Ginseng: Keeping Secrets in Registers When You Distrust the Operating System

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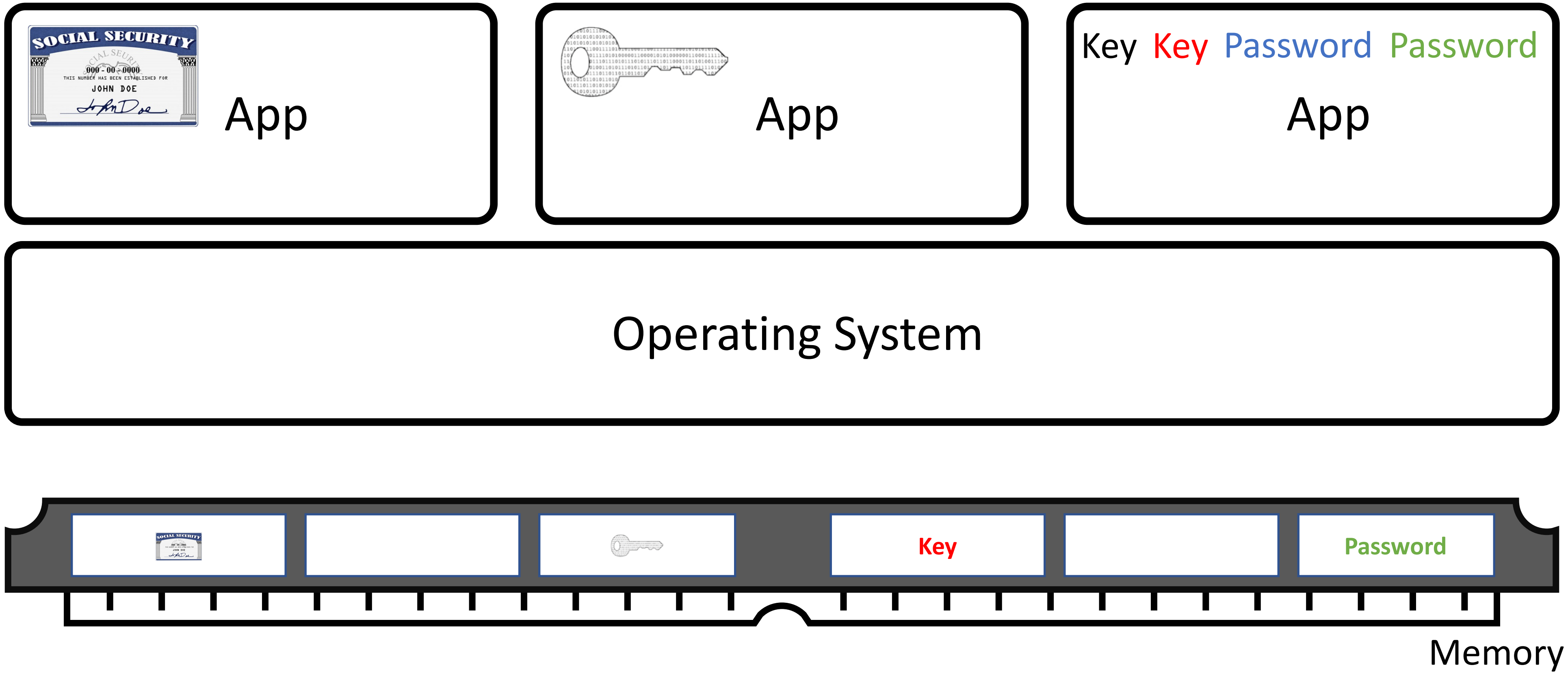
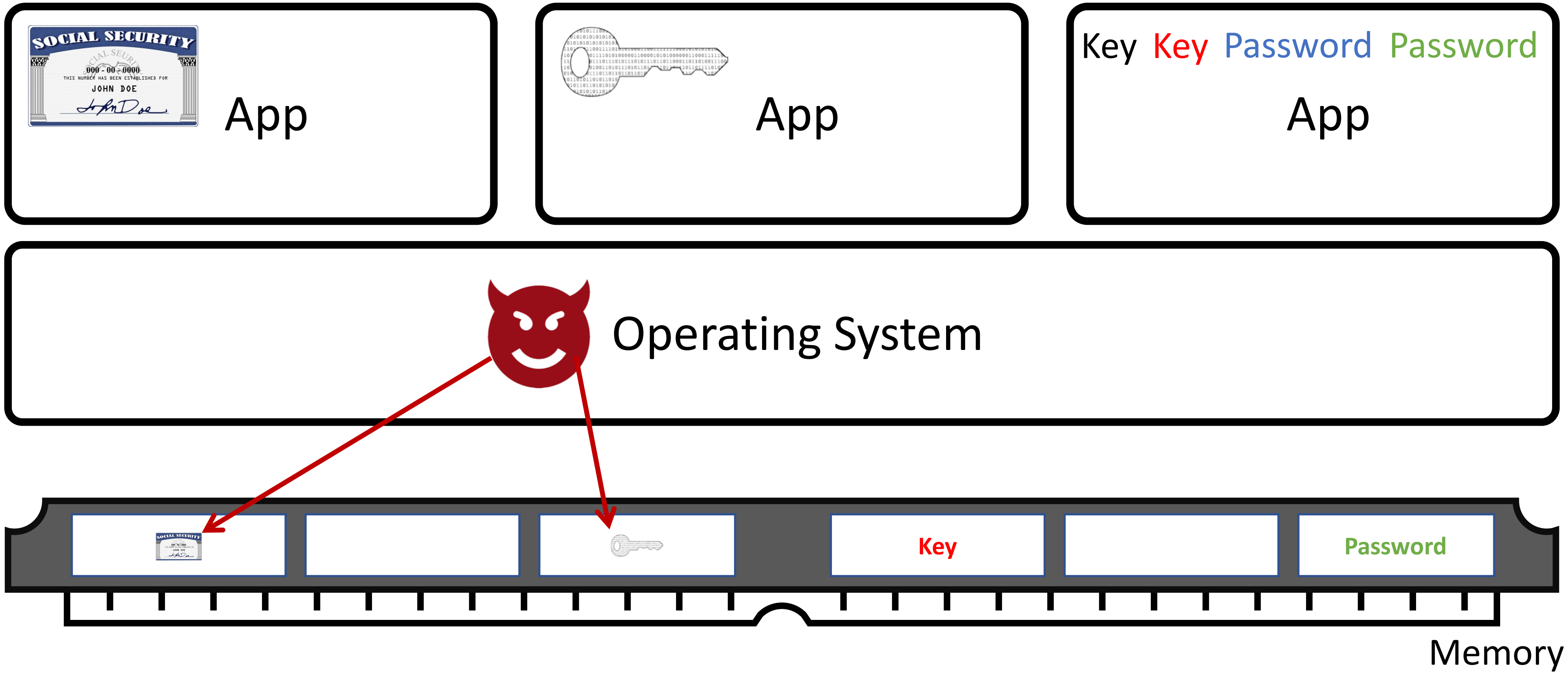
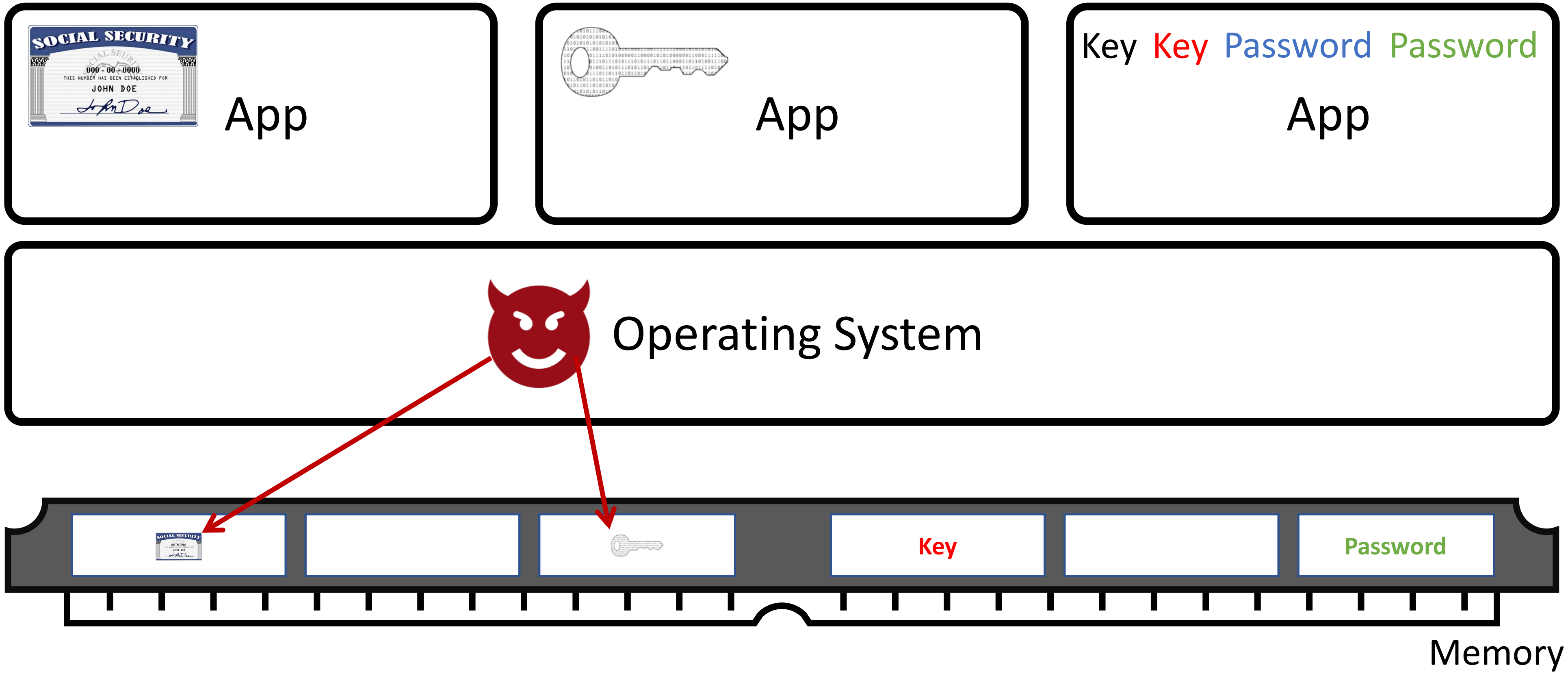
Sensitive data in memory



