Hardening Application Security using Intel SGX

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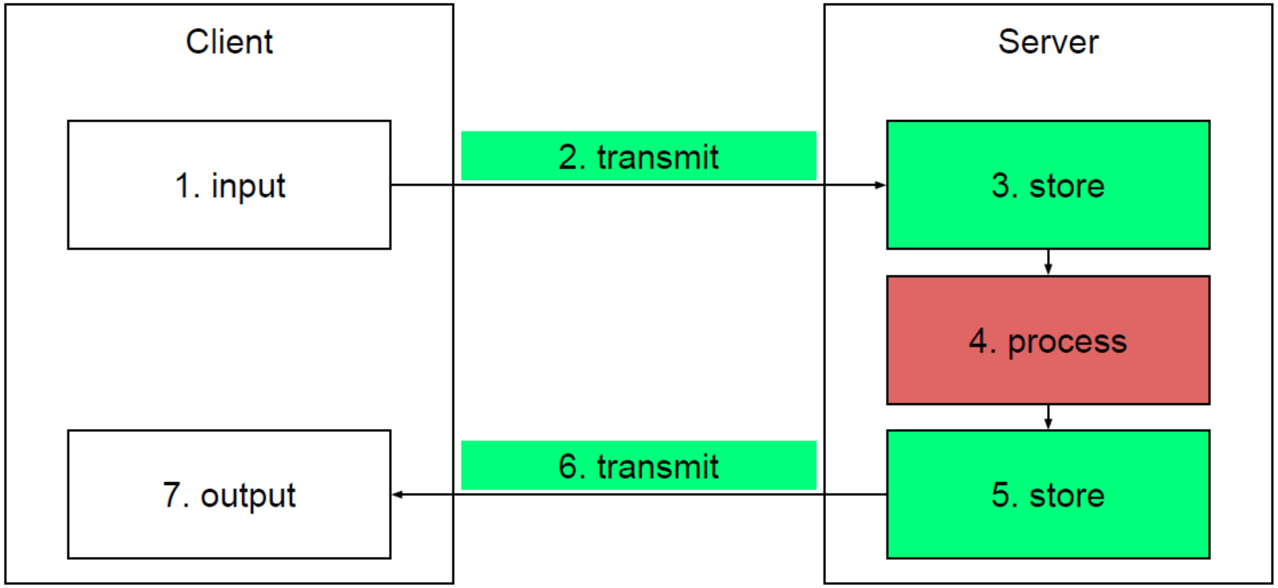
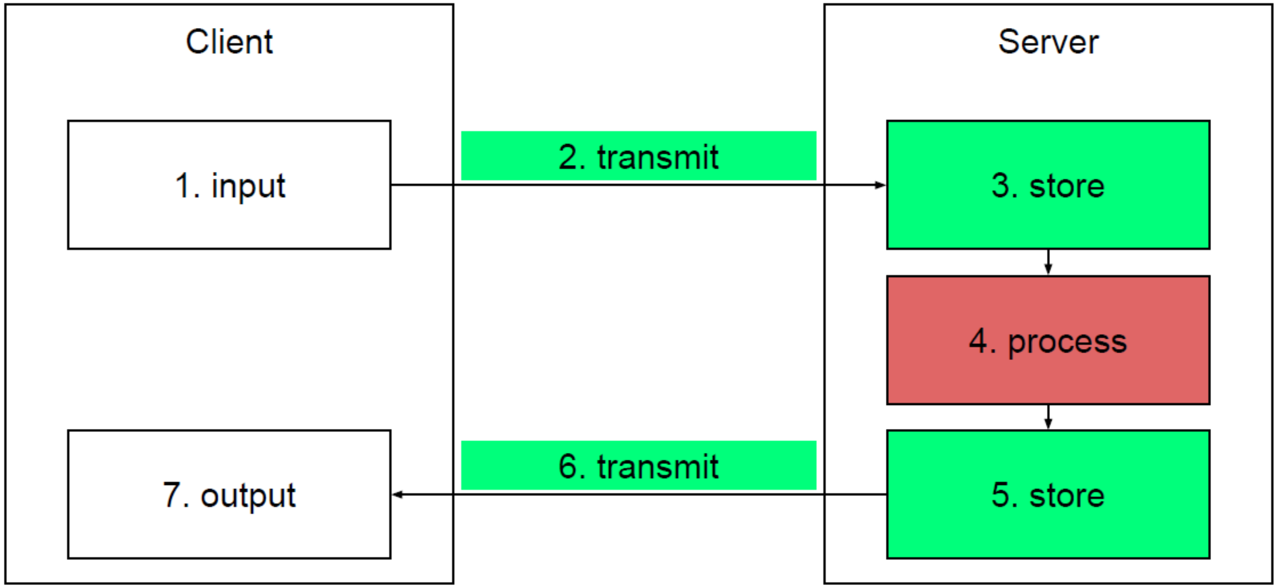
Motivation

