

PV204 Security technologies



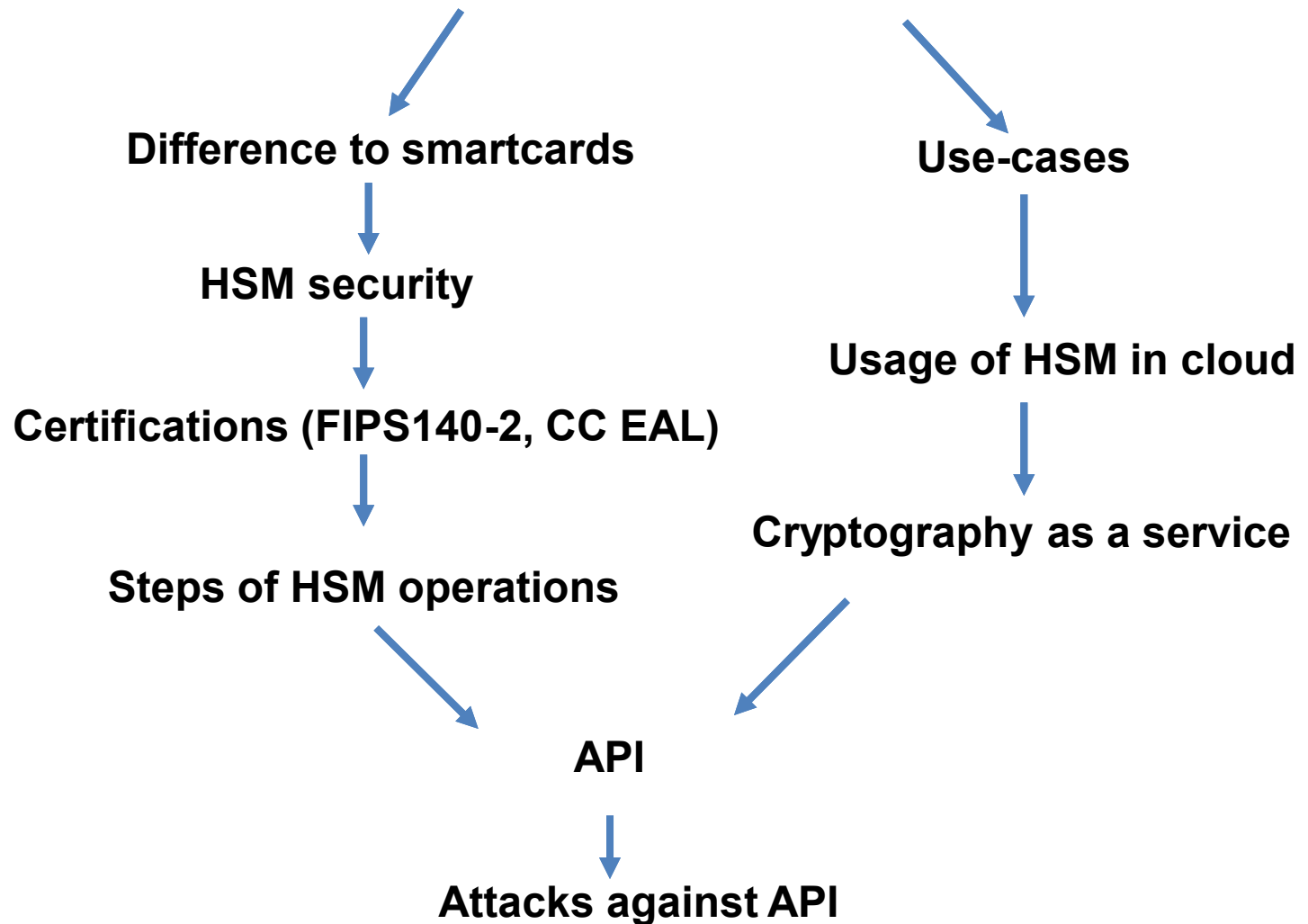
Hardware Security Modules (HSM), PKCS#11

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Hardware Security Modules (HSMs)



Hardware Security Module

HARDWARE SECURITY MODULE

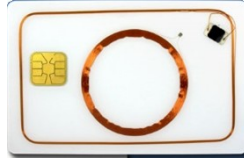
Hardware Security Module - definition

- HSM is trusted hardware element
 - Contains own physical and logical protection
 - May provide increased performance (compared to CPU)
- Attached to or put inside PC/server/network box
- Provides in-device:
 - Secure key generation (and entry)
 - Secure storage (and backup)
 - Secure use (cryptographic algorithms)
- Should never export sensitive data in plaintext
 - Especially keys = **Critical Security Parameters** (CSP)

You already know one example of HSM



Smart cards



- Price: \$3-30
- 2-3 RSA signs/sec
- USB/serial connection
- Mostly disconnected
- No battery
- 3KB RAM, 100KB flash
- Limited algs support

HSMs



- \$100-\$10000
- 100-10000 RSA signs/sec
- UTP/PCI connected
- Always connected
- Own battery (time...)
- MBs-GBs, SSD
- Wide range of algorithms
- Rich API + management
 - Common applications
- Trusted input interface (smartcard reader)

Typical use-cases for HSMs

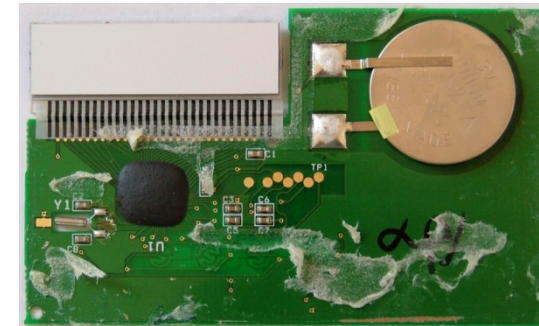
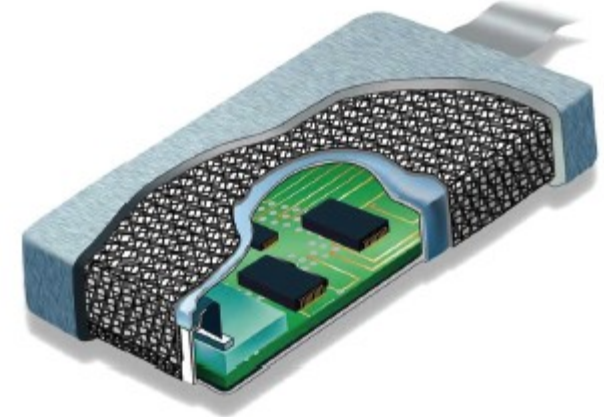
- Payment industry (PIN and transaction verification)
 - TLS accelerator (server's private key)
 - Certification authority (protection of CA private key)
 - Key management (distribution, derivation)
 - Software signing
 - Custom uses (DRM...)
-
- Vendors - market is now consolidating
 - ~~IBM, nCipher~~, Thales, ~~Safenet, Gemalto~~, Utimaco...

Hardware Security Module - protection

- Protections against physical attacks (tamper)
 - Invasive, semi-invasive and non-invasive attacks
- Protection against logical attacks
 - API-level attacks, Fuzzing...
- Preventive measures
 - Statistical testing of random number generator
 - Self-testing of cryptographic engines (encrypt twice, KAT)
 - Firmware integrity checks
 - Periodic reset of device (e.g., every 24 hour)
 - ...

HSM – tamper security

- Protection epoxy
- Wiring mesh
- Temperature sensors
- Light sensors
- Variations (glitches) in power supply
- Erasure of memory (write 0/random)
 - After tamper detection to mitigate data remanence
- ...



Which one is tamper resistance, evidence, detection and/or reaction?

HSM – logical security

- Access control with limited/delayed tries
 - $< 1:1000\ 000$ probability of random guess of password
 - $< 1:100\ 000$ probability of unauthorized access in one minute
- Integrity and authentication of firmware update
 - Signed firmware updates
- Logical separation of multiple users (memory)
 - Additional protection logic for separate memory regions
- Audit trails
- ...



