TZ-DATASHIELD: Automated Data Protection for Embedded Systems via Data-Flow-Based Compartmentalization

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Data Security of MCU

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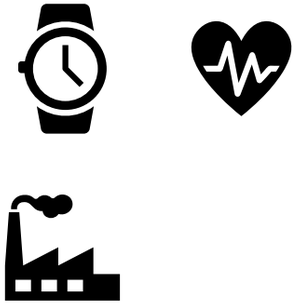

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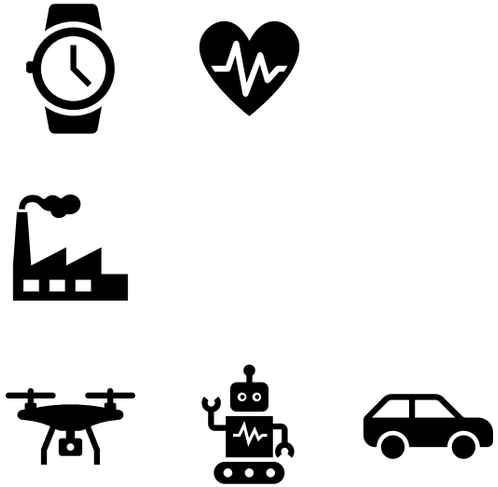

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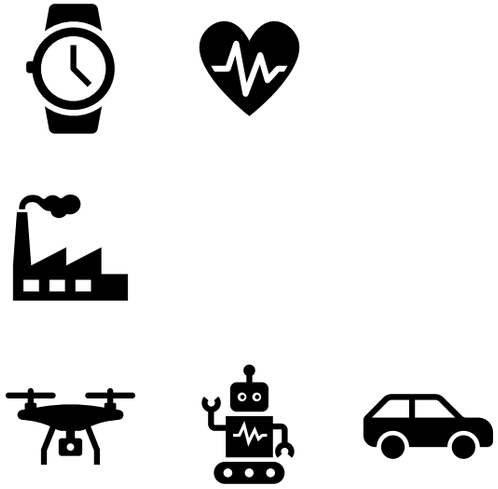

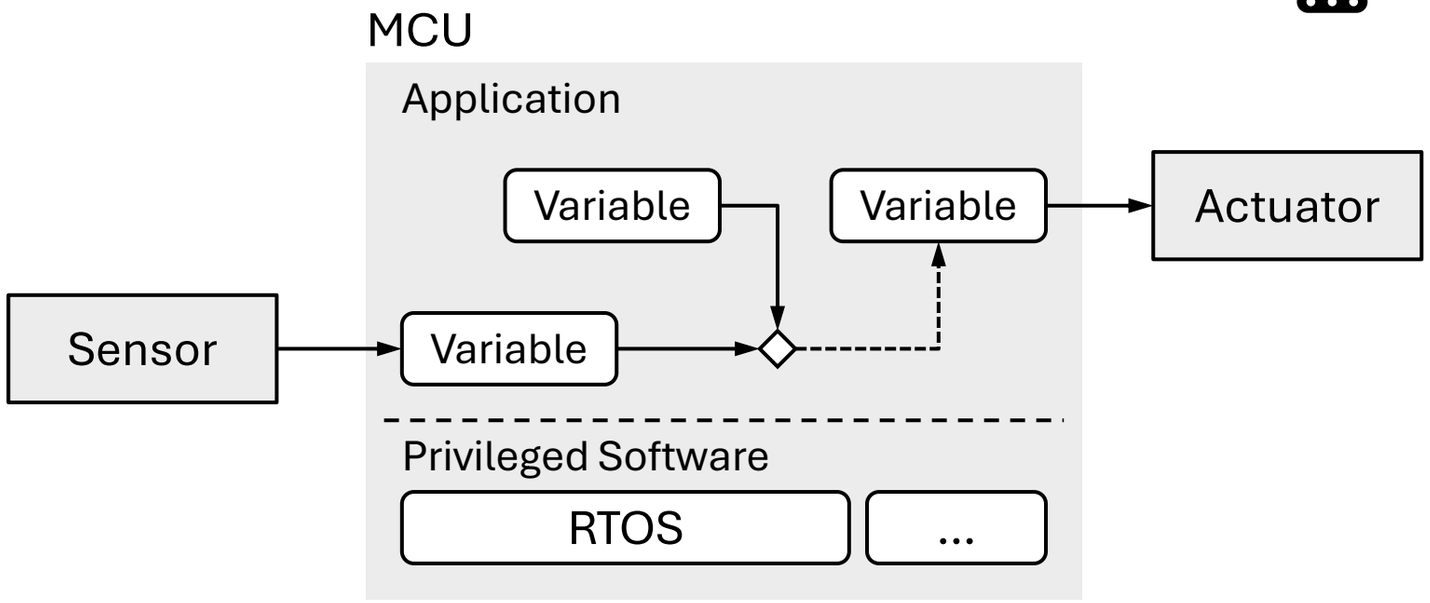

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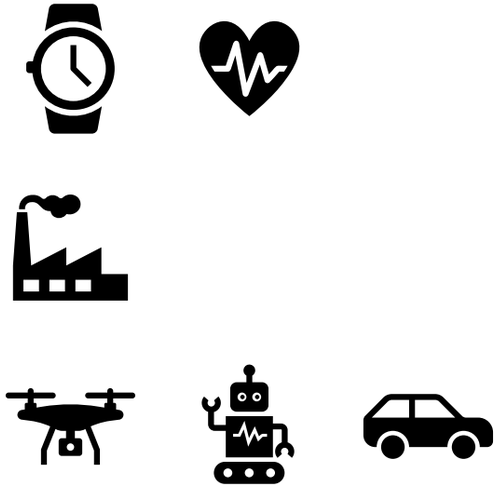

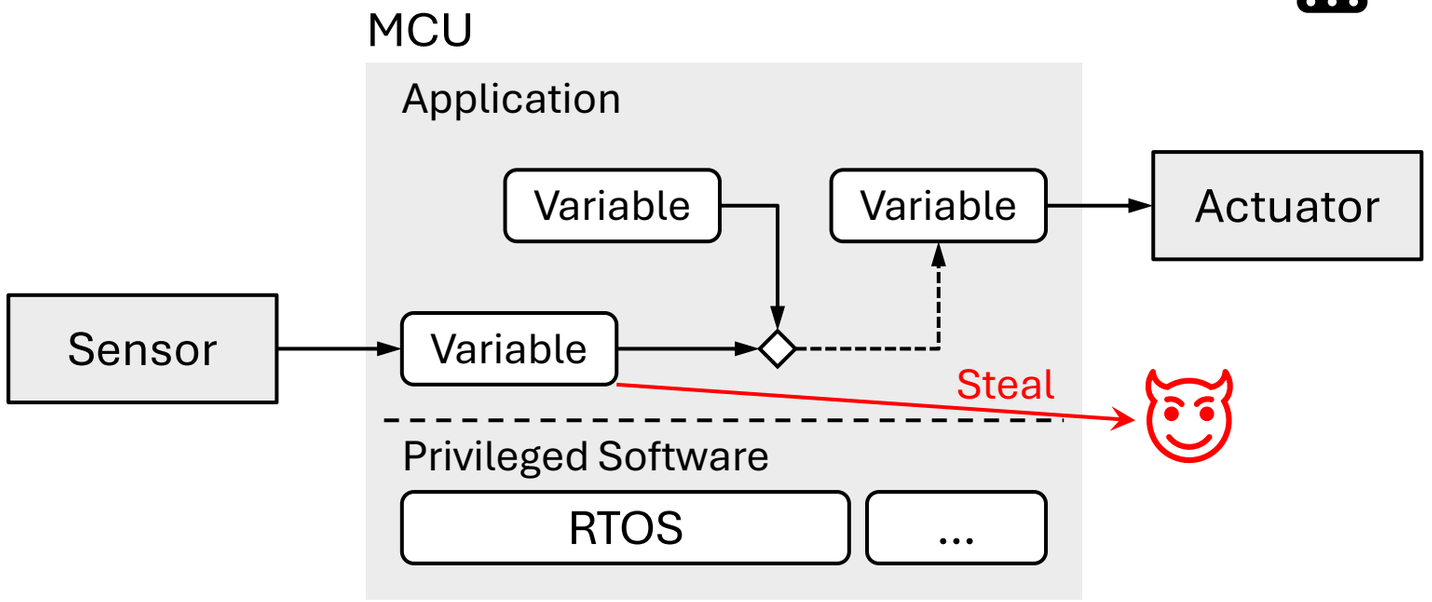

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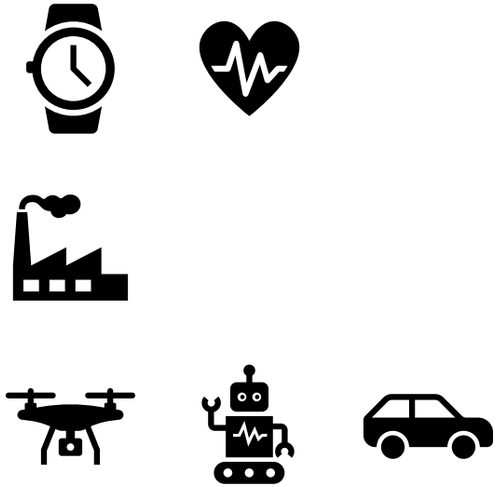

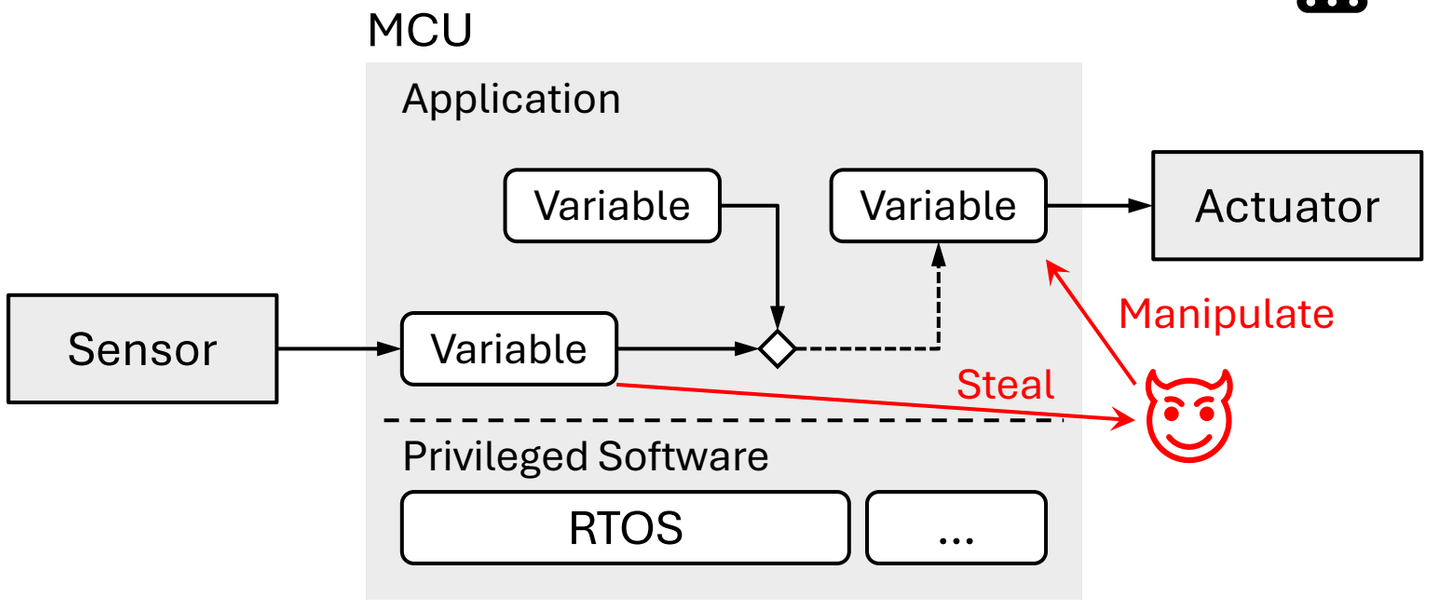

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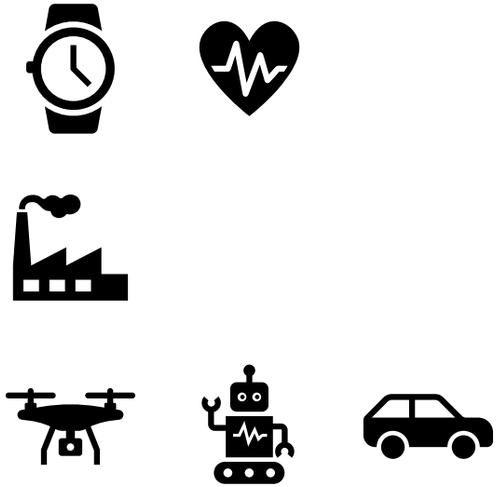
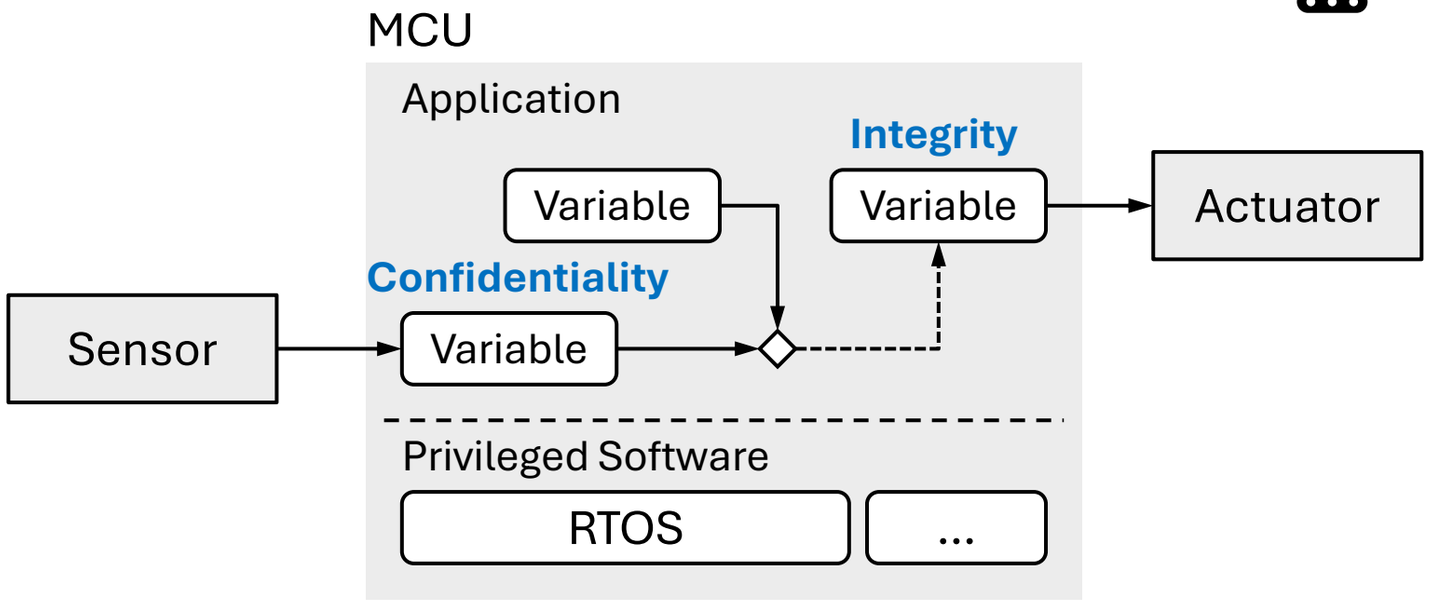
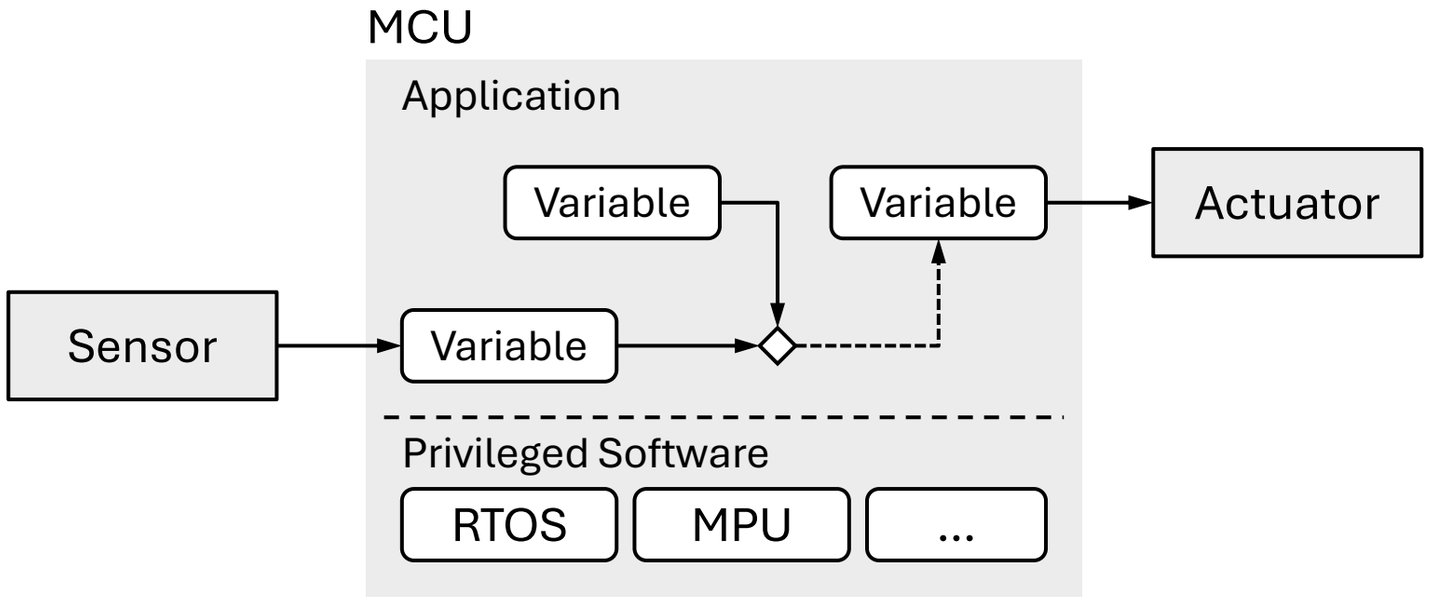




