
# Everybody be Cool, This is a Robbery!

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## Disclaimer

- The Donjon (Ledger Security Team) assess the security of technologies used by Ledger
- The vulnerabilities in this presentation were found during a security audit
- We don’t want to single out one particular vendor
- Goals:
  - Raise awareness about HSM security
  - Lay the groundwork for other security researchers
  - Improve the overall security

# Agenda

- What is an HSM?
- Characteristics of the HSM assessed
- Brief intro to PKCS #11
- Developing tools for vulnerability discovery
- Vulnerability research and exploitation

# HSM?

# What is an HSM?

- Security enclaves to store and process sensitive data
  - Computes cryptographic operations
  - Generate keys
  - Keys never leave the enclave
- Physical computing device:
  - PCI card or network appliance
  - One or more crypto-processors
  - Anti-tampering countermeasures

## Usage Examples

- PKI:
  - CA’s private key generation and storage, certificates signing
  - Requirement for all CAs (CA-Browser Forum Baseline)
- Banking: CVV verification, transaction authorization, payment card personalization
- Telecommunications: strong cryptographic material for key injection by SIM manufacturer
- DNSSEC: storage of Root Zone keys (FIPS 140-2 level 4 HSM)
- Cloud services: encryption/decryption of customer data
- HSM-as-a-Service: Google, Microsoft, Amazon, etc.

## How much does it cost?

- Only a few vendors, no market share information
- No public prices, large range of models for each vendor
- According to Hackable Security Modules (REcon Brussels 2017):
  - Brand X, Model A: $29,500.00
  - Brand Y, Model B: $9,500.00
  - Brand Z, Model C: $15,000.00

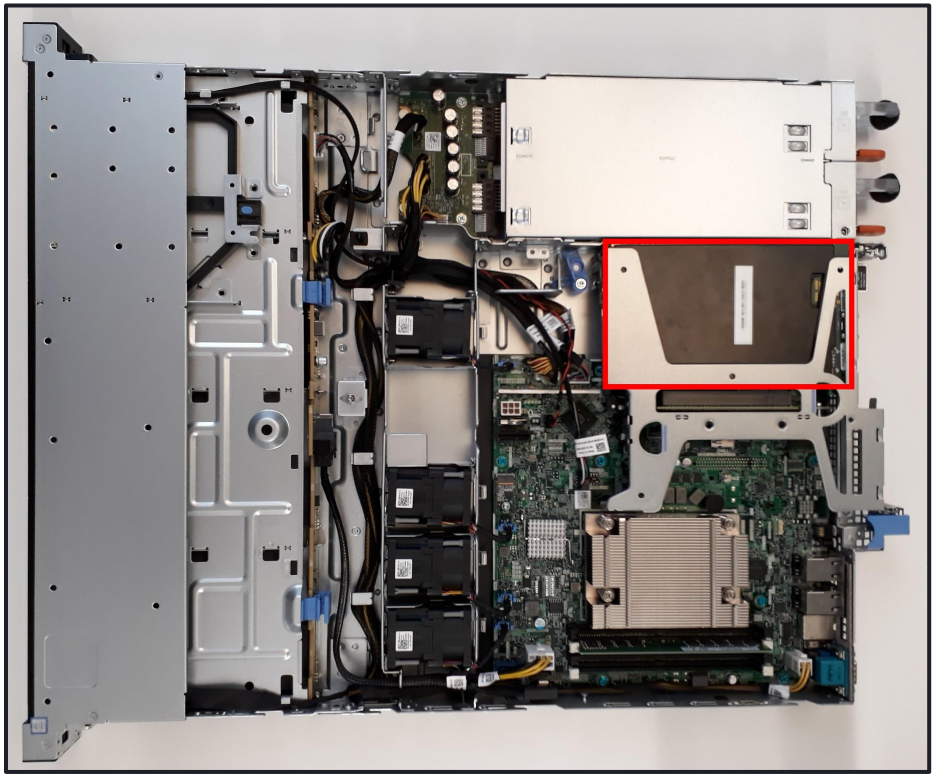
# Appliance (Host + HSM)

HSM

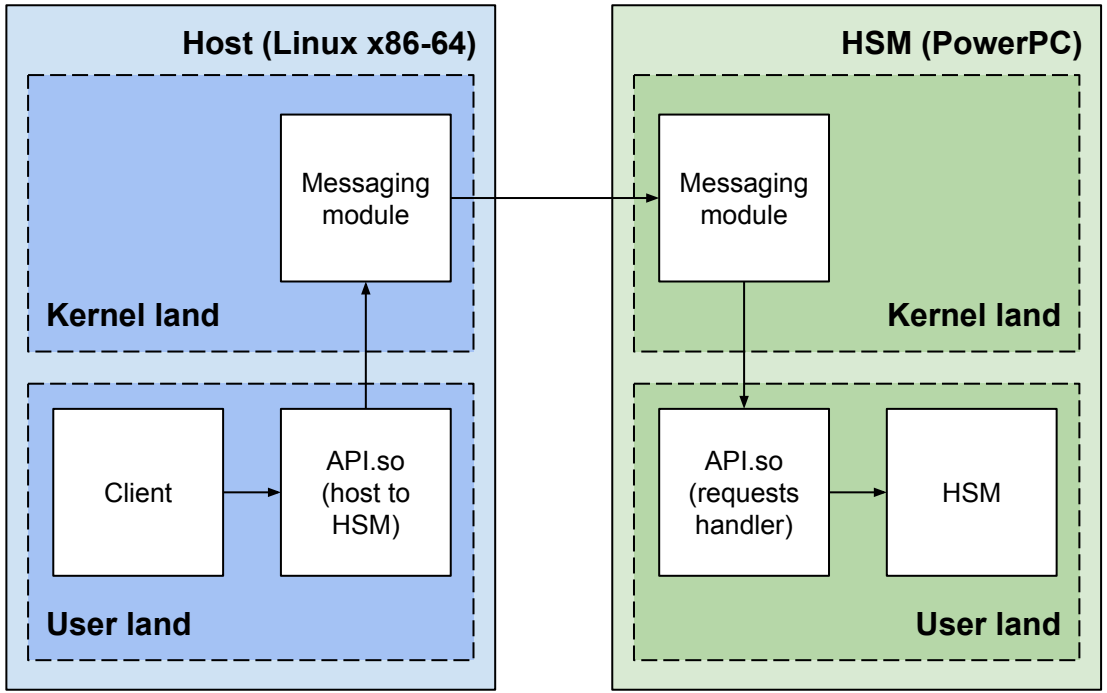
- PCI Express card
  - Also available as a network appliance)
- FIPS 140-2 level 3 certified
- Components are coated in epoxy
- USB and serial ports for an optional smart-card reader
- Ethernet controller without connector