When the OS is compromised



Goal: Protect sensitive data against a compromised OS



Threat Model

- Trusted
  - Hardware
  - ARM TrustZone
  - A chain of trust

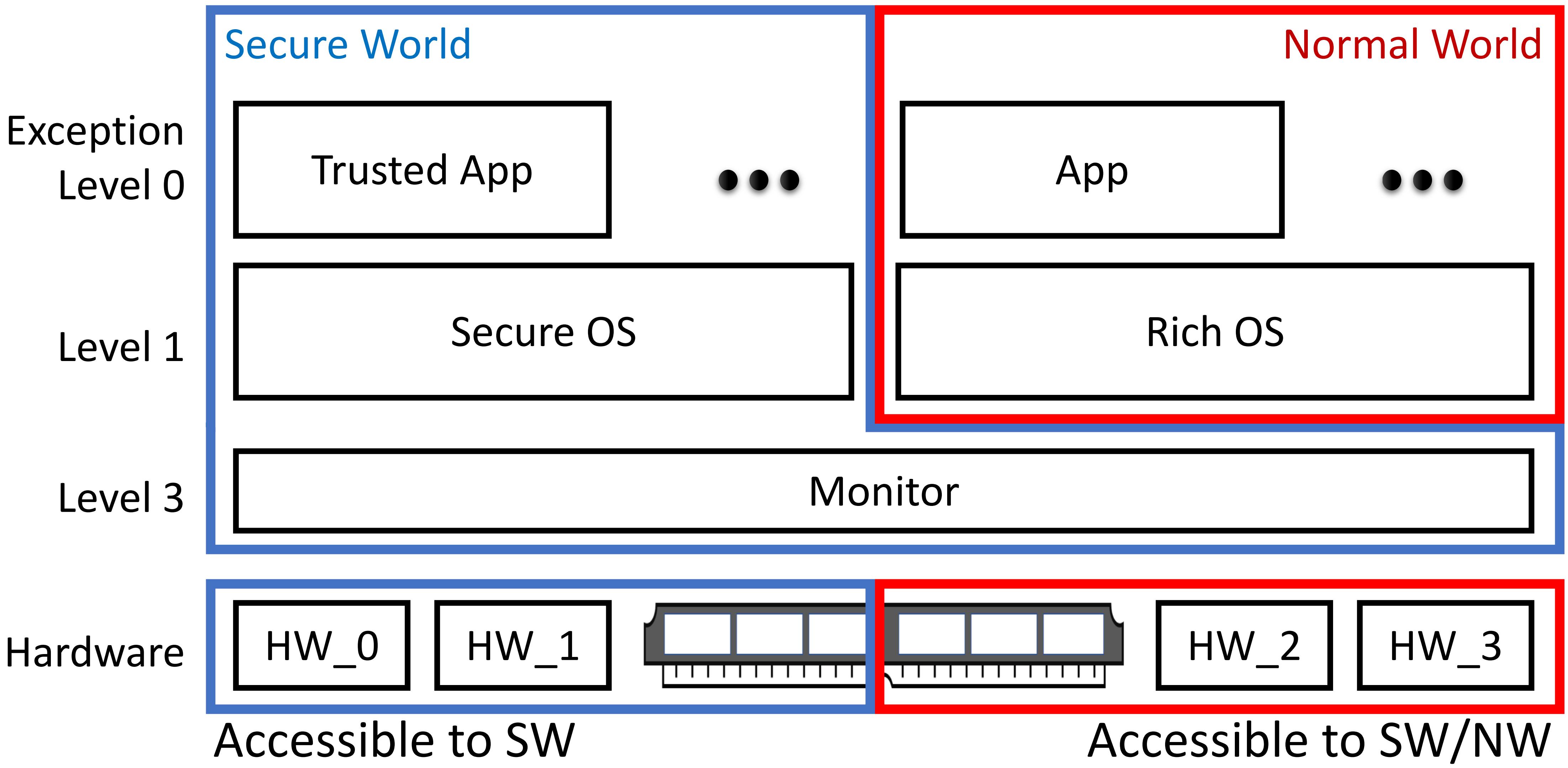
Threat Model

- Trusted
  - Hardware
  - ARM TrustZone
  - A chain of trust

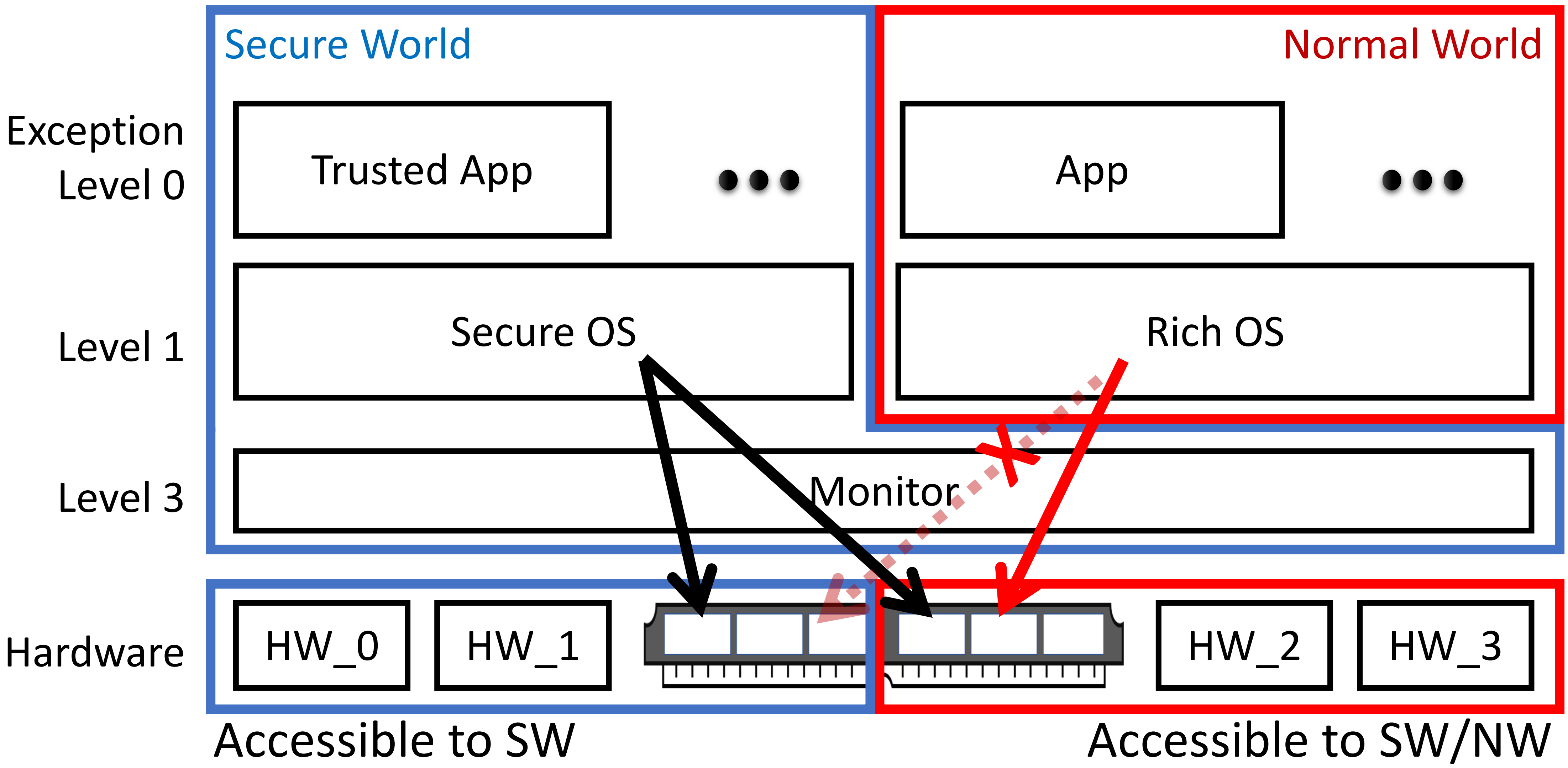
- Untrusted

Everything else
i.e., apps, system software, and OS

ARM TrustZone

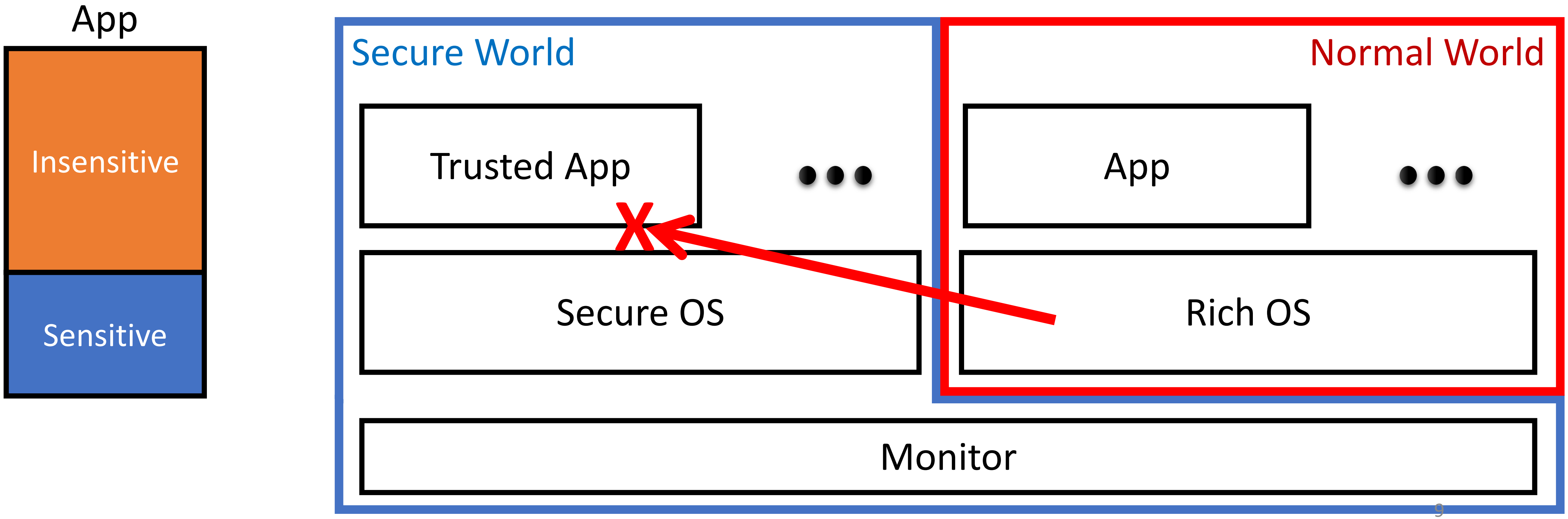


ARM TrustZone



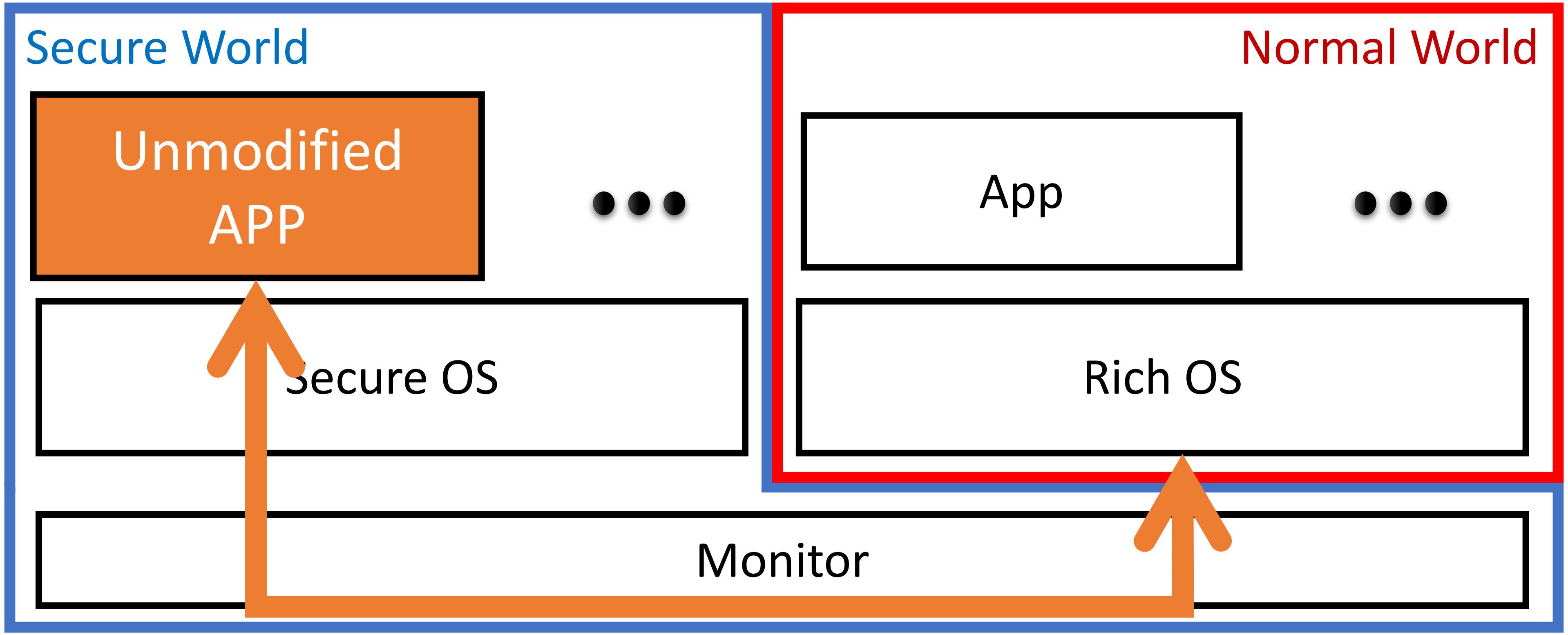
State of the Art #1: Divide an app into sensitive and insensitive parts

