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Building Secure Applications with Attestation

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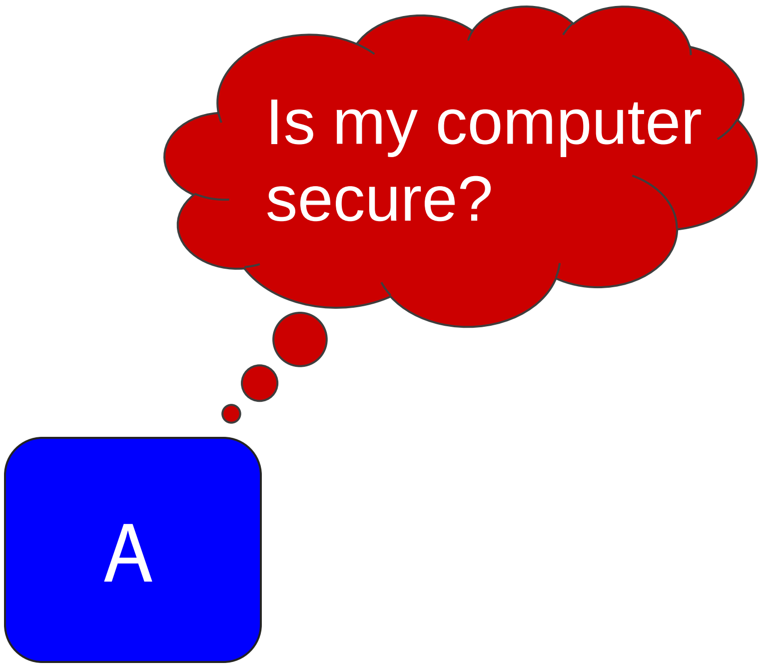
Anupam Datta, Virgil Gligor, Pradeep Khosla, Leendert van Doorn


Is my computer secure?
A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Is my computer secure?
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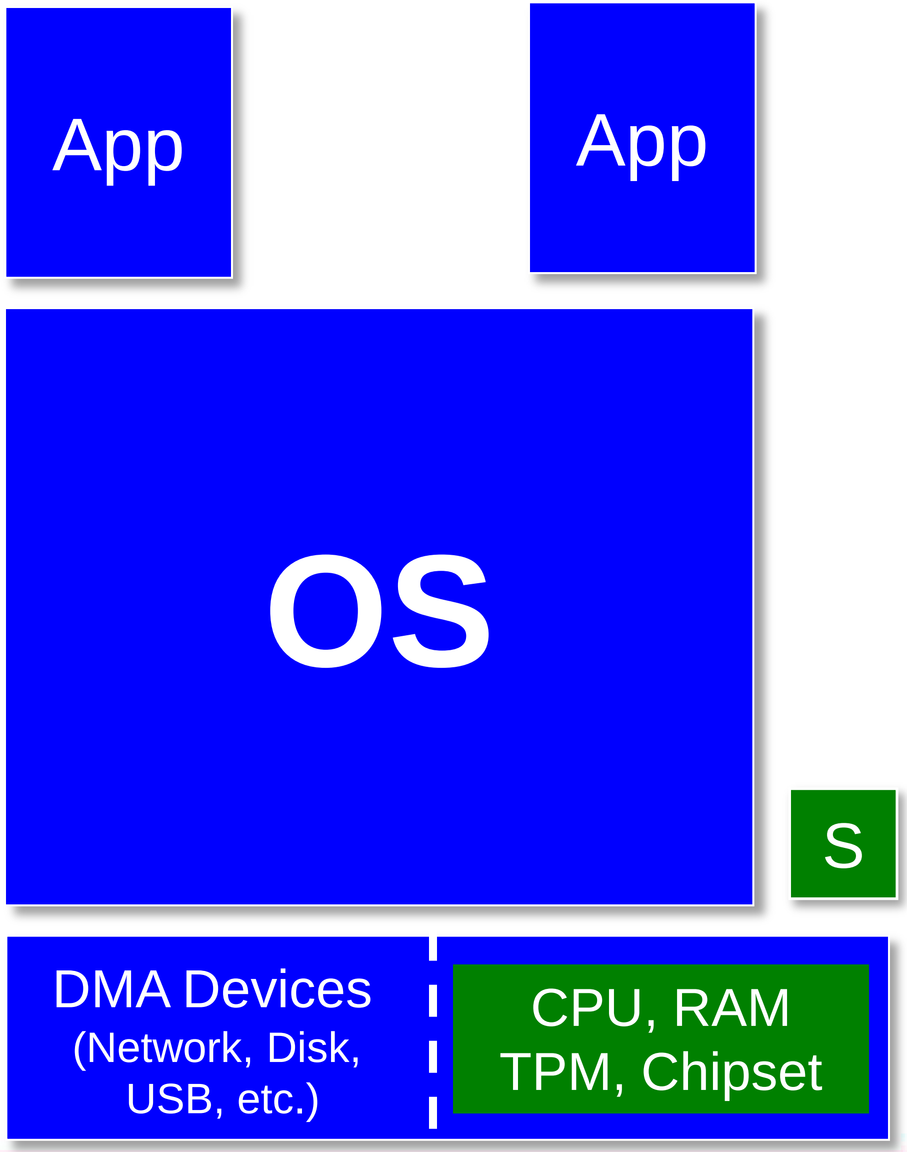
Goals

- Provide user with strong security properties
  - Execution integrity
  - Data secrecy and authenticity
  - Cyber-secure moments! © Virgil Gligor
- Compatibility with existing systems (both SW and HW)
- Efficient execution
- In the presence of malware
  - Assuming remote attacks: HW is trusted

Isolated Execution Environment (IEE)

- Execution environment that is defined by code S executing on a specific platform
  - Code is identified based on cryptographic hash H(S)
  - Platform is identified based on HW credentials
- IEE execution protected from any other code



Basic Trusted Computing Primitives

- Create isolated execution environment (IEE)
  - Create data that can only be accessed within isolated environment
- Remote verification of IEE
- Establish secure channel into IEE
- Externally verify that output O was generated by executing code S on input I protected by IEE

Basic Trusted Computing Primitives

- How to create IEE?
- How to remotely verify IEE?
- How to establish a secure channel into IEE?
- How to externally verify that output O is from S's computation on input I within IEE?

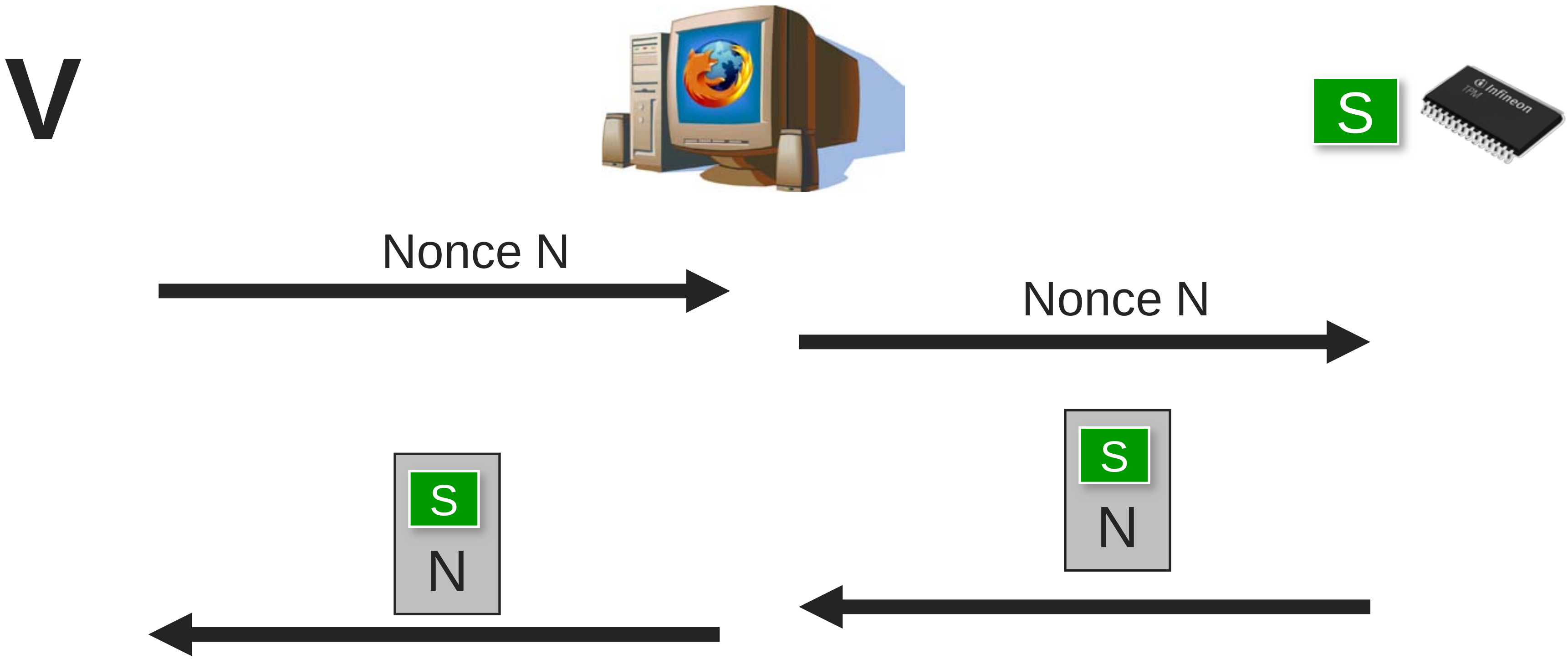
TPM Background

- The Trusted Computing Group (TCG) has created standards for a dedicated security chip: Trusted Platform Module (TPM)
- Contains a public/private keypair $\{K_{Pub}, K_{Priv}\}$
- Contains a certificate indicating that K_{Pub} belongs to a legitimate TPM
- Not tamper-resistant

How to Create IEE?

