Hardware Security Modules and their APIs

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Basic terminology

- Hardware security modules (HSM)
  - Cryptographic coprocessors
  - Cryptographic accelerators
  - Cryptographic smartcards
- Host devices, API
- Security & attacks on HSMs
  - Physical attacks
  - Logical attacks
    - Attacks on and with API
  - We are not interested in any form of DoS attacks!
- Top-level crypto keys – always stored inside HSM
  - Other keys can be stored outside HSM encrypted by these
- Trusted platform modules (TPM)

Attacks on and with API

- Examples of commonly used API
  - Public Key Cryptographic Standard (PKCS) #11
  - Common Cryptographic Architecture (CCA)
- Three major problems of cryptographic API
  - Insufficient ensuring integrity of keys
    - Problems with backward compatibility (e.g., support of DES/RC2)
    - Meet in the Middle Attack, 3DES Key Binding Attack, Conjuring Keys From Nowhere …
  - Insufficient checking of function parameters
    - Banking API & working with PINs => PIN recovery attacks
    - Decimalisation Table Attacks, ANSI X9.8 Attacks, EMV Secure Messaging Attacks …
  - Insufficient enforcing of security policy
    - PKCS #11 – only set of functions, designed for one-user tokens

Known Key Attack I

- Surprising attack on Visa Security Module (VSM)
  - VSM mostly installed in banks and first generation ATMs
  - Keys generated, securely encrypted inside VSM by master key (KM), and stored outside VSM
    - To perform key generation API contains command `GenerateKeyPart()`
  - Shared terminal key (KMT) in ATM established manually
    - XORed from at least two parts (Dual Control Policy) by using API command `CombineKeyParts()`

- Correctly entered enciphered key parts K_{MT1} & K_{MT2}
  - $\texttt{CombineKeyParts}(E_{KM}(\texttt{KMT1}), E_{KM}(\texttt{KMT2})) = E_{KM}(\texttt{KMT1 xor KMT2}) = E_{KM}(\texttt{KMT})$

Known Key Attack II

- Attack misuses a lack of separation of key parts
  - You can enter the same (e.g., first) part twice
  - `CombineKeyParts`(E_{KM}(KMT1),E_{KM}(KMT1)) = E_{KM}(KMT1 xor KMT1) = E_{KM}(0)

- The attacker (e.g., malicious banking programmer) now know the terminal key of ATM
  - Can be misused to export Pin Derivation Key (KPD)
  - KPG uses bank to PIN generation and verification
    - PIN verification in ATM only if network is down
  - With knowledge of KPD and personal account number (PAN) can attacker generate PIN for arbitrary account

A “Two-time Type” Attack I

- Separating of different key types in VSM ensured by enciphering with different master key (KM)
  - VSM support 9 types and have thus 9 master keys

- Terminal key (KMT) often used to protect transfer of other secret communication keys (KC)
  - Short-term keys used to protect ATM communication
    - No restriction for enciphering/deciphering
  - Existence of function `InsertKey()` for entering clear KC
    - KC automatically encrypted by particular KMT (say KMC)
  - Existence of function `ReEncrypt()` for reencrypting KC by different KMT (say KMD)

A “Two-time Type” Attack II

- Correct calls of these functions
  - Entering of clear KC
    - InsertKey(KC) = E_{KMC}(KC)
  - Reencrypting of KC by KMD
    - ReEncrypt(E_{KMC}(KC),E_{KM}(KMD)) = E_{KMD}(KC)
- PIN Generating Key (PGK) and various terminal keys (e.g., KMC, KMD, …) have the same type
  - This imply that they are enciphered by the same KM
- The attack allows easily derive PIN from PAN
  - InsertKey(PAN) = E_{KMC}(PAN)
  - ReEncrypt(E_{KMC}(PAN),E_{KM}(KPD)) = E_{KPD}(PAN) = PIN
- Observation: encrypted data are still sensitive

Meet in the Middle Attack I

- Attack is based on three independent flaws
  - Poorly designed key types separation
  - No upper limits on key generation
  - Small length of single DES key
- Attack technique is follows
  - HSM capable to generate keys very fast
    - More then ten thousand keys after a few minutes
  - Attacker use 2^{16} keys to encrypt(& store) the same data
    - Typically encrypted block of binary zeros (test vector)
  - Attacker perform exhaustive parallel search for keys
    - Each key is used to encrypt these data and compared with all 2^{16} stored ciphertexts
    - Equality imply that one key is successfully found

