *inode* data structure represents information about a single file existing on a file system. All objects, not only files, are *backed* by inodes. No pathname is assigned at this level; this is provided at a higher level of abstraction. An inode does however indicate ownership, access restrictions and content type, and is identified by its *inode number*.

⁷Defined in `include/uapi/linux/magic.h`.

Dentries Each item in the *direct entry cache* (*dcache*), shortened to *dentry*, represents a connection between an inode its path in the VFS. This glue layer is responsible for building the tangible folder structure, and as the name suggests, metadata caching. A *file* consists of a *dentry-inode* pair.

File descriptors Whenever a process opens a file, it is presented with a *file descriptor* by the kernel. This structure is unique to a process, providing the gateway between the process and the underlying file it describes. All active descriptors can be viewed at `/proc/<pid>/fd/`; for standard processes *0* globally refers to *stdin*, *1* to *stdout*, and *2* to *stderr*. Reads and writes to a file (or socket, pipe, etc.) are performed on the relevant file descriptor, not the object directly.

2.3.1.1 Extended Attributes

Files can have additional, external, key-value pairs attached to them. These attributes, shortened to *xattrs*, are permanent and saved to disk alongside the file's content. Values must be in the form of a null-terminated string, however they are optional and may be left empty if the attribute is just a flag. *xattrs* are namespaced to define different classes of functionality; the user namespace is open to all (e.g. `user.example_attribute`), but `trusted`, `system`, and `security` are reserved for specific uses by the kernel — the `security` namespace belongs exclusively to LSMs (§ 2.3.2).

2.3.1.2 *sysfs*

sysfs is a pseudo-filesystem provided by the VFS, that the kernel uses to export its subsystems via a virtual file interface (`/sys`). Specific instantiations of *sysfs* are used for various purposes — for example, LSMs and *SecurityFS* (`/sys/kernel/security`).

2.3.2 Linux Security Modules

Linux supports the inclusion of third-party security models in the kernel itself using a unified framework, LSM. This provides developers with *hooks* into kernel functionality at every point a userspace *syscall* is about to access fundamental kernel primitives,

such as inodes or task control structures. Each of these hooks can influence the behaviour of the kernel by allowing or denying the operation.

LSM attaches a `void*` security field to every instance of kernel primitives, such as `struct inode`, to allow security implementations to attach additional state to each, tracking them as appropriate. Decisions taken within an LSM affect all aspects of a Linux system; *superuser* privilege cannot override it and every component in the system can be restricted.

2.3.2.1 Integrity Measurement Architecture

Linux's IMA subsystem is responsible for calculating the hashes of files and programs as they are loaded (*measurement*), verifying them against an allowed list if required (*appraisal*). Its driving purpose is to detect if files have been maliciously altered remotely or locally; the file's hash is stored as an *xattr* (`security.ima`). IMA supports many use cases, the majority of which are complementary to the LSM framework, but we shall focus on one here — EVM.

The Linux *Extended Verification Module*, *EVM*, protects *xattrs* in the `security` namespace — this covers both the IMA hash and any labels created by security modules. Two tamper-detection methods are provided:

1. The *HMAC-SHA1* hash of the `security` namespace is stored as `security.evm` for reference, and
2. A digital signature of this value is stored alongside using a key that is sealed either using a *TPM*⁸ or passphrase.

⁸Trusted Platform Module. [25]

Chapter 3

Related Work

There is a wealth of theoretical and practical research, forming an essential background to the work presented here. To provide adequate grounding, we discuss a handful of the most notable — split into two distinct fields, *Information Flow Control* and Intel SGX. Little study has been conducted in this overlap, but that which exists will be highlighted as appropriate.

3.1 *Flume* and *CamFlow*

Both *Flume* [10] and *CamFlow* [5] present practical DIFC systems for generic, OS-level protection in Linux. Their models are not dissimilar, with *CamFlow* refining the basic *Flume* approach. A detailed overview of the *CamFlow* model has already been presented in § 2.1, but there are important differences in the implementation of the two works.

Flume *Flume* takes the form of a userspace reference monitor. Processes confined by *Flume* are not able to perform most *syscalls* directly — an *interposition layer* replaces *syscalls* with IPC¹ to the reference monitor, which enforces IFC policies and ensuring operation safety on processes' behalf. The majority of complexity lies in the reference monitor, with its LSM only a small auxiliary companion. The authors report a 30 – 40%

¹Interprocess Communication.

overhead.

CamFlow In contrast, the *CamFlow* core IFC implementation lies entirely within its LSM, efficiently exploiting kernel functionality to minimise the overhead it creates. File operations in microbenchmark tests produce an 11% average overhead.

3.1.1 Other IFC Systems

Many different approaches to IFC have been published; the most influential to this project will be briefly summarised.

Asbestos is a prototype OS by Efstathopoulos et al. [26] that provides entity labelling and isolation as an OS primitive. Applications express individual policies via a custom kernel interface, and all dataflow is protected, including IPC and system-wide information flows. Additionally, a novel event abstraction and sub-process *security contexts* allows processes to act on behalf of multiple entities. *HiStar* (Zeldovich et al. [27]) builds on the *Asbestos* model, minimising the size of the system’s TCB — the system has no notion of *superuser*, with no code other than the kernel being fully trusted. An important consequence of this is that the risk of data leaking via *covert channels* is drastically reduced. *DStar* (Zeldovich et al. [28]) translates *HiStar* into a distributed context, translating labels between IFC-enabled hosts with the help of a globally-meaningful set of tags. In contrast, *Aeolus* (Cheng et al. [29]), derived from *Asbestos*, deploys a common TCB across all nodes in a distributed system to enforce IFC; it filters I/O and both inter- and intra- process communication.

Laminar (Roy et al. [30]) takes a similar approach to *Flume*, using an LSM for policy enforcement, but extends it with customisation to the JVM² to support thread-level isolation and heap-object protection. This approach has proved powerful in applying DIFC to popular processing systems such as *MapReduce* [32] and *Hadoop*. [33]

²Java Virtual Machine. [31]

3.2 Interoperation between Linux and SGX

The relationship between SGX and Linux has at times been difficult; Intel has been attempting to upstream *isgx*, the SGX driver, into the mainline kernel for 6 years.³ A source of extreme friction lies in the fact that enclaves are not operable in ring-0, forcing research seeking to use SGX to harden the kernel itself to be creative integrating it.

The *TresorSGX* [34] project was one of the first to consider the practicalities of this relationship seriously, constructing an externalised interface for kernel functionality to be offloaded to an enclave via a specialised kernel module. Mainly focusing on disk encryption, the prototype achieved its security goals but struggled with performance, only performing at 1% the bandwidth of its kernel-embedded counterpart. The most prevalent performance hit came from kernel \leftrightarrow enclave communication overhead, made worse by the need to exit and re-enter ring-0.

Various other studies touch upon these issues, including:

- *Custos* (Paccagnella et al. [35]); tamper-detection for audit logs using SGX. The design attaches itself to the pre-existing Linux Audit Framework, deliberately avoiding execution tied to the kernel. Performance overheads are 2 – 7%.
- *DelegaTEE* (Matetic et al. [36]); credential delegation between two computer systems by enforcing either centrally brokered or P2P⁴ *discretionary access control*. The system does not operate at the OS-layer, but presents an effective capability-sharing system for modified applications via an SGX mediator.
- *NeXUS* (Djoko et al. [37]); practical access control for remote storage systems such as *Google Drive*. The design uses a *stackable* filesystem to interface with encrypted volumes — SGX is used to protect and share these encryption keys. Performance overheads are 100%.

³The *linux-sgx* patch set is currently in its 32nd revision; <https://lore.kernel.org/linux-sgx/>.

⁴Peer to peer.

3.3 Dataflow Protection using SGX

Research into applying the protections afforded by SGX to large-scale distributed computation accelerated recently — the most prominent projects are detailed here.

- *SCONE* [38] presents a secure container framework for *Docker*. [39] Using a secured version of the standard library for C it transparently encrypts/decrypts I/O crossing the container’s boundary. The authors claim $\times 0.6$ – 1.2 the performance of native throughput.
- *VC3* [40] secures *Hadoop MapReduce* computations — the *Hadoop* platform is not considered part of the TCB, thus allowing the system’s security invariants to remain unaffected if it were to be compromised. The reported performance overhead is 8% (for full read/write integrity).
- The *Maru* project [41] added support for running distributed *Apache Spark* in SGX enclaves. Data residing outside of a worker in *HDFS* is sealed, removing the need for *Hadoop* to be a part of the TCB. A notable difficulty was porting the *JVM*⁵ to function efficiently inside an enclave; SGXv1 restricts the EPC size to 128MB, severely penalising applications that struggle to run in relatively small memory footprints.
- *Ryoan* [42] provides a distributed sandbox environment to confine untrusted applications running on sensitive data in the cloud; a specific use case is computation outsourcing. It uses *confining labels* to create a weakened form of IFC tracking; processing nodes must be stateless and once tainted by a request cannot access resources outside the execution environment. Enforcement is managed both by SGX and *NaCl* [43] for the host application.

⁵Java Virtual Machine

Chapter 4

CITADEL

In this chapter we shall introduce and detail a prototype implementation of a modular, SGX-protected *reference monitor* — CITADEL. We start by considering this project’s motivation and discussing the challenges faced. Then, we explain the three-part architecture, relating design decisions to its DIFC model. We discuss the architecture’s performance and effectiveness in § 5.