Protection against Strong Adversaries



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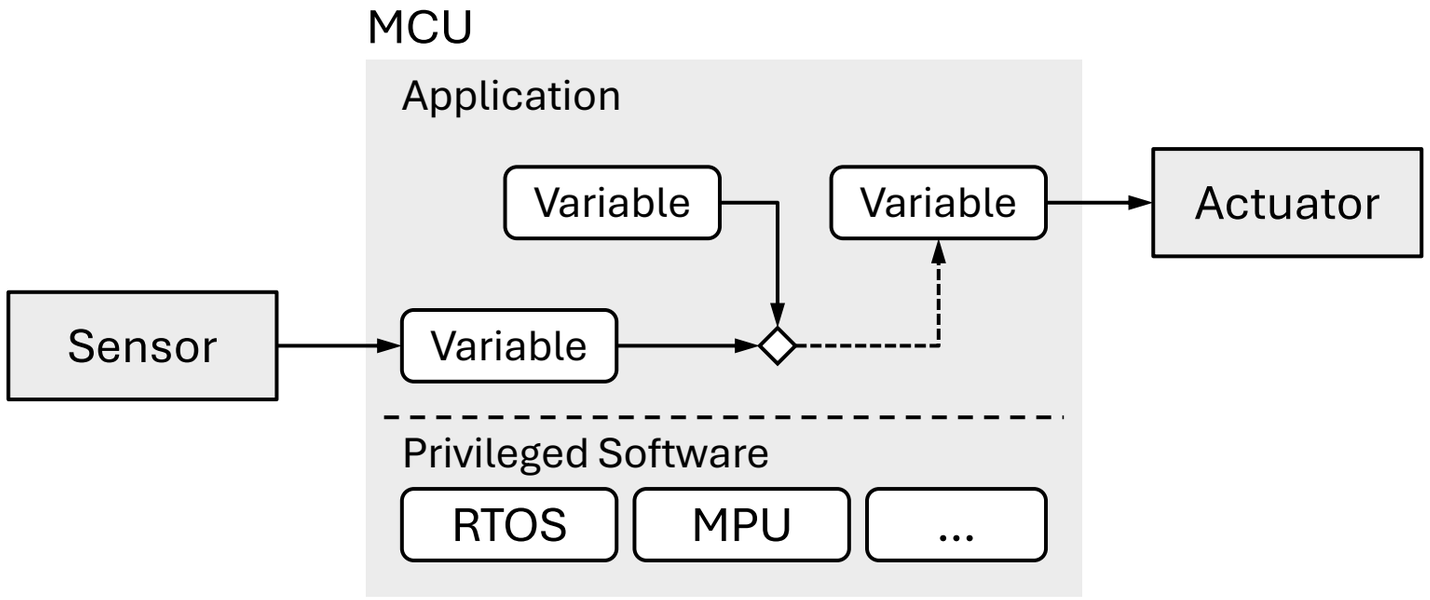

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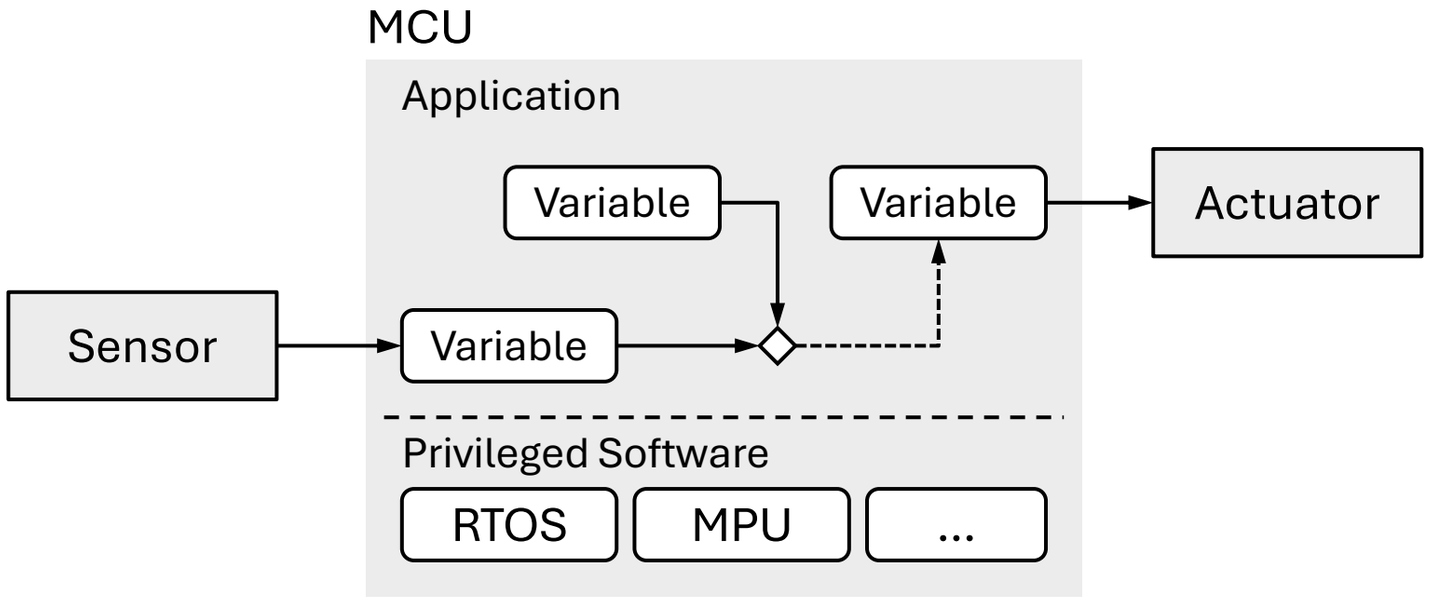

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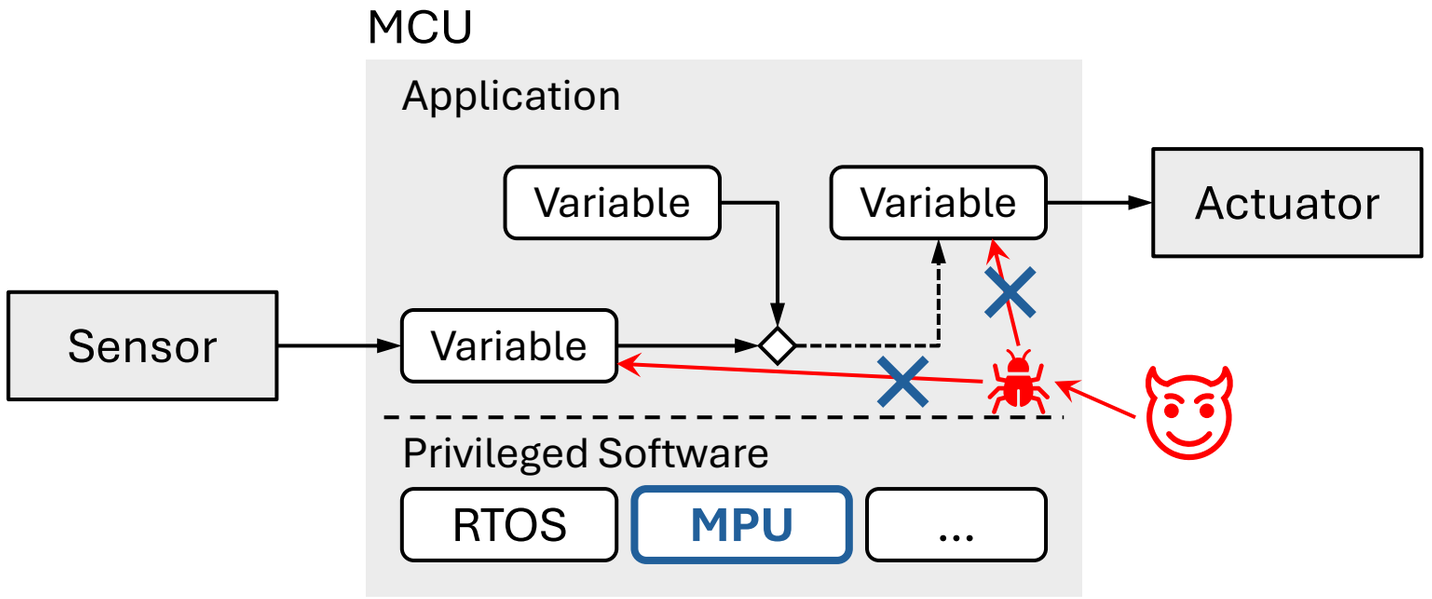

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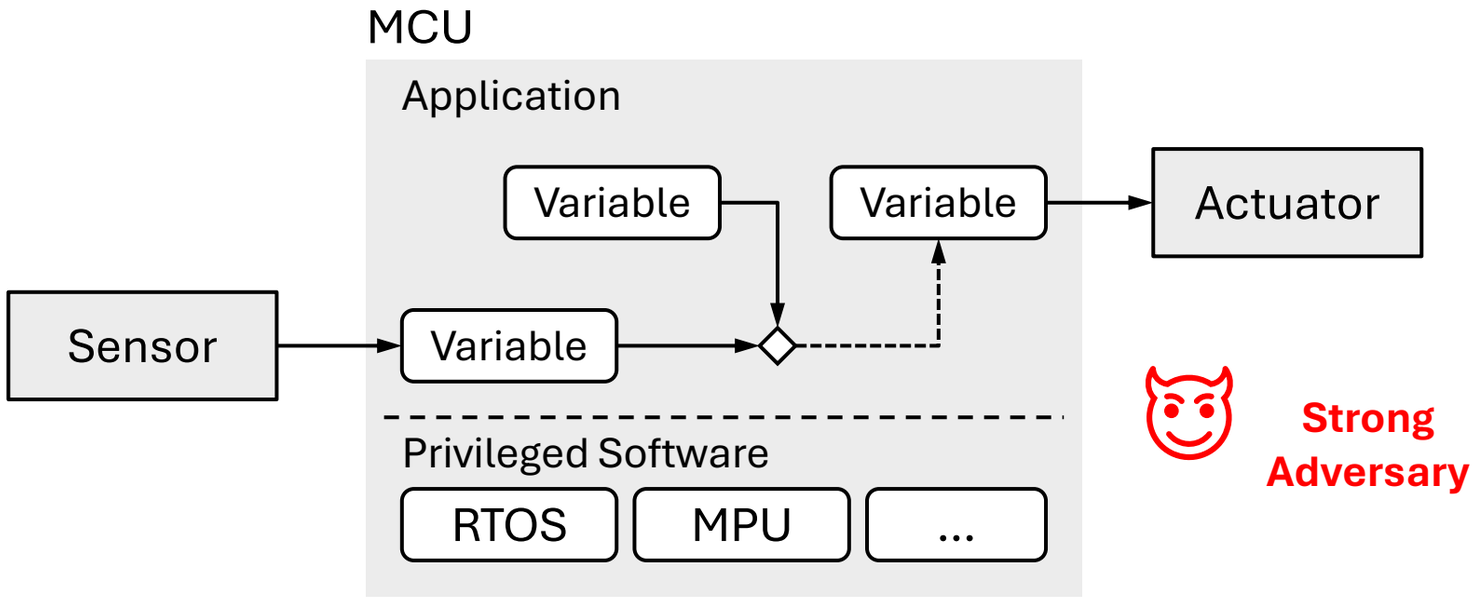

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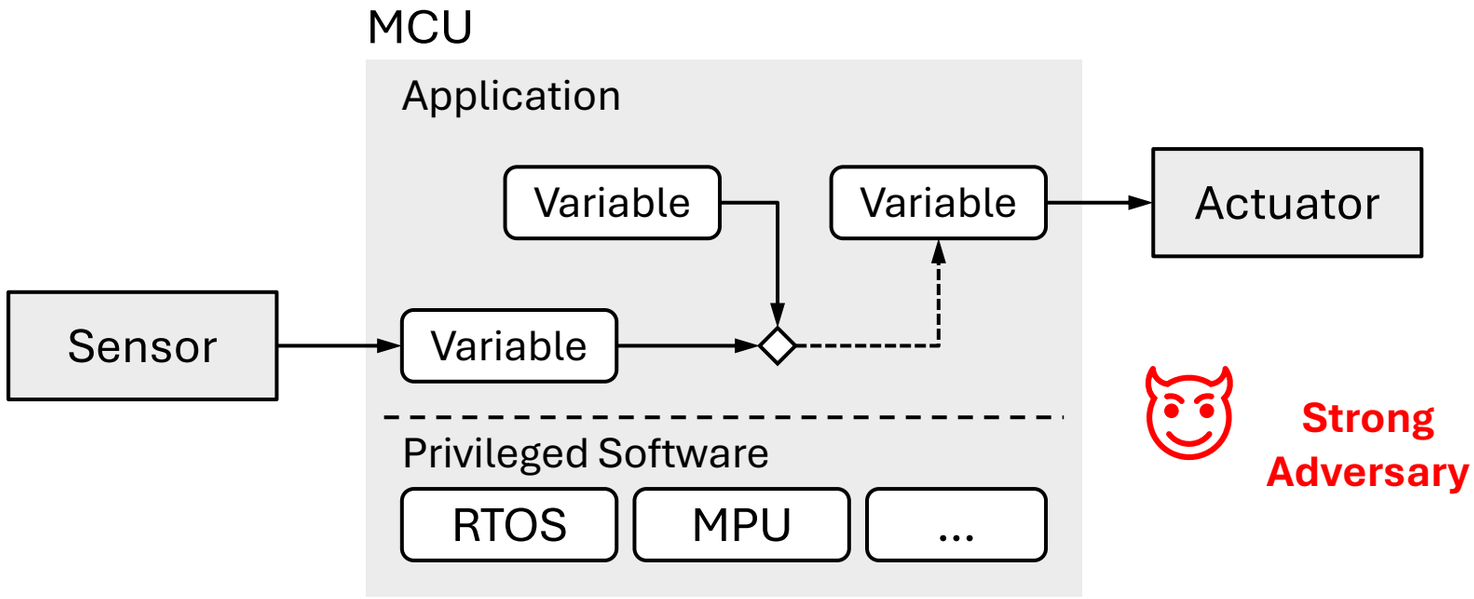

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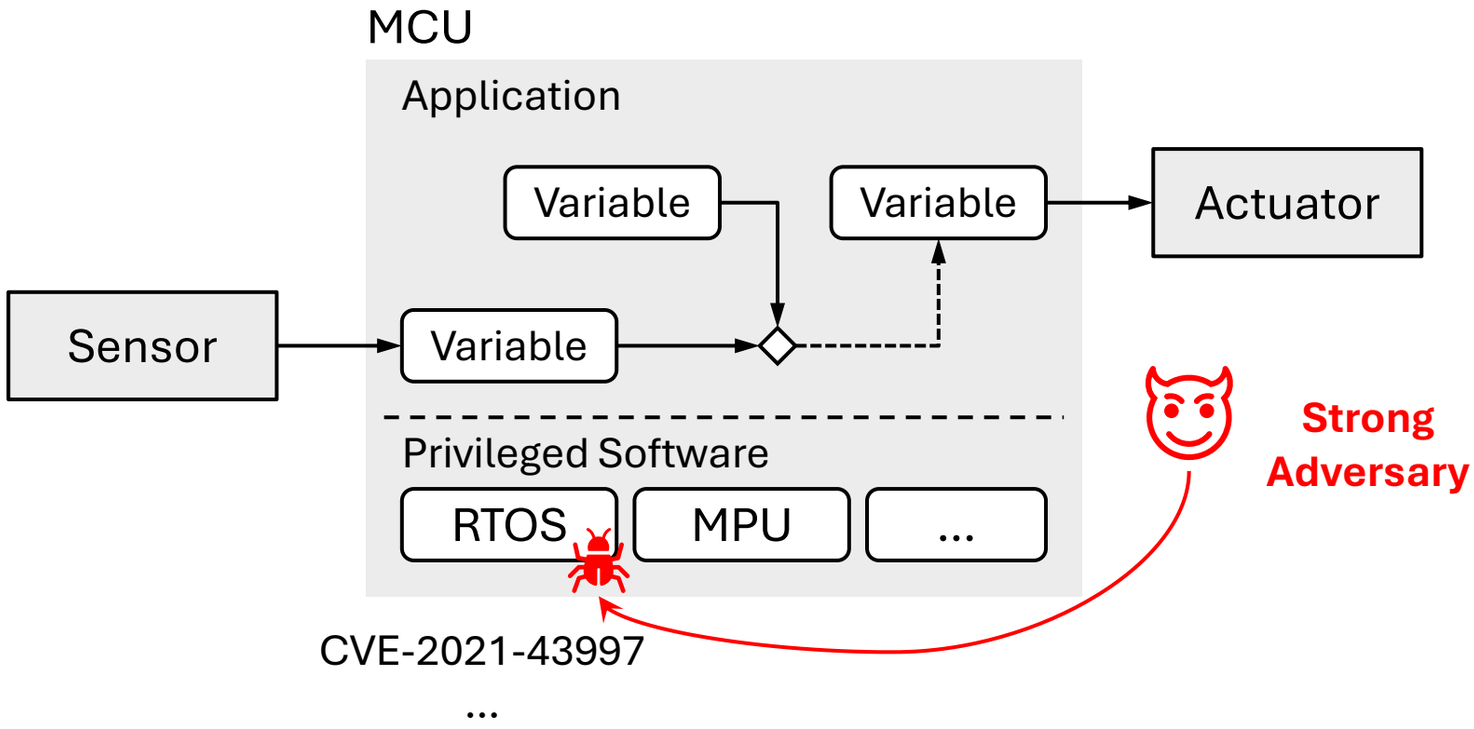