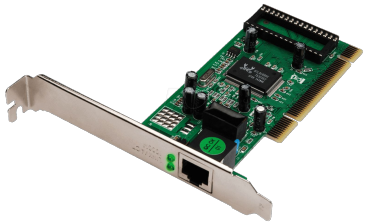
Host

- Standard Linux server
- Linux Kernel modules
- CLI and GUI software, SDK



# Communication: Shared DRAM



# FIPS 140-2: Security Requirements for Cryptographic Modules

- U.S. government computer security standard
- Level 1: basic software requirements
- Level 2, 3, 4: physical requirements
  - Level 3: Detection and response to attempts at physical access, use or modification of the cryptographic module

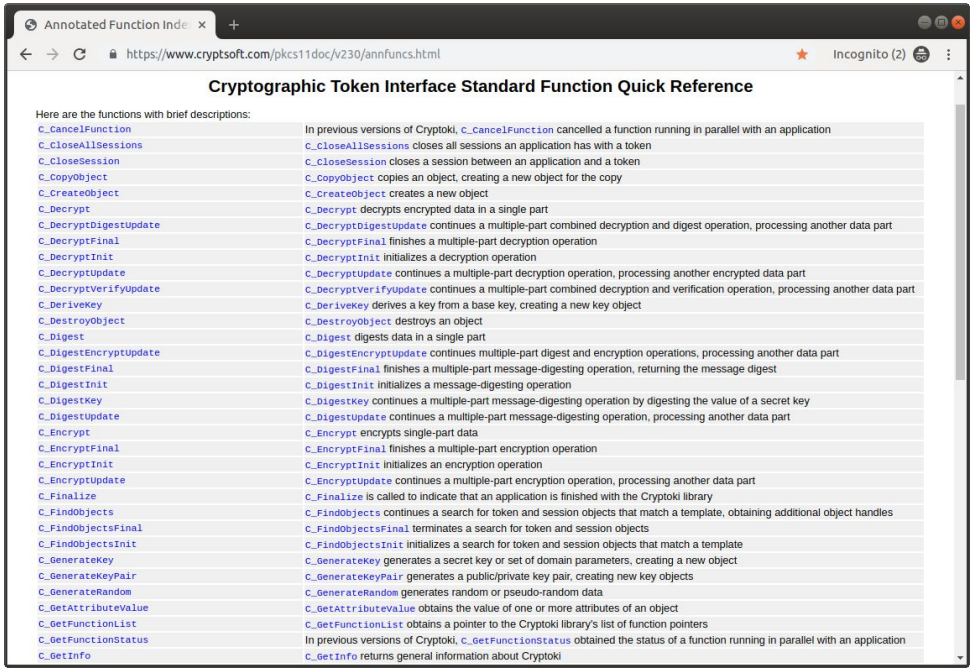
Not a certification about software attacks

# PKCS #11

# PKCS #11: Introduction

- Generic interface to communicate with a cryptographic device
  - Smart card
  - HSM, etc.
- Portable API: Cryptographic Token Interface (Cryptoki)
  - Session management
  - Cryptographic objects manipulation
  - Operations on these objects (encryption, decryption, signature, etc.)

# Cryptographic Token Interface




**Cryptographic Token Interface Standard Function Quick Reference**

Here are the functions with brief descriptions:

| | |
|---|---|
| C_CancelFunction | In previous versions of Cryptoki, C_CancelFunction cancelled a function running in parallel with an application |
| C_CloseAllSessions | C_CloseAllSessions closes all sessions an application has with a token |
| C_CloseSession | C_CloseSession closes a session between an application and a token |
| C_CopyObject | C_CopyObject copies an object, creating a new object for the copy |
| C_CreateObject | C_CreateObject creates a new object |
| C_Decrypt | C_Decrypt decrypts encrypted data in a single part |
| C_DecryptDigestUpdate | C_DecryptDigestUpdate continues a multiple-part combined decryption and digest operation, processing another data part |
| C_DecryptFinal | C_DecryptFinal finishes a multiple-part decryption operation |
| C_DecryptInit | C_DecryptInit initializes a decryption operation |
| C_DecryptUpdate | C_DecryptUpdate continues a multiple-part decryption operation, processing another encrypted data part |
| C_DecryptVerifyUpdate | C_DecryptVerifyUpdate continues a multiple-part combined decryption and verification operation, processing another data part |
| C_DeriveKey | C_DeriveKey derives a key from a base key, creating a new key object |
| C_DestroyObject | C_DestroyObject destroys an object |
| C_Digest | C_Digest digests data in a single part |
| C_DigestEncryptUpdate | C_DigestEncryptUpdate continues multiple-part digest and encryption operations, processing another data part |
| C_DigestFinal | C_DigestFinal finishes a multiple-part message-digesting operation, returning the message digest |
| C_DigestInit | C_DigestInit initializes a message-digesting operation |
| C_DigestKey | C_DigestKey continues a multiple-part message-digesting operation by digesting the value of a secret key |
| C_DigestUpdate | C_DigestUpdate continues a multiple-part message-digesting operation, processing another data part |
| C_Encrypt | C_Encrypt encrypts single-part data |
| C_EncryptFinal | C_EncryptFinal finishes a multiple-part encryption operation |
| C_EncryptInit | C_EncryptInit initializes an encryption operation |
| C_EncryptUpdate | C_EncryptUpdate continues a multiple-part encryption operation, processing another data part |
| C_Finalize | C_Finalize is called to indicate that an application is finished with the Cryptoki library |
| C_FindObjects | C_FindObjects continues a search for token and session objects that match a template, obtaining additional object handles |
| C_FindObjectsFinal | C_FindObjectsFinal terminates a search for token and session objects |
| C_FindObjectsInit | C_FindObjectsInit initializes a search for token and session objects that match a template |
| C_GenerateKey | C_GenerateKey generates a secret key or set of domain parameters, creating a new object |
| C_GenerateKeyPair | C_GenerateKeyPair generates a public/private key pair, creating new key objects |
| C_GenerateRandom | C_GenerateRandom generates random or pseudo-random data |
| C_GetAttributeValue | C_GetAttributeValue obtains the value of one or more attributes of an object |
| C_GetFunctionList | C_GetFunctionList obtains a pointer to the Cryptoki library's list of function pointers |
| C_GetFunctionStatus | In previous versions of Cryptoki, C_GetFunctionStatus obtained the status of a function running in parallel with an application |
| C_GetInfo | C_GetInfo returns general information about Cryptoki |