4.1 Motivation

Since its introduction in Anderson’s 1972 report, [44] the reference monitor concept has proved a reliable workhorse for many security models. It does not refer to any exact policy, nor limit itself to any particular implementation — its abstractness is one of its greatest strengths, reserving any judgement about what policy is *appropriate* in a particular setting. [45]

Fundamental Properties of a Reference Monitor

- *Always invoked.* To guarantee that adversaries are unable to bypass the system’s security policies, every access to the system must be mediated
- *Evaluable.* It “must be small enough to be subject to analysis and tests, the completeness of which can be assured”; [44] to be trustworthy, it must be *auditable*,

with, ideally, a restricted TCB.

- *Tamper proof.* To ensure that an attacker cannot disable the authorisation mechanisms mandated by the security policy, the integrity of a reference monitor cannot be in question.

No computer system is ever completely secure, and Linux is no exception. Having grown by 1.7 million lines of code (LoC) in the past year alone, to 27.8 million LoC in total,¹ bugs are inevitable — almost 2000 have been reported in the past year,² and 662 *severe* bugs are still outstanding.³ Therefore we must question whether Linux alone can provide a reference monitor implementation the guarantees it requires, [46, 47] thus motivating the use of SGX.

Applying SGX to this problem brings two attractive benefits;

- The system’s IFC policy can be evaluated both during offline analysis and online using *attestation*, building other enclaves’ confidence in the underlying system.
- SGX’s hardware protections are very capable of defending a reference monitor’s state, even if adversaries have ring-0 privileges or in the presence of a kernel bug.

4.2 Challenges

The natural location for a reference monitor is embedded directly into the kernel, in the path of *syscalls*’ control flows. *CamFlow* does this using the LSM framework, silently tagging processes and other entities as they are encountered by the kernel, and additionally providing an external LSM-interface for any active changes. However, an SGX enclave is incompatible with this workflow (§ 2.2.3) as it cannot execute alongside kernel code. Thus a significant, unavoidable design feature is that the reference monitor must be distributed across rings 0 and 3 — an enclave *policy* component, and an LSM for *enforcement*.

¹https://www.theregister.com/2020/01/06/linux_2020_kernel_systemd_code/

²<https://bugzilla.kernel.org/>

³<https://www.cvedetails.com/product/47/Linux-Linux-Kernel.html>

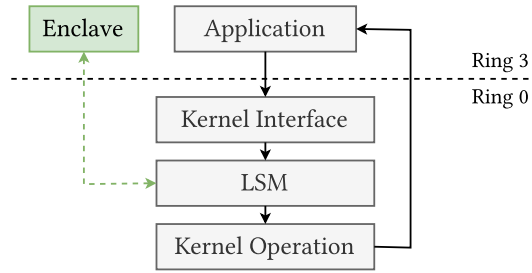


Figure 4.1: Abstract *syscall* control flow route. Grey components show the natural Linux design. Green additions highlight the externalised enclave LSM component.

The disruption this change causes could severely impact performance; Figure 4.1 highlights the significant change to overall control flow. Most notably, externalising part of the LSM to an enclave forces, in the worst case, an additional pair of context switches for each *syscall*.

Given a ring-3 component is unavoidable, we seek to minimise the overhead caused by its integration, while maintaining *safety* (every operation must be mediated). This situation is reminiscent of *exokernels*; [48] forcing a portion of the system into userspace could, if treated carefully, help overall performance. [49]

Two architectures, as illustrated in Figure 4.2, were initially considered.

1. An *isolated* extension of the LSM. Only the security implementation communicates with the *policy* enclave, acting as a naïve reimplement of a fully self-contained LSM, and using an additional kernel module as an I/O relay.
2. An *integrated* userspace service, through which permission is *requested* ahead of time and decisions stored in the LSM until needed. Backflow of information is facilitated asynchronously, but no additional kernel relay is required.

Architecture 1 can be implemented without changing the IFC model presented in § 2.1.3, reducing concerns regarding correctness and safety. However it adds significant overhead to the critical sections [50] of core LSM functions, in most cases while the kernel holds locks for various objects being accessed.

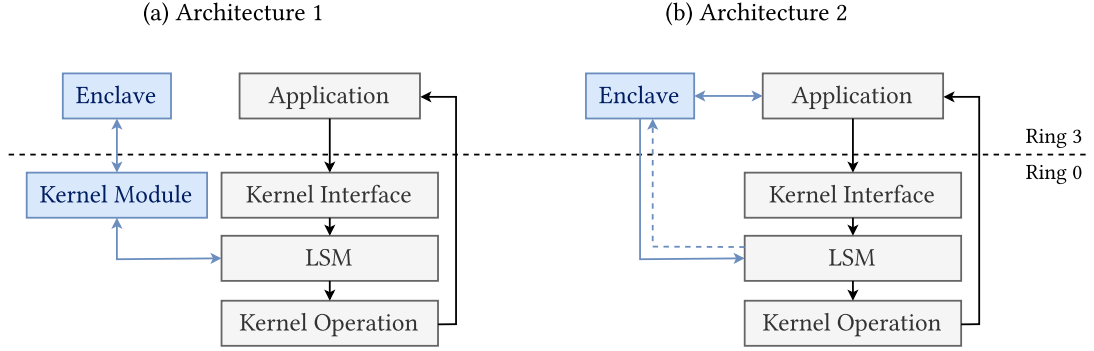


Figure 4.2: Two possible enclave integration designs.

Architecture 2 is more flexible, requiring all negotiation be conducted ahead of time, and importantly, without leaving userspace: any overhead only impacts the application, leaving the kernel’s critical sections to execute with minimal interference. A notable downside, however, is that the system’s security model will need an extension because *policy decisions and enforcement are no longer one and the same*.

Preliminary experiments showed that performance of the two architectures was similar in light workloads, but that *Architecture 1* degrades significantly due to resource contention. Additionally, as will be explained in § 5.2.1, the dependence on a kernel module conflicts with the desired constrained TCB of the system. For these reasons *Architecture 2* forms the basis of the prototype.

An additional challenge is one of incomplete information — an enclave is not privy to internal kernel datastructures such as `task_struct`, which will store the taint and capabilities of processes. A potential solution would be a request–response model via a custom kernel interface for any queries, though the performance impact would be severe, requiring additional context switches. Instead, the approach adopted creates an abstract interface that purposefully removes the minutiae of the underlying system. Any solution must be trustworthy and safe, and malicious entities must not be able to exploit any *eventually consistent* components. [51]

As a final comment, it must be noted that SGX is not flawless; § 5.2.3 discusses the impact of this on the project.

4.3 The CITADEL IFC Model

Before work on the final CITADEL implementation began, we constructed a formalisation describing the distributed nature of its design. A model helps reason about the safety and correctness of the final system, and provides the notation to properly discuss its features. Our model directly extends the one presented in § 2.1.3.

4.3.1 Reservations

Previously we defined the concept of a *safe flow*, $A \rightarrow B$, which underpins our IFC restrictions. In previous works permission is granted while *implicitly* considering *how* the flow is to take place (4.1). An isolated *enforcement* component does not understand the concept of *flows*, forcing policy decisions to be defined *explicitly*; CITADEL uses *reservations* for this purpose (4.2). This distinction is simple but very important when introducing *laziness* and other optimisations between the two halves of the reference monitor.

$$operation \rightarrow \boxed{\text{reference monitor}} \xrightarrow{\text{decision}} \{0, 1\} \quad (4.1)$$

$$operation \rightarrow \boxed{\text{policy} \xrightarrow{\text{reservation}} \text{enforcement}} \xrightarrow{\text{decision}} \{0, 1\} \quad (4.2)$$

Let Ω be the set of all operations mediated by the reference monitor, for example, `file_read` or `socket_open`, and \mathcal{R} , the set of all *reservations*, as follows.⁴

$$\mathcal{R} = \mathcal{T} \times \wp(\Omega)$$

Further, we define a shorthand, t^α ;

$$r \in \mathcal{R} . (r = (t, \alpha) = t^\alpha \implies t \in \mathcal{T} \wedge \alpha \subseteq \Omega)$$

⁴Recalling that \mathcal{T} is the set of all tags.

For a process A , $A_r \subseteq \mathcal{R}$ defines the set of all reservations it holds. Once a decision has been made, it is important for a reference monitor to be able to change it, revoking access if required. Thus we specify *validity* with an indicator function, $\mathcal{V} : \mathcal{R} \mapsto \{0, 1\}$. A reservation can only be used if valid; invalid reservations are discarded.

4.3.2 Permissible Operations

Satisfiability To determine if an operation is permissible, the *constraint reservation* representing it is compared against reservations held by the process. For example, $t^{\{\text{file_read}\}}$ is the constraint for reading a file tagged t .