AdAttester [MobiSys '15], Liu et al. [MobiSys '12], TLR [ASPLOS '14], and so on



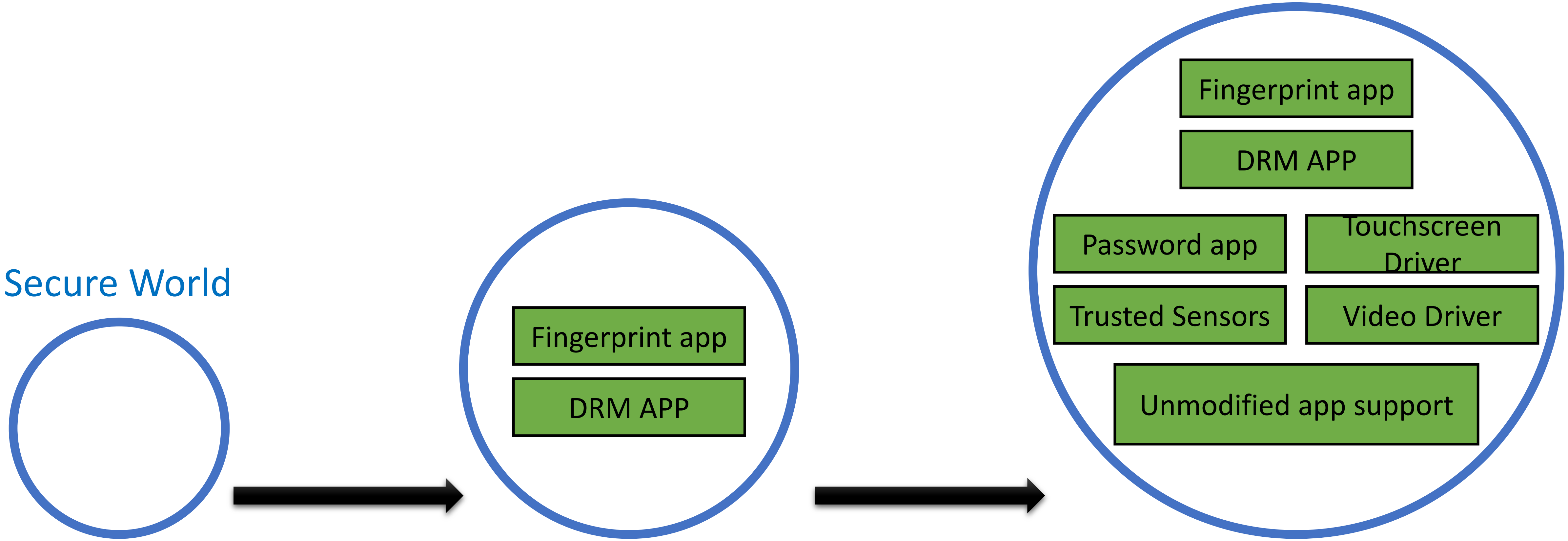
State of the Art #2:
Run an unmodified app in the secure world

TrustShadow [MobiSys`17]



System calls, exceptions, library calls, and etc.

All proportionally increase the secure world



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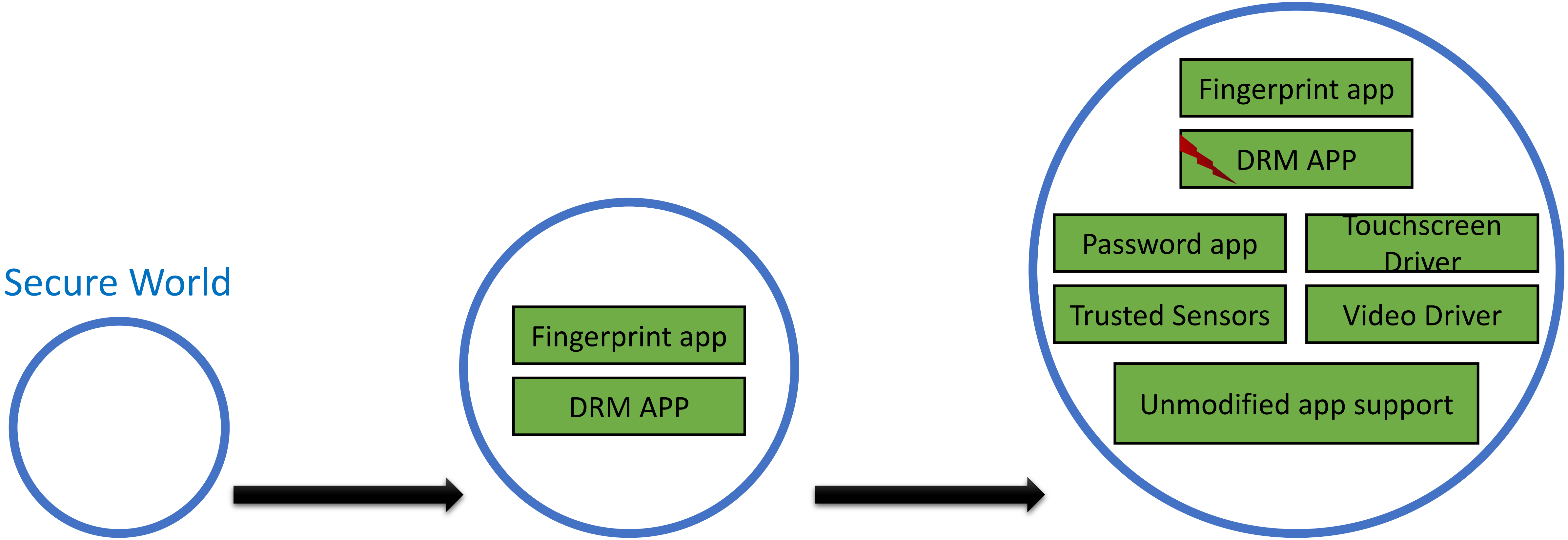

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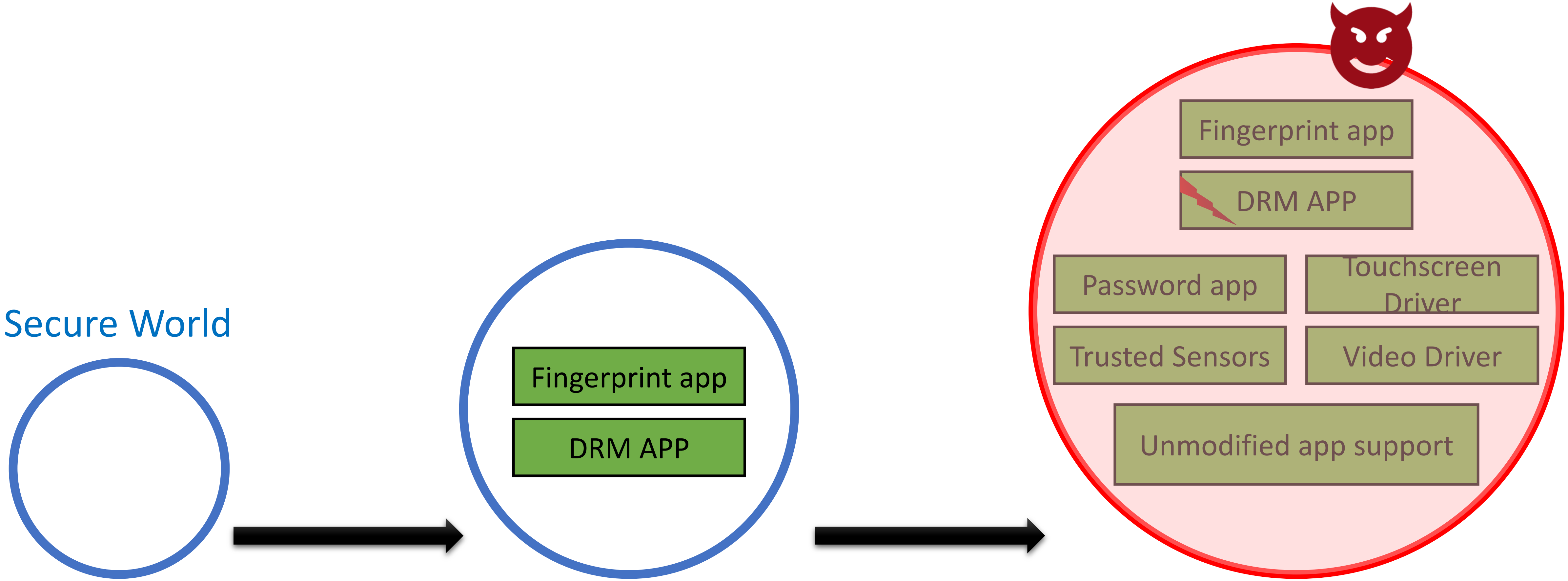


QSEE Integer Overflow [BlackHat14]
TEE API bug [BlackHat15]
TRUSTNONE [TR15]

Two Principles

1. No app logic in the Secure world
    - We should not include third-party apps in the secure world
    - It leads to vulnerabilities
      e.g., CVE-2015-6639, CVE-2015-8999, CVE-2015-9007, CVE-2016-1919,
      CVE-2016-1920, CVE-2016-2431, CVE-2016-3996, CVE-2016-5349, and so on

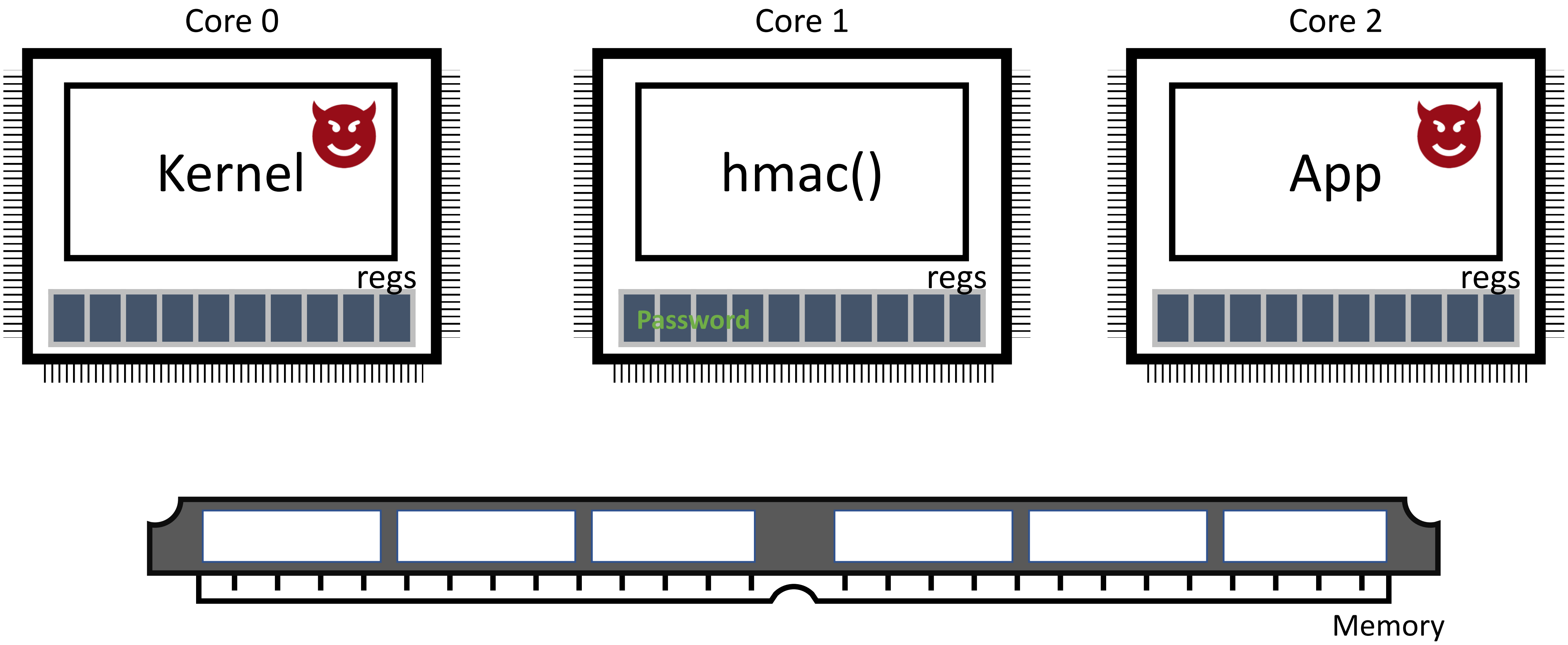
2. Protect only sensitive data
    - Protecting insensitive data only increases overhead
    - Not all data are important. E.g, time vs. password