- data security: encryption
  - securely **transporting** data
  - secure data **processing**



Motivation

- trusted computing approaches
  - *Trusted Platform Modules*
  - ARM's *TrustZone*
  - **Intel's *Software Guard Extensions* (SGX)**



Intel SGX

- not widely utilized
- high complexity
  - needs profound knowledge in fields of cryptography, operating systems, and hardware design

- our goal: practical perspective, approaching the challenges of **trusted computing** from a **software engineer's point of view**
  - helper library overcoming hurdles of integrating SGX API with code base
  - case study: porting existing applications to run inside SGX enclaves

Background

Software Guard Extensions

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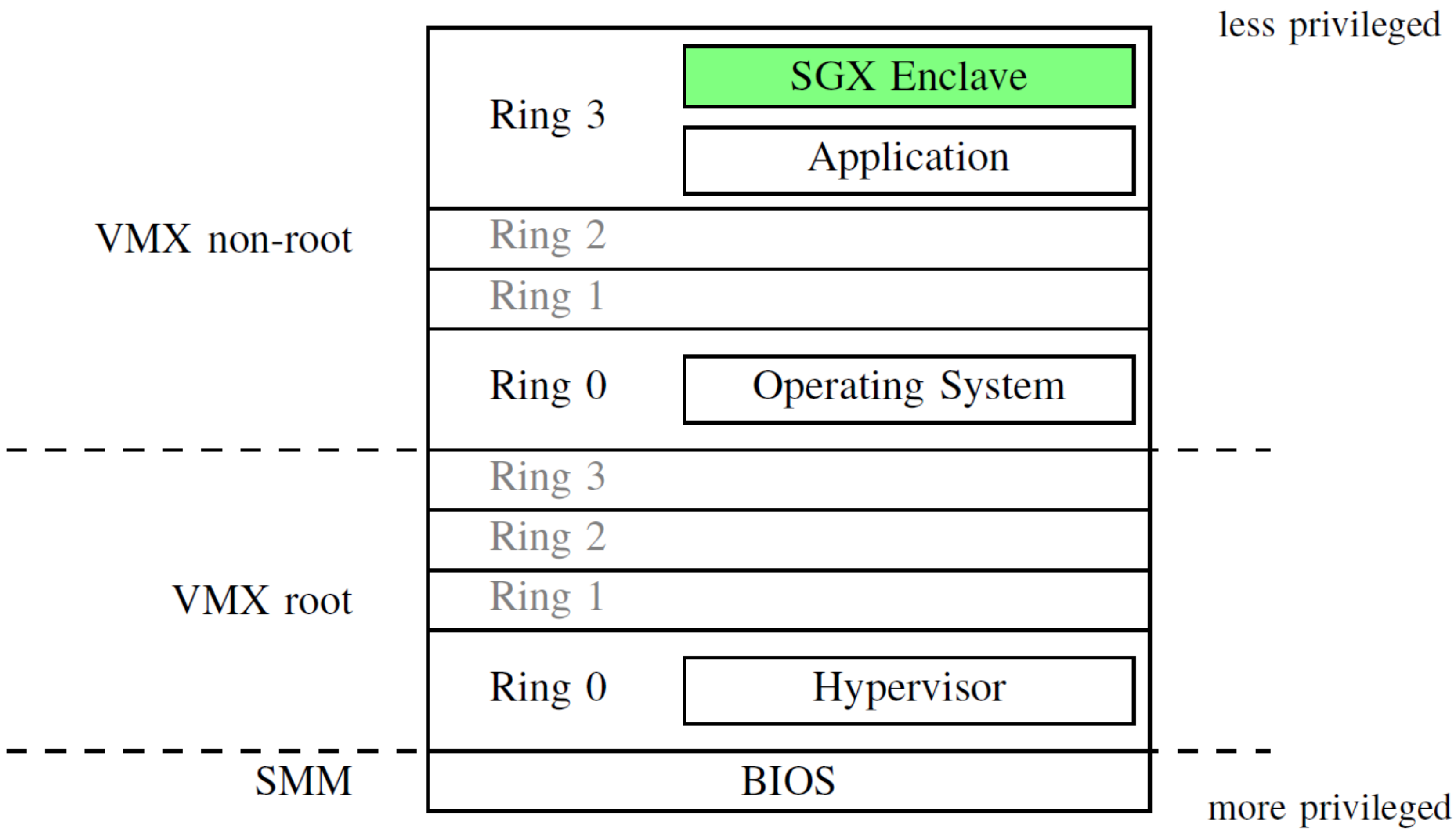
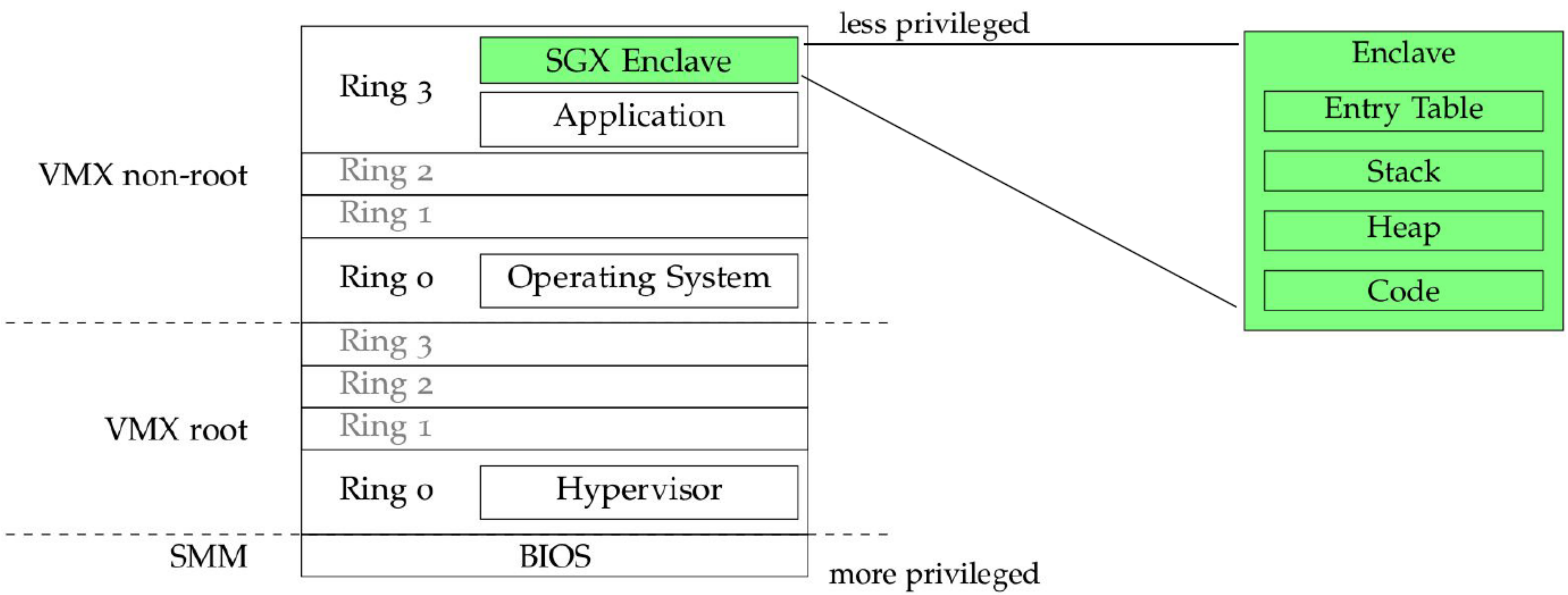
- implemented entirely CPU hardware
- exposed by instruction set extensions
- **Enclave**
  - encrypted, process-like memory regions
  - code, stack + heap memory
- decrypt memory when loading into CPU cache
- protected from being accessed by privileged code
  - even from code in *System Management Mode* (SMM) and *Direct Memory Access* (DMA)