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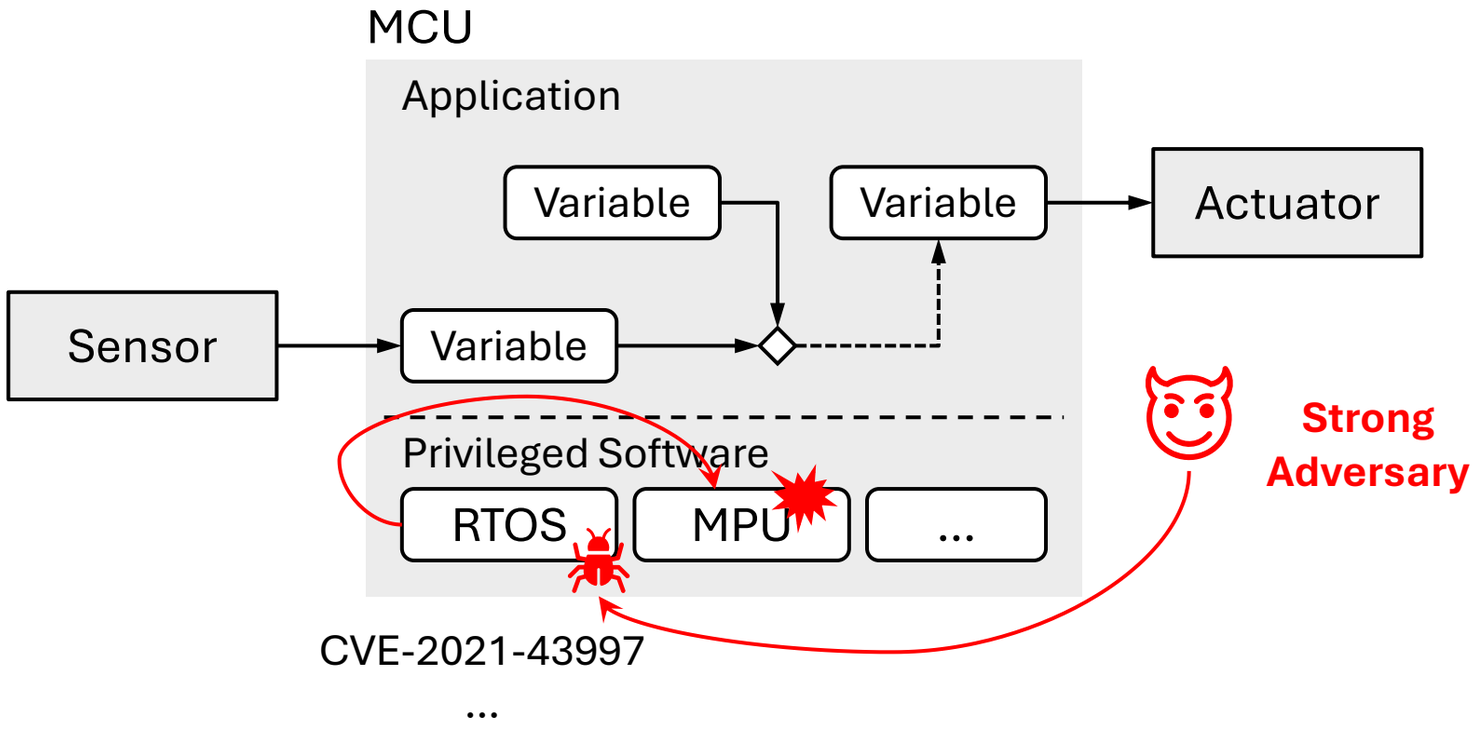

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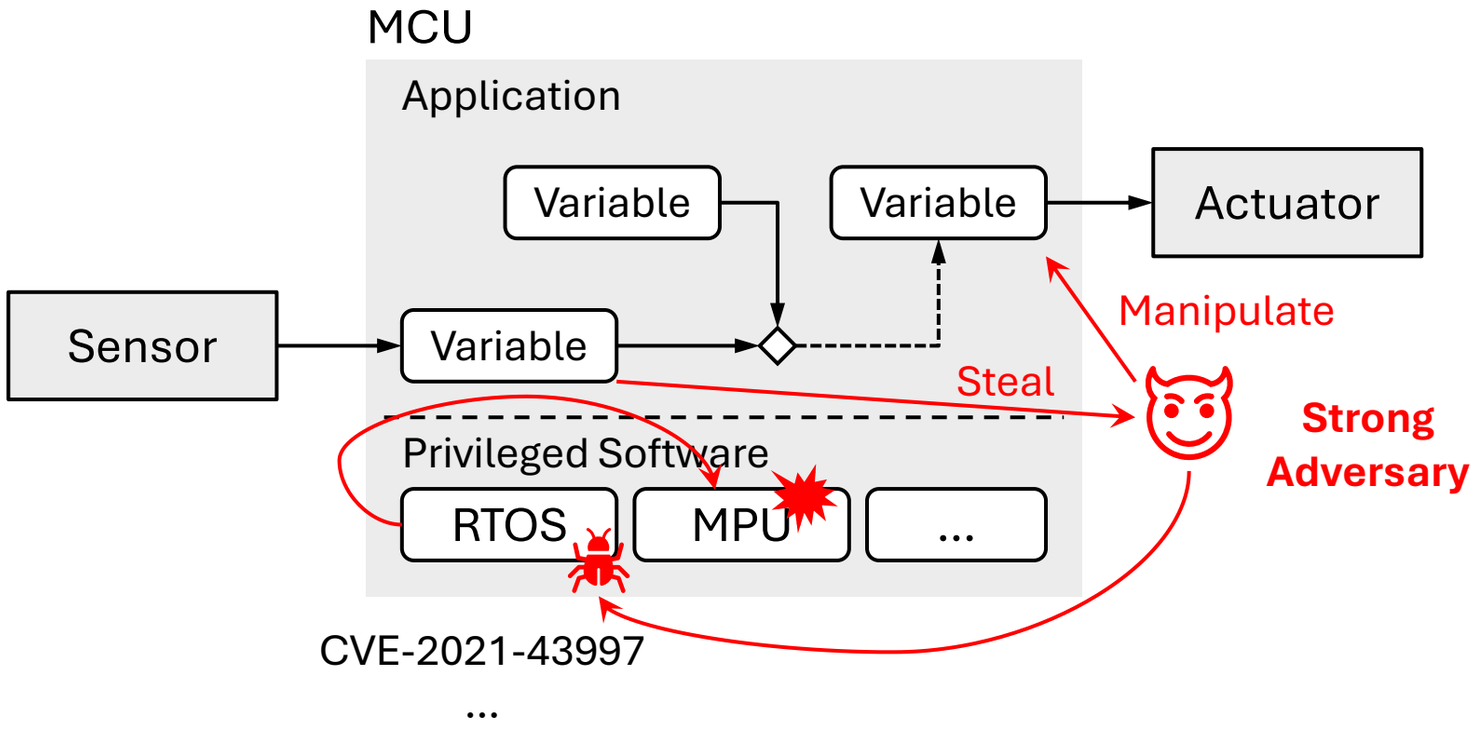

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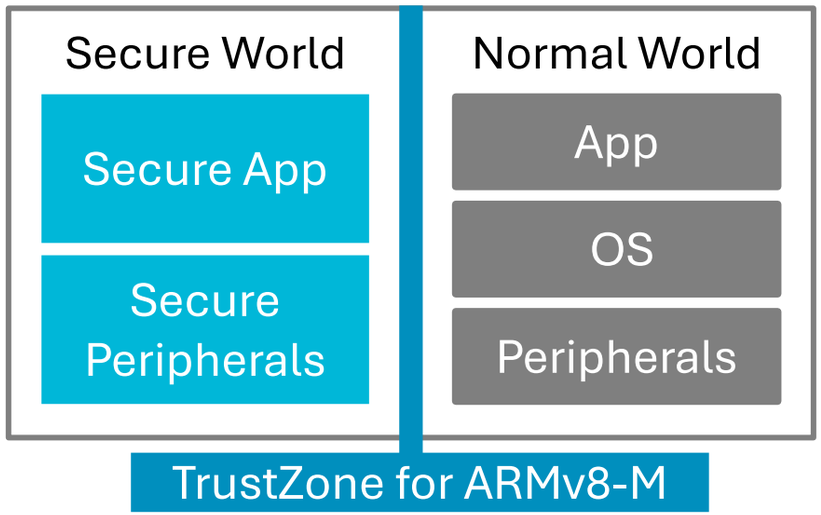

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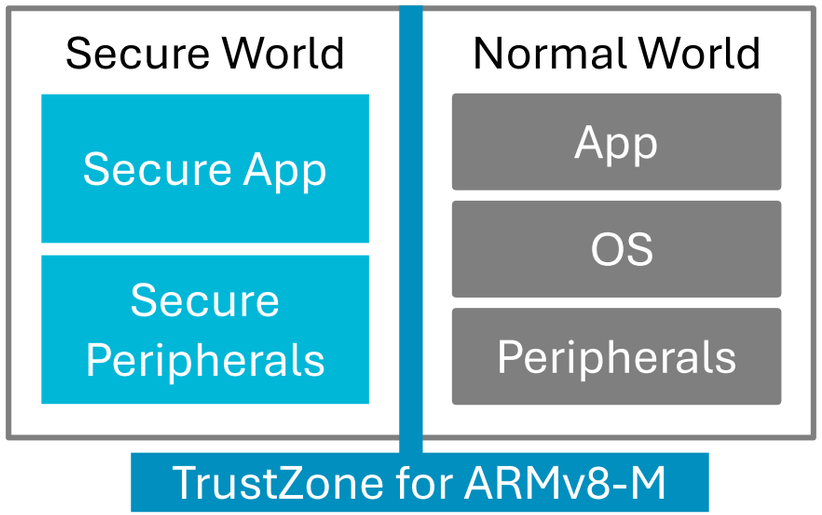
- The secure world of ARM TrustZone for MCU provides a Trusted Execution Environment



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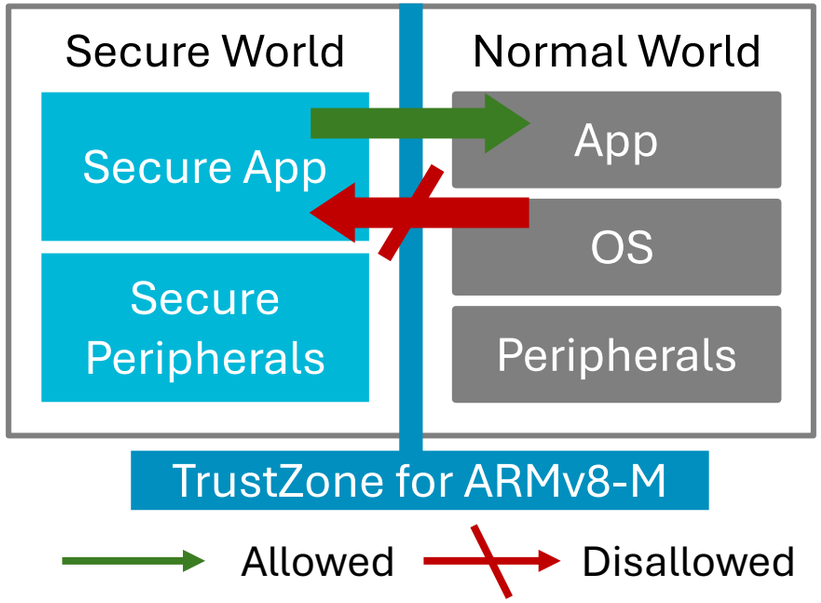
ARM TrustZone

- The secure world of ARM TrustZone for MCU provides a Trusted Execution Environment
- Protect against strong adversaries in normal world



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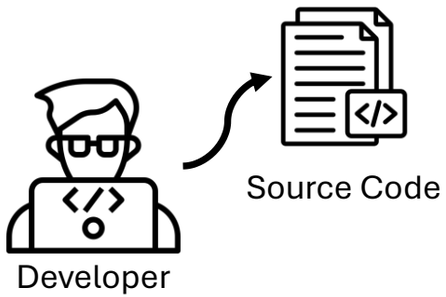

Code Annotation

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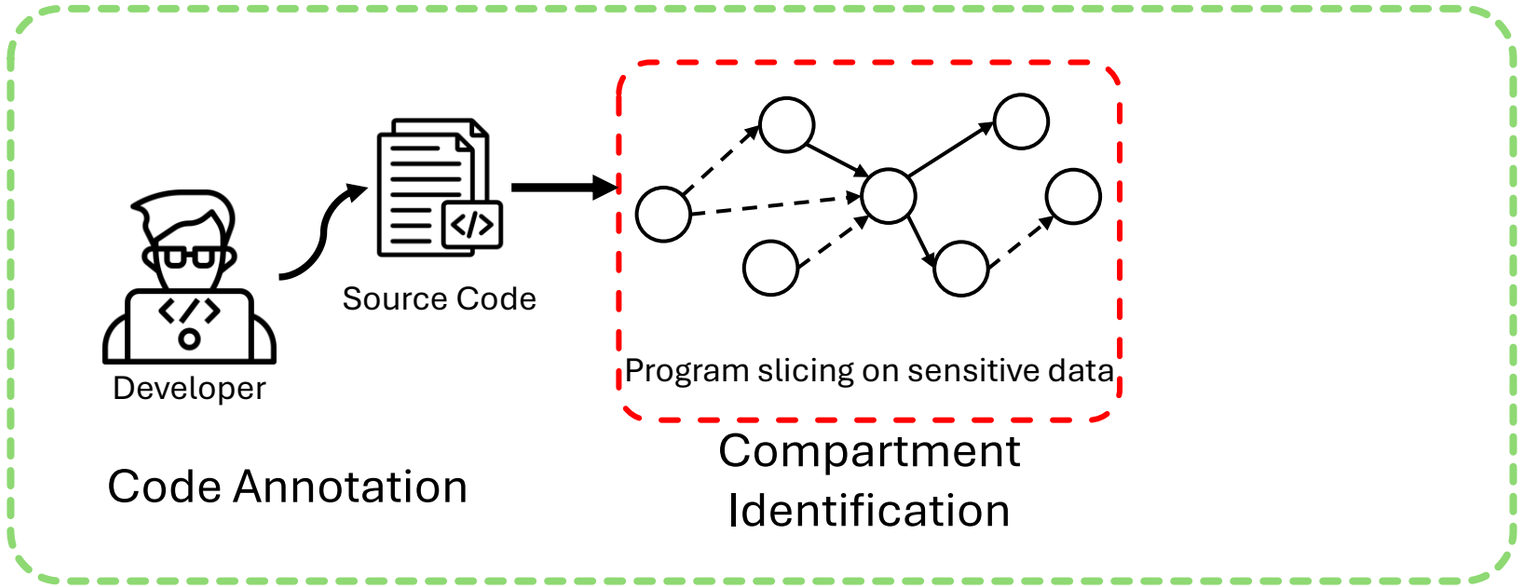
- Identify compartments based on data flow of sensitive data



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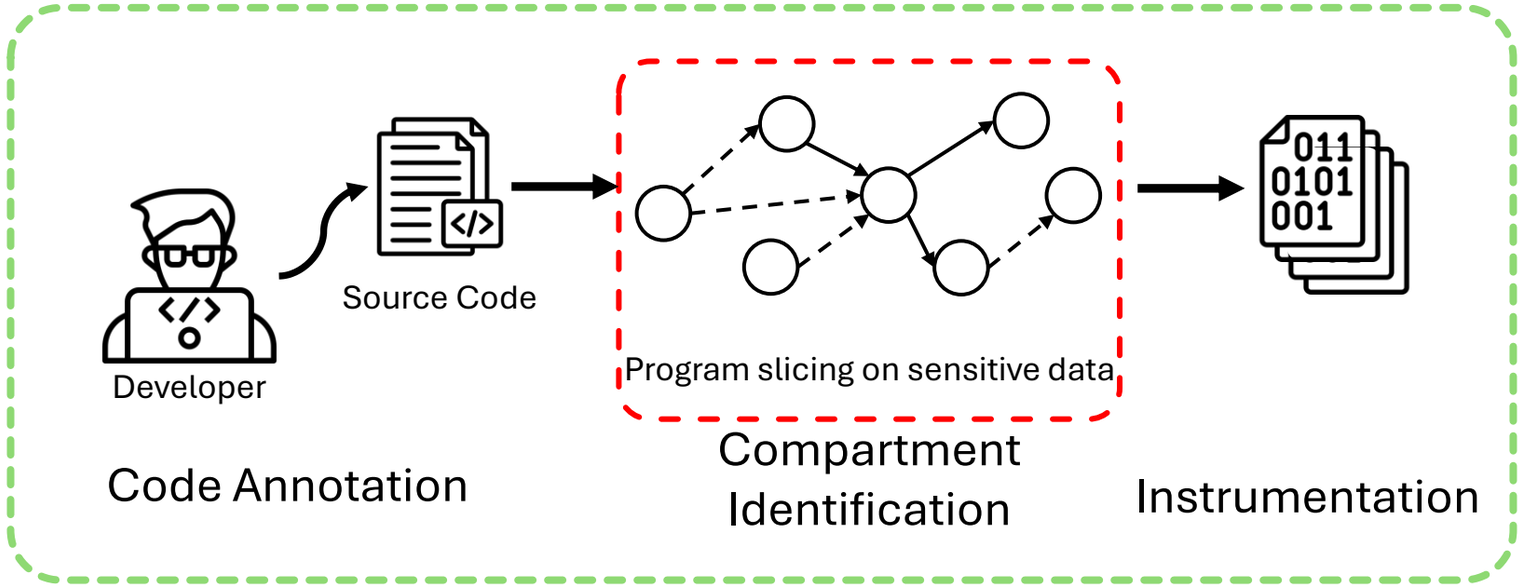