In **Ginseng**,

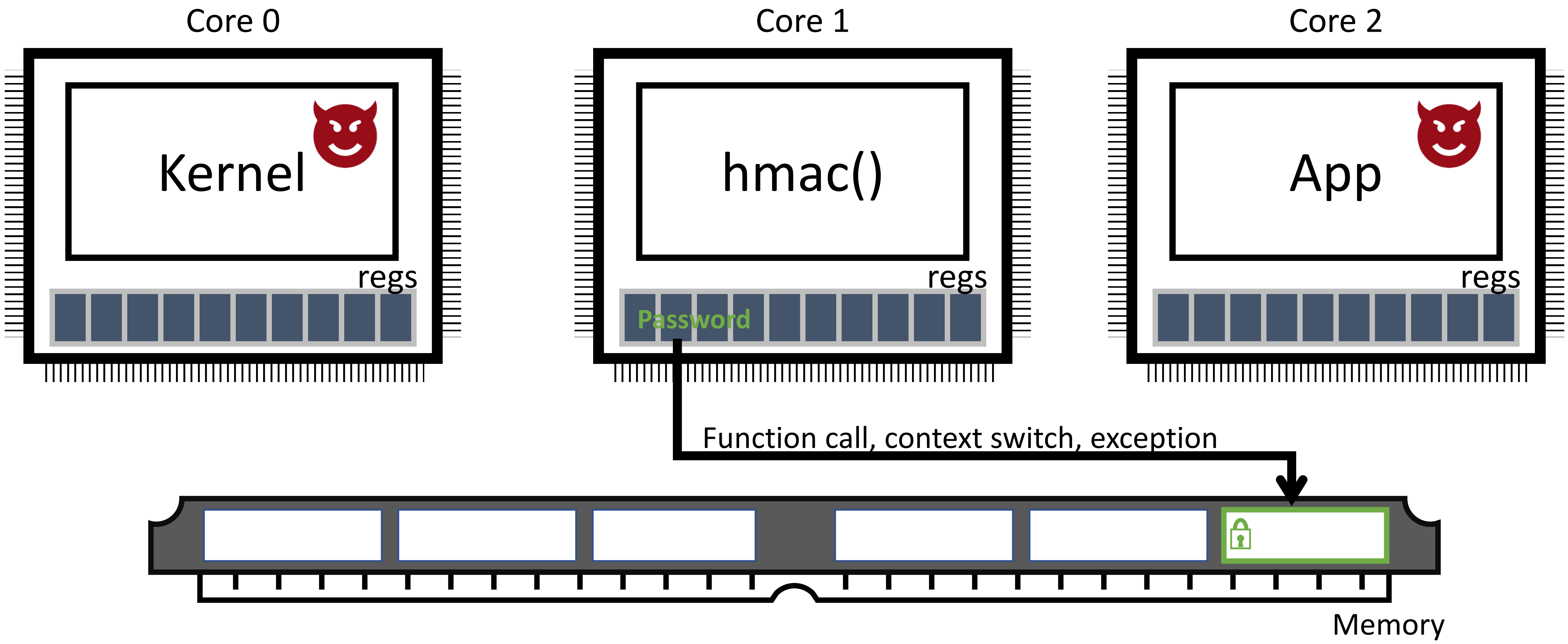
- Secure world : a trusted computing base for the normal world
- Normal world : the execution environment for apps

➡ Protect secrets of third-party apps in the Normal world

Idea: Keep sensitive data in registers only when being used



Idea: Encrypt sensitive data to memory when not being used



Challenges

1. Data must be saved in memory, or stack
    - on a subroutine call,
    - on an exception, e.g., page fault and interrupt

2. A function with sensitive data can be compromised
    - E.g., code injection by the kernel

3. A function with sensitive data can jump to a compromised function

Challenges

1. Data must be saved in memory, or stack → Confidentiality
   - on a subroutine call,
   - on an exception, e.g., page fault and interrupt

2. A function with sensitive data can be compromised → Code Integrity
   - E.g., code injection by the kernel

3. A function with sensitive data can jump to a compromised function → CFI

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today

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3. A function with sensitive data can jump to a compromised function → CFI

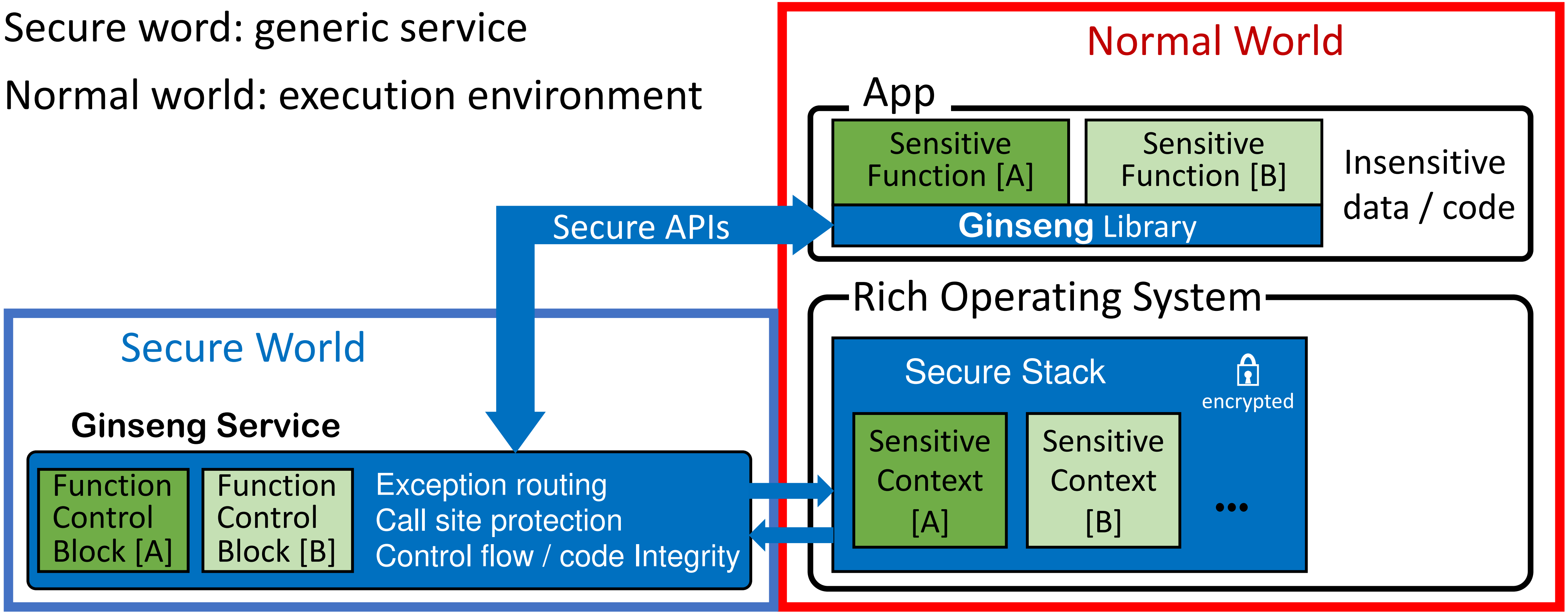
paper

Design

- Programing Model ➡ Developer-marked sensitive variables
- Static Protection ➡ Sensitive variables are always in registers
- Dynamic Protection ➡ Runtime support for functions with sensitive data
- Secure Stack ➡ Encrypted memory in the Normal world

Software Architecture

- Secure word: generic service
- Normal world: execution environment



Static Protection:
The compiler keeps sensitive data in registers

- Goals:
  - Allocate registers to sensitive variables and **never spill** them
  - Use as **less registers** as possible for sensitive variables
  - Protect registers with sensitive data at a **call site**

Static Protection:
The compiler keeps sensitive data in registers

- Goals:
  - Allocate registers to sensitive variables and **never spill** them ← Register allocator
  - Use as **less registers** as possible for sensitive variables
  - Protect registers with sensitive data at a **call site** ← Secure stack

Where to save sensitive data?

x14 x15

```
sensitive long key_top, key_bottom;
// all other variables are insensitive

/* computing with key_top and key_bottom */


  printf("Generating code...\n");

  /* use HAMC_SHA1 to compute 20-byte hash */
  hmac_sha1(key_top, key_bottom, // sensitive data
            challenge,           // current time / 30sec
            resultFull);         // (out) full hash
```

Problem Sensitive registers must not be saved to stack

Sensitive registers ⟶ *secure stack*

```
                      x14        x15
sensitive long key_top, key_bottom;
// all other variables are insensitive

/* computing with key_top and key_bottom */


  printf("Generating code...\n");

  /* use HAMC_SHA1 to compute 20-byte hash */
  hmac_sha1(key_top, key_bottom, // sensitive data
            challenge,           // current time / 30sec
            resultFull);         // (out) full hash
```

Callsite Protection req.

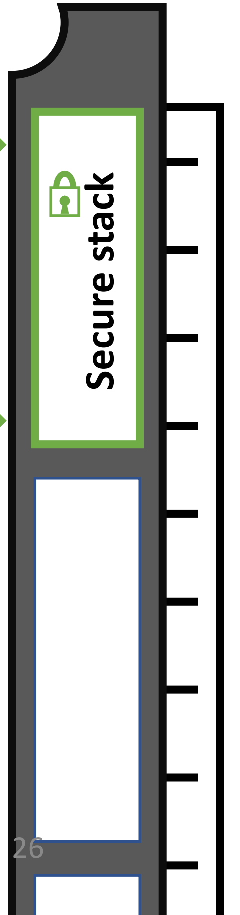
Call site ID

Hide x14 and x15

Callsite Protection req.

Call site ID

Restore x14 and x15



Sensitive data are protected at a call site

```
                  x14         x15
sensitive long key_top, key_bottom;
// all other variables are insensitive

/* computing with key_top and key_bottom */


  printf("Generating code...\n");

  /* use HAMC_SHA1 to compute 20-byte hash */
  hmac_sha1(key_top, key_bottom, // sensitive data
            challenge,           // current time / 30sec
            resultFull);         // (out) full hash
```

Sensitive data -> secure stack

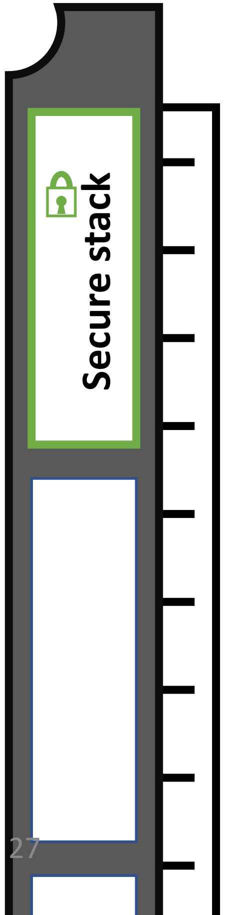
↓

`printf()` implementation

```
/* No sensitive data
 in regs or memory*/
```

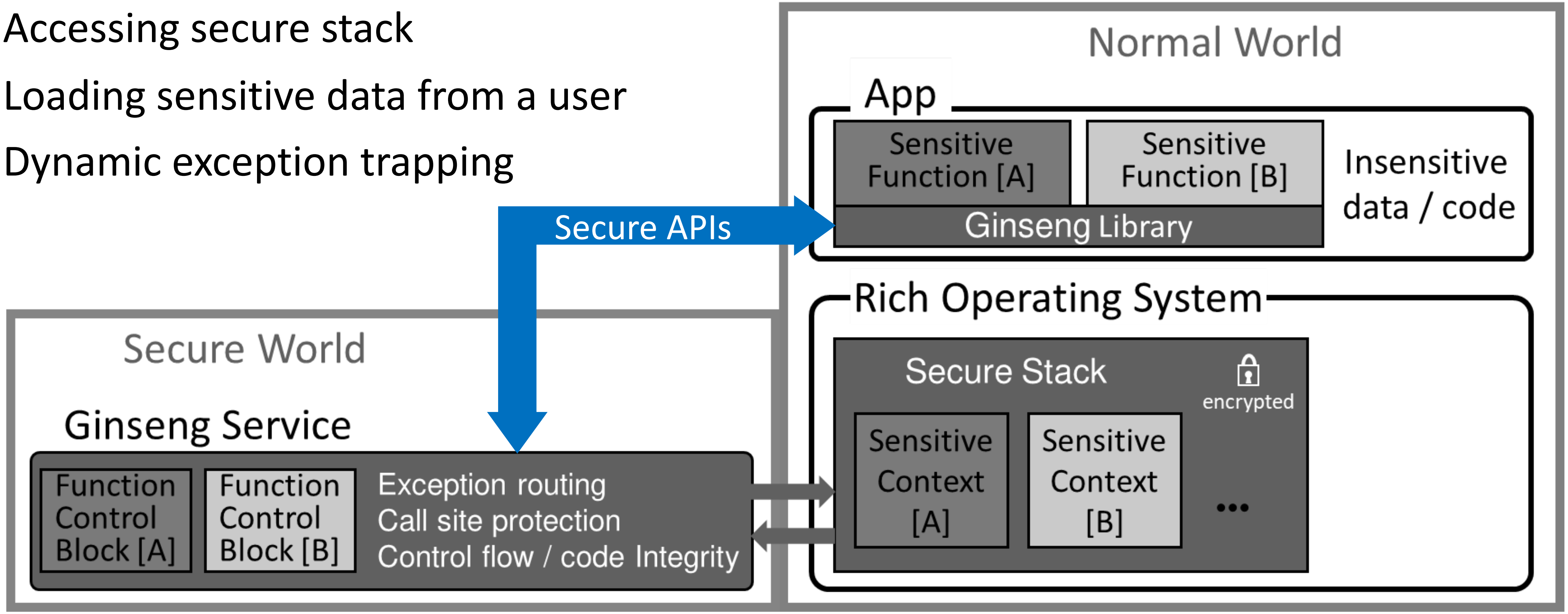
↓

Sensitive data <- secure stack



Secure API bypasses the OS

- Accessing secure stack
- Loading sensitive data from a user
- Dynamic exception trapping