- AMD / Intel late launch extensions
- Secure Loader Block (SLB) to execute in IEE
- SKINIT / SENTER execute atomically
  - Sets CPU state similar to INIT (soft reset)
  - Enables DMA protection for entire 64 KB SLB
  - Sends [length bytes of] SLB contents to TPM
  - Begins executing at SLB's entry point

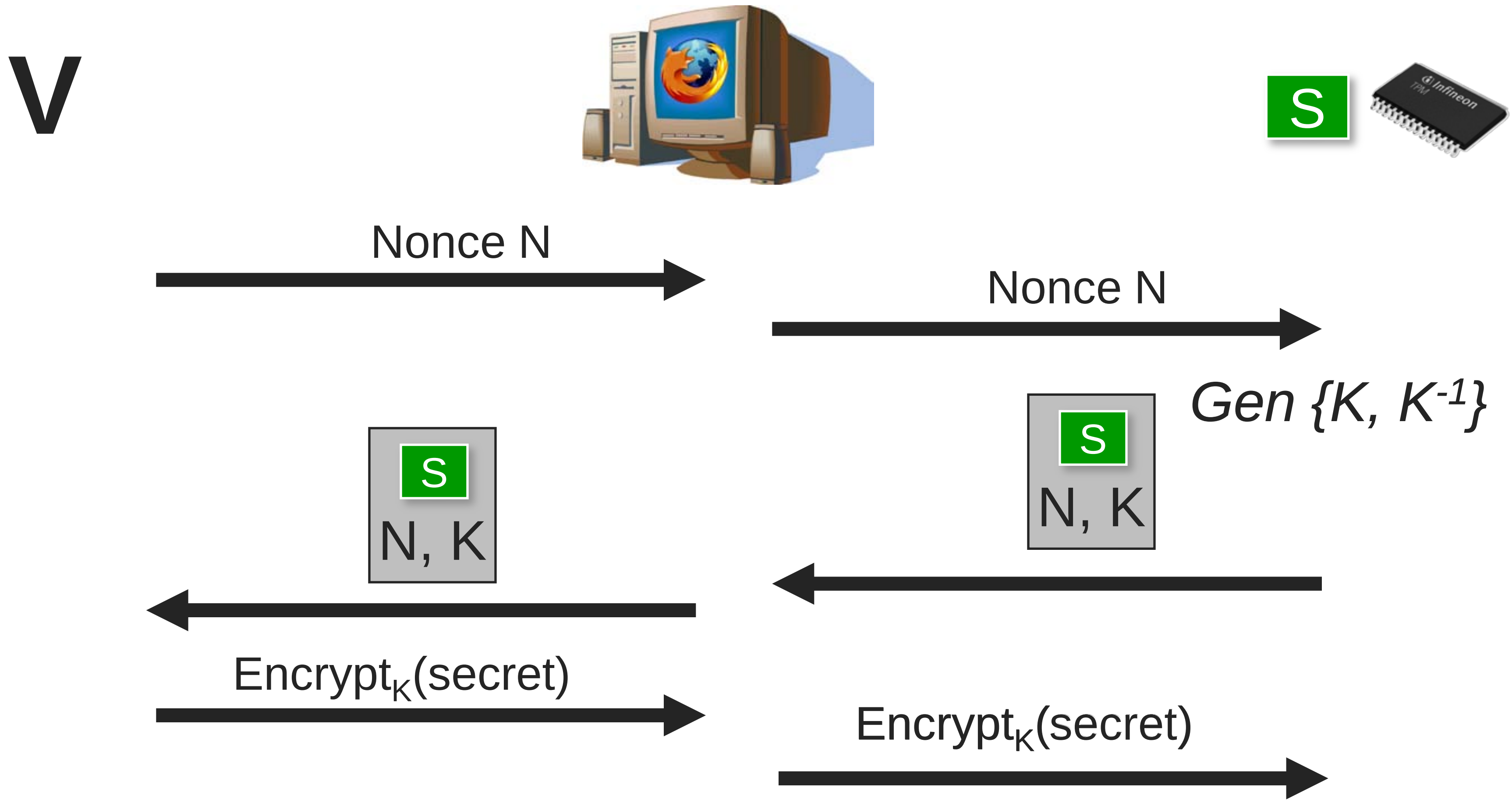
How to Remotely Verify IEE?



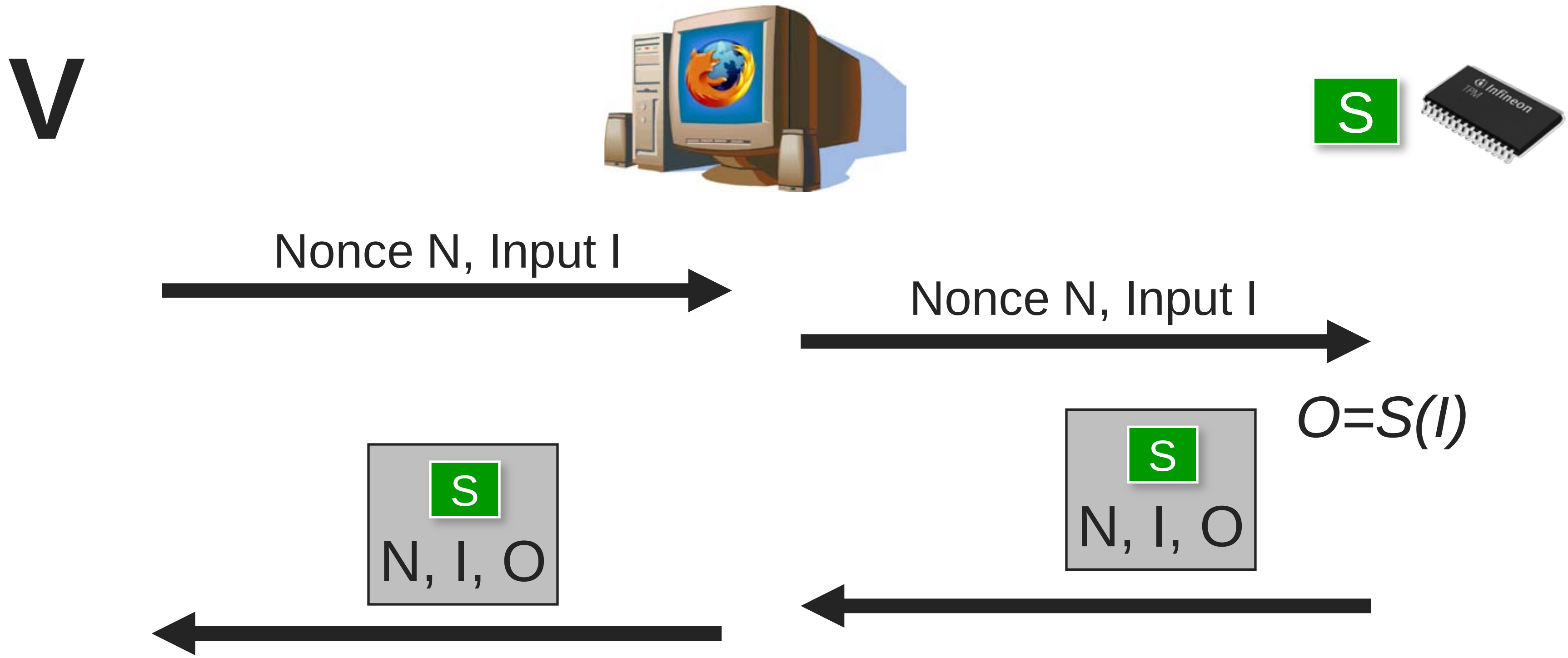
S
N

Means H(S) and N are signed by platform key

Secure Channel to IEE

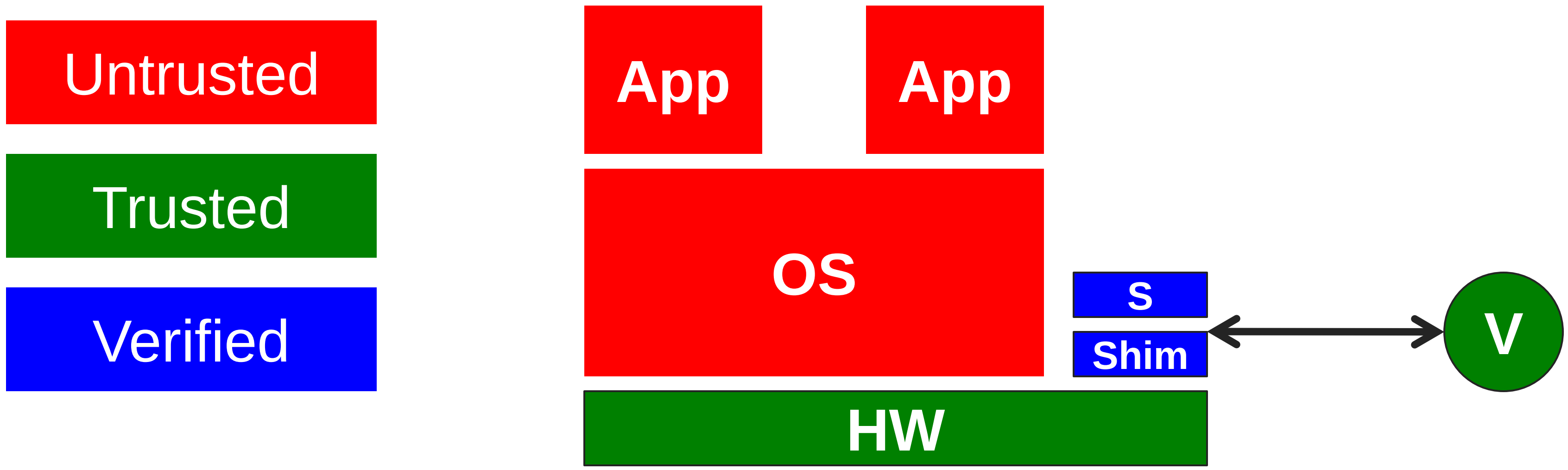


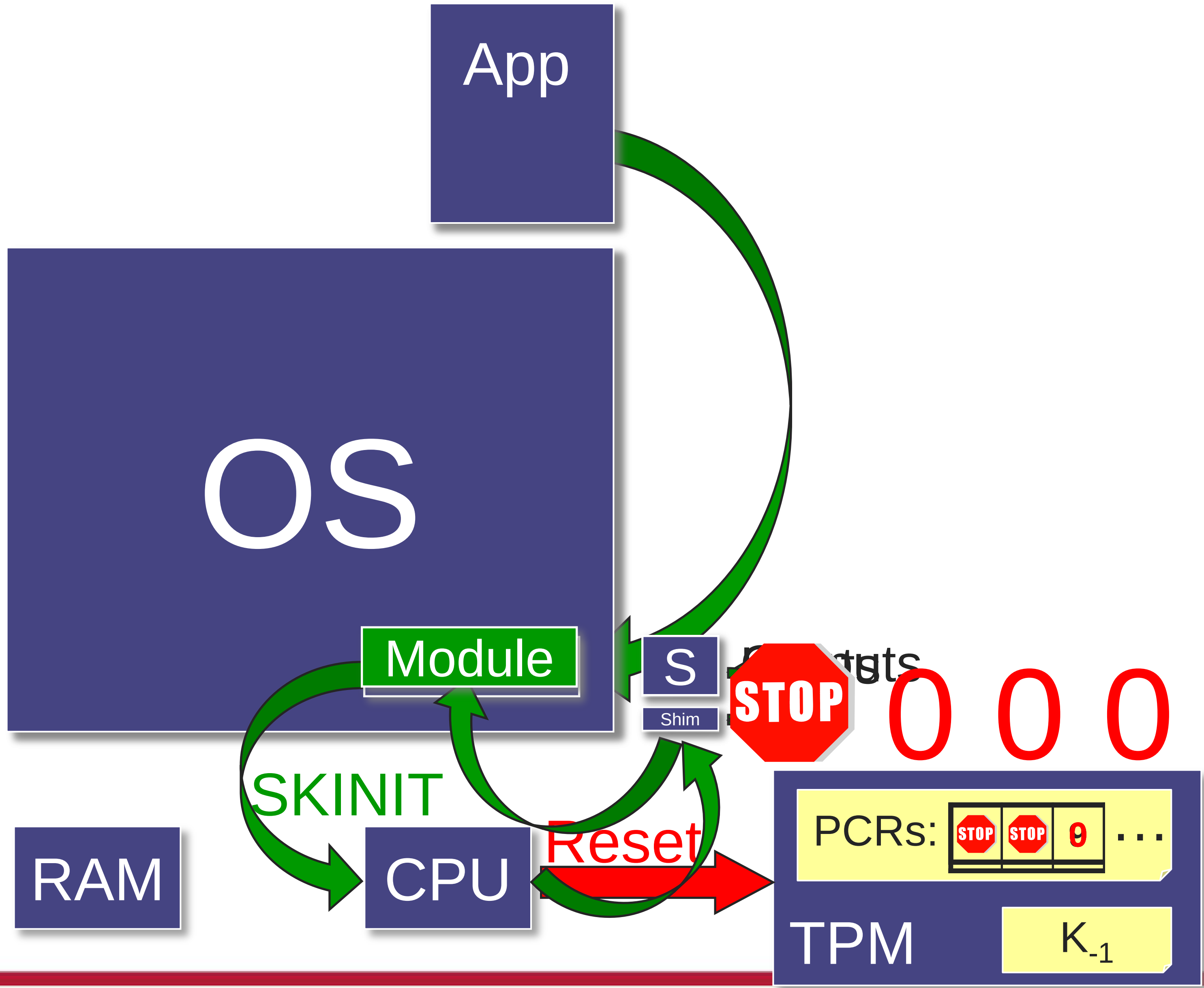
O=S(I) within IEE?