A constraint τ^x is said to be satisfied by a reservation τ^y ($\tau^x \lesssim \tau^y$) if the tags match, the reservation is valid, and y permits *at least* the required form of access (4.3).

$$\sigma^\alpha, \tau^\beta \in \mathcal{R} . (\sigma^\alpha \lesssim \tau^\beta \iff \sigma = \tau \wedge \alpha \subseteq \beta \wedge \mathcal{V}(\tau^\beta)) \quad (4.3)$$

From here we define a *permissible operation*, $A \xrightarrow{\omega} t$; process A may perform operations ω on an entity tagged t . An operation is only permissible if the process holds a reservation explicitly granting permission (4.4).

$$A \xrightarrow{\omega} t \iff (\exists t^\alpha \in A_r \implies t^\omega \lesssim t^\alpha) \quad (4.4)$$

To bridge the gap between permissible flows and operations, a final definition is required; a *specific permissible flow*, $A \xrightarrow{\omega, \tau} B$, meaning that A may send information to B using operations ω , via entities tagged with τ . Thus:

$$(\exists \omega, \tau . A \xrightarrow{\omega, \tau} B) \implies A \rightarrow B \quad (4.5)$$

$$A \xrightarrow{\omega, \tau} B \implies (\exists \omega' . A \xrightarrow{\omega'} \tau \wedge \omega \subseteq \omega') \quad (4.6)$$

Together, these define the relationship between an abstract policy space ($A \rightarrow B$, § 4.4.2) and concrete implementation ($A \xrightarrow{\omega} \tau$, § 4.4.1). A policy decision may grant

a greater set of permissions than asked for (4.6) – e.g. allowing both read and write when only write was explicitly requested. [10, 52]

Some small updates are required to make the existing rules consistent with the new: reservations are not transferred when creating a new entity (4.7), and reservations are not affected by capabilities as they represent a centralised component of the DIFC system.

$$A \Rightarrow B \implies A_s = B_s \wedge A_i = B_i \wedge B_r = \emptyset \quad (4.7)$$

4.3.3 Transient Entities

Alongside active and passive entities, we introduce a third type; *transient* entities. These are passive entities that are privately held by an owning active entity; they are used to model Linux functions such as `pipe()` and unclaimed tainted files.

To facilitate this, all processes are assigned a unique tag $p \in \mathcal{T}$, and any files it creates are initially also be tagged with p . Using \mathcal{P} as the set of all process identifiers, we define \mathcal{I} as the function returning a process's transient identifier;

$$\mathcal{I} : \mathcal{P} \mapsto \mathcal{T} \quad (4.8)$$

The expression for a *permissible operation* now becomes;

$$A \xrightarrow{\omega} t \iff \mathcal{I}(A) = t \vee (\exists t^\alpha \in A_r \implies t^\omega \preceq t^\alpha) \quad (4.9)$$

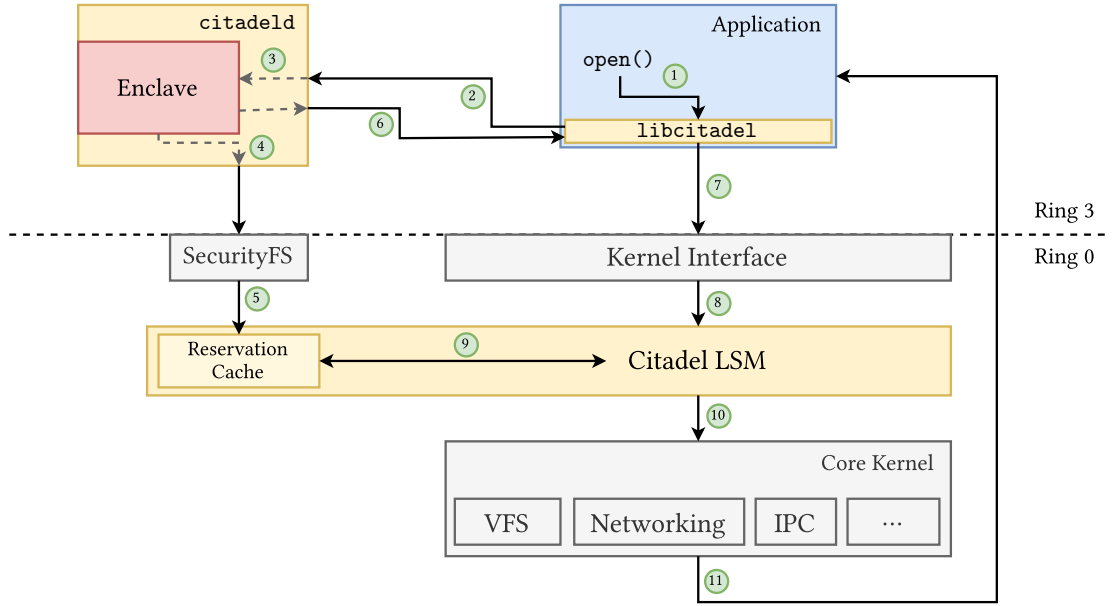


Figure 4.3: High level overview of the CITADEL architecture.

4.4 Implementation

CITADEL consists of three components; an LSM, `citadeld`, and `libcitadel`. Each plays an essential, symbiotic role in the operation of the reference monitor. The prototype is in excess of 9,000 lines of C and C++, and extends the Linux kernel build system (§ 4.4.6). This section shall present CITADEL’s architecture, guided by Figure 4.3.

Analogy The system is well illustrated by the *will-call* system used by theatres — customers (*processes*) reserve tickets (*permission*) to attend a show (*perform an operation*) ahead of time via phone or the internet (`citadeld`), but only receive their tickets (*reservations*) at the venue (*LSM*) on the day (*at the point of execution*).

CITADEL’s LSM comprises its *enforcement domain* (§ 4.4.1), and `citadeld` its *policy domain* (§ 4.4.2). Enforcement is *policy-agnostic*, implementing an abstract, tagged taint tracking system that exposes decision points to policy influence via reservations. Policy components need not be aware of the enforcement strategy to successfully express their protection schemes. Communication between the two domains is discussed separately in § 4.4.3.

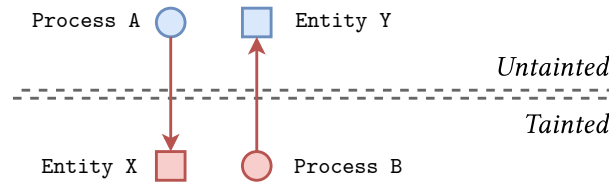


Figure 4.4: Accesses across the taint boundary taint the untainted party.

4.4.1 Enforcement

The CITADEL LSM tracks all entities within the Linux system by allocating and attaching a small data structure (< 48 bytes) to each; it computes and tracks a conservative notion of *taint* for each to ensure *safety*. Tainting in CITADEL is dynamic, meaning that entities are only policed if needed. This process is *additive*, only tainting an object if it is involved in a successful operation crossing the taint boundary (Figure 4.4). In addition to automatic propagation, taint for the majority of entities is amendable on request from the policy domain.

A variety of metadata is tracked for each type of entity:

- **Active.** The only active entities in Linux are processes — these require a plethora of markers and flags, including; *taint* and its *reservation list*.
- **Passive.** There are many forms of passive entity, the most prevalent being files and other inode-backed structures. These carry *taint*, an *identifier* (tag), and an *anonymous flag*. Inode tracking is detailed first, with other types of passive entities, such as shared memory, discussed in § 4.4.2.5.

4.4.1.1 Identifiers

Entities may be tagged with a single identifier; a randomly assigned 128-bit number which corresponds to a tag in the IFC model. If a security policy wishes to maintain pseudonyms for secrecy and integrity, for example, it may internally, but must convert back to the system tag for enforcement.

4.4.1.2 Extended Attributes

An inode-backed entity's taint flag and identifier are copied to *xattrs* attached to it via the VFS. These occupy the `security.citadel` namespace, and are essential for ensuring that taints and identifiers persist between boots. Certain entities may be *anonymous*, indicated by an anonymous flag, meaning that their identifier is not present as an *xattr*. This may either be because the entity does not support *xattrs* (such as files created using `pipe()`) or that the identifier is temporary (§ 4.4.1.5).

4.4.1.3 Permissions

Tainted processes must hold a valid reservation to perform any operation that may allow data to flow to another entity (Appendix X) — enforcement strictly follows the rules presented in § 4.3.2. Untainted processes bypass all checks, and thus lie outside the IFC model; the security implications of this are discussed in § 5.2.2

4.4.1.4 Reservation Cache

When the system's policy enclave presents a new reservation to the LSM, it is stored in a structure called the *reservation cache*. Implemented as a red-black tree, this maps a process's identifier to a linked list of its pending reservations. This intermediary storage is necessary as LSMs are event-driven, and thus can only access an entity's state when it is presented for review. Before a permission check is carried out, the LSM ensures that the process's reservation list is up to date by;

1. *Installing pending tickets*. All reservations held for the process are moved to its internal reservation list, ready for inspection.
2. *Disposing of expired entries*. The validity function the LSM uses is time-based. When a reservation is inserted into the reservation cache, it is timestamped with an explicit expiry date — this lifetime is 15 seconds by default.

4.4.1.5 Entity Creation

As detailed in § 4.3.3, every newly spawned process is privately tagged by the LSM as if it were a passive entity. The purpose of this identifier is not to directly identify the process, but to provide a mechanism for associating any private, passive entities it

creates with it. This includes the file descriptors provided by `pipe()`, and any new files it creates using `open()`. Every process always has permission to access its transient entities, and external entities can only gain the right to access them if they;

1. Are a child processes and request access to their parent, or
2. The process officially *claims* them via the policy enclave, which gives them an independent tag and removes the entity's status as transient.