CERTIFICATIONS



Certifications: FIPS140-2, CC EAL, PCI HSM

- NIST FIPS 140-2
 - Verified under Cryptographic Module Validation Program (CMVP)
 - NIST FIPS 140-2 Level 1+2 – basic levels, tamper evidence (broken shell, epoxy), role-based authentication (user/admin))
 - NIST FIPS 140-2 Level 3 – addition of physical tamper-resistance, identity-based auth, separation of interfaces with different sensitivity
 - NIST FIPS 140-2 Level 4 + additional physical security requirements, environmental attacks (very few devices certified)
 - NIST FIPS 140-3 (2013, but still draft)
 - Additional focus on software security and non-invasive attacks
- List of validated devices
<http://csrc.nist.gov/groups/STM/cmvp/validation.html>

Certifications: Common Criteria EAL 4-5+

- Common levels for HSMs
 - EAL4: Methodically Designed, Tested and Reviewed
 - EAL5: Semi-formally Designed and Tested
- Protection profiles
 - Specifies generic security evaluation criteria to substantiate vendors' claims (more technical)
 - Crypto Module Protection Profile (BSI)
 - https://www.bsi.bund.de/cae/servlet/contentblob/480256/publicationFile/29291/pp0045b_pdf.pdf
- + means “augmented” version (current version + additional requirements, e.g., EAL4+)



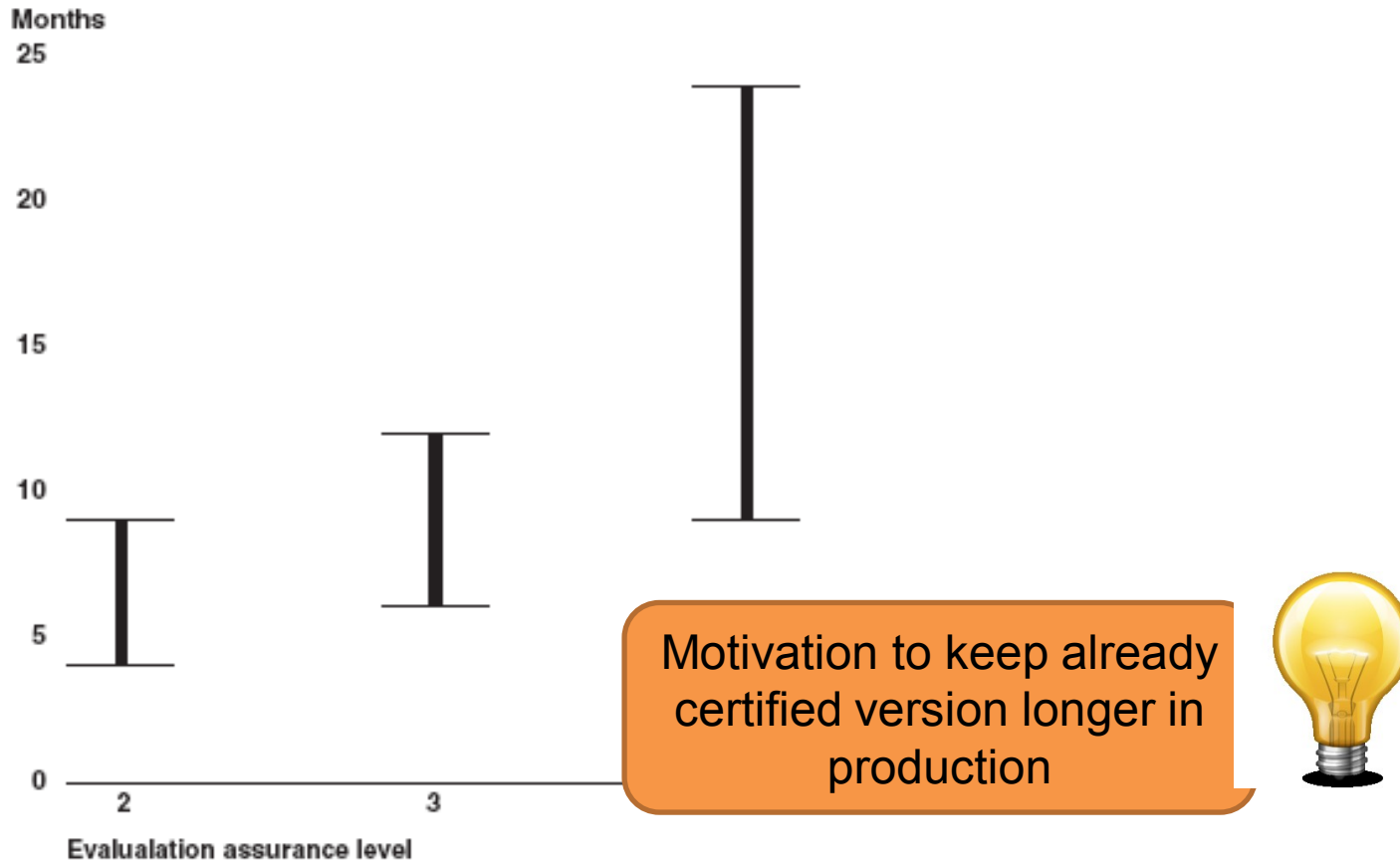
Certifications: PCI HSM version 1,2

- PCI HSM v1 (2009), v2 (2012)
 - https://www.pcisecuritystandards.org/security_standards/documents.php
- Focused on area of payment transactions
 - Payment terminals, backend HSMs...
 - Payment transaction processing
 - Cardholder authentication
 - Card issues procedure
- Set of logical and physical requirements relevant to payment industry
 - Closer to NIST FIPS 140-2 than to CC (more concrete requirements)

Cost of certification

- Certification is usually done by commercial “independent” laboratories
 - Laboratories are certified by governing body
 - Quality and price differ
 - Usually payed for by device manufacturer
- 1. Certification pre-study
 - Verify if product is ready for certification
- 2. Full certification
 - Checklist if all required procedures were followed

Cost of CC EAL (US GAO, 2006)



Source: GAO analysis of data provided by laboratories.

Be aware what is actually certified

- Certified != secure
 - Satisfies defined criteria, producer claims were verified to be valid
 - Infineon's RSA prime generation algorithm (BSI, CVE-2017-15361)
- Usually certified bundle of hardware and software
 - Concrete underlying hardware
 - Concrete version of firmware, OS and pre-loaded application
- Certification usually invalidated when:
 - New hardware revision used (less common)
 - New version of firmware, OS, application (common)
 - Any customization, e.g., user firmware module (very common)
- Pragmatic result
 - “I'm using product that was certified at some point in time”

HSM PERFORMANCE

HSM – performance I.

- Limited independent public information available
 - Claim: “up to 9000 RSA-1024b operations / second”
- But...
 - Real operations are not just raw crypto (formatting of messages...)
 - Longer key length may be needed (RSA-2048b)
 - Internal vs. external speed (data in/out excluded)
 - Measurements in “optimal” situations (single pre-prepared key, large data blocks...)
 - ...

HSM – performance II.

- Relatively difficult to obtain fair comparison
- F. Demaertelaere (2010)
 - <https://handouts.secappdev.org/handouts/2010/Filip%20Demaertelaere/HSM.pdf>
- RSA 1024 bit private key operation: 100 – 7000 ops/sec
- ECC 160 bit ECDSA signatures: 250 – 2500 ops/sec
- 3DES: 2 - 8 Mbytes/sec
- AES: 6 - 40 Mbytes/sec (256 bit key)

- No significant breakthrough in technology since 2010
- Higher throughput achieved by multiple HSMs

Recent update (Feb 2018)



Available Models and Performance

nShield Connect Models	500+	XC Base	1500+	6000+	XC Mid	XC High
RSA Signing Performance (tps) for NIST Recommended Key Lengths						
2048 bit	150	430	450	3,000	3,500	8,600
4096 bit	80	100	190	500	850	2,025
ECC Prime Curve Signing Performance (tps) for NIST Recommended Key Lengths						
256 bit	540	680	1,260	2,400	5,500	14,400
Client Licenses						
Included	3	3	3	3	3	3
Maximum	10	10	20	100	20	100

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HSM - load balancing, failover

- HSMs often used in business critical scenarios
 - Authorization of payment transaction
 - TLS accelerator for internet banking
 - ...
- Redundancy and load-balancing required
- Single HSM is not enough
 - At least two in production for failover
 - At least one or two for development and test

Hardware Security Module

STEPS OF CRYPTO OPERATION

Steps of cryptographic operation

-  1. Transfer input data
-  2. Transfer wrapped key in
-  3. Initialize unwrap engine
-  4. Unwrap data/key (decrypt/verify)
-  5. Initialize key object with key value
-  6. Initialize cryptographic engine with key
-  7. Start, execute and finalize crypto operation
-  8. Initialize wrap engine
-  9. Wrap data/key (encrypt/sign)
-  10. Erase key(s)/engine(s)
-  11. Transfer output data
-  12. Transfer wrapped key out



