

HasTEE - Confidential Computing on Trusted Execution Environments with Haskell

ANONYMOUS AUTHOR(S)

Growing concerns about data privacy and confidentiality have spurred the development of Confidential Computing, a security paradigm that facilitates deploying applications in low-trust environments like the cloud and IoT. Confidential Computing allows this low level of trust on various platforms through the support of hardware-enforced memory isolation units known as Trusted Execution Environments (TEEs). Popular TEEs, such as Intel SGX or ARM TrustZone, isolate applications from low-level system software with large codebases, such as operating systems and hypervisors, reducing the Trusted Computing Base (TCB) of applications.

However, the adoption of this technology has been obstructed by the awkward programming model enforced by most TEEs, which requires partitioning an existing application into trusted and untrusted components. The toolchain that supports these components relies entirely on low-level C/C++ libraries that are error-prone, memory-unsafe, and have the potential for accidental information leakage.

We address the above concerns through HasTEE, a Haskell library for programming TEEs. HasTEE presents a type-safe, high-level programming model that enables the execution of Haskell programs on the Intel SGX TEE. The library is capable of automatically partitioning a Haskell application, using the type system, and then running the trusted component of the application on an SGX *enclave* via our modified GHC runtime. Furthermore, the purity and expressive type system of Haskell allows HasTEE to enforce Information Flow Control (IFC) techniques that prevent unintentional leakage of confidential data from the TEE memory.

Our partitioning approach is notably lightweight and does not involve any modification of the Glasgow Haskell Compiler. We demonstrate the practicality of HasTEE across a variety of domains through case studies on (1) privacy-preserving machine learning, (2) an encrypted password wallet, and (3) a data clean room providing differential privacy.

CCS Concepts: • **Security and privacy** → **Trusted computing; Information flow control; Security in hardware;** • **Software and its engineering** → **Functional languages; Domain specific languages.**

Additional Key Words and Phrases: Trusted Execution Environment, Intel SGX, Haskell, Enclave

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1 INTRODUCTION

Confidential Computing is an emerging security paradigm that is progressively transforming the semiconductor industry, with a consequential shift in how software is designed [Mulligan et al. 2021]. At its core, confidential computing aims to secure what is known as *data in use*.

Data in use refers to in-memory data that is distributed across the DRAM, cache lines, page tables and other CPU registers. While encryption has been fairly successful in protecting secrets for *data at rest* (such as databases and file systems) as well as *data in transit* (such as networks using TLS), the need for efficiency and performance has prevented encryption from effectively protecting *data in use*, which has seen an unprecedented rise in vulnerabilities in the last decade [Checkoway and Shacham 2013; Kocher et al. 2018; Lipp et al. 2018].

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To protect *data in use*, hardware vendors such as Intel, ARM, and AMD have introduced the concept of a *Trusted Execution Environment (TEE)*, which provides hardware-enforced isolation for in-memory data. A TEE unit, such as the Intel SGX [Intel 2015] or ARM TrustZone [ARM 2004], provides a *disjoint* region of code and data memory that allows for the physical isolation of a program's execution and state from the underlying operating system, hypervisor, I/O peripherals, firmware, and even the physical compromise of a device. As such, the TEE hardware unit has been heralded as a leading contender to enforce a strong notion of *trust* in areas such as cloud computing [Baumann et al. 2015; Zegzhda et al. 2017], IoT [Lesjak et al. 2015] and blockchain [Bao et al. 2020].

However, despite providing such a strong threat model, the adoption of TEEs in modern software development has faced resistance due to their awkward programming model [Decentriq 2022]. At a high level, the programming model requires splitting the state of the program into trusted and untrusted components and dividing the entire logic into two separate software projects. This is often a complex and error-prone process. The issue is further exacerbated by the fact that the API provided by the hardware is entirely based on languages such as C/C++, which are low-level and can open further opportunities to exploit well-known memory-unsafe vulnerabilities such as return-oriented programming (ROP) [Shacham 2007].

Efforts have been made to port high-level managed languages such as GoTEE [Ghosn et al. 2019], a superset of Go, and J_E [Oak et al. 2021], a subset of Java, onto TEEs. Both efforts, however, make large modifications to the respective compiler to parse the source code for effective identification of the trusted and untrusted parts of the code.

Virtualization-based solutions, such as AMD SEV [AMD 2018], on the other hand, typically virtualize an entire application platform, such as the hypervisor. The tradeoff is that the trusted computing base becomes larger and the granularity of secure data becomes coarser.

Our contribution through this paper is the *HasTEE* Haskell library, which offers a high-level programming model for developing TEE applications. In contrast with GoTEE and J_E , our implementation does not require any modification of the canonical Glasgow Haskell Compiler (GHC) [Jones et al. 1993]. The GHC runtime requires modification to run on the enclave but remains capable of hosting the entire Haskell language (with extensions) supported by GHC 8.8.

The partitioning of a TEE program is accomplished entirely through a 200-line library that uses the Haskell type system to distinguish between the trusted and untrusted components of a program. The granularity of secure data and code in HasTEE remains finer than virtualization-based solutions such as AMD SEV, while keeping a much smaller trusted code base. One benefit of running Haskell on a TEE is the ability to enforce language-based information flow control [Russo et al. 2008] on data that crosses the boundary between the trusted and untrusted parts of the application.

Listing 1 presents a sample password checker application written in HasTEE. HasTEE adopts the term *Enclave* from Intel's nomenclature to refer to the software that runs inside the TEE unit.

```

1 pwdChkr :: Enclave String -> String -> Enclave Bool
2 pwdChkr pwd guess = fmap (== guess) pwd
3
4 passwordChecker :: App Done
5 passwordChecker = do
6   paswd      <- enclaveConstant "secret"
7   enclaveFunc <- secure $ pwdChkr paswd
8   runClient $ do -- the Client monad
9     userInput <- liftIO $ putStrLn "Enter your password" >> liftIO getLine
10    res       <- onEnclave (enclaveFunc <.> userInput)
11    liftIO $ putStrLn $ "Your login attempt returned " <> (show res)

```

Listing 1. A password checker written in HasTEE

HasTEE internally uses conditional compilation provided by GHC to swap in different implementations of the HasTEE API depending on whether it is compiling for the trusted execution environment or the untrusted client. The two compilations use modules that export the same API but differ in the underlying implementations of the functions.

The distinction between the trusted and untrusted parts of the application is done via the type system that encodes the former as the `Enclave` type (line 1) and the latter as the `Client` type (type inferred in line 8). At a high level, the untrusted *client* is in charge of driving the application, while the *enclave* is assigned the role of a computational and/or storage resource that services the client's requests instead of driving the program.

Line 6 holds the secret string that we want to protect. The `enclaveConstant` function accepts the secret string and gets compiled to a no-op term for the client. As a result, the untrusted client can never observe the secret string. The TEE, on the other hand, is the one that holds the string in memory. Line 7 uses the secure call to obtain a reference to the `secure pwdChkr` function and then uses a combination of the `onEnclave` and `<.>` combinators (Line 10) to execute the function `pwdChkr` on the enclave and obtain the result on the client side.

HasTEE connects an application (`passwordChecker`) to Haskell's main method using the `runApp :: App a -> IO a` function that executes the application. We explain the HasTEE API in detail in Section 4.2 and the semantics in Section 4.3.

Partitioning is done by compiling Listing 1 twice using a conditional flag to assign different semantics to the two programs. Fig 1 shows the partitioning at a high level. This approach is inspired by work on the `Haste.App` library, used to partition a server and client [Ekblad and Claessen 2014] for web programming.

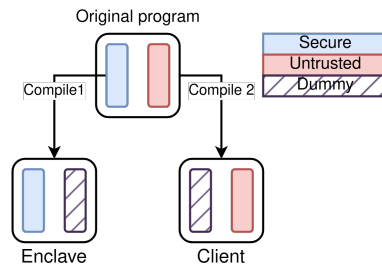


Fig. 1. The HasTEE partitioning scheme

For the information flow control (IFC), the underlying implementation of the `Enclave` type uses a restricted IO monad in the style of MAC monads [Russo 2015]. The monad significantly constrains the scope of side-effecting operations to protect the confidentiality of data within the enclave. A detailed account is given in Section 4.5. We summarise our contributions below.

Contributions

- **A type-safe, high-level programming model.** The HasTEE library enables developers to program a TEE environment, such as Intel SGX, using Haskell - a type-safe, memory-managed language whose expressive type system can be leveraged to enforce various security constraints. Additionally, HasTEE allows programming in a familiar client-server style programming model (Section 4.2), an improvement over the low-level Intel SGX APIs.
- **Automatic Partitioning.** A key part of programming TEEs, partitioning the trusted and untrusted part of the program, is done automatically using the type system (details in Section 4.4). Crucially, our approach does not require any modification of the GHC compiler

and can be adapted to other programming languages, as long as their runtime can run on the desired TEE infrastructure.

- **Information Flow Control (IFC).** Drawing inspiration from *restricted* IO monad families in Haskell, we designed an Enclave monad that prevents accidental leaks of secret data by TEE programmers (details in Section 4.5). Hence, our Enclave monad enables writing applications with a relatively low level of trust placed on the enclave programmer.
- **Practicality.** We illustrate the practicality of the HasTEE library through three case studies across different domains - (1) a Federated Learning example (Section 5.1), (2) an encrypted password wallet (Section 5.2) and (3) a *differentially-private* data clean room (Section 5.3). The examples also demonstrate the simplicity of TEE development enabled by HasTEE.

2 BACKGROUND

This section provides background information on the specific TEE environment that we target with the HasTEE library - Intel SGX.

Intel Software Guard Extensions (SGX)

Intel Software Guard Extensions (SGX) [Intel 2015] is a set of security-related instructions supported since Intel's sixth-generation Skylake processor, which can enhance the security of applications by providing a *secure enclave* for processing sensitive data. The enclave is a disjoint portion of memory separate from the DRAM, where sensitive data and code reside, beyond the influence of an untrusted operating system and other low-level software. Fig. 2 illustrates the difference in attack surface between an application without enclaves and one that has them.