`fork()` In Linux, child processes are initially exact clones of their parent, with access to the same state and file descriptors. Thus children of tainted processes are also tainted, but importantly do not assume the same rights as their parents — open file descriptors will not function without revalidation (§ 4.4.4), and children must request the right to their parent's transient entities to use pipes or similar.⁵ It is the policy enclave's responsibility to validate that the security contexts of the parent and child have not diverged.

4.4.2 Policy Components

The policy counterpart to the LSM's enforcement is contained within `citadeld`, a userspace service that hosts the core SGX enclave. `citadeld` is modular, hosting an independent policy module sitting on top of an enforcement translation library (Figure 4.5).

4.4.2.1 Abstract Policy Module

The policy module embedded in `citadeld` is presented with a simple, event-driven interface; this streamlines their implementation, allowing more emphasis to be put on correctness. Their implementation is based around a single method, through which their permission is sought when required; `asm_handle_request(3)`.

The simplest possible policy is that any operation is deemed permissible. The request parameter, amongst other things, holds the target identifier and set of operations.

⁵Unrelated processes are unable to do this.

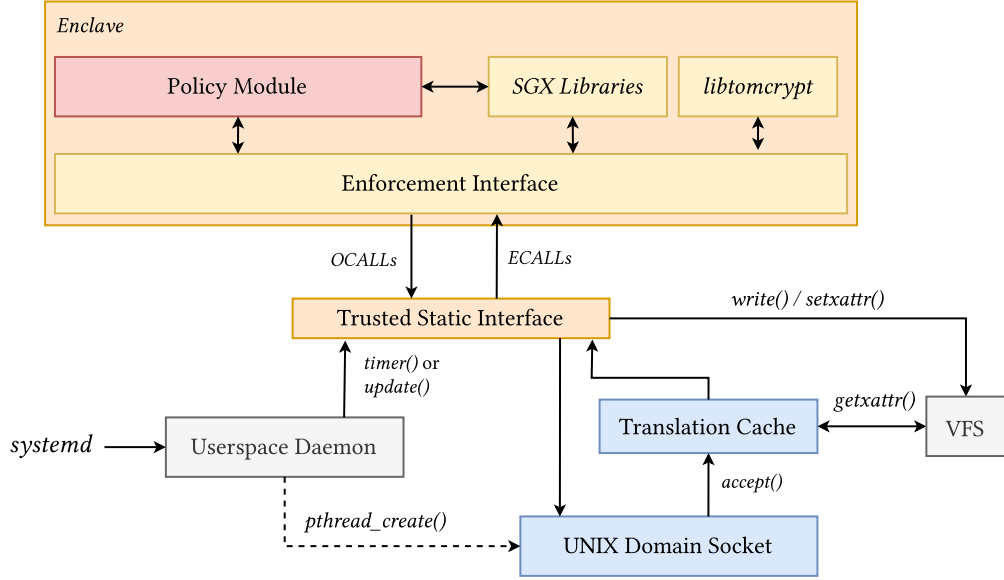


Figure 4.5: Overview of the components inside citadeld.

```

1  citadel_response_t asm_handle_request (pid_t pid,
2      struct citadel_op_request *request, void *metadata) {
3      return CITADEL_OP_APPROVED;
4  }

```

This can be considered to determine the validity of an operation, $A \xrightarrow{\omega} t$, based on its knowledge of any implicated flows ($A \rightarrow *$).

Operations Entity operations, Ω , are presented as `citadel_operation_t`, a simple bit mask over the operations CITADEL recognises (Appendix X). Similarly, policy decisions are represented using `citadel_response_t`; these may be *approved*, *rejected*, *error*, *invalid*, *granted*,⁶ and *forged*.⁷

4.4.2.2 Host Application

Various steps need to be taken before requests are presented to the resident policy module (§ 4.4.3). Requests often refer to absolute filepaths, requiring retrieval of

⁶Approved, and confirming that the process is recognised as the owner of the entity.

⁷Discussed in § 4.4.5.

their tags, if they exist — security *xattrs* attached to the VFS file serve these requests. Translation is performed pre-emptively depending on the operation requested, and to minimise any lookup overhead, results are cached in a *translation cache*. This is implemented using *sparsehash*,⁸ and great care is taken to detect stale entities that may confuse the internal decision process.

4.4.2.3 Enforcement Interface

The policy module is interchangeable, but the enforcement interface acts as the backbone of the enclave. All requests are routed through it as a sanitisation step, detecting forgery or invalid data, and all information leaving it is formatted and signed⁹ as appropriate. The process of installing reservations created by the enforcement interface, on behalf of the policy module, is detailed in § 4.4.3.

4.4.2.4 libtomcrypt

We ported *libtomcrypt*,¹⁰ a leading open-source cryptography library, to function inside an SGX enclave. This was necessary to support many encryption mechanisms the system requires, on top of those provided by SGX. This was achieved by replacing its backing precision arithmetic library with an SGX-aware version of *GMP*,¹¹ and forcing it to statically allocate its memory (as SGX v1 lacks support for dynamic memory management). Further changes rewrote the internal random number generator to use the one provided by SGX, and rework its exception strategy to remove `abort()`, an illegal instruction inside an enclave.

4.4.2.5 Shared Memory

CITADEL also supports the tagging and restriction of shared memory (SHM). This is managed not via a backing inode, but directly using *System V* identifiers granted to allocated memory segments. Internally, restrictions function in the same way as files, but per-access mediation is not directly possible – we can only detect when segments are allocated and attached. Thus this workflow requires special consideration, and a

⁸<https://github.com/sparsehash/sparsehash>

⁹Encryption is discussed in § 4.4.3

¹⁰<https://github.com/libtom/libtomcrypt>

¹¹<https://github.com/intel/sgx-gmp>

new reporting mechanism from the LSM back to the policy enclave. Using a specialised *xattr* interface (4.10) to drive a request-response model, the LSM tracks and reports the PIDs of everything that has touched an SHM segment.

$$\text{security.citadel.shm.[shm_id]} \rightarrow \{145, 267, 1120, \dots\} \quad (4.10)$$

4.4.3 Communication Pathways

There are three notable I/O pathways between components within CITADEL;

1. APPLICATIONS \longleftrightarrow POLICY ENCLAVE.

All application requests (via `libcitadel`, § 4.4.4) are sent to the policy enclave using a standard domain socket; `/run/citadel.socket`. To ensure that all processes have the right to communicate with the reference monitor, a special tag, $\tau = 2^{128} - 1$, is assigned, asserting the reference monitor's ownership of it and whitelisting it in the LSM.

2. POLICY ENCLAVE \longleftrightarrow LSM.

These parties communicate using two mediums; *SecurityFS* and *xattrs*. All messages between these are encrypted using AES-256-GCM [53, 54]; the key is chosen during the system's initialisation (§ 4.4.3.1).

Reservations are installed using a custom *SecurityFS* interface,¹² and are synchronously inserted into the reservation cache. The policy enclave may invoke an operation directly on a file using `setxattr()`, which the LSM intercepts, triggering it to enact the required changes to the entity. One common use of this is entity tagging.

3. LSM \longrightarrow APPLICATIONS.

To verify their identities with the policy enclave, applications present a *ptoken* with each request; this process is described in § 4.4.5.1, but can be generated by reading from a globally readable *SecurityFS* interface.¹³

In addition to this, `libcitadel` occasionally needs to check the tag associated

¹²/sys/kernel/security/citadel/update

¹³/sys/kernel/security/citadel/ptoken

with a path or file descriptor; this is managed using the existing `libc xattr` methods.

4.4.3.1 Initialisation and Encryption

Whenever the system boots, the LSM is first to come online — `citadeld` may start any time afterwards, meaning that the LSM must be capable of operating independently. In this case, when the LSM is isolated, the system will tend towards a state of complete lockdown (for tainted processes). Thus the mechanism by which the LSM and policy enclave initialise communication is vital for secure operation; CITADEL achieves this with a pair of 2048-bit RSA keypairs, one for the enclave ($E_{P/S}$) and one for the kernel ($K_{P/S}$).

SGX does not provide protection against reverse engineering, thus the enclave's keys must be provided to it as a sealed entity; sealing here uses `MRSIGNER`, allowing any policy enclave provided by the *sealing authority* to fully function, and is compiled into the kernel, available via `SecurityFS`.¹⁴

Once a policy enclave has been initialised it must verify itself; the LSM issues a random challenge¹⁵ encrypted using the enclave's public key, and expects a reply using the corresponding private key.

$$\begin{aligned} \text{LSM} &\rightarrow \text{Enclave} : \{\text{challenge}\}_{E_P} \\ \text{Enclave} &\rightarrow \text{LSM} : \{\text{challenge}, \text{PID}, \text{identifier}, \text{aes_key}, \dots\}_{E_S} \end{aligned}$$

Given E_S is only held sealed, any entity providing a valid challenge is trusted and considered part of the CITADEL TCB. The challenger's PID is stored to detect any adversarial replay messages. RSA is only used for this initial exchange; it would be too slow to use for all messages. Thus the AES key provided in the response forms the basis of all future communication.

