Please comment on slides with anything unclear, incorrect or suggestions for improvement
https://drive.google.com/file/d/1DD5tgyaS8Nk_Wze97_IJpVBRQhXuwgT8/view?usp=drive_link

PV204 Security technologies

JavaCard optimizations, Secure Multiparty Computation and Trhreshold signatures

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(part of MPC slides done by Antonín Dufka)

Centre for Research on Cryptography and Security

BEST PRACTICES (FOR APPLET DEVELOPERS)

Quiz

1. Expect that your device is leaking in time/power channel. Which option will you use?
   – AES from hw coprocessor or software re-implementation?
   – Short-term sensitive data stored in EEPROM or RAM?
   – Persistent sensitive data in EEPROM or encrypted object?
   – Conditional jumps on sensitive value?
2. Expect that attacker can successfully induct faults (random change of bit(s) in device memory).
   – Suggest defensive options for applet's source code
   – Change in RAM, EEPROM, instruction pointer, CPU flags…

Security hints (1)

- Use algorithms/modes from JC API rather than your own implementation
  - JC API algorithms fast and protected in cryptographic hardware
  - general-purpose processor leaks more information (side-channels)
- Store session data in RAM
  - faster and more secure against power analysis
  - EEPROM has limited number of rewrites (10^5 – 10^6 writes)
- Never store keys, PINs or sensitive data in primitive arrays
  - use specialized objects like OwnerPIN and Key
  - better protected against power, fault and memory read-out attacks
  - If not possible, generate random key in Key object, encrypt large data with this key and store only encrypted data
- Make checksum on stored sensitive data (=> detect faults)
  - check during applet selection (do not continue if data are corrupted)
  - possibly check also before sensitive operation with the data (but performance penalty)

Security hints (2)

- Erase unused keys and sensitive arrays
  - use specialized method if exists (Key.clearKey())
  - or overwrite with random data (Random.generate())
  - Perform always before and after start of new session (new select, new device…)
- Use transactions to ensure atomic operations
  - power supply can be interrupted inside code execution
  - be aware of attacks by interrupted transactions - rollback attack
- Do not use conditional jumps with sensitive data
  - branching after condition is recognizable with power analysis => timing/power leakage

Security hints (3)

- Allocate all necessary resources in constructor
  - applet installation usually in trusted environment
  - prevents attacks based on limited available resources later during applet use
- Don’t use static attributes (except constants)
  - Static attribute is shared between multiple instances of applet (bypasses applet firewall)
  - Static pointer to array/engine filled by dynamic allocation cannot be removed until package is removed from card (memory “leak”)
- Use automata-based programming model
  - well defined states (e.g., user PIN verified)
  - well defined transitions and allowed method calls

Security hints (4)

- Treat exceptions properly
  - Do not let uncaught native exceptions to propagate away from the card
    - 0x6f00 emitted – unclear what caused it from the terminal side
    - Your applet is unaware of the exception (fault induction attack in progress?)
  - Do not let your code to cause basic exceptions like OutOfBoundsException or NullPointerExceptions…
    - Slow handling of exceptions in general
    - Code shall not depend on triggering lower-layer defense (like memory protection)

Secure Application Programming in the presence of Side Channel Attacks, Riscure

Security hints: fault induction (1)

- Cryptographic algorithms are sensitive to fault induction
  - Single signature with fault from RSA-CRT may leak the private key
  - Perform operation twice and compare results
  - Perform reverse operation and compare (e.g., verify after sign)
- Use constants with large hamming distance
  - Induced fault in variable will likely cause unknown value
  - Use 0xA5 and 0x5A instead of 0 and 1 (correspondingly for more)
  - Don’t use values 0x00 and 0xff (easier to force all bits to 0 or 1)
- Check that all sub-functions were executed [Fault.Flow]
  - Fault may force program stack or stack to skip some code
  - Idea: Add defined value to flow counter inside target sub-function, check later for expected sum. Add also in branches.

Secure Application Programming in the presence of Side Channel Attacks, Riscure

Security hints: fault induction (2)

- Replace single condition check by complementary check
  - **`conditionalValue`** is sensitive value
  - Do not use boolean values for sensitive decisions

```
if (conditionalValue == 0x3CA5965A) { // enter critical path
  // . . .
  if (~conditionalValue != 0xC35A69A5) {
    faultDetect(); // fail if complement not equal to 0xC35A69A5
  }
  // . . .
}
```

- Verify number of actually performed loop iterations

```
int i;
for ( i = 0; i < n; i++ ) { // important loop that must be completed
//. . .
}
if (i != n) { // loop not completed
  faultDetect();
}
```

Secure Application Programming in the presence of Side Channel Attacks, Riscure

Security hints: fault induction (3)

- Insert random delays around sensitive operations
  - Randomization makes targeted faults more difficult
  - for loop with random number of iterations (for every run)
- Monitor and respond to detected induced faults
  - If fault is detected (using previous methods), increase fault counter.
  - Erase keys / lock card after reaching some threshold (~10)
    - Natural causes may occasionally cause fault => > 1

How and when to apply protections

- ✓ Does the device need protection?
- ✓ Understand the resistance of the hardware
- ✓ Identify potential weakness in design
- ✓ Select patterns to use
- ✓ Understand your compiler
- ✓ Code it
- ✓ Test the resistance of the device

Execution speed hints (1)

- Big difference between RAM and EEPROM memory
  - new allocates in EEPROM (persistent, but slow)
    - do not use EEPROM for temporary data
    - do not use for sensitive data (keys)
  - JCSystem.getTransientByteArray() for RAM buffer
  - local variables automatically in RAM
- Use algorithms from JavaCard API and utility methods
  - much faster, cryptographic co-processor
- Allocate all necessary resources in constructor
  - executed during installation (only once)
  - either you get everything you want or not install at all

Execution speed hints (2)

- Garbage collection limited or not available
  - do not use **`new`** except in constructor
- Use copy-free style of methods
  - foo(byte[] buffer, short start_offset, short length)
- Do not use recursion or frequent function calls
  - slow, function context overhead
- Do not use OO design extensively (slow)
- Keep Cipher or Signature objects initialized
  - if possible (e.g., fixed master key for subsequent derivation)
  - initialization with key takes non-trivial time

JCPROFILERNEXT – PERFORMANCE PROFILING, NON-CONSTANT TIME DETECTION

JCProfilerNext: on-card performance profiler

- Open-source on-card performance profiler (L. Zaoral)
  - https://github.com/lzaoral/JCProfilerNext
- Automatically instrumentation of provided JavaCard code
  - Conditional exception emitted on defined line of code
  - Spoon tool used https://spoon.gforge.inria.fr/
- Measures time to reach specific line (measured on client-side)
- Fully automatic, no need for special setup (only JavaCard + reader)
- Goals:
  - Help developer to identify parts for performance optimizations
  - Help to detect (significant) timing leakages
  - Insert “triggers” visible on side-channel analysis
  - Insert conditional breakpoints…

Instrumented code (Spoon)

```java
// if m_perfStop equals to stopCondition, exception is thrown (trap hit)
public static void check(short stopCondition) {
    if (PM.m_perfStop == stopCondition) {
        ISOException.throwIt(stopCondition);
    }
}
```

```java
private void example(APDU apdu) {
  PM.check(PMC.TRAP_example_Example_example_argb_javacard_framework_APDU_arge_1);
  short count = Util.getShort(apdu.getBuffer(), ISO7816.OFFSET_CDATA);
  PM.check(PMC.TRAP_example_Example_example_argb_javacard_framework_APDU_arge_2);
  for (short i = 0; i < count; i++) {
    PM.check(PMC.TRAP_example_Example_example_argb_javacard_framework_APDU_arge_3);
    short tmp = 0;
    PM.check(PMC.TRAP_example_Example_example_argb_javacard_framework_APDU_arge_4);
    for (short k = 0; k < 50; k++) {
      PM.check(PMC.TRAP_example_Example_example_argb_javacard_framework_APDU_arge_5);
      tmp++;
      PM.check(PMC.TRAP_example_Example_example_argb_javacard_framework_APDU_arge_6);
    }
    PM.check(PMC.TRAP_example_Example_example_argb_javacard_framework_APDU_arge_7);
  }
  PM.check(PMC.TRAP_example_Example_example_argb_javacard_framework_APDU_arge_8);
}
```

JCProfilerNext – timing profile of target line of code

example.Example.example2(javacard.framework.APDU)

TRAP_example_Example_example2_argb_javacard_framework_APDU_arge_12

Card ATR: 3BFA1800008131FE454A434F5033315632333298
Number of rounds: 1000
APDU header: 80010000
Input regex: 00[0-9A-F]{2}
Elapsed time: 0 days 00:00:02.814
Source measurements: measurements.csv

Show explicit traps

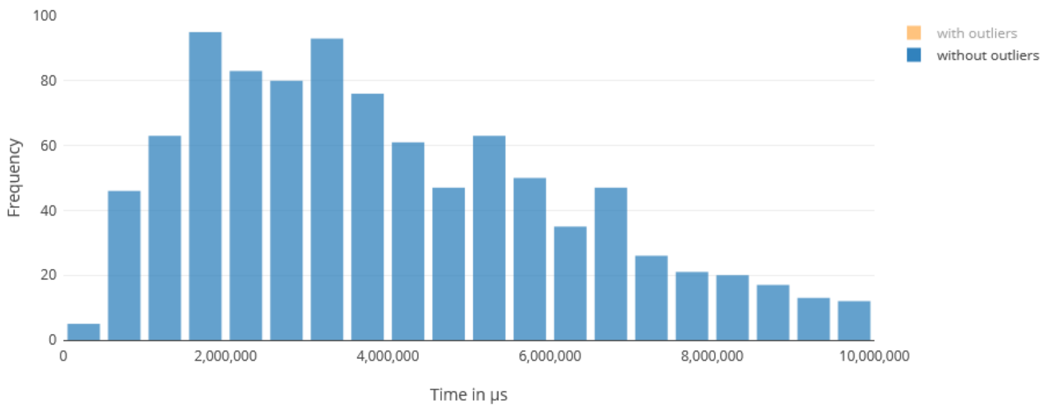
Avg μs

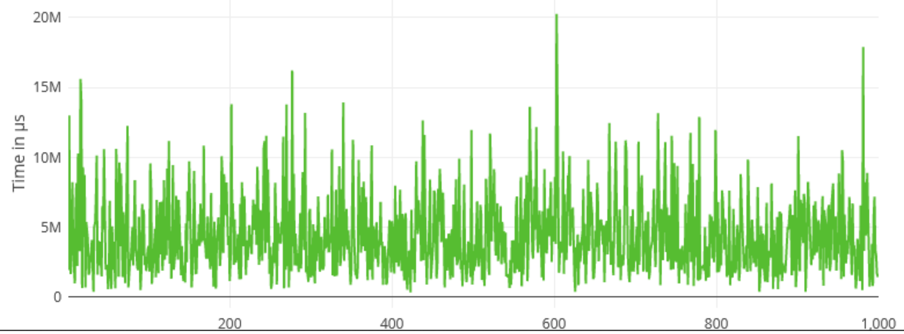
```java
private void example2(APDU apdu) {
    byte[] apdubuf = apdu.getBuffer();
    short dataLen = apdu.setIncomingAndReceive();
    // SET KEY VALUE
    m_aesKey.setKey(apdubuf, ISO7816.OFFSET_CDATA);
    // INIT CIPHERS WITH NEW KEY
    m_encryptCipher.init(m_aesKey, Cipher.MODE_ENCRYPT);
    m_decryptCipher.init(m_aesKey, Cipher.MODE_DECRYPT);
    m_encryptCipher.doFinal(apdubuf, ISO7816.OFFSET_CDATA, ((short) (0x10)), m_ramArray, ((short) (0)));
    m_decryptCipher.doFinal(apdubuf, ISO7816.OFFSET_CDATA, ((short) (0x10)), m_ramArray, ((short) (0)));
    // Hash input
    m_hash.doFinal(apdubuf, ISO7816.OFFSET_CDATA, dataLen, m_ramArray, ((short) (0)));
    // GENERATE DATA
    m_secureRandom.generateData(apdubuf, ISO7816.OFFSET_CDATA, ((short) (0x10)));
    // Sign data
    short signLen = m_sign.sign(apdubuf, ISO7816.OFFSET_CDATA, ((byte) (dataLen)), m_ramArray, ((byte) (0)));
    // Generate fresh key pair on-card
    m_keyPair.genKeyPair();
    m_publicKey = m_keyPair.getPublic();
    m_privateKey = m_keyPair.getPrivate();
    // INIT WITH PRIVATE KEY
    m_sign.init(m_privateKey, Signature.MODE_SIGN);
}
```

Colour explanation

Currently selected trap | Trap was never reached | Trap was reached only sometimes

Click on a bin to get a list of corresponding inputs.