- Few exposed functions (~70)
- But > 300 standard mechanisms, + proprietary mechanisms.

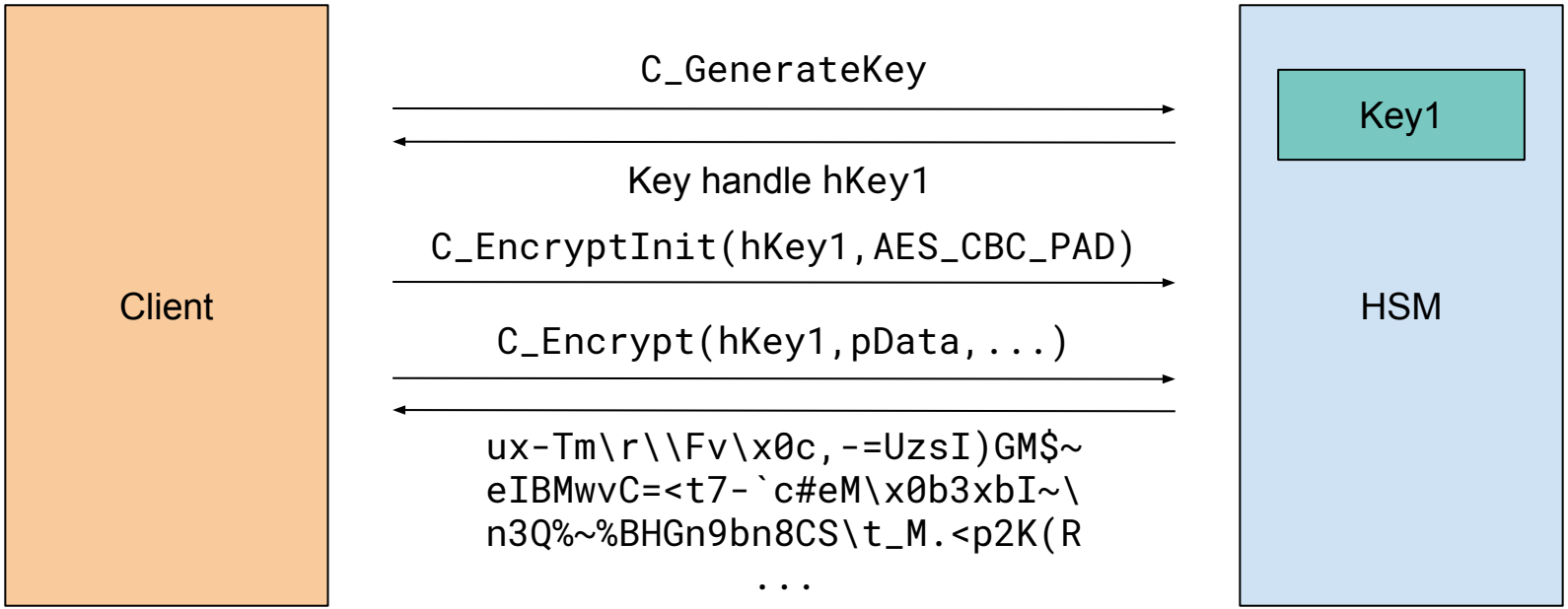
## Mechanisms

- Define how to perform a cryptographic operation.
- Mechanisms for encryption, decryption, hashing, wrapping, etc.
- Depends on the device. HSM: many mechanisms.
  - `CKM_SHA512_HMAC`
  - `CKM_RSA_PKCS_KEY_PAIR_GEN`
  - `CKM_WRAPKEY_AES_CBC`
  - `CKM_AES_GCM`
  - Mechanisms for telecom, banking...
- Some mechanisms take parameters: IV, salt, etc.

# Objects

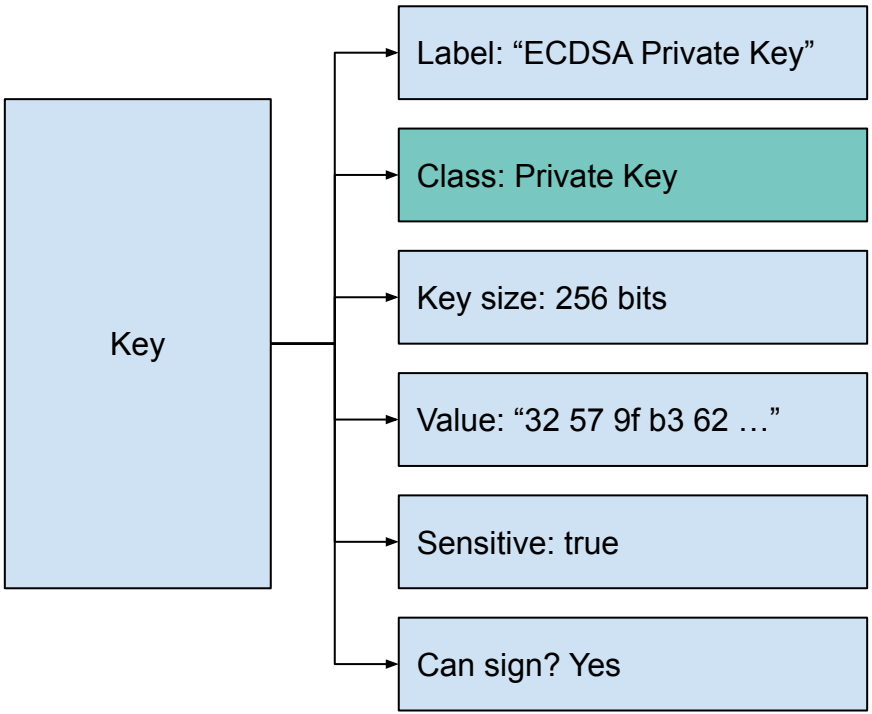
- 3 types
  - Keys: secret, public, private
  - Certificates
  - Data: DSA / ECDSA parameters, etc.
- Cryptoki manipulates objects through their handles