¹⁴/sys/kernel/security/citadel/sealed_keys

¹⁵/sys/kernel/security/citadel/challenge

CITADEL uses AES to protect sensitive messages as every SGX-capable processor supports *AESNI* [55] to accelerate AES in hardware. SGX provides this natively inside enclaves, and the official *Intel AESNI* driver is included in the mainline kernel. *AESNI* provides an encryption bandwidth of over 1 Gbps,¹⁶ far exceeding the capacity required, and thus adding negligible overhead. The system’s AES key updates with every message sent from the enclave using an SGX-approved source of entropy;¹⁷ this adds minimal overhead and constitutes good practice. A copy of the first key presented in the challenge-response is retained and used in cases when a static key is essential.

4.4.4 libcitadel

CITADEL provides a userspace auxiliary library to make integrating existing programs as effortless as possible. For each mediated *syscall* (e.g. `open()`), it provides a proxy function (`c_open()`): this would, in a future iteration of this design, be integrated directly into `libc`, but currently requires no major changes to applications’ workflows. A good example of this in action is the ported version of *Nginx* (§ 5.1.4).

`libcitadel` performs two main functions;

1. Communication with the policy enclave.
2. Tracking and predicting what permissions it believes the process has.

Communication is facilitated via the UNIX domain socket provided by `citadel.d`. A zero-copy approach¹⁸ is used to minimise latency on both sides; this is optimised for in the protocol design, and the cost of communication minimised. Each communicant verifies the PID of the other party, as detailed in § 4.4.5.1.

Caching at this level has a tremendous impact on overall performance. When reading a large file, for example, a program may make thousands of calls to `c_read()` — making external calls to `citadel.d` would be wasteful as processes usually have enough information to infer their current position.

¹⁶Our experiments exceed this, however this value is fair given the plethora of processors supporting SGX.

¹⁷ $new \leftarrow old \oplus update$

¹⁸Of course excluding copying in the kernel and when transferring the request into the enclave.

```

1  int c_open(const char *pathname, int oflag, mode_t mode) {
2      int fd; bool from_cache = false;
3      bool creating = access(pathname, F_OK) < 0 && (oflag & O_CREAT) > 0;
4
5      // Pre-emptively attempt access if I suspect I'm not tainted.
6      // Alternatively, register a transient file if we're creating it.
7      // -- close and reopen to ensure it is independently tagged.
8      if (!am_tainted() || creating) {
9          fd = open(pathname, oflag, mode);
10         if (!am_tainted() && fd > 0)
11             return fd;
12         if (fd == -1 && errno != -EPERM)
13             return -1;
14         if (fd != -1)
15             close(fd);
16     }
17
18     // Request access from the policy enclave. Claim file if not tagged.
19     if (!citadel_file_open(pathname, strlen(pathname)+1, &from_cache))
20         return -EPERM;
21
22     // Continue as normal.
23     fd = open(pathname, oflag, mode);
24     citadel_declare_fd(fd, CITADEL_OP_OPEN);
25     if (!am_tainted()) set_taint();
26     return fd;
27 }

```

Listing 1: The libcitadel shim function for `open()`.

Therefore every process maintains a list of *expectations* — the reservations it believes it has, including their validity — and inferred taint status. They cannot exactly know their true values, especially as the policy enclave may grant different permissions than asked for, but in *Nginx* over 97% of requests were servable locally in a realistic workload. Using the same workflow, untainted processes speculatively execute operations, again removing the need to involve `citadel`. The performance gain of requests served from the cache reduces the overhead from $\mathcal{O}(10\mu s)$ to $\mathcal{O}(100ns)$.

A core challenge of the cache is relating open file descriptors to the permissions they require. This requires some manual work, including fetching its `xattr` tag with

`fgetxattr()` and estimating the expiration time of the LSM’s underlying reservation. Ideally `libcitadel` requests revalidation just before expiry to ensure no unexpected drop-in service; this is particularly important for applications unaware of CITADEL.

Special care has to be taken when handling child processes. As already discussed, children are given a copy of their parent process’s state — this includes its `libcitadel` cache. Although the LSM does not pass any reservations on to the child, `libcitadel` maintains the same *expectation* cache. Entries in it are marked as invalid, to force the child to revalidate a file descriptor before first use. Additionally, we assume that a process trusts the initialisation code of its child, enabling `libcitadel` to delete the parent’s *ptoken* (§ 4.4.5.1); the `c_fork()` function handles this automatically.

4.4.5 Additional Security Features

CITADEL implements additional security mechanisms to reinforce potentially vulnerable aspects of the system. Both the policy enclave and LSM use a process’s PID as its primary identifier — CITADEL implements two schemes to protect this notion of identity and help prove it.

4.4.5.1 *ptokens*

Before a process may interact with `citadeld`, it must retrieve its *ptoken* from the LSM.¹⁹ The purpose of this (4.11) is twofold;

- a. Inform `libcitadel` about the process’s metadata in the eyes of the LSM, and
- b. Provide an authenticable access token to present to `citadeld`, verifying the process’s identity. This is AES encrypted using K , the system’s designated static AES key, which is unknown to the process.

$$ptoken \rightarrow (\text{citadel_pid}, \text{identifier}, \text{token}, \{\text{identifier}, \text{token}, \text{pid}\}_K) \quad (4.11)$$

Whenever a process connects to the `citadeld` socket, its identity is retrieved from the underlying transport mechanism. At both the sender and receiver the identity of

¹⁹Read from `/sys/kernel/security/citadel/ptoken`

the other is verified using this method, and additionally `libcitadel` expects the decrypted *token*, a randomly generated byte-array, to be returned by `citadeld`, inspiring confidence that the response has not been forged.

```
1 // Get PID of sender.
2 struct ucred cred;
3 socklen_t len = sizeof(struct ucred);
4 getsockopt(socket, SOL_SOCKET, SO_PEERCRED, (void*)&cred, &len);
5 uint64_t pid = cred.pid;
```

4.4.5.2 PID Protection

The LSM also implements a mechanism to detect PID forgery, as it is theoretically possible for a process to modify its PID with the help of a malicious kernel module (Appendix A). This, if unchecked, would be detrimental for the LSM's integrity, allowing a process to silently assume another's identity. To this end, the LSM stores a process's PID within its security structure and routinely checks to ensure it does not change unexpectedly.²⁰ Any process deemed to have an illegitimate PID is denied access to all entities, effectively killing it.

4.4.6 CITADEL Build System

Building CITADEL requires both the kernel and policy enclave to be in agreement about the RSA keys to be used; without this building will fail. This is achieved using a preparatory script that does the following;²¹

1. Generate two *OpenSSL*²² 2048-bit RSA keys in *DER* format — the kernel's *Crypto API* requires keys to present themselves as *ASN.1 structures*.²³
2. Compile and launch CITADEL's *preparatory enclave*; this must be signed with the same *signing identity* as any policy enclaves generated. This ingests the two keys and generates a sealed keyset to be presented to initialising enclaves.

²⁰A valid change would be on `fork()`, in which case the stored PID should equal the parent process's.

²¹The script assumes a valid kernel with the CITADEL LSM installed is present.

²²<https://www.openssl.org/>

²³<https://tls.mbed.org/kb/cryptography/asn1-key-structures-in-der-and-pem>

3. An interface file (`keys.h`) is then generated in the kernel's source directory — this file contains the kernel's keypair, the enclave's public key, and the aforementioned sealed keyset. The key files are now deleted.
4. The policy enclaves are then built and signed. The kernel may now be compiled.

Chapter 5

Evaluation

Three core questions hang over CITADEL’s viability — its security, expressivity, and performance. This chapter presents a thorough investigation of the prototype’s performance and a discussion of its security implications and application to real-world scenarios.

5.1 Performance

The CITADEL prototype demonstrates impressive performance, matching, and in places surpassing, related approaches, despite its architectural disadvantage. We present its behaviour relative to native Linux kernel as follows;

1. Application-level microbenchmarks, tracing the duration of *syscalls* both natively and through `libcitadel`. (§ 5.1.2)
2. IPC bandwidth microbenchmarks in both *intra*- and *inter*-process contexts. (§ 5.1.3)
3. Real-world NGINX performance benchmarks for both low-latency and high-bandwidth configurations. (§ 5.1.4)

The following results are best compared to *Flume* [10] — *CamFlow*, although implemented similarly, has a different scope than this project. *Flume* reports $\sim 40\%$ decrease in real-world performance; we report $\sim 25\%$ (§ 5.1.4).

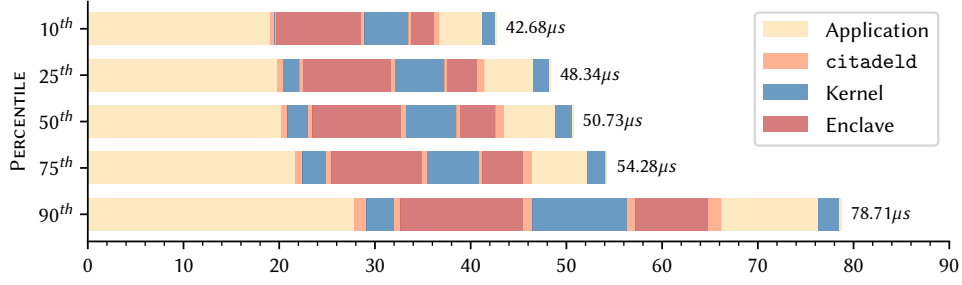


Figure 5.1: Control flow inhabitation for libcitadel’s `c_open()` function, $n = 100$.

