Securing Access to Untrusted Services From TEEs with GateKeeper

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Abstract

Applications running in Trusted Execution Environments (TEEs) commonly use untrusted external services such as host File System. Adversaries may maliciously alter the normal service behavior to trigger subtle application bugs that would have never occurred under correct service operation, causing data leaks and integrity violations. Unfortunately, existing manual protections are incomplete and ad-hoc, whereas formally-verified ones require special expertise.

We introduce GateKeeper, a framework to develop mitigations and vulnerability checkers for such attacks by leveraging lightweight formal models of untrusted services. With the attack seen as a violation of a services' functional correctness, GateKeeper takes a novel approach to develop a comprehensive model of a service without requiring formal methods expertise. We harness available testing suites routinely used in service development to tighten the model to known correct service implementation. GateKeeper uses the resulting model to automatically generate (1) a correct-by-construction runtime service validator in C that is linked with a trusted application and guards each service invocation to conform to the model; and (2) a targeted model-driven vulnerability checker for analyzing black-box applications.

We evaluate GateKeeper on Intel SGX enclaves. We develop comprehensive models of a POSIX file system and OS synchronization primitives while using thousands of existing test suites to tighten their models to the actual Linux implementations. We generate the validator and integrate it with Graphene-SGX, and successfully protect unmodified Memcached and SQLite with negligible overheads. The generated vulnerability checker detects novel vulnerabilities in the Graphene-SGX protection layer and production applications.

1 Introduction

Trusted Execution Environments (TEE) are available in several widely used CPUs from Intel, AMD, RISCV, and ARM [4, 5, 8, 24, 42, 46] and are supported by public clouds [2, 36, 61]. They protect the confidentiality and integrity of hosted code and data, treating the rest of the system including privileged software as untrusted.

Often, TEE applications use external untrusted services. For example, it is common to run unmodified applications in Intel SGX enclaves with the help of library OSs (libOSs), such as Haven, SCONE, and Graphene-SGX [9, 10, 56, 68], which enable seamless invocation of untrusted OS services. Similarly, trusted virtual machines in AMD SEV and Intel TDX use services provided by an untrusted hypervisor [4, 31].

The use of untrusted services inevitably creates security risks for TEE applications. While data confidentiality and integrity protection are broadly deployed, a less obvious vector of attacks is via an untrusted interface: an attacker may deliberately manipulate arguments, return values, and semantics of the service to trigger application-related bugs that inadvertently cause data leakage or control-flow violations [13, 19, 28, 65, 69]. For example, a futex may violate the mutual exclusion property [71], a file system may mix up file descriptors (§3.1), or a virtual device may return an unexpected error code [28]. We adopt the term Iago attacks [13, 69] to refer to all such interface attacks.

Defending against Iago attacks is an open challenge. In general, the mitigation entails validating the correctness of all possible outcomes of each service invocation – an increasingly difficult and error-prone task for complex stateful interfaces such as the POSIX file system (FS) API. Unfortunately, many production applications turned out to be vulnerable [19].

To narrow the interface to an external service and make it easier to secure, one common solution is to reimplement part of the service inside the TEE. For example, SGX-LKL includes an in-enclave FS implementation that calls into the untrusted OS only to store and retrieve raw data blocks [56]. Unfortunately, even a narrower block-based interface was found to be vulnerable [28, 69]. Closest to our approach, the BesFS project develops an FS model and formally proves a set of correctness invariants on it. The model is used to validate that the underlying untrusted FS does not mount Iago
attacks [65]. However, its development requires extensive expertise in formal methods and manual translation of the model into C to make it usable, which is harder to scale.

**GateKeeper** provides a general and comprehensive solution to Iago-attack mitigation and vulnerability testing that is easy to use and deploy for a variety of services, and without assuming formal verification skills. Our target users are (1) service providers seeking to enable safe and secure access to their services from TEE programs; (2) TEE developers seeking to secure access to existing untrusted services; (3) TEE security analysts testing existing applications resilience to attacks.

Inspired by the recent success of lightweight formal methods [11], we set to build our solution around an abstract service reference model, which omits implementation details and represents only the visible functional behavior.

Given a model, GateKeeper automatically generates a trusted validator layer (GKValidator) in C which can be readily integrated into an application or TEE runtime to securely invoke the service. GKValidator embeds an executable model and performs runtime checks to ensure conformance to the expected service behavior expressed by the model. While the executable model is similar to a reference implementation used for property checking [11], it differs in that it invokes an untrusted service and validates its conformance to the model, without implementing the service itself, which is particularly important when validating service behavior (as we show in the case of mutex in §3.3). Moreover, checking that the service output is the same as that of the model’s is not enough, because multiple correct outputs could be allowed, as in the case of different POSIX-compliant FS implementations. GKValidator correctly handles these cases.

The same model is used to generate a targeted vulnerability checker (GKVulnChk), which can serve to drive effective fuzzing sessions or be integrated into existing Iago vulnerability fuzzers [19]. GKVulnChk leverages the service model to check for deep vulnerabilities by automatically generating malicious values violating the model constraints tailored to the current state of the model (§4.4).

The fundamental question remains: how to build a complete and correct functional model of a service? We address this issue by introducing a novel approach that specifically targets the prevention of Iago attacks for existing services. We observe that to be effective against Iago attacks, the model must be tight to a service high-level specification (i.e., POSIX for an FS) or an existing uncompromised widely-used implementation, e.g., ext4. We refer to such implementations as etalon implementations. Thus, we enable model development by using both the etalon implementation and existing regression and conformance testing originally used for service development. This is particularly applicable to OS and hypervisor services which often provide extensive high-coverage testing suites.

Our method works as follows. Given an initial version of a model, we test the generated GKValidator layer on top of the etalon implementation with the testing suites (this is done outside the TEE). Any failure implies that the model is over-constrained. On the other hand, we introduce a tool to automatically generate GKMock, an executable mock of the service. GKMock is checked for correctness using the same testing suites, spotting additional bugs. Both GKMock and GKValidator can be regenerated effortlessly and tested again, until no new bugs are discovered. This method also makes it easy to adjust the model to the changes in the service API.

Our approach does not aim to replace formal verification of a model, rather it is complementary. In fact, we made initial steps toward model verification by proving safety of the mutex model by manually translating it into mypyvy [23]. However, even models with proven key safety properties do not guarantee complete model correctness [59]. Thus, we believe that our approach can be useful to raise the confidence in the model correctness with modest development efforts, under a reasonable assumption of the availability of high-coverage service tests.