JCProfilerNext – memory consumption

opencrypto.jcmathlib.OCUnitTests()

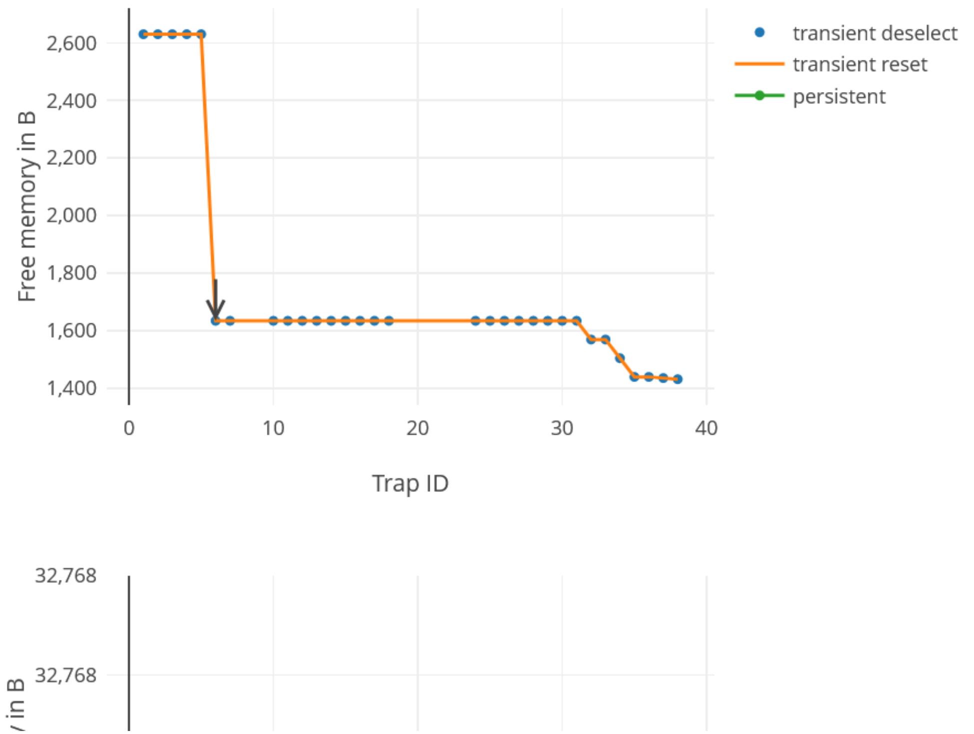
TRAP_opencrypto_jcmathlib_OCUnitTests_argb_arge_6

Mode: memory
Card ATR: 3B80800101
APDU header: measured during installation
Input: measured during installation
Elapsed time: 0 days 00:00:00.294
Source measurements: measurements.csv

☐ Show explicit traps

Diff in B

```
public OCUnitTests() {
    OperationSupport.getInstance().setCard(OperationSupport.SIMULATOR);// TO
    m_memoryInfo = new short[((short) (7 * 3))];// Contains RAM and EEPROM r
    m_memoryInfoOffset = snapshotAvailableMemory(((short) (1)), m_memoryInfo
    if (bTEST_256b_CURVE) {
        m_ecc = new ECConfig(((short) (256)));
    }
    if (bTEST_512b_CURVE) {
        m_ecc = new ECConfig(((short) (512)));
    }
    m_memoryInfoOffset = snapshotAvailableMemory(((short) (2)), m_memoryInfo
    // Pre-allocate test objects (no new allocation for every tested operat
    if (bTEST_256b_CURVE) {
        m_testCurve = new ECCurve(false, SecP256r1.p, SecP256r1.a, SecP256r1
        m_memoryInfoOffset = snapshotAvailableMemory(((short) (3)), m_memory
        // m_testCurveCustom and m_testPointCustom will have G occasionally
        m_customG = new byte[((short) (SecP256r1.G.length))];
        Util.arrayCopyNonAtomic(SecP256r1.G, ((short) (0)), m_customG, ((sho
        m_testCurveCustom = new ECCurve(false, SecP256r1.p, SecP256r1.a, Sec
    }
    if (bTEST_512b_CURVE) {
```



Checking for non-constant time execution

opencrypto.jcmathlib.OCUnitTests#test_BN_MOD(javacard.framework.APDU,short)

TRAP_opencrypto_jcmathlib_OCUnitTests_hash_test_BN_MOD_argb_javacard_framework_APDU__short_arge_10

Mode: time
Card ATR: 3B80800101
Number of rounds: 1000
APDU header: B0252100
Input regex: 00[0-9A-F]{64}[4-7][0-9A-F]{63}
Elapsed time: 0 days 00:58:39.803
Source measurements: measurements.csv

☐ Show explicit traps

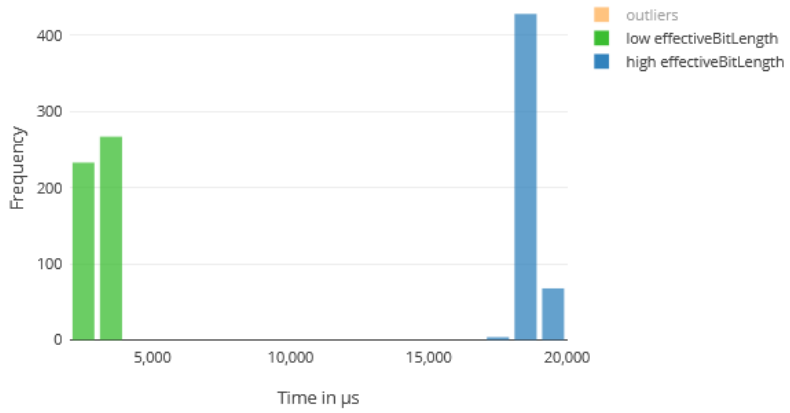
Avg μs

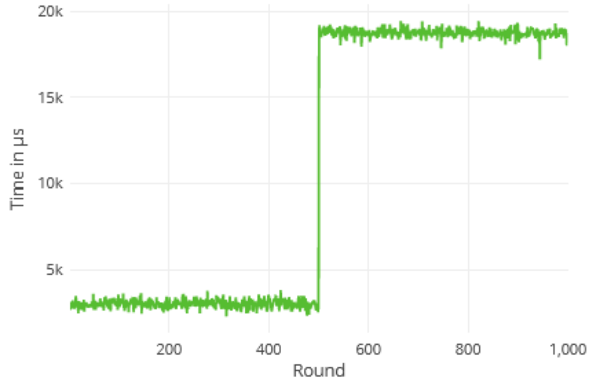
```
void test_BN_MOD(APDU apdu, short dataLen) {
    byte[] apdubuf = apdu.getBuffer();
    short p1 = ((short) (apdubuf[ISO7816.OFFSET_P1] & 0xff));
    Bignat num = m_testBN1;
    num.set_size(p1);
    Bignat mod = m_testBN2;
    mod.set_size(((short) (dataLen - p1)));
    num.from_byte_array(p1, ((short) (0)), apdubuf, ISO7816.OFFSET_CDATA);
    mod.from_byte_array(((short) (dataLen - p1)), ((short) (0)), apdubuf,
    num.mod(mod);
    short len = num.copy_to_buffer(apdubuf, ((short) (0)));
    apdu.setOutgoingAndSend(((short) (0)), len);
}
```

Colour explanation

Currently selected trap | Trap was never reached | Trap was reached only sometimes

Click on a graph item to get a list of corresponding inputs.