# Objects



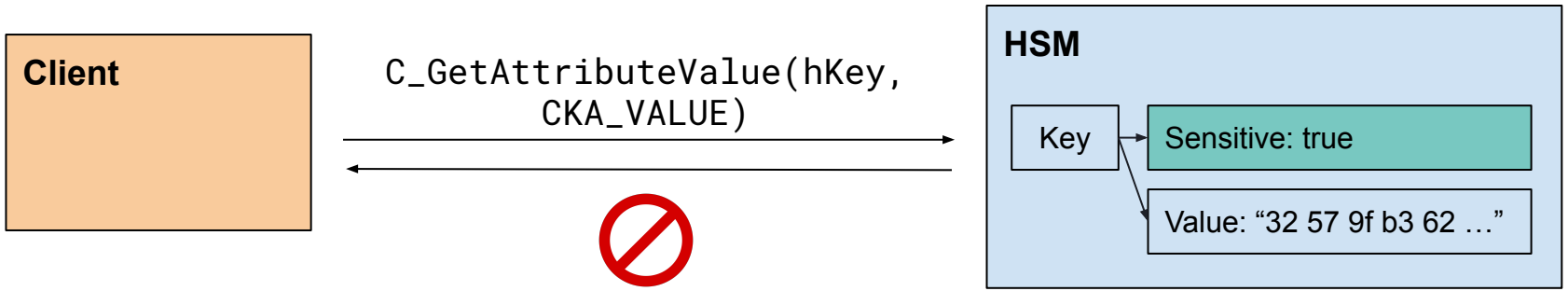

Key values are (usually) not sent to the host

# Object attributes

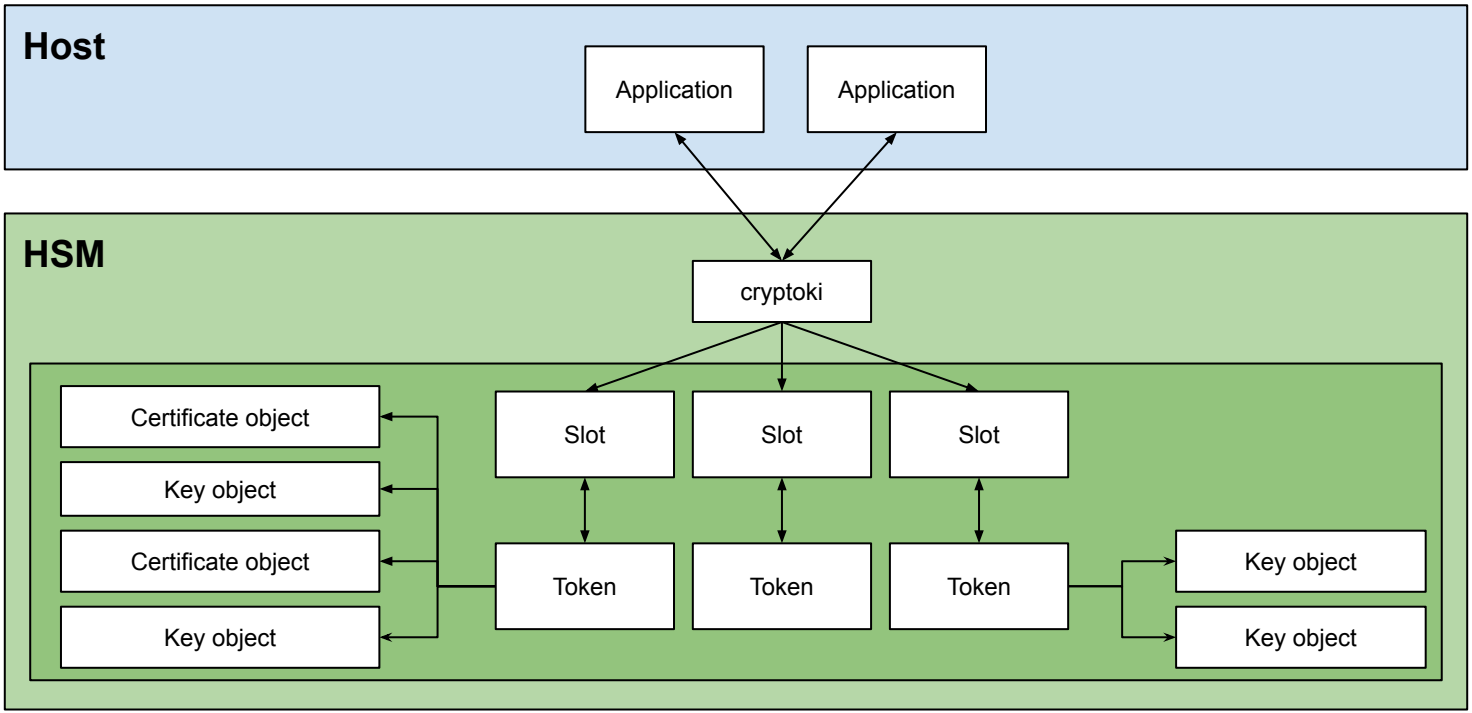


# Attributes for Security

- Sensitive: value cannot be extracted in plain text, must be wrapped
- Not extractable: value cannot be exported
- Private: user has to be logged to access the object



# Slots and tokens



## Threats

- Unauthenticated attackers gain access to private objects
- Attackers extracts keys marked as non-extractable
- Authenticated attackers gain access to other slots
- ...