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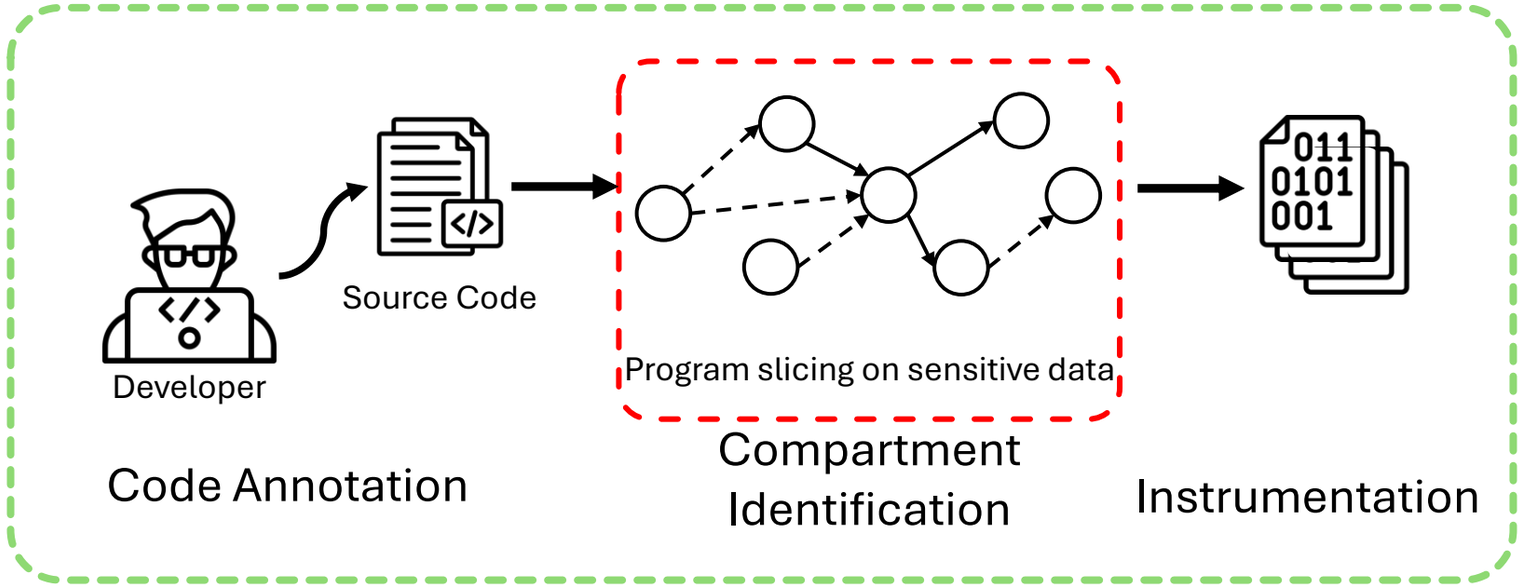

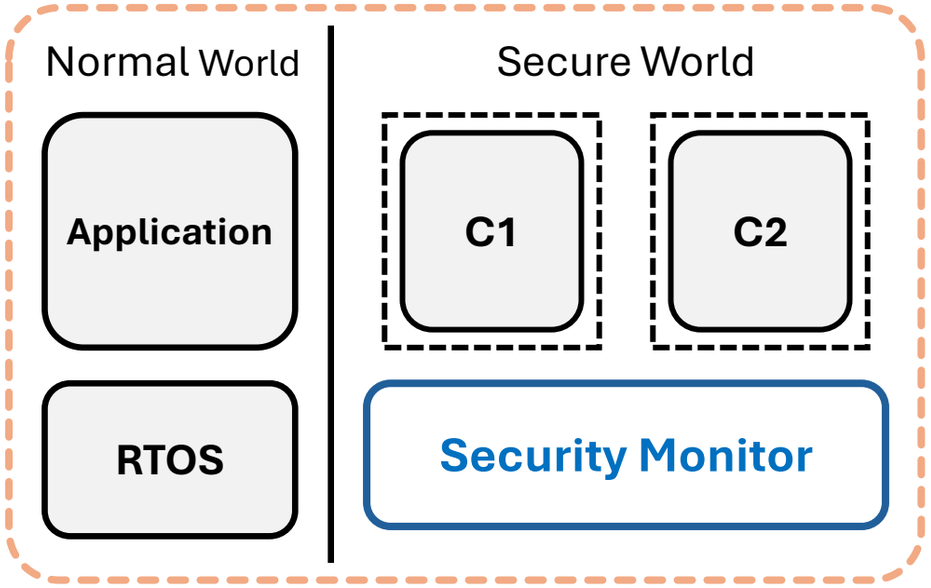

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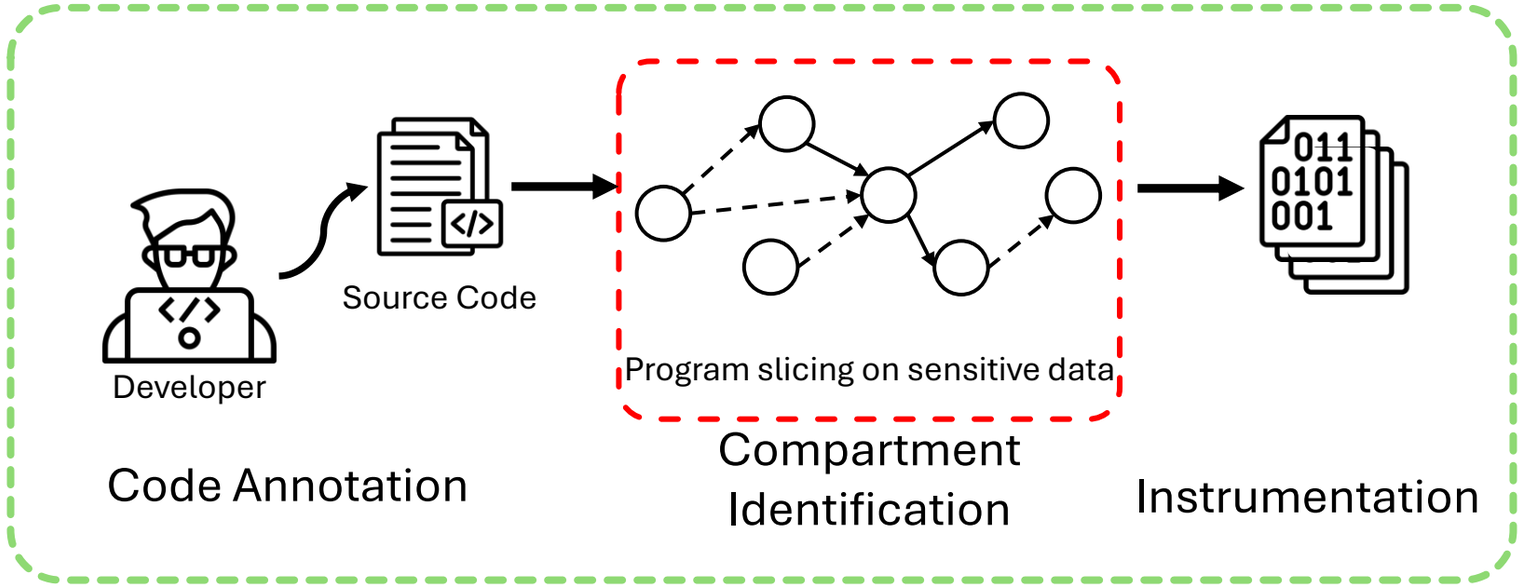

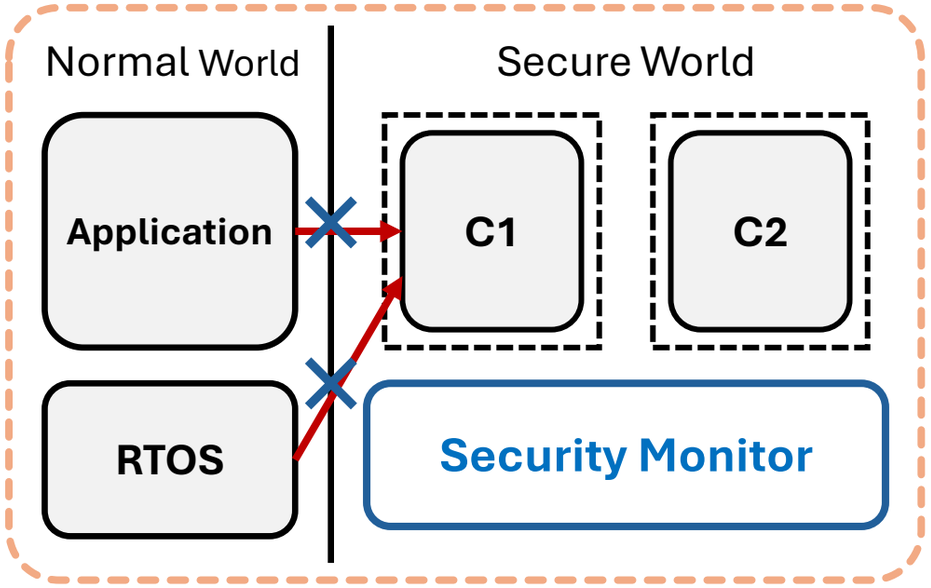

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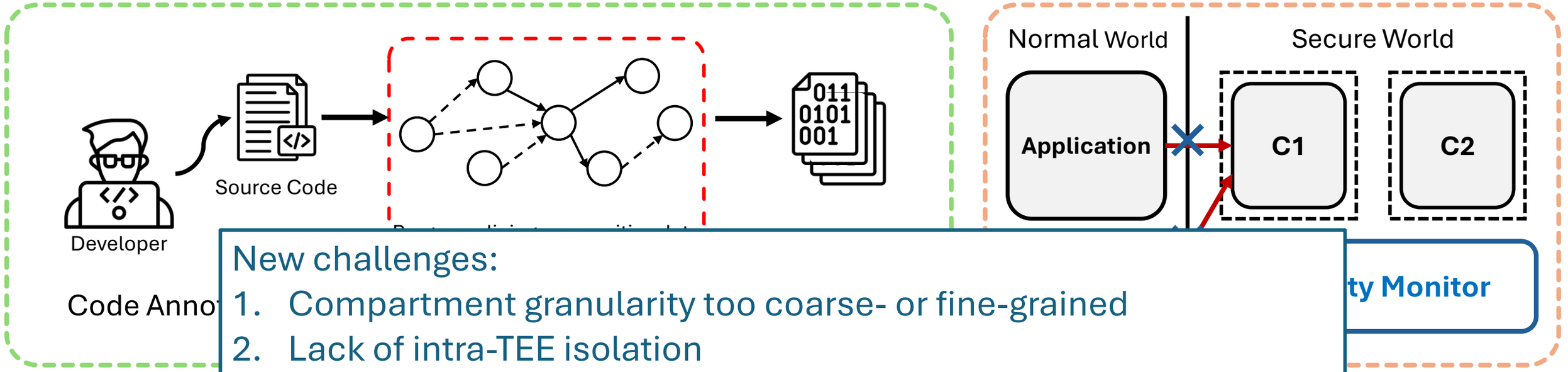

New challenges:

1. Compartment granularity too coarse- or fine-grained
2. Lack of intra-TEE isolation
3. Protection on shared data/peripheral between compartments

Challenge 1: Compartment Granularity

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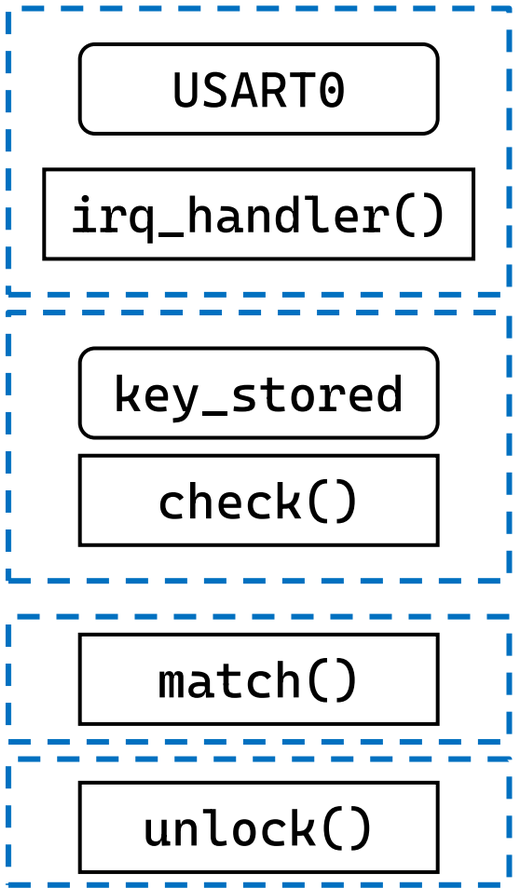

Fine-grained Compartment

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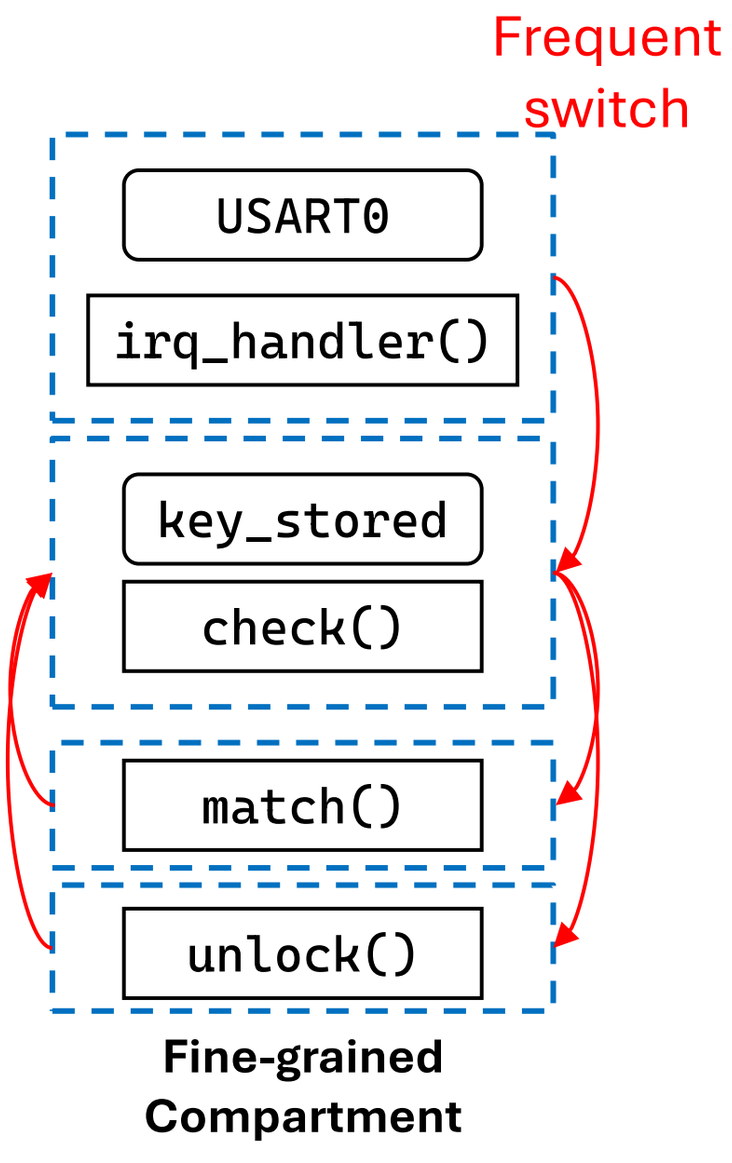

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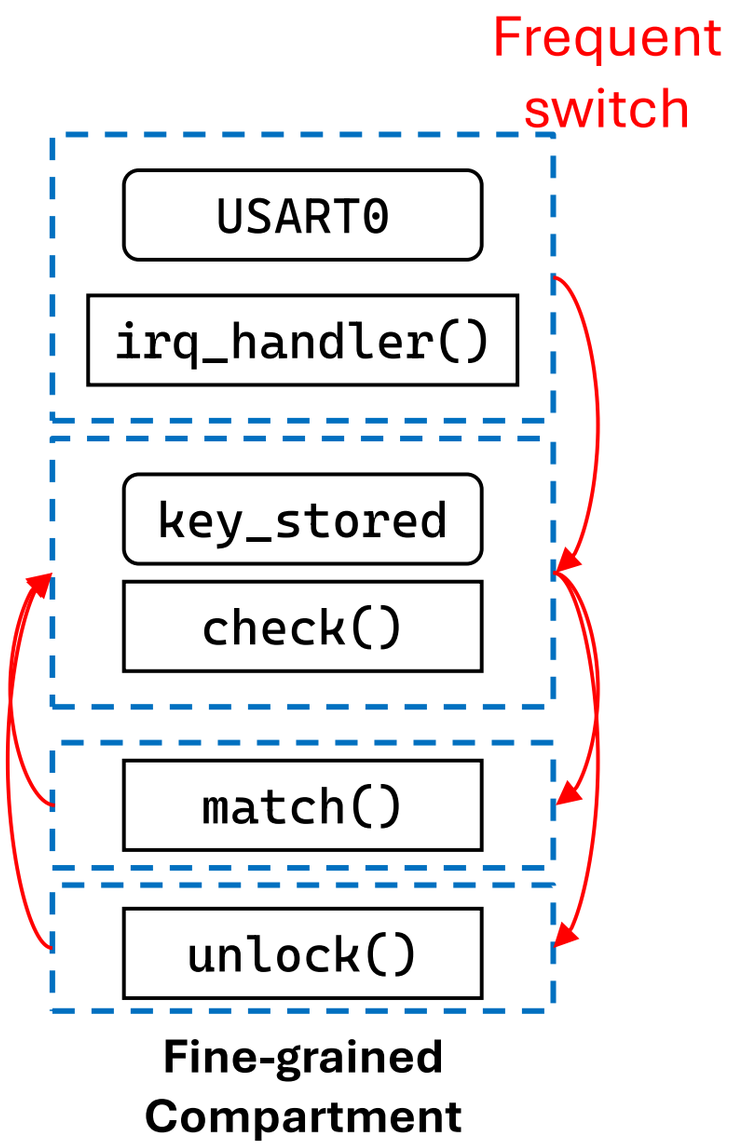