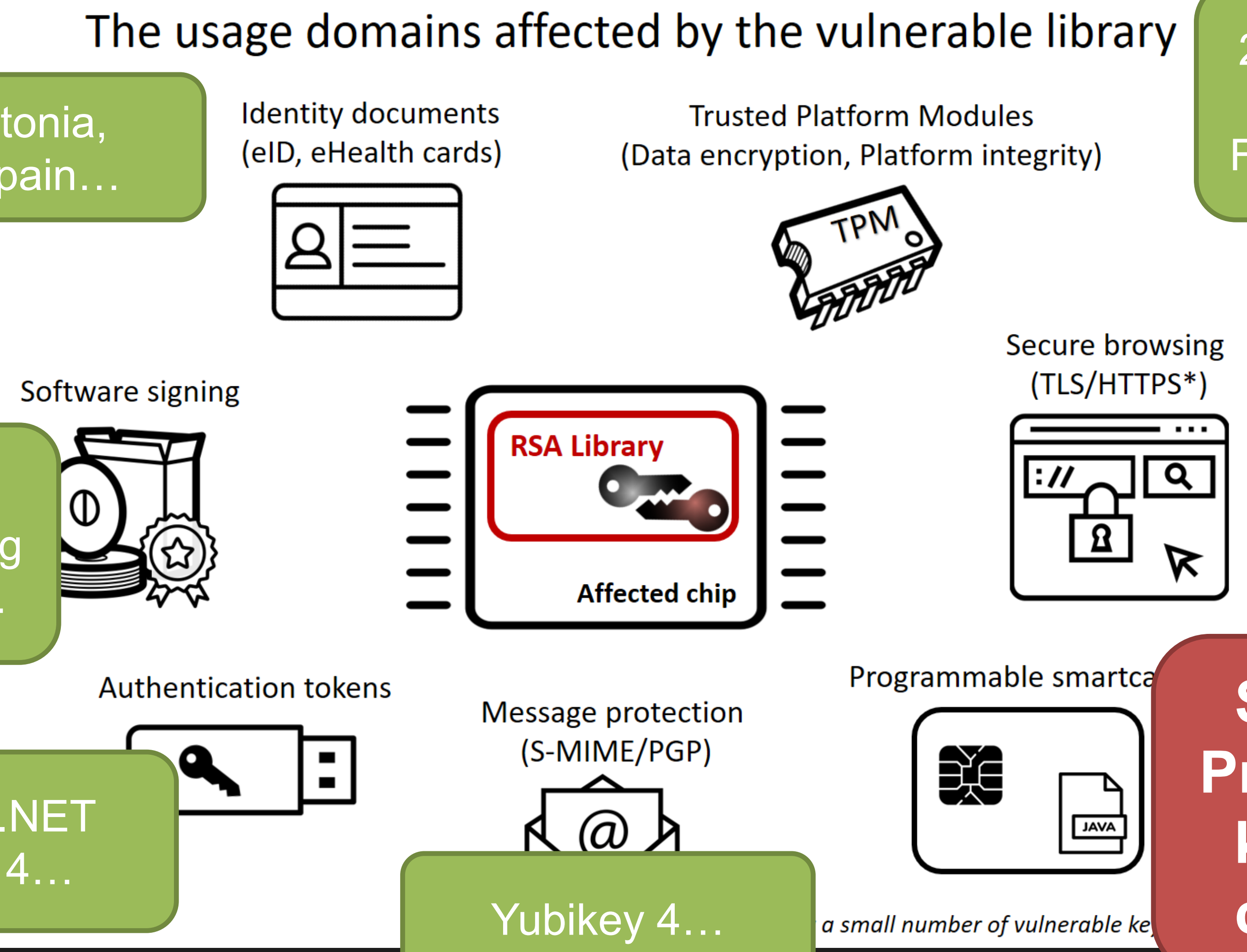




THRESHOLD CRYPTOGRAPHY
(TO REMOVE SINGLE POINT OF FAILURE)

Possibly heard of ROCA vulnerability CVE-2017-15361

M. Nemec, M. Sys, P. Svenda, D. Klinec, V. Matyas: The Return of Coppersmith's Attack..., ACM CCS 2017



Austria, Estonia, Slovakia, Spain…

25-30% TPMs worldwide, BitLocker, ChromeOS… Firmware update available

Commit signing, Application signing GitHub, Maven…

Very few keys, but all tied to SCADA management

Gemalto .NET Yubikey 4…

Yubikey 4…

Single point of failure: Prime generation of RSA keygen in widely used chip (1-2 billion chips)

Single point of failure

- We already try to avoid single point of failure at many places
  – Personal: dual control, people from different backgrounds…
  – Technical: Load-balancing web servers, RAID, periodic backups…
  – Supply chain: no reliance on single supplier…
- Problems: Appropriate trade-off between security, cost and usability
- Systems without single point of failure tend to be:
  – More complex
  – More expensive
  – Less performant
  – Backward incompatible
  – (not really without single point of failure)

REMOVING SINGLE POINT OF FAILURE IN CRYPTOGRAPHIC SIGNATURES

Secure Multi-Party Computation

- "Offload heavy computation to untrusted party while not leaking info"

Example:

- Amazon evaluates trained neural network on medical image (on behalf of user)
- Amazon learns neither the trained NN, nor the processed image
- *Technology*: Homomorphic encryption, garbled circuits (slow, but getting better)

- "Distribute critical cryptographic operation among N parties"

Example:

- 3 devices collaboratively compute digital ECC signature
- Private key never at single place, secure unless all devices are compromised
- Technology: purpose tailored schemes (efficient, provably secure)

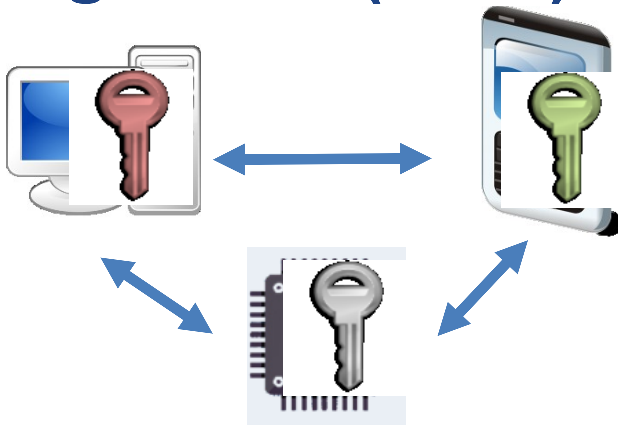
Focus of this lecture (threshold cryptography)

Goals of threshold cryptography

1. Remove single point of failure
   - Reduce trust requirements (no single party can fail you)
   - Better protect against attacks like malware (no single device with full key)
   - Provide resiliency against subset compromise (k-of-n)
2. Provide fault tolerance (n-of-n vs. k-of-n)
   - Perform operation with some parties not available
3. Enable different signing/decryption policies to be enforced (each party)
   - Regulatory requirements (e.g., “four eyes principle”)

Analogically for decryption (single person decrypts, multiple people, k-of-n)

Threshold Signature (MPC)



Single signature

Shamir TSS

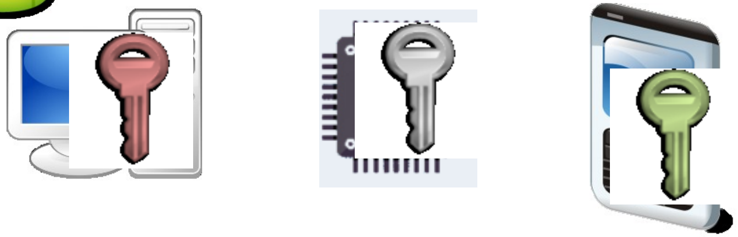
Share 1

Share 2

Share 3

Signature

Multiple signatures

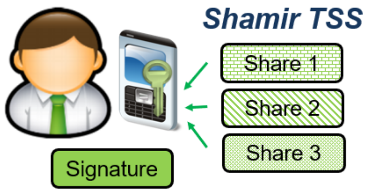


Signature Signature Signature

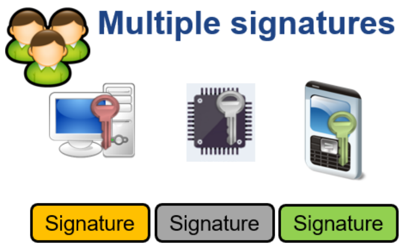
Signature

How to “split” key for threshold cryptography?

- (Shamir threshold secret sharing)

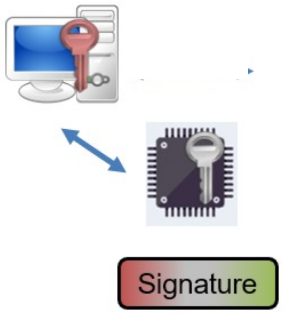


- Multiple separate signatures (same algorithm)



- Cryptographic “garden” (multiple keys, different keys)

- n-of-n MPC signature (multiple keys, all must contribute)
  – k-of-n MPC threshold signature (multiple keys, k must contribute)



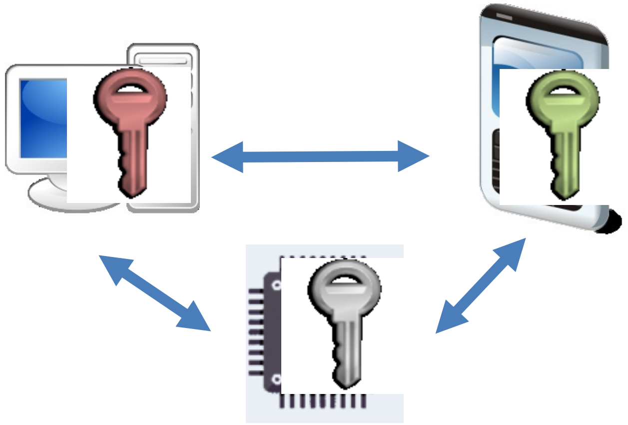
Option: Cryptographic “garde

- Electronic signature == sign_RSA(SHA256(message))
  - Failure in RSA or SHA256 algorithm or its implementation => forgery of signatures

- Signature using cryptographic “garden”
  - Differently computed (algorithm) signatures over same message
  - Signature = sign_RSA+ sign_ECC + sign_PostQuantumAlg
  - Mitigate design problems of particular algorithm

- Disadvantages: backward (in-)compatibility, larger storage space…

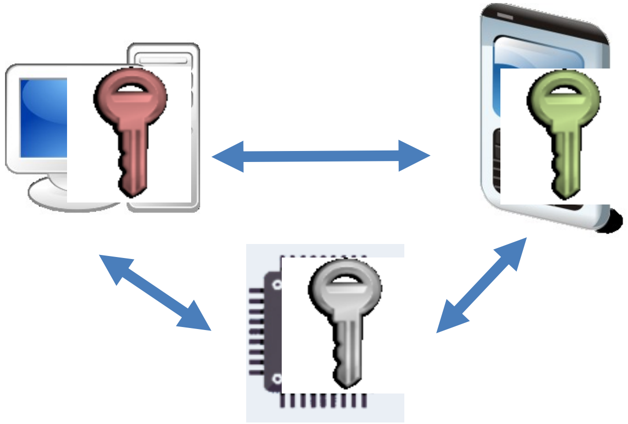
Threshold cryptography



- Proposed already in 1987 by Y. Desmedt
- Principle
  - Private key split into multiple parts (“shares”)
  - Shares used (independently) by separate parties during a protocol to perform desired cryptographic operation
  - If enough shares are available, operation is finished successfully
- Properties
  - Better protection of private key (single point of failure removed)
  - Key shares can be distributed to multiple parties (independent usage condition)
  - Resulting signature may be indistinguishable from a standard one (e.g., ECDSA)
- Significant research progress made in the cryptocurrency context

Threshold cryptography protocols

- Typically, distributed key generation is also included
  - Private key is not generated on a single device
- Output signatures can be indistinguishable from single party signatures
  - ECDSA ([GGN16], [LN18], [GG18], [GG20], [Can+20], …)
  - Schnorr (MuSig, MuSig2, FROST…)
  - RSA ([DF91], [Gen+97], [DK01], Smart-ID…)
- Various designs with different properties
  - Supported setups (n-of-n / k-of-n)
  - Number of communication rounds
  - Computation complexity
  - Security assumptions…



PRACTICAL EXAMPLES OF MPC

Smart-ID signature system

Server-Supported RSA Signatures for Mobile Devices

Ahto Buldas[1,2](✉), Aivo Kalu[1], Peeter Laud[1], and Mart Oruaas[1]