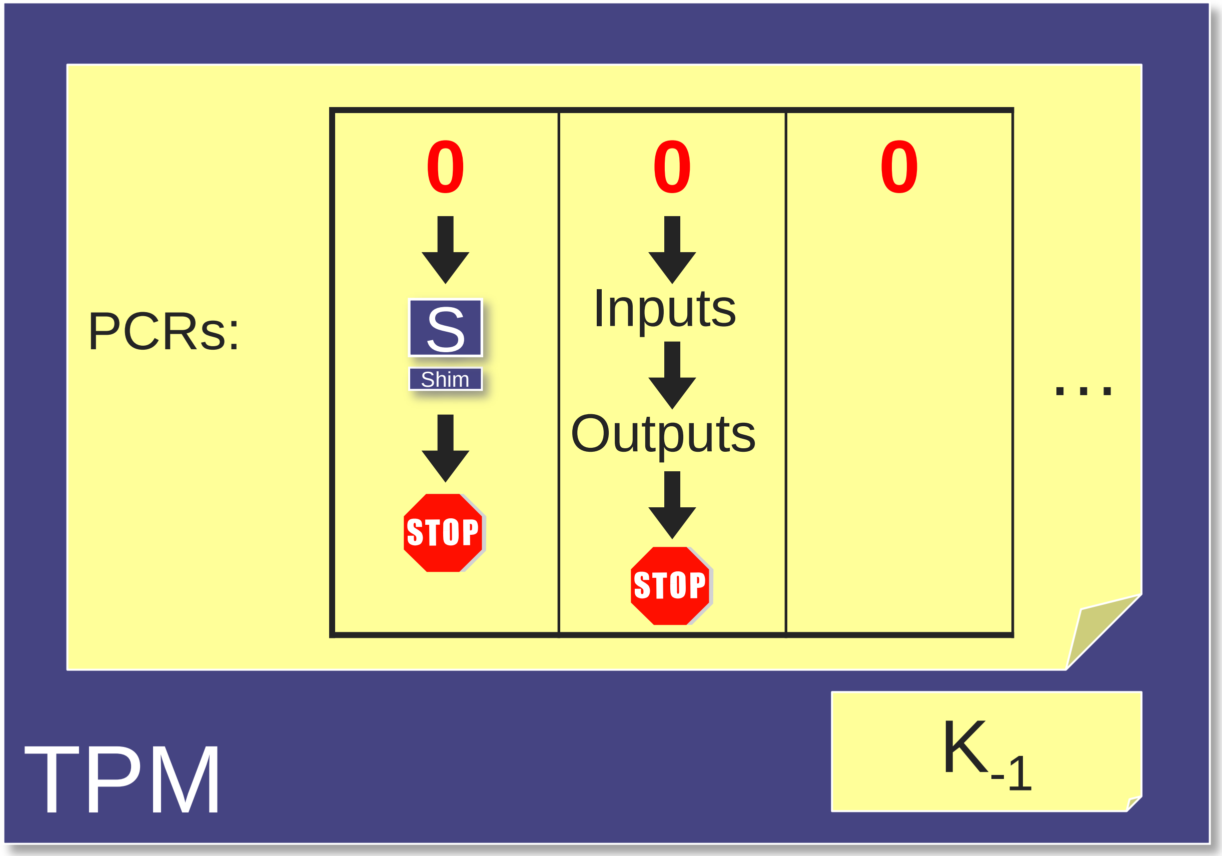


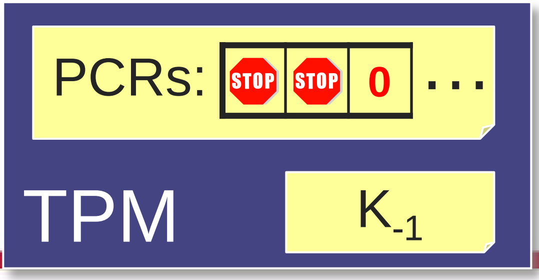
Flicker

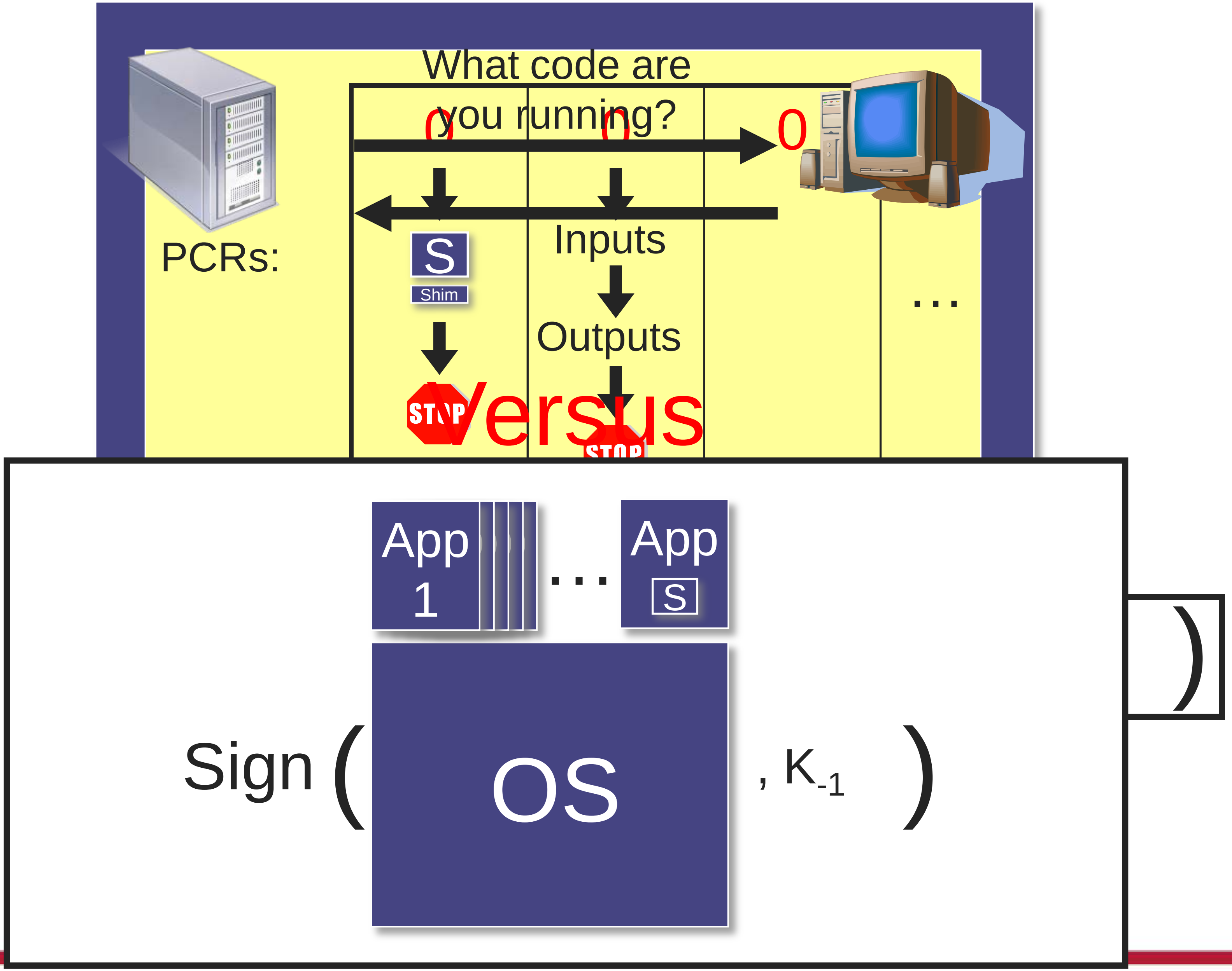
- McCune, Parno, Perrig, Reiter, and Isozaki, "Flicker: An Execution Infrastructure for TCB Minimization," EuroSys 08
- Goals
  - Isolated execution of security-sensitive code S
  - Attested execution of Output = S(Input)
  - Minimal TCB




App
OS
Module
S
Shim
STOP
0 0 0
SKINIT
Reset
RAM
CPU
PCRs:
STOP
STOP
0
...
TPM
K_{-1}


PCRs:
0
0
0
S
Shim
STOP
Inputs
Outputs
STOP
…
TPM
K_{-1}


PCRs:
STOP
STOP
0
…
TPM
K_{-1}

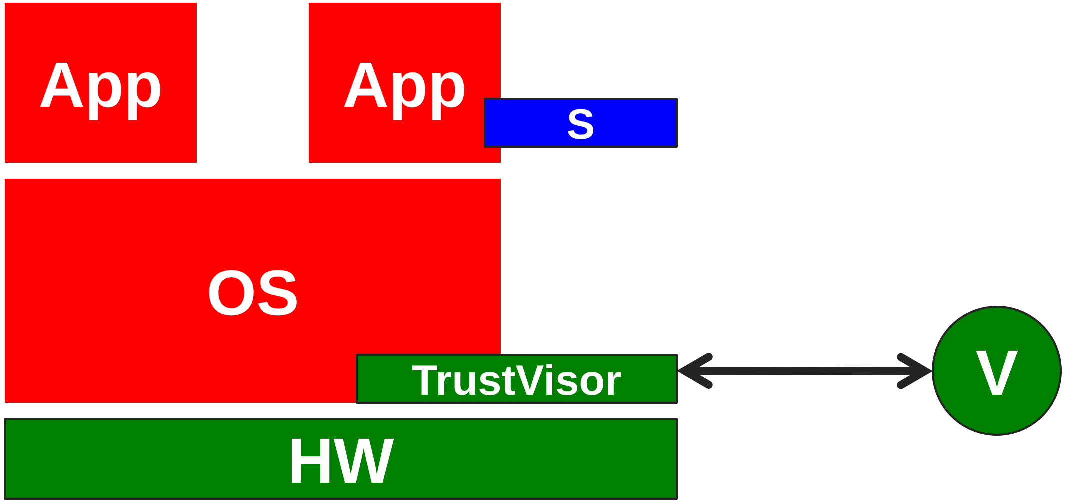

What code are you running?
PCRs:
0
0
0
S
Shim
Inputs
Outputs
STOP
Versus
STOP
...
App 1
...
App
S
OS
Sign (
, K_{-1}
)
)