Our goal: access to all objects from all slots, without authentication

## State of the art

- On the security of PKCS #11 (Clulow, CHES, 2003)
  - Much information on PKCS #11 security model
  - Encrypt then wrap, weak mechanisms…
- Your Bitcoin Wallet may be at risk: SafeNet HSM key-extraction vulnerability (Cem Paya, Gemini, 2015)
  - Weak mechanism in PKCS #11, enabled by default by SafeNet
- Hackable Security Modules - Reversing and exploiting a FIPS 140-2 Level 3 HSM firmware (Fotis Loukos, REcon Brussels, 2017)
  - Exotic CPU, focused on reverse engineering

Our contribution: attacks on PKCS #11 implementations

# Vulnerability Research and Exploitation

# Threat Model

- The attacker is able to execute commands on the host
  - Insider threats
  - Malicious data center employee with physical access
  - Administrator account compromise
  - Software vulnerabilities on the host
  - etc.

## Firmware

- CD-ROM provided by the vendor
- CLI and GUI software
- PKCS #11 API examples in C
- Documentation for developers and administrators
- Firmware update: signed, unencrypted, Linux 2.6.28.8 for PowerPC (2009)

- Big Cryptoki library, very few other files
- Few weeks of reverse engineering

# Tooling

## Module

- Unexpected option: new features can be added thanks to custom *modules*
- Expected usage:
  - PKCS #11 functions hook
  - New handlers on custom messages
- Not a vulnerability: requires admin privileges for loading
- Internals:
  - The SDK along a toolchain produces PowerPC ELF binaries from C source code
  - Modules loaded into the main process thanks to `dlopen()`
  - No `libc`

## Shell

```
user@host:~$ ./module-shell --init
[*] uploading busybox-powerpc to /sbin/busybox
[*] creating symlinks (might take a few seconds)

user@host:~$ ./module-shell id
uid=0 gid=0

user@host:~$ ./module-shell ps fauxwww
PID   USER     TIME   COMMAND
    1 0          0:00 /init
    2 0          0:00 [kthreadd]
…
 1086 0          0:00 /sbin/busybox ps fauxwww
```

## Debugger

- The main process handles communication
- SDK functions (using standard communication channels) can't be used
- *Auxiliary* channels available (eg. shared memory)
- `gdb` on the host, `gdbserver` on the HSM
- Additional challenge:
  - The main process is monitored with *ptrace*
  - Reboots the HSM in case of crashes

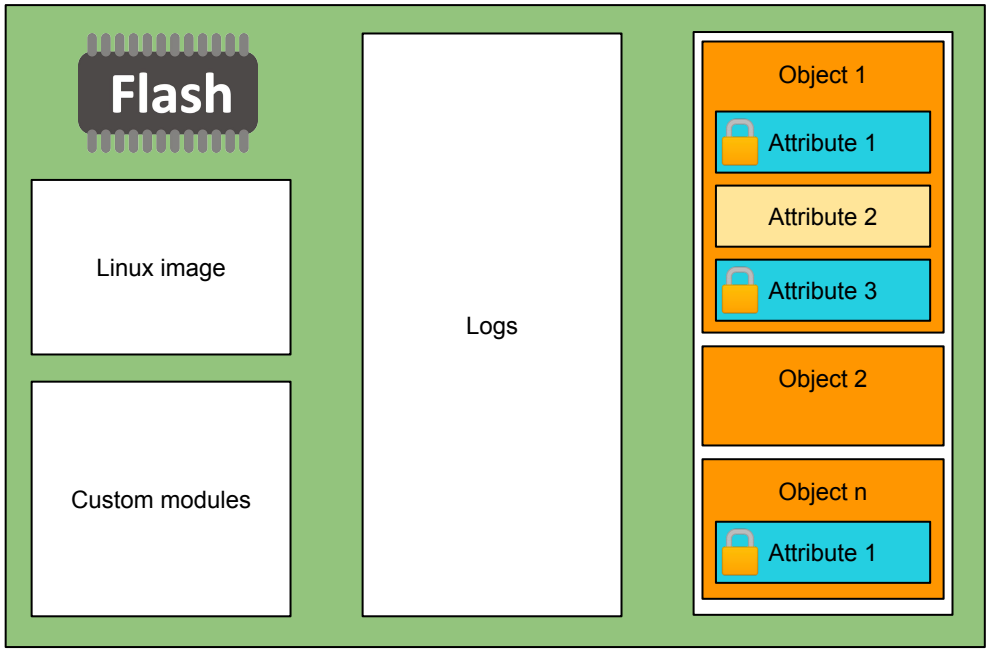
## Information gathered

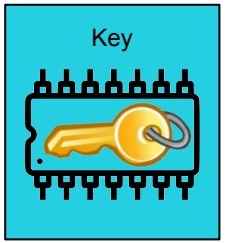
- Dynamic analysis ability
  - Every process run as *root*
  - No hardening nor mitigation options
- The bootloader is a slightly modified version of U-Boot:
  - No secure boot mechanism

## Storage

- Persistent data stored to a 64 Mb flash memory on the PCI card:
  - Linux image
  - Custom modules
  - Logs
  - PKCS #11 objects
- PKCS #11 objects and authentication information are stored into a dedicated partition using a proprietary filesystem
- Sensitive object attributes are stored encrypted and decrypted on-the-fly

# Storage


Flash
Linux image
Custom modules
Logs
Object 1
Attribute 1
Attribute 2
Attribute 3
Object 2
Object n
Attribute 1


Key

## Storage

- No logical separation across HSM slots
- Each objects from each slots are stored in the same flash partition
- Reverse engineering shows that secrets are stored with the same key