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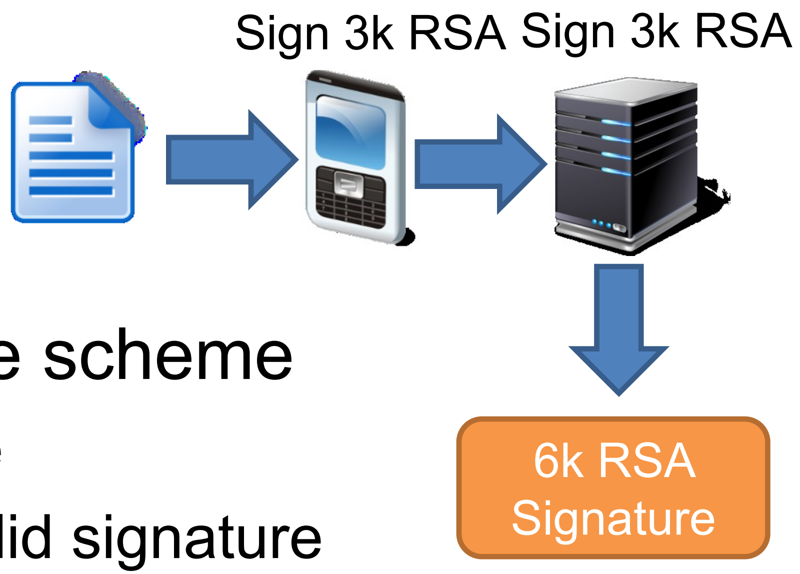
[2] Tallinn University of Technology, Tallinn, Estonia

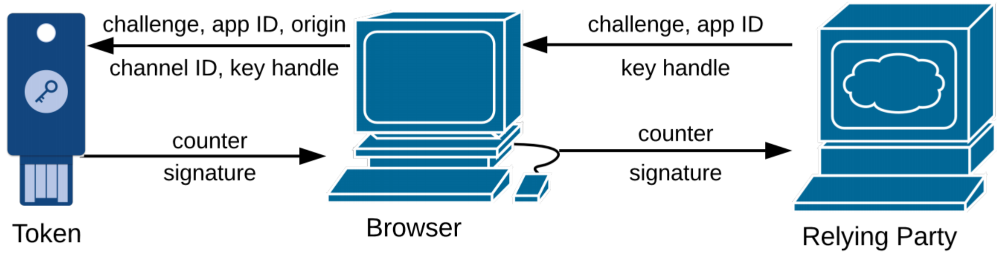
- Banks in Baltic states, >4M users
  – Qualified Signature Creation Device (QSCD)!
- Collaborative computation of signature using:
  1. User's mobile device (3072b RSA)
  2. Smart-ID service provider (3072b RSA)
- Two-party RSA signatures, threshold signature scheme
  – Whole signature key never present at a single place
  – Smart-ID service provider cannot alone compute valid signature
- Final signature is 6144b RSA => compatible with existing systems
  – Assumed security level is equivalent to 3072b RSA (as if one party compromised)



MPC wallets (software, hardware)

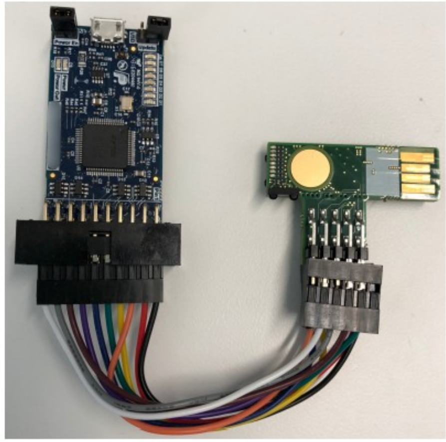
- Number of cryptocurrencies uses ECDSA/EdDSA/Schnorr algorithm to authorize TX
  - Funds are lost if private key is stolen/lost
- Multiple separate signatures by separate private keys possible (so called multisignature)
  - More costly (more onchain space => higher fee)
  - Privacy leaking (structure of approval)
  - Not always (directly) supported (Bitcoin has IP_CHECKMULTISIG, Ethereum needs special contract)
- MPC to compute threshold multiparty signature
  - Interaction between multiple entities, single signature as a result
  - Not recognizable from standard transactions on-chain
- ECDSA
  - Several end-user wallets like ZenGo, Binance, Coinbase… as well as institutional custodians
  - Usually one share by user, second by server
- Schnorr-based signatures easier to compute (e.g., Musig-2, FROST)
  - Available in Bitcoin after Taproot

True2F FIDO U2F token



- Yubikey 4 has single master key
  - To efficiently derive keypairs for separate Relying parties (Google, GitHub…)
  - Inserted during manufacturing phase (what if compromised?)
- Additional two MPC protocols (as protection against backdoored token)
  - Verifiable insertion of browser randomness into final keypairs
  - Prevention of private key leakage via ECDSA padding

- Backward-compatible (Relying party, HW)
- Efficient: 57ms vs. 23ms to authenticate



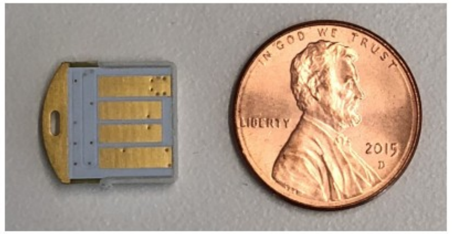
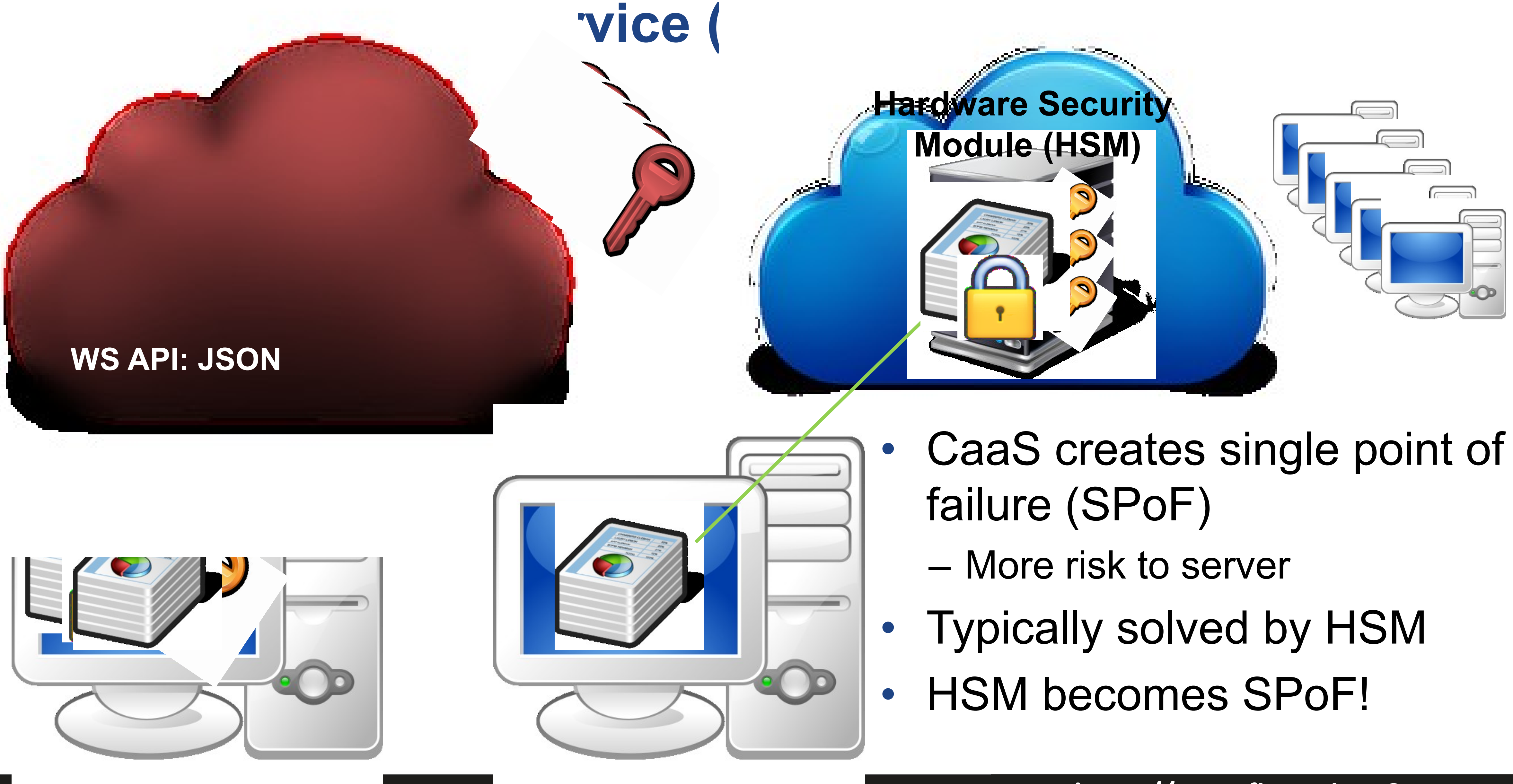


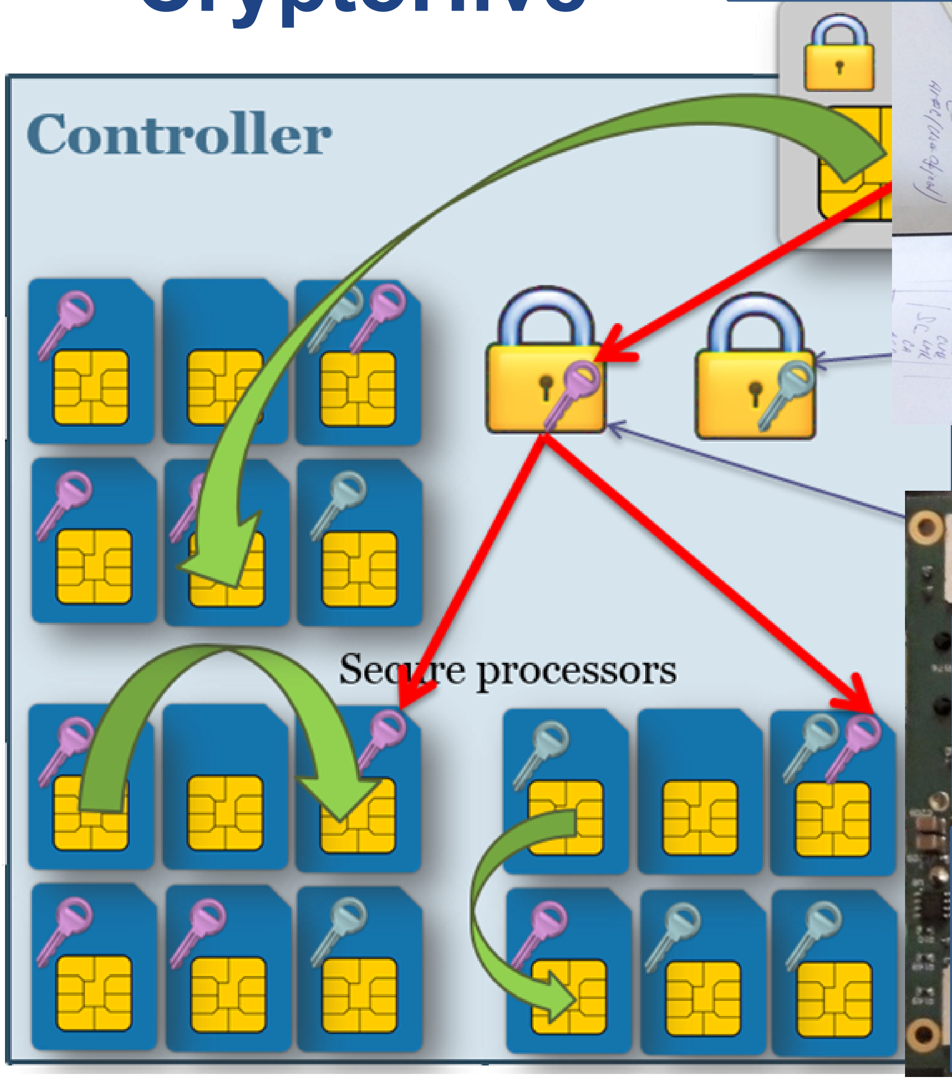
Figure 1: Development board used to evaluate our True2F prototype (at left) and a production USB token that runs True2F (above).