In summary, our contributions are:

**Model and compiler (§5).** We introduce a simple C-like Domain Specific Language (DSL) for model development, which offers the primitives to specify the model, untrusted calls, and their conformance checks, including details needed for generating GKValidator, GKMock and GKVulnChk by a compiler we develop (2,770 LOC).

**Models for an FS and synchronization APIs (§7).** We develop the models of two complex OS interfaces while covering most of their APIs sufficient to run commodity applications. The models are much smaller than the full interface implementations: only 1,226 lines for the FS model and 300 lines for the futex and mutex models. Notably, writing the model is intuitive: the mutex and futex models took roughly a month for a single undergraduate student.

**Streamlined model development (§4).** We validate that the models are tight to the POSIX specification and the respective Linux implementations, by generating their executable mocks (§5). In particular, the generated FS mock is equivalent to a tmpfs in-memory file system when mounted via the FUSE library. We test the FS model by running a high-coverage SibylFS POSIX conformance suite which includes over twenty thousand tests [60], and the synchronization model using an LTP [41] Linux stress-testing suites, obtaining error-free execution in these experiments.

**Iago protection for FS and synchronization APIs in SGX enclaves (§7).** We use the models to protect real applications running in Intel SGX enclaves. We generate GKValidator and integrate it with Graphene-SGX [68]. GKValidator intercepts all calls to the respective OS services, and validates conformance to the models. We execute two large real-world applications: Memcached [47], and SQLite [54], and observe the added assertions has negligible performance overheads.
Targeted vulnerability checker (§8.2). We test for Iago vulnerabilities in existing applications and libOSs by generating GKVulnChk from the FS model. We find one new vulnerability in Graphene-SGX, which we responsibly disclosed (GKValidator successfully detects this vulnerability). Additionally, we test large applications such as Redis [58] and detect more vulnerabilities than the Emilia fuzzer [19].

2 Background and threat model

Trusted Execution Environments (TEEs). TEEs offer an isolated execution environment protected from privileged software adversaries. Two types of TEEs exist: secure enclaves that protect a part of processes’ address space [3, 18, 42, 46], and trusted virtual machines (VMs) such as AMD SEV, Intel TDX, and ARM CCA [4, 7, 31] that protect entire VMs with their OS. The hardware protects a TEE context’s control flow integrity and manages TEE’s entry, exit, and exceptions, thereby shielding the TEE from a strong adversary.

Enclaves. Hardware-based enclaves are supported in many cloud platforms [2, 36, 61]. Moreover, even trusted-VM TEEs are also used as an enclave to reduce their TCB [22]. As Intel SGX enclaves are the most mature technology, we use them as the target platform for prototyping our work.

Untrusted interface attacks. Checkoway and Shacham [13] demonstrated that an untrusted OS can perform attacks that may break the application’s control flow integrity. They coined the term Iago attacks. In brief, Iago attacks return maliciously crafted values instead of valid results. Later, Van Bulck et al. [69] generalized Iago attacks to calls to an untrusted interface from SGX enclaves. In this paper, we generalize this notion further by referring to any TEE (not just SGX) and permitting the adversary to perform arbitrary modifications to the service behavior.

TEE runtimes. One common trait among enclave technologies is the difficulty in executing legacy applications because they cannot directly invoke untrusted external functions, such as system calls. Further, some OS services require in-enclave runtime support (e.g., fork() in SGX). LibOSs alleviate this problem [9, 10, 56, 64, 68]. They place the entire application and its library dependencies in the enclave and serve system calls by implementing them internally or forwarding them to the OS, in which case they may be targeted by Iago attacks. LibOSs usually protect I/O-related system calls using encryption and integrity authentication tags. This allows applications to use external OS services, such as a host FS (e.g., in Keystone [42], Komodo [24], and Amazon Nitro [3]) with the data protection implemented by the libOS. SDK-based enclave applications aim to minimize the TCB by breaking existing applications into trusted and untrusted components. This allows control over the untrusted interface implementation, which includes the protection mechanism employed. Finally, in trusted virtual machines the guest VM can secure the data plane similarly from an untrusted hypervisor. We collectively refer to these frameworks facilitating TEE usage and protection as TEE runtime.

Threat model. We focus on the standard TEE threat model [4, 46], which excludes side-channel, speculative execution, and denial-of-service (DoS) attacks. In the context of enclaves we do not consider attacks on the enclave ABI tier, which may exploit incorrect register values and incorrect sanitization by the TEE runtime, or attacks due to bugs in the trusted code, such as buffer overflows. These attacks are orthogonal and their mitigation is well-understood [67, 69].

3 Motivation

TEEs may define different trust boundaries: in enclaves, the OS services are out of the Trusted Computing Base (TCB). In VM-based TEEs the OS is trusted, but the hypervisor services are not. However, many programs rely on services, which are no longer trusted to function correctly. For example, to access a host FS from enclaves, or a virtio device from a trusted VM, programs invoke respective system- or hyper-calls. Excluding these services from the trust boundary is supposed to improve security by reducing the TCB. However, accessing untrusted services without special care might expose the trusted software to Iago attacks.

Using untrusted services is not unique to TEEs, and was considered in other contexts. For example, programs executing on top of microkernels [1] may also require access to an untrusted FS to run legacy software [72]. However, we are not aware of systematic solutions to this problem so far.

3.1 Examples of Iago attacks

Many examples of Iago attacks have been published in prior work [13, 19, 65]. Our goal in this section is to show that mitigating them is not trivial. As an example, we use a compromised FS that attacks enclave applications using it.

Handled by libOS: data tampering. Malicious OS returns incorrect file contents. This attack is easy to mitigate, and most existing advanced libOSs do so by using well-known secure cryptographic integrity tools [10, 33, 68].

API attack: incorrect return values. A malicious FS returns an already existing file descriptor for an open() call.

```c
fd1=open("foo", O_CREAT | O_RDWR, 0644);
// OS returns fd1 value maliciously
fd2=open("foo", O_CREAT | O_RDWR, 0644); // TEE runtime updates auth tag for fd1 at offset 0
write(fd1, w1_buf, 100);
// TEE runtime updates auth tag for fd1 at offset 100
write(fd2, w1_buf, 100);
```

This is a real attack that exploits a vulnerability in the Graphene-SGX FS protection layer that we find automatically using GKVulnChk. The vulnerability stems from the way
Graphene-SGX handled data tampering attacks above. Specifically, it maintains a shadow in-TEE state for each opened file descriptor to store data authentication tags for the file contents at block granularity, and updates them on every write. Since the protection layer uses the OS-returned file descriptor value to index the shadow state it results in incorrect storage of the authentication tag if the file descriptor is incorrect.