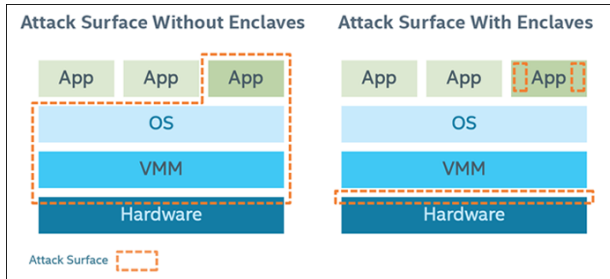


Fig. 2. Intel SGX Attack Surface (Image source [Intel 2018a])

Internally, SGX reserves a 128 MB segment of the physical memory called the *Processor Reserved Memory*. A subset of this memory holds the enclave memory pages in an area called *Enclave Page Cache (EPC)*. The CPU protects the confidentiality of the memory residing in shared cache lines by encrypting the cache when it gets evicted, and decrypting it as it is loaded into the enclave memory while the CPU runs in enclave mode. This incurs a four-fold performance hit [Zhao et al. 2016] but provides stricter hardware-enforced memory isolation.

Intel offers an SGX SDK [Intel 2016] for programming applications with enclaves. The SDK requires partitioning an application into two parts such that the sensitive data resides in a separate trusted C/C++ project from the untrusted data and code. The SDK provides a specialised set of function calls, referred to as *ecall*, to access the enclave, as well as an *ocall* API for the enclave to communicate with the untrusted client.

The boundary between the client and enclave is defined using a specialised *Enclave Description Language (EDL)*. The SGX SDK parses EDL files using a special tool called *edger8r*, which is part of

the SDK. This tool generates two *bridge* files that ensure data transfer between projects is done through *copying*, rather than *sharing* via pointers, to prevent an adversary from compromising the state of the enclave through pointer manipulation. Fig 3 shows the SDK's programming model.

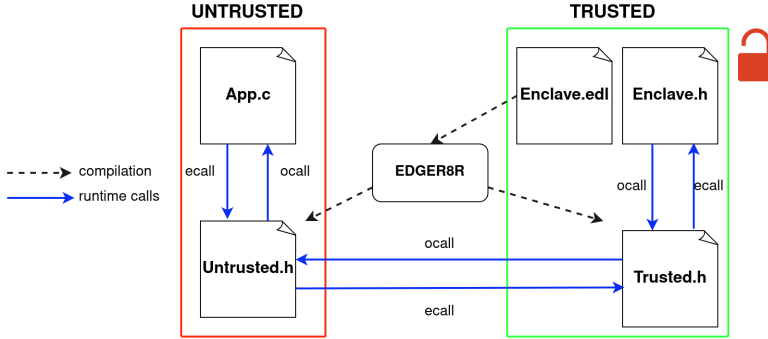


Fig. 3. Intel SGX SDK Programming Model

The primary objective of an application developer when working with enclaves is to minimize the *Trusted Computing Base* (TCB). By placing the operating system, hypervisor, and other system software outside the enclave, the size of the TCB is drastically reduced compared to an application without an enclave. For the very essential system software, such as `libc` (the C standard library), which is required to run any software application, the SGX SDK provides a minimal and lightweight implementation called `tlbnc` [Intel 2018b].

Overall, the programming of an SGX enclave involves understanding a fairly complex control flow between the untrusted and the trusted project. The SDK provides an API of 200+ functions to manage the life cycle of an enclave. One of the key difficulties observed in programming enclaves was the awkwardness of enforcing this multi-project programming model on a typical software project. Additionally, the restricted `tlbnc` library significantly hinders the ability to run complex applications on the enclaves, beyond those written in vanilla C/C++.

3 KEY IDEA: A TYPED, HIGH-LEVEL PROGRAMMING MODEL FOR ENCLAVES

The key contribution of this paper is the HasTEE library, which aims to simplify the programming of enclaves. The library contributes the following:

- (1) HasTEE enables the programming of enclaves in a high-level, memory-managed, statically-typed programming language - Haskell. By running Haskell on an enclave, developers can utilize its expressive type system to type-check the safety of interactions between the client and the enclave.
- (2) HasTEE allows expressing enclave-based programs in a familiar single-program, client-server-based programming model rather than the low-level, multi-project approach provided by the SGX SDK.
- (3) HasTEE, being embedded in Haskell, enables the expression of language-based security constraints such as Information Flow Control (IFC) on sensitive data that moves in and out of the enclave memory.

One of the key challenges in accomplishing point (1) is running the GHC Haskell Runtime [Marlow et al. 2009] on an enclave. A Haskell program relies on the runtime for essential tasks such as memory allocation, concurrency, I/O management, etc. The GHC runtime heavily depends on well-known C standard libraries, such as `glibc` on Linux [GNUDevs 1991] and `msvcrt` on

Windows [Microsoft 1994]. In contrast, the Intel SGX SDK, as discussed in the previous section, provides a much more restricted libc known as tlibc.

This results in the fact that several libc calls used by the GHC runtime such as mmap, madvise, epoll, select and 100+ other functions become unavailable. Even the core threading library used by the GHC runtime, pthread, has a much more restricted API on the SGX SDK. To solve this conundrum, we have patched portions of the GHC runtime and used functionalities from a library OS, Gramine [C. Tsai, Porter, et al. 2017], to enable the execution of GHC-compiled programs on the enclave.

The Programming Model and Partitioning

Once Haskell programs are capable of running on an enclave, there is the requirement of partitioning the original source program. As mentioned in point (2) above, HasTEE doesn't require the programmer to manually partition the program but uses a conditional compilation trick to partition the same compilation unit into two parts.

The conditional compilation tactic was first presented in Haste.App [Ekblad and Claessen 2014], which is a Haskell library for web programming. The library automatically partitions the application into a Client and Server type using a conditional compilation trick that swaps in different implementations of the terms corresponding to the above types. The function calls between the Client and Server are checked for type safety at compile time, where they are replaced with corresponding remote procedure calls (RPC) at runtime.

We adopt the same partitioning tactic owing to its simplicity, as it does not require any compiler extensions or elaborate dependency analysis passes to distinguish between the underlying types. The codebase involved in other complex partitioning approaches [Ghosn et al. 2019; Oak et al. 2021] becomes part of the Trusted Computing Base (TCB), creating a larger TCB. In contrast, the conditional compilation approach does not add any code to the TCB. Fig 4 shows the partitioned software stack in the HasTEE approach.

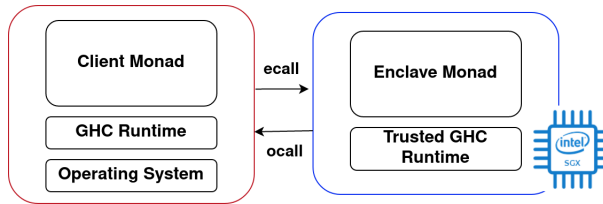


Fig. 4. The untrusted software (left) and the trusted software stack (right)

Post-partitioning, it is natural to use the client-server-style programming model for programming the enclave. In this model (example in Listing 1), the client remains the primary driver of the program while utilizing the enclave as a computational and/or storage resource, rather than making it the main driver of the program. At compile time, the source program gets type safety because of being written in Haskell, while at runtime, the HasTEE library handles the copying of the actual messages between the client and the enclave memory. The detailed API is presented in Section 4.2.

Information Flow Control on Enclaves

As stated in point (3) above, being a Haskell library enables HasTEE to tap into the library-based Information Flow Control techniques in Haskell [Buiras et al. 2015; Russo 2015; Russo et al. 2008]. The IFC literature distinguishes between security-critical and security-relaxed monad families using a Sec H and a Sec L monad. We have a similar security-level hierarchy between the Enclave

and Client monads, respectively. Accordingly, we design the Enclave monad such that it restricts the possible variants of I/O operations. Due to the security-critical nature of the Enclave monad, we include a trust operator, which is similar to the endorse function found in IFC literature.

TEE Independence

Another benefit of being a high-level programming model is that it provides an abstraction over low-level system APIs offered by the SGX SDK. As a result, the principles applied in programming Intel SGX, should translate to the programming of other popular TEEs, such as the ARM TrustZone. TrustZone employs a similar two-project approach as Intel SGX, along with a gateway description header file similar to the .edl file used in the SGX SDK. An important point to note here is that while the high-level API and programming model can be easily translated, considerable effort is required to port the GHC runtime to the TrustZone infrastructure.

4 DESIGN AND IMPLEMENTATION OF HASTEE

This section first outlines the high-level design and semantics of the HasTEE library. Later in this section, we will describe the internal implementation details of the library.

4.1 Threat Model

We begin by discussing the threat model of the HasTEE library. HasTEE has the very same threat model as that of Intel SGX. In this model, only the software running inside the enclave memory is trusted. All other application and system software, such as the operating system, hypervisors, driver firmware, etc., are considered compromised by an attacker. A very similar threat model is shared by a number of other work based on Intel SGX [Arnavtsov et al. 2016; Baumann et al. 2015; Ghosn et al. 2019; Lind et al. 2017].

In this work, we enhance the application-level security firstly by using a memory-safe language, Haskell, and secondly by introducing information flow control via the Enclave monad. Our implementation strategy of loading the GHC runtime on the enclave allows us to handle Iago attacks [Checkoway and Shacham 2013] (see Section 4.4.1). We trust the underlying implementation of the SGX hardware and software stack (such as tlibc) as provided by Intel. Known limitations of Intel SGX such as denial-of-service attacks and side-channel attacks [Schaik et al. 2022] are beyond the scope of this paper.