S1: One user, few keys

- No sharing, all engines fully prepared

 1. Transfer input data

 7. Start, execute and finalize crypto operation

 11. Transfer output data

S2: One user, many keys

- No sharing, frequent crypto context change



1. Transfer input data
2. Transfer wrapped key in



4. Unwrap data/key (decrypt/verify)



5. Initialize key object with key value

6. Initialize cryptographic engine with key



7. Start, execute and finalize crypto operation



9. Wrap data/key (encrypt/sign)



10. Erase key(s)/engine(s)



11. Transfer output data



12. Transfer wrapped key out

S3: Few users, few keys

- Device is shared → isolation of users



1. Transfer input data



6. Initialize cryptographic engine with key

7. Start, execute and finalize crypto operation















10. Erase key(s)/engine(s)



11. Transfer output data

S5: Many users, many keys

- High sharing, frequent crypto context change

-  1. Transfer input data
-  2. Transfer wrapped key in
-  3. Initialize unwrap engine
-  4. Unwrap data/key (decrypt/verify)
-  5. Initialize key object with key value
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-  11. Transfer output data
-  12. Transfer wrapped key out

HSM IN CLOUD

Security topics in cloud environment

1. Move of legacy application into cloud
 - Previously used locally connected HSMs
2. Protection of messages exchanged between multiple cloud-based applications
 - Key exchange of used key without pre-distribution?
3. Volume encryption in cloud
 - Encrypted block mounted after application request (e.g., Amazon's Elastic Block Storage)
4. Encrypted databases
 - Block encryption of database storage, encryption of rows/cells
5. Cryptography as a Service
 - Not only key management, also other cryptographic functionality

Use case: Microsoft Azure KeyVault

Microsoft Azure

SALES 800-701-208 MY ACCOUNT PORTAL

Why Azure Solutions Products Documentation Pricing Partners Blog Resources Support

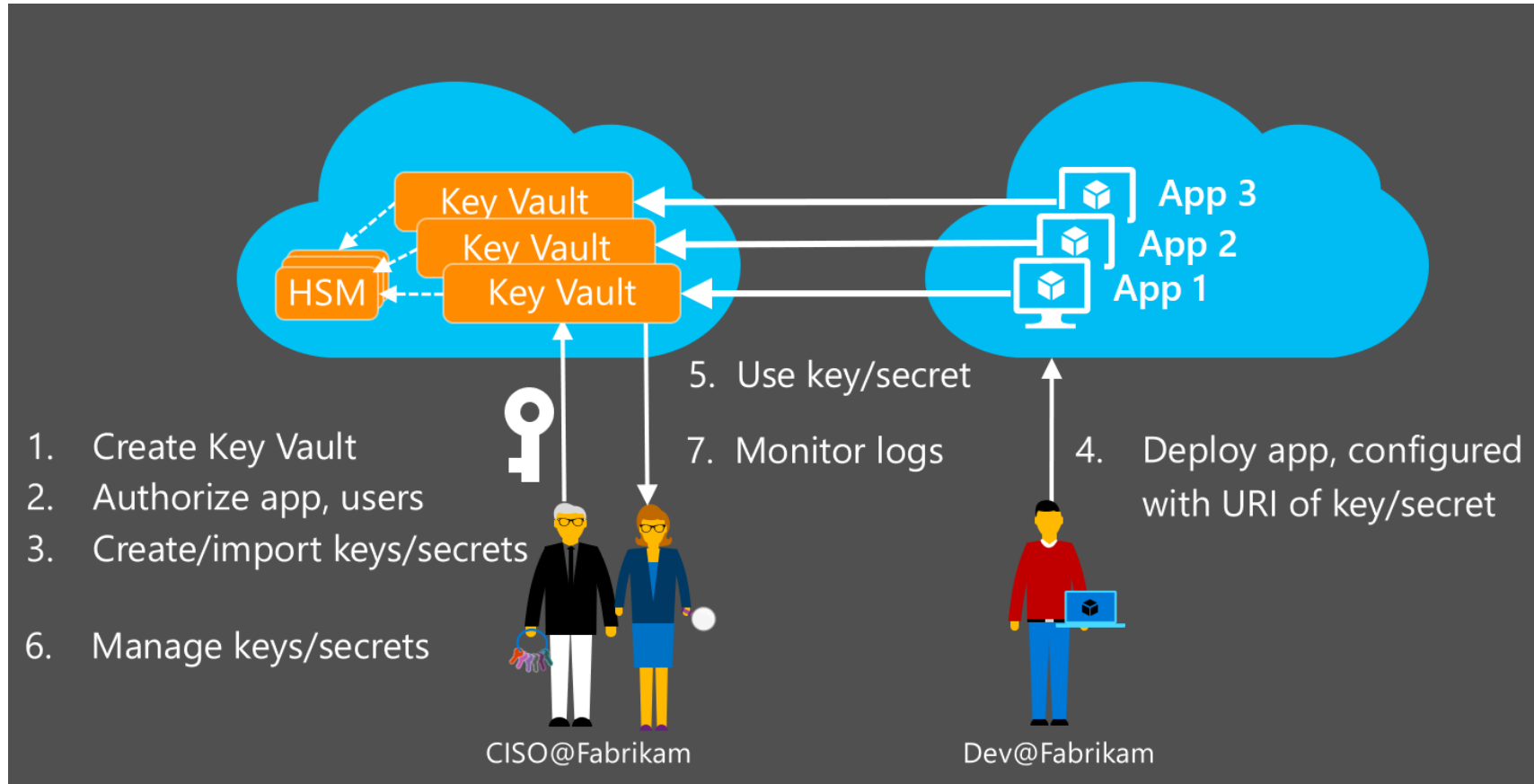
Key Vault

Safeguard cryptographic keys and other secrets used by cloud apps and services

- ✓ Increase security and control over keys and passwords
- ✓ Create and import encryption keys in minutes
- ✓ Applications have no direct access to keys
- ✓ Use FIPS 140-2 Level 2 validated HSMs
- ✓ Reduce latency with cloud scale and global redundancy
- ✓ Simplify and automate tasks for SSL/TLS certificates

- REST API to generate keys, export pub, use keys...
 - <https://docs.microsoft.com/en-us/rest/api/keyvault/>
- Language bindings (language specific wrappers)
 - JS, PowerShell, C#...

Microsoft Azure KeyVault



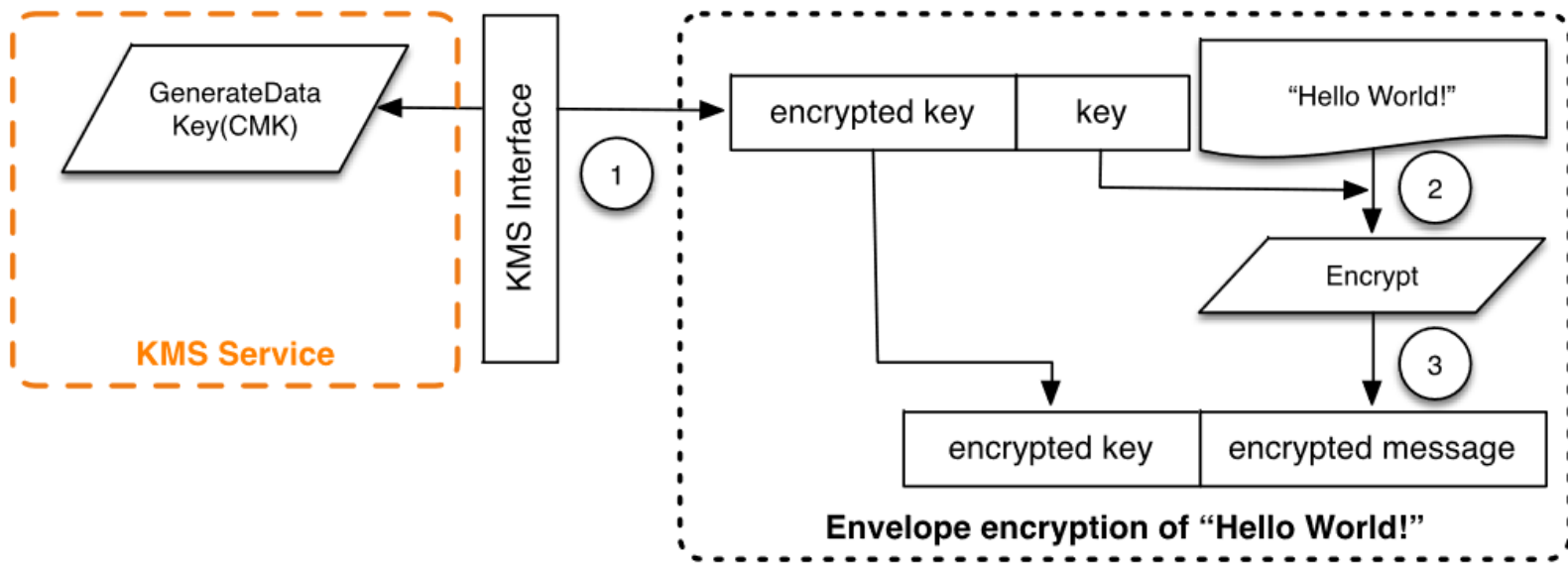
<https://channel9.msdn.com/Events/Ignite/2015/BRK2706>