Intel SGX Enclaves



Intel SGX Enclaves



Intel SGX Enclaves

- untrusted operating system
  - scheduling & memory allocation
  - setting up an enclave
- Enclave attestation
  - each SGX-capable CPU has embedded cryptographic private key
  - use this key + special group signature schema to attest state of Enclave
  - remote attestation with “architectural enclaves”

Intel SGX Enclaves

- code in Enclaves may not execute certain calls
  - calls that may case a VMEXIT, input/output instructions, calls requiring change of privilege levels
- multiple threads
  - number must be statically defined
- maximum enclave size (memory) must be defined before initialization of Enclave

Enclave Development

Software Development Kit

- SDK provided by Intel
  - Windows + Linux
  - language support: C and C++
  - interface definition: *Enclave Definition Language* (EDL)
  - trusted library: helper functions
    - subset of standard C library (e.g. without file input/output)
    - random number generation, cryptographic primitives, key exchange and data sealing
  - debug mode: all protection mechanisms disabled
  - simulation mode: if SGX hardware is absent
  - complete authoring chain

Enclave Definition Language

- trusted section (**E-call**, enclave calls)
  - proxies are generated for the untrusted wrapper
- untrusted section (**O-call**, outside of enclave calls)
  - proxies are generated for the enclave
- parameter marshalling
  - direction of data flow
  - pass-by-value (recommended) & pass-by-reference
  - annotations (size, sizefunc, count) for pointer arguments

Enclave Definition Language

```
enclave {
 trusted {
  public void add_secret(int secret);
  public void print_secrets();
  public void test_encryption();
  public void set_key([in, size=128] uint8_t *key);
 };
 from "sgx_lib.edl" import *;

 untrusted {
        };
};
```

SGX Helper Library

SGX Helper Library

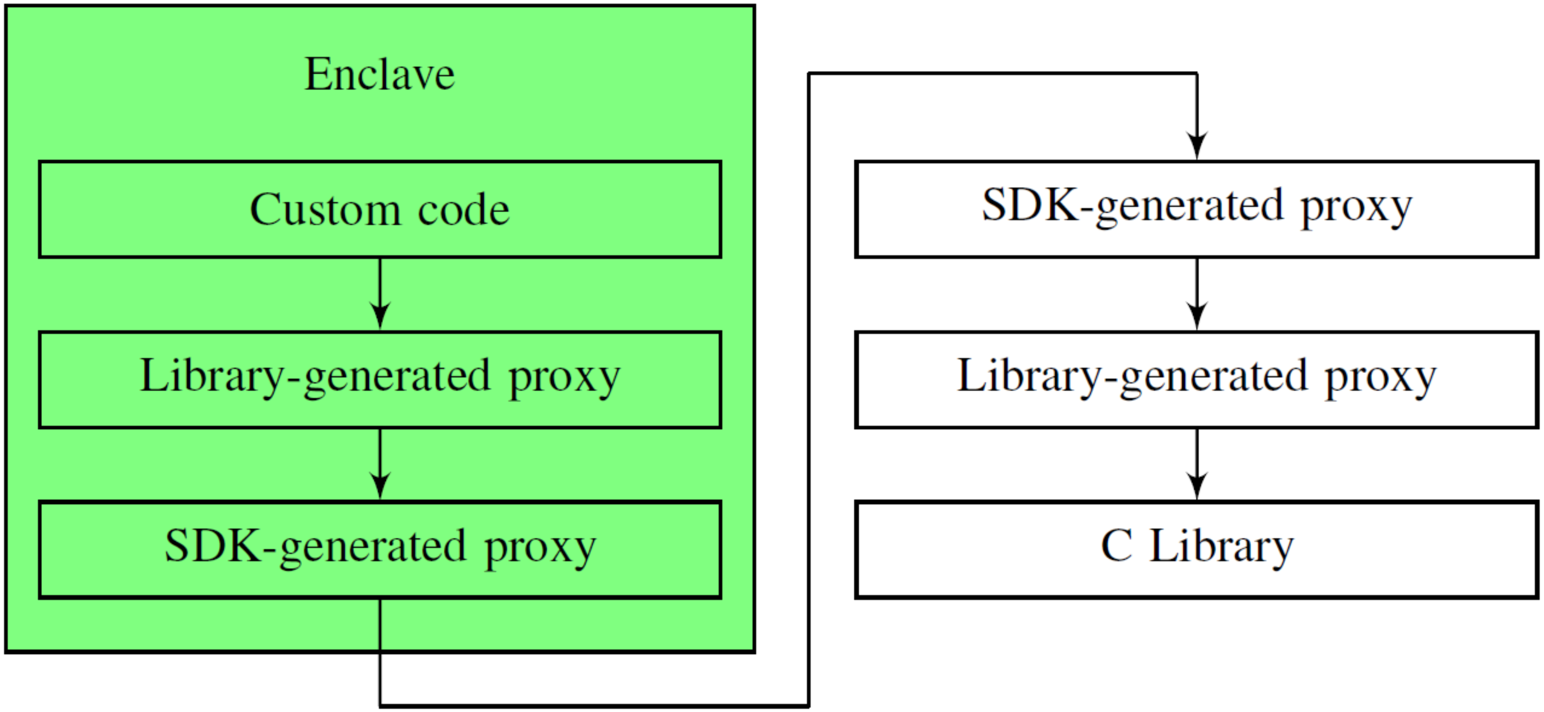
- enable easier and faster prototyping
- contains scripts and wrapper functions to make working with the SDK easier:
  - **Generation of O-call Proxies**
  - **Error Code Handling**
  - **Easy-to-Use Encryption**
  - **Transparent Encryption of Input/Output**
- available for public use: https://github.com/ftes/sgx-lib