…vice (…

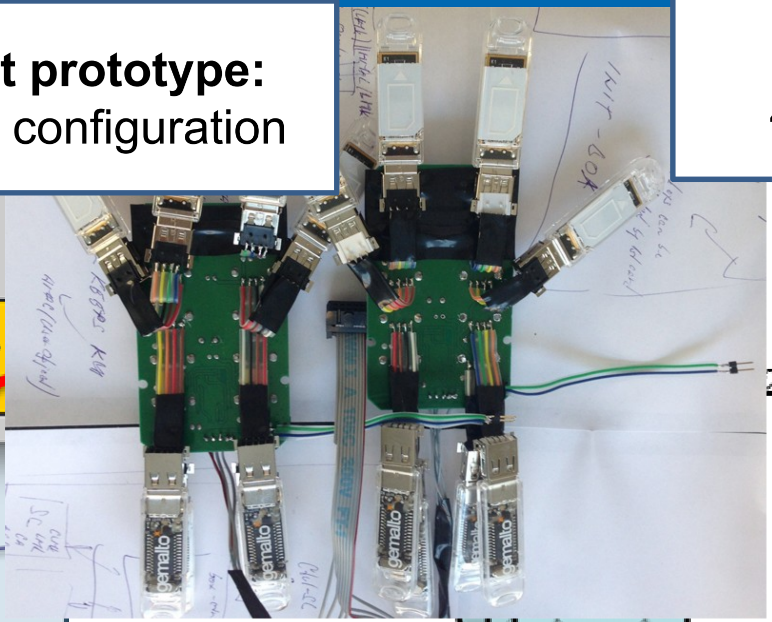


- CaaS creates single point of failure (SPoF)
  - More risk to server
- Typically solved by HSM
- HSM becomes SPoF!

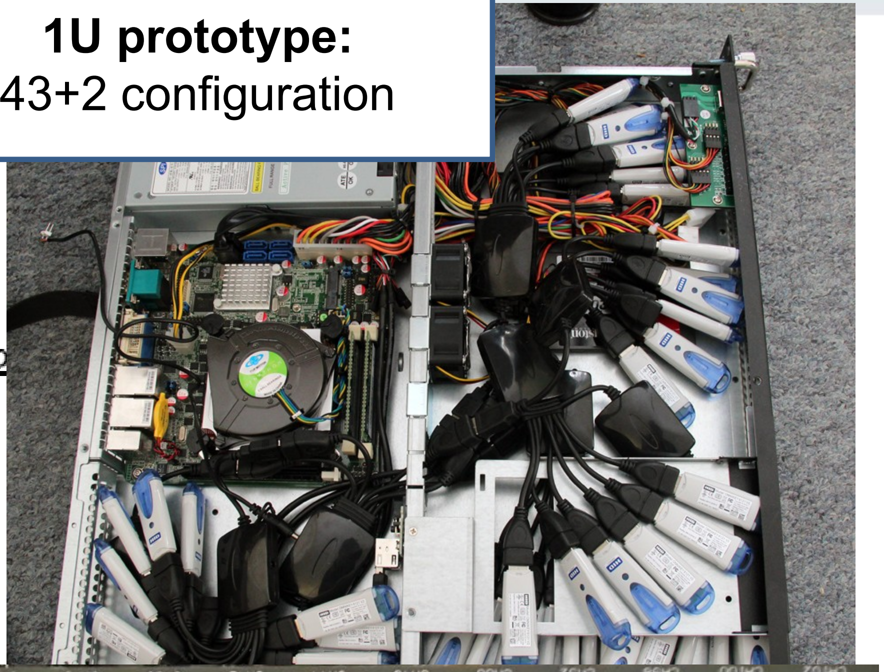
CryptoHive

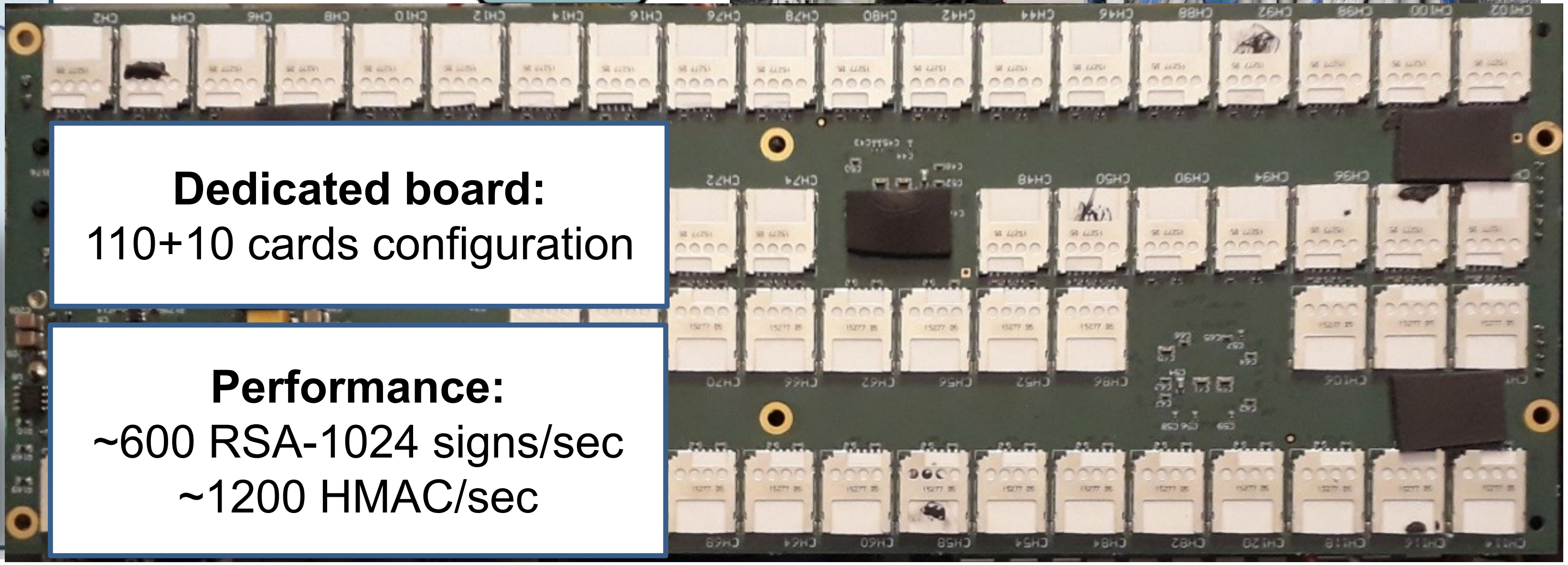


First prototype:
12+2 configuration



1U prototype:
43+2 configuration

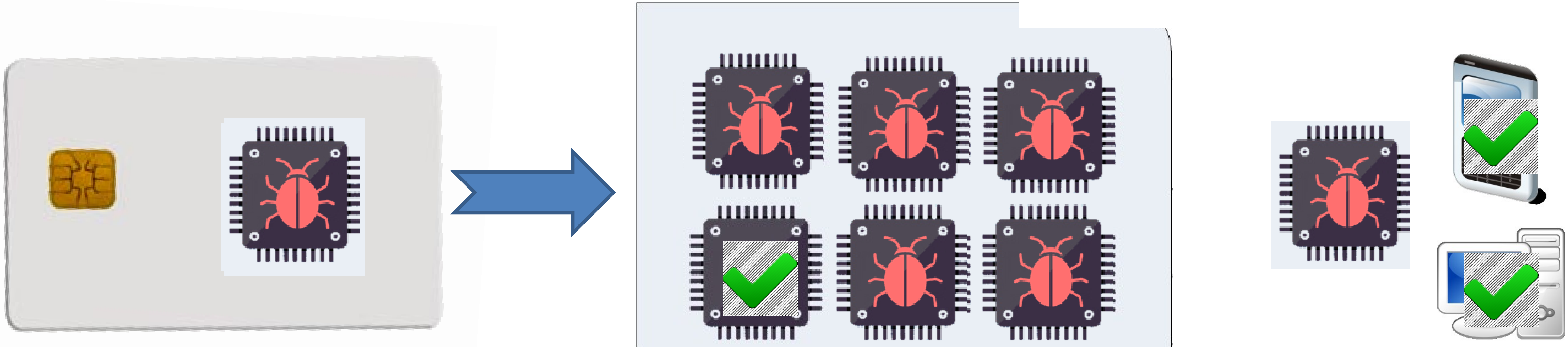




Dedicated board:
110+10 cards configuration

Performance:
~600 RSA-1024 signs/sec
~1200 HMAC/sec

Problem: buggy or subverted chip



- Prevention of supply chain compromise or buggy chip
- Suite of ECC-based multi-party protocols proposed
  – Distributed key generation, ElGamal decryption, Schnorr signing
- Efficient implementation on JavaCards + high-speed box
- Combination with non-smartcard devices possible

SmartHSM for multiparty (120 smartcards, 3 cards/quorum)