API attack: incorrect behavior. Malicious OS creates a new file instead of a link to an existing file. Accessing both the linked and original files would result in inconsistent content.

Data integrity validation is insufficient to protect against API attacks since the file contents are returned correctly. The attack on the link call is particularly difficult to mitigate without validating the file system state is updated correctly.

3.2 Manual protection

Existing mitigation approaches rely on correctness validation following the trust-but-verify model [29, 40]. In a nutshell, TEEs invoke untrusted interface calls and validate that the response matches the expected service semantics.

Interface complexity. The difficulty of establishing a secure perimeter for an application and supporting access to untrusted services depends on the service semantics complexity. Taking SGX enclaves and libOSs as an example, there are several approaches for providing secure access to untrusted services, which trade the size of the TCB with the protection complexity. We explain this tradeoff next, using an FS API as a running example.

Complex semantics, smaller TCB. LibOSs, such as Graphene-SGX [68] and SCONE [9] forward system calls to an untrusted FS. In turn, they internally implement a comprehensive FS layer that strives to protect against interface attacks. Unfortunately, this protective layer is written manually and the effectiveness of the protection is hard to validate. Our work discovered a vulnerability in the Graphene-SGX protection layer as we mentioned in the example above.

Simple semantics, larger TCB. Some other libOSs include a partial or complete FS implementation [10, 56, 63], reducing reliance on the untrusted OS. For example, Haven [10] and SGX-LKL [56] include a complete FS implementation in the libOS, which reduces the interface to virtio-blk with simpler semantics and fewer inter-dependencies between operations. Unfortunately, a narrower interface still requires a protection layer of its own. This is written manually by libOS developers and shares the same validation problem as before.

Furthermore, the inclusion of an FS implementation in the TCB has multiple disadvantages. A larger TCB implies a larger probability of bugs. Further, enclave applications are forced to use a particular FS offered by the libOS, instead of any host OS-supported FS. Moreover, the deployment of an internal FS complicates integration with the host: users can use neither the existing FS structure nor tools such as backup with the rsync utility. Last, the libOS implementation replaces

3.3 Model-based protection to the rescue

Recent successes in applying formal methods to developing provably-correct operating systems and services [11, 38, 49, 65, 66] motivate us to consider a principled approach to mitigation of Iago attacks that a service functional correctness model can drive.

However, we found it challenging to apply these approaches to achieve our goals. The push-button verification methods used to develop an OS [49] and an FS [66] had to modify certain aspects of the modeled services (i.e., via finitization) to allow proof completion. In contrast, we aim to model existing unmodified services.

BesFS [65] developed a Coq-based model to prove correctness invariants but required manual translation into C to integrate the FS implementation into an SGX enclave.

Fundamentally, these approaches require extensive expertise in formal methods to develop and prove, whereas our goal is to make model development accessible to non-experts.

We share this sentiment with the recent work on the application of lightweight formal methods to check a complex application [11]. They develop a simple reference executable (mock) of a service to check compliance with a full-service implementation [11] by running them side-by-side. However, we cannot apply this approach as is. First, it checks for exact equivalence of outputs with the reference model, and thus cannot be used to represent services that can produce multiple valid results (i.e., different FSs that conform to POSIX specification, or file read that returns a different number of bytes). In addition, it is not clear how to check the blocking behavior of calls such as mutex.lock() with the help of the reference model. Last, this approach does not allow us to leverage the model to generate a vulnerability checker.

Challenge: correct model. To be useful for mitigating Iago attacks, a model should correctly represent a concrete reference implementation or high-level service specification (see Figure 1 for illustration). However, proving model correctness is an open problem [59]. An attacker can leverage a model
bug to compromise the system. Formally proving key model correctness properties indeed increases the confidence in the model correctness, yet is challenging for non-experts.

In GateKeeper, we seek to develop a complementary approach to create service models, validate them faithfully reflect the correct service implementation using existing tests, and reuse them to generate both a validator and a vulnerability checker to mitigate Iago attacks systematically.

4 Approach overview

We use two model examples to demonstrate our approach: a mutex, and a simplified FS with a single directory that is empty at the start, files have no attributes other than their size and permissions, and there are no links. We use a simplified read() call to demonstrate the main concepts.

4.1 Service model

In GateKeeper, developers write models in the GKSpec DSL. Each model encapsulates the user-visible state of the untrusted interface and a set of operations that manipulate this state to reflect the expected behavior of the modeled interface. FS abstract state. In our simplified FS, the state includes three abstract maps. The first map holds the file size and the contents1 indexed by a unique identifier (ino) akin to an inode. The other two maps translate paths or open file descriptors to ino values and the cursor.

Map ino_state(ino: int) returns(sz:int, data:char)
Map fs_state(path:string) returns(ino:int);
Map fd_state(fd:int) returns(off:off_t, ino:int);

FS operations. For each of the FS API calls, the model includes a respective action. An action resembles regular program code and specifies the state updates performed by the call. The action specifies constraints on the call’s semantics using the abstract states via requires statements. This is an intuitive way to specify conformance of the untrusted call to the model. The read() action sketch is as follows:

\[
\text{action read(fd: int, buf: void[], cnt: size_t) := } \begin{cases} \\
\text{# valid file descriptor?} \\
\text{# untrusted interface call} \\
\text{# cannot read past end of file} \\
\text{# update cursor} \\
\text{\textbf{returns} (nread: ssize_t) := {} } \\
\text{if (fd_state(fd) == NULL) return -EBADF;} \\
\text{nread := extern call untrusted_os_read(fd,buf,cnt);} \\
\text{off:off_t := fd_state(fd).off;} \\
\text{ino:int := fd_state(fd).ino;} \\
\text{requires (nread \geq 0 and nread \leq cnt);} \\
\text{requires (cnt \geq ino_state(ino).sz - off) \rightarrow} \\
\text{nread \leq (ino_state(ino).sz - off));} \\
\text{requires (ino_state(ino).data[off:off+nread] == buf[0:nread])}; \\
\text{fd_state(fd).off := fd_state(fd).off + nread;} \\
\text{return nread;}
\end{cases}
\]

Listing 1: read call model.

A return before the untrusted interface call is a shorthand to invoking the call and checking that it returned this value. However, this structure is more succinct, as it does not require checking for individual errors and allows specifying preconditions along with corresponding error codes for when they are violated.