→ Code execution on the HSM allows to dump all secrets

# First Code Execution

## Grepping for memcpy

- ~700 calls to `memcpy` in `API.so`
- Manual analysis:
  - `memcpy` called from PKCS #11 functions
  - Variable size parameter and stack destination
- `MilenageDerive` is the only one vulnerable to a stack overflow
- `CKM_MILENAGE_DERIVE` mechanism:
  - UMTS (Universal Mobile Telecommunication System) authentication algorithms
  - Used by HSMs in Telco environment
  - Key derivation for *f3*, *f4*, *f5* and *f5** MILENAGE functions

# Bug

- `CKM_MILENAGE_DERIVE` requires a handle on a 16-byte MILENAGE key
- Stored as a generic secret key, installed with `CreateSecretKey`
- `MilenageDerive` does not check the length of the secret key

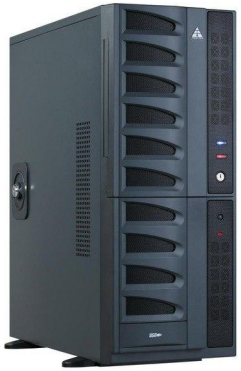
```
int MilenageDerive(...) {
    uint8_t aesKey[16];
    ...
    GetObjectClassAndKeyType(keyObject, &attributeClass, &keyType);
    if (attributeClass == CKO_SECRET_KEY) {
        keyValue = FindAttr(CKA_VALUE, keyObject);
        if (keyValue) {
            valueLen = keyValue->valueLen;
            memcpy(aesKey, keyValue->pValue, keyValue->valueLen);
            ...
}
```

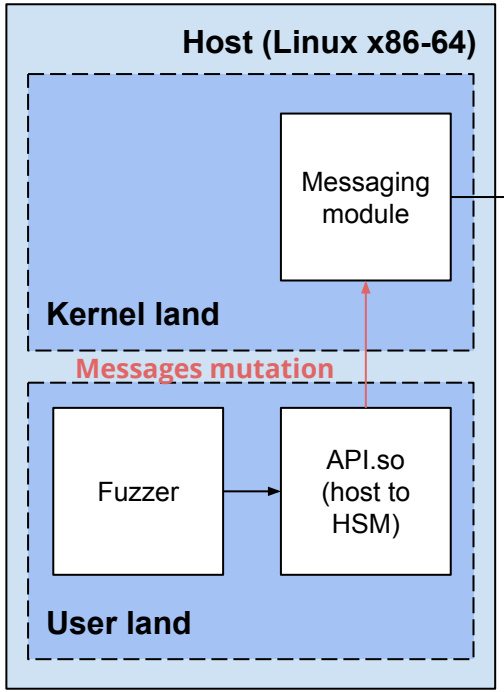
## Exploit

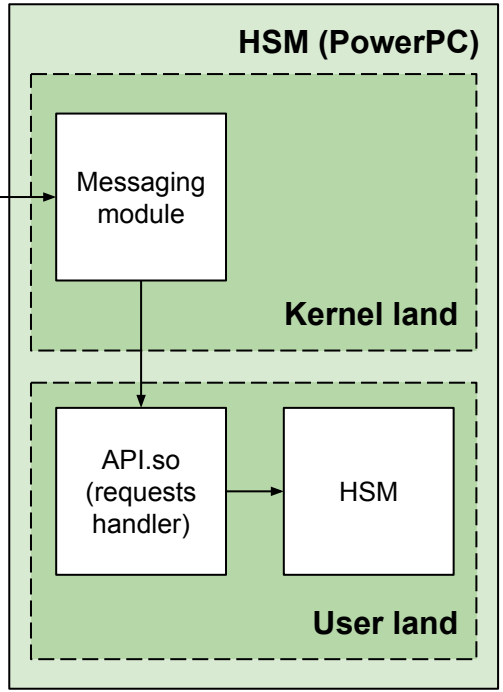
- Code exec is trivial
  - No stack cookie
  - No ASLR
- But
  - Resuming execution is tricky
  - `CreateSecretKey` requires to be authenticated
  - MILENAGE is present only on recent firmware versions

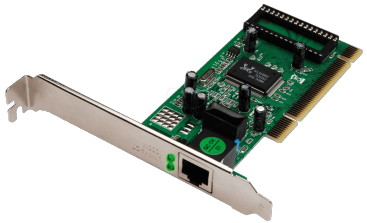
→ Better look for another bug

# Fuzzing




Host (Linux x86-64)
Messaging module
Kernel land
Messages mutation
Fuzzer
API.so (host to HSM)
User land


HSM (PowerPC)
Messaging module
Kernel land
API.so (requests handler)
HSM
User land



## Fuzzing

- Testsuite from PKCS #11 usage examples
- Random bytes mutation
- Main challenges:
  - Host kernel module crashes
  - HSM Denial of Service due to OOM
- Results:
  - 14 vulnerabilities, several classes of memory corruption bugs
  - *Heartbleed*-like vulnerability
  - Stack and heap overflows
  - etc.

# Heartbleed

- Memory leak of the HSM's heap
- Authentication required

```
attacker@host:~$ ./heartbleed user $((0x78)) | hd
[*] modifying buffer size to 0x78
00000000  62 6c 61 68 00 90 47 6c |blah..Gl|
00000008  00 00 00 04 01 00 00 00 |........|
00000010  01 00 00 00 01 00 00 00 |........|
00000018  01 01 01 00 00 01 01 00 |........|
00000020  00 00 08 01 73 75 62 6a |....subj|
00000028  65 63 74 00 00 00 01 02 |ect.....|
00000030  00 00 00 01 01 00 00 00 |........|
00000038  00 11 00 00 00 08 01 10 |........|
00000040  43 d8 5c 37 a7 57 6b 00 |C.\7.Wk.|
00000048  00 01 61 00 00 00 04 01 |..a.....|
00000050  00 00 00 01 80 00 01 02 |........|
00000058  00 00 00 10 01 32 30 31 |.....201|
00000060  38 30 39 30 33 30 38 30 |80903080|
00000068  33 34 39 30 30 00 00 01 |34900...|
00000070  0a 00 00 00 01 01 01 80 |........|
```