An ideally secure development process should include auditing the code running on the enclave either through static analyses or manual code reviews or both. The conciseness of Haskell codebases should generally facilitate the auditing process. However, the mechanisms for fail-proof audits are beyond the scope of this paper as well.

4.2 HasTEE API

We show the core API of the HasTEE library in Fig 5. The functions presented operate over three principal Haskell data types: (1) Enclave, (2) Client, and (3) App. All three types are instances of the Monad typeclass, which allows for the use of do notation when programming with them. One of the key differences in functionality provided by the Client and Enclave monads is the restriction on arbitrary IO actions enforced by the Enclave monad. The App monad sets up the infrastructure for communication between the Client and Enclave monad. We show a simple secure counter example written using most of the API in Listing 2.

Listing 2 internally gets partitioned into the trusted and untrusted components via conditional compilation. In line 3, liftNewRef is used to create a secure reference initialised to the value 0. Followed by that, the computation to increment this value inside the enclave is given in lines 4 - 7. Applying secure on the enclave computation (line 4) yields the type App (Secure (Enclave

```

-- mutable references
liftNewRef :: a → App (Enclave (Ref a))
readRef    :: Ref a → Enclave a
writeRef   :: Ref a → a → Enclave ()

-- get a reference to call a function inside the enclave
secure :: Securable a ⇒ a → App (Secure a)

-- runs the Client monad
runClient :: Client () → App Done

-- used for function application on the enclave
onEnclave :: Binary a ⇒ Secure (Enclave a) → Client a
(<.>)      :: Binary a ⇒ Secure (a → b) → a → Secure b

-- call this from `main` to run the App monad
runApp    :: App a → IO a

```

Fig. 5. The core HasTEE API

```

1 app :: App Done
2 app = do
3   enclaveRef <- liftNewRef 0 :: App (Enclave (Ref Int))
4   count <- secure $ do
5     r <- enclaveRef
6     v <- readRef r
7     writeRef r (v + 1) >> return v :: Enclave Int
8   runClient $ onEnclave count >>= (\v -> liftIO $ print $ "Counter's #" ++ show v)
9
10 main = runApp app

```

Listing 2. A secure counter written in HasTEE (types annotated for clarity)

Int)). The Secure type is an internal representation used by HasTEE to represent a closure that is present in the enclave memory. Line 8 uses the critical onEnclave function to actually execute the enclave computation within the enclave memory and get the result back in the client memory. This resulting value, v, is displayed to the user.

The only function from Fig. 5 not used in Listing 2 is the <.> operator, used to collect arguments that are sent to the enclave. For example, an enclave function, f, that accepts two arguments, arg1 and arg2, would be executed as onEnclave (f <.> arg1 <.> arg2). Listing 1 in Section 1 shows a concrete usage of the operator. We have larger case studies in Section 5.

4.3 Operational Semantics of HasTEE

In this section, we provide a big-step operational semantics of the core functionalities within the HasTEE library. We present the operational semantics through the use of an evaluator (interpreter) for the core operators of HasTEE, which intends to show how the client and enclave memory evolve as a program executes. We show our *expression language* and the abstract machine values to which we evaluate below:


```

393 type Name = String
394
395 data Exp = Lit Int | Var Name | Fun [Name] Exp | App Exp [Exp]
396         | Let Name Exp Exp | Plus Exp Exp
397         -- HasTEE operators
398         | Secure Exp | OnEnclave Exp | EnclaveApp Exp Exp -- (<.>)
399
400 data Value = IntVal Int | Closure [Name] Exp Env
401           -- HasTEE values
402           | SecureClosure Name [Value] | ArgList [Value] | Dummy
403           -- Error values
404           | Err ErrState

```

The Exp language above is a slightly modified version of lambda calculus with the restriction of allowing only fully applied function application. This restriction is done to reflect the nature of the HasTEE API, which through the type system, only permits fully saturated function application for functions residing in the enclave. The lambda calculus language is then extended with the core HasTEE operators.

In the Value type, the Closure constructor represents a very standard approach to capture closures. Owing to saturated function application, it captures a list of variable names rather than a single name. Notable in the Value type is the SecureClosure constructor that represents a closure residing in the enclave memory. This constructor does not capture the body of the closure as the body could hold any hidden state that lies protected within the enclave memory. The SecureClosure value is used by the onEnclave function to invoke functions residing in the enclave.

The ArgList constructor, as the name suggests, collects the arguments that are to be sent over to the enclave. The <.> operator, when applied to various arguments, builds up this list. Lastly, the Dummy value is used as a placeholder for operators that do not have any semantics depending on the client or the enclave memory. For instance, the onEnclave function has no meaning inside the Enclave monad, it is only usable from the Client monad. The Dummy value is an important value type that enables the conditional compilation trick in HasTEE by acting as a placeholder for meaningless functions in the respective client and enclave memory.

The evaluator operates on an environment that maps variable names to values. As there are two distinct memories here - the enclave memory and the client memory, we have two environments.

```

424 type ClientEnv = [(Name, Value)]
425 type EnclaveEnv = [(Name, Value)]

```

Interestingly, the conditional compilation of HasTEE requires us to define an evaluator that operates in two passes. In the first pass, it runs a program and loads up the necessary elements in the enclave memory and then in the second pass, the loaded enclave memory is additionally passed to the client's evaluator. The following demonstrates this:

```

430 eval :: Exp -> Value
431 eval e =
432   let newEnclaveEnv = snd $ evalState (evalEnclave e initEnclaveEnv)
433                                   (initStateVar initEnclaveEnv)
434   in fst $ evalState (evalClient e initClientEnv) (initStateVar newEnclaveEnv)
435   where
436     initEnclaveEnv = []
437     initClientEnv = []
438
439 data StateVar = StateVar { varName :: Int, encState :: EnclaveEnv }
440
441 initStateVar :: EnclaveEnv -> StateVar
442 initStateVar = StateVar 0

```

The `StateVar` type exists to generate variable names and to hold the enclave environment when the evaluator for the client is run. The `evalEnclave` and `evalClient` functions are presented in Fig 6 and Fig. 7, respectively. The type signature of both the functions are similar and they represent the change in state of the respective environments as a term of the `Exp` language is evaluated.

Two helper functions, `genEncVar` and `evalList` are not shown for concision. The first one is a standard function for generating unique variable names using the `Int` held by the `StateVar` type. The `evalList` function is effectively a fold function over a list of expressions using the respective evaluators. Appendix A contains the complete, executable semantics written in Haskell.

```

1  evalEnclave :: (MonadState StateVar m)
2      => Exp -> EnclaveEnv -> m (Value, EnclaveEnv)
3  evalEnclave (Lit n) env = pure (IntVal n, env)
4  evalEnclave (Var x) env = pure (lookupVar x env, env)
5  evalEnclave (Fun xs e) env =
6      pure (Closure xs e env, env)
7  evalEnclave (Let name e1 e2) env = do
8      (e1', env') <- evalEnclave e1 env
9      evalEnclave e2 ((name,e1'):env')
10 evalEnclave (App f args) env = do
11     (v1, env1) <- evalEnclave f env
12     (vals, env2) <- evalList args env1 []
13     case v1 of
14     Closure xs body ev ->
15         evalEnclave body ((zip xs vals) ++ ev)
16     _ -> pure (Err ENotClosure, env2)
17 evalEnclave (Plus e1 e2) env = do
18     (v1, env1) <- evalEnclave e1 env
19     (v2, env2) <- evalEnclave e2 env1
20     case (v1, v2) of
21     (IntVal a1, IntVal a2) -> pure (IntVal (a1 + a2), env2)
22     _ -> pure (Err ENotIntLit, env2)
23 evalEnclave (Secure e) env = do
24     (val, env') <- evalEnclave e env
25     varname <- genEncVar
26     let env'' = (varname, val):env'
27     pure (Dummy, env'')
28 -- the following two are essentially no-ops
29 evalEnclave (OnEnclave e) env = evalEnclave e env
30 evalEnclave (EnclaveApp e1 e2) env = do
31     (_, env1) <- evalEnclave e1 env
32     (_, env2) <- evalEnclave e2 env1
33     pure (Dummy, env2)

```

Fig. 6. Operational Semantics of the Enclave

We demonstrate the semantics by examining a simple example program (Listing 3) written in the above expression language and discuss the differences between the client and enclave memories for this program.

Our semantic evaluator operates in two passes. In the first pass, the `evalEnclave` evaluator from Fig. 6 is run. Fig. 8a shows the state of the enclave environment after the evaluator has completed evaluating Listing 3. Notably, the variable `y` maps to a value with no semantic meaning, as the evaluator is already running in the secure memory.

```

491 1  evalClient :: (MonadState StateVar m)
492 2      => Exp -> ClientEnv -> m (Value, ClientEnv)
493 3
494 4  {- evalClient for Lit, Var, Fun, Let, App, Plus not shown as
495 5      they have the identical semantics as evalEnclave above -}
496 6
497 7  evalClient (Secure e) env = do
498 8      (_, env') ← evalClient e env
499 9      varname ← genEncVar
500 10     let env'' = (varname, Dummy):env'
501 11     pure (SecureClosure varname [], env'')
502 12 evalClient (OnEnclave e) env = do
503 13     (e', env1) ← evalClient e env
504 14     case e' of
505 15         SecureClosure varname vals -> do
506 16             enclaveEnv ← gets encState
507 17             let func = lookupVar varname enclaveEnv
508 18             case func of
509 19                 Closure vars body encEnv -> do
510 20                     (res, enclaveEnv') ←
511 21                         evalEnclave body ((zip vars vals) ++ encEnv)
512 22                     pure (res, env1)
513 23             _ -> pure (Err ENotClosure, env1)
514 24         _ -> pure (Err ENotSecClos, env1)
515 25 evalClient (EnclaveApp e1 e2) env = do
516 26     (v1, env1) ← evalClient e1 env
517 27     (v2, env2) ← evalClient e2 env1
518 28     case v1 of
519 29         SecureClosure f args ->
520 30             case v2 of
521 31                 ArgList vals -> pure (SecureClosure f (args ++ vals), env2)
522 32                 v -> pure (SecureClosure f (args ++ [v]), env2)
523 33         v -> pure (ArgList [v,v2], env2)

```

Fig. 7. Operational Semantics of the Client

```

524 1 testProgram = let m = 3 in
525 2     let f = λ x -> x + m in
526 3     let y = secure f in
527 4     onEnclave (y <.> 2)

```

Listing 3. A simple program for illustrating the operational semantics of HasTEE

In the second pass, the environment from Fig. 8a is additionally passed as a state variable to the evaluator `evalClient` from Fig. 7. Line 3 creates a different mapping from the enclave evaluator when evaluating the client, as shown in Fig 8b. The `<.>` operator is evaluated as the `EnclaveApp` constructor on lines 25-33 in Fig 7. It collects the arguments to generate `SecureClosure` "*EncVar₀*" [Lit 2].

