Uprooting Trust: Learnings from an Unpatchable Hardware Root-of-Trust Vulnerability in Siemens S7-1500 PLCs

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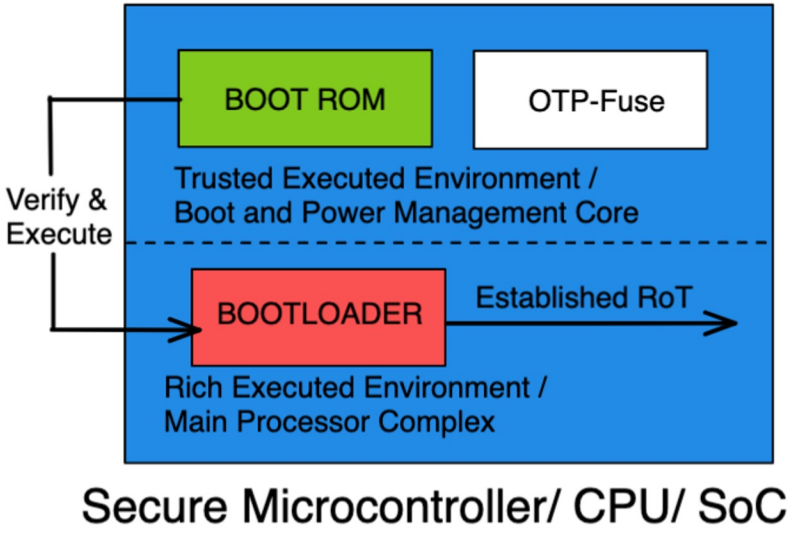
Hardware Root-of-Trust

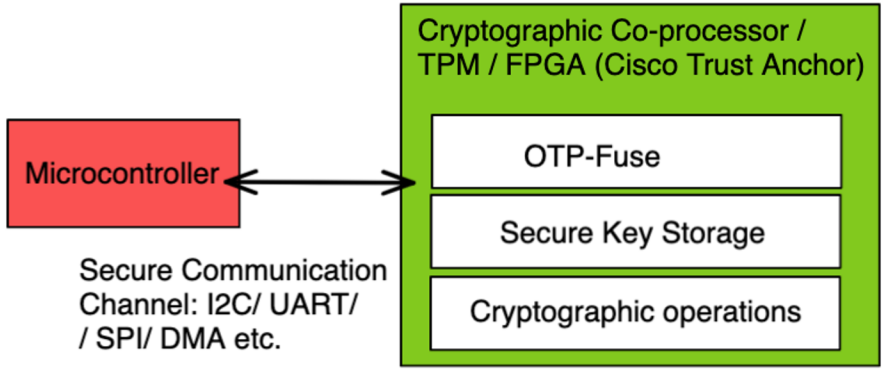
- What is Hardware Root-of-Trust (RoT)[1] for embedded systems?
  - A hardware RoT is a set of functions in a trusted computing module that securely stores cryptographic keys and performs secure operations
  - Secure cryptographic keys storage, cryptographic operations and anti-tampering
  - Provides a foundation for secure boot, secure firmware updates, and authentication
  - Ensures the integrity and security of critical systems

- Challenges in implementing discrete RoT components
  - Integration with the overall system architecture (With legacy systems that require backward compatibility)
  - Ensuring secure communication channels (Physically and protocol vise)
  - Protecting critical materials from exposure (Dedicated Crypto-coprocessor / TPM chip / On die cryptostorage and crypto accelerator)