5.1.1 Evaluation Environment

The research machine used for evaluation contained a quad-core Intel® Core™ i5-6600 (supporting SGX v1), 16 GiB RAM, and a 1-Gbps NIC. The primary disk provided 389 MBps read and 210 MBps write.¹ For all experiments running under CITADEL, `citadeld` was running via `systemd` — all debugging tools were disabled and the enclave was built in hardware pre-release mode with the *transition_using_threads* optimisation. [56] Linux v5.6.0 was used as the base kernel.

Both Tables 5.1 and 5.2 report the sample mean and standard deviation. Figures 5.2, 5.3, and 5.4 plot the sample medians and interquartile range (IQR) for each point. The Wilcoxon paired signed rank test was chosen to determine statistical significance at 5% confidence. [57]

5.1.2 *syscall* Microbenchmarks

A custom benchmark tool was built to assess the overall impact CITADEL has on *syscall* performance — for example, the duration of `open()` compared to `c_open()`. Table 5.1 presents these results. To give a fair comparison, two figures are reported for CITADEL. *Amortised* refers to the normal operation of libcitadel, in which the majority of queries are served from the cache; overhead arises from both local cache operations and added kernel latency from the LSM. The other column, *Cache Miss*, gives the overhead when caching is disabled, thus including communication with `citadeld`.

¹As reported by the `dd` tool.

	NATIVE	CITADEL		
		<i>Amortised</i>	<i>Cache Miss</i>	<i>99th %ile</i>
<code>open()</code>	1.675 ± 0.076	6.083 ± 0.129	50.133 ± 1.482	$2.38\times$
<code>read()</code>	5.724 ± 0.206	7.010 ± 0.192	54.736 ± 1.556	$1.26\times$
<code>write()</code>	14.340 ± 0.208	15.597 ± 0.250	63.824 ± 1.902	$1.05\times$
<code>close()</code>	0.651 ± 0.005	0.718 ± 0.011		$1.10\times$
<code>socket()</code>	1.446 ± 0.179	3.156 ± 0.291		$1.02\times$
<code>bind()</code>	0.762 ± 0.023	1.911 ± 0.183	49.110 ± 1.746	$2.78\times$
<code>listen()</code>	0.705 ± 0.015	1.882 ± 0.149	48.411 ± 1.386	$2.91\times$
<code>connect()</code>	16.570 ± 0.278	17.961 ± 0.330	66.273 ± 2.147	$1.05\times$
<code>shmget()</code>	1.880 ± 0.122	1.913 ± 0.111	49.326 ± 1.466	$0.98\times$
<code>shmat()</code>	0.420 ± 0.005	1.575 ± 0.134	47.997 ± 1.560	$0.99\times$
<code>shmctl()</code>	0.418 ± 0.005	0.743 ± 0.083	45.912 ± 1.114	$0.97\times$
<code>shmdt()</code>	0.415 ± 0.003	1.342 ± 0.040		$1.01\times$
<code>pipe()</code>	1.110 ± 0.061	1.288 ± 0.069	47.334 ± 1.147	$1.02\times$
<code>mkfifo()</code>	3.865 ± 0.048	11.509 ± 0.405	59.623 ± 1.788	$1.93\times$
<code>fork()</code>	47.866 ± 3.175	48.647 ± 3.457	81.174 ± 3.829	$15.77\times$
<code>citadel_init()</code>	—	0.801 ± 0.009	34.940 ± 1.329	—

Table 5.1: libcitadel microbenchmarks.

All values are in μs and the sample standard deviation is shown alongside the mean. For CITADEL, both the amortised and average cache-miss durations are given. Only one value is given if the operation is not affected by a cache miss. The overhead between CITADEL and Native Linux at the 99th percentile is also presented. $n = 10^6$.

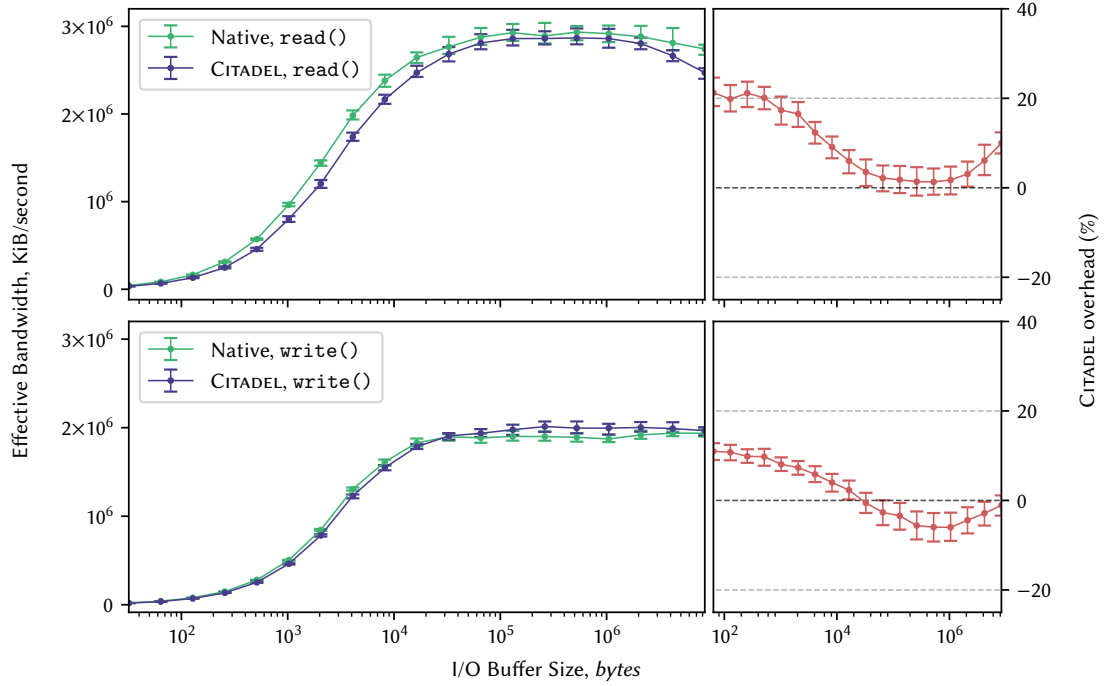


Figure 5.2: Effective `read()`/`write()` bandwidths for both the native Linux kernel and CITADEL. The percentage overhead is also presented. $n = 200$ per buffer size.

Overall `libcitadel` contributes $\sim 1\mu s$ of overhead (amortised) on average — this rises to $\sim 40\mu s$ on a cache miss. Figure 5.1 presents a more detailed view of where exactly this overhead arises, approximately plotting where the control flow for `c_open()` moves (on a cache miss). Interestingly, the slowest component is the communication channel between `libcitadel` and `citadeld` (median $26\mu s$);² as a result, the core reference monitor functionality only adds a median penalty of $24\mu s$. The final *Kernel* call before terminating is the internal call to `open()`. Additionally, the 10th percentile demonstrates that the first *Kernel* call is not always required if the entity’s metadata is resident in the `citadeld` cache. During these experiments, `citadeld` showed to reliably handle over 30,000 requests/second and between 90 – 100% usage of a single thread.

²Included in the *Application* regions.

Figure 5.2 plots observed effective bandwidth whilst reading from and writing to a 16 MiB file with different sized buffers; the corresponding percentage overhead inflicted by CITADEL is plotted to the right. The benchmark driving this was adapted for Linux from one written by R. Watson for FreeBSD. [58] The results clearly show CITADEL having a more adverse effect on performance for smaller buffer sizes; unsurprising, as smaller buffers force a larger number of calls to `read()` / `write()`. It is unclear why CITADEL provides better performance for large buffers with `write()`, an unexpected artefact — the difference is statistically significant for buffers in the range 256KiB and 2 MiB, and reproducible. More work is required to determine the root causes, but hypotheses include the slight optimisation afforded by regular, small delays easing pressure on microarchitectural caches.

5.1.3 IPC Microbenchmarks

Again using the modified Watson benchmark, we investigated CITADEL’s effect on end-to-end IPC performance. We investigate *pipes*, *local sockets* (`socketpair()`), and *regular sockets*, between 2 threads (Figure 5.3) and between a parent and child process (Figure 5.4).

Overall, the results between the two contexts are similar — both see approximately 20% degradation in the worst cases, tending towards equal performance when using $\sim 10^5$ -byte blocks. At first glance it appears that CITADEL affects the performance between 2 threads slightly more than 2 processes, but in fact CITADEL performs near-identically in both. Native performance is more heavily optimised when sending between two threads; CITADEL overshadows any latency gained by the kernel.

In a similar way to `write()`, CITADEL unexpectedly outperforms the native kernel in both contexts using `pipe()`. The readings are noisy, but statistically significant for buffers in the range 16 KiB to 8 MiB, and reproducible. The cause is again unknown, but observing that the native kernel’s throughput halves after buffers of 8 KiB, we suspect that this is the result of cache exhaustion or inopportune paging. Notably, CITADEL’s readings exhibit a far larger IQR for large buffer sizes than the native kernel, a side effect that is repeated in real-world testing.