The most significant part of Listing 3 occurs on line 4 when the client evaluates the `onEnclave` call. The semantics for this evaluation can be found in lines 12-24 of Fig 7. The evaluator finds a reference *EncVar₀* with no semantics in the client memory (as shown in Fig 8b). The evaluator

$m \mapsto 3$	$m \mapsto 3$
$f \mapsto \text{Closure } ["x"] (x + m) [m \mapsto 3]$	$f \mapsto \text{Closure } ["x"] (x + m) [m \mapsto 3]$
$\text{EncVar}_0 \mapsto \text{Closure } ["x"] (x + m) [m \mapsto 3]$	$\text{EncVar}_0 \mapsto \text{Dummy}$
$y \mapsto \text{Dummy}$	$y \mapsto \text{SecureClosure } \text{"EncVar}_0" []$
(a) Enclave Environment	(b) Client Environment

Fig. 8. The Enclave Environment in (a) is loaded during the first pass of the evaluator, and the Client Environment is empty during this pass. In the second pass, the Client Environment (b) gets loaded while having access to the memory (a), as can be seen in Fig 7

then looks up the variable in the enclave environment (Fig 8a) and finds a Closure with a body. Crucially, **it evaluates the Closure by invoking the evalEnclave function on line 21 of Fig. 7 using the enclave environment.** This part models how the SGX hardware switches to the enclave memory when executing the secure function f rather than the client memory. An important point is generating an identical fresh variable name, EncVar_0 , that the client uses to identify and call the functions in the enclave memory.

4.4 HasTEE implementation

We now discuss the implementation details required to support HasTEE.

4.4.1 Trusted GHC Runtime. One of the crucial challenges in implementing the HasTEE library is enabling Haskell programs to run within an Intel SGX enclave. As already discussed in Section 3, all Haskell programs compiled via the Glasgow Haskell Compiler (GHC), rely on the GHC runtime [Marlow et al. 2009] for crucial operations such as memory allocation and management, concurrency, I/O management, etc. As such, it is essential to port the GHC runtime in order to run Haskell programs on the enclave.

The GHC runtime is a complex software that is heavily optimized for specific platforms, such as Linux and Windows, to maximize its performance. For instance, on Linux, the runtime relies on a wide variety of specialised low-level routines from a C standard library, such as `glibc` [GNUDevs 1991] or `musl` [Felker 2005], to provide essential facilities like memory allocation, concurrency, and more. The challenge lies in porting the runtime due to the limited and constrained implementation of the C standard library in the SGX SDK, called `tlbnc` [Intel 2018b]. Specifically, `tlbnc` does not support some of the essential APIs required by the GHC runtime, including `mmap`, `madvise`, `munmap`, `select`, `poll`, a number of `pthread` APIs, operations related to timers, file reading, writing, and access control, and other functionalities that add up to 100+ functions.

Given the magnitude of engineering effort required to port the GHC runtime, we fall back on a library OS called Gramine [C. Tsai, Porter, et al. 2017]. Gramine internally intercepts all `libc` system calls within an application binary and maps them to a Platform Abstraction Layer (PAL) that utilizes a smaller ABI. In Gramine's case, this amounts to only 40 system calls that are executed through dynamic loading and runtime linking of a larger `libc` library, such as `glibc` or `musl`. Importantly, to protect the confidentiality and integrity of the enclave environment, Gramine uses a concept known as *shielded execution*, pioneered by the Haven system [Baumann et al. 2015], where a library is only loaded if its hash values are checked against a measurement taken at the time of initialisation. Shielded execution further protects applications against *Iago attacks* [Checkoway and Shacham 2013] in Gramine.

However, there are additional difficulties in loading the GHC runtime on the SGX enclave via Gramine. Owing to Gramine's diminished system ABI, it has a dummy or incomplete implementation for several important system calls that the runtime requires. For instance, the absence of the `select`, `pselect`, and `poll` functions, which are used in the GHC IO manager, required us to modify the GHC I/O manager to manually manage the polling behavior through experimental heuristics. Similarly, the critical `mmap` operation in GHC uses specific flags (`MAP_ANONYMOUS`) that require modification. In addition, other calls, such as `madvise`, `getrusage`, and timer-based system calls, also require patching. We hope to quantify these modifications' performance in the future.

After the GHC runtime is loaded onto an enclave, communication between the untrusted and trusted parts of the application effectively occurs between two disjoint address spaces. Communication between them can happen over any binary interface, emulating a remote procedure call. As our implementation is in its early prototype stage, we transmit serialised data as TCP packets (Fig 9). A production implementation should communicate via the C ABI using the Foreign Function Interface (FFI) supported by Haskell.

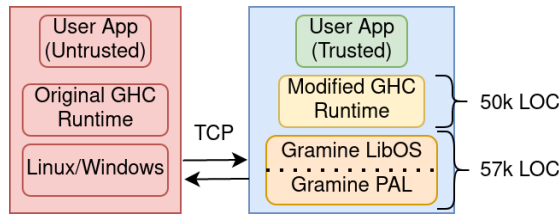


Fig. 9. The high-level overview of communication between the untrusted and trusted parts of the app

The Gramine approach results in an increase of 57,000 lines of code in the Trusted Computing Base (TCB) [C. Tsai, Porter, et al. 2017]. However, this is still an improvement over traditional operating systems, like Linux, with a TCB size of 27.8 million lines of code [Larabel 2020].

4.4.2 HasTEE Library. The API of the HasTEE library was already shown (Figure 5) and discussed in Section 4.2. The principal data types, `Enclave` and `Client`, have been implemented as wrappers around the IO monad, as shown below:

```
1 newtype Enclave a = Enclave (IO a) -- data constructor not exported
2 type Client = IO
```

A key distinction is that the `Enclave` data type does not instantiate the `MonadIO` typeclass, as a result of which arbitrary IO actions cannot be lifted inside the `Enclave` monad. However, it does instantiate a `RestrictedIO` typeclass that will be discussed in the following section. The conditional-compilation-based partitioning technique is achieved by having dummy implementations of certain data types in one of the modules, while the concrete implementation of those types is defined in the second module. We give an example of this using two different data types from the API.

```
1 -- Enclave.hs
2 data Secure a = SecureDummy
3
4 type Ref a = IORef a

1 -- Client.hs
2 data Secure a =
3   Secure CallID [ByteString]
4 type Ref a = RefDummy
```

A notable aspect of the API is the `Securable` typeclass, which constrains the secure function and enables it to label functions with any number of arguments as residents of the enclave memory. The `Securable` typeclass accomplishes this using a well-known typeclass trick in Haskell, used to represent statically-typed variadic functions such as `printf` [Augustsson and Massey 2013].

The operational semantics presented in Section 4.3 should provide an intuition for the core implementation techniques used in the library. The actual Haskell code of the HasTEE library has been open-sourced¹. Additionally, the Haste.App paper [Ekblad and Claessen 2014] provides more details on the techniques used.

4.5 Information Flow Control for Enclaves

The HasTEE library, being written in Haskell, allows using language-based Information Flow Control (IFC) techniques available in Haskell [Russo et al. 2008]. IFC approaches in Haskell aim to protect the confidentiality of data by encapsulating computations within a Sec monad. Typically, the monad employs a lattice of *labels* [Denning 1976] to model various security levels and then enforces policies on how data can flow between the levels. For a two-label lattice, where confidential data is marked with H and public data with L, a security policy known as *non-interference* is to prevent information flow from the secret to public channels [Goguen and Meseguer 1982]. In other words, $L \sqsubseteq L$, $H \sqsubseteq H$, $L \sqsubseteq H$, but $H \not\sqsubseteq L$, where \sqsubseteq indicates the *flows to* relation.

A similar scenario arises in HasTEE, where the Enclave monad can be compared to a security-critical Sec H monad that attempts to prevent information leakage to a public Sec L channel represented by the Client monad. Enforcing the non-interference policy in this scenario would imply that no data can flow out of the Enclave monad to the Client, which would make the enclave very restrictive for any real-world use cases. As such, the IFC literature relaxes the non-interference policy by the means of *declassification* [Sabelfeld and Sands 2005], which allows controlled leak of data from H to L.

In the HasTEE API, the `onEnclave :: (Binary a) => Secure (Enclave a) -> (Client a)` function is an *escape hatch* [Hedin and Sabelfeld 2012] that allows the enclave to leak *any* data to the client. We prioritise the usability of the API and trust that the enclave programmer will make the `onEnclave` call when they are certain they want to intentionally leak information to a public channel. However, there is a hidden line of defence in the `onEnclave` function. If the programmer intends to transmit any user-defined data type to the untrusted client, they are required to provide an instance of the Binary typeclass. Writing this typeclass instance for some confidential data type, such as a private key, equips the confidential data with the capacity to leave the enclave boundary, which should be done in a highly controlled manner.