Mutex model. Modeling mutex is different since operational behavior must be specified additionally to the return value. The abstract mutex state is represented by an abstract map holding a counter representing the mutex is locked (>0) or unlocked (0) indexed by a mutex identifier.

Map mutex_state(id:int) returns(counter:int);

The action corresponding to mutex_lock is as follows:

\[
\text{action mutex_lock(id: int) returns (res: void) := {} } \\
\text{\textbf{external call untrusted_os_lock}(id);} \\
\text{atomic (mutex_state(id)) {}} \\
\text{\textbf{await requires}} (\text{mutex_state(id).counter == 0}); \\
\text{mutex_state(id).counter:=mutex_state(id).counter+1;} \\
\}
\]

Listing 2: mutex_lock call model.

It invokes the untrusted mutex call first, and then atomically checks (thanks to the keyword atomic) that the respective mutex is indeed unlocked according to the model state, and turns it into locked. Indeed, the model can successfully identify the case when the untrusted mutex call would not block even though the mutex is locked. The await keyword is used to allow correct generation of blocking calls by GKMock (§5). We explain correctness in §7.2.

Summary: models. While these examples are simple they demonstrate the core concepts of the models used in GateKeeper. First, models are free of implementation details (i.e., the waiting queue for mutex). Second, the models are both succinct and expressive. Modeling mutex_lock only requires a few lines while capturing important semantic behaviors of the call: it is a blocking call, and abstract state checks and updates must happen atomically with respect to other operations performed on the same abstract mutex object.

4.2 From model to GKValidator

The model cannot be used as is to protect TEEs. TEE developers use GateKeeper’s compiler to auto-generate a correctness (w.r.t. the model) GKValidator module. GKValidator is a C library that integrates with TEE runtimes to validate the service’s conformance to the model (see Figure 3, left). GKValidator tracks concrete values used by TEEs
programs, invokes untrusted calls, and performs runtime assertions based on the model’s constraints in requires statements.

Consider the example in-enclave function in Listing 3 (we also use it in another context, hence the name). create, write and read functions invoke the GKValidator calls which internally call and validate the respective system calls. In this example, the model state is updated as follows; the fs_state map will contain an entry “foo” with a unique ino. ino_state map in ino will store the first nw bytes from the w_buf as the file’s content. After the untrusted system call invocation, runtime asserts are invoked, e.g., to validate that the file contents returned by the untrusted call match the expected contents in ino_state map.

```c
void conformance_read() {
    fd = create("foo", S_IRUSR | S_IWUSR); 
    assert (fd >= 0);
    char w_buf[100], r_buf[100];
    memset(w_buf, 0xff, 100);
    int nw = write(fd, w_buf, 100);
    lseek(fd, 0, SEEK_SET);
    int nr = read(fd, r_buf, nw);
    assert (!memcmp(r_buf, w_buf, nr));
}
```

Listing 3: Sample conformance test.

**Model initialization.** In our example, we consider an empty FS with no files. But if there were (i.e., “bar” in the listing below), GateKeeper allows specifying initial concrete state that would be compiled into GKValidator, linked with the TEE runtime, and included in its attestation report [17].

```c
    # Example: FS contains a single empty file "bar"
    init {
        fs_state("bar").ino := 0;
        ino_state(0).sz := 0;
    }
```

4.3 Model debugging and tightening

GateKeeper facilitates iterative model debugging and tightening. A model developer runs the tests used in the original service development, fixes the model based on the outcome, and reruns the tests until an error-free test execution (Fig 2).

To enable this process, GateKeeper compiler uses the model to generate GKMock, which is a functional executable implementation of the service (also called a reference implementation in [11]). GKMock for the FS model is a functional in-memory FS. Unlike the validator, the mock does not invoke the real service. Instead, it encodes the requires constraints to a Satisfiability Modulo Theories (SMT) formula, and uses an SMT solver to compute the return value that satisfies it. It chooses a random value if multiple are permitted, or generates an error when none is found.

GateKeeper model debugging approach relies on service test-suites. The tests are invoked both on the etalon implementation through the GKValidator, and on the mock (Figure 2). This process strives to achieve a tight approximation of the model to the service (assuming high coverage of the available service tests), which is highlighted in the following Lemmas.

**Lemma 4.1.** If a test invoked on the GKValidator-on-etalon combination fails then the model is over-restrictive.

**Proof.** Assume the model is not over-restrictive, there are no added runtime assertions that would cause the test to fail. Therefore, the test should pass.

For example, assume that in the read() model (Listing 1), we replace the constraint nread <= cnt with nread < cnt. As a result, the test in Listing 3 would fail.

**Lemma 4.2.** If a test invoked on a non-over-restrictive GK-Mock fails, then the model is over-permissive.

**Proof.** Assume the model is not over-permissive and not over-restrictive, the mock-returned values must satisfy all the available constraints. A conformance test should not have an invalid assertion and the test should pass.

For example, assume that we drop the constraint on the number of bytes read from the read() model. Thus, the test in Listing 3 would fail when the mock would return 1000 bytes, which satisfies a vacuous constraint.

When running tests on GKMock we execute each test multiple times, to test the model behavior when multiple possible outputs are permitted.

4.4 From model to GKVulnChk

We use a model to generate GKVulnChk to enable targeted lago-vulnerability checking of TEE programs that cannot be modified. GKVulnChk is a C library to be integrated into a fuzzer (see Figure 3, right). Internally, GKVulnChk generates
a set of malicious values that violate the model constraints tailored to the tested program.

For example, consider testing the program in Listing 3. When invoked with GKVulnChk instead of real service, the read call may return incorrect file contents or an incorrect number of bytes read. This approach allows targeted and more effective fuzzing. However, we allow minimizing the search space even further with the model hints (§5).

5 Design

Model language. We settle on representing service in an abstract model rather than developing a simplified reference implementation [11] to simplify the derivation of GKValidator, GKValidator and GKMock. Prior work used either language intended for modeling such as Alloy [6, 30, 34], or a subset of general-purpose languages such as Python and Rust to write models as they are used for the implementation as well [11, 49, 66]. We introduce a custom DSL: GKSpec, with a syntax that is close to C as seen in examples in Section 4. This is a pragmatic choice, as we find it easier to implement a compiler for GKSpec instead of a Python compiler.