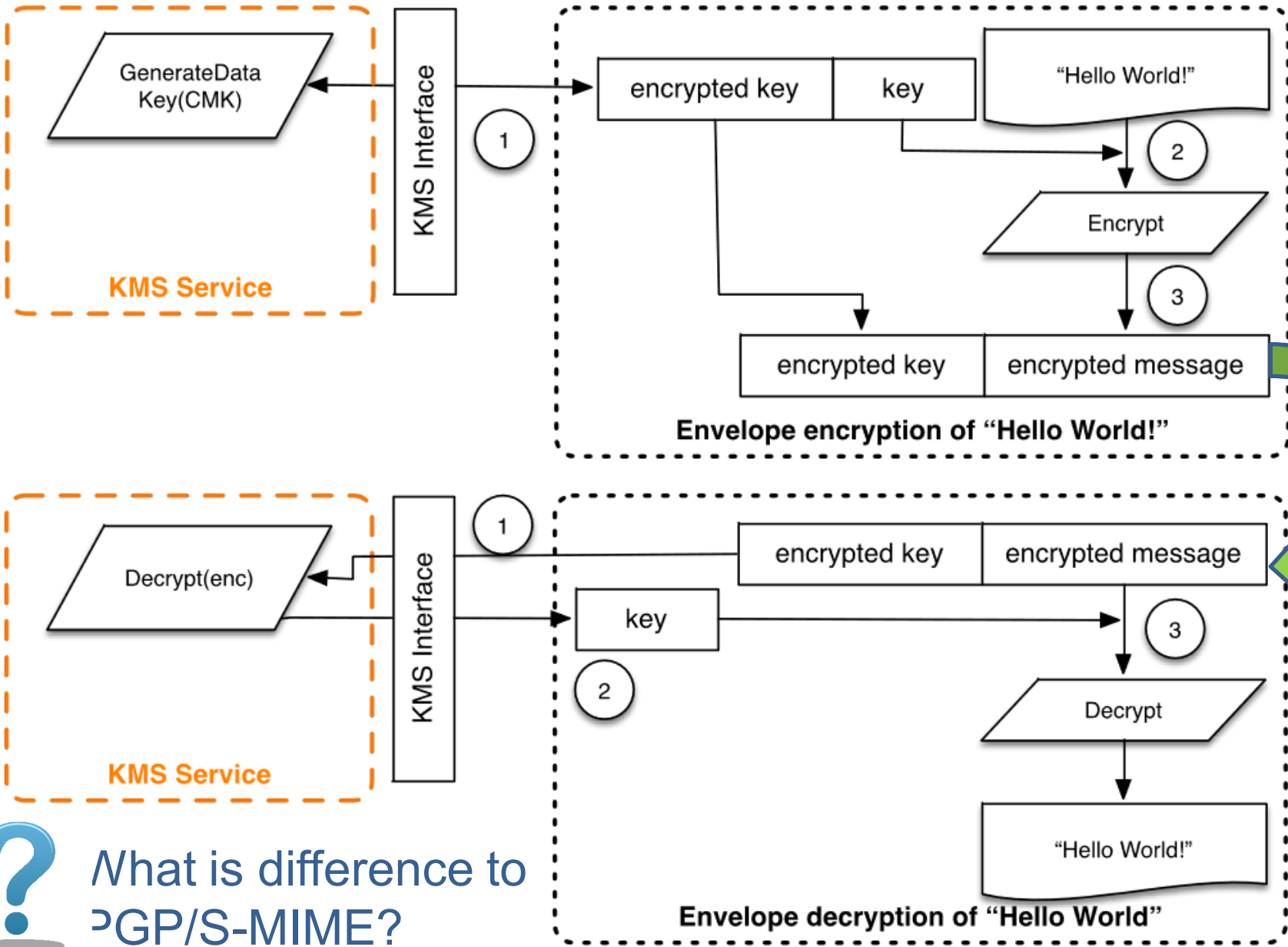
Use case: AWS Key Management Service

- AWS Key Management Service Cryptographic Details, M. Campagna (2015)
 - <https://d0.awsstatic.com/whitepapers/KMS-Cryptographic-Details.pdf>
- Centralized key management
 - Used by cloud-based applications
 - Used by any client application
 - Replication of wrapping keys into HSMs in different datacenters

Usage scenario: envelope encryption

- Protected message exchange between multiple (cloud-based) application
 1. Random key generated in one application
 2. Key protected (wrap) using trusted element (HSM)
 3. Wrapped key appended to message
 4. Key unwrapped in second application (via HSM)





<https://d0.awsstatic.com/whitepapers/KMS-Cryptographic-Details.pdf>



What is difference to PGP/S-MIME?

Who is trusted?

- KMS Service to wrap envelope keys properly
- KMS Service not to leak wrapping key
- Cloud operator not to read unwrapped keys from memory

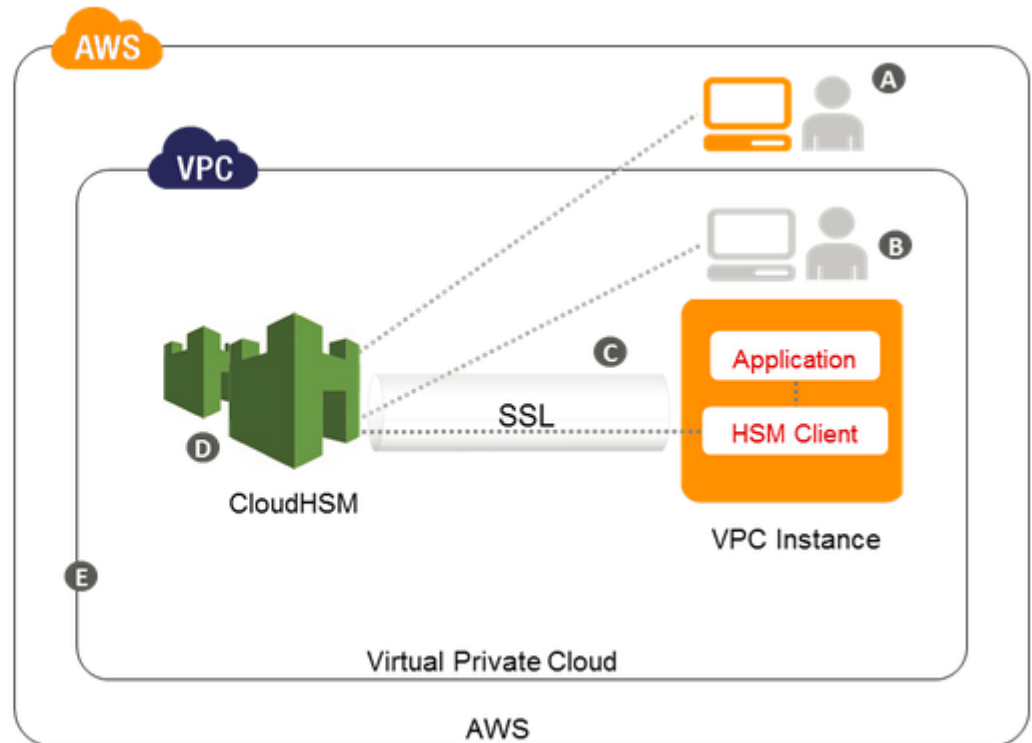
Use case: Amazon AWS CloudHSM



- Amazon's AWS CloudHSM
 - Based on SafeNet's Luna HSM
 - Only few users can share one HSM (probably no sharing)
 - => High initial cost (~\$5000 + \$1.88 per hour)
- Note: significantly different service from AWS KMS
 - “Whole” HSM is available to single user/application, not only key (un)wrapping functionality
 - Suitable for legacy apps, compliancy requirements