Besides the `onEnclave` function, the Enclave monad has occasional requirements to interact with general I/O facilities like file reading/writing or random number generation. For such operations, the Enclave monad would need a MonadIO instance in Haskell to perform any I/O operations. However, as discussed in the previous section, we do not provide the lenient MonadIO instance to the Enclave monad but instead, use a RestrictedIO typeclass to limit the types of I/O operations that an Enclave monad can do.

4.5.1 Restricted IO. RestrictedIO, shown in Listing 4, is a collection of typeclasses that constrains the variants of I/O operations possible inside an Enclave monad. For instance, if a programmer, through the usage of a malicious library, mistakenly attempts to leak confidential data through a network call, the typeclass would not allow this.

```
1 type RestrictedIO m = (EntropyIO m, UnsafeFileIO m) -- other typeclasses not shown
2
3 class EntropyIO (m :: Type -> Type) where
4     type Entropy m :: Type
5     genEntropyPool :: m (Entropy m)
6
```

¹github link hidden for the review process


```

687 7 class UnsafeFileIO (m :: Type -> Type) where
688 8   untrustedReadFile :: FilePath -> m (Untrusted String)

```

Listing 4. The Restricted IO typeclass

This approach is invasive in that it restricts how a library (malicious or otherwise) that interacts with a HasTEE program conducts I/O operations. For instance, we had to modify the HsPaillier library [L.-T. Tsai and Sarkar 2016] that used the `genEntropy` function for random number generation. Initially, the library could use the Haskell IO monad freely, but to interact with a package written in HasTEE, it had to be modified to use the more restricted type class constraint (`EntropyIO`) for its *effectful* operations. This limits potential malicious behaviour within the library. Notably, our changes involve only five lines of code that instantiate the type class and generalize the type signature of effectful operations.

Another aspect of IFC captured in our system is the notion of *endorsement* [Hedin and Sabelfeld 2012], which is essentially the dual of declassification. Endorsement is concerned with the integrity, i.e., trustworthiness, of information. In our scenario, we utilize endorsement to ensure that the integrity of secrets is not compromised by data being introduced into the enclave.

HasTEE allows file reading operations inside the Enclave monad, which can potentially corrupt the enclave's data integrity. To control this, HasTEE provides two forms of file reading operation - (1) untrusted file read and (2) trusted encrypted file reads. For (1), data can be read from untrusted files but the enclave programmer is required to manually endorse the untrusted data read using the trust operator. This provides an additional check before untrusted data interacts with the trusted domain. The types involved are shown below:

```

709 1 data Untrusted a -- | A wrapper over untrusted data
710 2
711 3 -- | Indicate trust in a potentially untrusted value
712 4 trust :: Untrusted a -> a

```

For point (2), HasTEE relies on an Intel SGX feature known as *sealing*. Every Intel SGX chip is embedded with a unique 128 bit key known as the Root Seal Key (RSK). The SGX enclave can use this RSK to encrypt trusted data that it wishes to persist on untrusted media. This process is known as sealing, and HasTEE provides a simple interface to seal as well as unseal the trusted data being persisted. The API is shown below:

```

718 1 data SecurePath = SecurePath String
719 2
720 3 securefile :: FilePath -> SecurePath
721 4 securefile fp = "/secure_location/" <> fp -- this path is hidden from the user
722 5
723 6 readSecure :: SecurePath -> Enclave String
724 7 writeSecure :: SecurePath -> String -> Enclave ()

```

In the above, the `writeSecure` operation corresponds to *ciphertext declassification* [Askarov et al. 2008], while `readSecure` to an operation that applies automatic endorsement if the file can be decrypted successfully by the enclave RSK. If an attacker were to locate the secure location, the worst possible outcome would be the deletion of the file. However, the contents of the file cannot be read or modified outside the enclave, so the attacker would not be able to access the sensitive information stored within.

5 CASE STUDIES

In this section, we will demonstrate how HasTEE can be used to enforce data confidentiality using three case studies spread across a variety of domains.

5.1 Federated Learning

Federated Learning is an emerging *privacy-preserving* machine learning [Al-Rubaie and Chang 2019] approach that allows multiple parties to train a model without sharing the raw training data. A typical federated learning setup involves multiple decentralized edge devices holding local datasets, training a model locally and then aggregating the trained model on a cloud server. Fig. 10 shows the desired setup.

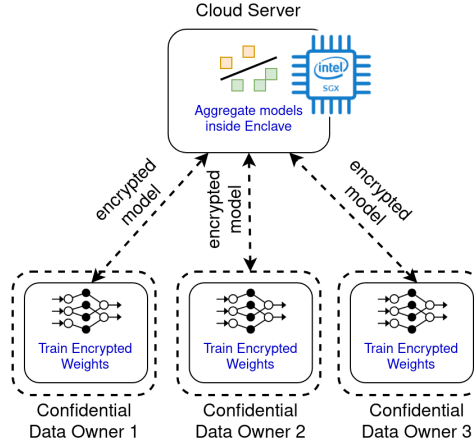


Fig. 10. A Federated Learning setup where the data owners are protecting their data and the ML model owner is protecting their model. The training with encrypted weights can be done using homomorphic encryption.

The setup in Fig. 10 above is facilitated by a combination of TEEs and homomorphic encryption. Homomorphic Encryption (HE) [Gentry 2009] is a form of encryption that enables direct computation on encrypted data, revealing the computation result only to the decryption key owner. We emulate the very same setup for our case study where we have two mutually distrusting parties -

- (1) Confidential data owner: The data owner could, for instance, be a hospital that does not want to send confidential patient data to an untrusted cloud server. They additionally want to protect their private data from other participants. The training process is conducted on a data owner's machine locally and only the encrypted weights are transferred between the cloud server and data owner so that the data privacy of the model is protected.
- (2) ML model owner: The ML model owner wants to protect their model as it could be considered their intellectual property. They want the model to remain confidential in both the client machines where the training occurs, as well as from the cloud server, which may be an untrusted multi-tenant virtual machine. Weights from each data owner are aggregated and updated in an enclave of the cloud server before being sent back to the data owner. Although the model owner has the private key of HE, it has no chance to speculate on the data owners' private data from the weights.

The above setup only requires the cloud server supporting Intel SGX technology so that even mobile devices can participate in training as a worker role. We can very conveniently model this entire setup as three clients and a server with an enclave in HasTEE. For illustration purposes, we will use GHC's threads to represent the three clients instead of three separate data owner machines.

The server's state is modelled in Listing 5. Note that the state keeps the weights in plaintext form. The enclave state holds both its public and private keys. However, only the public key should be

```

785 1 data SrvSt = SrvSt { publicKey  :: PubKey, privateKey :: PrvKey
786 2                      , updWts    :: Vector Double, numClients :: Int
787 3                      , wtsDict   :: Map -- (key=Epoch, value=[Vector CipherText]) }

```

Listing 5. The Federated Learning server state

allowed to move to the client. We enforce this by not providing an instance of the Binary typeclass for the private key. As discussed in Section 4.5, the lack of a Binary instance for the privateKey will prevent the enclave programmer from accidentally leaking the security-critical private key.

Listing 6 shows the API exposed to the client machine. Instead of the complex SGX_ECALL machinery, our API is expressed in idiomatic Haskell. Calling any function *f* from the record *api* with an argument *arg* in this API is expressed simply as `onEnclave ((f api) <.> arg)`.

```

797 1 type Accuracy = Double
798 2 type Loss     = Double
799 3 data API = API { aggregateModel :: Secure (Epoch -> Vector CipherText
800 4                      -> Enclave (Maybe (Vector CipherText)))
801 5                      , validateModel :: Secure (Enclave (Accuracy, Loss))
802 6                      , getPublicKey  :: Secure (Enclave PubKey)
803 7                      , reEncrypt    :: Secure (CipherText -> Enclave CipherText)}

```

Listing 6. The Federated Learning client API

We also show the main machine learning loop running on the data owner's machine in Listing 7. A number of important functions have been elided for brevity, but the key portions of the client-server interaction in HasTEE should be visible. The Config type holds the encrypted weights sent from the cloud server and after each epoch updates to the new aggregated value (Line 13). The value *x'* is the data set that the data owners are protecting and *y* is the result of the learning algorithm. The `adjustModelWithLearningRate` function (body elided, line 8) takes the computed gradient (line 7) and tries to converge on the desired result.

The client-server communication happens in both lines 9 and 10. On line 9 the server is communicated to aggregate models spread across different clients, with the server returning the encrypted updated weights *wt'*. We use a wrapper over `onEnclave`, called `retryOnEnclave` (body elided), that functionally allows the server to move in lock step with all the clients. Then in line 10, the server is communicated again to collect the accuracy and loss in the ongoing epoch number, which gets displayed in line 11. Finally, the loop continues in line 13.

```

819 1 handleSingleEpoch :: API -> CurrentEpochNum -> MaxEpochNum -> Matrix Double
820 2                      -> Vector Int -> Config -> Client Config
821 3 {- The Config type is a record that stores configuration info such as the learning
822 4    rate, the current epoch number, encrypted weights and the public key-}
823 4 handleSingleEpoch api n m x' y cfg'
824 5   | n == m    = return cfg'
825 6   | otherwise = do
826 7     grad <- computeGradient api cfg' x' y
827 8     cfgNew <- adjustModelWithLearningRate api (cfg' { iterN = n }) grad
828 9     wt'    <- retryOnEnclave $ (aggregateModel api) <.> n <.> (weights cfgNew)
829 10    (acc, loss) <- onEnclave (validateModel api)
830 11    printClient $ " Iteration no: " <> show n <> " Accuracy: " <> show acc
831 12                  <> " Loss : " <> show loss
832 13    handleSingleEpoch api (n+1) m x' y (cfgNew { weights = wt' })

```

Listing 7. The key machine learning loop; a number of functions have been elided for brevity

Listing 7 above features a complex control flow with at least two interactions visible in the loop itself. Internally, both the `computeGradient` as well as `adjustModelWithLearning` functions also talk to the enclave, calling the `reEncrypt` function to remove noise from the homomorphic encryption operation. HasTEE can represent a fairly complex, asynchronous control flow as simple Haskell function calls.