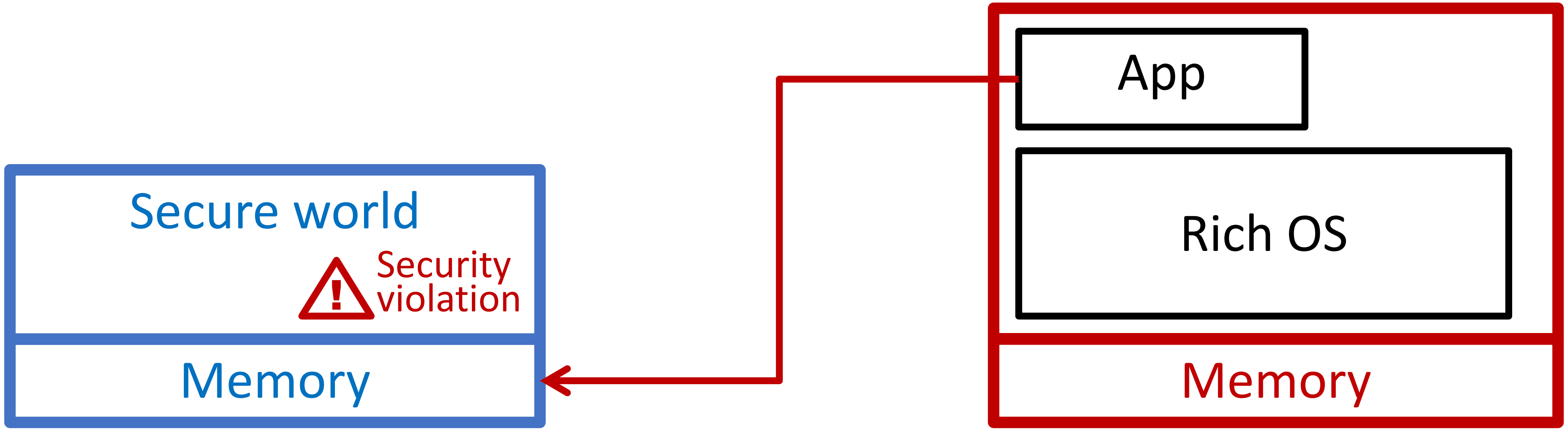
Secure Monitor Call is not enough.

Secure Monitor Call (SMC) instruction

- invoked the Secure world
- only available to the kernel

Problem	We must not send cleartext data to secure stack via the untrusted OS

Idea for Secure API:
Trigger a security violation from the Normal world



The rich OS is unaware of the communication

Static Protection is not enough

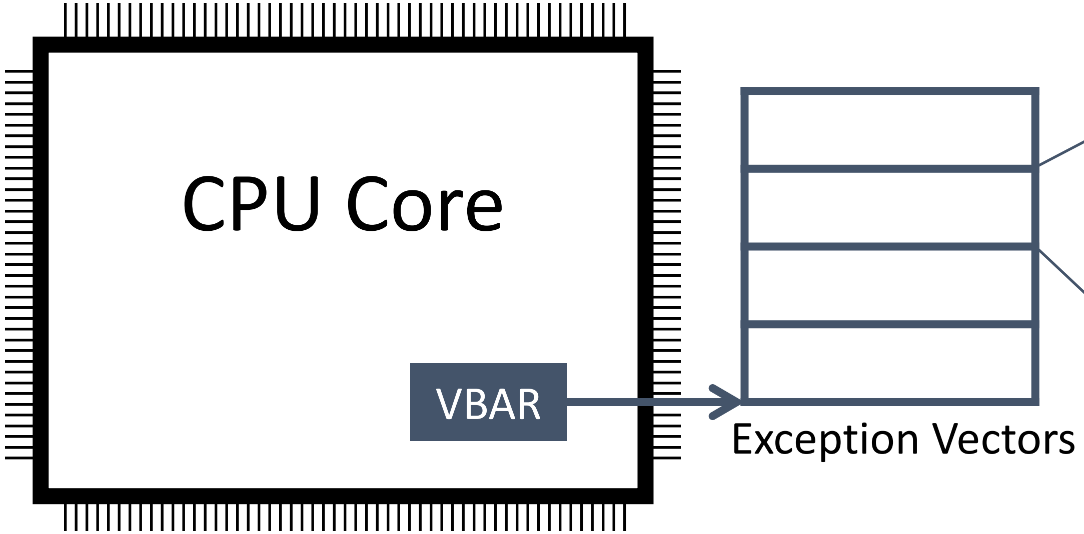
Challenge #1: Data must be saved in memory, or stack

- ~~on a subroutine call,~~
- on an exception, e.g., page fault and interrupt

Dynamic Exception Trapping

Any sensitive data	→	**GService** intercepts exceptions
No sensitive data	→	No intercept

Dynamic Exception Trapping



VBAR: Vector Base Address Register

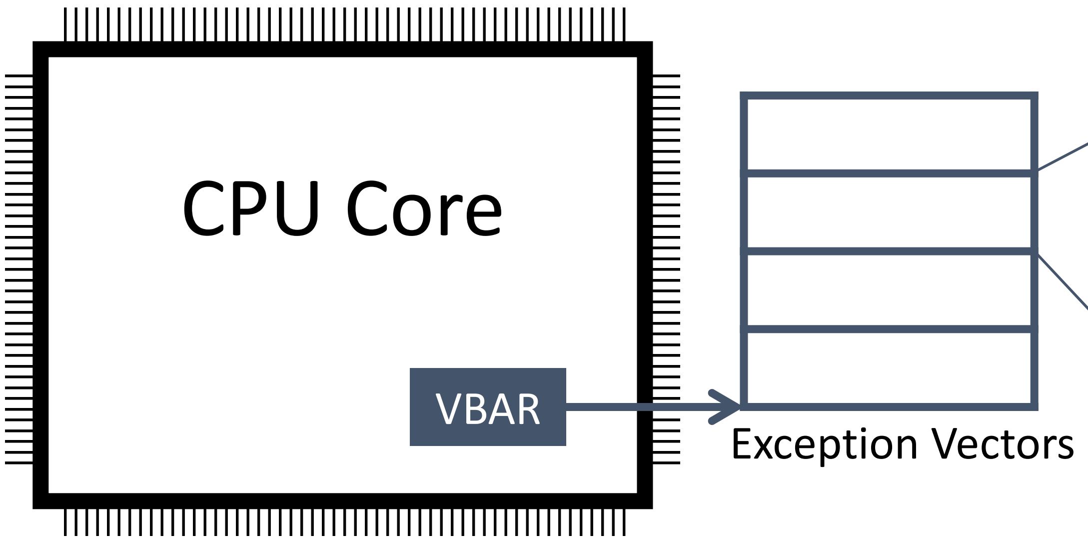
entry.S

```
/*
 * Common to all vectors
 * Save registers to the stack
 */
sub       sp, sp, #S_FRAME_SIZE
stp       x0, x1, [sp, #16 * 0]
stp       x2, x3, [sp, #16 * 1]
stp       x4, x5, [sp, #16 * 2]
stp       x6, x7, [sp, #16 * 3]
          ...


/* Exception
   Service
   Routine */
```

Preprocessed and simplified

Dynamic Exception Trapping



VBAR: *Vector Base Address Register*

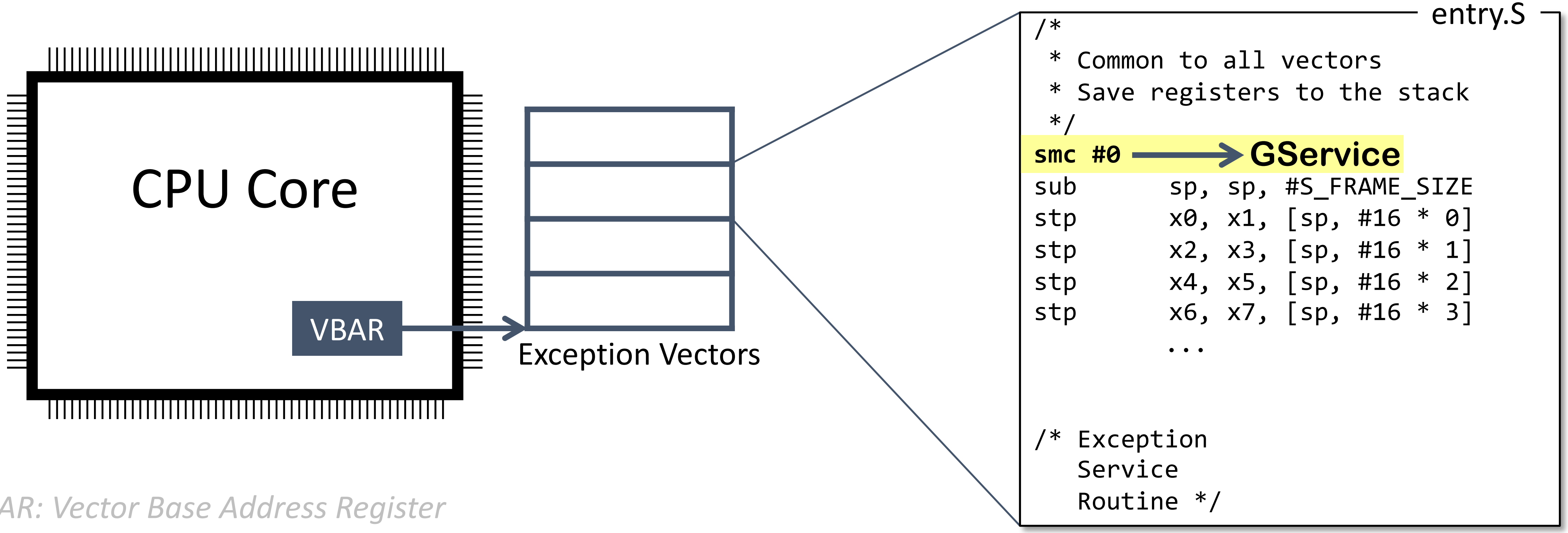
entry.S

```
/*
 * Common to all vectors
 * Save registers to the stack
 */
nop         // place holder
sub         sp, sp, #S_FRAME_SIZE
stp         x0, x1, [sp, #16 * 0]
stp         x2, x3, [sp, #16 * 1]
stp         x4, x5, [sp, #16 * 2]
stp         x6, x7, [sp, #16 * 3]
            ...


/* Exception
   Service
   Routine */
```

Preprocessed and simplified

Before loading any sensitive data, **GService** inserts **smc**



VBAR: Vector Base Address Register

Preprocessed and simplified

The OS handles an exception, but **GService** encrypts data.