Hardware RoT examples



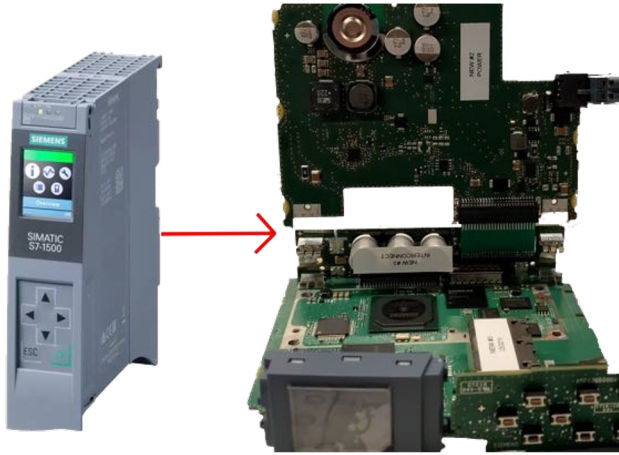
Hardware RoT examples



Dedicated Hardware RoT solutions

Background on Siemens S7-1500 PLCs

- Adoption in critical infrastructures (Critical Systems!)
  - Energy, Water, Transportation, Oil and gas: Nuclear facility
  - Manufactory and Building automation
- Stuxnet Target (early models) [2]
  - Discovered in June 2010
  - Targeted Siemens S7-300 and S7-400 PLCs
  - Altered programmable logic controller (PLC) code to cause physical damage to centrifuges used in uranium enrichment
  - First known malware to cause real-world physical damage to critical infrastructure
- Siemens PLC 31% market share
- Next generation S7-1500 PLCs
  - Hardware RoT implementation detail was NOT known by public



How Secure is Siemens S7-1500?

- Objective:
  - Determine how the S7-1500 PLC is protecting itself from adversarial activity.
- Challenges:
  - Encrypted Firmware!
  - No Debug Access (JTAG[3], Serial[4], etc)
  - **Opaque Boot Process**

Challenge

Limited visibility - need to get creative to understand how RoT is protecting these embedded platforms.

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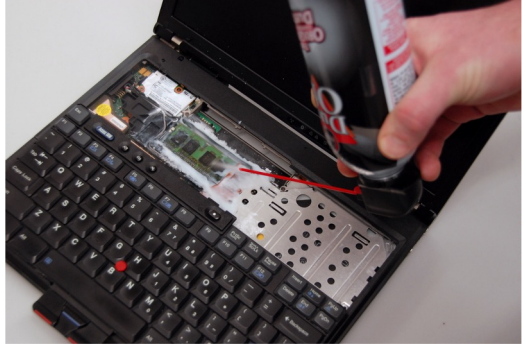
Cryo-mechanical memory extraction

- Data remanence property of DRAM
- Leak secret authentication material in device memory

“Cold boot” => Cryomechanical Memory Extraction

Cold Booting is a reverse-engineering activity that leverages the memory-resonance effect to pin certain bits in memory only during a boot or restart.

Traditional Cold-Boots attacks rely on physical peripherals (DIMM) or Debug access (JTAG).



Traditional Cold boot Attack

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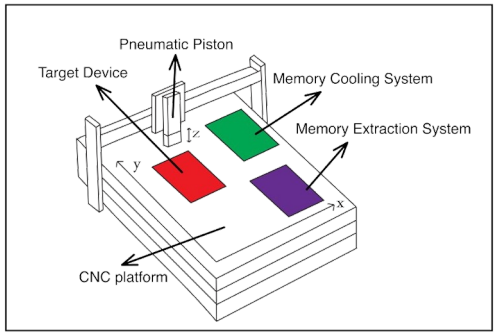
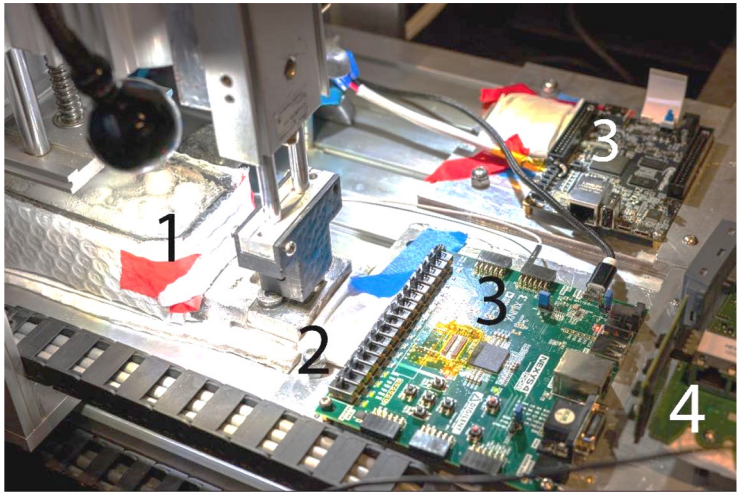
Engineered a novel CNC-based platform which transferred the physical dedicated RAM integrated circuit to transfer the chip between the target platform, cooling system, and a memory readout device.