GKSpec details. Types in GKSpec closely follow the C language types. We remove pointers, however. Instead, arrays and nested arrays are supported as in C with explicit element type. We add the string type to distinguish strings from character arrays. The operators resemble C, except for small changes such as range comparison and assignment for array types. In addition, GKSpec introduces quantifier logic operators within the requires statements, abstract maps, atomic, await, fuzz, and external calls into C functions. They are parsed by the compiler to generate all the artifacts as explained next.

Model compiler. The compiler generates C code from input models. This choice is due to three reasons. First, it enables simple integration with existing systems, as we show with Graphene-SGX (§8), FUSE [25] for mounting a mock FS, and existing test suites, e.g., the Linux Test Project (LTP) [41]. Second, TEE developers can use familiar tools such as profilers, debuggers, and compilers with mature optimizations, which reduces the validator’s performance impact. Third, GKSpec similarity to C simplifies the compiler. In addition, GateKeeper includes a trusted runtime library with data structures and functions invoked by the compiler as described next.

Code generation. Generating GKValidator, GKMock, and GKVulnChk from a model has common building blocks. The compiler parses the model, assigns a type to each variable, and checks for type safety. Code generation for C-like statements is straightforward. We focus on the new DSL statements next. First, abstract maps are generated using hashtables: the compiler emits code for memory management such that entries are allocated before inserting them into the hash table and deleted when they are freed. Assignments and validations using abstract maps in the model are translated to GET and SET operation on the hash table entry. Primitive types assignment is handled with the C assignment operator. Complex types rely on memory copying functions, e.g., buffer assignment via memcpy. External calls are a simple invocation of existing functions, and the init keyword generates a function with unique name for the concrete model initial state. This function is intended to be invoked at the application’s startup.

Atomicity. To support fine-grained atomic transactions via the atomic keyword the compiler emits a spinlock in each hash table definition. Spinlocks are values stored in memory and used to implement user-space spinlocks that do not rely on untrusted OSs. These spinlocks cannot be used in user programs instead of OS futexes or mutexes, however. The reason is that they lack much of the functionality of futexes, including fairness. Instead, they are intended to protect only a few memory assignments in the model itself.

Correct-by-construction. Assuming the compiler correctly parses the model and has no bugs, the executables are correct-by-construction w.r.t the model. Specifically, GKValidator asserts the correct semantics of the untrusted service; GKMock emulates the untrusted service’s semantics; GKVulnChk returns only values that violate the untrusted service’s semantics.

GKValidator. For GKValidator, the compiler generates a runtime assertion per requires statement. The predicate logic expressions are generated via the respected C operators. Notably, universal and existential quantifiers are generated using loops. Similarly, higher-order logic generates nested loops.

GKMock. For GKMock, the compiler aggregates scoped constraints for every variable, encodes them to an SMT formula and invokes z3 SMT solver [20]. The solver outputs values that must satisfy all the constraints, which in turn are assigned to the corresponding variables.

The services behavior is not limited to updating values. For example, an attempt to lock an already locked mutex cannot return until the same corresponding mutex is unlocked. The keyword await marks blocking calls in the model and expresses the constraints for which they wait (c.f. mutex_lock() in §4). To simulate it, the compiler generates busy-wait loops waiting for the condition to become true. In the case of mutex_lock(), GKMock waits for another thread to unlock: change the lock state, which clears the condition.

GKVulnChk. GKVulnChk is generated similarly to GKMock, except the constraints are negated before passing them to the SMT solver. The compiler generates a configurable number of solutions by calling the SMT solver with added constraints for the previously generated value at subsequent calls. Unfortunately, this approach can still result in a large number of candidate malicious values. For example, the negation of the read constraints (Listing 1) is:

nread < 0 or nread > cnt or
cnt != ino_state(ino).sz -> nread > ino_state(ino).sz-off

We overcome this by introducing hints to GKSpec that
direct the value generation in GKValidator to those that are more likely to trigger bugs. These are only soft hints, and they do not preclude the generation of all permitted values. For example, the read call in the FS model chooses from valid Linux error codes first, or prefers large numbers that may result in buffer overflows if used to access memory.

```c
fuzz { requires ( nread>=-131 or nread > (1<<30)); }
```

**Model debugging and refinement.** The compiler may be configured to output a trace file of invoked untrusted calls and their parameters. We find this useful when running the validator and model implementation with the test suites. Effectively, the trace and the failed test source code acts as a counter-example, similar to a verifier based on SMT solvers, allowing to debug invalid constraints in the model.

**Implementation.** The compiler prototype is written in PLY v3.10 and consists of 2,770 LOC. GKVulnChk and GKMock use the z3 v4.8.10 SMT solver [20]. The FS and synchronization primitives models consist of 1,226 and 300 lines, respectively. Our trusted library consists of 2,177 lines, including the uthash [27] hash table.

## 6 Securing untrusted interfaces in TEEs

Applying our approach in TEEs poses two additional requirements: trusted initial state, and coordinated state changes. At the same time, not all external services used in TEEs can and should be protected. We explain these below.

**Trusted initial state.** When a TEE is started, a service usually already has some initial state that must be reflected in the model state as well. This initial state however must be trusted.

Usually, TEEs are invoked with an initial state that is embedded with the trusted binary and thus attested at TEE invocation time. For example, Graphene-SGX uses a manifest containing trusted files and their expected paths on the host.

GKSpec includes special constructs for specifying the initial state. We require the TEE developer to generate these constructs from the TEE’s trusted state, and then compile them with GKValidator, as part of the integration of the validator with the TEE runtime.

**Coordinated model state changes.** An internal state of an untrusted service may be modified as a result of interaction with other entities, or due to the internal service logic. For example, an FS may service multiple processes concurrently.

This scenario would trigger an assertion by GKValidator because the model state would diverge from the actual service state. While seems to be a problem, this is exactly the behavior expected of the correct trusted system if such service state changes were not coordinated with the TEE. Indeed, this situation is indistinguishable from an Iago attack.

Thus, to support services whose state can be modified outside the current TEE, the changes must be coordinated explicitly with GKValidator. This coordination request may originate from a trusted party, or otherwise, the request should be rejected. For example, to share a file among two enclaves they must establish a trusted communication channel (i.e., via TLS connection to a remote enclave [21], or via local attestation [17]), through which they can coordinate file accesses.

**Trusted hardware services.** TEE technologies offer a variety of trusted hardware primitives, which therefore do not require additional protection. For example, if TEE hardware provides a trusted page table, then the OS services using it would not be vulnerable to Iago attacks from the OS virtual memory subsystem. In the case of Intel SGX, for example, process creation and virtual memory management are two cases that are validated by SGX hardware. GateKeeper is flexible to model and validate them, but it is not necessary.

