RUN-TIME ATTACK DETECTION IN CRYPTOGRAPHIC APIS

Marco Squarcina[1], joint work with Riccardo Focardi[1]

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[1]Università Ca' Foscari Venezia (IT) / Cryptosense (FR)

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OUTLINE

- Background
- Run-time monitor
- Model
- Analysis
- Implementation
- Conclusions

Background

CRYPTOGRAPHIC API

Host Machine

Crypto API

Trusted Device

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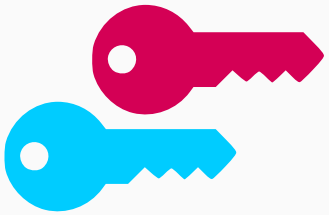
KEY MANAGEMENT

Host Machine

Trusted Device



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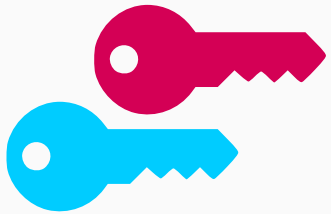

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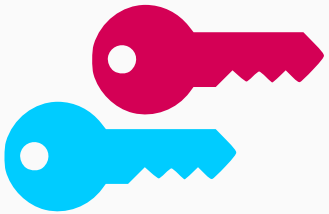

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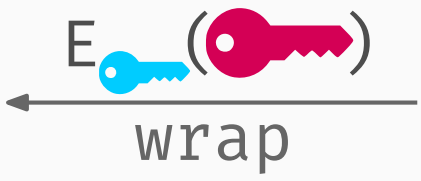

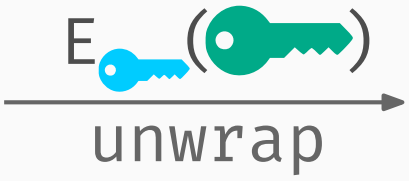

WRAP/DECRYPT ATTACK [Clu03]

Host Machine

Trusted Device

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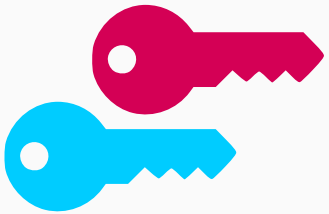
genkey



WRAP/DECRYPT ATTACK [Clu03]

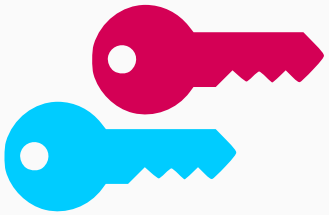
Host Machine

Trusted Device

genkey

$E_{\text{key}}(\text{key})$

wrap



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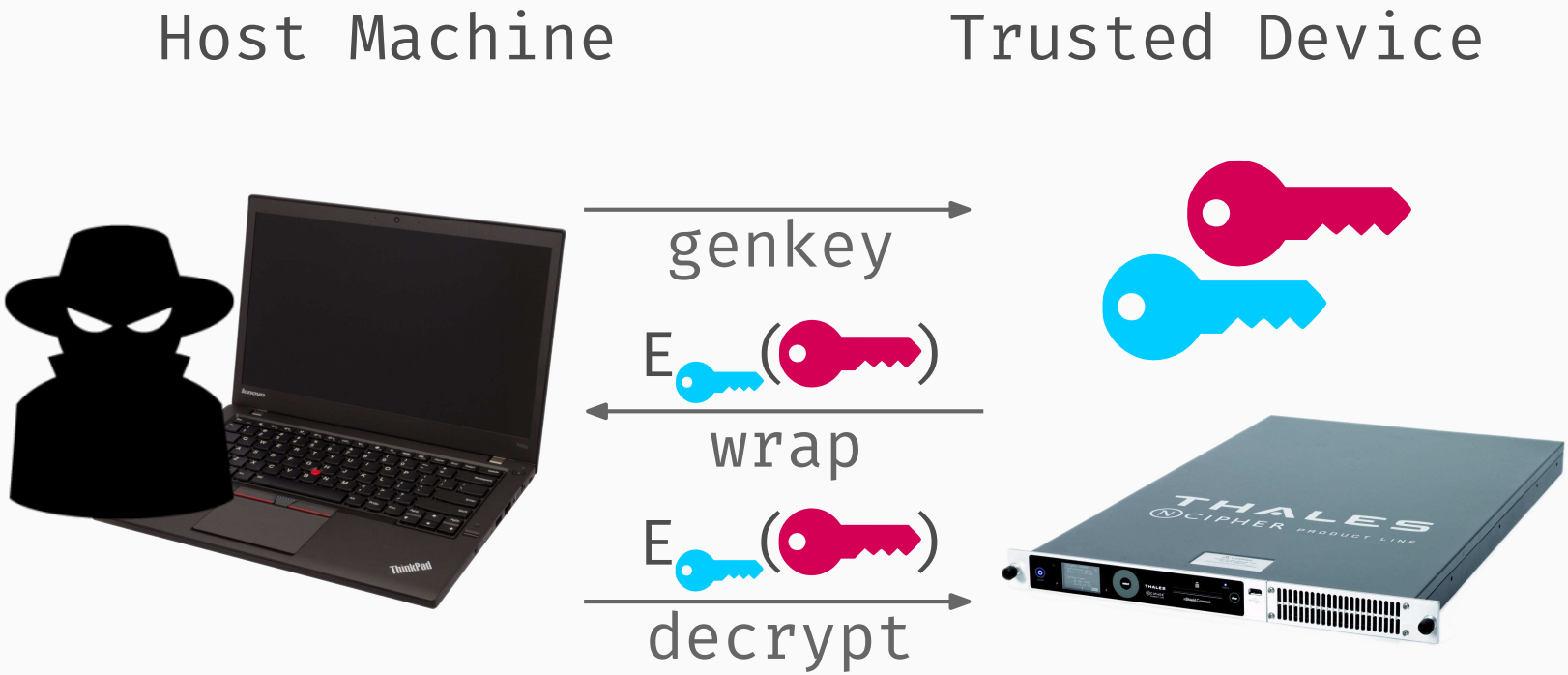