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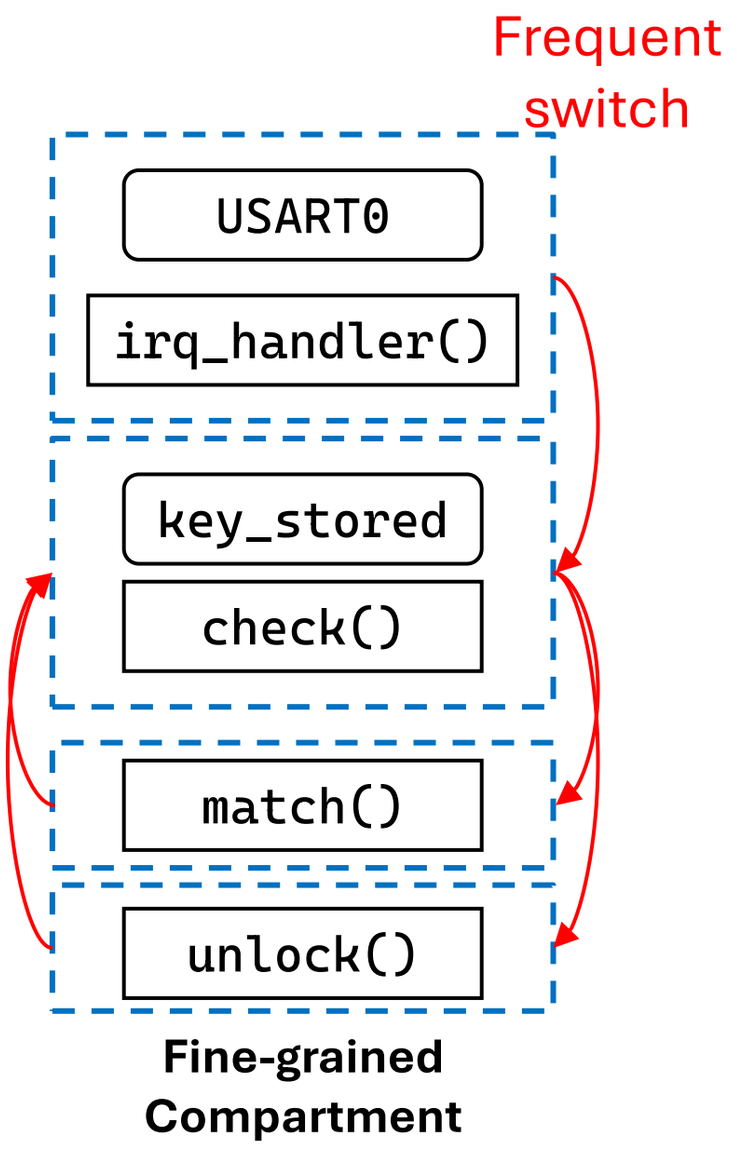

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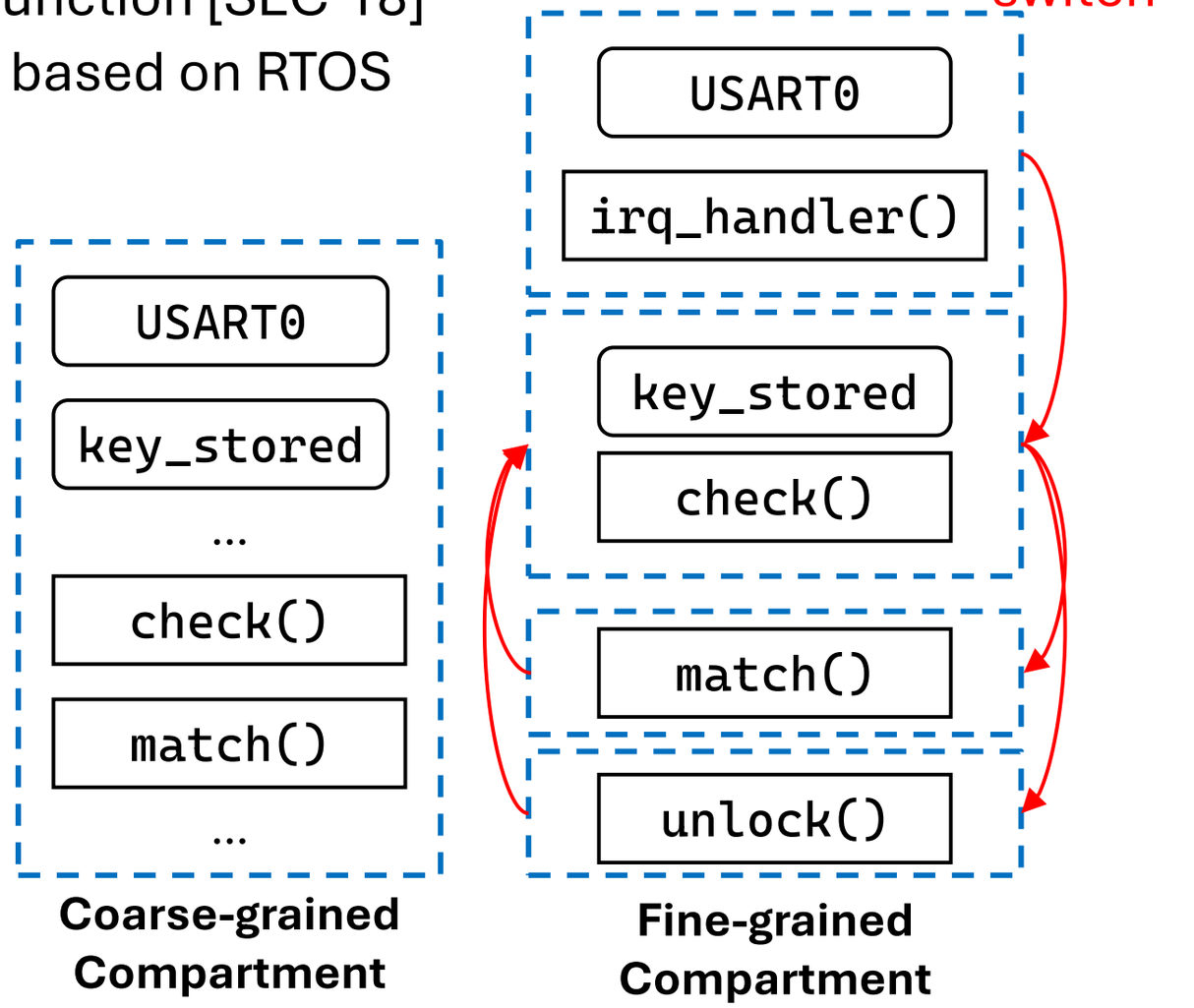

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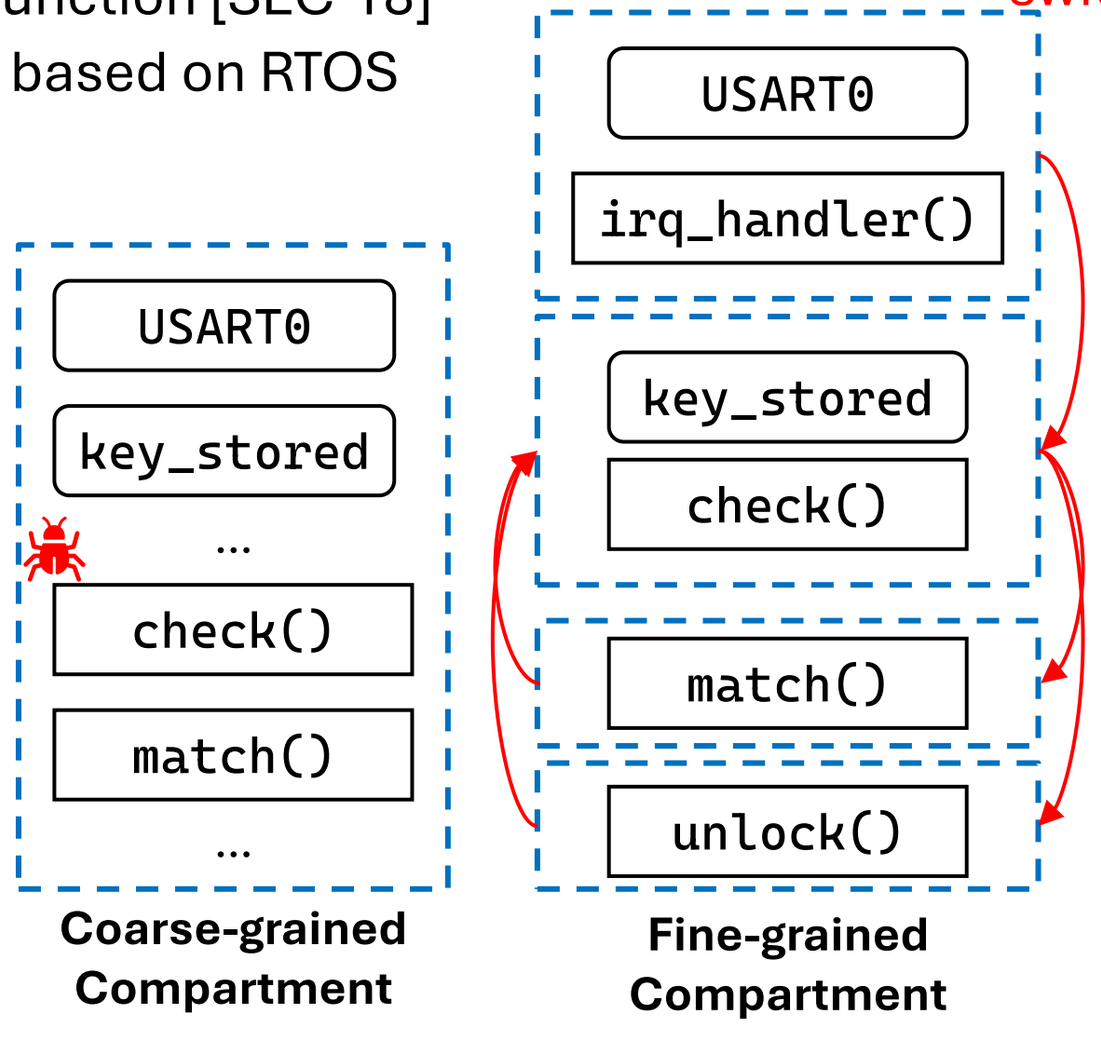

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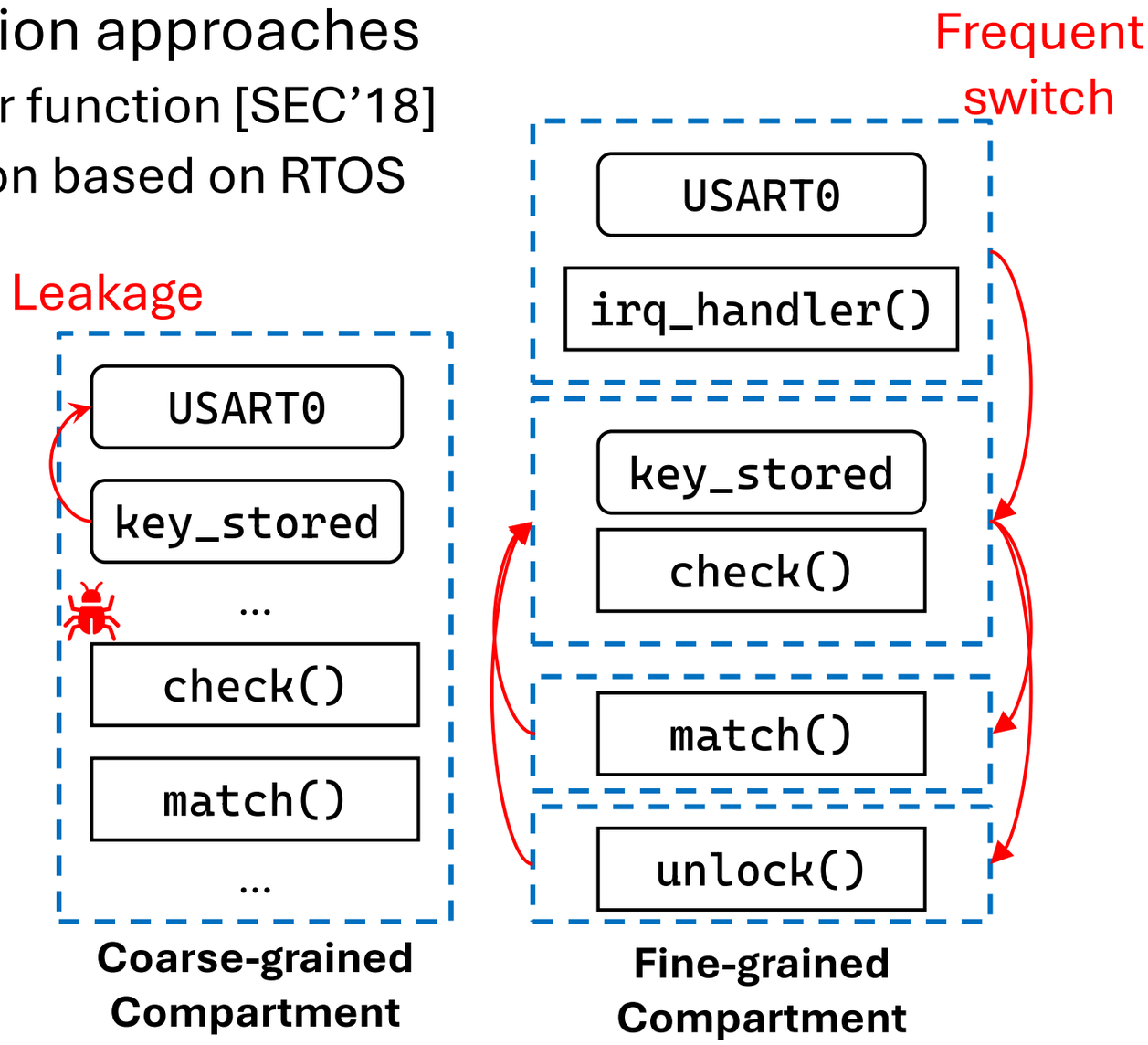

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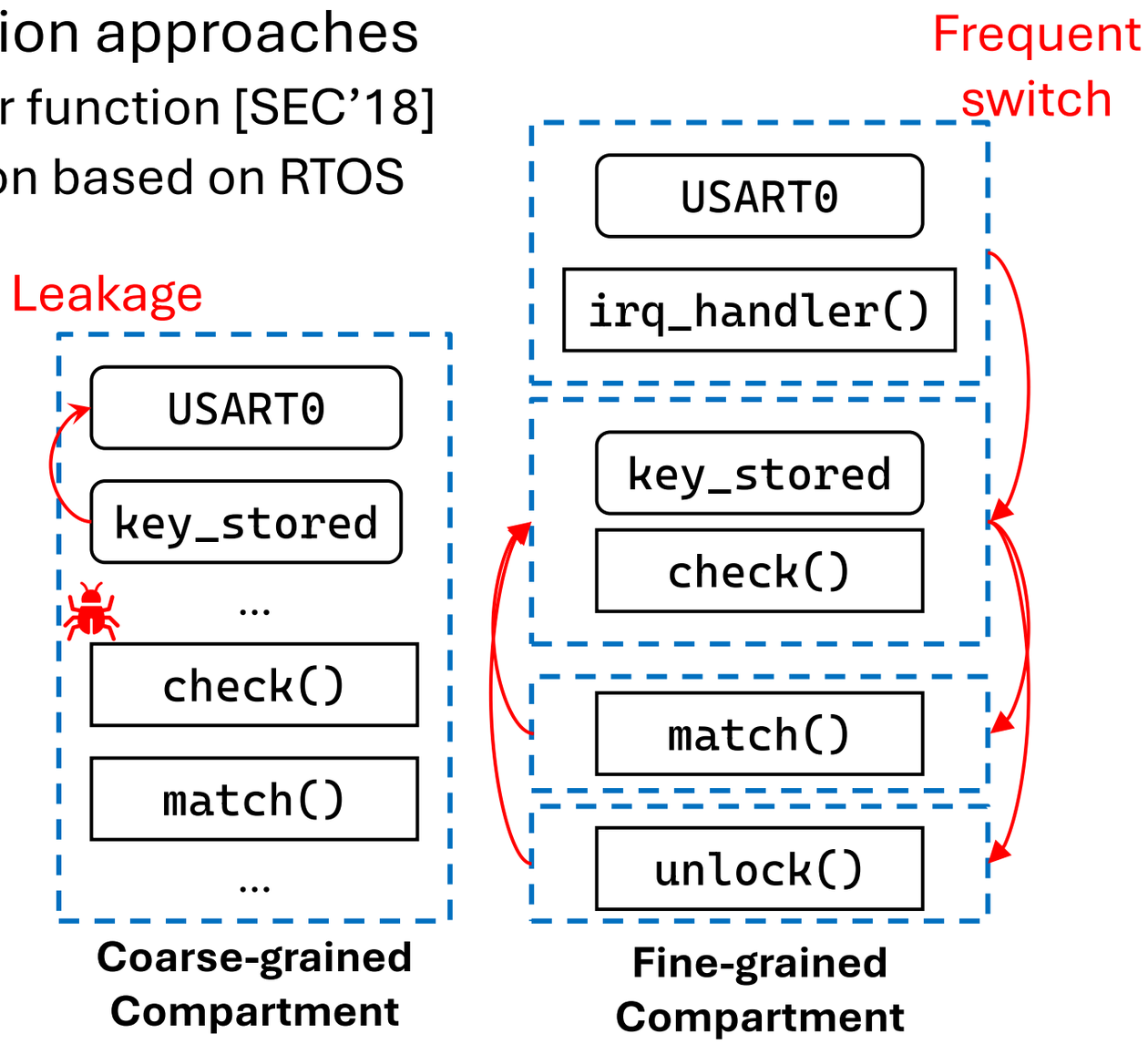