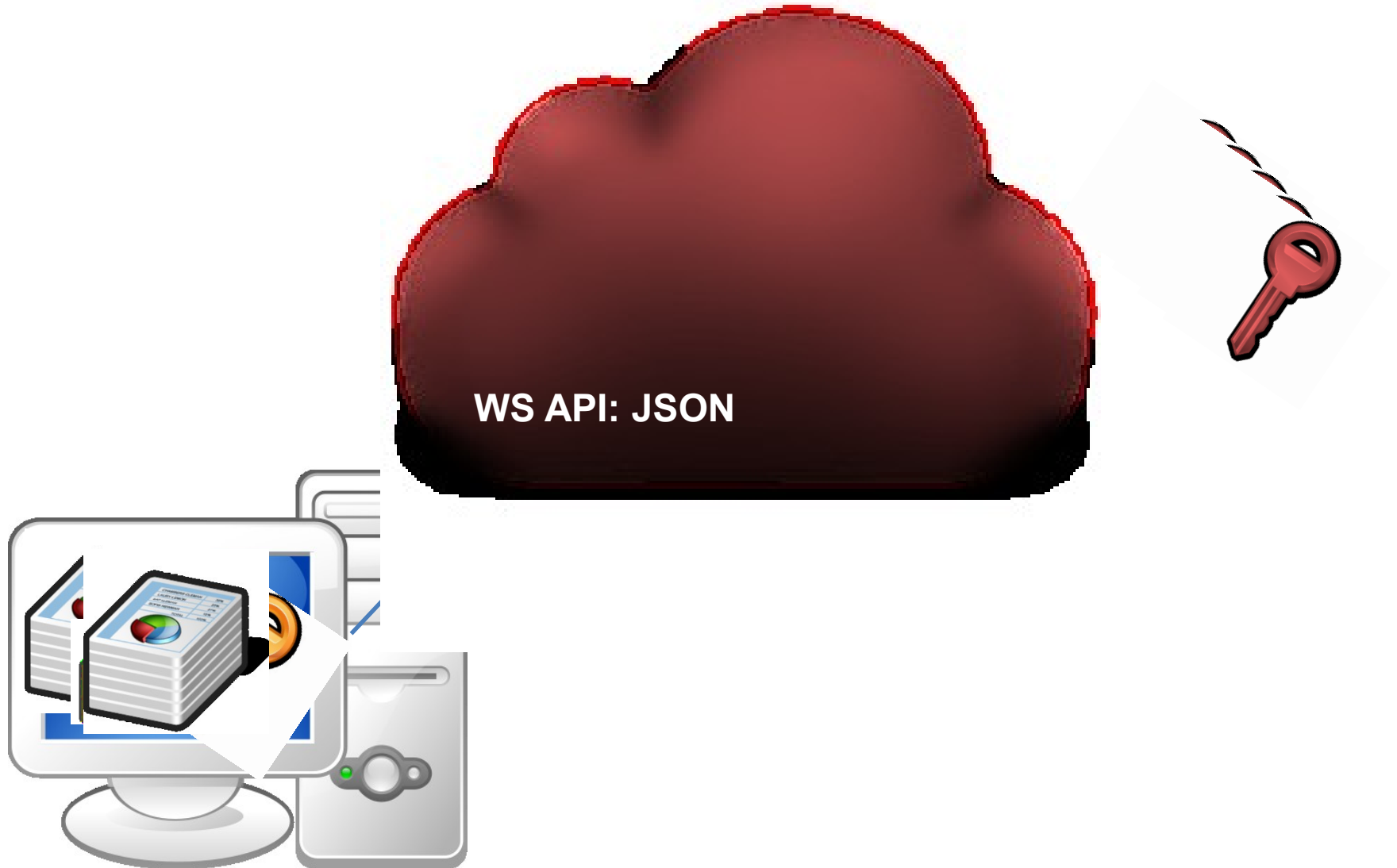
Use case: Amazon AWS CloudHSM

- A AWS manages the HSM appliance but does not have access to your keys
- B You control and manage your own keys
- C Application performance improves (due to close proximity with AWS workloads)
- D Secure key storage in tamper-resistant hardware available in multiple regions and AZs
- E CloudHSMs are in your VPC and isolated from other AWS networks



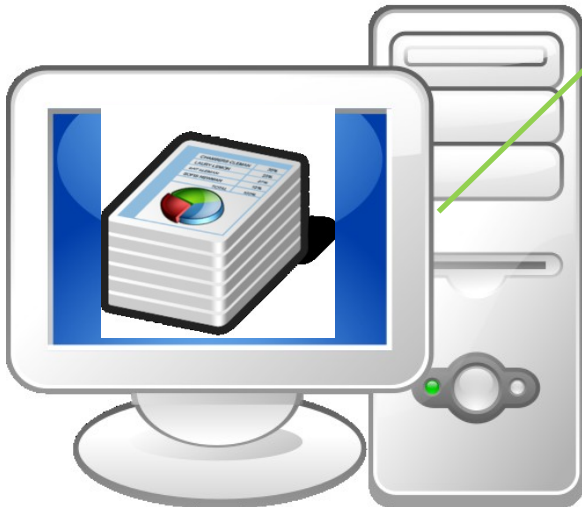
CRYPTOGRAPHY AS A SERVICE

Offloading s



... into secured environment

Cryptography as a Service (CaaS)



How to import key(s) securely?
Which hardware platform to use?
High number of clients?



Requirements – client view

- Untrusted CaaS provider (handling secrets)
- Secure import of app's secrets - enrollment
- Client \leftrightarrow CaaS communication security
 - Confidentiality/integrity of input and output data
 - Authentication of input/output requests
- Key use control
 - Use constraints – e.g., number of allowed ops
- Easy recovery from client-side compromise



Requirements – CaaS provider view

- Massive scalability
 - W.r.t. users, keys, transactions...
- Low latency of responses
- Robust audit trail of key usage
- Tolerance and recovery from failures
 - hardware/software failures
- Easy to use API
 - also easy to use securely

CaaS - implementation issues

- Security
 - Software-only CaaS more vulnerable to attacks
 - Access control and operation authorization critical
- Performance
 - Classic HSMs are not build for high-level of sharing
 - Performance degradation due to frequent context exchange (key scheduling, engine preparation)
 - Logical separation only to few entities (16-32)
 - Physical separation on device-level (=> very limited)

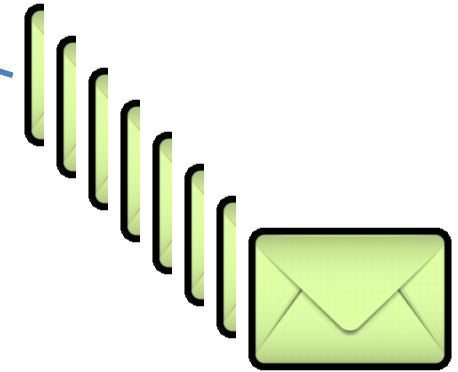
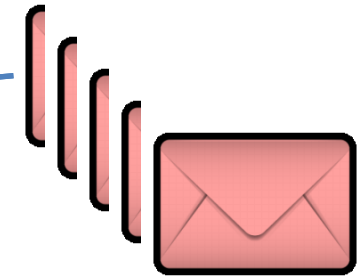
HSM from smartcards