Generation of O-Call Proxies

- O-call proxies – shim inside Enclave to proxy calls to outside world
- provide trusted functions with original signature
  - e.g. for directly linking against the C library implementation
  - different signatures in EDL for calls with return values
- automate process of defining these proxies

Generation of O-Call Proxies

- SDK proxies deal with parameter handling
- untrusted library proxy delegates to the C library



Error Code Handling

- utility function to check return values
- looking up error codes scraped from Intel SDK's *sgx_error.h*

```
SGX_ERROR_UNEXPECTED          = SGX_MK_ERROR(0x0001),      /* Unexpected error */
SGX_ERROR_INVALID_PARAMETER   = SGX_MK_ERROR(0x0002),      /* The parameter is incorrect */
SGX_ERROR_OUT_OF_MEMORY       = SGX_MK_ERROR(0x0003),      /* Not enough memory is available to complete this operation */
SGX_ERROR_ENCLAVE_LOST        = SGX_MK_ERROR(0x0004),      /* Enclave lost after power transition or used in child process creat
SGX_ERROR_INVALID_STATE       = SGX_MK_ERROR(0x0005),      /* SGX API is invoked in incorrect order or state */

SGX_ERROR_INVALID_FUNCTION    = SGX_MK_ERROR(0x1001),      /* The ecall/ocall index is invalid */
SGX_ERROR_OUT_OF_TCS          = SGX_MK_ERROR(0x1003),      /* The enclave is out of TCS */
SGX_ERROR_ENCLAVE_CRASHED     = SGX_MK_ERROR(0x1006),      /* The enclave is crashed */
SGX_ERROR_ECALL_NOT_ALLOWED   = SGX_MK_ERROR(0x1007),      /* The ECALL is not allowed at this time, e.g. ecall is blocked by th
SGX_ERROR_OCALL_NOT_ALLOWED   = SGX_MK_ERROR(0x1008),      /* The OCALL is not allowed at this time, e.g. ocall is not allowed d
SGX_ERROR_STACK_OVERRUN       = SGX_MK_ERROR(0x1009),      /* The enclave is running out of stack */

SGX_ERROR_UNDEFINED_SYMBOL    = SGX_MK_ERROR(0x2000),      /* The enclave image has undefined symbol. */
SGX_ERROR_INVALID_ENCLAVE     = SGX_MK_ERROR(0x2001),      /* The enclave image is not correct. */
SGX_ERROR_INVALID_ENCLAVE_ID  = SGX_MK_ERROR(0x2002),      /* The enclave id is invalid */
SGX_ERROR_INVALID_SIGNATURE   = SGX_MK_ERROR(0x2003),      /* The signature is invalid */
SGX_ERROR_NDEBUG_ENCLAVE      = SGX_MK_ERROR(0x2004),      /* The enclave is signed as product enclave, and can not be created a
SGX_ERROR_OUT_OF_EPC          = SGX_MK_ERROR(0x2005),      /* Not enough EPC is available to load the enclave */
```