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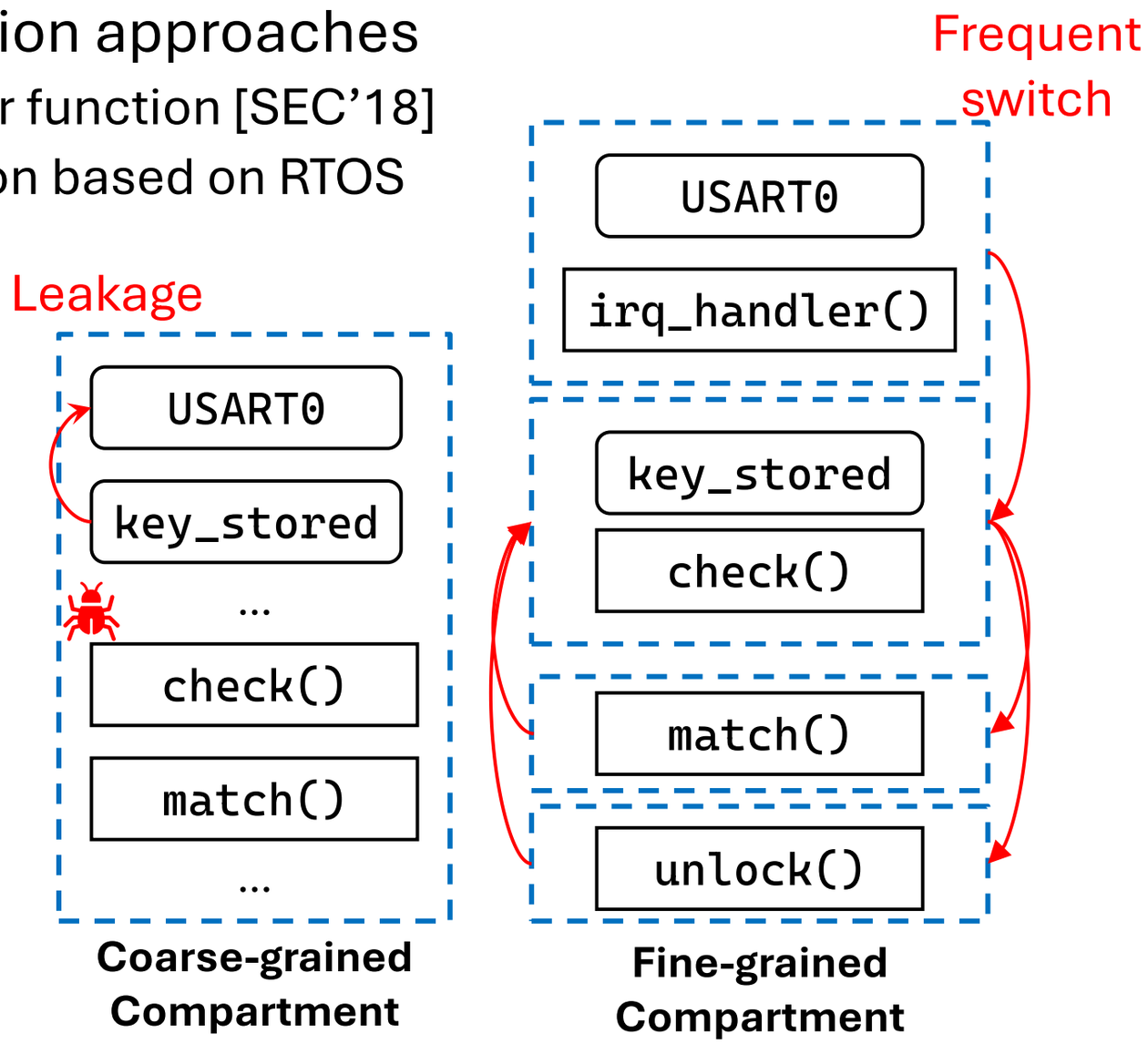

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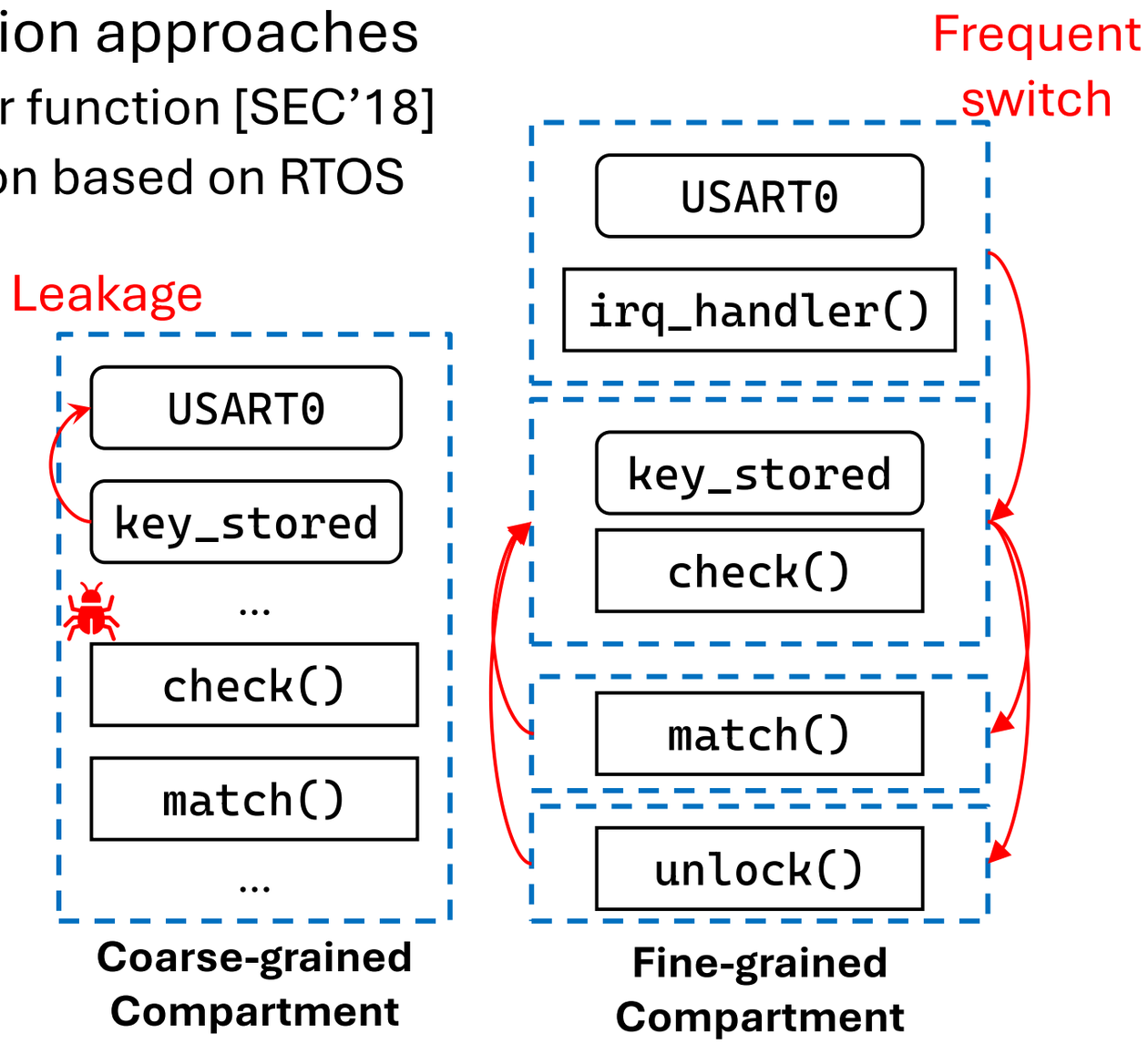
Our solution: **Sensitive Data Flow** (SDF) Compartmentalization



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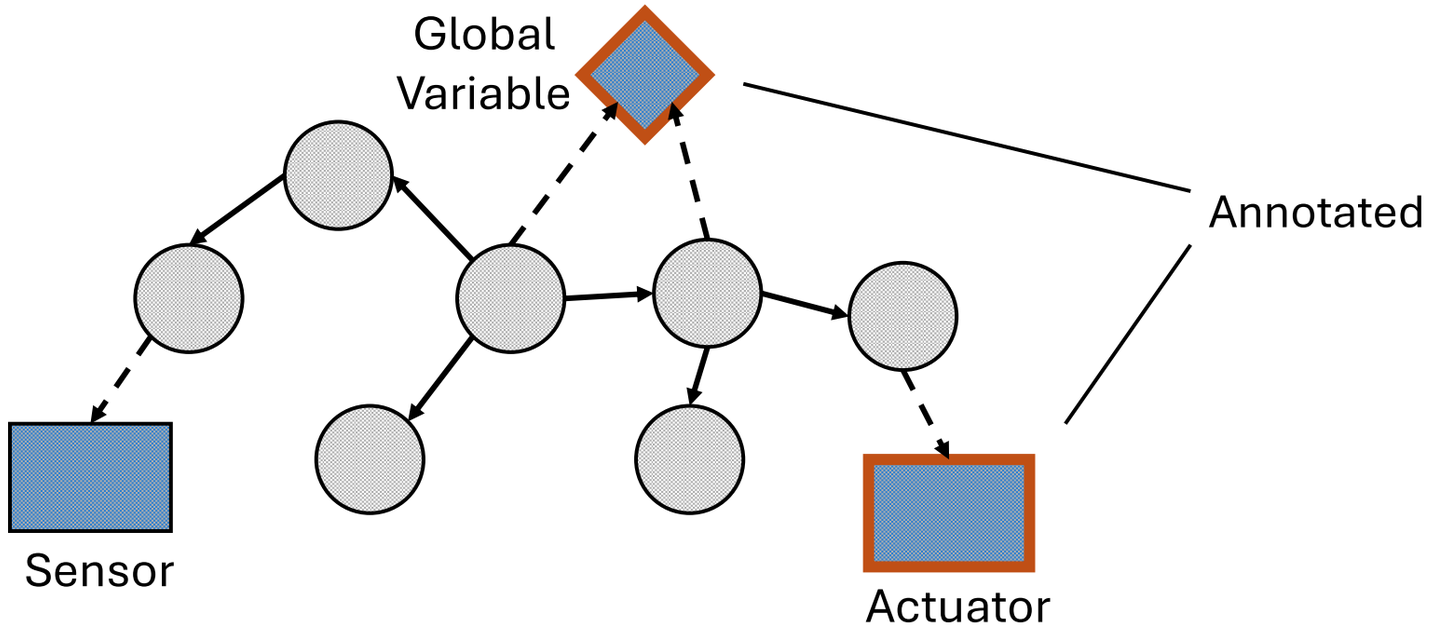

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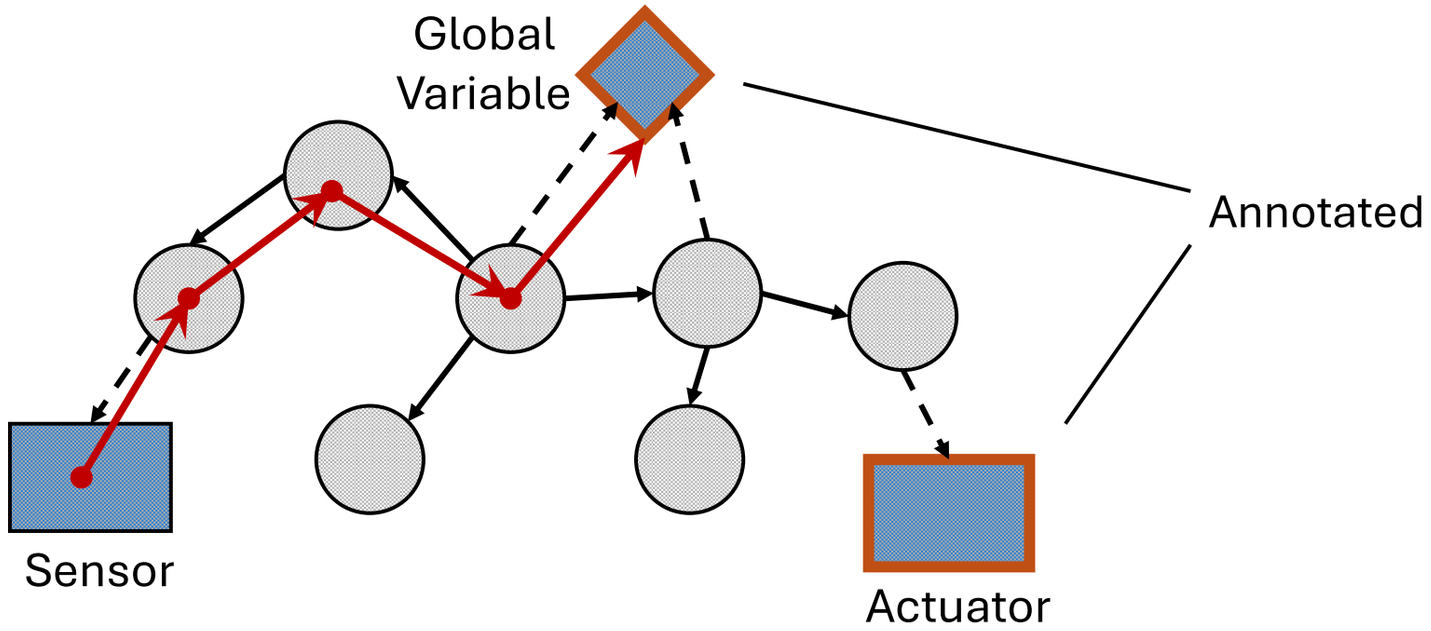

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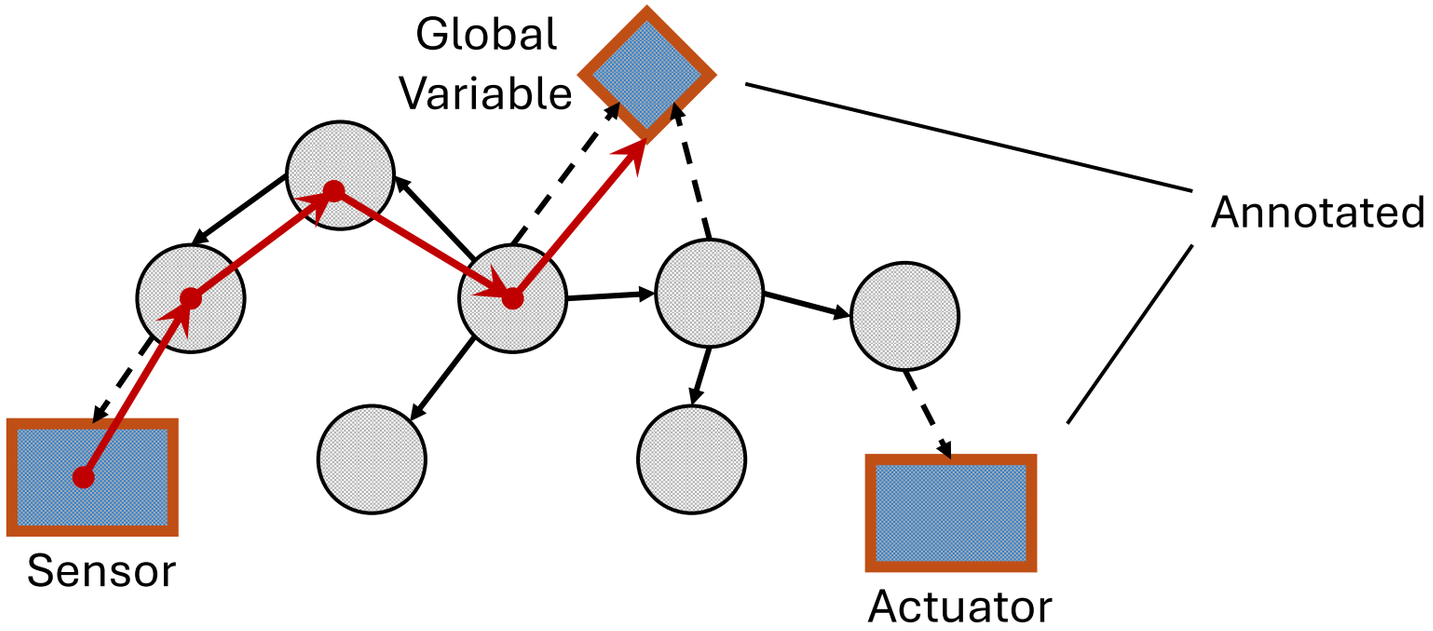

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Forward slicing:

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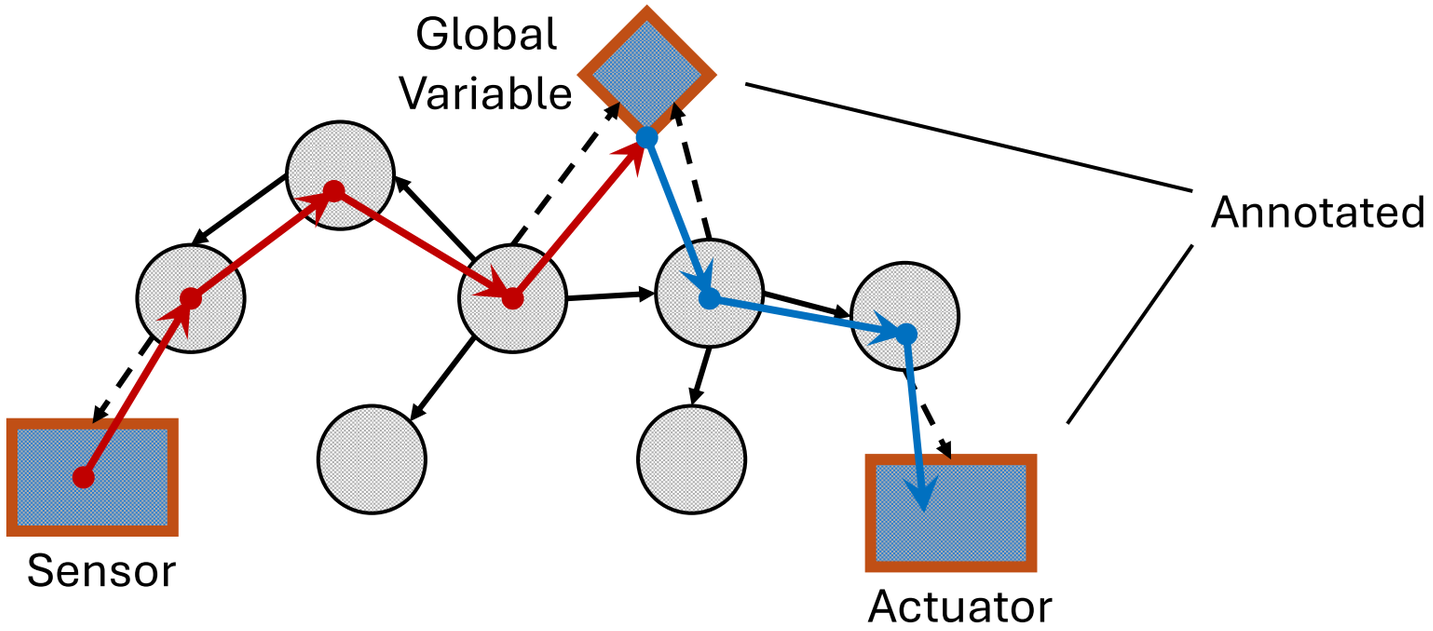