# Reliable Code Execution

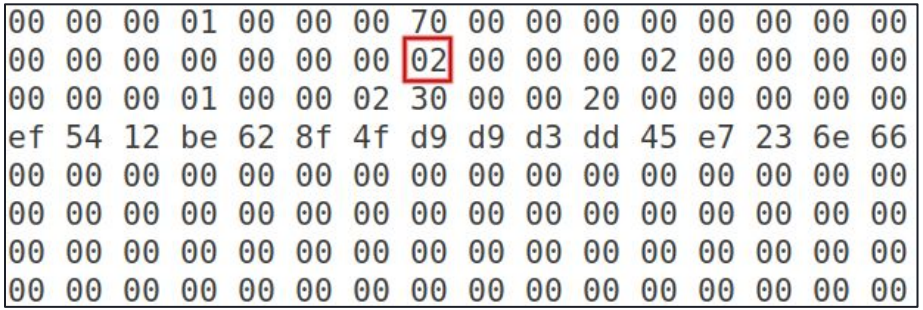
## Bug Discovery

```
CK_MECHANISM digestMechanism = { CKM_RIPEMD128, NULL_PTR, 0 };
unsigned char state[4096], data[32];
CK_ULONG ulStateLen;

C_DigestInit(hSession, &digestMechanism);
C_GetOperationState(hSession, state, &ulStateLen);
mutate(state, ulStateLen);
C_SetOperationState(hSession, state, ulStateLen, 0, 0);
C_DigestUpdate(hSession, data, sizeof(data));
```

# Crash Analysis

- A single byte mutation triggers a crash during restore
- NULL-deref but unusual stacktrace
- Static and dynamic analysis
- Type confusion bug:
  - The mutated byte describes the object type
  - An unexpected digest object can be restored
  - Object A's methods can be called object B



## Exploit Development

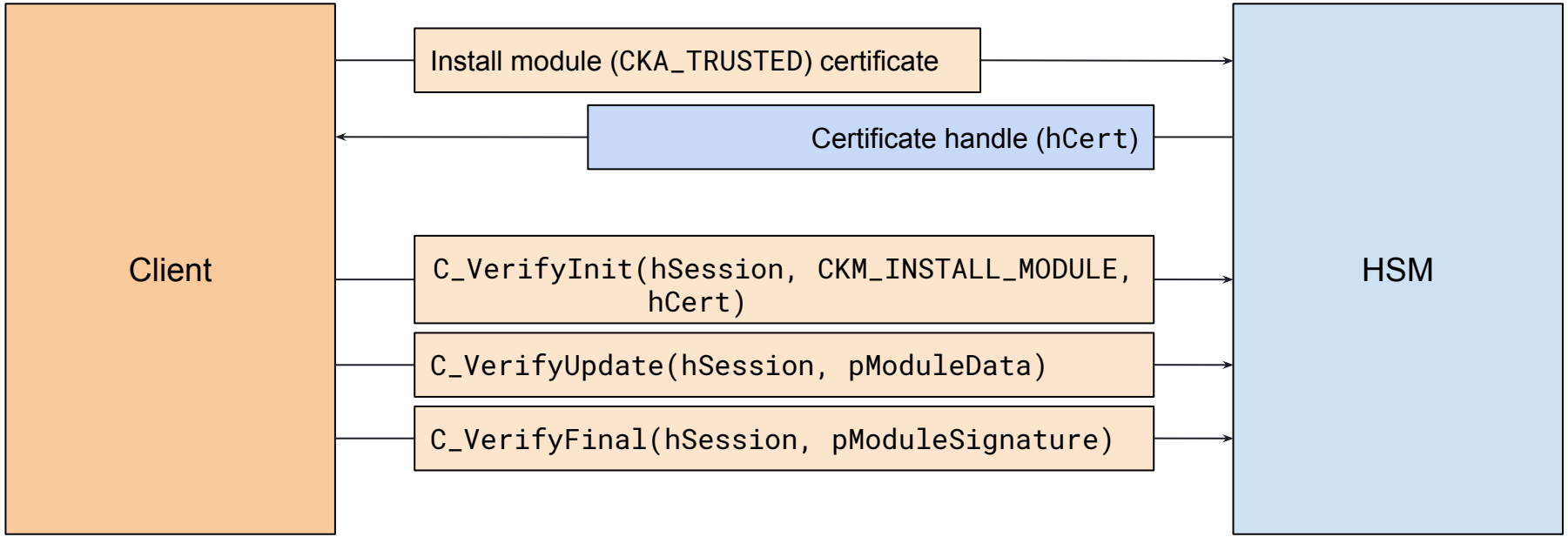
- Digest mechanisms analysis:
  - Memory leak
  - Relative write primitive
- Complex but reliable exploit
  - Heap feng shui
  - Shellcode across various and not consecutive objects
  - Cache coherency
  - etc.

## Payload issue

- Payload executed with root privileges
- `system("/bin/sh")` shellcodes won't work
  - No interesting binary on the HSM to execute
  - No simple way to communicate between the host and the HSM
- Final payload
  a. Patch of the PIN verification function
  b. Login as admin
  c. Evil module installation: dump of the flash and the decryption key
  d. Offline decryption
- The exploit is a single binary executed from the host