In terms of Information Flow Control, there are two important aspects in this case study. Firstly, the `RestrictedIO` typeclass constrains potentially malicious libraries from misbehaving. For example, consider the library `HsPaillier` [L.-T. Tsai and Sarkar 2016], which implements the Paillier Cryptosystem [Paillier 1999] for partial homomorphic encryption. All effectful operations from this library, such as `genKey :: Int -> IO (PubKey, PrvKey)`, need to be rewritten for them to be usable within the `Enclave` monad. The following snippet shows our typeclass instantiation and a sample type signature change needed inside the library.

```
1 instance (IO ~ m) => EntropyIO m where
2   type Entropy m = EntropyPool
3   genEntropyPool = createEntropyPool
4
5 -- genKey :: Int -> IO (PubKey, PrvKey) -- original type
6 genKey :: (Monad m, EntropyIO m) => Int -> m (PubKey, PrvKey)
```

The second aspect of IFC arises when the client machine queries the server for accuracy and loss by asking it to validate the model. Internally, when this call is made to the server equipped with the enclave, the enclave has to read a file with test data. This test data resides outside of the enclave and is potentially an attack vector. In order to not inadvertently trust such an exposed source, the enclave uses the `untrustedReadFile` function from the `RestrictedIO` typeclass. The file is marked as `Untrusted` and requires explicit programmer *endorsement* via the trust operator as shown below. The compiler will not typecheck if the user does not trust the file source.

```
1 validate :: Enclave (Ref SrvSt) -> Enclave (Accuracy, Loss)
2 validate srv_ref_st = do
3   -- ...
4   testDataSet <- untrustedReadFile testfile
5   let (x, y) = parseDataSet $ trust testDataSet -- trust the contents
6   -- ...
7   return (acc, loss)
```

Overall the case study constitutes only 500 lines of code. It naturally fits into the client-server programming model, and the usage of Haskell provides type safety and enables IFC-based security.

5.2 Encrypted Password Wallet

For this case study, we use HasTEE to implement a secure password wallet that stores authentication tokens in encrypted form on the disk. An authentication token can be retrieved from the wallet if the right master password is supplied. The definition of a password wallet used by the case study follows in Listing 8.

The `Show` and `Read` instances are used to convert a wallet to and from a string. This allows us to write the wallet to disk, and by writing to a secure file path we ensure that the stored wallet is encrypted, as described in section 4.5.1. By omitting a `Binary` instance we ensure that the wallet is not inadvertently leaked to the client directly. The code in Listing 9 implements the functions that store and load the wallet. We emphasize that the code does not need to explicitly reason about encryption and decryption, except for defining the secure file path.

```

883 1 -- | A single entry of authentication tokens
884 2 data Item = Item { title :: String, username :: String, password :: Password }
885 3   deriving (Show, Read)
886 4
887 5 -- | The secure wallet
888 6 data Wallet = Wallet { items :: [Item], size :: Int, masterPassword :: Password }
889 7   deriving (Show, Read)

```

Listing 8. The definition of a password wallet as a regular Haskell data type.

```

893 1 -- | Secure file path to the wallet
894 2 wallet :: SecureFilePath
895 3 wallet = secureFile "wallet.seal"
896 4
897 5 -- | Try to load the secure wallet into the enclave
898 6 loadWallet :: Enclave (Maybe Wallet)
899 7 loadWallet = do b <- doesSecureFileExist wallet
900 8               if b then do contents <- readSecure wallet
901 9                   return $ readMaybe contents
902 10              else return Nothing
903 11
904 12 -- | Store the wallet on disk in encrypted form
905 13 saveWallet :: Wallet -> Enclave ReturnCode
906 14 saveWallet w = writeSecure wallet (show w) >> return Success

```

Listing 9. The code that stores the wallet in encrypted form, and loads it up into the enclave memory. The only part of this code that indicates that encryption & decryption are taking place is the fact that we use a secure filepath. The programmer is relieved from dealing with encryption keys.

Our password wallet has the following features - (1) adding an authentication token, (2) retrieving a password, (3) deleting a token and (4) changing the master password. It is designed as a command-line utility where the commands are handled by an untrusted client and the passwords are protected by the enclave. The complete implementation is roughly 200 lines of Haskell code.

The hardware-enforced security provided by our secure wallet makes it a natural fit for designing password wallets that are protected by biometrics. A similar approach is used on modern iPhones, where passwords are stored in a secure enclave [Apple 2021] to ensure confidentiality, and the user's biometric data is used as the master password. In our case, the usage of a high-level language like Haskell enables expressing this relatively complex application concisely.

5.3 Data Clean Room with Differential Privacy

A *Data Clean Room* (DCR) [AWS 2022] is a technology that provides aggregated and anonymised user information to protect user privacy while providing advertisers and analytic firms with non-personally identifiable information to target a specific demographic with advertising campaigns and analytics-based services.

A DCR can be provisioned with user data, but very strict privacy controls ensure that user data does not leave the DCR. The DCR can, however, compute aggregated results based on the user data within, and release that. The DCR can further employ *differential privacy* [Dwork 2006] as a security guarantee. Differential privacy is a guarantee that states that a query over a data set does not produce a result that makes it possible to say whether a specific individual was in the data set

or not. This is done by adding a calibrated amount of noise to the result. The amount of noise can be calibrated to increase privacy (add more noise) or increase accuracy (add less noise).

Our third case study implements a DCR within an SGX enclave using HasTEE. To protect user confidentiality, the analytics applied in the DCR use basic differential privacy techniques (written in Haskell). User records are encrypted before they are provisioned to the DCR, after which we use the *Laplace Mechanism* [Dwork and Roth 2014] when performing counting queries to add noise to the result. The mechanism introduces noise by sampling a Laplace distribution. The code implementing the Laplace mechanism can be found in the appendix, in Listing 14. The definition of user records is shown in Listing 10.

```

1 data User = User { name :: String , occupation :: Occupation, salary :: Integer
2                   , gender :: Gender, age :: Integer, origin :: Country
3                   } deriving (Show, Read)
4 -- | The client can encrypt a user
5 encryptUser :: User -> PubKey -> Client [CipherText]
6 -- | The enclave can decrypt a user
7 decryptUser :: [CipherText] -> PrvKey -> PubKey -> Enclave (Maybe User)

```

Listing 10. Definition of user records that are recorded in the enclave. User records should only enter the enclave in encrypted form, so we expose two functions for encrypting and decrypting a user record.

The DCR does not provide a Binary instance for the User type to ensure that the user records are not transferred to the enclave via plain serialisation. Instead, we expose functions that encrypt and decrypt users. The [CipherText] type has a Binary instance, allowing for an encrypted user to be sent to the enclave.

The Laplace Mechanism used for adding noise requires a source of randomness. In our implementation, we use Haskell’s System.Random package, which internally reads from /dev/urandom. Although the /dev/urandom file is located outside of the enclave, the Gramine library OS intercepts the application’s read calls to /dev/urandom, and instead of reading from the file directly, it samples randomness from a secure source within the enclave. This secure source of randomness can be accessed through the RestrictedIO (4.5.1) typeclass.

An example query that one might want to run over the data set is to see how many individuals in the data set have a salary in a specific range. Constructing the query that answers this for a single individual is shown in Listing 11.

```

1 salaryWithin :: Integer -> Integer -> User -> Bool
2 salaryWithin l h u = l <= salary u && salary u <= h

```

Listing 11. A query that checks whether an individual has a salary within a certain bound.

The HasTEE code that implements the main method of this example is shown in listing 12. Lines 3 to 8 specify the API of the data clean room. The DCR’s API supports (1) initialisation, (2) fetching of the public key, (3) provisioning user data to the enclave, and (4) executing the salary query. Line 8 is used to generate some arbitrary users (for testing), after which the client code takes over. The client initializes the DCR and fetches its public key. After this, the users are encrypted and sent to the DCR. On line 15 the salary query is executed in the DCR, and then the result is printed.

Generating arbitrary users to test the setup is done purely for illustration purposes. In a more faithful implementation, the client would relay the public key to data owners that would then send already encrypted user records to the client, which provisions them to the DCR. Owing to HasTEE’s client-server programming model and the use of a high-level language like Haskell, the implementation becomes very compact with roughly 200 LOC.


```

981 1 app :: App Done
982 2 app = do
983 3   ref    <- liftNewRef undefined
984 4   initSt <- secure $ initEnclave ref
985 5   pkey   <- secure $ getPublicKey ref
986 6   prov'  <- secure $ provisionUserEnclave ref
987 7   lm     <- secure $ laplaceMechanism ref $ salaryWithin 10000 50000
988 8   dataset <- liftIO $ sequence $ replicate 500 (generate arbitrary)
989 9   runClient $ do
990 10    onEnclave $ initSt <.> 0.1 -- initialize enclave with privacy budget
991 11    key <- onEnclave pkey      -- fetch public key
992 12    mapM_ (\u -> do ct <- encryptUser u key
993 13                onEnclave $ prov' <.> ct) dataset -- provision users
994 14    result <- onEnclave lm -- run the salary query
995 15    liftIO $ putStrLn $ concat ["randomized response: ", show result]

```

Listing 12. The client running the salaryWithin query over the data set in the clean room.

6 EVALUATION

6.1 Discussion

Through the case studies presented in Section 5, we have demonstrated the applicability of HasTEE in a variety of domains, including privacy-preserving machine learning, hardware-encrypted wallets, and data clean rooms with differential privacy. In all of the case studies shown above, we rely on a particular TEE implementation - Intel SGX.