Easy-to-Use Encryption

- some of SDK's cryptography functions are cumbersome to use
  - size of encrypted/sealed data not trivial to determine
- extensive wrapper for encryption

```
uint32_t get_sealed_data_size(uint32_t
    ↪ plaintext_data_size);
int seal(const void* plaintext_buffer, uint32_t
    ↪ plaintext_data_size, sgx_sealed_data_t*
    ↪ sealed_buffer, size_t sealed_data_size);
int unseal(void* plaintext_buffer, uint32_t
    ↪ plaintext_data_size, sgx_sealed_data_t*
    ↪ sealed_buffer);

uint32_t get_encrypted_data_size(uint32_t
    ↪ plaintext_data_size);
int encrypt(const void* plaintext_buffer, uint32_t
    ↪ plaintext_data_size, sgx_lib_encrypted_data_t
    ↪ * encrypted_buffer, sgx_aes_ctr_128bit_key_t*
    ↪  key);
int decrypt(void* plaintext_buffer, uint32_t
    ↪ plaintext_data_size, sgx_lib_encrypted_data_t
    ↪ * encrypted_buffer, sgx_aes_ctr_128bit_key_t*
    ↪  key);
```

Transparent I/O Encryption

- transparent de- & encryption of input/output data – protects data operated on by legacy code without requiring any code modifications
- intercepting calls to C library for file input/output
- choose desired security level (at compile time)
  - **no security**: plain file input/output
  - **encryption with custom key**: use of symmetric encryption key
  - **data sealing** (default): seals all input/output to the Enclaves identity

Case Study: KISSDB

Case Study: KISSDB

- hardening security of existing database management system using SGX
- interesting target for trusted computing
  - stored data may be sensitive, requiring protection from the infrastructure, provider or other tenants
- avoid excessively complex code: KISSDB
  - simple key/value store
  - implemented in plain C using only file I/O functions
  - https://github.com/adamierymenko/kissdb
- goal: protect data KISSDB operates on