Meet in the Middle Attack II

- Keyspace for search is roughly $2^{56}/2^{16} = 2^{40}$
- In the case of VSM is possible to generate all 2^{16} keys as terminal keys
  - Compromised key is thus also a terminal key
  - 8 of 9 types of keys can be compromised by this attack due to bad key type separation
- Efficient variant of attack allows to crack top-level master key of Prism HSM
  - After loading each part of master key is returned test vector encrypted by the current master key
  - No limits for entering key parts
  - Attacker gather 2^{16} encrypted vectors and search the key

Conjuring Keys From Nowhere

- Unauthorized generating of keys stored outside HSM
  - Random value of encrypted key is given to HSM
    - Older HSMs used this technique to legitimate key generation
    - Today is it considered as attack
      - Even modern HSMs (e.g., IBM 4758 with CCA) are vulnerable
  - After decryption is the value of key also random
    - In the case of DES has with probability $1/2^8$ good parity
      - DES key is stored with odd parity – LSB in each octet is parity bit
    - In the case of two-keyed 3DES-2 has a good parity with probability $1/2^{16}$ (and this is still achievable)
  - These keys can served to form more complicated attacks
- The defense lies in carefully designed key formats

  => e.g., add before encryption checksum & timestamp

3DES Key Binding Attack

- Misuse insufficient binding of 3DES key parts
- Applicable on IBM 4758 with CCA
  - Attacker generate large number of 3DES-2 keys with the same parts
  - By using Meet in the Middle Attack find two of them
    - Searching in keyspace 2^{41}
  - Exchange of key halves lead to creating two 3DES keys with different halves
    - If generated keys were export keys then also the found key is an export key
    - This key can be used to export all exportable keys
  - Exchange of known key half with half of no exportable key lead to decreasing its keyspace from 2^{112} to 2^{56}

PIN Generation and Verification

- Terminology
  - Personal Identity Number (PIN) & Account Number (PAN)
  - Clear PIN block (CPB); Encrypted PIN block (EPB)

- Techniques of PIN generation and verification
  - IBM 3624 and IBM 3624 Offset
    - Based on validation data (e.g., account number – PAN)
    - Validation data encrypted with PIN derivation key
    - The result truncated, decimalised => PIN
    - IBM 3624 Offset – decimalised result called IPIN (Intermediate PIN)
    - Customer selects PIN: Offset = PIN – IPIN (digits mod 10)
  - Verification process is the same
    - result is compared with decrypted EPB (encrypted PIN from cash-machine)

PIN Verification Function

- Simplified example of verification function and its parameters:
  1. PIN (CPB) encryption/decryption key
  2. PIN derivation key – for PIN generation process
  3. PIN-block format
  4. Validation data – for PIN extraction from EPB (e.g., PAN)
  5. Encrypted PIN-block
  6. Verification method
  7. Data array – contains decimalisation table, validation data and offset
- Clear PIN is not allowed to be a parameter of verification function!

PIN Verification – IBM 3624 Offset

- Inputs – (4-digit PIN)
  - PIN in EPB is 7216 (delivered by ATM)
  - Public offset (typically on card) – 4344
  - Decimalisation table – 0123 4567 8901 2789
  - Personal Account Number (PAN) is 4556 2385 7753 2239
- Verification process
  - PAN is encrypted => 3F7C 2201 00CA 8AB3
  - Truncated to four digits => 3F7C
  - Decimalised according to the table => 3972
  - Added offset 4344, generated PIN => 7216
  - Decrypt EPB and compare with the correct PIN

Decimalisation Table Attacks I

- Attacks utilising known PINs
    - Assume four-digit PINs and offset 0000
    - If decim. table (DT) is 0000 0000 0000 0000 generated PIN is always 0000
    - PIN generation function with *zero* DT outputs EPB with PIN 0000
    - Let D_{orig} = 0123 4567 8901 2345 is original DT
    - D_i is a *zero* DT with “1” where D_{orig} has *i*
      e.g., D_5 = 0000 0**1**00 0000 000**1**
    - The attacker calls 10x verification function with EPB of 0000 PIN and with D_0 to D_9
    - If *i* is not in PIN, the “1” will not be used and verification against 0000 will be successful

Decimalisation Table Attacks II

- Results
  - All PIN digits (but not their order) are discovered
  - PIN space reduced from 10^4 to 36
    - Worst case for four digit PINs with three different digits
- Extended attack without known PINs
  - Assume, that we obtain customers EPB with correct PIN
  - D_i are DTs containing $i-1$ on positions, where D_{orig} has i, e.g., D_5 = `0123 4`**`4`**`67 8901 234`**`4`**
  - Verification function is called with intercepted EPB and D_i
  - Position of PIN digits is discovered by using *offset* with digits incremented individually by 1
    - Bold “**4**” changes to “5”