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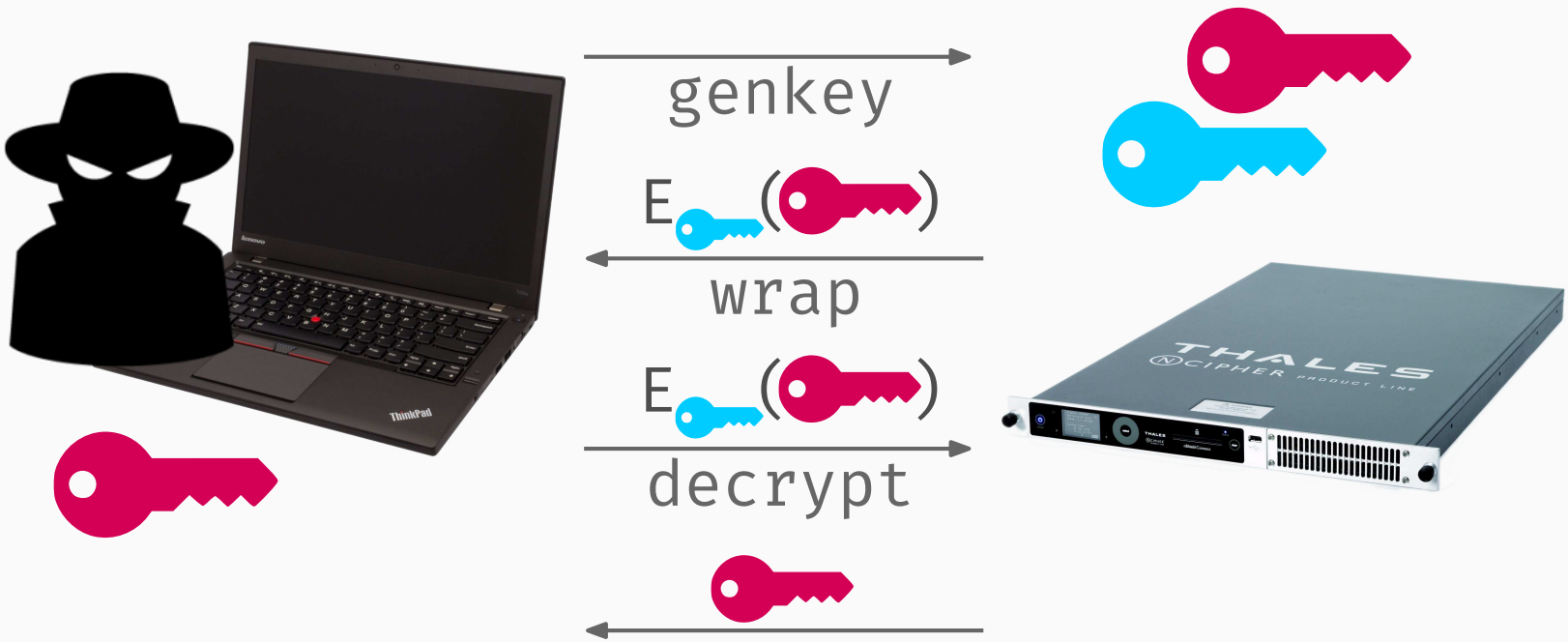