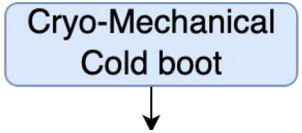
Note: Detail of this work will be provided in a separate paper to appear at WOOT’23 [5]





CNC-based Cryo-mechanical memory extraction platform

Revealing Trust



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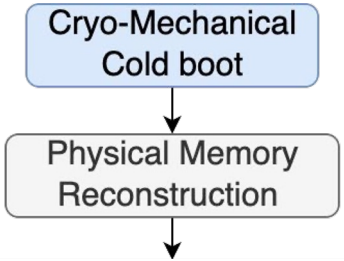

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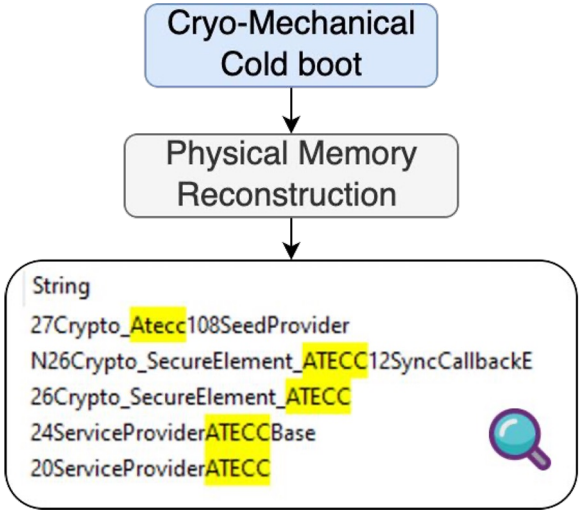

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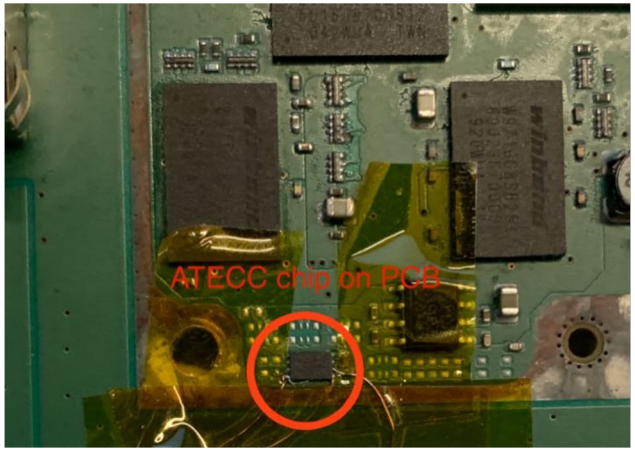