Flicker Discussion

- Assumptions
  - Verifier has correct public keys
  - No hardware attacks
  - Isolated code has no vulnerabilities
- Observations
  - TCG-style trusted computing does not prevent local physical attacks
  - However, prevents remote attacks which are most frequent attacks

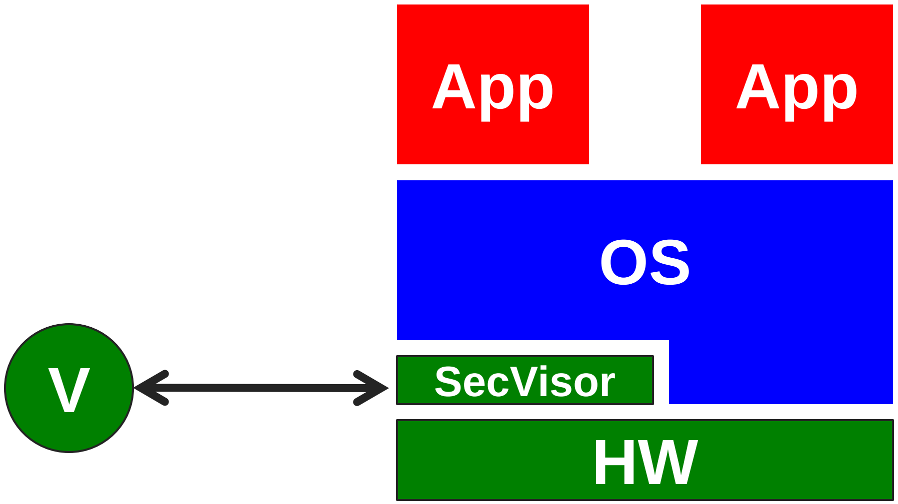
TrustVisor

- Goals
  - Similar to Flicker, replace min TCB by high efficiency
  - Isolated execution of security-sensitive code S
  - Attested execution of Output = S(Input)



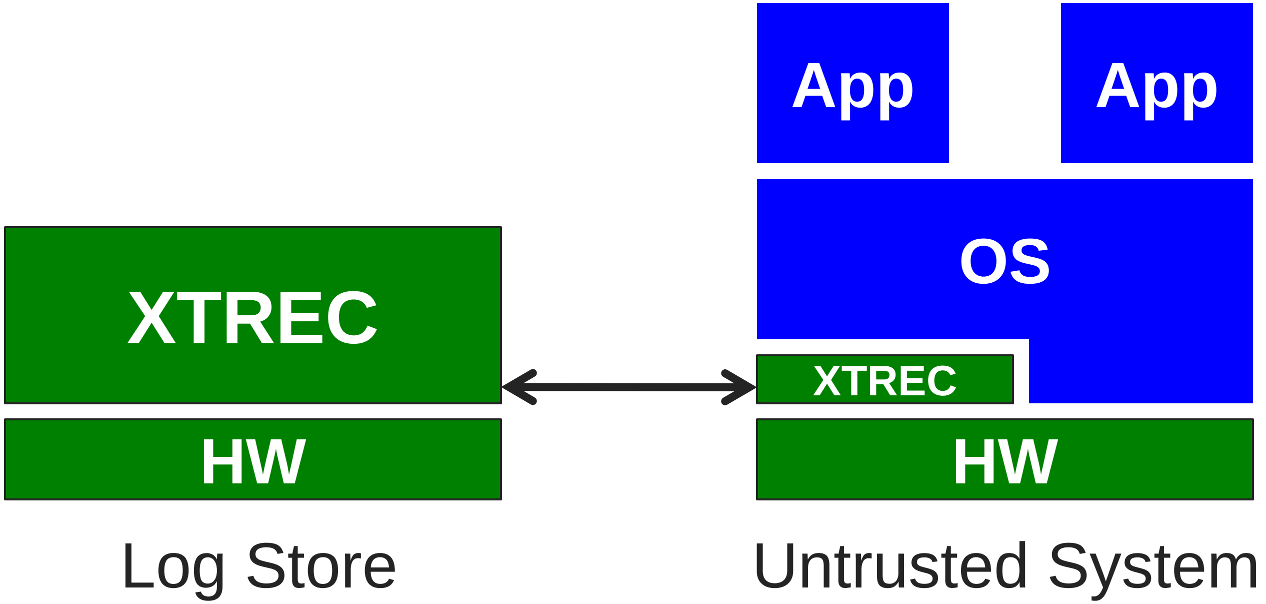
SecVisor

- Goals
  - Protect OS legacy against unauthorized writes
  - Code integrity property for untrusted OS: only approved code can execute in kernel mode
  - Attest to OS state to remote verifier



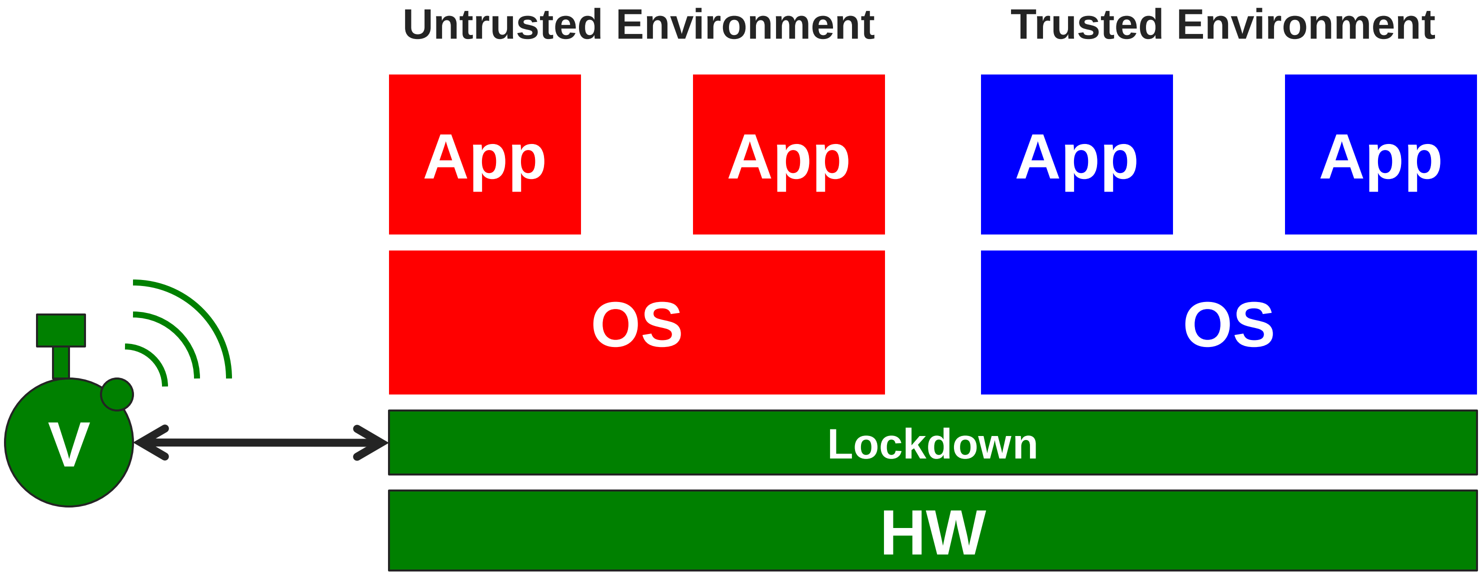
XTREC

- Goals
  - Complete execution tracing of a target system
  - Non-invasive, transparent
  - High performance



Lockdown

- Goals
  - Isolated execution of trusted OS environment
  - Trusted path to user
  - Protected secure browser in trusted OS



Conclusions

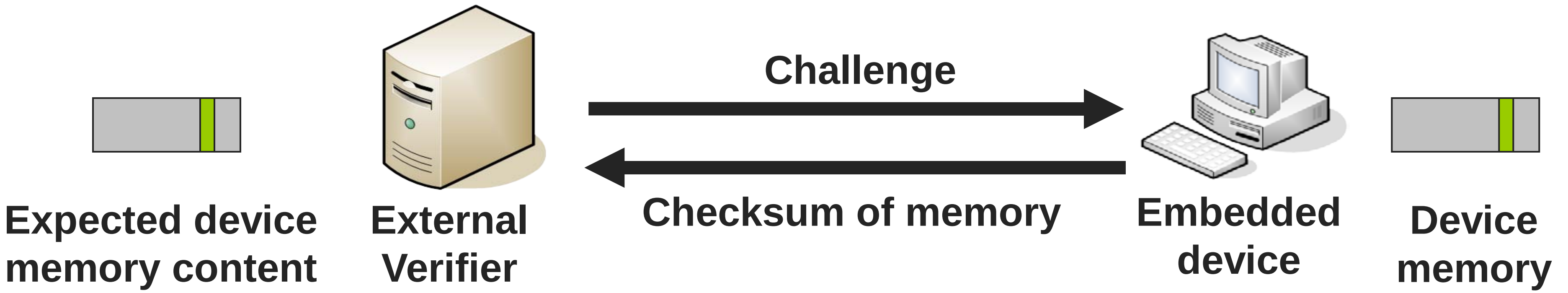
- Trusted computing mechanisms enable fundamentally new properties
  - On host: protect code & data even from admin
  - In distributed applications: simple data verification based on code that produced it
- Trusted computing mechanisms provide new primitives to build secure systems
- Trusted device can provide strong guarantees to local user

Software-Based Attestation

- Goal: provide attestation guarantees on legacy hardware, without trusted TPM chip
- Projects
  - SWATT: Software-based attestation, with Arvind Seshadri, Leendert van Doorn, and Pradeep Khosla [IEEE S&P 2004]
  - Pioneer: Untampered code execution on legacy hosts, with Arvind Seshadri, Mark Luk, Elaine Shi, Leendert van Doorn, and Pradeep Khosla [SOSP 2005]

Software-based Attestation Overview

- External, trusted verifier knows expected memory content of device
- Verifier sends challenge to untrusted device
  - Assumption: attacker has full control over device's memory before check
- Device returns memory checksum, assures verifier of memory correctness