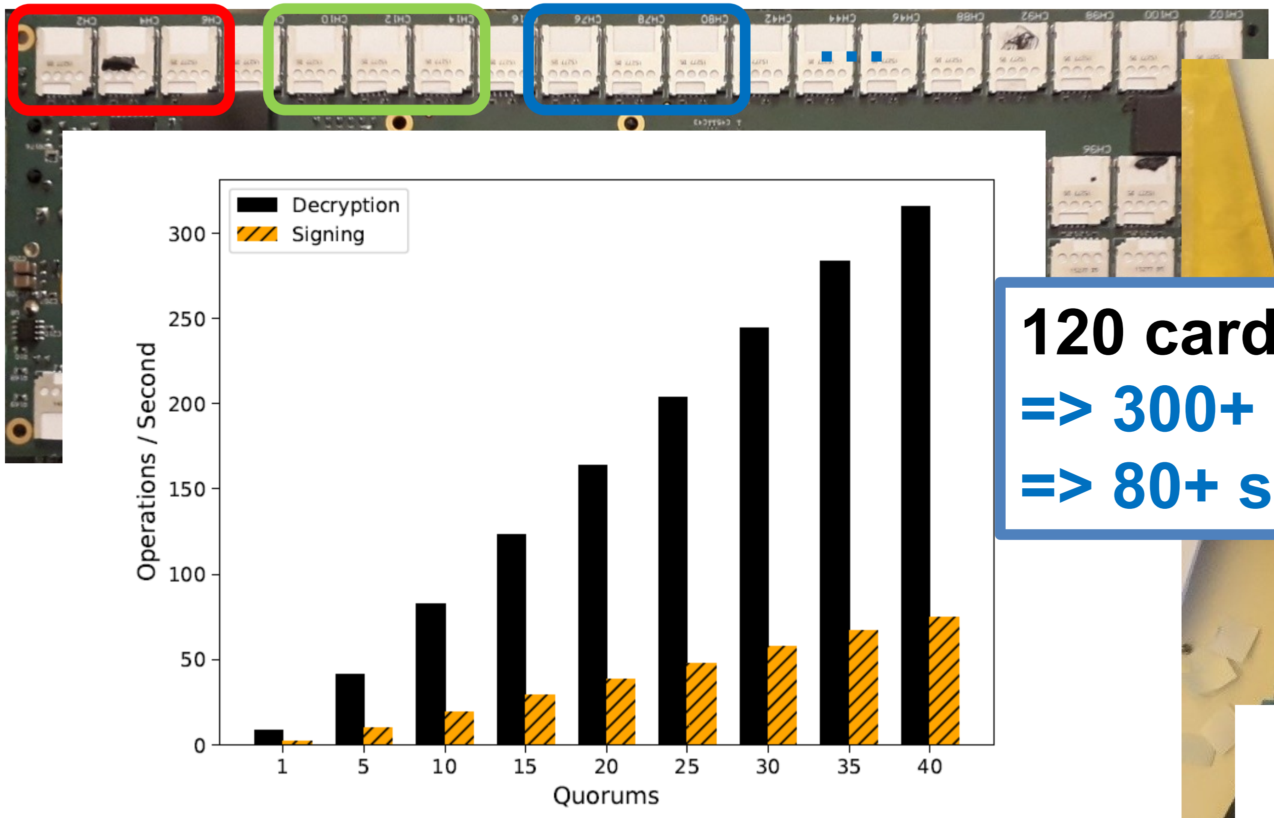
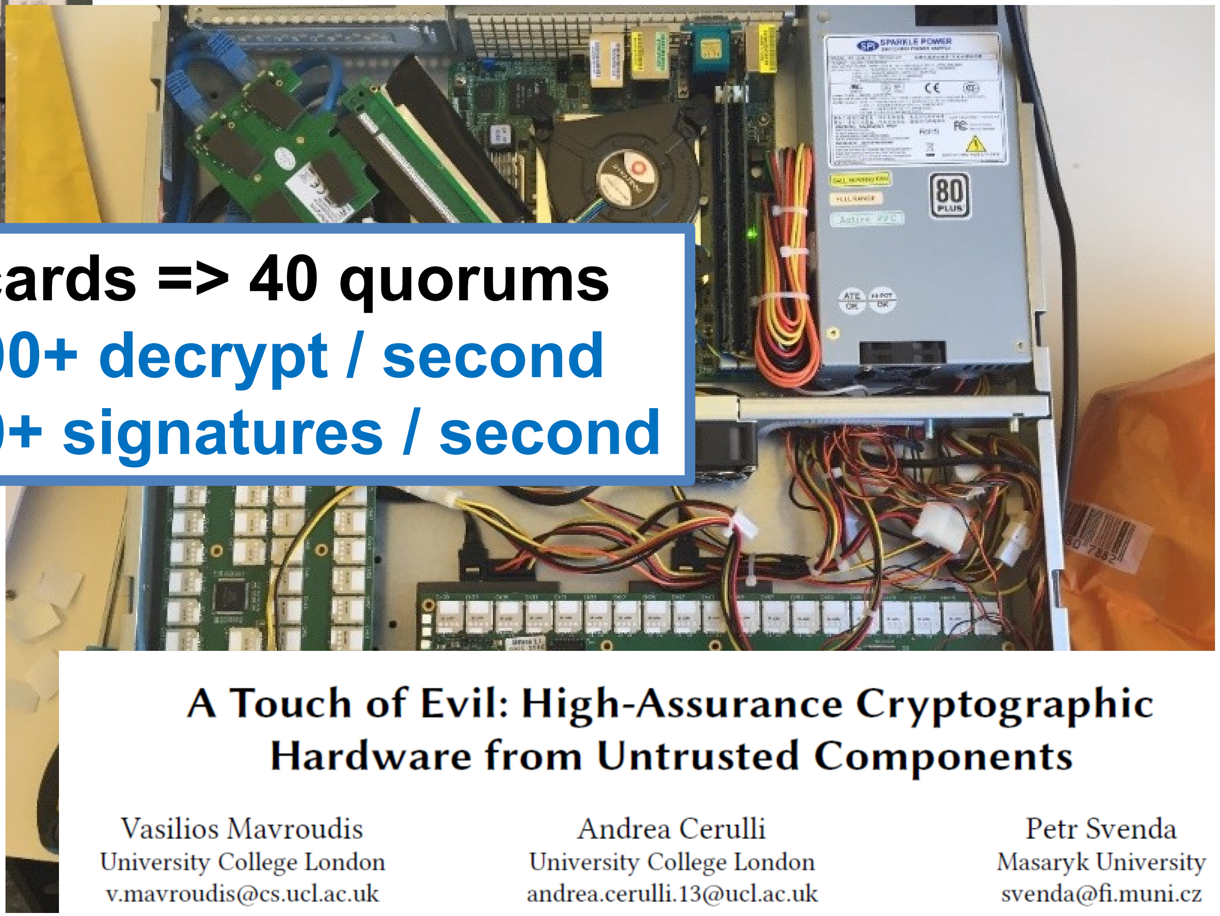


Figure 10: The average system throughput in relation to the number of quorums ($k = 3$) that serve requests simultaneously. The higher is better.



120 cards => 40 quorums
=> 300+ decrypt / second
=> 80+ signatures / second

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

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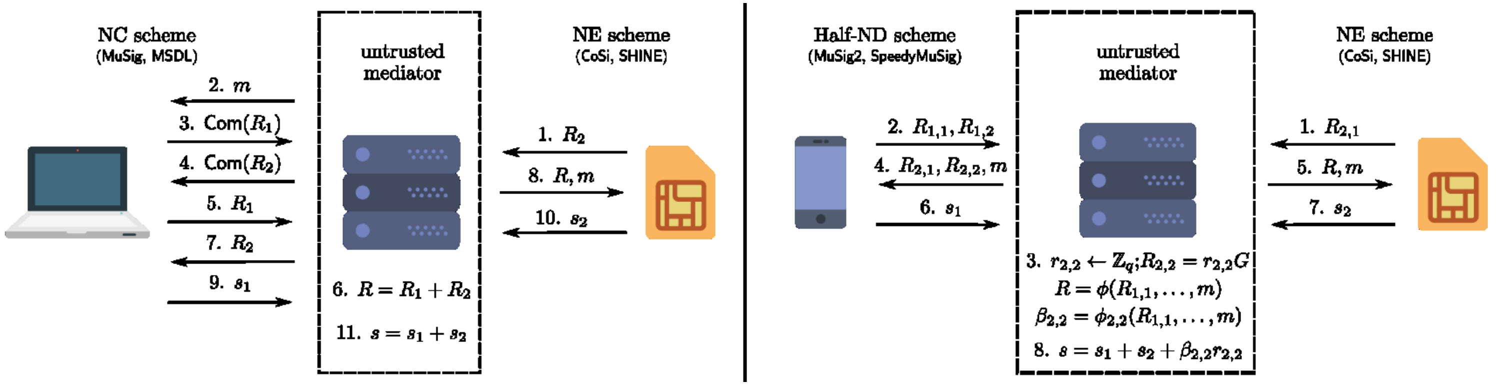
How to run MPC on JavaCards

JCMathLib

- MPC applets: https://github.com/OpenCryptoProject/Myst, https://github.com/crocs-muni/JCFROST
- Schnorr-based MPC protocols requires low-level curve operations
  - Supported by card, but not exposed by standard JavaCard API
- JCMathLib https://github.com/OpenCryptoProject/JCMathLib
  - Adds support for low-level classes/methods like ECPoint and Integer
    - Which are otherwise not supported by public JavaCard API
    - (available via proprietary extensions, but requires NDA)
  - Main goals
    1. Expose helpful functions for research/FOSS usage (e.g., Schnorr MPC sigs)
    2. Allow for publication of functional applets originally based on proprietary API
  - Low-level methods build (mis)using existing JC API
    - E.g., ECPoint.multiply() using ECDH KeyAgreement + additional computation
  - Optimized for low RAM memory footprint and performance

SHINE: Interoperability of MPC signatures

- Idea: make existing Schnorr-based MPC protocols interoperable via untrusted mediator
  - NE-based schemes (CoSi, Myst)
  - NC-based schemes (MuSig, MSDL)
  - Half-ND-based schemes (MuSig2, SpeedyMuSig)
- Additional multi-signature protocol optimized for smartcards (SHINE)
  - JCMathLib used



USE-CASE SCENARIOS

High-level usage scenarios

1. Digital signature
2. User authentication
3. Data decryption
4. Key / randomness generation

Multiparty signatures – configurations and use-cases

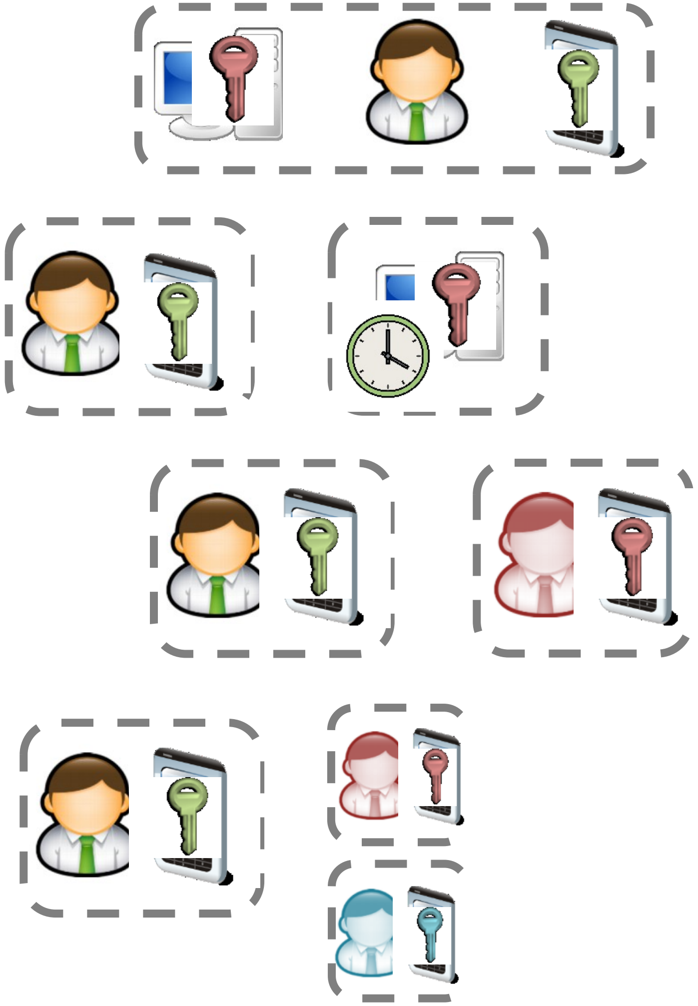
- 2-out-of-2 (two signers, both required)
  - One share on mobile phone, second on server (Smart-ID, eIDAS compliant)
  - One share on US smartcard, second on Chinese smartcard (backdoor resistance)
- 2-out-of-3 (three signers total, at least two required)
  - Two shares user, one share backup server (backup if user lose one share)
  - One share lender, one share lendee, one share arbiter (for disputes)
- 1-out-of-3 (very robust backup against key loss)
- 3-out-of-5 (shares distribution voting)
  - CEO has 2 shares, all other have only single one
- 11-out-of-15 (Liquid consortium signing blocks on Liquid sidechain)