Easily accessible I2C bus for ATECC Crypto Co-Processor

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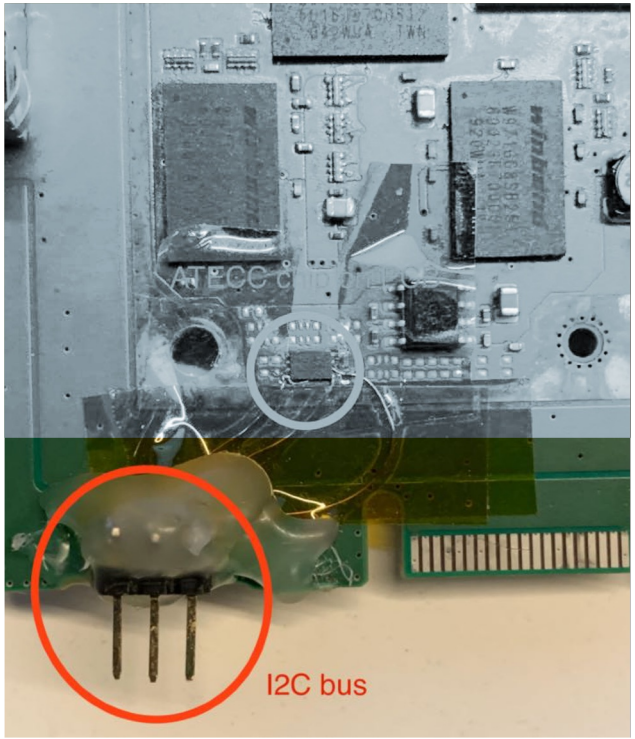
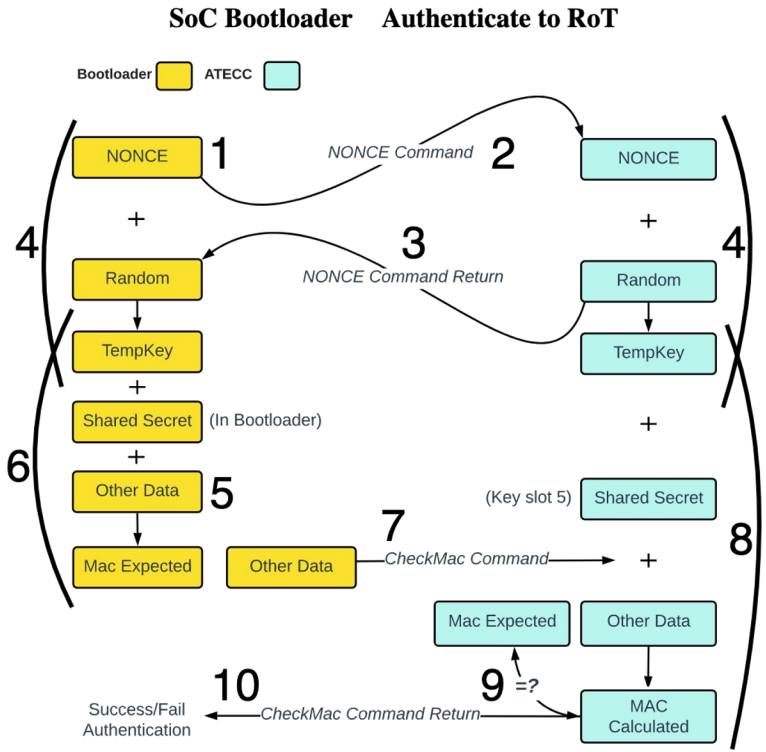