Considering the shortcomings of SGX, it has been shown to be vulnerable to a wide variety of side-channel attacks [Schaik et al. 2022]. HasTEE's API and implementation, however, are much more high-level and are not reliant on anything SGX-specific. A TEE design, such as ARM TrustZone, which provides a disjoint cache hierarchy, could alleviate several side-channel attacks affecting Intel SGX. The main effort then lies in porting the GHC runtime to the TrustZone infrastructure.

The concision and brevity provided by Haskell are notable in all three case studies. In contrast to development on the Intel C/C++ SGX SDK, HasTEE's high-level programming model entirely abstracts away the complexity of dealing with the low-level edl files in the SGX SDK. The remote procedure calls that happen between the untrusted client and trusted enclave are typechecked in Haskell, unlike the SGX SDK.

In terms of Information Flow Control, HasTEE's API represents a significant improvement over the SGX SDK. The latter does not warn or typecheck a program against accidental data leaks. On the other hand, HasTEE has stronger compile-time guarantees. For instance, in all three case studies, the lack of the Binary typeclass constraint would by construction prevent accidental leakage of the secret data from the enclave.

Additionally, in all three case studies, we observe the RestrictedIO typeclass constraining the I/O operations possible in the Enclave monad. Notably, in the federated learning example, we had to modify the homomorphic encryption library to limit its types that involved the IO monad. Finally, in the password wallet example, the readSecure and writeSecure relieves the enclave programmer from the burden of key management.

6.2 Comparing HasTEE to GoTEE and J_E

Implementation. Table 11 presents a comparison between HasTEE and its two closest counterparts - GoTEE [Ghosn et al. 2019] and J_E [Oak et al. 2021]. While both GoTEE and J_E had to modify the

Framework	HasTEE	GoTEE	J_E
IFC support	Standard declassification	None	Robust declassification
Partitioning scheme	Type-based	Process-based	Annotation-based
Modified compiler	No	Yes	Yes
Modified runtime system	Yes	Yes	No
Secure by construction	Yes	No	No
Trusted Components	GHC compiler, GHC runtime, Gramine	GoTEE compiler, Go-TEE runtime	Java parser and partitioner, Jif compiler, JVM, SGX-LKL[Priebe et al. 2019]
Programming model	Client-server	Synchronous Message-Passing	Using the object-framework provided by Java

Fig. 11. Comparison of HasTEE, GoTee, and J_E . We specify the core components involved in the Trusted Computing Base in all three frameworks.

respective compilers, HasTEE required no modifications to the compiler. The specific runtime used by J_E is not mentioned in the paper [Oak et al. 2021]; however, it suggests that no modification of the runtime was required, as it was run on a large virtualized host - SGX-LKL [Priebe et al. 2019]. In contrast, the runtimes for HasTEE and GoTEE required modification. GoTEE required significant modifications to the Golang runtime system to enable communication between the trusted and untrusted memory. The modifications required by HasTEE are all related to running any general Haskell program in the enclave (Section 4.4.1) rather than the library's primitives.

Secure by construction. Both GoTEE and J_E use sophisticated static analysis passes and program transformations to partition a program into its two components. These passes have to properly identify which code should go into each respective component and generate the correct RPC code. This is a complicated but very important process. In contrast, HasTEE does not require such analyses. HasTEE makes the assumption that the computation in the Enclave monad is secure, and computation in the Client monad is untrusted. Since the two components are not meant to rely on each other's logic, the same program is compiled twice. When the Enclave is compiled the Client monad is swapped for a dummy implementation, and vice versa. Fig. 1 in the Introduction (Sec 1) conveyed this general idea.

7 RELATED WORK

In this section, we will compare the key aspects of HasTEE with its closely related counterparts.

Programming Language support for TEE programming. HasTEE presents, to the best of our knowledge, one of the first instances of a functional language, Haskell, running on a TEE environment. Among imperative and object-oriented languages, GoTEE [Ghosn et al. 2019] extends the Go programming language with a feature called *secured routines* to model message-passing between an untrusted client and a trusted enclave. Similarly, J_E [Oak et al. 2021] adds security-based annotations to a subset of Java, which allows partitioning Java applications into trusted and

untrusted components and then enforcing information flow control across the trusted boundary. Civet [C. Tsai, Son, et al. 2020] is another example of a partitioned Java runtime for enclaves.

In the Rust ecosystem, the Rust-SGX [Wang et al. 2019] project provides foreign-function interface (FFI) bindings to the C/C++ Intel SGX SDK. The goal of the project is different from HasTEE in that it does not aim to introduce any programming model for programming TEEs. The main goal of Rust SGX is to introduce application-level memory safety when programming with the low-level SGX SDK. HasTEE provides memory safety by the virtue of running on an already memory-safe language, Haskell. TrustJS [Goltzsche et al. 2017] takes a similar FFI-based approach as Rust-SGX for programming enclaves with JavaScript.

An important project in this space is the WebAssembly (WASM) initiative [Rossberg 2019]. There have been WASM projects, both academic, such as Twine [Ménétrety et al. 2021], as well as commercial, such as Enarx [Red Hat 2019], aimed at allowing WASM runtimes to operate within SGX enclaves. Our initial approach was to use the experimental Haskell WASM backend [Tweag.io 2022] to run Haskell on SGX enclaves. However, the aforementioned runtimes are not supported by GHC and lack several key features required for loading Haskell onto an enclave.

Partitioning application and programming model. An important contribution of HasTEE is the seamless program partitioning and familiar client-server-based programming model for enclaves. The partitioning approach in HasTEE has been adapted from the Haste.App library [Ekblad and Claessen 2014]. The most well-known automatic partitioning tool for C programs on an SGX enclave is Glamdring [Lind et al. 2017]. The general idea of partitioning a single program, irrespective of the application domain, has been studied as multitier programming [Weisenburger et al. 2021]. Among the existing approaches to multitier programming, HasTEE provides a lightweight alternative that does not require any compiler modification or elaborate dataflow analysis to partition the program.

In terms of various programming models, GoTEE utilizes a synchronous message-passing-based approach. A similar but asynchronous message-passing-based model is given by EActors [Sartakov et al. 2018], an actor-model-based framework for confidential computing, written in C.

Intel SGX application development. The partitioning-based two-project programming model of Intel SGX has been a significant obstacle to the technology’s adoption. As such, there have been attempts to virtualize entire platforms within the enclave memory. Haven [Baumann et al. 2015] virtualizes the entire Windows operating system as well as an entire SQL server application running on top of it. SCONE [Arnautov et al. 2016] virtualizes a Docker container instance within an SGX enclave. The Gramine [C. Tsai, Porter, et al. 2017] library operating system, which is used in this work, is also an example of lightweight virtualization.

While a larger body of work has been dedicated to Intel SGX, AMD introduced TEEs in the form of AMD SEV [AMD 2018], which is natively a virtualization-based approach. Virtualization can result in drastically increasing the size of the Trusted Computing Base (TCB). Hence, in HasTEE, we chose the approach with the smallest TCB of 57k lines of code (Gramine). We intend to eventually move away from Gramine and make the GHC runtime a standalone library inside the SGX enclave (see Section 8).

Information Flow Control for enclaves. HasTEE draws inspiration from the library-based lightweight Information Flow Control (IFC) approaches in Haskell [Buiras et al. 2015; Russo 2015; Russo et al. 2008] for its IFC implementation. This approach relies on the purity of Haskell to detect and stop malicious behaviour. In contrast, J_E [Oak et al. 2021] compiles down to the Jif Java compiler [Myers 1999], which statically checks confidentiality and integrity policies. J_E employs a stronger IFC policy based on robust declassification [Myers et al. 2004]. This policy ensures that low-integrity data cannot influence the declassification of secret data. We relax this policy in favour of a more user-friendly API.

Another interesting line of work is Moat [Sinha et al. 2015], which formally models and verifies enclave programs running on Intel SGX such that data confidentiality is respected. It uses IFC to enforce the policies and automated theorem proving to verify the policy enforcement mechanism.

8 FUTURE WORK

This paper lays the foundation for several threads of future work.

- The IFC scheme in HasTEE operates on two security levels - private (Enclave) and public (Client). A natural extension of this work is to enable the use of a hierarchical security *lattice* consisting of multiple security levels, where each security level is mapped to unique enclaves, allowing multi-enclave IFC.
- Another promising line of work is *Remote Attestation* [Knauth et al. 2018], which allows an SGX enclave to prove its identity to a challenger using the private key embedded in the enclave. This unique identification property can facilitate secure communication between multiple enclaves, both in a multi-enclave and a distributed-enclave setting. It would also be interesting to see if there could be language-level support for remote attestation.
- Currently, it is unclear how to bring legacy packages into the enclave without extensive modification. Additionally, the `RestrictedIO` typeclass makes any library that uses IO unusable without modification. Future work should look into more principled ways of bringing legacy packages into the enclave while retaining the ability to analyze their effects and understand their implications for a security policy.
- A significant obstacle when developing HasTEE was running Haskell programs on an Intel SGX enclave. While the GHC runtime is extensively optimized for performance, having a more compact and portable runtime of GHC that sacrifices some performance by using a restricted set of libc operations could result in a considerably smaller Trusted Computing Base. A more portable runtime would facilitate HasTEE experiments on other TEE infrastructures such as ARM TrustZone and RISC-V PMP [RISC-V 2017].

9 CONCLUSION

In this paper, we introduce HasTEE - a type-safe library in Haskell that enables the programming of Trusted Execution Environments using a familiar client-server-based programming model. HasTEE raises the level of abstraction over the low-level and error-prone programming APIs provided by TEE SDKs. Additionally, the partitioning framework proposed by HasTEE is secure by construction, which is an improvement over other high-level imperative language frameworks.