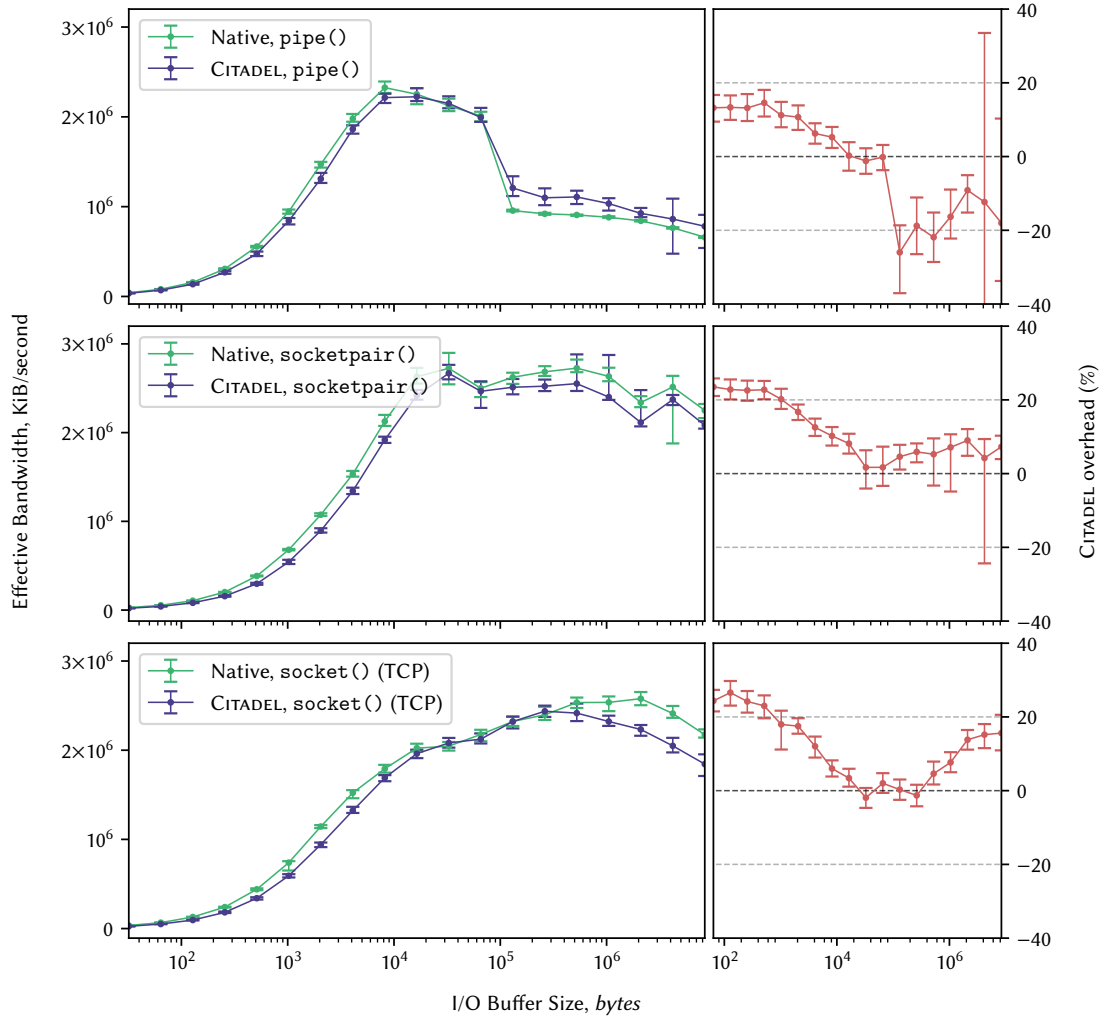


Figure 5.3: Effective bandwidths for various types of IPC between 2 threads, $n = 200$.

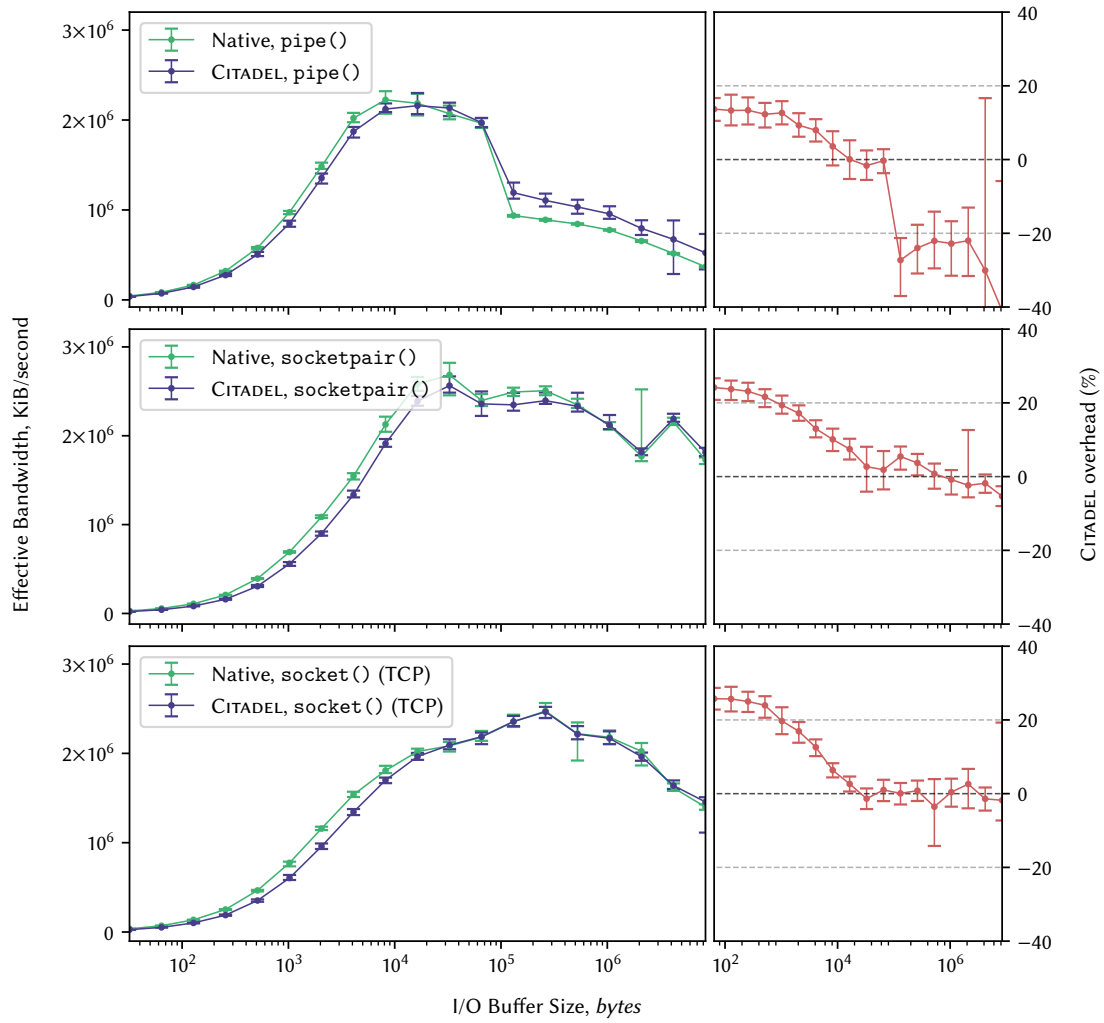


Figure 5.4: Effective bandwidths for various types of IPC between 2 processes, $n = 200$.

	NATIVE	CITADEL		
		<i>Untainted</i>	<i>Tainted</i>	<i>Overhead</i>
WEBSERVER BENCHMARK, 100-byte packets				
<i>Latency</i>	35.73 μ s	36.18 μ s	44.35 μ s	24%
— <i>std. dev.</i>	13.85 μ s	14.12 μ s	13.26 μ s	
— <i>max.</i>	536 μ s	554 μ s	508 μ s	
<i>Requests/s</i>	$2.748 \cdot 10^4$	$2.717 \cdot 10^4$	$2.214 \cdot 10^4$	19%
<i>Bandwidth</i>	177.28 Mbps	168.72 Mbps	143.04 Mbps	18%
10GB FILE TRANSFER				
<i>Bandwidth</i>	1.404 Gbps	1.410 Gbps	1.413 Gbps	$\sim 0\%$
— <i>std. dev.</i>	0.428 Gbps	0.440 Gbps	0.549 Gbps	
<i>Duration</i>	56.98s	56.74s	56.62s	$\sim 0\%$
— <i>std. dev.</i>	19.45s	18.97s	23.63s	

Table 5.2: NGINX performance comparinon between native Linux, and both untainted and tainted CITADEL, $n = 25$.

5.1.4 NGINX Benchmarks

To validate the performance results presented thusfar, we ported the entirety of the NGINX webserver³ to function alongside CITADEL. No optimisations were made to the codebase – the only changes made replaced core `libc` function calls to use their `c_*libcitadel` counterpart.

Two trials were run; a low-latency benchmark⁴ and a 10GB HTTP file transfer (high-bandwidth). The webserver was configured to only run a single server process to ensure it was exercised to its full extent, and was set up to use the *loopback* interface⁵ to eliminate any interference from outside the OS.

³<https://www.nginx.com/>

⁴<https://github.com/wg/wrk>

⁵<http://127.0.0.1/>.