Solution 1: Sensitive Data Flow-based Compartment

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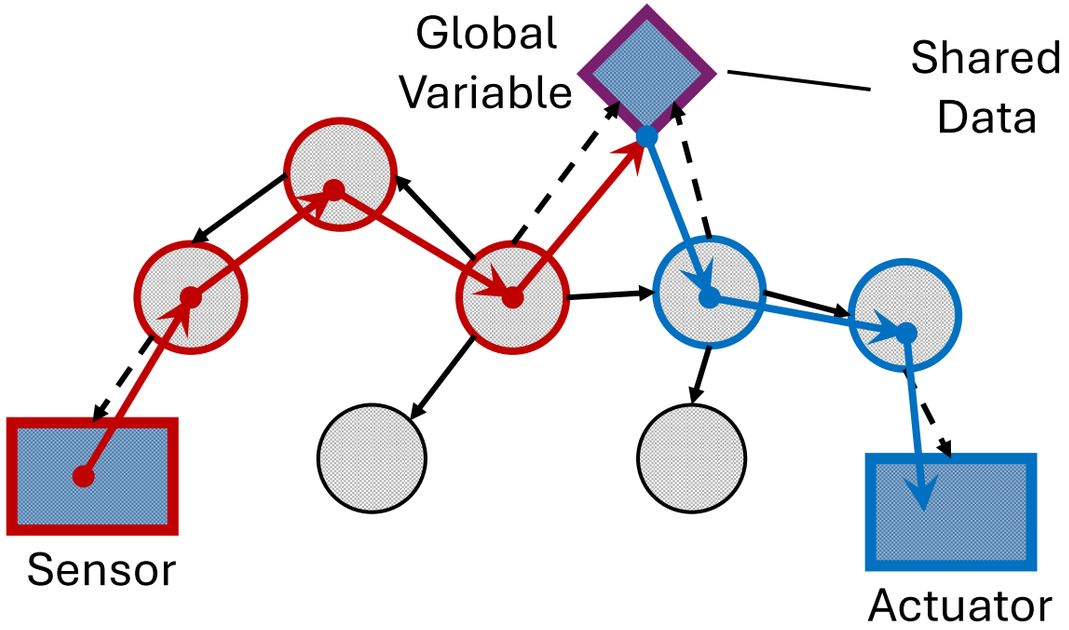
- Tracks all instructions and data objects that influence sensitive data
- Ensures integrity

Forward slicing:

- Tracks all instructions and data objects that are influenced by sensitive data
- Ensures confidentiality



Challenge 2: Lack of Intra-TEE Isolation

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One compartment can access another and even security monitor

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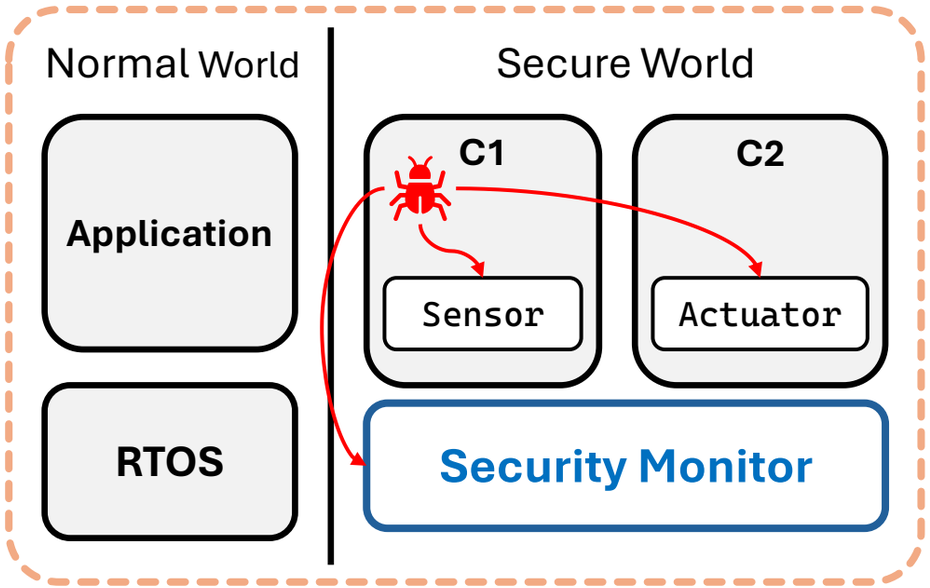
One compartment can access another and even security monitor

- Steal/manipulate sensitive data
- Bypass security checks



Solution 2: Software Fault Isolation

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int func3() {
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Compile-time instrumentation:

- Add checks before indirect control transfer and memory accesses

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Runtime enforcement by the security monitor:

- Isolating accesses within the compartment

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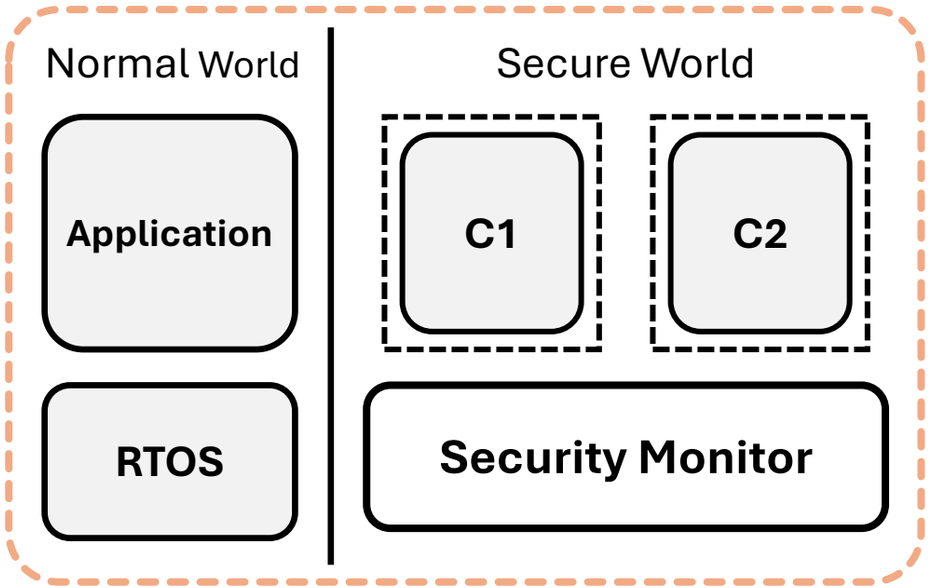
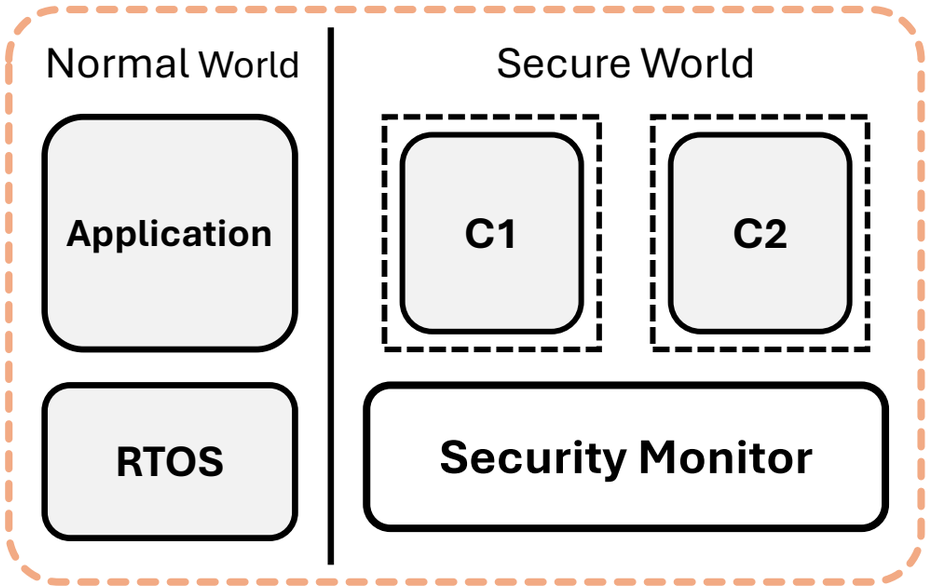
Challenge 3: Shared Data/Peripheral Protection



Challenge 3: Shared Data/Peripheral Protection

- Compartments may share data/peripherals



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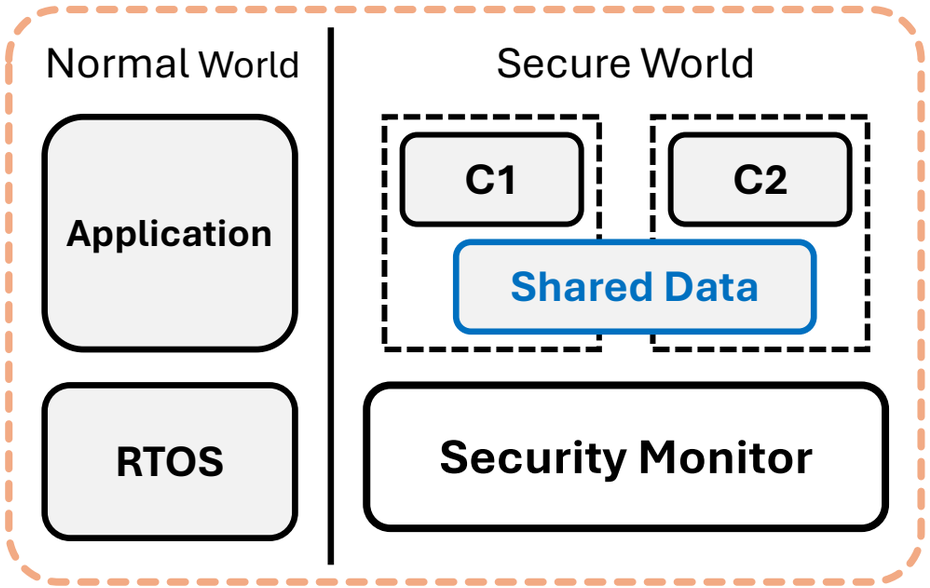

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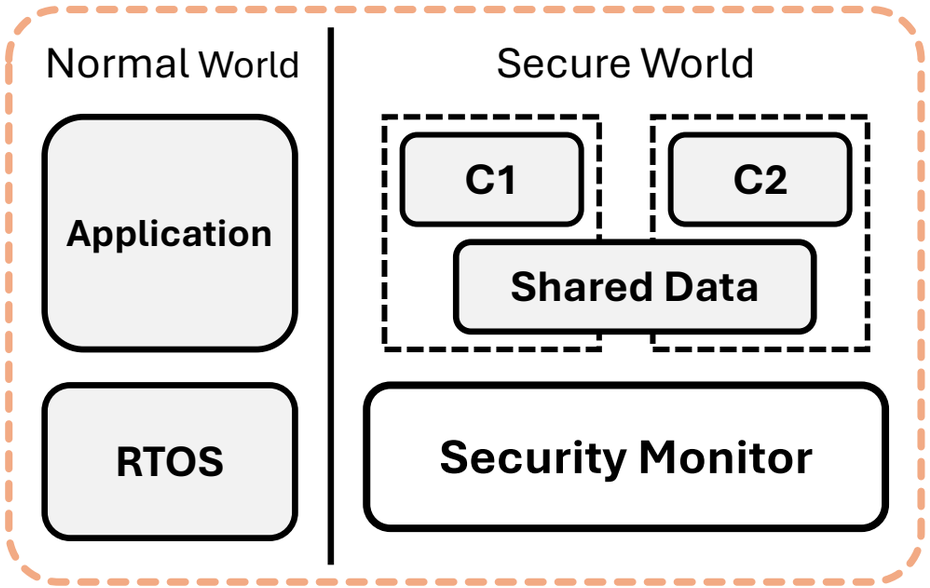
- Adversaries may exploit this to illegally access other compartments



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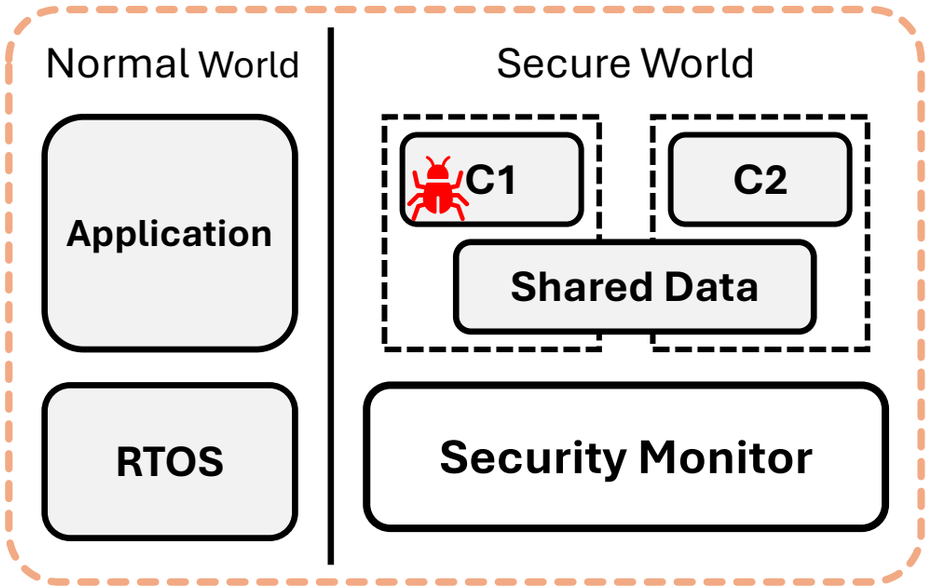

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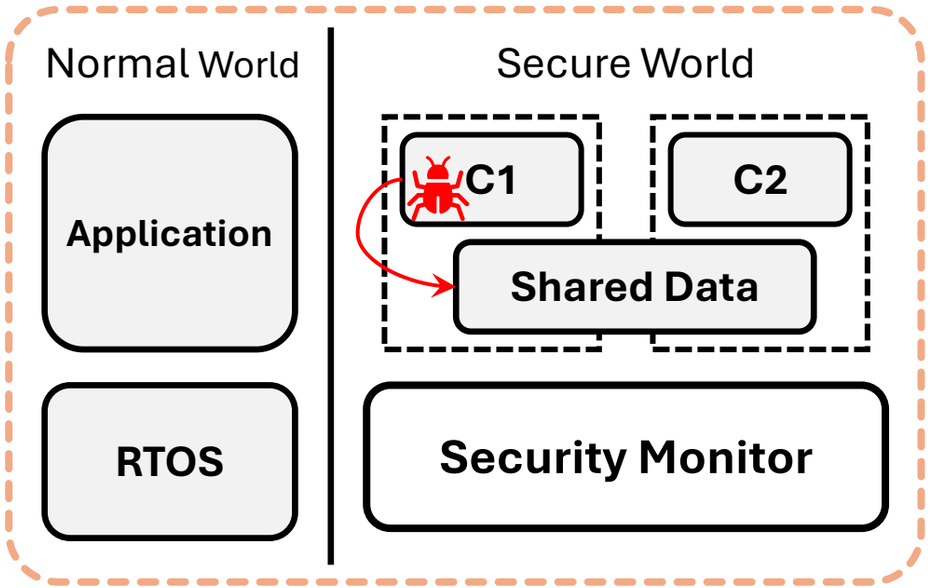

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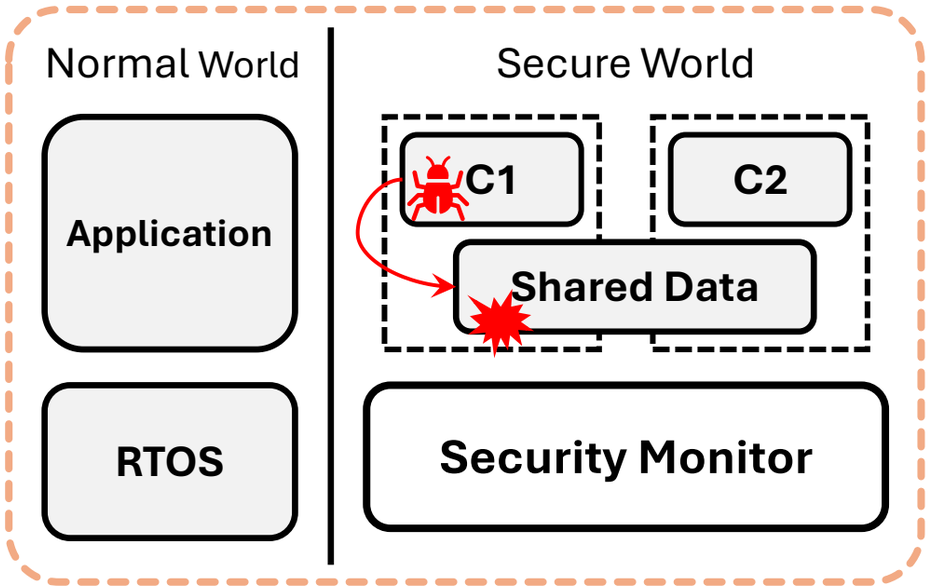

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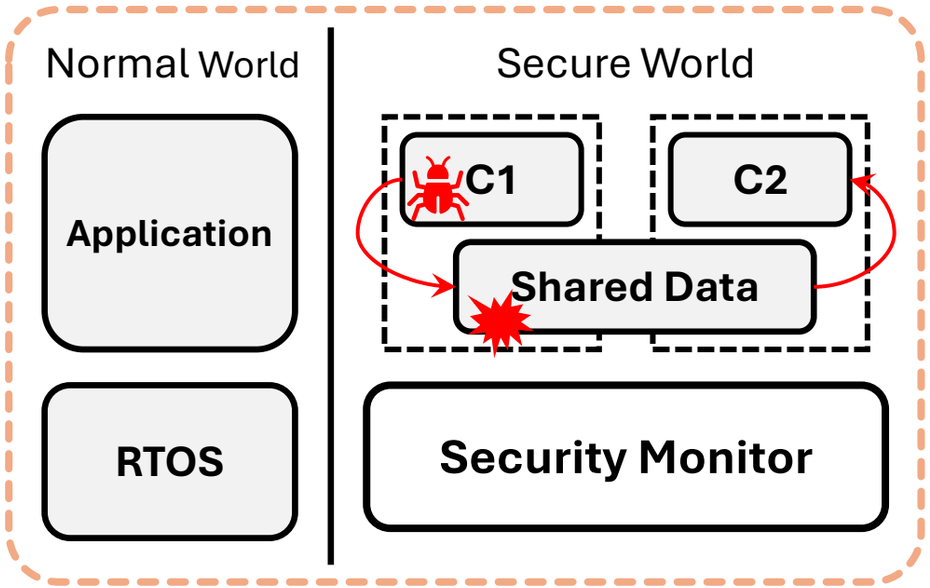

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Control/Data flow integrity (CFI+DFI)