Controller



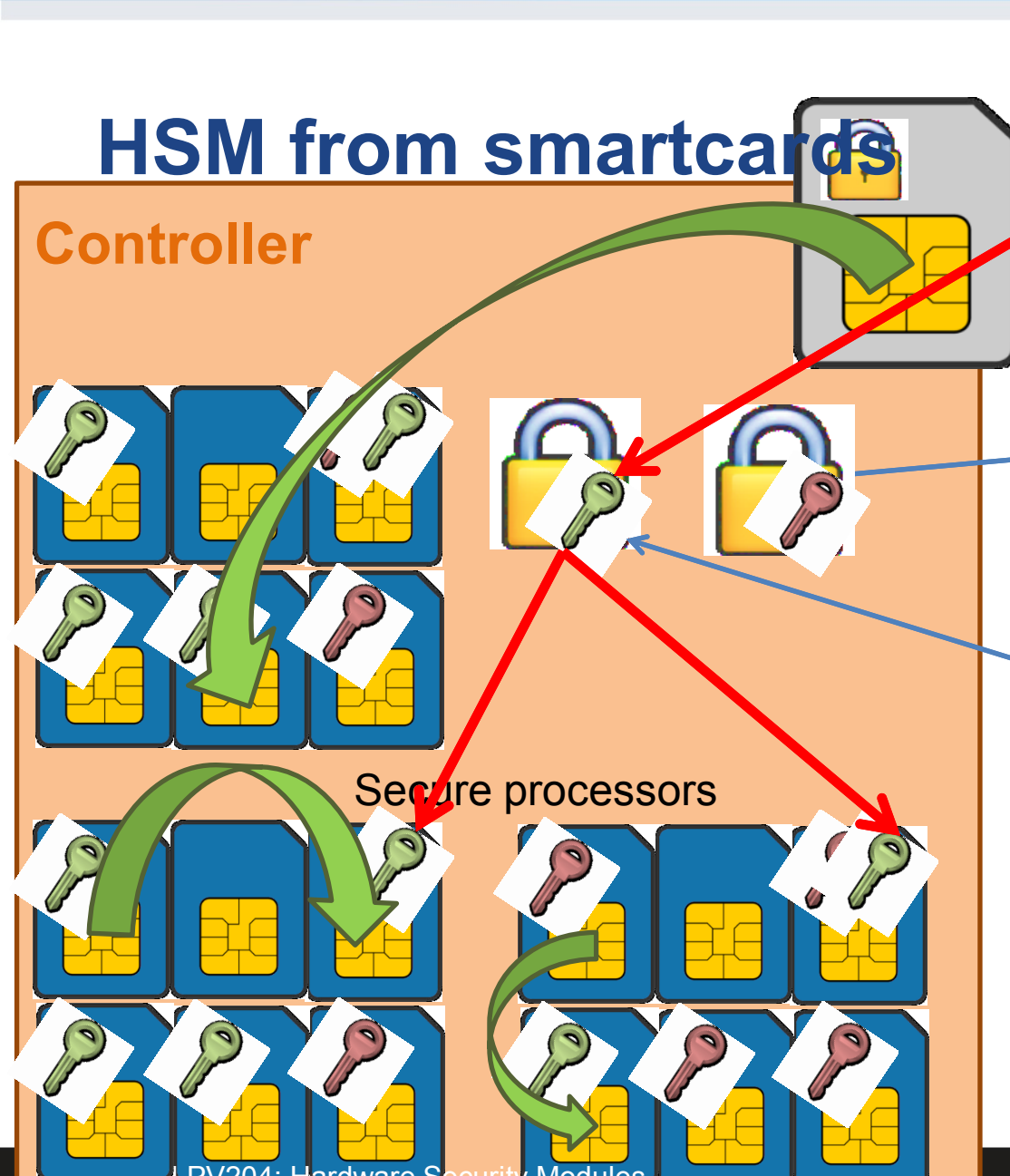
User key (encrypted)