Easily accessible I2C bus for ATECC Crypto Co-Processor

Trusting Trust Step 1: Authenticate the bootloader



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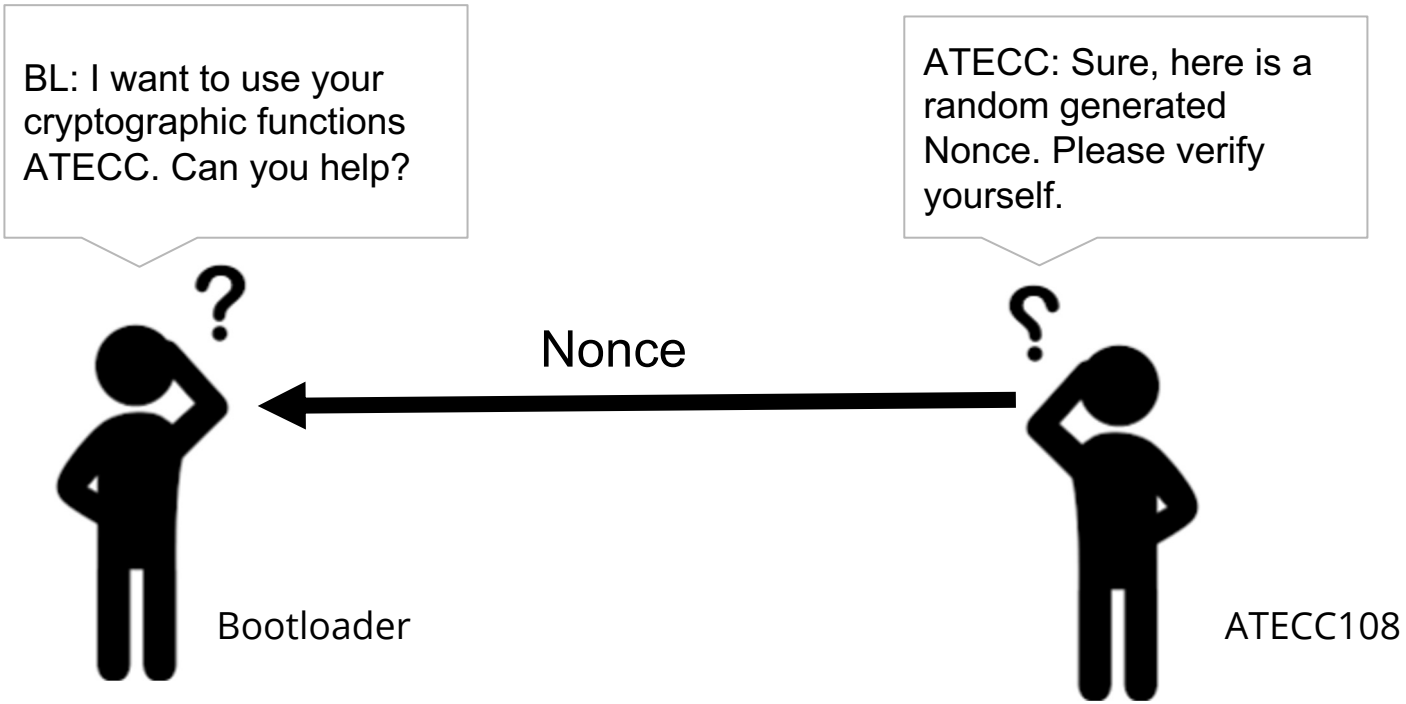