Multiparty signatures with additional policy

- Signers can also enforce specific signing policy
  - Only during certain time, documents, type of operations, certain amount…
- 2-out-of-2 with policy
  - One person, second automatic signer only during office hours
- 2-out-of-3 with policy (two people, one automated device with policy)
  - Two people together can always sign/transfer, one person alone only up to limit)
- 3-out-of-3 (two people, one automated device with policy)
  - Automated device signs only when previous two already signed and additionally impose 1-month delay (timelock)

MPC for authentication – configurations

- 2-of-2: one user, two devices
  - (higher security against device compromise)
- 2-of-2: one user, one server-side automatic process
  - (check time interval when authentication is allowed)
- 2-of-2: two users (user, approving controller)
  - (access must be approved by controller)
- 2-of-3: three users (user, redundant approvers)
  - (one user, two controllers – one approval is enough)
- Bonus: Independent log of authentication attempt



Threshold crypto protocols – tradeoffs and limitations

- Security vs. usability
- More difficult to finalize signature (more parties, communication)
- More complex software (bugs more likely)
- Number of rounds, interaction
- Amount of data exchanged
- Active research field => possibility for new attacks against whole schemes

Backward compatibility

- Existing systems already use some crypto algorithm (RSA, ECDSA…)
  - Difficult to switch all information systems to new algorithm
- Threshold algorithm is backward compatible, if verification is unchanged
  - Only signer needs to update its software (to create threshold MPC signature)
  - Verification software stay unchanged
  - Allows for gradual opt-in (improve signing security of people who upgrade)
  - (similarly for decryption – if encryption is unchanged)
- Backward-compatible signatures exists for commonly used algorithms
  - RSA, ECDSA, EdDSA, Schnorr…

Summary

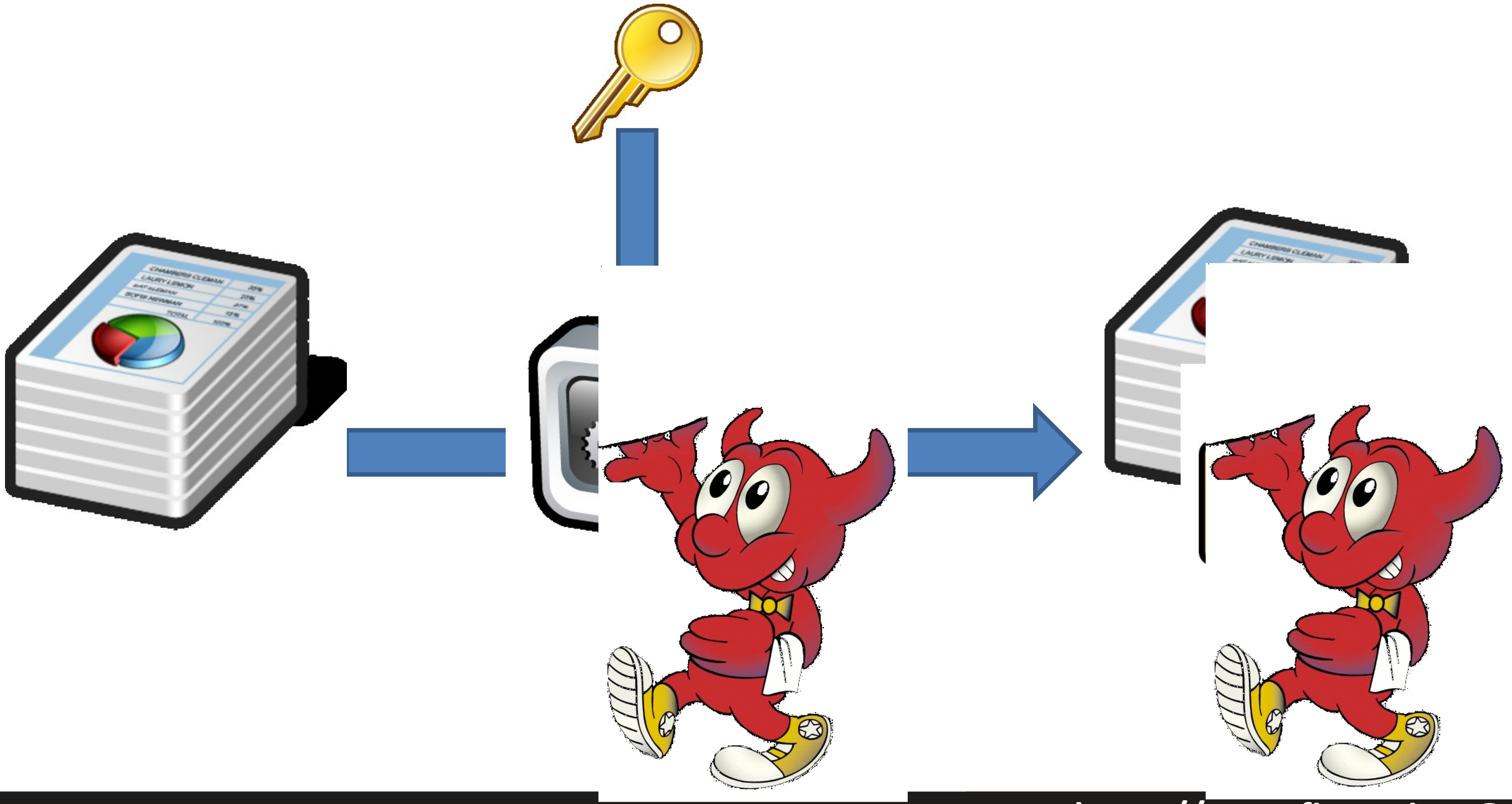
- JavaCard programming
  - Optimizations need to consider underlaying hardware (RAM, co-processors…)
  - Programs shall anticipate faults during computation (injected by an attacker)
- Secure Multiparty Computation
  - Exciting domain, active research, many practical uses
  - Collaborative computation of signatures, decryption, keygen…
  - Can be backward compatible (k-ECDSA, k-RSA, k-Schnorr…)
  - Usually more computational demanding (common CPU is enough)
  - Some protocols efficient enough to run on smartcards (Schnorr-based sigs…)
- Split to multiple parties provides:
  - Better protection of private key against bugs and compromise
  - Possibility of additional policy before party participation

Additional slides for generic multiparty computation and whitebox cryptography construction (for interested, not mandatory part of PV204 course)

Protections Against Reverse Engineering

HOW TO PROTECT

Standard vs. whitebox attacker model (symmetric crypto example)



Classical obfuscation and its limits

- Provides only time-limited protection
- Obfuscation is mostly based on obscurity
  - add bogus jumps
  - reorder related memory blocks
  - transform code into equivalent one, but less readable
  - pack binary into randomized virtual machine...
- Barak’s (im)possibility result (2001)
  - family of functions that will always leak some information
  - but practical implementation may exist for others
- Cannetti et. al. positive results for point functions
- Goldwasser et. al. negative result for auxiliary inputs

Computation with Encrypted Data and Encrypted Function

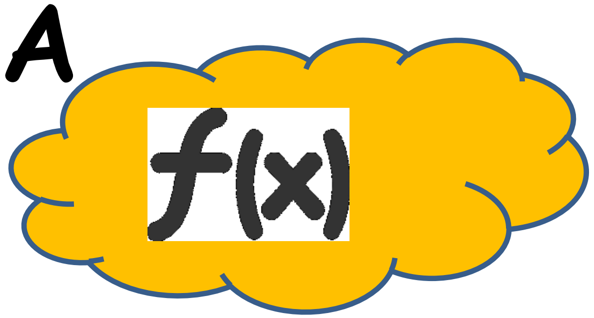
CEF&CED

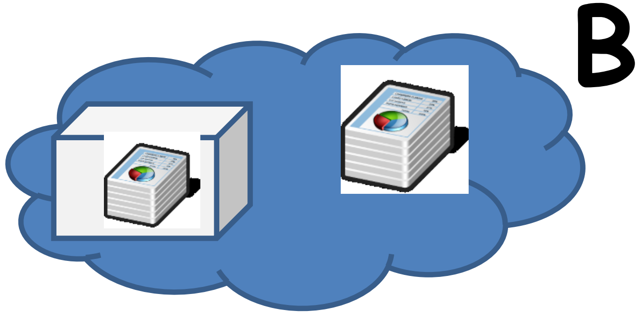
CEF

- Computation with Encrypted Function (CEF)
  - A provides function F in form of P(F)
  - P(F) can be executed on B's machine with B's data D
  - B will not learn function F during its computation (except D_i to $F(D_i)$ mapping)

CED

- Computation with Encrypted Data (CED)
  - B provides encrypted data D as E(D) to A
  - A is able to compute its F as F(E(D)) to produce E(F(D))
    - result of F over D, but encrypted
  - A will not learn data D
  - E(F(D)) is returned back to B and decrypted





CED via homomorphism

1. Convert your function into Boolean circuit with additions (`xor`) and multiplications (`and`)
2. Compute addition and/or multiplication “securely”
   - an attacker can compute E(D1+D2) = E(D1)+E(D2)
   - but can learn neither D1 nor D2
3. Execute whole circuit over encrypted data

Types of homomorphic schemes

- Partial homomorphic scheme
  - either addition or multiplication is possible, but not both; any number of times
- Somewhat homomorphic scheme
  - Both operations possible, but only limited number of times
- Fully homomorphic scheme
  - both addition and multiplication; unlimited number of times (any computable function)

Partial homomorphic schemes

- Example with RSA (*multiplication*)
  - $E(d_1).E(d_2) = d_1^e \,.\, d_2^e \bmod m = (d_1 d_2)^e \bmod m = E(d_1 d_2)$
- Example Goldwasser-Micali (*addition*)
  - $E(d_1).E(d_2) = x^{d1} r_1^2 \cdot X^{d2} r_2^2 = x^{d1+d2}(r_1 r_2)^2 = E(d_1 \oplus d_2)$
- Limited to polynomial and rational functions
- Limited to only one type of operation (*mult* or *add*)
  - or one type and very limited number of other type
- Slow – based on modular mult or exponentiation
  - every operation equivalent to whole RSA operation

Somewhat Homomorphic Encryption

- Both operations (*mult* and *add*) possible, but only limited number of times
- BGV (Barrat, Gentry and Vaikuntanathan) scheme
- GSW (Gentry-Sahai-Waters) scheme

Fully homomorphic scheme (FHE)

- Holy grail - idea proposed in 1978 (Rivest et al.)
  - both addition and multiplication securely
- But no scheme until 2009 (Gentry)!
- Fully homomorphic encryption
  - based on lattices over integers
  - noisy somewhat homomorphic encryption usable only for few operations
  - combined with repair operation (enable to use it for more operations again)

Fully homomorphic scheme - usages

- Outsourced cloud computing and storage
  - FHE search, Private Database Queries
  - protection of the query content
- Secure voting protocols
  - yes/no vote, resulting decision
- Protection of proprietary info - MRI machines
  - expensive algorithm analyzing MR data, HW protected
  - central processing restricted due to private patient’s data
- …

Fully homomorphic scheme - practicality

- Not very practical (yet ☺) (Gentry, 2009)
  - 2.7GB key & 2h computation for every repair operation
  - repair needed every ~10 multiplication
- FHE-AES implementation (Gentry, 2012)
  - standard PC ⇒ 37 minutes/block (but 256GB RAM)
- Gentry-Halevi FHE accelerated in HW (2014)
  - GPU / ASICS, many blocks in parallel => 5 minutes/block
- Replacing AES with other cipher (Simon) (2014)
  - 2 seconds/block
- Very active research area!