Input data: user key #2

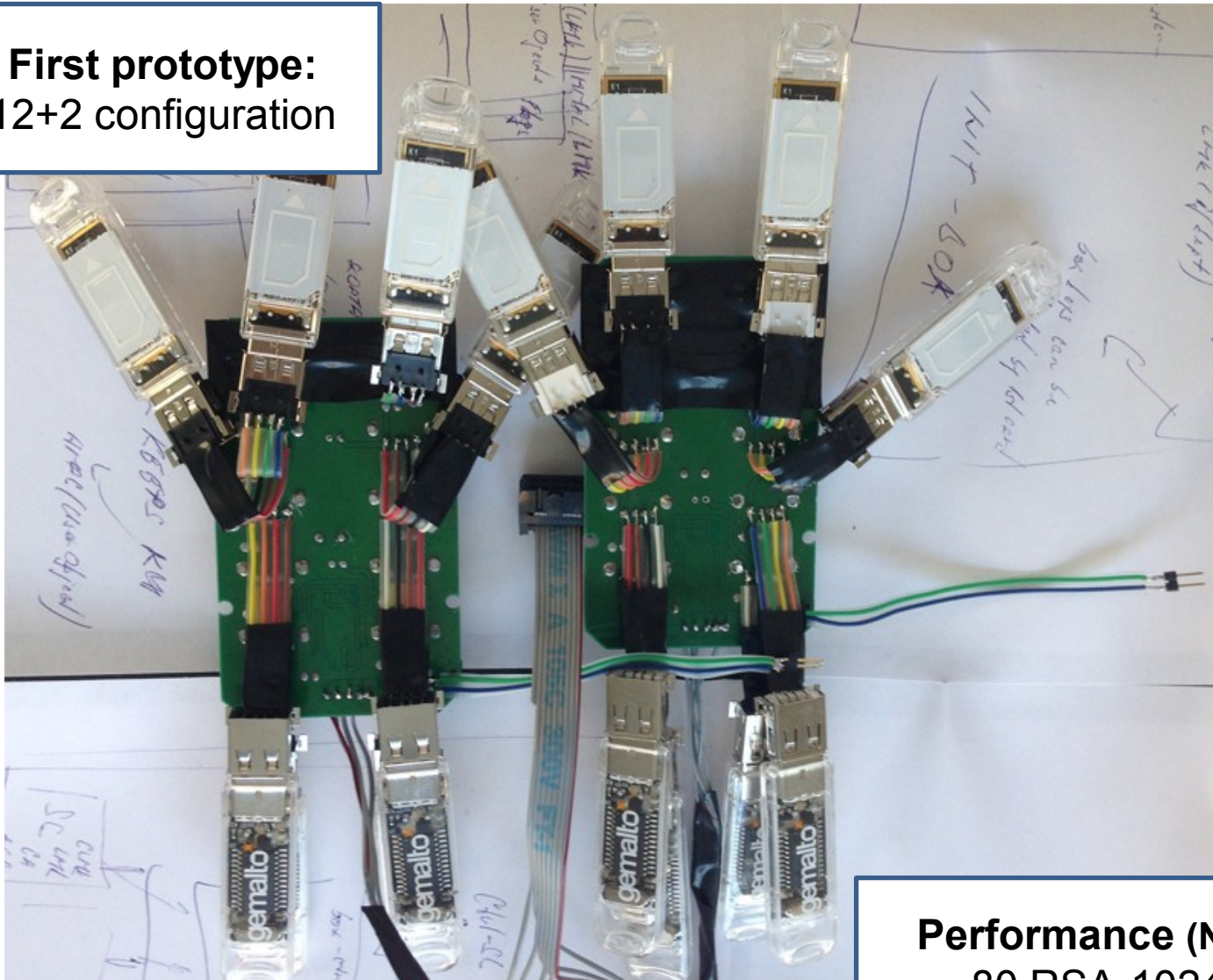


Input data: user key #1

Secure processors



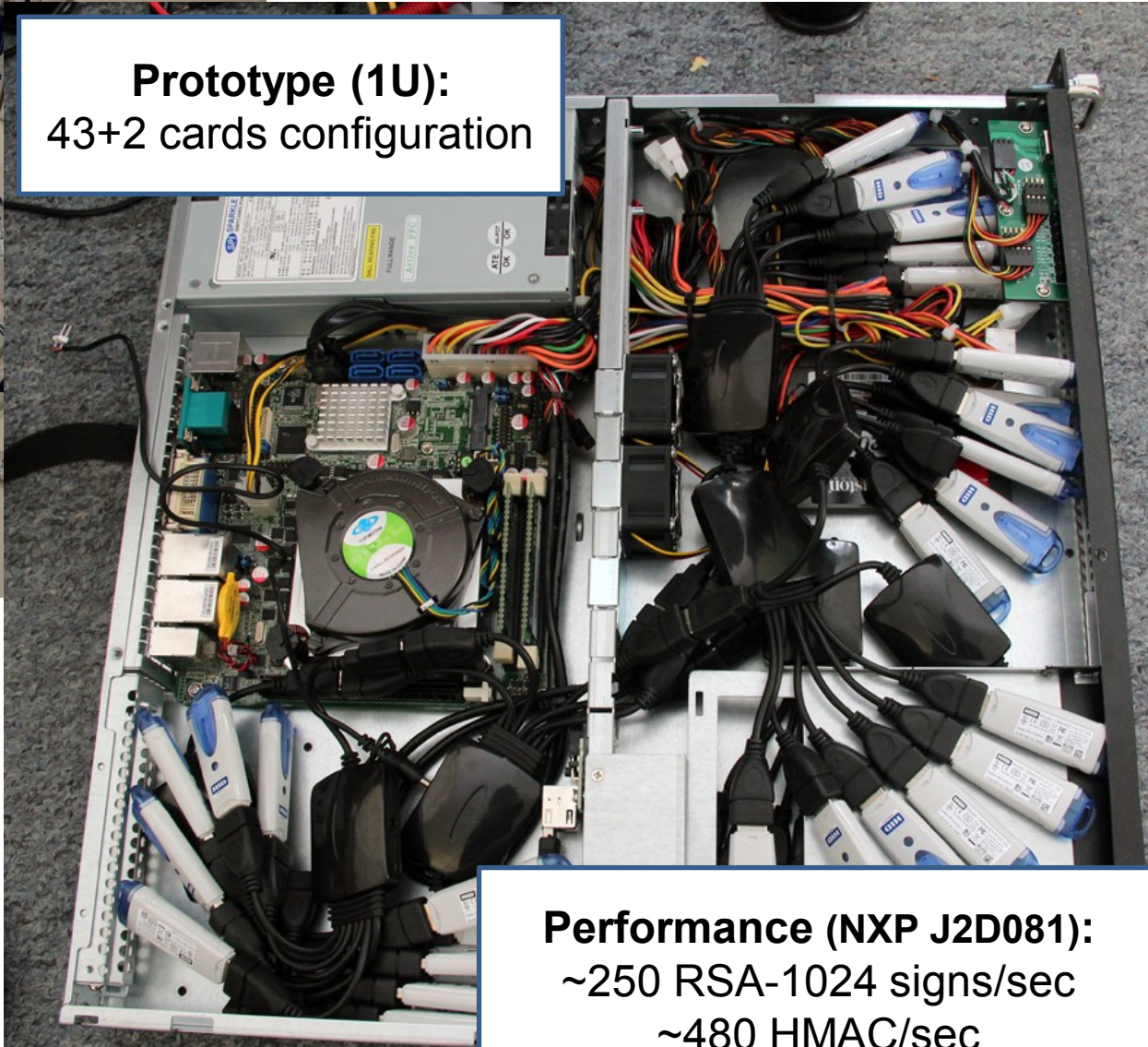
First prototype:
12+2 configuration



Performance (NXP J2D081):
~80 RSA-1024 signs/sec
~150 HMAC/sec



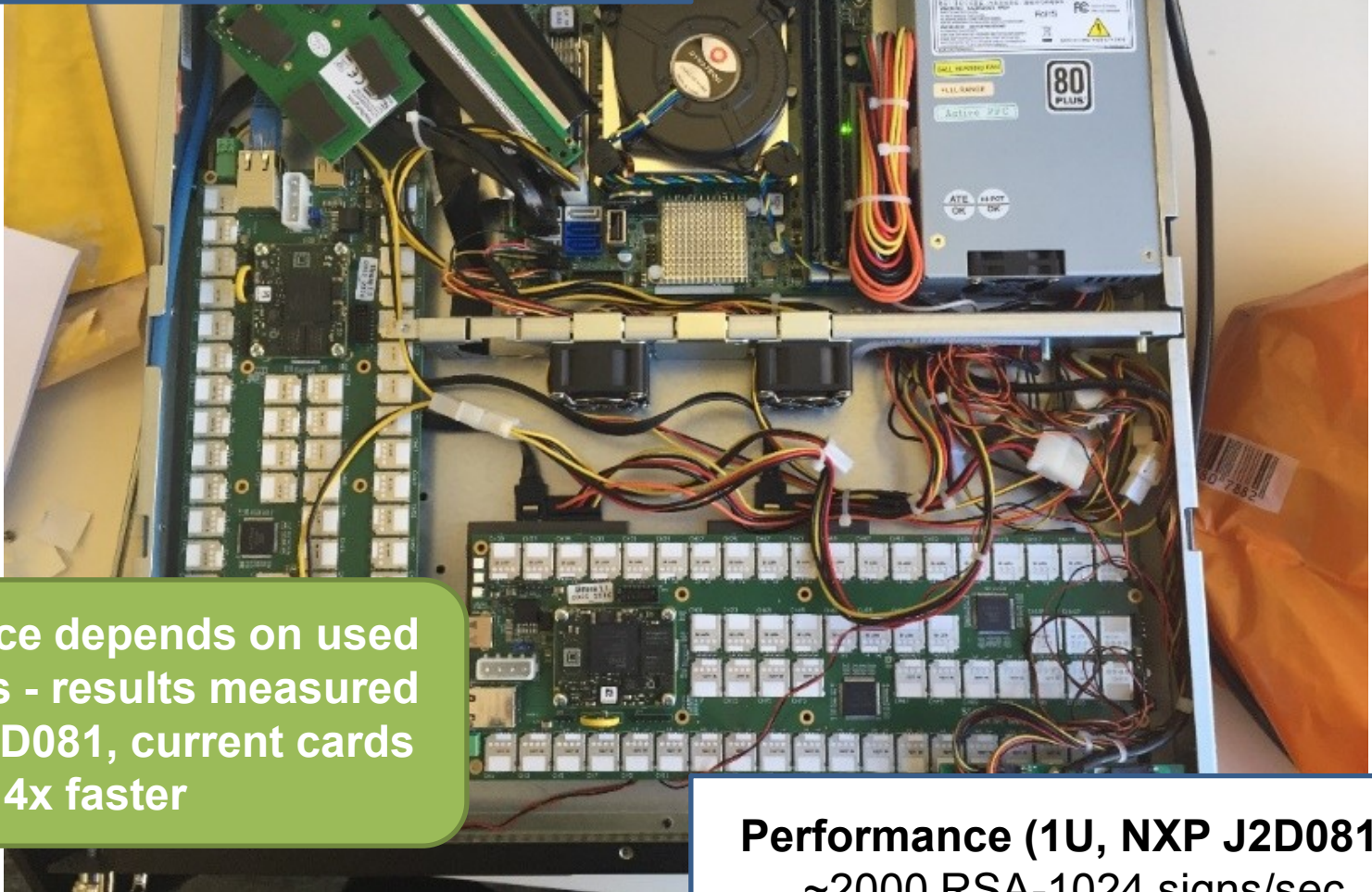
Prototype (1U):
43+2 cards configuration



Performance (NXP J2D081):
~250 RSA-1024 signs/sec
~480 HMAC/sec

Simona boards (1U):

120 cards configuration / board,
3 boards fits into 1U, 20 boards into 3U



Performance depends on used
smartcards - results measured
for NXP J2D081, current cards
4x faster

Performance (1U, NXP J2D081):

~2000 RSA-1024 signs/sec
~4000 HMAC/sec

Not just “send and encrypt fast”

- Protection of incoming/outgoing data
- Device is shared – secure load/unload user ctxs
- Hierarchical control of loaded keys
- User specifies limited use for its key (credits)
- Signed audit trail collected from processors
 - independently verifiable, control over uses
- If interested, read more at
 - Architecture Considerations for Massively Parallel Hardware Security Platform, Space’15 <http://crocs.cz/papers/space2015>
 - High-Assurance Cryptographic Hardware from Untrusted Components, ACM CCS’17, https://crocs.fi.muni.cz/public/papers/mpc_ccs17

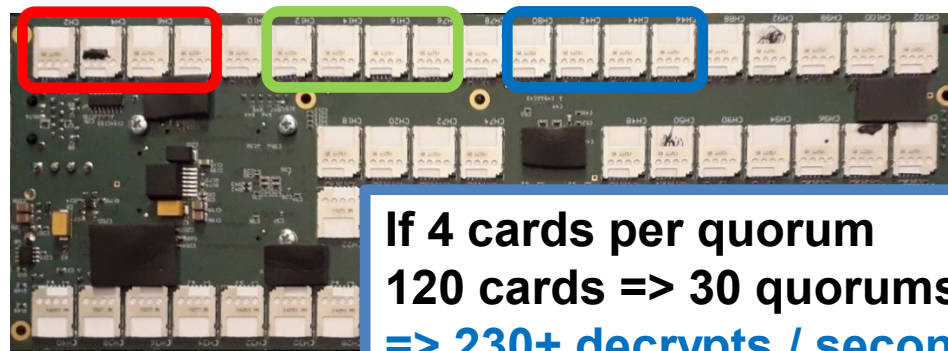
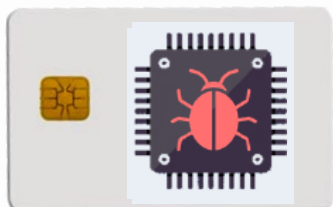
SINGLE POINT OF FAILURE

Motivation: Single point of failure

- Single device can be malfunctioning or just break
 - Availability problem, redundancy required
- Software/hardware design flaws or coding errors
 - Leakage of sensitive data or key material
- Supply chain can be compromised
 - Introduction of backdoor
- ...