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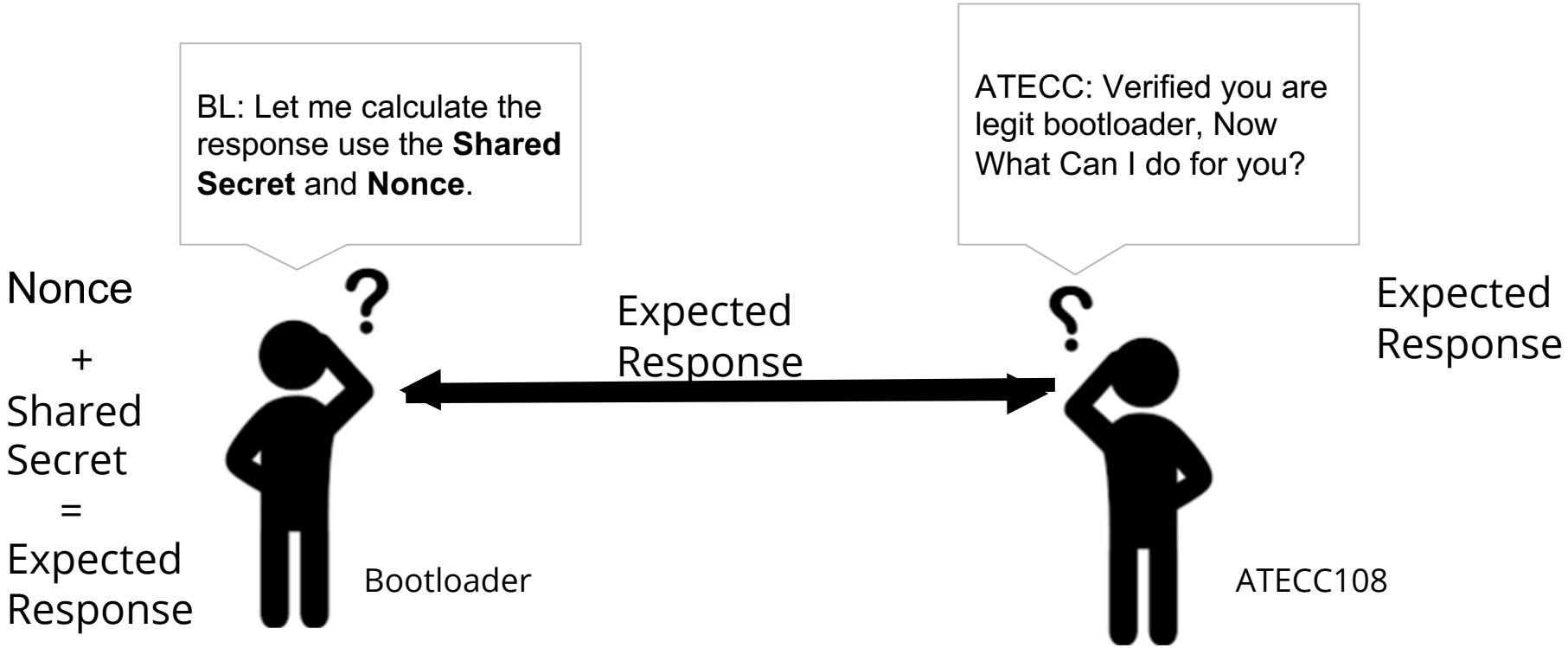
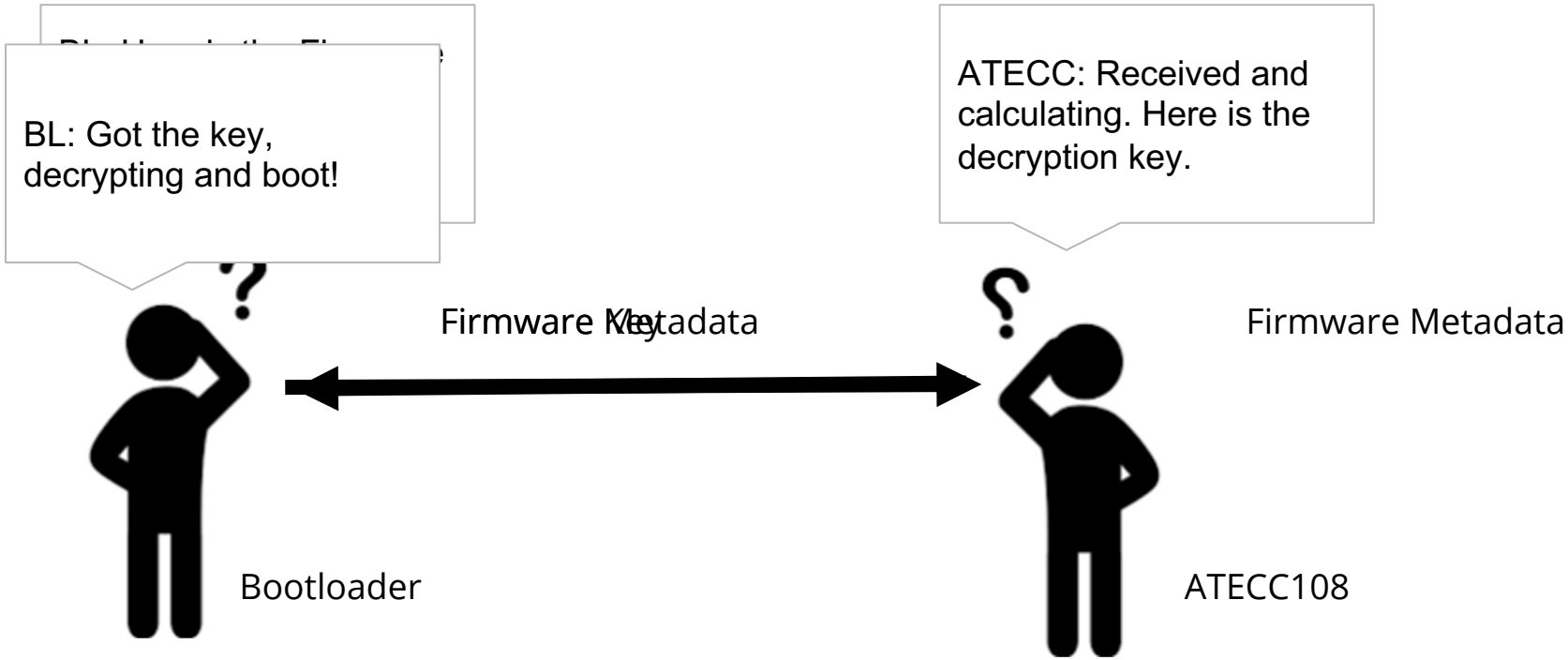