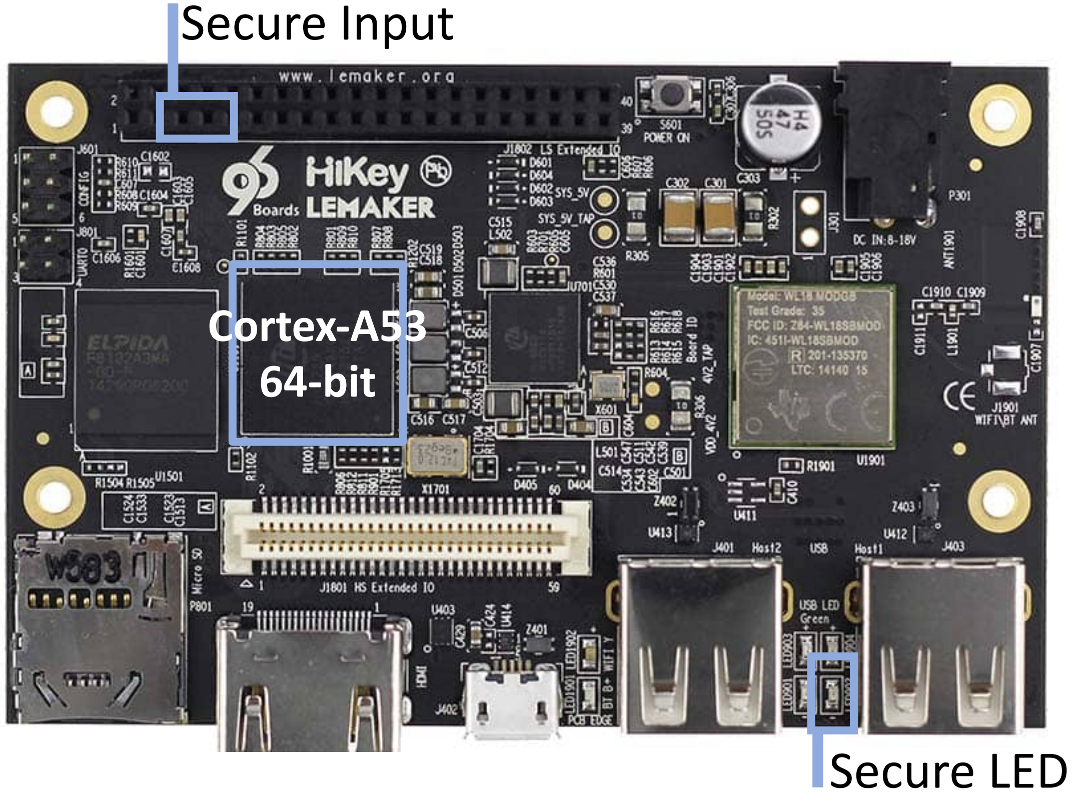
Design Summary

• Programing Model	➡	the *sensitive* keyword
• Static Protection	➡	**Ginseng** compiler
• Dynamic Protection	➡	Code and control flow Integrity
• Secure Stack	➡	Encrypted Normal world memory

Implementation

- LLVM v6.0
- **Ginseng Service** in Rust
- Linux v4.9

- Benchmark
  - Two-factor authenticator
  - wpa_supplicant
  - Learned classifier (C4.5)
  - Nginx



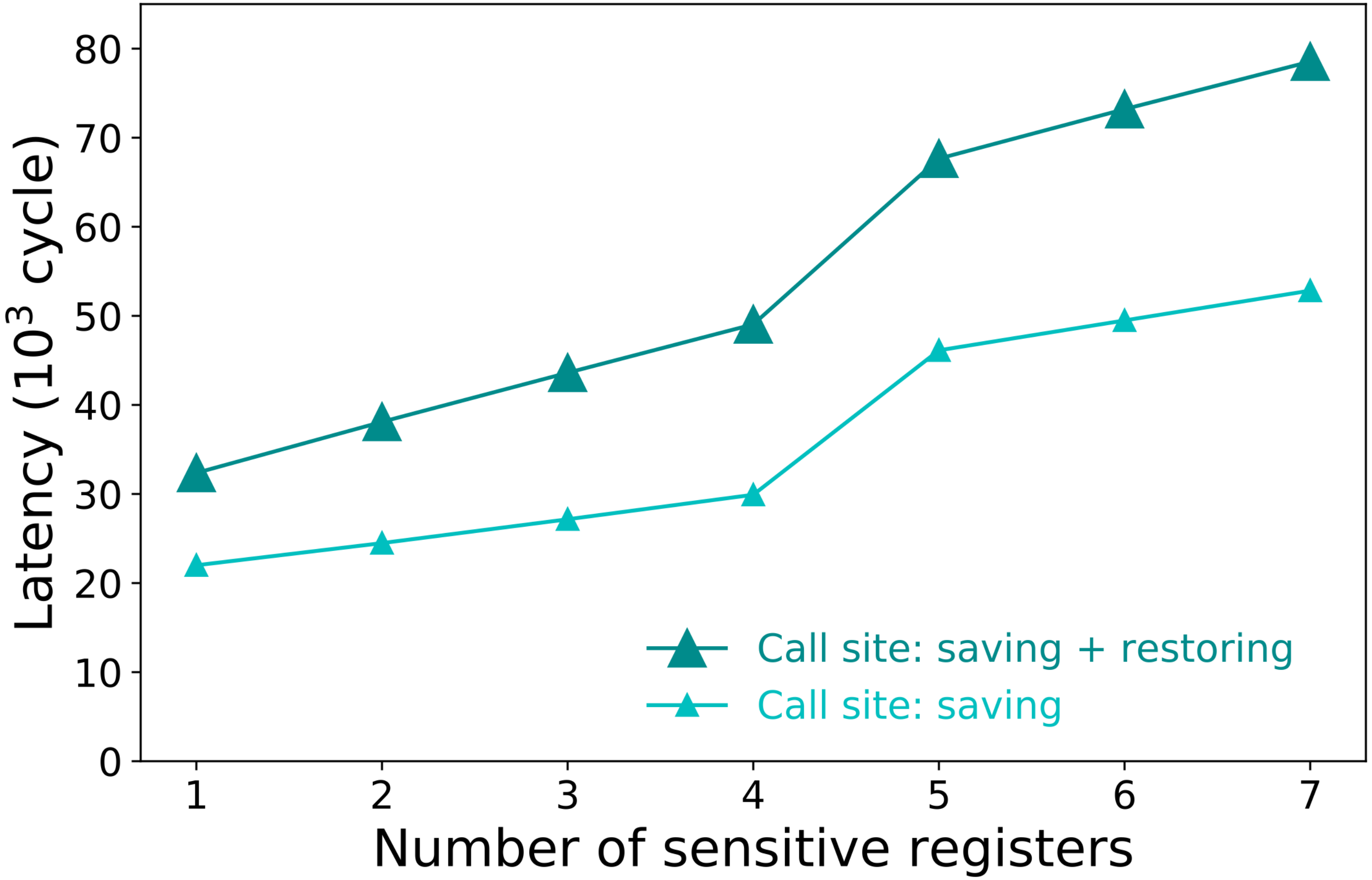
Evaluation

Q1. Microbenchmark for the protections

Q2. End-to-end overhead in real applications

Q3. Difficulty of applying **Ginseng**

Microbenchmark: Overhead for accessing secure stack



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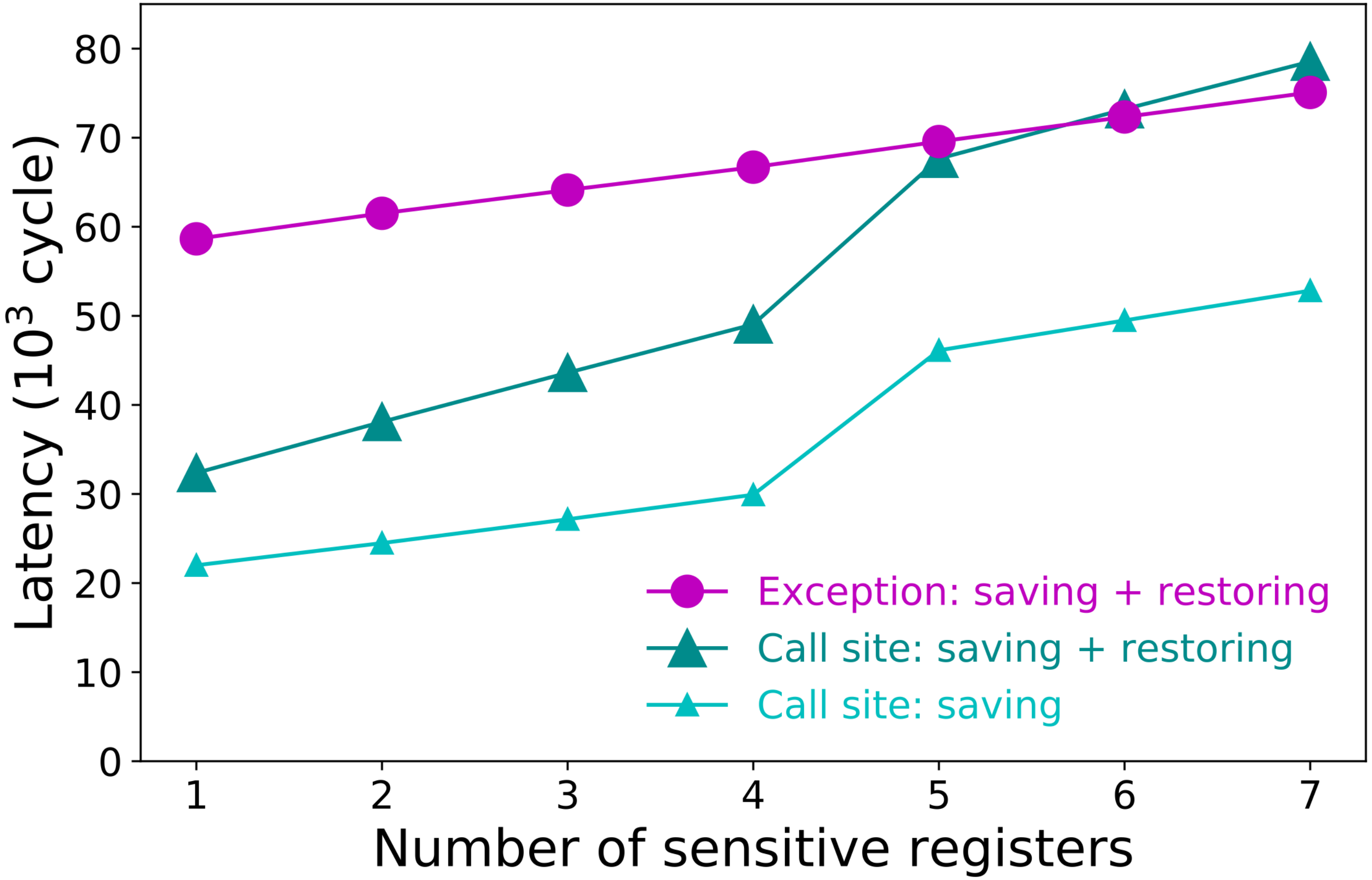


End-to-end Overhead

(cycle)		Authenticator	wpa_supplicant		Classifier
Baseline		37 K	219 M		1.7 M
Overhead	Code Integrity	45,356 K	45 M	23 M	11.3 M
	Callsite	680 K (17 times)	6,429 M (131,078	1,640 M 40,988 times)	4.4 M (137 times)
	Exception	9 K (0.13 times)	6 M (99.40	6 M 78.52 times)	0.4 M (5.4 times)
	GService overhead	851 K	661 M	411 M	1.7 M
Total		46,933 K	7,361 M	2,299 M	19.6 M
			naïve	*optimized*	

Nginx: no meaningful overhead

Development Effort

In SLoC	**Authenticator**	**wpa_supplicant**	**Classifier**	**Nginx**
Baseline	250	400 + 513 K	5 K	145 + 513 K
Modified (added)	10	25 + 90†	6	0 + 200†
Time	0	1 d	3 h	1 d