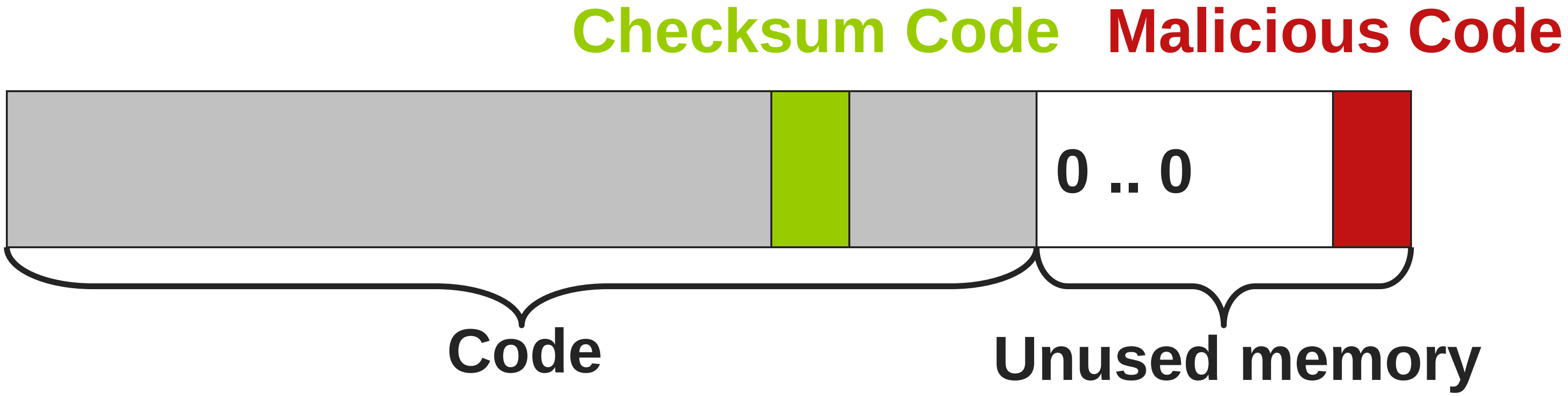


Assumptions and Attacker Model

- Assumptions on verifier
  - Knows hardware configuration of device
- Assumptions on device (untrusted host)
  - Hardware and firmware is trustworthy
  - Can only communicate with verifier: no proxy attacks
- Attacker controls device's software and OS before verification

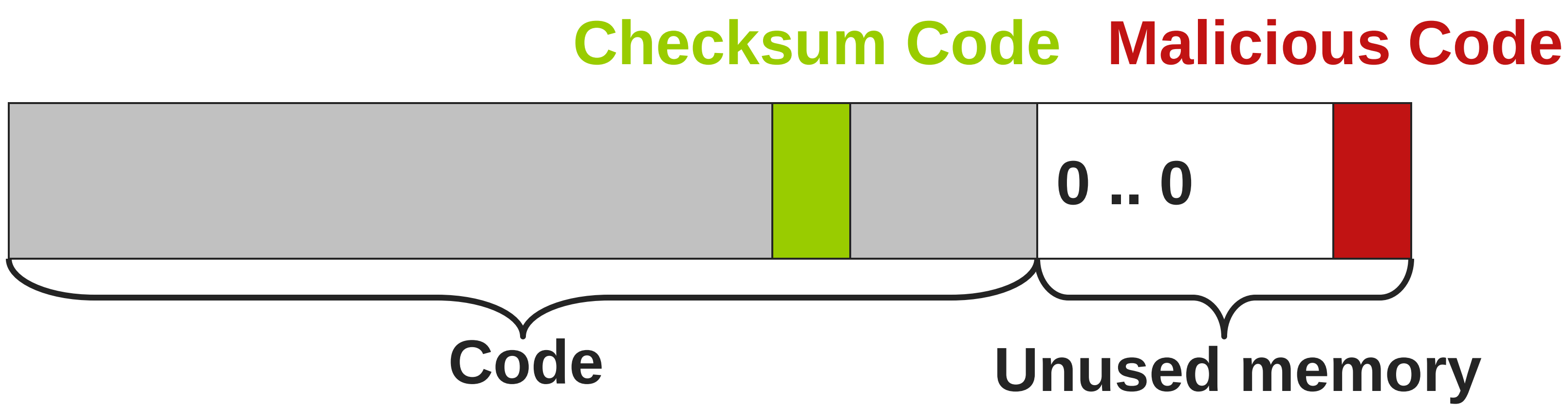
Checksum Function Design

- Approach 1: Verifier asks device to compute a cryptographic hash function over memory
  - V → D: Checksum request
  - D → V: SHA-1(Memory)
- **Attack**: malicious code pre-computes and replays correct hash value



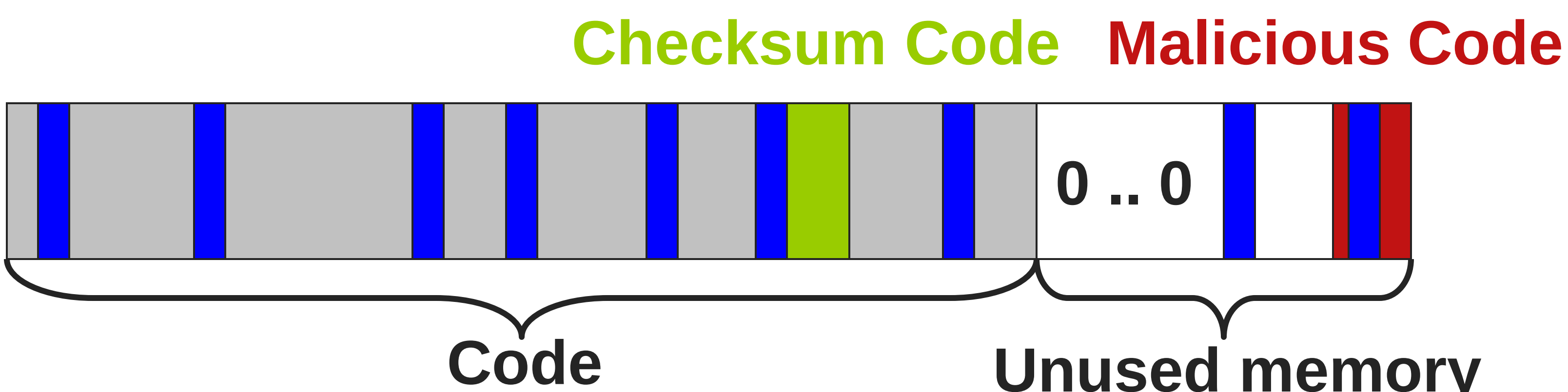
Checksum Function Design

- Approach 2: Verifier picks a random challenge, device computes Message Authentication Code (MAC) using challenge as a key
  - V → D: Checksum request, random K
  - D → V: HMAC-SHA-1(K, Memory)
- **Attack**: Malicious code computes correct checksum over expected memory content



Checksum Function Design

- Observation: need externally detectable property that reveals tampering of checksum computation
- Approach
  - Use time as externally detectable property, create checksum that slows down if tampering occurs
  - Compute checksum in pseudo-random order
  - Attacker needs to verify each memory access → slowdown

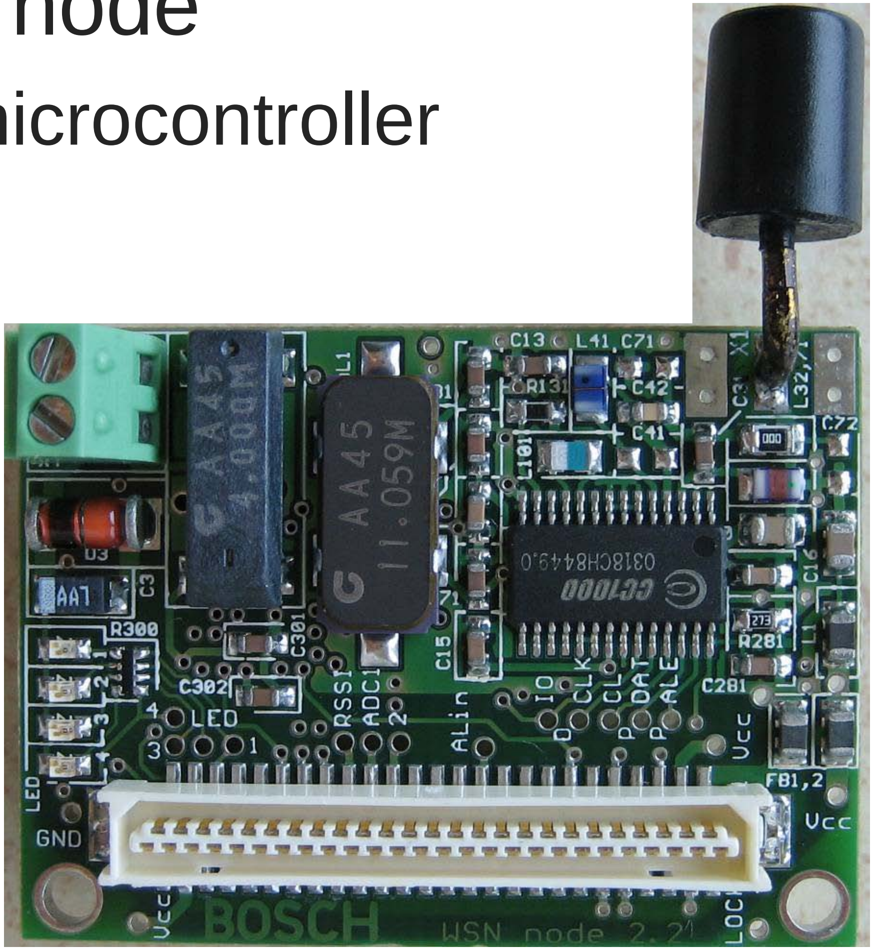


Checksum Requirements

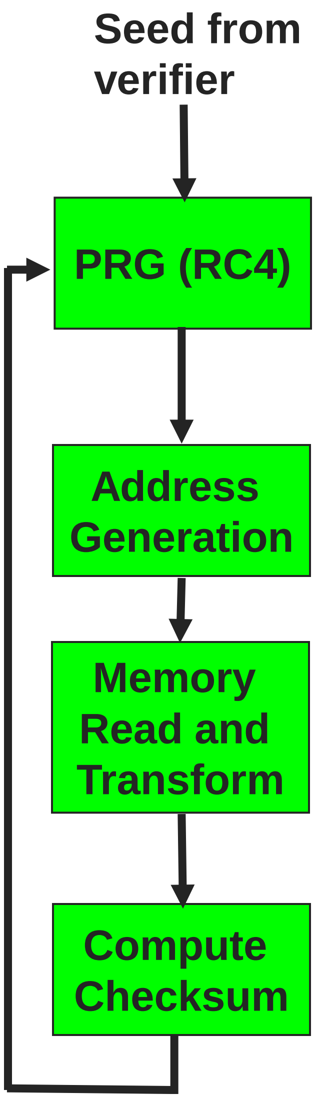
- Optimal implementation: code cannot be optimized
  - Denali project @ HP labs provides proof of optimal implementation of short pieces of code
  - GNU superopt
  - Open challenge to prove optimality of SWATT checksum
- No algebraic optimizations
  - Checksum has to be computed in entirety
  - Given a memory change, checksum cannot be "adjusted" without recomputation