Trusting Trust Step 2: Decryption key generation



trusting Trust

I2C communication bus is **NOT** vulnerable to replay attack: Nonce is randomly generated each time of the authentication process

Bootloader's authenticity is being verified by the ATECC when establish RoT

Firmware is being protected and verified by symmetric AES-CBC encryption

Firmware Master key material to generate Firmware decryption key is protected by the ATECC chip anti-tampering hardware design.

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Successfully decryption of the Firmware  Firmware can be trusted

The Microcontroller blindly trust and execute whatever data it decrypts.This is **WRONG**.

Mistrusting Trust

I2C communication bus **exposes** the entire authentication process!!

ATECC chip act as a peripheral: **Cannot** verify the integrity of the **bootloader** before execution, instead only Shared Secret is verified.

The **Shared Secret** is **exposed** in the plain text bootloader (thank you cold boot robot!).

Symmetric Firmware verification goes **both way**

ATECC chip doesn't need to be soldered on Siemens S7-1500 PLC PCB to operate.

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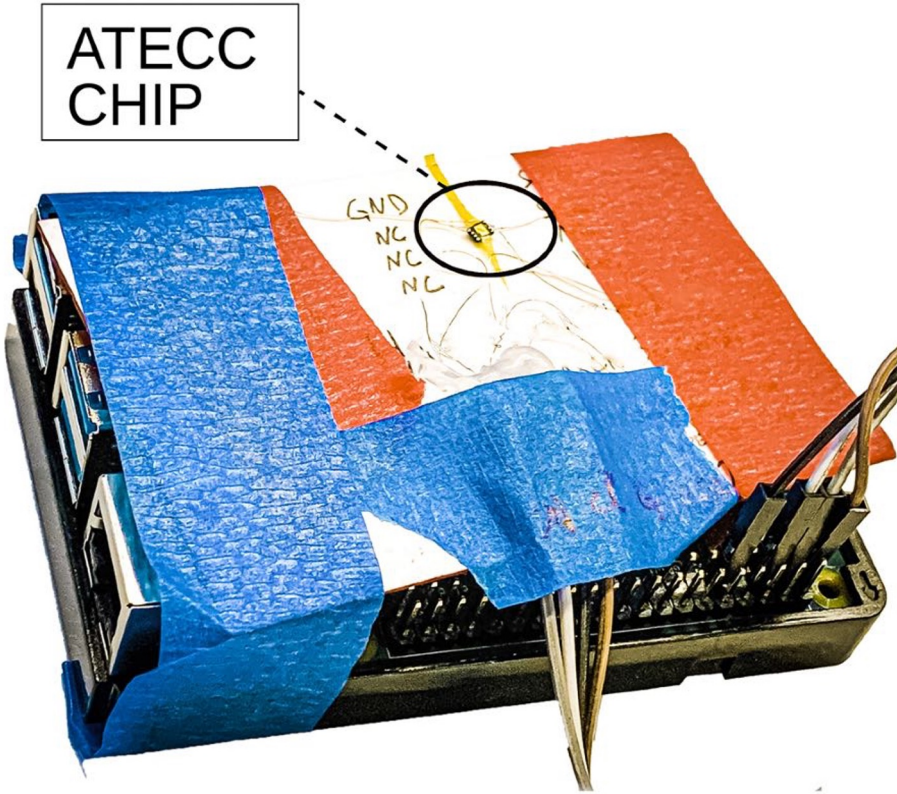

ATECC chip as Oracle through Raspberry Pi

Impact

Adversaries may use the hardware RoT protections as a lever against the very same mechanisms meant to thwart attackers.

One single S7-1500 PLC can be used as an oracle to decrypt, re-encrypt, re-authenticate, tampered firmware for an entire generation of devices (Over 100 models affected**)**.

The designs flaws we discovered constitute a physical hardware vulnerability which cannot be patched by vendor security updates.

As embed not frequentl Γ for years to come.

Affected Product and Versions	Remediation
SIMATIC Drive Controller CPU 1504D TF (6ES7615-4DF10-0AB0): All versions	Currently no fix is planned See recommendations from section Workarounds and Mitigations
SIMATIC Drive Controller CPU 1507D TF (6ES7615-7DF10-0AB0): All versions	Currently no fix is planned See recommendations from section Workarounds and Mitigations

Conclusion - What Can We Learn?

100% secure hardware does not exist! Too much trust placed in ‘secure’ hardware is a double-edged sword!

Trusted Peripherals do not exist! Attestation should ideally be both forward and backwards facing to ensure device has not been compromised.

Low-Cost Cryptographic processors are a useful for adding cryptography into systems which would otherwise go without - however, integrators should carefully consider implementation and approach integration from a Zero-Trust perspective.

References

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[3] I. . W. Group et al., “IEEE std. 1149.1 — standard test access port and boundary-scan architecture,” Retrieved March, vol. 9, 2017.

[4] U. Nanda and S. K. Pattnaik, “Universal asynchronous receiver and transmitter (UART),” in 2016 3rd International Conference on Advanced Computing and Communication Systems (ICACCS), vol. 01, 2016, pp. 1–5.

[5] Y. Wu, G. Skipper, and A. Cui, “Cryo-mechanical RAM content extraction against modern embedded systems,” In 2023, 17th IEEE Workshop on Offensive Technologies (WOOT’23). To appear.

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