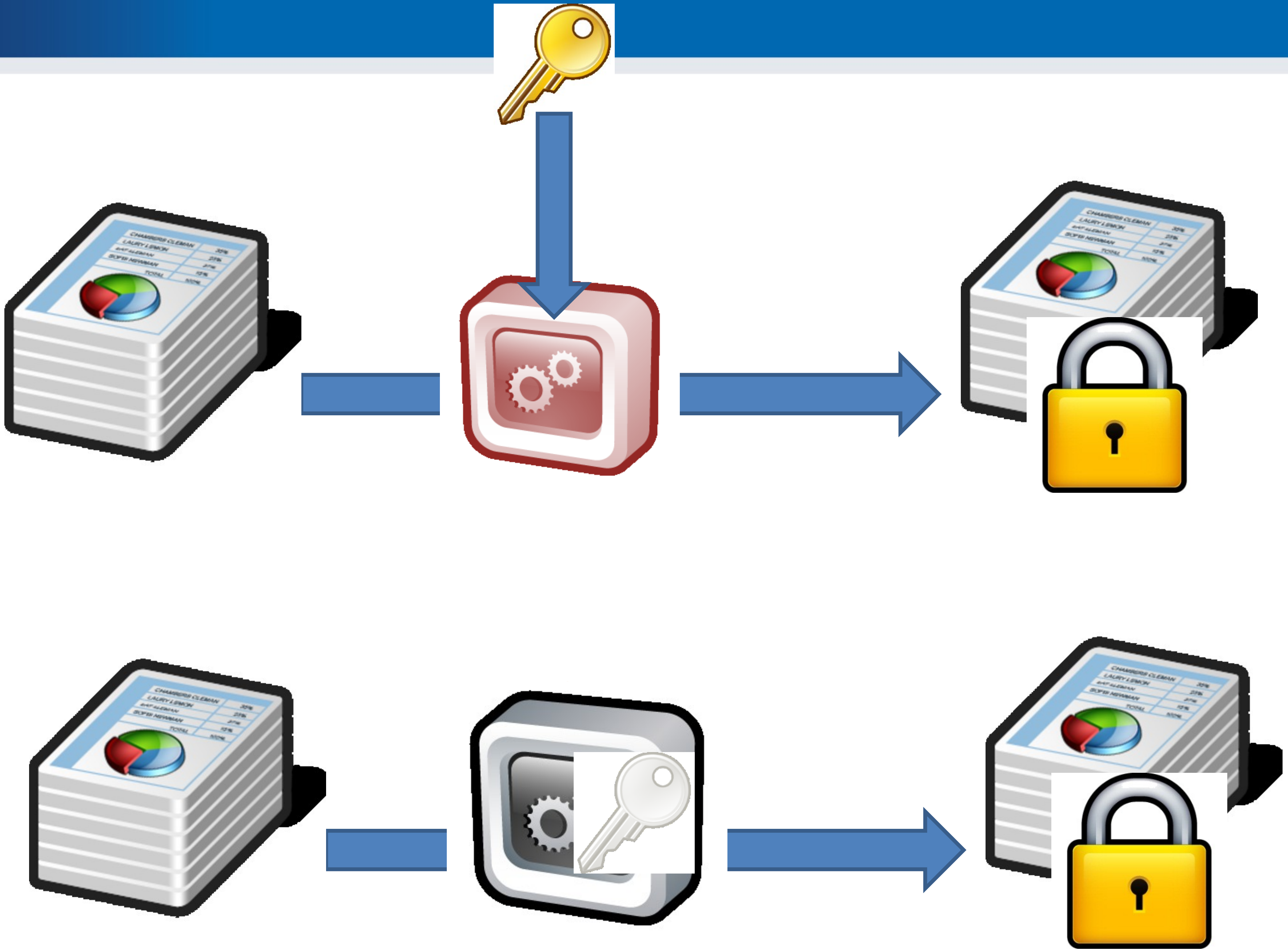
Partial/Fully Homomorphic Encryption libraries

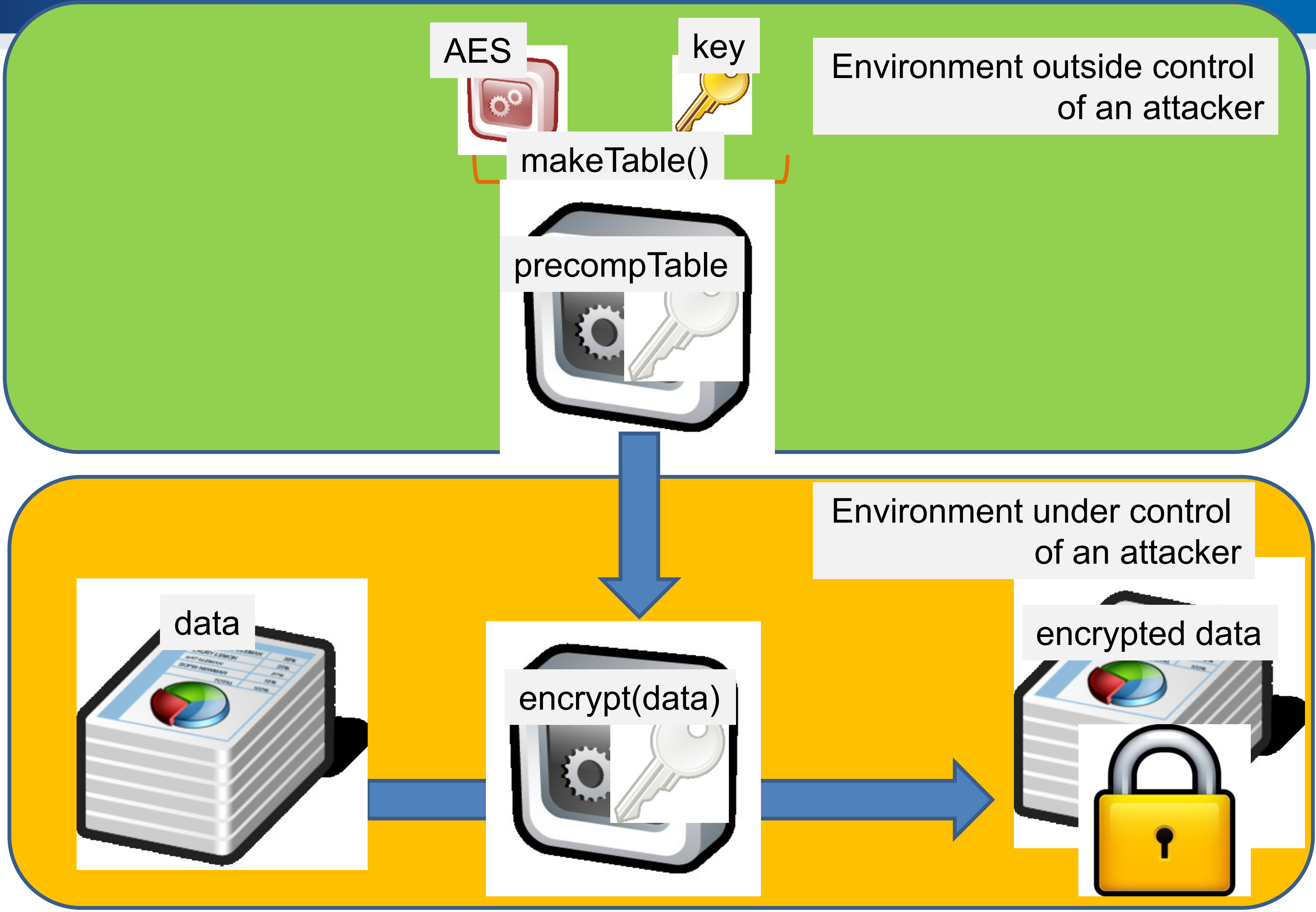
- Homomorphic encryption libraries: HElib, FV-NFLlib, SEAL
- Comparison of features and performance
  - https://arxiv.org/pdf/1812.02428v1.pdf
  - https://link.springer.com/chapter/10.1007/978-3-030-12942-2_32

WHITEBOX CRYPTOGRAPHY

White-box attack resistant cryptography

- How to protect symmetric cryptography cipher?
  - protects used cryptographic key (and data)
- Special implementation fully compatible with standard AES/DES… 2002 (Chow et al.)
  - series of lookups into pre-computed tables
- Implementation of AES which takes only data
  - key is already embedded inside
  - hard for an attacker to extract embedded key
  - Distinction between key and implementation of algorithm (AES) is removed




AES
key
Environment outside control of an attacker
makeTable()
precompTable
Environment under control of an attacker
data
encrypt(data)
encrypted data

WBACR Ciphers - pros

- Practically usable (size/speed)
  - implementation size ~800KB (WBACR AES tables)
  - speed ~MBs/sec (WBACRAES ~6.5MB/s vs. 220MB/s)
- Hard to extract embedded key
  - Complexity semi-formally guaranteed (if scheme is secure)
  - AES shown unsuitable (all WBARC AESes are broken)
- One can simulate asymmetric cryptography!
  - implementation contains only encryption part of cipher
  - until attacker extracts key, decryption is not possible

WBACR Ciphers - cons

- Implementation can be used as oracle (black box)
  - attacker can supply inputs and obtain outputs
  - even if she cannot extract the key
  - (can be partially solved by I/O encodings)
- Problem of secure input/output
  - protected is only cipher (e.g., AES), not code around
- Key is fixed and cannot be easily changed
- Successful cryptanalysis for several schemes ☹
  - several former schemes broken
  - new techniques being proposed

Space-Hard Ciphers

- Space-hard notion of WBACR ciphers
  - How much can be fnc compressed after key extraction?
    - WBACR AES=>16B key=>extreme compression (bad)
  - Amount of code to extract to maintain functionality
- SPACE suite of space-hard ciphers
  - Combination of l-line target heavy Feistel network and precomputed lookup tables (e.g., by AES)
  - Variable code size to exec time tradeoffs

Whitebox transform IS used in the wild

- Proprietary DRM systems
  - details are usually not published
  - AES-based functions, keyed hash functions, RSA, ECC...
  - interconnection with surrounding code
- Chow at al. (2002) proposal made at Cloakware
  - firmware protection solution
- Apple's FairPlay & Brahms attack
  - http://whiteboxcrypto.com/files/2012_MISC_DRM.pdf
- ...