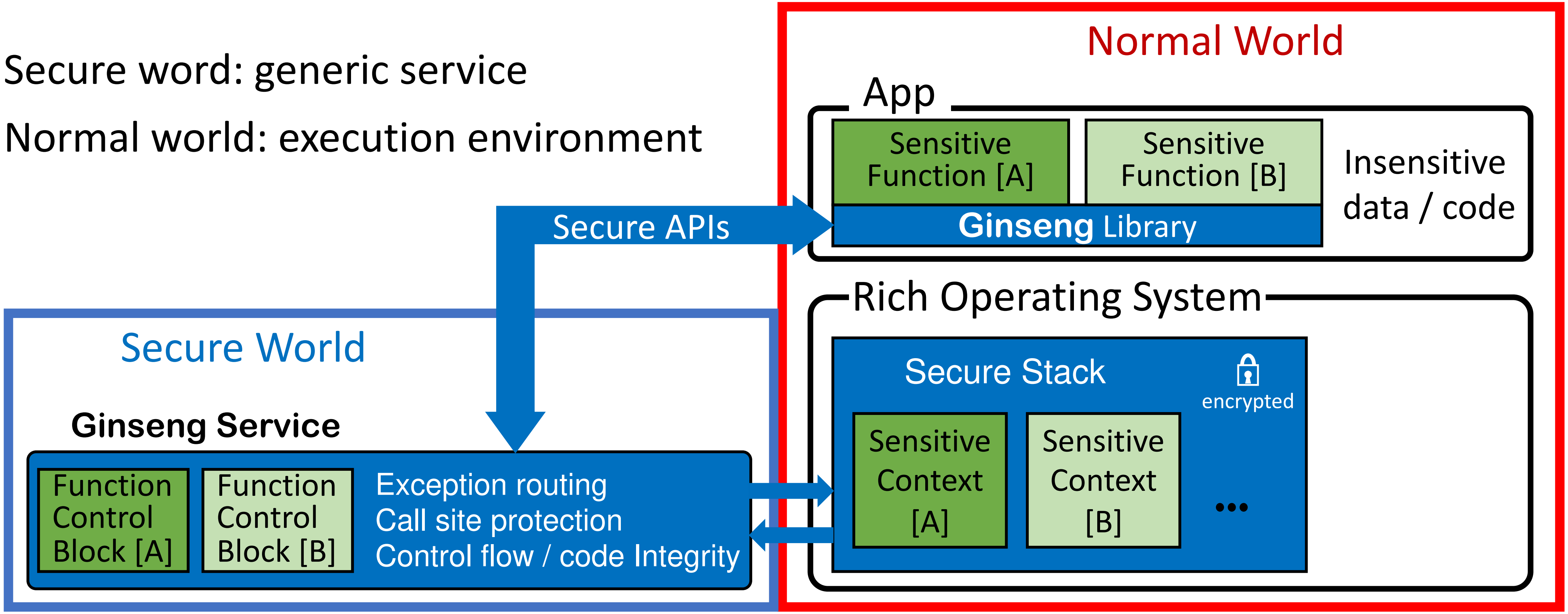
†OpenSSL

Mainly due to the prototype's limitation: supporting only primitive types

➔ can be reduced only by *engineering* effort

Ginseng protects sensitive data with no app logic in the Secure world

- Secure word: generic service
- Normal world: execution environment



backup

Programming Model: A developer marks a sensitive variables

- Not all data are sensitive
- Not all function are protected

```
void hmac_sha1(sensitive long key_top,
               sensitive long key_bottom,
               const uint8_t *data, uint8_t *result) {
  sensitive long tmp_key_top, tmp_key_bottom;
  /* all other variables are insensitive */

  /* HMAC_SHA1 implementation */
}

int genCode (sensitive long key_top,
             sensitive long key_bottom) {
  /* all other variables are insensitive */

  /* use HAMC_SHA1 to compute 20-byte hash */
  hmac_sha1(key_top, key_bottom, // sensitive data
            challenge,           // current time / 30sec
            resultFull);         // (out) full hash

  /* truncate 20-byte hash to 4-byte */
  result = truncate(resultFull);

  printf("OTP: %06d\n", result);
  return result;
}
```

```
void run () {
  sensitive long key_top, key_bottom;

  /* read a secret key from GService or a user */
  s_read(TKN_KEY1_TOP, TKN_KEY1_BOTTOM, key_top);
  s_read(TKN_KEY2_TOP, TKN_KEY2_BOTTOM, key_bottom);

  genCode(key_top, key_bottom);
}
```

A simplified two-factor authenticator

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  /* truncate 20-byte hash to 4-byte */
  result = truncate(resultFull);
    insensitive
  printf("OTP: %06d\n", result);
  return result;
}
```

```
void run () {
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  s_read(TKN_KEY1_TOP, TKN_KEY1_BOTTOM, key_top);
  s_read(TKN_KEY2_TOP, TKN_KEY2_BOTTOM, key_bottom);

  genCode(key_top, key_bottom);
}
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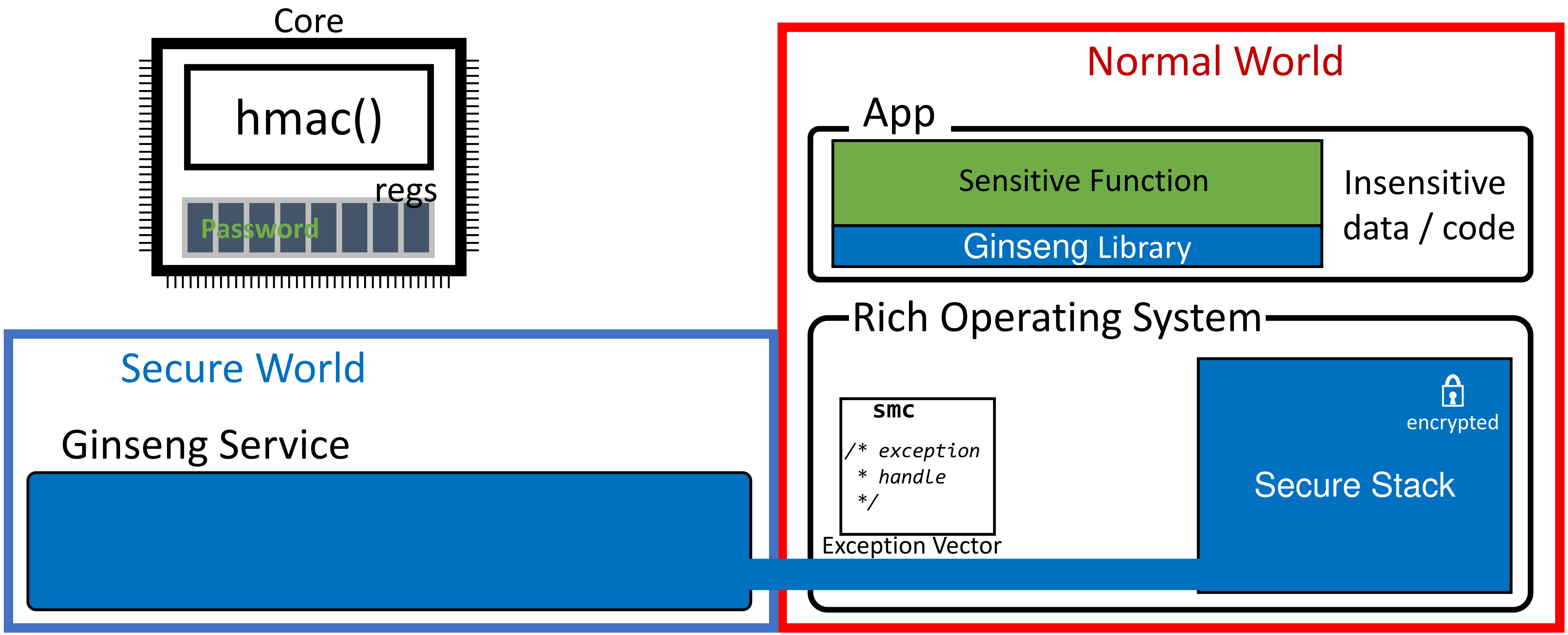
A simplified two-factor authenticator

An exception is handled by the kernel after sensitive registers are saved to secure stack



ELR: Exception Link Register

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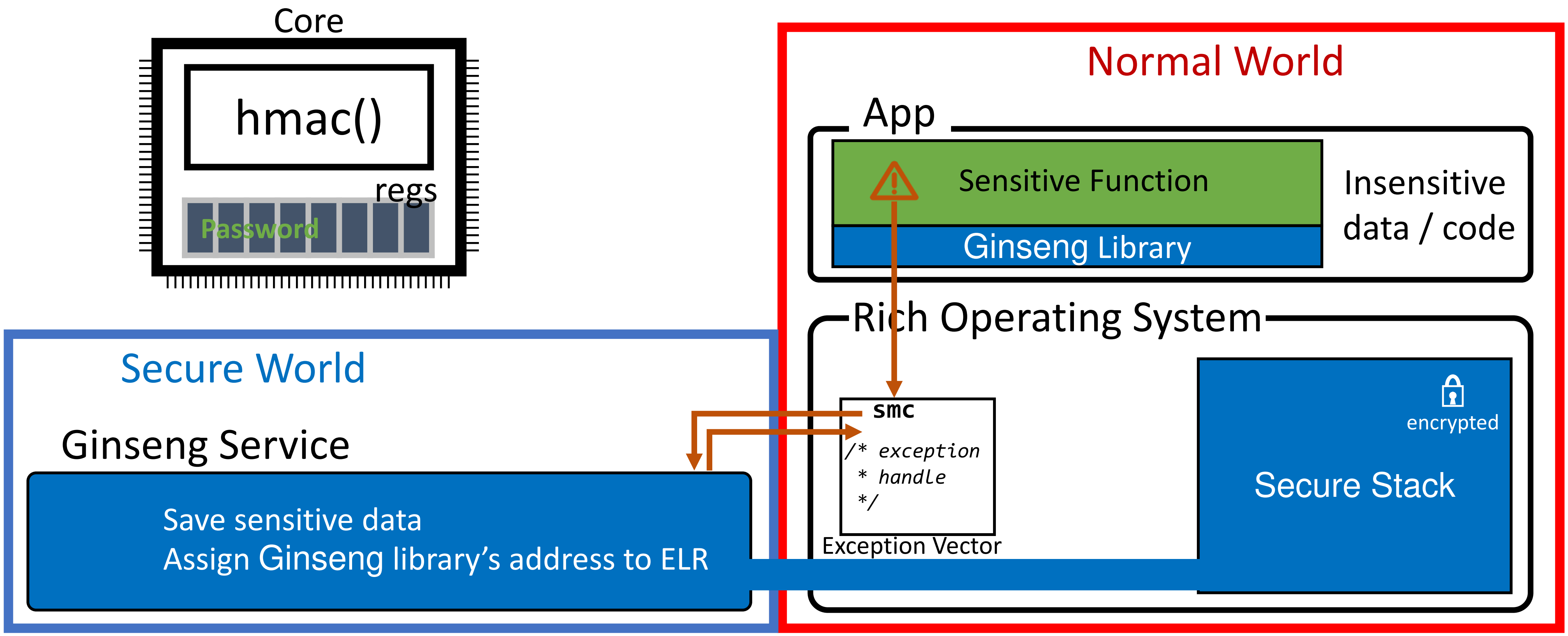