**GKValidator security guarantees.** GKValidator protects against Iago attacks that may modify the behavior of calls to untrusted services invoked from trusted code [69]. Specifically, it protects against illegal control-flow modifications of a bug-free, trusted code that can circumvent its integrity or confidentiality. If the service behavior is modified by the adversary but it conforms to the permitted behavior of correct service, an application must handle such cases correctly; otherwise, it is considered an application bug.

In practice, GateKeeper cannot protect against corruption of trusted data if an attack does not compromise a running application. For example, a malicious OS may change the behavior of a write() call such that it corrupts the file contents; GateKeeper would not be able to detect this change unless the file contents are later read. In other words, GateKeeper may not be able to catch the invocation of the maliciously modified service itself. However, it guarantees that it will prevent the attempts to use the results of such a call by TEE software.

**Services that cannot be protected.** GateKeeper cannot be used to secure access to externally modified untrusted state, e.g., time sources, because the change to the state is not coordinated. Further, both hardware and privileged software may deny the service altogether. For example, the OS scheduler cannot be validated for SGX because the OS is in control of scheduling and may deny cycles to enclaves. The same is true for a storage drive that does not persist data. These DoS are out of scope.

## 7 Experience with protecting SGX enclaves

To evaluate the utility of GateKeeper we seek to protect untrusted FS API, futex OS call, and pthread mutex API in SGX enclaves. These are three complex services with non-trivial interfaces and are broadly used in trusted applications.

We develop the respective models following the proposed iterative development approach (§4.3) and generate their respective GKValidator, and GKVulnChk. We integrate GKValidator into Graphene-SGX to protect enclave applications, and use GKVulnChk to find Iago vulnerabilities in Graphene-SGX and production applications.
7.1 File system

We model a rich FS with support for directories, hard and soft links, data, metadata, and permissions.

**Model states.** We use four groups of abstract maps: process-related, path-related, in-use files/directories handles, and inode-related. Process maps are used to model global metadata used by the FS operations, e.g., user and groups for checking permissions, and the current working directory for path resolution. Path-related maps are indexed by a *canonical path* and maps to the corresponding inode. Note, in our model the inode does not represent stored disk blocks locations. Instead, we refer to inode as an identifier that acts as a key to the inode abstract map, which in turn contains data and metadata on the corresponding directory, or link (depending on the file type), and metadata for files. We discuss the file data below. Our model stores the data for different file types in different fields in the abstract map to simplify the model. Finally, the in-use handles map contains the unique inode identifier. For directories, we also maintain a list of visited entries to model getdents correctly by placing constraints that each entry is returned exactly once to the user.

**File content protection.** Our model contains a configurable encryption and authentication mechanism for file contents by using external calls to formally-verified cryptographic implementations [57] and storing authentication tags in the *inode_state* map at block granularity. Writes update the tags and reads validate them. This is similar to TEE runtimes that provide FS shields [9, 68] However, this check is redundant if the TEE runtime already validates the contents, so we can turn it off in the model. This is possible because we separately model the state for regular files, directories, and symbolic links.

**Model operations.** We model the core FS system calls that are sufficient for generating a mock that allows mounting it over FUSE [25] and passing a rigorous POSIX conformance suite (§8.1). The complete model in GKSpect is 1,226 lines, and contains the following FS operations: open, close, read, pread, write, pwrite, mkdir, chdir, getcwd, lseek, unlink, lstat, fstat, access, getdents, readdir, remkdir, symlink, rename, link, fchmod, chmod, lchown, ftruncate, truncate.

**Canonical path representation.** Using file paths as keys to our FS map can be ambiguous, i.e., ”f.txt” refers to the same file as "spec/../f.txt". We use canonical path representation as the key in the path abstract map. To simplify the model we implement the path resolution function in C and add it to the trusted runtime library. This function retrieves the directory states from the model abstract maps.

**Limitations.** We do not model asynchronous I/O, signals, internal memory allocations, or read-only FS. We also exclude resource exhaustion (inodes, memory) and respective errors as they constitute DoS attacks. Finally, our FS model must run in a single thread, the limitation shared by prior works on formal modeling of FSs [60, 65, 66]. These limitations do not preclude running large real-world applications (§8.3).

7.2 Synchronization primitives

We model three types of mutexes, *normal*, *errcheck*, and *recursive*, and futex wait and wake operations. These synchronization primitives are broadly used by multithreaded applications running in enclaves, both small (with Intel SDK [33]) and large (with a libOS). Graphene-SGX uses the futex API to implement higher-level synchronization primitives.

**Model states.** We use mutex and futex abstract maps with the respective identifier as a key that maps to metadata values, e.g., counter that is used to model a recursive mutex.

**Mutex operations.** The *mutex_lock* implementation (Listing 2) does not enclose the call to the untrusted mutex into the atomic clause. Thus, *mutex_lock*, and the state access is not atomic with respect to each other. This might seem to lead to state divergence and a potential TOCTOU attack. A strawman approach to include the untrusted call into the atomic block would cause a deadlock.

We observe, however, that the atomicity of the model state check and the untrusted call invocation is unnecessary. For *mutex_lock*, the states are checked and updated after the invocation of the untrusted call, whereas for *mutex_unlock* the checks and updates are performed before the call. In both cases, the model validates that the untrusted call indeed succeeds. As a result, even if the untrusted mutex is compromised, an attempt to lock it twice would fail on validation assertion (rather than block). Further, even if the unlocking thread is preempted after the state is updated but before the untrusted mutex unlock is invoked, the calling thread already left the critical section protected by the mutex, and will resume from the same point.

**Futex operations.** The original futex API is as follows: *futex_wait* puts the current thread to sleep and *futex_wake* wakes one or several sleeping threads. The first argument is a pointer and is used as a unique futex identifier. The pointed value acts as a condition to block or not. Thus, the pointed address must be accessible to the OS (cannot be stored in the TEE's memory). A malicious OS can modify the memory contents, without the TEE being notified. This problem precludes secure updates and validation of the futex states.

We introduced new calls to the futex API: *futex_init*, *futex_destroy*, and *futex_cmxchg*. This allows us to maintain a shadow state in the TEE’s memory and atomically update it together with the untrusted variable used for the futex.

The model tracks sleeping and waking threads to validate that the OS cannot the too large number of woken up threads. If the OS does not wake up these threads, it is equivalent to a DoS attack.