The results are not surprising (Table 5.2). For the low latency tests we observe the same 20 – 25% overhead as seen from TCP sockets in § 5.1.3 using the same buffer size. The high-bandwidth tests show CITADEL performing equally to the native kernel, only differing by its larger sample standard deviation. This trial is also interesting as this is the first time we see file descriptor revalidation happening automatically on `read()` and `write()`. The CPU overhead from `citadeld` was $< 1\%$.

5.2 Security

5.2.1 CITADEL TCB

One of the core initial goals of this project was to build an enclave-based reference monitor whilst *minimising inflation to the system's TCB*; to this end we present the trusted components of a CITADEL system.

- The SGX Platform, including all libraries and `isgx`.
- The *policy enclave* implementation.
- The untrusted `citadeld` application; discussed further below.
- The core Linux kernel, including the CITADEL LSM and the Linux VFS.
- The Intel *AESNI* Linux driver.

Essentially, we assume that the build environment is entirely trusted; preparation need not be done on the final system. A notable exclusion from the TCB is the majority of Linux drivers and other kernel modules — this was a strong motivation for using SGX, as it can effectively defend against malicious and misbehaving ring-0 parties. However there are security questions so far unanswered;

1. How does the system defend against `citadeld`, an unprivileged, userspace application, from being replaced by a malicious adversary?
2. Can the kernel actually be held to the same integrity level as an enclave? Additionally, by extension, how trustable is a system that enclaves can only attest to half of?

To the first question we present a proposed solution. In exactly the same way as CITADEL defends its socket, `/run/citadel.socket`, with a reserved identifier, the compiled `citadeld` application may also be protected. For example, opting to mark it with an *xattr* such as `security.citadel.daemon` with a *nonce* value during the build process would provide the LSM ample confidence that an executable is a valid product of a CITADEL build,⁶ and protect it from tampering while resident on the end system. This may also be valuable for defending the enclave object files themselves; although they cannot be tampered with, an adversary may try to remove them to deny service. These features would require extending the CITADEL build system further.

To the second question we provide a discussion; in short, not entirely, but any risks can be minimised as follows. Enclaves are unique in that their online attestation process inspires absolute trust, but offline provenance can be equally valuable. Although not SGX-based, *UEFI Secure Boot* [59] is an industry-standard mechanism for verifying that an OS is legitimate. Ensuring that a CITADEL system's installation is properly signed by a trusted party defends against many types of attack. One example that CITADEL cannot defend against has a malicious superuser compiling a new kernel with a modified LSM, using valid keys scraped from the Linux system binary, and booting into it to bypass CITADEL's protections. Although not a bespoke solution, verifying an OS is well-explored and thus not a direct concern for this work. Additional protections include Linux's *Integrity Measurement Architecture* (§ 2.3.2.1).

Another question, though, asks whether the core kernel protects itself adequately from malicious kernel modules — our response, *to an extent*. Appendix A presents a proof of concept kernel module that changes a process's PID dynamically. This is highly concerning, as a process's PID is its core identifier in CITADEL's eyes; defence against this is discussed in § 4.4.5.2. The Linux kernel is a soup of *exported* and *un-exported symbols*,⁷ which is exploitable to access internal functions never designed to be called from a different context. This work does not assess the implications for the LSM framework, but highlights the potential need for *defensive programming* when

⁶Using the `bprm_check_security` LSM hook.

⁷Symbols include functions and variables held in the global namespace; exporting is the process of exposing it publicly to be called by third parties.

designing the LSM. Such protection is effective and possible, but must be considered seriously.

Thus we firmly believe that CITADEL, with its restricted TCB, can be trustworthy, creating a system of integrity checks based upon, and complementing, the trust placed in SGX itself.

5.2.2 IFC Model Implications

The CITADEL IFC model deviates from the designs and implementations of Pasquier et al. and Krohn et al. in three key ways;

1. Policy and enforcement decision are separated.
2. Passive entities may exist in a temporary *transient* state.
3. Operations between untainted entities are not mediated.

The first is handled with an extension to the core model to make policy decisions explicit and communicable (§ 4.3.2). This relationship is the core focus of this work, and CITADEL at all points relies on conservative assumptions — if not explicitly granted, permission is withheld. By default the system tends towards complete lockdown,⁸ a defensive measure to preserve *safety* if subjected to denial of service.

The second point is justified with an extension to the *creation flow* rule (§ 4.3.2, (4.7)). Transient entities are only created from a secure context, under which it automatically assumes the labelling of its parent entity. This may informally be considered an extension of the process's internal state, and held to the same restrictions. Such entities may only alter their security context (via another active entity) after being declared explicitly, leaving their transient states.

Regarding the final point — tainting in CITADEL assumes the worst, treating any potential infraction as cause for mediation; only the policy enclave may clear a taint. Assuming that all sensitive entities are correctly labelled, CITADEL will protect them

⁸For restricted entities.

against anything within the system. Unlabelled entities are assumed to be in the public domain, which allows normal execution and access control to proceed until the taint boundary is crossed.

5.2.3 SGX Vulnerabilities

This work assume that the SGX platform is itself secure; a successful attack on SGX obviously compromises any protection offered by CITADEL. A number of SGX vulnerabilities have been detailed; [60, 61, 62, 63, 64] these are effective and highly concerning, but mitigating them is not in the scope of this project.

5.3 Use Cases

In the introduction, we laid out the motivation and goals for CITADEL, including using it as a platform for reasoning about the relationship between an enclave and its host. Standard workflows for creating an SGX application uses a library OS, such as *SGX-LKL* [65] and *Graphene-SGX*, [66] to create a synthetic Linux environment inside the enclave supporting the primary application — this approach subjects the enclave to some of the same flaws and issues as the underlying OS. Could we reach a point where the host OS is trusted to hold custody of sensitive assets, instead of a trend toward pure isolation?

Two hypothetical scenarios are presented — one requiring secrecy, and one integrity — to illustrate how CITADEL could aid enclave-application development.

Scenario 1 A social-media company provides a GDPR platform, through which members request an archive of their data and other assets; these may be over 10 GB. Processing and collation happen inside an enclave, and an external service authenticates requests. Must the enclave seal archives after creation, before storage, and unseal them when requested? A solution using CITADEL may offload unencrypted archives to the custody of the host OS, using IFC’s secrecy mechanic to prevent unauthorised release. On request, the webserver requests permission to declassify the archive from the au-

thentication authority — no penalty need be paid for encryption.⁹

Scenario 2 An Apache Spark application partitions input data into a large number of shards. Assuming that shard-processing is protected inside an enclave, do shards need to be cryptographically signed to verify their provenance? CITADEL would entrust this tracking to the policy enclave, which, once attested may be considered a part of the application's trusted components.

Although CITADEL may not be suitable for the most sensitive processing tasks — enclaves are still vital here — it offers a lightweight protection mechanism that could potentially be, in the interest of performance, trusted in a supporting role.

⁹Disk encryption should be used for offline protection.

Chapter 6

Conclusions

This dissertation presented CITADEL, a modular, enclave-backed reference monitor to securely and verifiably implement IFC methods in the Linux kernel. By separating policy decisions and enforcement, we demonstrated a feasible approach to deep kernel integration using Intel SGX; the prototype leverages Linux’s security framework to realise decisions at the lowest level of the OS. CITADEL optimises for performance via an auxiliary library, which conservatively predicts a process’s security context, enabling unobtrusive application integration.

A full implementation of the NGINX webserver running on CITADEL validates this work using real-world performance benchmarks; the most punitive trial produced a 25% overhead, but other scenarios reported performance parity with the native Linux kernel. Verifying the methods presented here should be the next step, but an extension of CITADEL in a distributed setting also has great potential; inter-machine attestation will likely establish an exceptional degree of trust between remote components.

There is a way to go before CITADEL is fully realised and production-ready, but this project successfully demonstrates the viability and potential of a symbiotic enclave-kernel relationship, which, in the long run, may prove valuable for both.

Appendix A

PID Tampering: Proof of Concept

```

1  static void* retrieve_symbol(const char *sym) {
2      static unsigned long faddr = 0;
3
4      // Compare kernel symbol with query.
5      int symcmp(void* data, const char* sym, struct module* mod,
6                  unsigned long addr) {
7          if(!strcmp((char*)data, sym)) {
8              faddr = addr;
9              return 1;
10         }
11         else return 0;
12     };
13
14     kallsyms_on_each_symbol(symcmp, (void*)sym);
15     return (void*)faddr;
16 }
17
18
19 static asmlinkage void (*_change_pid)
20     (struct task_struct *task, enum pid_type type, struct pid *pid);
21 static asmlinkage struct pid* (*_alloc_pid)(struct pid_namespace *ns);
22
23 static ssize_t change_pid(void)
24 {
25     struct pid* newpid = _alloc_pid(task_active_pid_ns(current));
26     _change_pid(current, PIDTYPE_PID, newpid);
27     /* current->pid has changed. */
28 }
29
30 static int __init module_init(void)
31 {
32     _change_pid = retrieve_symbol("change_pid");
33     _alloc_pid = retrieve_symbol("alloc_pid");
34     /* ... */
35     /* On SysFS call execute change_pid(void) */
36     return 0;
37 }

```

Listing 2: Outline for a proof of concept kernel module to change a process's PID.

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