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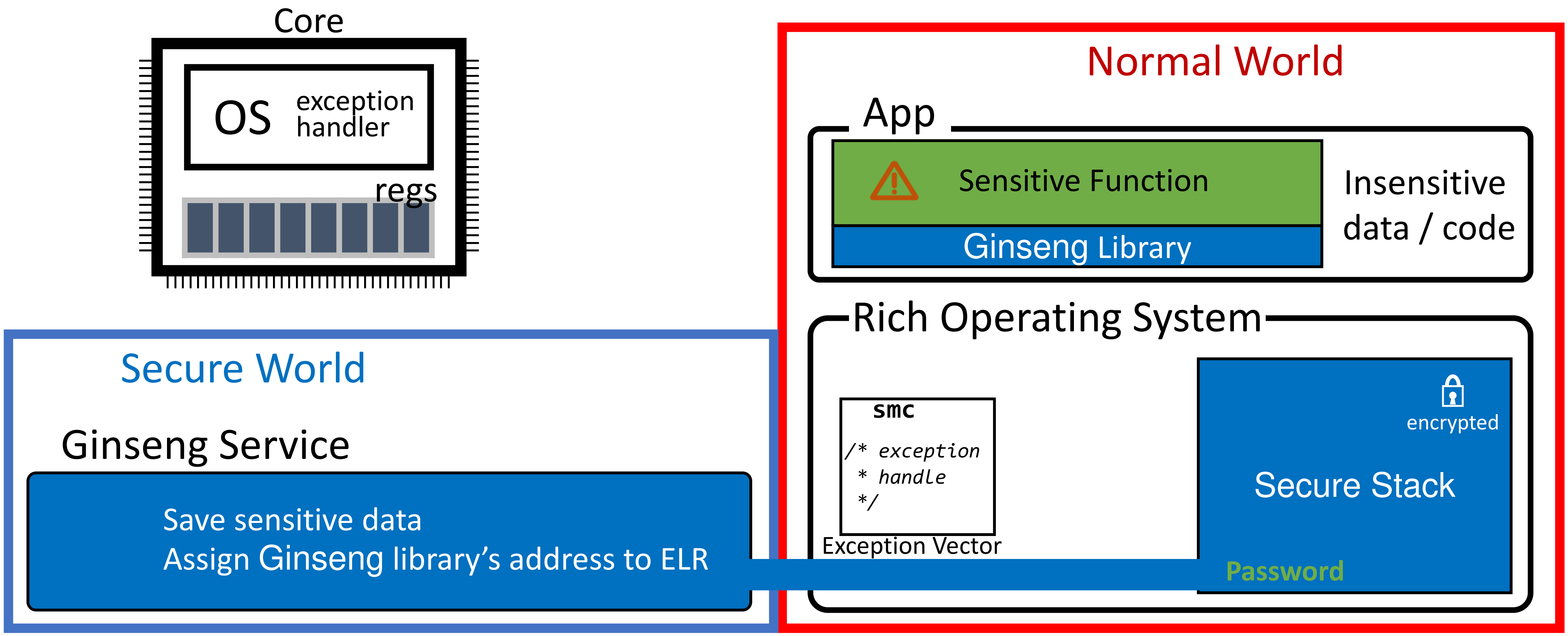
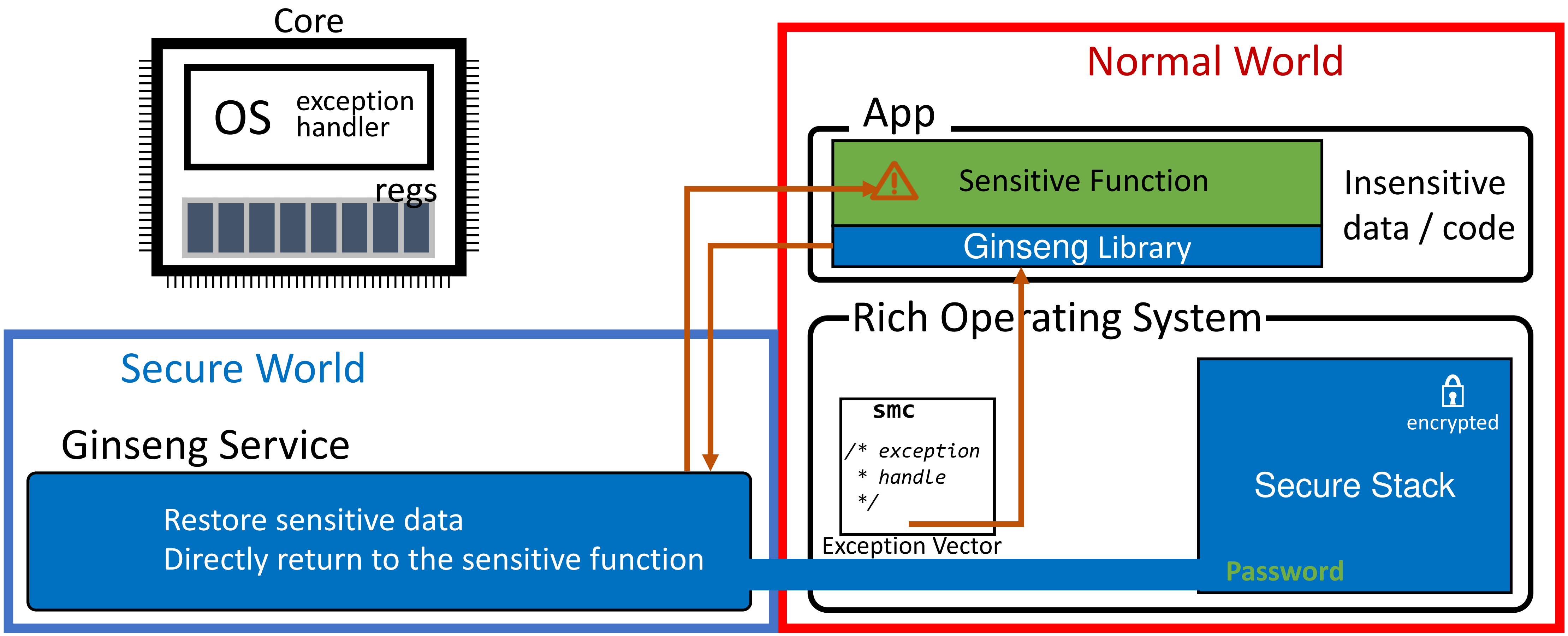


ELR: Exception Link Register

GService directly returns to the function



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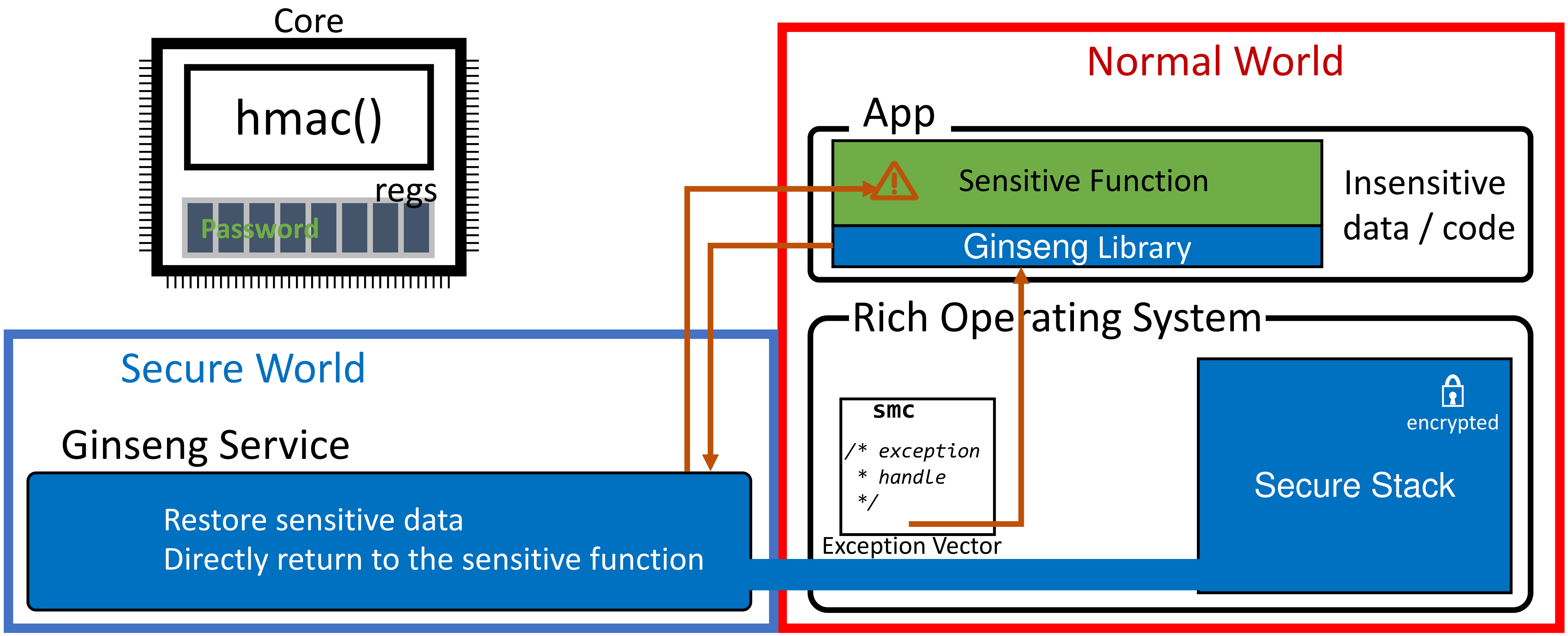
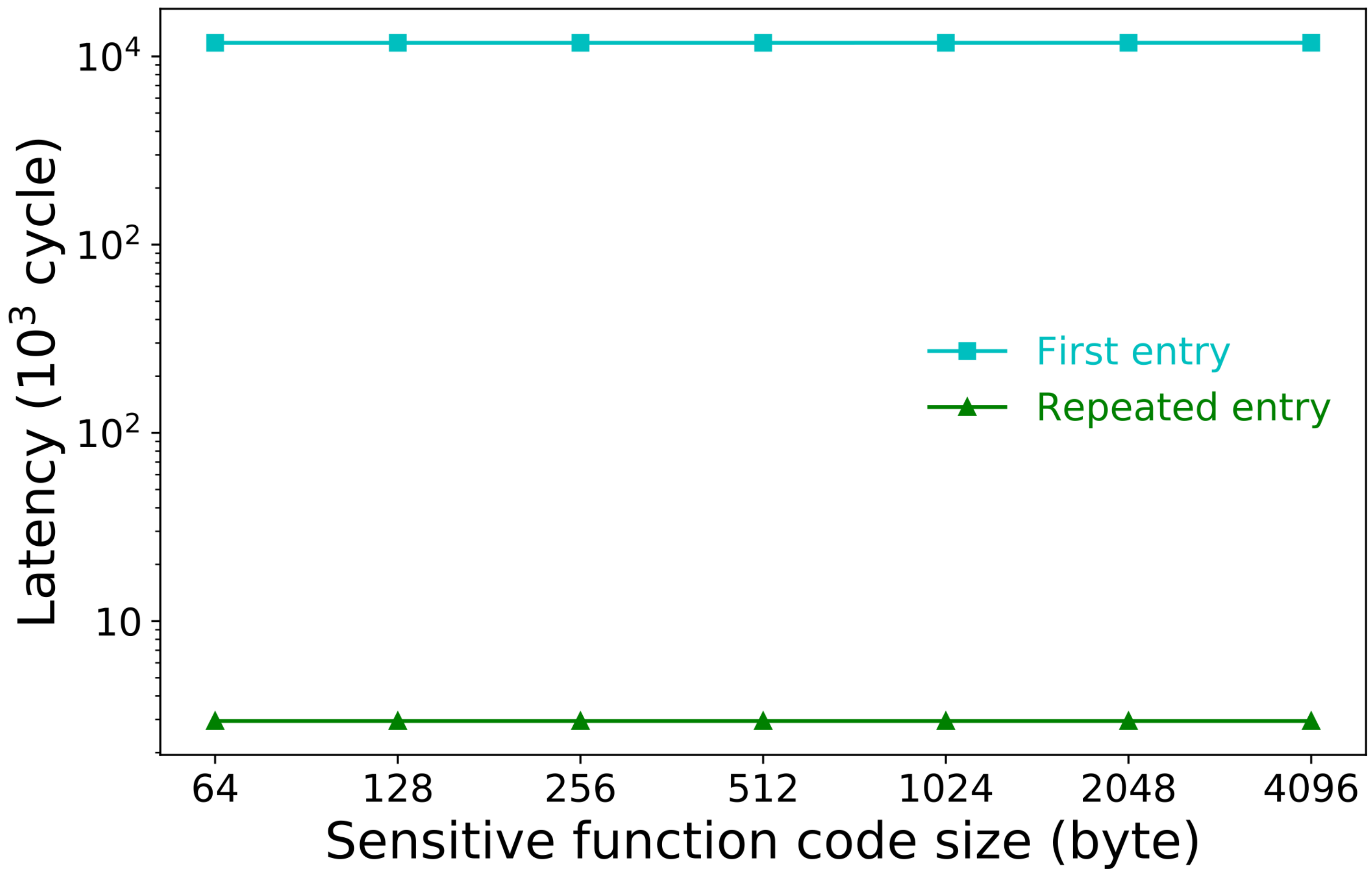


Microbenchmark: Overhead for code integrity



Kernels pagetable walk:
11 M cycles (≤ 10ms)

Onetime overhead per function

Re-enter a sensitive function:
3 K cycles