**Model verification attempts.** In an attempt to improve the model correctness guarantees, we experimented with formal verification manually translating the model to mypyvy [23, 55], which was previously used to prove complex transition system protocols such as Raft [50].
As an initial step, we translated our mutex model to prove that it guarantees mutual exclusion. The translation was straightforward and took a single day. We encode the mutual exclusion property in mypyvy as an invariant that each mutex is held by a single or no thread at any time.

```python
safety forall m in mutex_state :: mutex_state(m).
  counter == 1 || mutex_state(m).counter == 0;
```

These results are promising and encourage us to pursue verification of GateKeeper models in the future.

**Limitations.** We do not model timeouts (SGX has no trusted time source) or multi-process support. Non-default mutex types are supported but not other non-default attributes, such as protocol, sharing, and robustness. For futex, we provide a partial model that supports the most frequently used features, wait and wake.

### 7.3 Model development and deployment

**Development effort.** The development of GateKeeper was done in tandem with the FS model and took a roughly one-person year. The futex and mutex models took a month by an undergraduate student.

The model debugging approach helped discover numerous bugs, which the student was able to fix using the feedback provided by the traces of the failed tests. This positive experience indicates that non-experts in formal methods can efficiently develop services models.

We describe two bugs discovered in an early prototype.

**Over-restriction bug.** We placed an incorrect constraint asserting that the buffer size in the readlink call should always match the size of the symbolic link in the corresponding LTS state. However, the readlink semantics permit such a case and expect the partial target to be copied to the buffer. This was detected by running the respective tests with the validator on top of the ext4 FS.

**Over-permission bug.** We omitted the model of a constraint on the returned number of links for the fsstat system call. When running the test suites, we noticed failures. Further analysis revealed that the mock did not generate a the correct number of links because of this missing constraint.

**Mock testing.** We use several approaches. To run conformance tests on the FS, we connect it as a backend to FUSE and mount it regularly. To test the mutex-mock we use LD_PRELOAD when running the tests. Futex tests required manual integration.

**Integrating validator with SGX.** We integrate the GKVulnChk generator into Graphene-SGX v1.1 [68] to provide systematic protection when it accesses untrusted FS services and futexes. We modify 274 LOC. We place the generated validator in trusted code replacing the original Graphene-SGX logic that invokes untrusted calls. Finally, the validator code and the initial model state are compiled into a single enclave executable and attested together.

**Vulnerability checker.** We use two approaches to test for vulnerabilities using GKVulnChk. First, to fuzz existing applications we use GKVulnChk with Emilia [19], a fuzzer that intercepts system calls and detects crashes due to invalid memory accesses. GKVulnChk augments Emilia’s original value generator. Second, to fuzz the Graphene-SGX protection layer we replace system call invocation made by the trusted code with calls that return maliciously generated values. We do not use Emilia in this case, because its system call interception mechanism is based on strace, making the fuzzing too slow, and because it may detect Iago bugs in untrusted code that are unrelated to the TEE.

### 8 Evaluation

**Setup.** We evaluate GateKeeper on a server with Intel Skylake 17-6700 4-core CPU with 8 MB LLC, 16 GB RAM, Ubuntu Linux 18.04 64-bit, Linux kernel v4.15.0-135 and Intel SGX driver v2.10 [32]. We run each experiment 10 times and report the mean execution time. The standard deviation is below 5%.

**8.1 Model validation**

For all the tests we compile the GKM and GKV with address sanitizers [62] to ensure that the compiler-generated code is free of memory vulnerabilities.

For the FS model, we use the SibylFS POSIX conformance test suite, with 21,068 tests that achieve 98% coverage of SibylFS’s POSIX model [60]. For synchronization primitives, we use LTP [41] stress tests performing millions of mutex operations with 120 threads. We also test for conformance using mutex and futex LTP tests excluding tests with unsupported features by our model (8 out of 14).

**File system.** The SibylFS test suite is designed to work against a real FS. We use FUSE [25] for that purpose.

Testing with FUSE poses a challenge. The tests use multiple processes and assume a shared FS, while our model is intended for a single process. To allow testing with multiple processes, we add an action to our FS model that updates the current process properties (user, groups, cwd, and umask). The mounted FS invokes this function to update the requesting process’s properties before issuing any FS operation.

For the validator-FS and mock-fs, all tests terminate successfully, implying that To validate compliance, we also analyze the traces using the SibylFS compliance checker, which rejected 528 out of 21,068 tests. Manual investigation revealed that none were rejected because of bugs in the model itself. Two traces were rejected, as they exercised sparse files not included in our model. In another trace, the FS reported an empty root folder with two links instead of one. However, this is a common behavior, also found in ext4. The rest of the rejected traces revealed bugs in FUSE, which did not forward
We exclude the git application because its run was too long.

We demonstrate the use of GKVulnChk to find vulnerabilities. We run five mutex and three futex conformance tests. We select only the tests that use features in our model, e.g., without timeouts. All tests terminate successfully, revealing no bugs in our model.

### 8.2 Vulnerability checking

We use the mutex stress test from LTP [41], which generates high contention on locks, assuring that mutual exclusion is always maintained. To test our mutex model, we intercept mutex operations using LD_PRELOAD and replace them with calls to the mutex's validator and mock. To test the futex model, we integrate the futex's validator and mock into Graphene-SGX’s mutex implementation, replacing the original futex operations. Next, we run five mutex and three futex conformance tests. We select only the tests that use features in our model, e.g., without timeouts. All tests terminate successfully, revealing no bugs in our model.

#### Library OS vulnerabilities

We run our fuzzer against Graphene-SGX using a simple test we implement, which performs all file operations supported in Graphene-SGX and asserts that the results are as expected. This test is sufficiently simple to allow us to find vulnerabilities in the libOS itself.

Our fuzzer invokes the test, each time replacing a system call return value or output parameter with our generated adversarial values. Overall, we run our fuzzer with 4,000 different malicious values. Fortunately, Graphene-SGX successfully protects against most of these attacks. However, we find one vulnerability in their protection logic that results in illegal memory access (responsibly disclosed to developers). Such vulnerabilities are known to compromise entire enclaves [43].

### 8.3 Microbenchmarks and end-to-end performance

Finally, we study the performance overhead of our in-enclave runtime validation. We integrate both FS and futex validators into Graphene-SGX. We disable the validator’s internal file-content integrity validation and use Graphene’s file protection via authenticated encryption in both configurations. We call Graphene-SGX with the validator as GK-Graphene and to the original version as Vanilla-Graphene. In the following benchmarks, we execute the same tests with the same setup both in Vanilla-Graphene and GK-Graphene.