DT Attacks – Example

- Let PIN in EPB be 1492, offset is 1234
  - We want to find position of “2”
  - Verification function with D_2 results in 1491!=1492 => fails
  - Offsets 2234, 1334, 1244, 1235 increment resulting generated PIN (2491,1591,…)
  - Eventually the verification is successful with the last offset => 2 is the last digit
- To determine four-digit PIN with different digits is needed at most 6 calls of verification function

Clear PIN Blocks (CPB)

- Code Book Attacks => PIN-block formats
  - CPB in fact describes padding of PIN before its symmetric encryption in ECB mode

- ECI-2 format for 4 digits PINs
  - `ECI-2 CPB = pppprrrrrrrrrrrr`
- Visa-3 format for 4–12 digits PINs
  - `Visa-3 CPB = ppppFxxxxxxxxxxx`

p – PIN digit
r – random digit
x – arbitrary,
all the same
F – 0xF digit

- **ANSI X9.8 format for 4–12 digits PINs**
  - P_1 = ZlppppffffffffFF
  - P_2 = ZZZZaaaaaaaaaaaa
  - ANSI X9.8 CPB = P_1 xor P_2

Z – 0x0 digit
l – PIN length
f – either "p" of "F"
a – PAN digit

ANSI X9.8 Attacks I

- Attacking PAN with translation & verification functions – input parameters (key K, EPB, PAN)
  - Functions decrypt EPB & extract PIN
    CPB xor P_2 = 04ppppFFFFFFFFFF => PIN = pppp
  - Extraction tests PIN digits to be 0–9!
  - If a digit of PAN is modified by x
    - P_2' = P_2 xor 0000x00000000000
    - CPB xor P_2'= 04ppppFFFFFFFFFF xor
      xor 0000x00000000000
      it means that PIN = pppp xor 00x0
    - If p xor x < 10 function ends successfully, otherwise function fails

ANSI X9.8 Attacks II

  - The sequence of (un)successful function calls can be used by attacker to identify p as a digit from set `{p, p xor 1}`
  - For example if PIN digit is 8 or 9, then this sequence will be PPFFFFFFFPPPPPPP, where P is PASS, F is FAIL and x is incremented from `0` to 15

- Only last two PIN digits can be attacked
- PIN space is reduced from 10^4 to 400
- This attack can be extended to all PIN digits

ANSI X9.8 Attacks
Collision Attack (Basic Idea)

- Assuming well designed API (e.g., DT is fixed)
- Attack allows to partially identify last two PIN digits
  - Basic idea (simple example with one-digit PIN&PAN)

PAN	**PIN**	**xor**	**EPB**	**PAN**	**PIN**	**xor**	**EPB**
0	0	0	21A0	7	0	7	2F2C
0	1	1	73D2	7	1	6	345A
0	2	2	536A	7	2	5	0321
0	3	3	FA2A	7	3	4	FF3A
0	4	4	FF3A	7	4	3	FA2A
0	5	5	0321	7	5	2	536A
0	6	6	345A	7	6	1	73D2
0	7	7	2F2C	7	7	0	21A0
0	8	8	**4D0D**	7	8	F	**AC42**
0	9	9	**21CC**	7	9	E	**9A91**

  - Attacker knows for each PAN only the set of EPBs

EMV Secure Messaging Attacks I

- CCA functionality extended to support EMV
  - Secure messaging is EMV form of key export
    - Related control vector (CV) is `SECMSG`
  - Various message formats (due different manufacturers)
    - Message template is block aligned plaintext value
    - Offset pointer to template (points to the place where store key data) can be non-block aligned
- Encryption oracle for keys with `SECMSG` CV
  - ECB and CBC modes (without padding) allows ciphertext truncation (entire last block can be removed)
  - Extending template by zero block and setting offset to this block => the key will be in the last block
    - After its removing we get only encrypted template

EMV Secure Messaging Attacks II

- Cracking exportable keys by using non-aligned offsets and encryption oracle
  - Create 256 plaintext messages/templates `0x00000000000000xx` with `xx` from `00` to `ff`
  - Encrypt this 256 templates by encryption oracle
  - Perform API call with template of zeros, offset value 7, and exporting key KE
  - Comparing first encrypted block with 256 ciphertexts yields the first byte of key KE (denoted uu)
  - Create new 256 plaintext messages/templates `0x000000000000uuxx` with `xx` from `00` to `ff`
  - Repeating process with offset 6 yields second byte, etc.
- Entire k-byte key found after k·256 queries