Secure multiparty signature



If 4 cards per quorum
120 cards => 30 quorums
=> 230+ decrypts / second
=> 60+ signatures / second

- Secure multi-party computation
- Suite of ECC-based multi-party protocols proposed
 - Distributed key generation, ElGamal decryption, Schnorr signing
- Efficient implementation on JavaCards
 - Tested on grid of 120 cards

Try it!

- JavaCard Applet + controlling Java applica
 - <https://github.com/OpenCryptoProject/Myst>
- More information:
 - <https://trojantolerance.org>

A Touch of Evil: High-Assurance Cryptographic Hardware from Untrusted Components

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Hardware Security Module

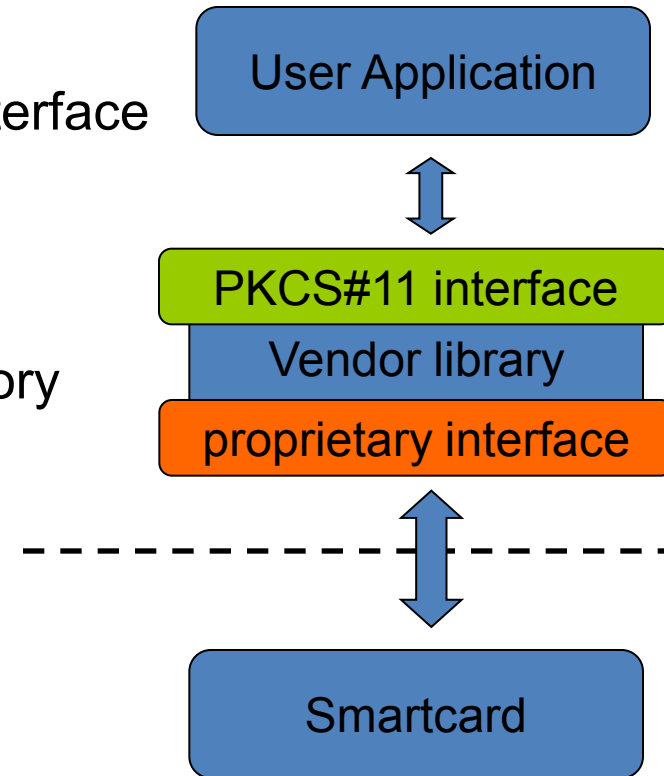
HSM SECURITY API

Application Programming Interfaces (API)

1. Proprietary API (legacy or custom functions)
2. Standardized API - but proprietary library required (PKCS#11)
3. Cryptographic service providers – plugin into standardized API (CNG, CSP...)
4. Standardized API - no proprietary component (PIV, EMV CAP...)
5. Proprietary (service-specific), but public API (MS KeyVault, AWS..)

PKCS#11

- Standardized interface of security-related functions
 - vendor-specific library in OS, often paid
 - communication library->card proprietary interface
- Functionality cover
 - slot and token management
 - session management
 - management of objects in smartcard memory
 - encryption/decryption functions
 - message digest
 - creation/verification of digital signature
 - random number generation
 - PIN management
- Secure channel not possible!
 - developer can control only App→PKCS#11 lib



PKCS#11 library

- API defined in PKCS#11 specification
 - <http://www.rsa.com/rsalabs/node.asp?id=2133>
 - functions with prefix 'C_' (e.g., C_EncryptFinal())
 - header files pkcs11.h and pkcs11_ft.h
- Usually in the form of dynamically linked library
 - cryptoki.dll, opensc-pkcs11.dll, dkck232.dll...
 - different filenames, same API functions (PKCS#11)
- Virtual token with storage in file possible
 - suitable for easy testing (no need for hardware reader)
 - Mozilla NSS, SoftHSM...

PKCS#11: role model

- Functions for token initialization
 - outside scope of the specification
 - usually implemented (proprietary function call), but erase all data on token
- Public part of token
 - data accessible without login by PIN
- Private part of token
 - data visible/accessible only when PIN is entered

PKCS#11: Cryptographic functionality

- C_GetMechanismList to obtain supported cryptographic mechanisms (algorithms)
- Many possible mechanisms defined (pkcs11t.h)
 - CK_MECHANISM_TYPE, not all supported
 - (compare to JavaCard API)
- C_Encrypt, C_Decrypt, C_Digest, C_Sign, C_Verify, C_VerifyRecover, C_GenerateKey, C_GenerateKeyPair, C_WrapKey, C_UnwrapKey, C_DeriveKey, C_SeedRandom, C_GenerateRandom...

PKCS#11 - conclusions

- Wide support in existing applications
- Low-level API
- Difficult to start with
- Requires proprietary library by token manufacturer
- Complex standard with vague specification => security problems
 - Hard to implement properly

Play with HSM (without HSM 😊)



- SoftHSM
 - Software-only HSM
 - Open-source implementation of cryptographic store
 - Botan library for cryptographic operations
 - <https://www.opendnssec.org/softhsm/>
 - <https://github.com/disig/SoftHSM2-for-Windows>
- Utimaco HSM simulator
 - <https://hsm.utimaco.com/download/>
 - Simulator of physical HSM (with PKCS#11 and other interfaces)

Microsoft CNG

- Cryptography API: Next Generation (CNG API)
- Long-term replacement for CryptoAPI
- CNG API
 - Cryptographic Primitives
 - Key Storage and Retrieval
 - Key Import and Export
 - Data Protection API: Next Generation (CNG DPAPI)
- <http://msdn.microsoft.com/en-us/library/windows/desktop/aa376210%28v=vs.85%29.aspx>

Cryptographic Service Providers (CSP)

- Generic framework with API for providers of cryptographic functionality
 - E.g., implementation of RSA
 - Different underlying storage (software vs. hardware-based)
- Allows for runtime selection
 - Connect to target provider (usually identification string)
 - E.g., “Microsoft Base Cryptographic Provider v1.0”
- Microsoft CSPs
 - <http://msdn.microsoft.com/en-us/library/windows/desktop/aa386983%28v=vs.85%29.aspx>
- Java CSPs (JCE)...

ATTACKS AGAINST API

Attacks against PKCS#11

- Lack of policy for function calls
 - functions are too “low-level”
 - sensitive objects can be manipulated directly
- Key binding attack (C_WrapKey)
 - target key with double length is exported from SC
 - encrypted by unknown master key
 - attacker divide key into two parts and import them as wrapped key for ECB mode
 - perform brute-force search on each half separately
- Missing authentication of wrapped key
 - attacker can create its own wrapping key
 - and ask for export of unknown key under his own wrapping key
- Export of longer keys under shorter, ...

RSA padding oracle attack

- Allows to recover content of encrypted message even when key is unknown
- Based on 1 bit leakage from correct/incorrect padding
 - Error status returned by device
- (cycle) mess with encrypted message, send to card, inspect error
- 30 minutes with HSM, hours/days with smart card
- See more at
 - <http://secgroup.dais.unive.it/wp-content/uploads/2012/11/Practical-Padding-Oracle-Attacks-on-RSA.html>

Tookan tool

- Formal verification with real device model
 - probe PKCS#11 token with multiple function calls
 - automatically create formal model for token
 - run model checker and find attack
 - try to execute attack against real token
- <http://secgroup.dais.unive.it/projects/tookan/>



Conclusions

- Hardware Security Module is device build for security and performance of cryptographic operations
- Security certifications (but be aware of limits)
- Initially mostly for banking sector
 - Now more widespread (TLS, key management..)
- Diverse APIs, potential logical attacks

PKCS#11 DETAILS