# Firmware Signature Bypass

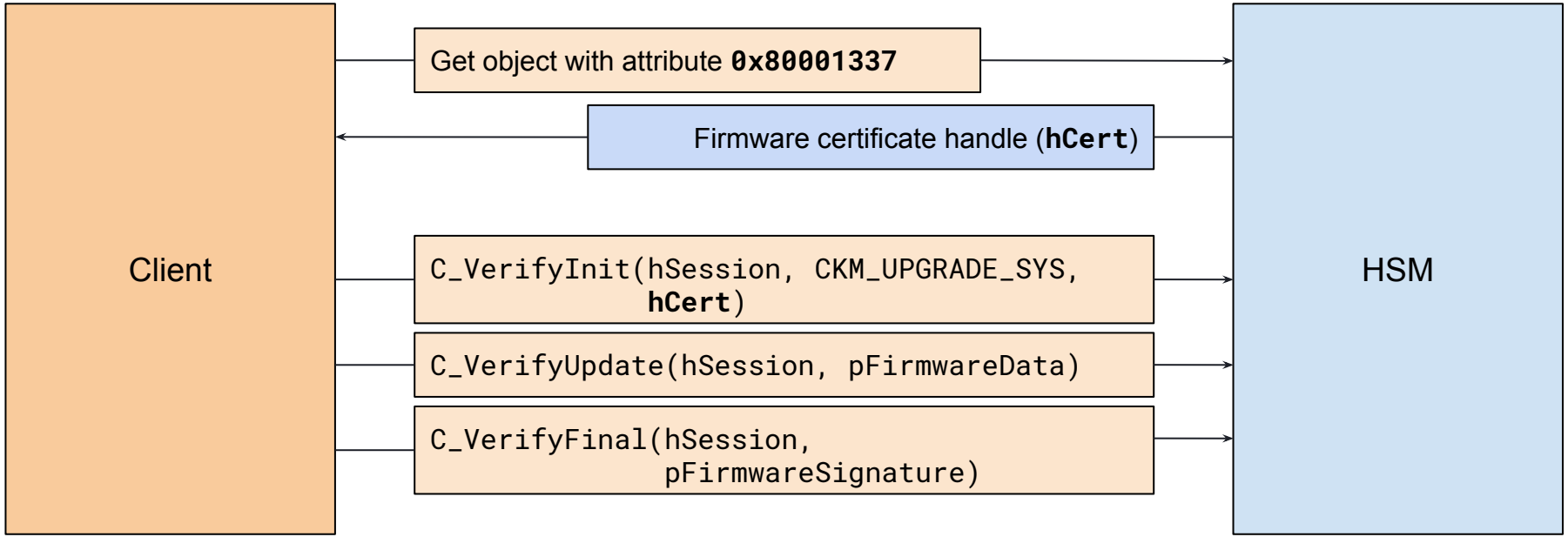
# Module Install



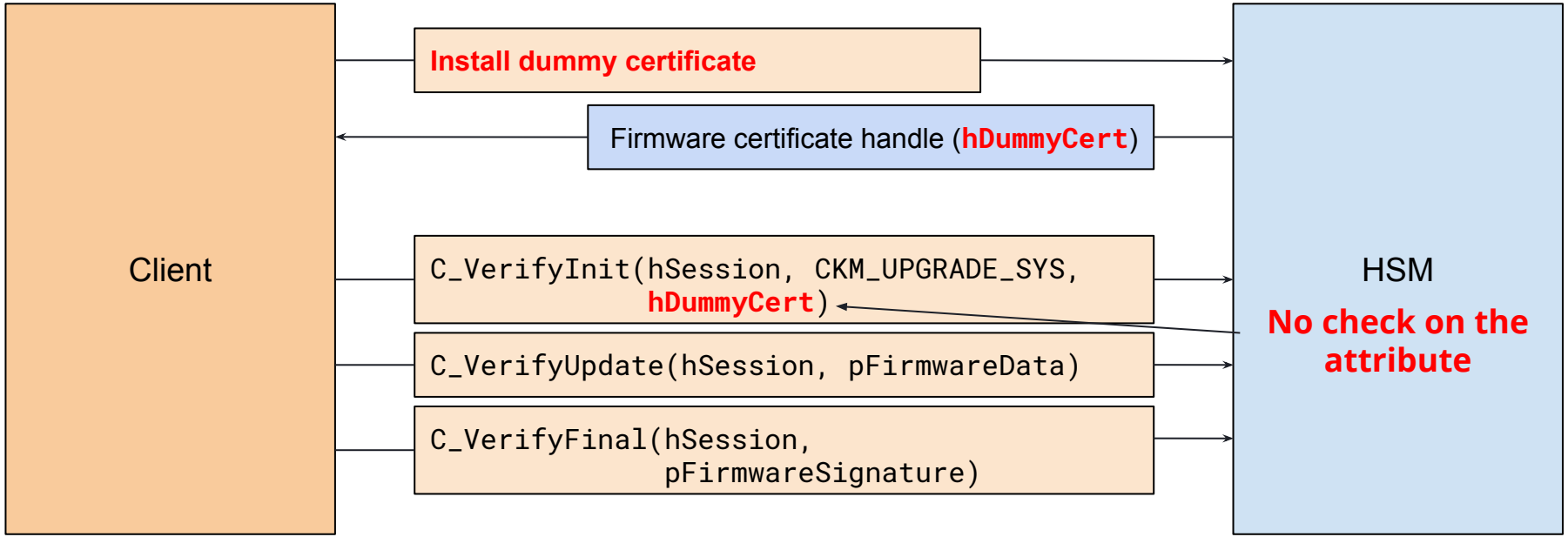
## Firmware Update

- Almost identical to modules install
- Firmware updates are signed by the vendor
  - Ensures integrity
  - No way to install a custom firmware
- Vendor certificate hardcoded in the (installed) firmware code
- `admin@hsm-host:~$ vendor-fw-update /tmp/firm-1.3.bin`

# Firmware Install



# Firmware Install without vendor signature



## Result

- Malicious firmware update
- Persistent backdoor
- Downgrade firmware attack
- (Requires admin privileges)

# Conclusion

## Arbitrary Code Execution

- Vulnerability research against unauthenticated PKCS #11 operations
- Several memory corruption vulnerabilities found
- Pre-auth reliable exploit
- Consequence: arbitrary code execution on the HSM
- Does it work against net HSMs?

## Secret Decryption

- Dump of the storage (containing encrypted secrets)
- Dump of the encryption key
- Offline decryption of the HSM secrets

## Persistence

- Malicious firmware installation using either:
  - The signature bypass
  - Code execution
- The HSM integrity cannot be guaranteed anymore:
  - No secure boot
  - This vulnerability can be exploited again because of downgrade attacks

## Responsible disclosure

- Every vulnerability reported to the vendor
- New firmware update
- Pay attention to your vendor security advisories and apply updates

# Key Takeaways

Ledger

- Not an exhaustive HSM study: what about other models and other vendors?
- Methodology to look for vulnerabilities, improve the overall security of the industry
- HSMs mostly certified against hardware attacks, what about software?

# Questions?