Implementation Platform

- Bosch sensor node
  - TI MSP430 microcontroller



Assembler Code



Generate i^th member of random sequence using RC4

```
zh  = 2               ldi zh, 0x02
r15 = *(x++)          ld r15, x+
yl  = yl + r15        add yl, r15
zl  = *y              ld zl, y
*y  = r15             st y, r15
*x  = r16             st x, r16
zl  = zl + r15        add zl, r15
zh  = *z              ld zh, z
```

Generate 16-bit memory address

```
zl  = r6              mov zl, r6
```

Load byte from memory and compute transformation

```
r0  = *z              lpm r0, z
r0  = r0 xor r13      xor r0, r13
r0  = r0 + r4         add r0, r4
```

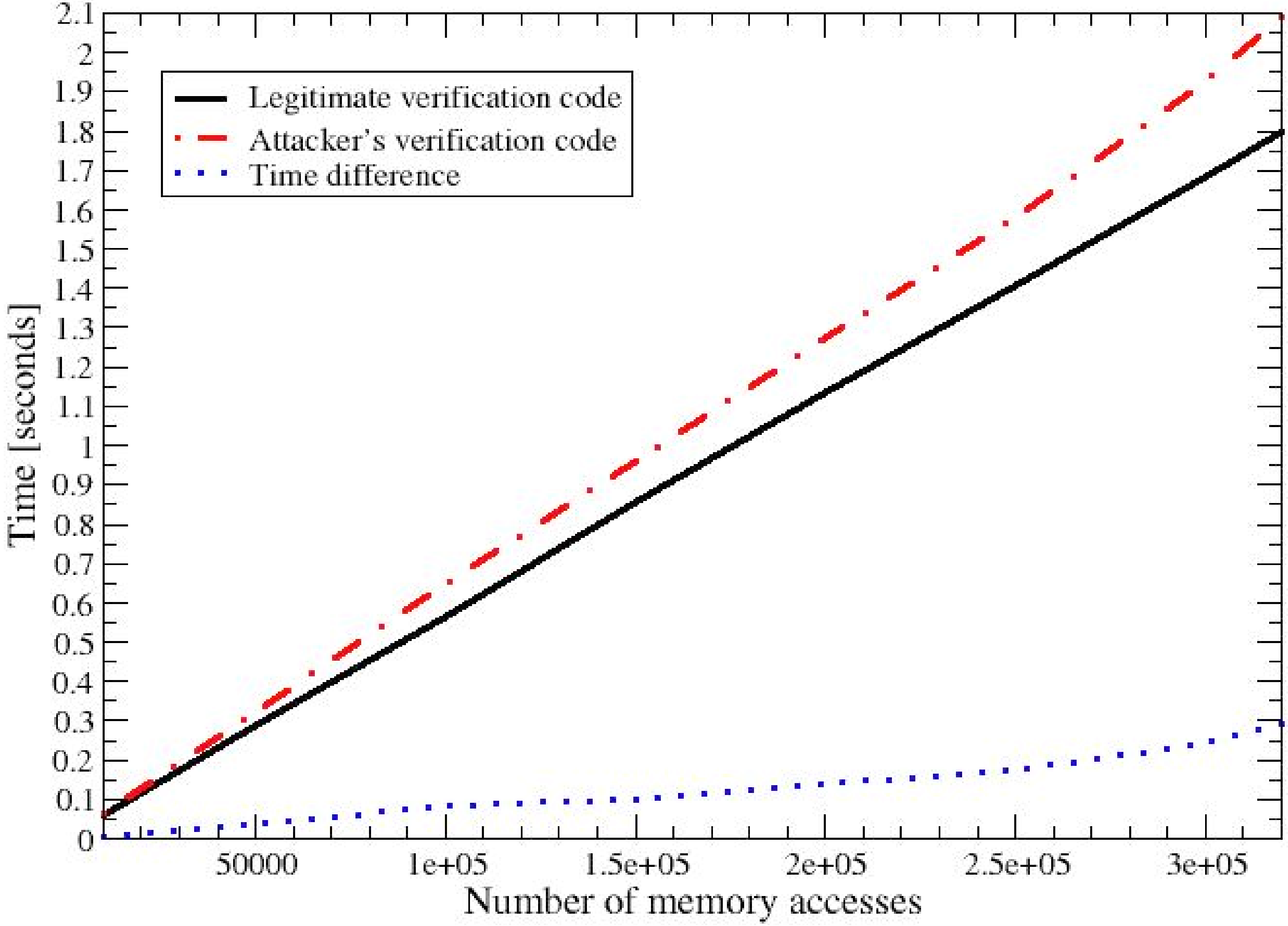
Incorporate output of hash into checksum

```
r7  = r7 + r0         add r7, r0
r7  = r7 << 1         lsl r7
r7  = r7 + carry_bit  adc r7, r5
r4  = zh              mov r4, zh
```

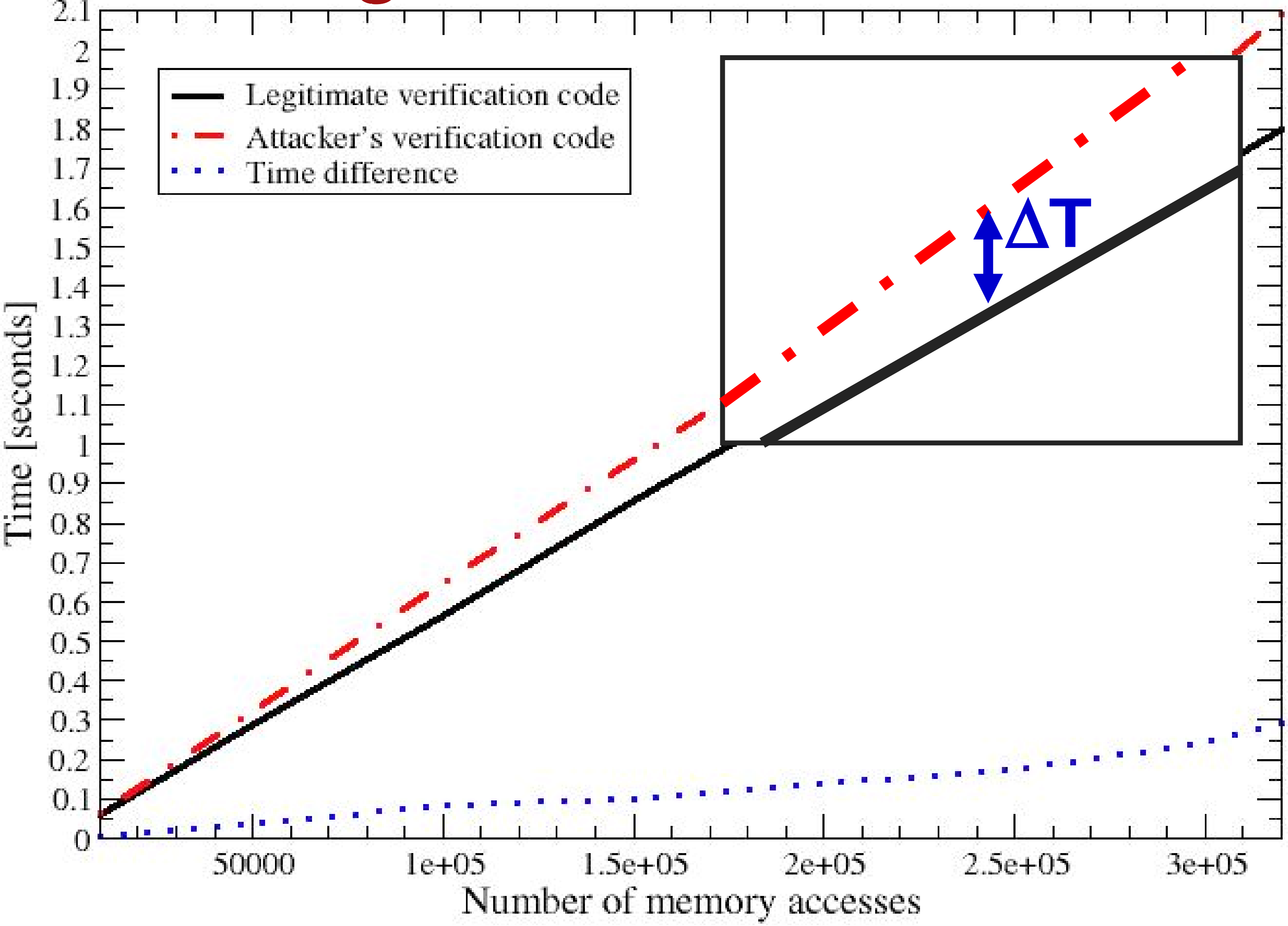
SWATT Advantage

- SWATT time advantage =
  running time of fastest attack code –
  running time of SWATT checksum code
- Verification procedure loop has 16 assembly instructions and takes 23 cycles
- Checks require “if” statements
  - Translates to compare + branch in assembly, requires 3 cycles
- Insertion of single “if” statement increases loop execution time
  - 13% increase per iteration in our implementation

Results


Legitimate verification code
Attacker's verification code
Time difference
Time [seconds]
Number of memory accesses
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2
2.1
50000
1e+05
1.5e+05
2e+05
2.5e+05
3e+05

Selecting Number of Iterations

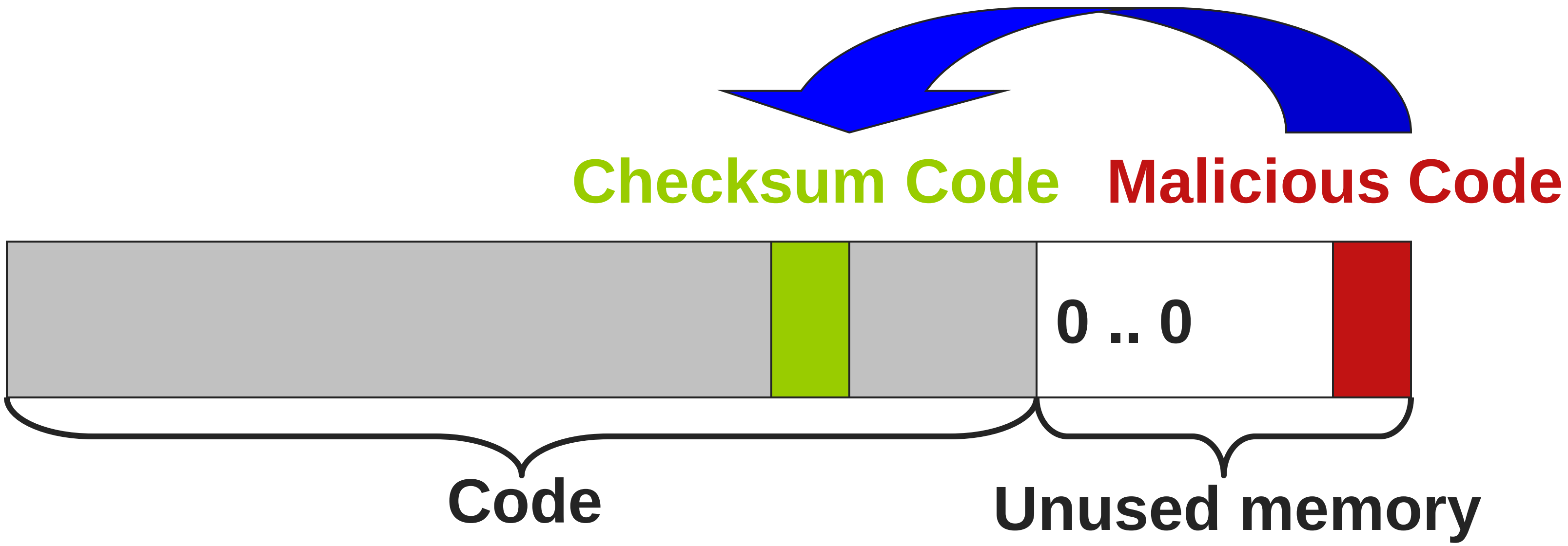


SWATT Extension

- Drawback: checksum computed over entire device memory
  - Does not scale to large memory sizes
  - Memory may contain secrets
  - Memory may contain dynamic data
- Solution: design checksum function that can check small memory areas
  - Memory area being checked includes checksum function
- Challenge: introduces many new attacks!