PKCS #11 Attacks I

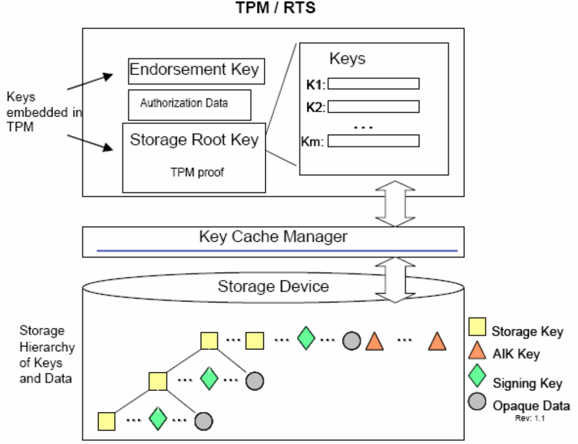
- Symmetric Key Attacks
  - 3DES Key Binding Attack
    - 3DES-2 key K with halves K1 and K2
    - Export as $E_{KEK}(K)=(E_{KEK}(K1),E_{KEK}(K2))$
  - Key Separation Attack
    - Conflict setting of key properties
      - Key encrypt vs. data decrypt
  - Weaker Key/Algorithm Attack
    - Encrypting by short keys RC2 (40 bits) or DES (56 bits)
  - Related Key Attack
    - 3DES-3 key K1=(KA,KB,KC) and K2=(KA xor DELTA,KB,KC)
    - $P'=D_{KA\ xor\ DELTA}(E_{KB}(D_{KC}(E_{KC}(D_{KB}(E_{KA}(P))))))=$
      $=D_{KA\ xor\ DELTA}(E_{KA}(P))$

PKCS #11 Attacks II

- Reduced Key Space Attack
  - Function `C_DeriveKey()` create new key from existing key by using successive series of its bits
  - This “feature” can be misused to reduce keyspace
  - Attacker create from 56bit single DES key 40bit RC2 key and by brute-force find its value
  - With this knowledge find rest of single DES key bits
- Public Key API Attacks
  - Small Public Exponent with No Padding Attack
  - Trojan Public Key Attack
  - Trojan Wrapped Key Attack
  - Private Key Modification Attack