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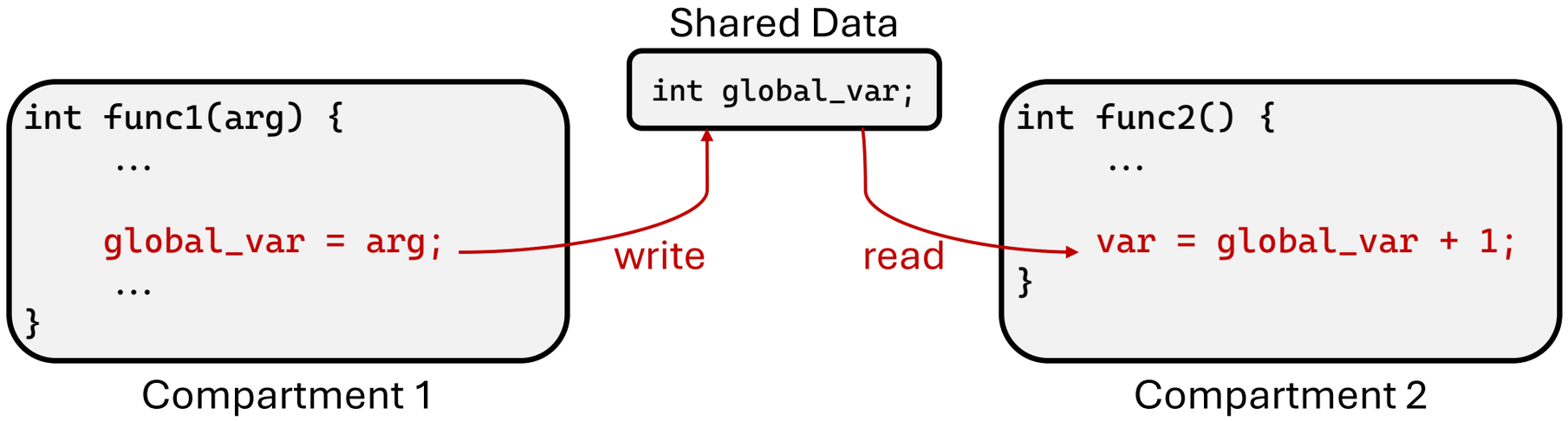

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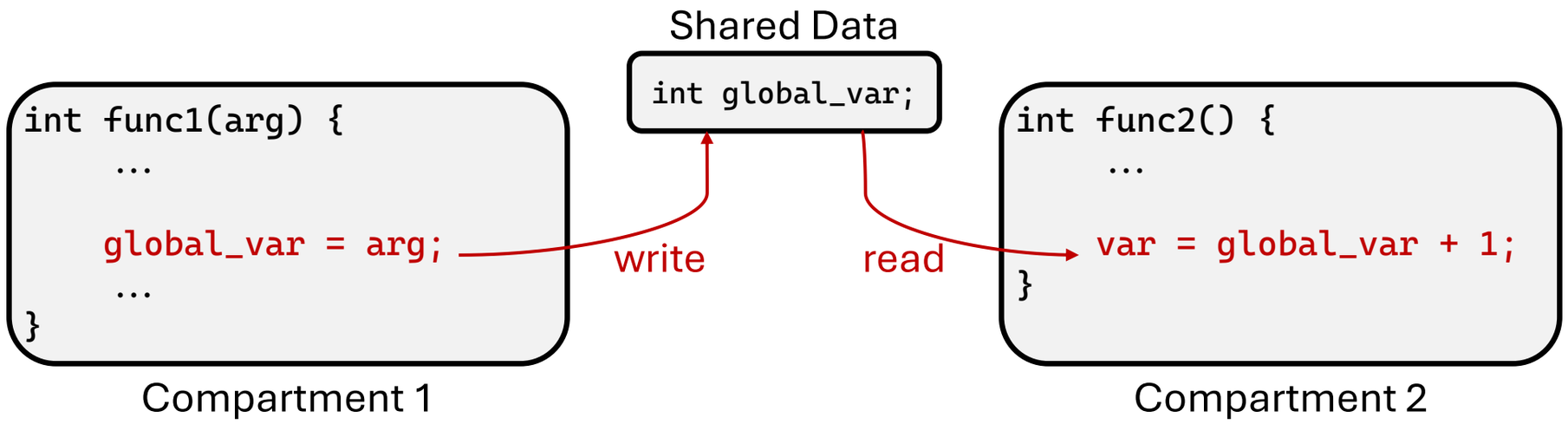

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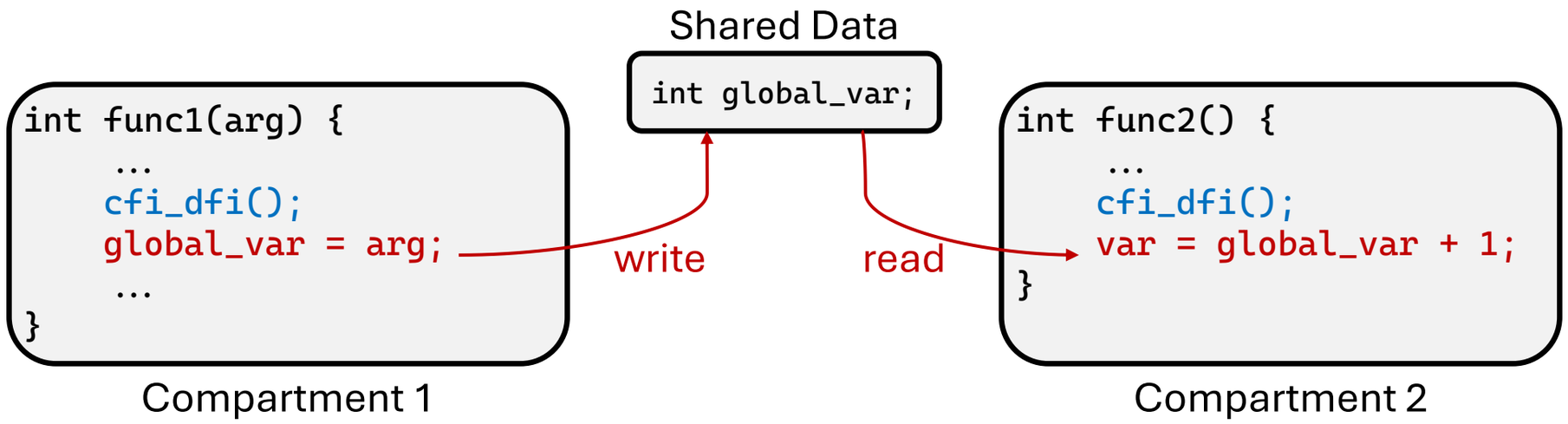

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Compile-time instrumentation:

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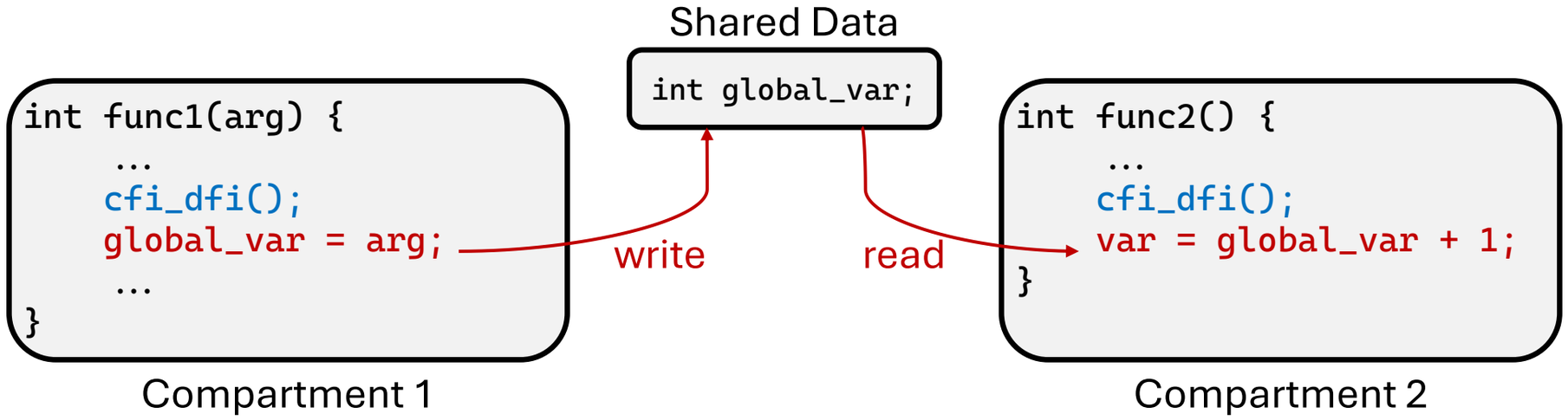
Runtime enforcement by security monitor:

- When reading data, check that it came from an allowed writing

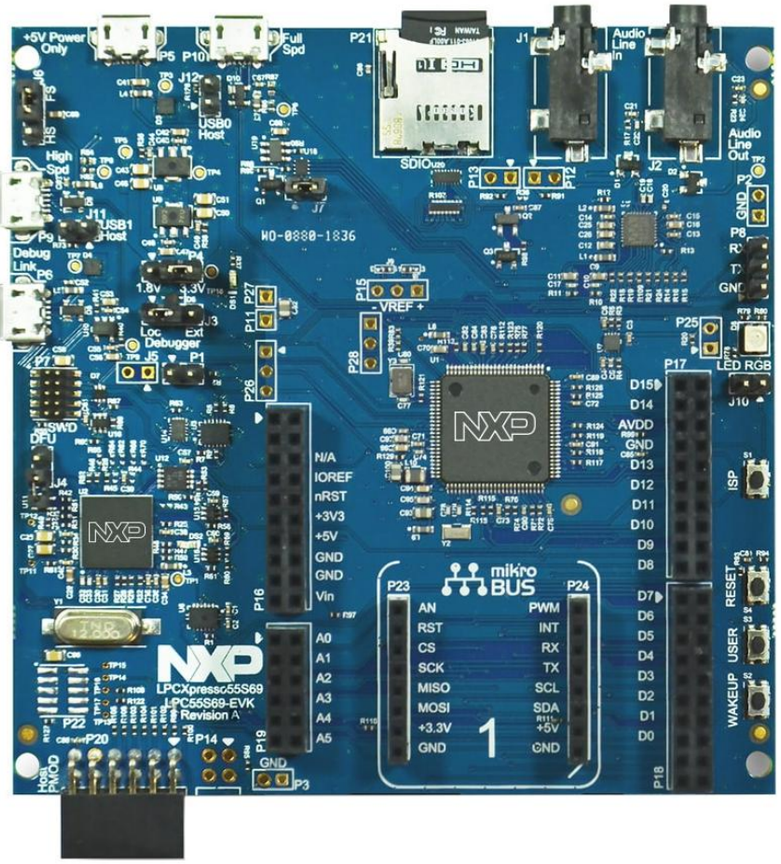


Experimental Setup

Experimental Setup

LPCXpresso55S69 development board

- ARM Cortex-M33 processor (Armv8-M)



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Evaluated on 12 different bare-metal and RTOS applications:

- **Bare-metal**: PinLock, Temp, Accel, Gyro, SD-FatFS, USBVCom
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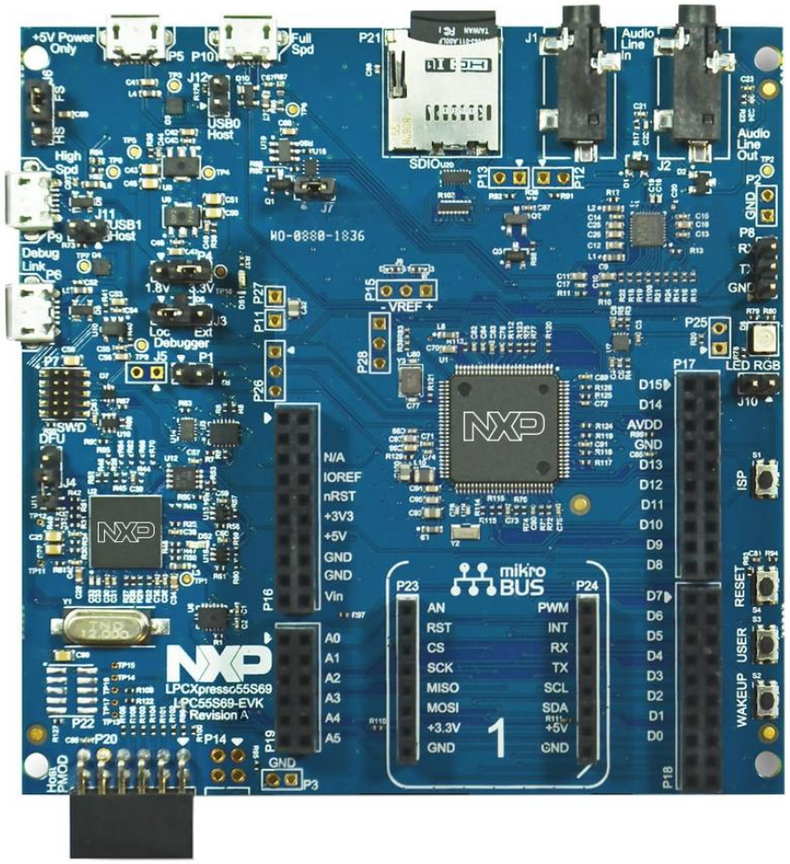

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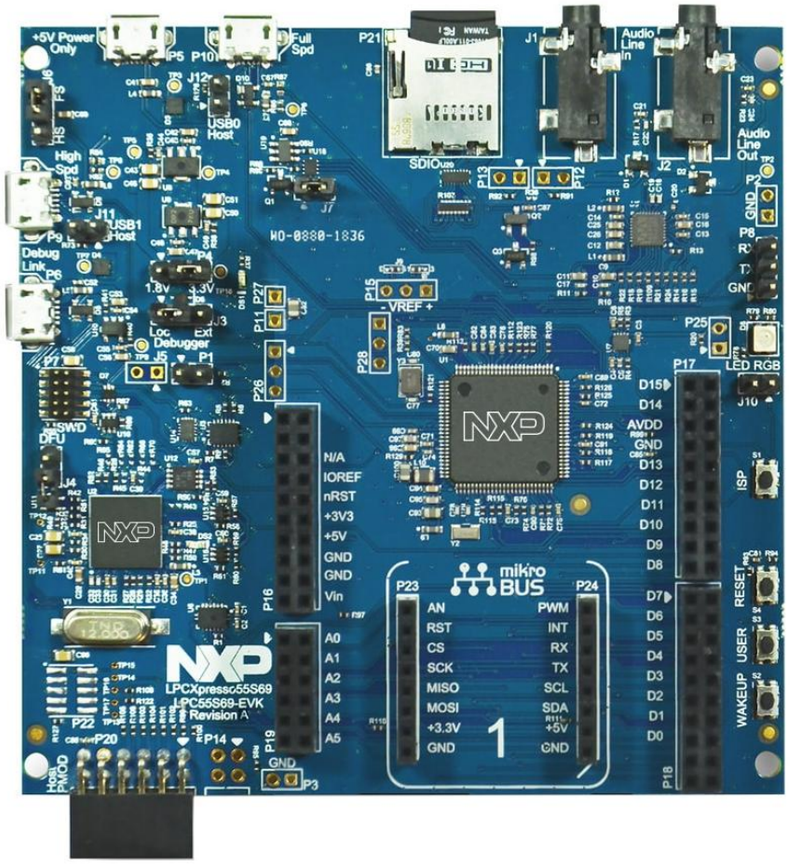
Other compartmentalization approach

- Thread, function, component



Security Evaluation

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Baseline: No isolation

Security Evaluation

Address Space Reduction

Granularity	Compartment	Rate
	SDF	80.8%
Fine	Function	96.2%
Coase	Component	38.4%
	Thread	62.7%

Baseline: No isolation

Address Space Reduction:

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Address Space Reduction:

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Security Evaluation

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 # ROP Gadgets Reduction

Compartment	Rate
SDF	88.6%
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Performance Evaluation

Performance Evaluation

Runtime Overhead

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Runtime overhead:

Performance Evaluation

Runtime Overhead

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Runtime overhead:

- Incurs an average 14.7% runtime overhead

Performance Evaluation

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Runtime overhead:

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- 1.4% compartment switch; 6.3% SFI; 7.0% CFI/DFI

Performance Evaluation

Runtime Overhead

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Memory Overhead

SDF	Overhead
Security Monitor	16.7 KB
Meta data	136 Bytes
Memory Pool	4 KB

Runtime overhead:

- Incurs an average 14.7% runtime overhead
- 1.4% compartment switch; 6.3% SFI; 7.0% CFI/DFI

Memory overhead:

- Incurs an average 31.4% memory overhead

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- Use ARM TrustZone to protect against strong adversaries

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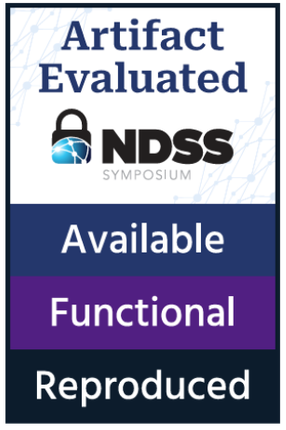
Thanks for listening.
Questions?



Code

Artifacts

Protecting IRQ Handlers

- IRQ handlers are also isolated into separate SDF compartments
- Secure Interrupt dispatcher:
  - Registered in the interrupt vector table (IVT)
  - **Intercepts IRQ requests** before invoking the actual handler

Comparison with Existing CFI/DFI

Unlike general CFI/DFI that checks universally

Selectively activates CFI/DFI only when accessing shared peripherals or data

Adjustable previous address targets

Lightweight

Annotation

```
/* Global data, confidentiality protection */
const uint8_t key_stored[KEY_SIZE] TZDS_DATA_R = {0x...};
void func() {
  /* Stack data, integrity protection */
  uint8_t buffer[BUFFER_SIZE] TZDS_DATA_W = {0x0};
  ...
}
/* Heap data, confidentiality and integrity protection */
static void *m_head TZDS_HEAP_RW = malloc(...);
/* Peripheral data at [GPIO_BASE,GPIO_BASE+0x1000),
   integrity protection */
#define GPIO_BASE (0x4008C000u)
TZDS_MMIO_W(GPIO_BASE, 0x1000)
GPIO_Type *gpio = (GPIO_Type *) GPIO_BASE;
```

Performance Overhead – CFI/DFI