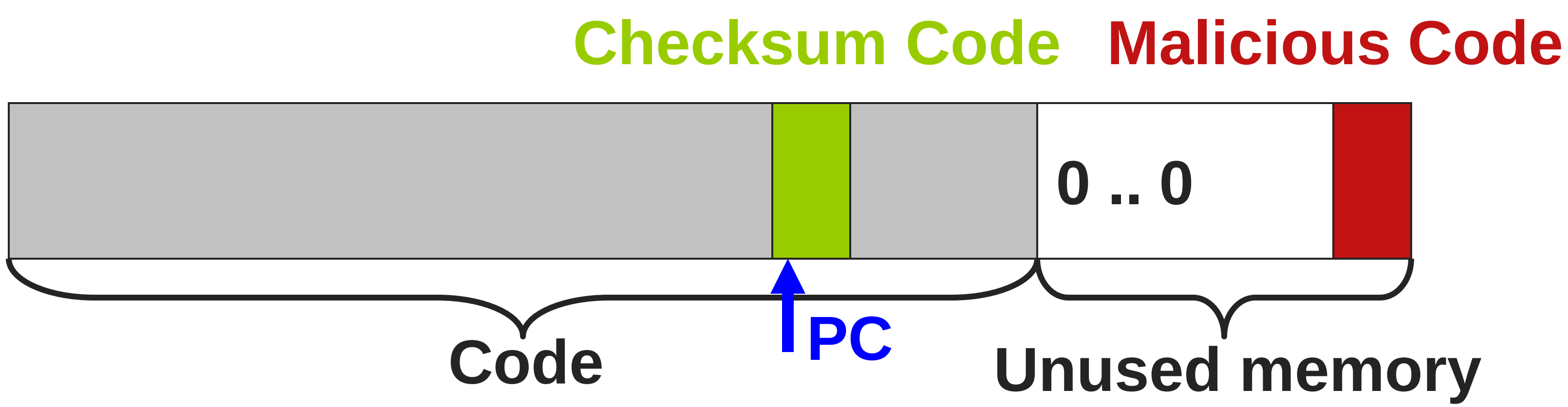
Attack on Partial Memory Verification

- Checksum computed over small part of memory
- Memory copy attack: attacker computes checksum over correct copy of memory

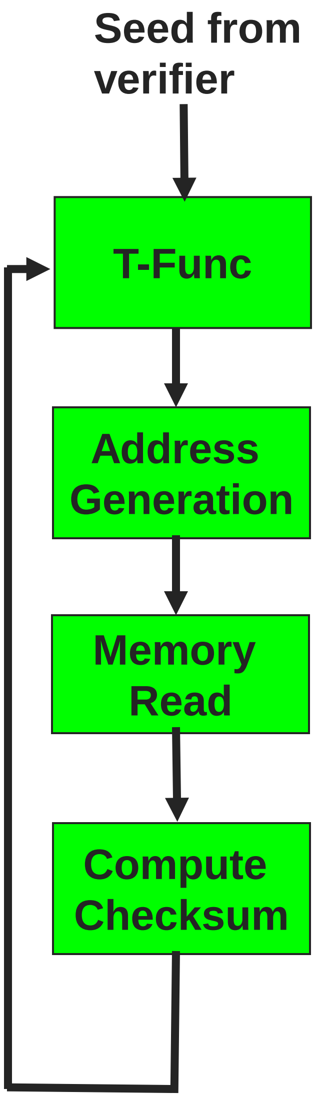


Improved Checksum Approach

- Add chksum function execution state to checksum
  - Include program counter (PC) and data pointer
- In memory copy attack, one or both will differ from original value
- Attempts to forge PC and/or data pointer increases attacker's execution time



ICE Assembler Code



Generate random number using T-Function

```
mov r15, &0x130
mov r15, &0x138
bis #0x5, &0x13A
add &0x13A, r15
```

Load byte from memory

```
add r0, r6
xor @r13+, r6
```

Incorporate byte into checksum

```
add r14, r6
xor r5, r6
add r15, r6
xor r13, r6
add r4, r6
rla r4
adc r4
```

Pioneer

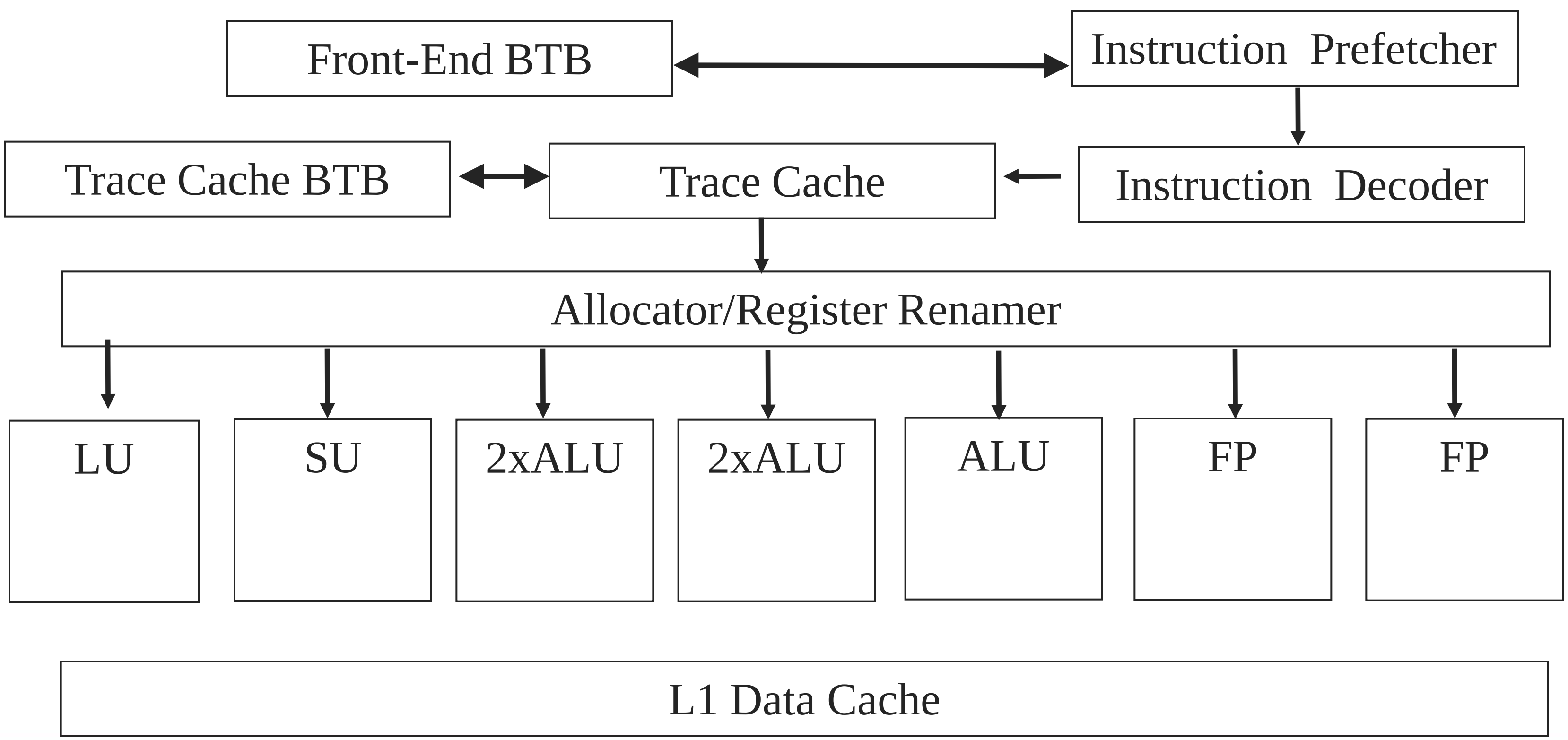
- First step to address untampered code execution on untrusted legacy hosts
- Implemented on Intel Pentium IV
  - Numerous challenges exist on this platform!
- Designed a kernel rootkit detector using Pioneer, to guarantee that correct code has executed on untrusted host

Challenges on x86 Platforms

- Execution time non-determinism
  - Out-of-order execution
  - Cache and virtual memory
  - Thermal effects
- Complex instruction set and architecture: how can we ensure that code is optimal?
- DMA-based attacks from malicious peripherals
- Interrupt-based attacks
  - SMM, NMI, etc.
- Attacks using exceptions
- Virtualization-based attacks