Trusted platform modules

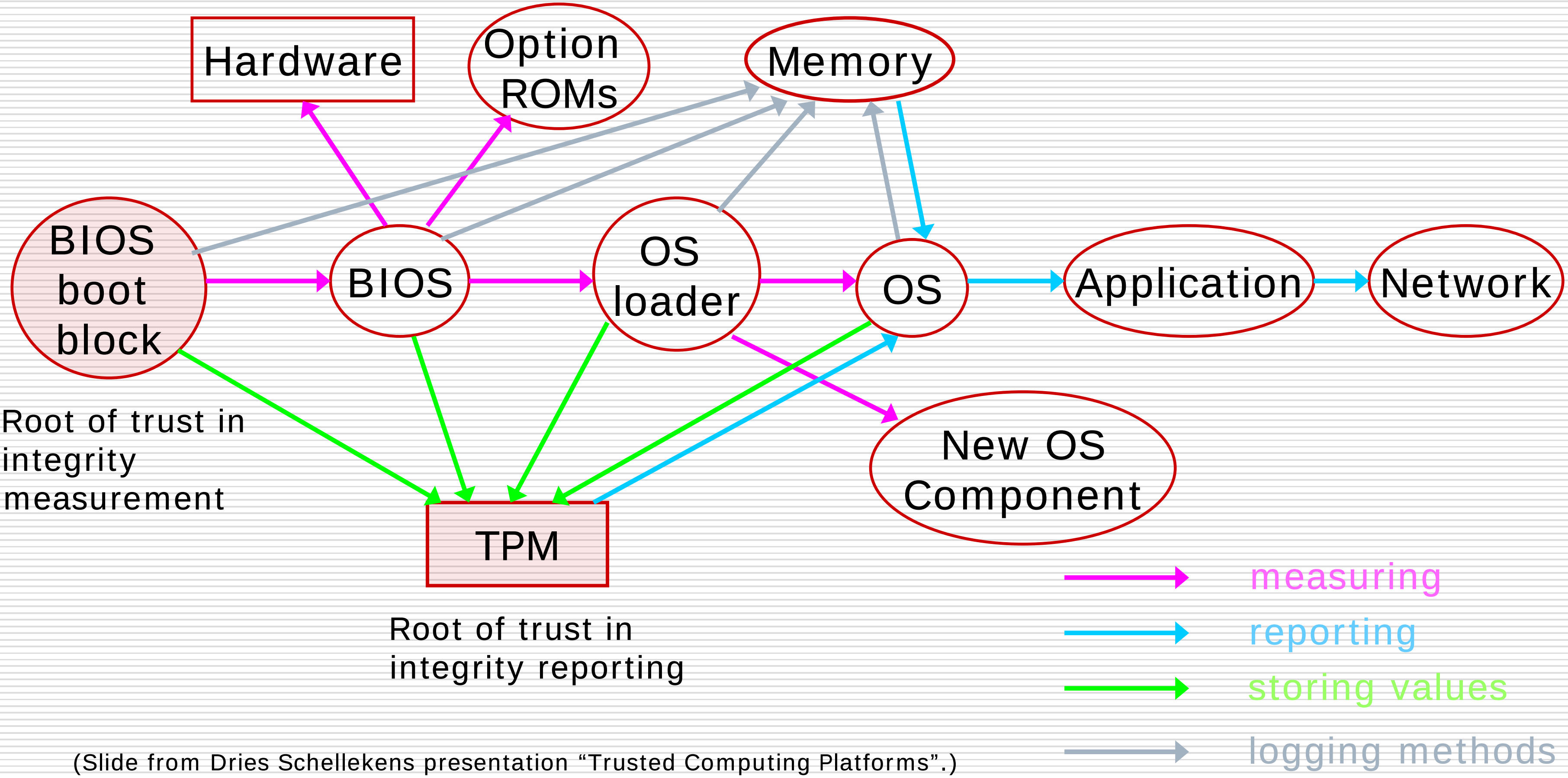
- TPM chip typically based on similar technology as secure microcontrollers for smart cards
- Fundamental features and functions of TPM
  - Trusted measurement, storage, and reporting
    - Complete integrity snapshot of HW&FW&SW components necessary for performing secure boot sequence
    - Three roots of trust serves to anchor a certificate verification chain that is unique to a given system
  - Identity/attestation (by external entities)
    - Shielded locations, protected capabilities, and roots of trust
- Shielded locations (memory, register, ...) for sensitive data
  - Storage of crypto keys to authenticate reported measurement
  - Platform configuration registers (PCRs) to protect integrity measurements



Roots of trust

- Three basic roots of trust
  - RTS: root of trust of storage (for external objects)
    - Endorsement key (EK) unique for TPM (=> platform)
  - RTR: Root of trust for reporting (and attestation)
  - RTM: Root of trust measurements
- Core root of trust measurement (CRTM)
  - First executed code is initialization code
  - Correctness and integrity is critical
  - Two basic variants
    - CRTM = trusted BIOS
    - CRTM = BIOS Boot Block (without BIOS POST)
  - CTRM called static S-CTRM (spec TPM 1.1), new independent dynamic D-CTRM (spec TPM 1.2)

Secure bootstrap



Root of trust in integrity measurement

Root of trust in integrity reporting

(Slide from Dries Schellekens presentation "Trusted Computing Platforms".)

TPM authorization protocols

- Commands accessing protected storage must be authorized to protect stored sensitive data
  - Authorization data based on SHA-1 hashed pass-phrase
  - Prevention of dictionary attacks (from version TPM 1.2)
- Five basic challenge-response protocols
  - Three to create and manage authorization information
    - Contained in objects under the control of TPM
  - Two to establish authorized session contexts
    - Object-Independent Authorization Protocol (OIAP)
      - Establishes an authorized clear-text session between the TPM and an external entity
      - Message integrity ensured by HMAC
    - Object-Specific Authorization Protocol (OSAP)
      - Authorized session is bound to a TPM object
      - Computes ephemeral secret

Conclusions

- Secure hardware (HSMs, TPMs)
  - Limited functionality – easier to verify – better security (than multipurpose hardware)
  - Dedicated circuits – faster than software implementation
- Secure hardware doesn't guarantee absolute security
  - Any secure hardware can be reengineered
  - Main reason of its usage is increased cost of attack
- Bad design and integration imply attacks
  - The security of current generation banking APIs is really bad with respect to insider attacks
  - Number of (banking) standards implemented ensures interoperability but also causes errors
- Issues of smartcards will be discussed in 2 weeks...