#### FS Stress Test

We use FSCQ to measure performance overheads of common FS operations, as done in previous work [14, 65]. We modify each test in the suite to measure end-to-end execution time. This puts the focus on the FS operations and excludes initialization time. Before each test, we add a setup step to validate that the FS operations succeed. Finally, we modify the write microbenchmark to perform sequential writes to avoid internal caches in Graphene-SGX, which forces all write operations to be forwarded to the OS.

The results are shown in Figure 4a. We observe that the overheads of most operations are relatively small. Specifically, note that with GK-Graphene read and write incur less than 10% overhead compared to Vanilla-Graphene. The file creation overhead is higher, about 60%, as expected because of the complexity of the file path validations.

#### Mutex Stress Test

We use the mutex stress test from LTP to measure the performance of our mutex model. We configure the test to run for 20 seconds. We observe negligible overheads: 4,238,450 and 4,227,715 lock/unlock operations performed in Vanilla-Graphene and GK-Graphene, respectively. This is expected: futex validations are simple comparisons and small compared to the sleep times under high lock contention.

#### SQLite: FS overheads

SQLite is a popular database used for libOS evaluation in prior work [39, 52]. We measure end-to-end latency with `speedtest` shipped with SQLite v3.34.1 while varying the cache size. We use a single thread and disable mmap-based access to the DB files. The results are shown in Figure 4b. We observe that GK-Graphene is on a par with Vanilla-Graphene, regardless of the cache size. This demonstrates that the FS validator overheads are negligible.

#### Memcached: futex overheads

Memcached [47] is a popular key-value store that was used in prior work on enclaves [9, 44, 51, 52]. We evaluate Memcached using the YCSB workload

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**Table 1: Fuzzing workloads and vulnerabilities found by GateKeeper (by Emilia [19])**

|       | curl | memcached | Redis | zlib |
|-------|------|-----------|-------|------|
| ver.  | 7.58 | 1.5.20    | 5.0.5 | 1.2.11 |
| LOC   | 130k | 18k       | 115k  | 18k  |
| Desc. | Web client | MemKVS | DB KVS | Library |
| Vuln. | 5 (3)  | 4 (4)     | 1 (1) | 2 (1) |

---

We manually validate each crash and filter duplicates. We report the results in Table 1. GKVulnChk identifies a superset of vulnerabilities as compared to Emilia. Specifically, it finds identical vulnerabilities for all the tests, plus new ones in zlib and curl that Emilia did not find.
generator [16] with the predefined workload C as in previous work [44, 53]. It performs 100% random GET operations for 1 KB records. To focus specifically on futex overheads, we evaluate Memcached with one or four serving threads, with uniform access and hotspot. In hotspot, we define 5% of the entries as a hot set with an access probability of 95%. This creates high and low contention on internal mutexes.

We co-locate YCSB and Memcached on the same machine and pin each one to a different core to avoid network overheads. We preload Memcached with 1 MB of data before each test to avoid SGX paging overheads [51]. We report the maximum throughput achieved. The results are shown in Figure 4c. Exactly as in the mutex stress tests, we observe negligible overheads in both high- and low-contention setups.

### 8.4 In-enclave software size comparison

We measure the code size of in-enclave FS implementation in SGX-LKL and compare it to the size of our FS model, compiler and trusted library (6,173 lines in total). Note that these components constitute the FS validator’s TCB as it is generated by them. Both protect against Iago attacks. As SGX-LKL includes a full Linux kernel, it includes many FS implementations. For completeness, we measure both the FS directory in LKL (887k LOC), and only for ext4 that SGX-LKL mounts by default (36k LOC). GateKeeper minimizes the TCB, while still protecting against Iago attacks. Yet, admittedly, our FS model does not support all the ext4 features.

### Interface defenses.

TeeRex [15] detects memory-related vulnerabilities via symbolic execution. The Intel edger8r tool generates ocalls that enforce type safety, and van Ginkel et al. [70] used separation logic to validate that pointers are entirely in/out of the enclave address space. COIN attacks [37] further generalize Iago attacks to the unexpected invocation of enclave functions and use symbolic execution to detect such vulnerabilities. SGXPecial [48] restricts valid control flows across the interface to mitigate code reuse exploits. Unlike these defenses, GateKeeper validates the completed semantics of cross-interface calls and detects any deviation from them.

Many runtime systems attempt to mitigate Iago attacks [9, 10, 12, 29, 40, 45, 56, 68]. We focus on Inktag and Sego, as TEE runtimes were already discussed (§2). Both use the trust-but-verify approach, as in GateKeeper. However, they rely on a trusted hypervisor that has access to devices and can therefore verify the OS behavior when accessing a certain file, which facilitates the validation of FS operations. GateKeeper cannot rely on a trusted hypervisor but still shows it is possible to verify OS services from within the enclave.

#### Iago fuzzers.

Emilia [19] provides a system call fuzzer to detect Iago vulnerabilities. Unlike Emilia, which performs static analysis on programs’ source code, GateKeeper generates malicious values based on the model.

#### Services models.

Modeling of services for verification was extensively studied [11, 14, 26, 38, 49, 65, 66]. Unlike previous models that were used to verify service implementations, GateKeeper generates validation, mock, and vulnerability checking tools.

### 9 Related Work

#### TEEs.

TEEs [4, 5, 8, 31, 35, 42, 46] protect against a privileged adversary. TEEs do not protect against Iago attacks on the untrusted software interface, which is the focus of GateKeeper.

#### Enclave interface attacks.

Van Bulck et al. [69] provided a comprehensive analysis of enclave interface attacks, generalizing Iago attacks from system calls to ocalls and manually inspecting libOSs code to find Iago vulnerabilities. GateKeeper, finds such vulnerabilities automatically via GKVulnChk.

### 10 Conclusion

GateKeeper is a framework that facilitates model development without expertise in formal methods. The model is used to systematically protect trusted code from untrusted services. We develop and refine models for FS and synchronization primitives and use them to protect Memcached and SQLite executing in SGX enclaves. We also find vulnerabilities in Graphene-SGX and production applications with the FS vulnerability checker. We believe that GateKeeper is not limited to TEEs, and forms a foundation for protecting general un-
trusted services, e.g., for microkernel and remote untrusted services.
GateKeeper’s source code will be publicly available.

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