Design Decisions

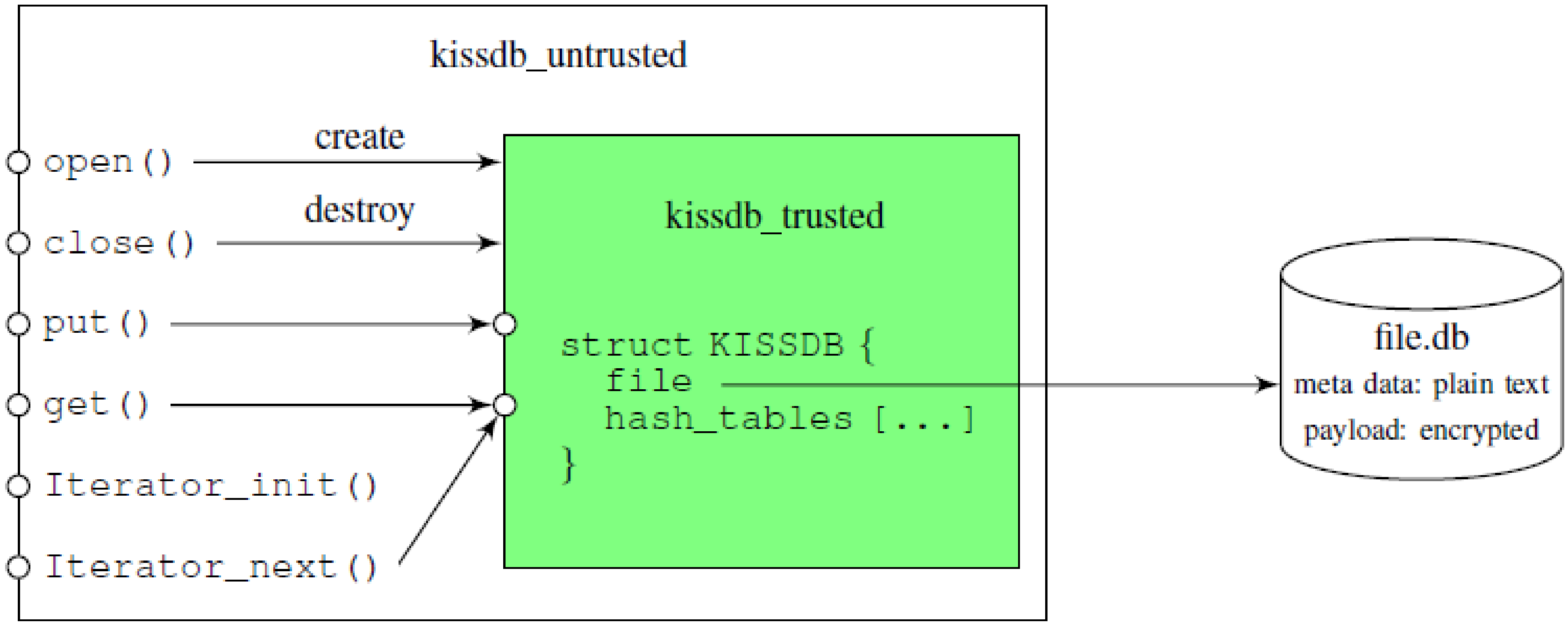
- Enclave Design
  - only move application code into enclave
  - shim C library to utilize external host C library
- Scope of Enclaves
  - no concurrency in KISSDB – one enclave per database
- Decomposition
  - a single enclave used for all trusted functionality
  - KISSB not sub-divided into trusted & non-trusted function and does not support data processing
- Unencrypted Metadata
  - metadata (header, hash tables) is not protected

Design Decisions

- Iterators
  - allows to iterating through all values, several iterators per database in parallel
  - iterator data (page number and offset) stored outside of the Enclave
- Encryption vs. Sealing
  - sealing: encryption with key derived from Enclaves identity
  - (user) encryption: empower user to specify key

Design Decisions

- hardened KISSSB architecture:



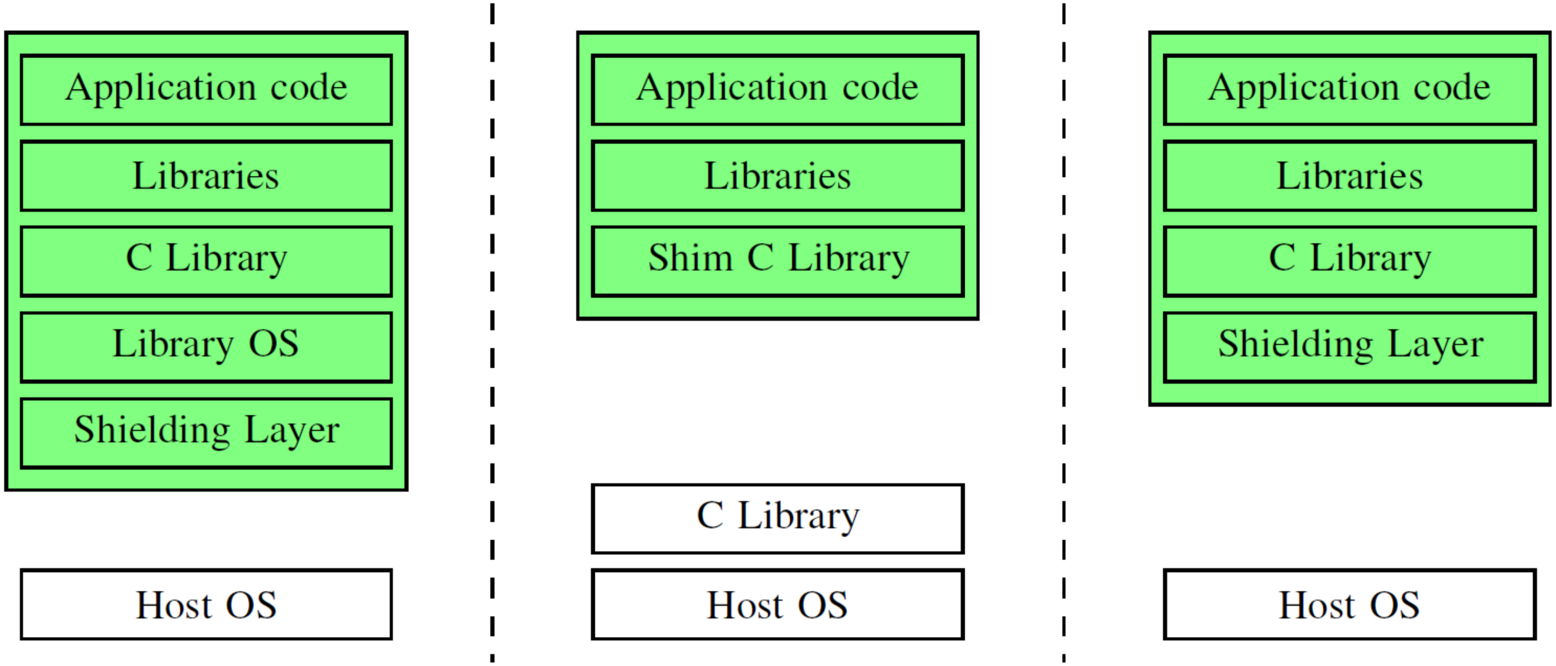
Unresolved Issues

- attestation & key-provisioning
  - attest enclave’s identity and perform key exchange in a production setting
- file integrity & freshness
  - use of cryptographic mechanisms to ensure file integrity (e.g. monotonic counters provided by SDK)
- cryptographic hash function
  - KISSDB does not use cryptographic hash function
- file layout
  - deterministic file layout (known plain text attacks)

Related Work

Enclave Design Alternatives

- library operating system inside enclave
- minimal enclave size with external C library
- untrusted system calls with internal C library



Related Work

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- application specific approaches
  - Verifiable Confidential Cloud Computing (VC3)

    F. Schuster, M. Costa, C. Fournet, C. Gkantsidis, M. Peinado, G. Mainar-Ruiz, and M. Russinovich, "VC3: Trustworthy Data Analytics in the Cloud Using SGX," in *2015 IEEE Symposium on Security and Privacy (SP). IEEE, 2015*, pp. 38–54.
  - Secure Keeper

    S. Brenner, C. Wulf, D. Goltzsche, N. Weichbrodt, M. Lorenz, C. Fetzer, P. Pietzuch, and R. Kapitza, "SecureKeeper: Confidential ZooKeeper Using Intel SGX," in Proceedings of the 17th International Middleware Conference, ser. Middleware '16. New York, NY, USA: ACM, 2016, pp. 14:1–14:13.
- general approaches
  - Haven

    A. Baumann, M. Peinado, and G. Hunt, "Shielding Applications from an Untrusted Cloud with Haven," ACM Trans. Comput. Syst., vol. 33, no. 3, pp. 8:1–8:26, Aug. 2015.
  - SCONE

    S. Arnautov, B. Trach, F. Gregor, T. Knauth, A. Martin, C. Priebe, J. Lind, D. Muthukumaran, D. O'Keeffe, M. L. Stillwell, D. Goltzsche, D. Eyers, R. Kapitza, P. Pietzuch, and C. Fetzer, "SCONE: Secure Linux Containers with Intel SGX," in 12th USENIX Symposium on Operating Systems Design and Implementation (OSDI 16). Savannah, GA: USENIXAssociation, 2016, pp. 689–703.
  - Software Partitioning Case Study

    A. Atamli-Reineh and A. Martin, Securing Application with Software Partitioning: A Case Study Using SGX. Cham: Springer International Publishing, 2015, pp. 605–621.

Summary

- Practical perspective: approaching the challenges of trusted computing in distributed scenarios from a software engineer's point of view.
  - We provide a brief overview of the core aspects of SGX.
  - We present a helper library assisting developers in overcoming the hurdles of integrating the official SGX Software Development Kit (SDK) with their code base.
    https://github.com/ftes/sgx-lib
  - In a case study, we demonstrate the steps necessary for porting existing applications to run inside SGX enclaves, using the KISSDB database as an exemplary application.
    https://github.com/ftes/kissdb-sgx