Pioneer Implementation

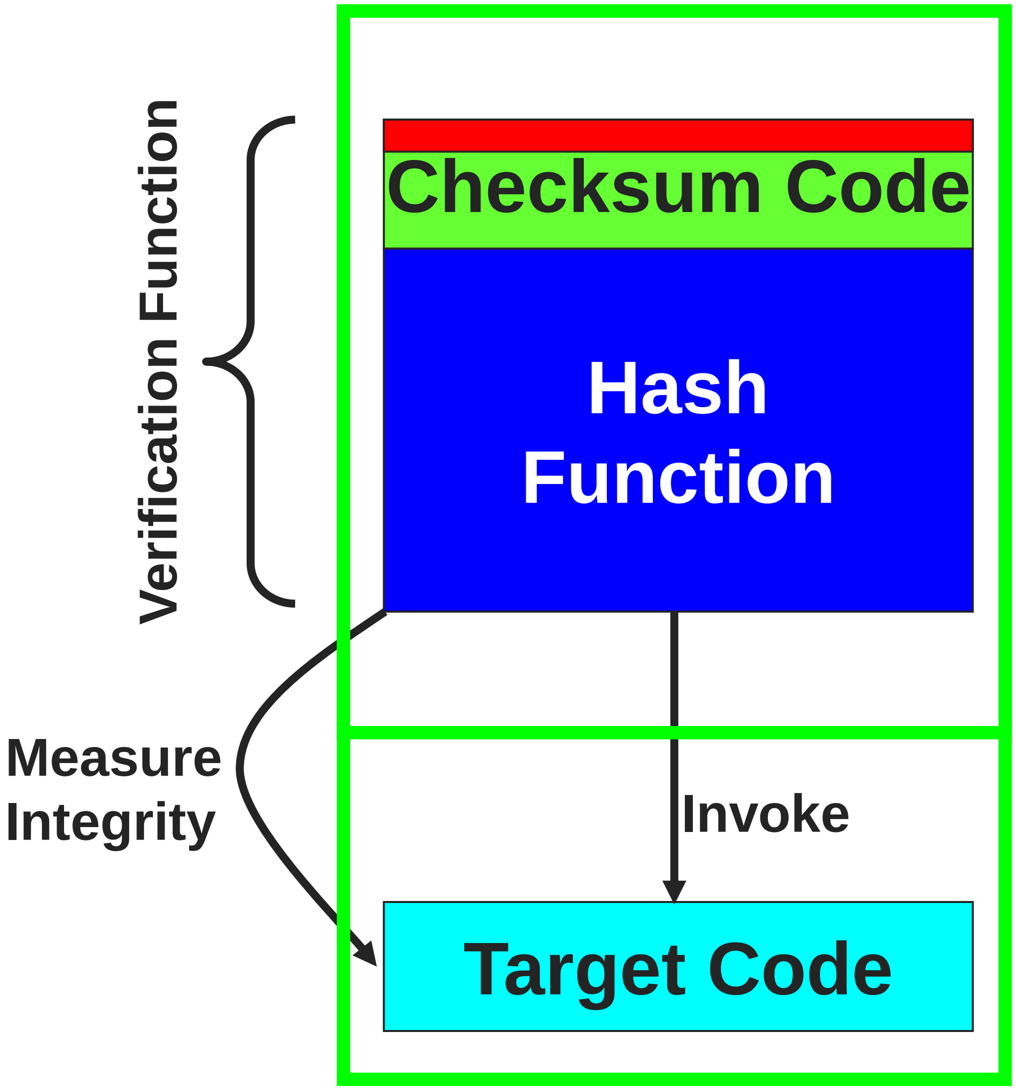
- Intel Xeon @ 2.8 GHz, Linux kernel 2.6.7
  - Intel Netburst Microarchitecture (Pentium 4)
  - Key: issue max 3 μops per cycle (3 way superscalar)
  - 64-bit extensions (no segmentation)



Verifiable Code Execution

- Goal: provide verifier with guarantee about what code executed on device
- Approach
  1. Verify code integrity through software-based attestation
  2. Set up untampered code execution environment
  3. Execute code

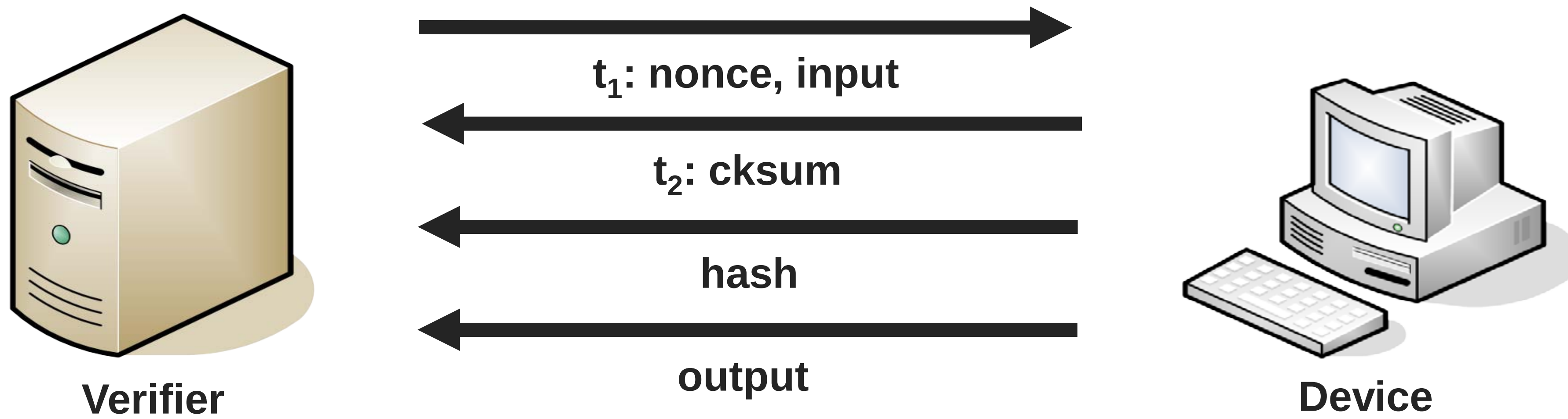
Design of Verification Function



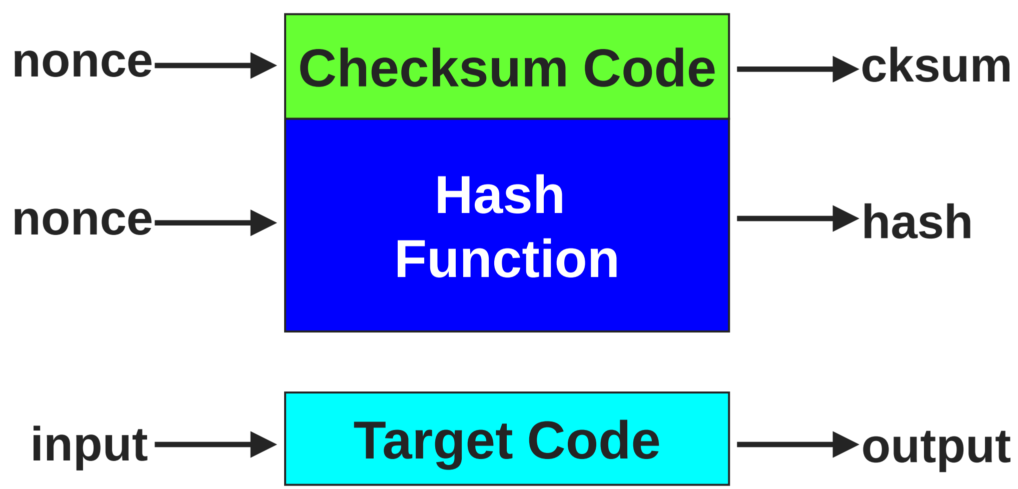
Root of Trust

- Compute checksum
- Set up untampered execution environment

The Pioneer Protocol



- **Successful verification if:**
  $t_2 - t_1$ < expected time &&
  cksum == exp. cksum



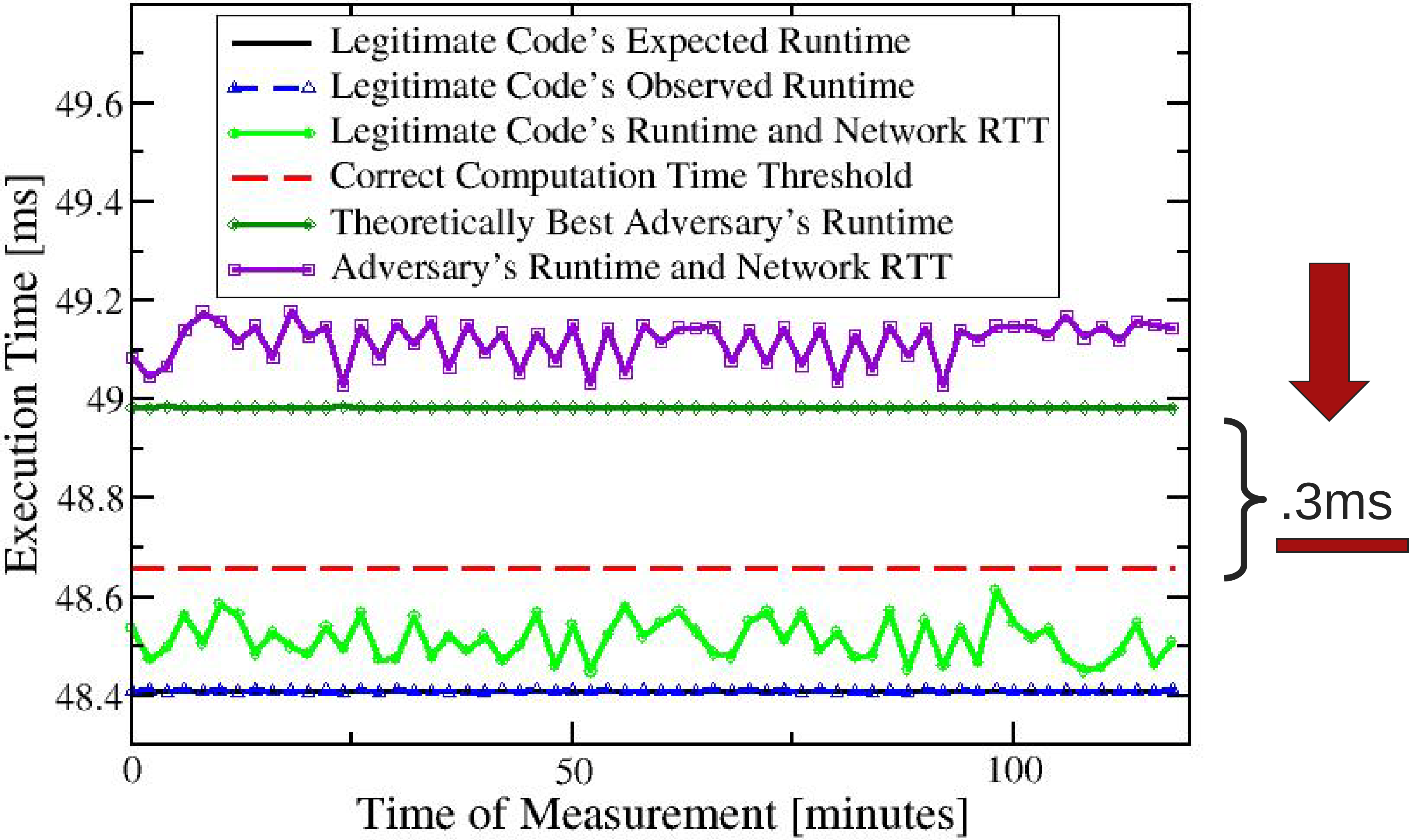
Desired Security Property

- Verifier's check is successful if and only if
  - Verification function is unmodified
  - Untampered execution environment is established
- Intuition: Checksum is incorrect or checksum computation slows down if attacker
  - Modifies verification function and forges correct checksum, or
  - Fakes creation of untampered code execution environment

Potential Attacks

- Execution tampering attacks
  - Running malicious OS/VMM at higher privilege level
  - Getting control through interrupts and exceptions
- Checksum forgery attacks
  - Memory-copy
  - Data substitution
  - Code optimization
  - Parallel execution
  - Exploiting superscalar architecture
  - Pre-computation/replay attacks

Results – Runtime Difference



Pioneer Discussion

- Verifier can obtain untampered execution guarantee for code executing on untrusted platform
- Similar attestation property to AMD SVM or Intel TXT
- Drawback: Requires defense against proxy attack