HasTEE being written in a pure and statically-typed functional language allows enforcing language-based information flow control mechanisms that protect data confidentiality. We have demonstrated through three diverse case studies how HasTEE's IFC mechanism can help prevent accidental data leakage while producing concise code. We hope that HasTEE will open up future research avenues at the intersection of hardware-based and programming-language-based security.

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A EXECUTABLE OPERATIONAL SEMANTICS OF HASTEE IN HASKELL

```

1 {-# LANGUAGE FlexibleContexts #-}
2 module HasTEEOrg where
3
4 import Control.Monad.State.Class
5 import Control.Monad.State.Strict
6
7
8
9 type Name = String
10
11 data Exp = Lit Int
12         | Var Name
13         | Fun [Name] Exp
14         | App Exp [Exp]
15         | Let Name Exp Exp
16         | Plus Exp Exp
17
18 -- HasTEE operators
19 | Remote Exp

```

```

1324 20 | OnServer Exp
1325 21 | RemoteApp Exp Exp -- (<.>)
1326 22 deriving (Show)
1327 23
1328 24 data Value = IntVal Int
1329 25 | Closure [Name] Exp Env
1330 26 -- HasTEE values
1331 27 | RemoteClosure Name [Value]
1332 28 | ArgList [Value]
1333 29 | Dummy
1334 30
1335 31 -- Error values
1336 32 | Err ErrState
1337 33 deriving (Show)
1338 34
1339 35 data ErrState = ENotClosure
1340 36 | EVarNotFound
1341 37 | ENotRemClos
1342 38 | ENotIntLit
1343 39
1344 40 instance Show ErrState where
1345 41 show ENotClosure = "Closure not found"
1346 42 show EVarNotFound = "Variable not in environment"
1347 43 show ENotRemClos = "Remote Closure not found"
1348 44 show ENotIntLit = "Not an integer literal"
1349 45
1350 46 type Env = [(Name, Value)]
1351 47
1352 48 type ClientEnv = Env
1353 49 type EnclaveEnv = Env
1354 50
1355 51
1356 52 type VarName = Int
1357 53
1358 54
1359 55 data StateVar =
1360 56 StateVar { varName :: Int
1361 57 , encState :: EnclaveEnv
1362 58 }
1363 59
1364 60 initStateVar :: EnclaveEnv -> StateVar
1365 61 initStateVar = StateVar 0
1366 62
1367 63
1368 64 eval :: Exp -> Value
1369 65 eval e =
1370 66 let newEnclaveEnv = snd $
1371 67 evalState (evalEnclave e initEnclaveEnv)
1372 68 (initStateVar initEnclaveEnv)
1373 69 in fst $ evalState (evalClient e initClientEnv) (initStateVar newEnclaveEnv)
1374 70 where
1375 71 initEnclaveEnv = []

```

```

1373 72     initClientEnv = []
1374 73
1375 74 genRemVar :: (MonadState StateVar m) => m String
1376 75 genRemVar = do
1377 76     n <- gets varName
1378 77     modify $ \s -> s {varName = 1 + n}
1379 78     pure ("RemVar" <> show n)
1380 79
1380 80 evallist :: (MonadState StateVar m) => [Exp] -> Env -> [Value] -> m ([Value], Env)
1381 81 evallist [] e vals = pure (reverse vals, e)
1382 82 evallist (e1:es) env xs = do
1383 83     (v, e) <- evalEnclave e1 env
1384 84     evallist es e (v:xs)
1385 85
1386 86
1387 87 evalEnclave :: (MonadState StateVar m)
1388 88     => Exp -> EnclaveEnv -> m (Value, EnclaveEnv)
1389 89 evalEnclave (Lit n) env = pure (IntVal n, env)
1390 90 evalEnclave (Var x) env = pure (lookupVar x env, env)
1391 91 evalEnclave (Fun xs e) env =
1392 92     pure (Closure xs e env, env)
1393 93 evalEnclave (Let name e1 e2) env = do
1394 94     (e1', env') <- evalEnclave e1 env
1395 95     evalEnclave e2 ((name,e1'):env')
1396 96 evalEnclave (App f args) env = do
1397 97     (v1, env1) <- evalEnclave f env
1398 98     (vals, env2) <- evallist args env1 []
1399 99     case v1 of
1400 100         Closure xs body ev ->
1401 101             evalEnclave body ((zip xs vals) ++ ev)
1402 102         _ -> pure (Err ENotClosure, env2)
1403 103 evalEnclave (Plus e1 e2) env = do
1404 104     (v1, env1) <- evalEnclave e1 env
1405 105     (v2, env2) <- evalEnclave e2 env1
1406 106     case (v1, v2) of
1407 107         (IntVal a1, IntVal a2) -> pure (IntVal (a1 + a2), env2)
1408 108         _ -> pure (Err ENotIntLit, env2)
1409 109
1410 110 evalEnclave (Remote e) env = do
1411 111     (val, env') <- evalEnclave e env
1412 112     varname <- genRemVar
1413 113     let env'' = (varname, val):env'
1414 114     pure (Dummy, env'')
1415 115 -- the following two are the essentially no-ops
1416 116 evalEnclave (OnServer e) env = evalEnclave e env
1417 117 evalEnclave (RemoteApp e1 e2) env = do
1418 118     (_, env1) <- evalEnclave e1 env
1419 119     (_, env2) <- evalEnclave e2 env1
1420 120     pure (Dummy, env2)
1421 121
1422 122 evallist2 :: (MonadState StateVar m) => [Exp] -> Env -> [Value] -> m ([Value], Env)
1423 123     )

```

```

1422123 evalList2 []      e vals = pure (reverse vals, e)
1423124 evalList2 (e1:es) env xs = do
1424125   (v, e) <- evalClient e1 env
1425126   evalList2 es e (v:xs)
1426127
1427128
1428129 evalClient :: (MonadState StateVar m)
1429130             => Exp -> ClientEnv -> m (Value, ClientEnv)
1430131 evalClient (Lit n) env = pure (IntVal n, env)
1431132 evalClient (Var x) env = pure (lookupVar x env, env)
1432133 evalClient (Fun xs e) env =
1433134   pure (Closure xs e env, env)
1434135 evalClient (Let name e1 e2) env = do
1435136   (e1', env') <- evalClient e1 env
1436137   evalClient e2 ((name,e1'):env')
1437138 evalClient (App f args) env = do
1438139   (v1, env1) <- evalClient f env
1439140   (v2, env2) <- evalList2 args env1 []
1440141   case v1 of
1441142     Closure xs body ev ->
1442143       evalClient body ((zip xs v2) ++ ev)
1443144     _ -> pure (Err ENotClosure, env2)
1444145 evalClient (Plus e1 e2) env = do
1445146   (v1, env1) <- evalClient e1 env
1446147   (v2, env2) <- evalClient e2 env1
1447148   case (v1, v2) of
1448149     (IntVal a1, IntVal a2) -> pure (IntVal (a1 + a2), env2)
1449150     _ -> pure (Err ENotIntLit, env2)
1450151
1451152
1452153 evalClient (Remote e) env = do
1453154   (_, env') <- evalClient e env
1454155   varname <- genRemVar
1455156   let env'' = (varname, Dummy):env'
1456157   pure (RemoteClosure varname [], env'')
1457158 evalClient (OnServer e) env = do
1458159   (e', env1) <- evalClient e env
1459160   case e' of
1460161     RemoteClosure varname vals -> do
1461162       enclaveEnv <- gets encState
1462163       let func = lookupVar varname enclaveEnv
1463164       case func of
1464165         Closure vars body environ -> do
1465166           (res,enclaveEnv') <- evalEnclave body ((zip vars vals) ++ environ)
1466167           pure (res, env1)
1467168         _ -> pure (Err ENotClosure, env1)
1468169         _ -> pure (Err ENotRemClos, env1)
1469170 evalClient (RemoteApp e1 e2) env = do
1470171   (v1, env1) <- evalClient e1 env
1471172   (v2, env2) <- evalClient e2 env1
1472173   case v1 of
1473174     RemoteClosure f args ->

```

```

1471175     case v2 of
1472176         ArgList vals -> pure (RemoteClosure f (args ++ vals), env2)
1473177         v -> pure (RemoteClosure f (args ++ [v]), env2)
1474178         v -> pure (ArgList [v,v2], env2)
1475179
1476180
1477181     -- onServer (f == RemoteClosure f [])
1478182     -- onServer (f <.> arg == RA f arg == RemoteClosure f [arg])
1479183     -- onServer (f <.> arg1 <.> arg2 == RA f (RA arg1 arg2) == RC f [arg1, arg2])
1480184
1481185 lookupVar :: String -> [(String, Value)] -> Value
1482186 lookupVar _ [] = Err EVarNotFound
1483187 lookupVar x ((y, v) : env) =
1484188     if x == y then v else lookupVar x env

```

Listing 13. Operational Semantics of HasTEE

B DATA CLEAN ROOM CODE

```

14881 countingQuery :: Enclave (Ref CleanRoomSt) -> (User -> Bool) -> Enclave Int
14892 countingQuery refst q = do
14903     st <- readRef =<< refst
14914     return $ length $ filter id $ map q (users st)
14925
14936 laplaceDistribution :: Enclave (Ref CleanRoomSt) -> Double -> Enclave Double
14947 laplaceDistribution refst b = do
14958     z <- int2Double <$> getRandom refst (0,1)
14969     u <- ((/) 1000 . int2Double) <$> getRandom refst (1,1000)
149710     return $ (2 * z - 1) * (b * log u)
149811
149912 laplaceMechanism :: Enclave (Ref CleanRoomSt) -> (User -> Bool) -> Enclave Double
150013 laplaceMechanism refst q = do
150114     st <- readRef =<< refst
150215     true <- int2Double <$> countingQuery refst q
150316     noise <- laplaceDistribution refst (1 / (epsilon st))
150417     return $ true + noise

```

Listing 14. Code for the laplace mechanism.