SOLUTIONS

Possible solutions

- New cryptographic API [CS09]
- Modifications to current standards [BCFS10]
- Reduction of functionalities

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Difficult to deploy in practice

- Systems are rarely modified
- Legacy applications
- Key management functionalities required

Run-time monitor

A NEW APPROACH

Our proposal

- Collect API invocation sequence for various devices
- Analyse log to detect any leakage of sensitive keys

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Goals

- Secure
- Accurate
- Distributed
- Efficient

Model

CORE MODEL

Generalisation of the DKS [DKS10] model

- No PKCS#11 specific features (attributes)
- States represent user's knowledge
- Labels on transitions (actions) to capture API calls

Wrap/Decrypt Attack

$$q_0 \xrightarrow{\text{Wrap}(h_{k_1}, h_{k_2})} q_1 \qquad q_1 = q_0 \cup \{E_{k_1}(k_2)\}$$

$$q_1 \xrightarrow{\text{Decrypt}(h_{k_1}, E_{k_1}(k_2))} q_2 \qquad q_2 = q_1 \cup \{k_2\}$$

$$q_0 = \{h_{k_1}, h_{k_2}\}$$

SECURE LOCAL EXECUTION

Dolev-Yao [DY83] model for attacker's deduction capabilities

- Given a set of sensitive keys SK we want to monitor
- Attacker can enc/dec using known keys and keys $\notin SK$
- Executions can include attacker's actions

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Definition (SK-Secure Execution)

An execution σ is secure iff does not leak any of its secure key

$$\sigma = q_0 \xrightarrow{\alpha}\!\!\!\!\rightarrow^{*} q_n \text{ is } SK\text{-secure} \iff SK \cap q_n = \emptyset$$

SECURE EXECUTION

Proposition (characterization of insecure executions)

An execution σ is SK-secure iff none of the following is in σ

- Wrap of a sensitive key under a key not in SK
- Decrypt of a sensitive key encrypted under a sensitive key

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Implications

- Only Wrap and Decrypt API calls must be monitored
- Soundness $\rightarrow$ no false attacks detected
- Completeness $\rightarrow$ all attacks are spotted

SECURE DISTRIBUTED EXECUTION

Definition (Secure Distributed Executions)

$\mathcal{S} = \{(SK_1, \sigma_1), \ldots, (SK_n, \sigma_n)\}$ is a set of distinct executions with their respective sets of sensitive keys.
Let $SK = \bigcup_{i=1,\ldots,n} SK_i$.

$$\mathcal{S} \text{ is secure} \iff \sigma_1, \ldots, \sigma_n \text{ are } SK\text{-secure}$$

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Distributed Wrap/Decrypt Attack

$$\sigma = q_0 \xrightarrow{\mathsf{Wrap}(\mathsf{h}_{\mathsf{k}_1}, \mathsf{h}_{\mathsf{k}_2})} q_1 \qquad q_1 = \{\mathsf{h}_{\mathsf{k}_1}, \mathsf{h}_{\mathsf{k}_2}\} \cup \{\mathsf{E}_{\mathsf{k}_1}(\mathsf{k}_2)\}$$

$$\sigma' = q'_0 \xrightarrow{\mathsf{Decrypt}(\mathsf{h}_{\mathsf{k}_1}, \mathsf{E}_{\mathsf{k}_1}(\mathsf{k}_2))} q'_1 \qquad q'_1 = \{\mathsf{h}_{\mathsf{k}_1}, \mathsf{E}_{\mathsf{k}_1}(\mathsf{k}_2)\} \cup \{\mathsf{k}_2\}$$

σ is $\{\mathsf{k}_1, \mathsf{k}_2\}$-secure, σ' is $\{\mathsf{k}_1\}$-secure but not $\{\mathsf{k}_1, \mathsf{k}_2\}$-secure!

Analysis

Distributed Wrap/Decrypt Attack (Partial Execution)

$$\sigma = q_0 \qquad q_0 = \{h_{k_1}, h_{k_2}\}$$

$$\sigma' = q'_0 \xrightarrow{\text{Decrypt}(h_{k_1}, E_{k_1}(k_?))} q'_1 \qquad q'_1 = \{h_{k_1}, E_{k_1}(k_?)\} \cup \{k_?\}$$

LOG ANALYSIS PROBLEM

Distributed Wrap/Decrypt Attack (Partial Execution)

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Key Fingerprint

- Terms can only be compared by syntactic equality
- Enrich logs with a special one-way deterministic function
- $h_y \xrightarrow{\text{KeyFprint}} \text{kf}(y),\ y' \to \text{kf}(y'),\ y = y' \iff \text{kf}(y) = \text{kf}(y')$

LOG ANALYSIS USING KEY FINGERPRINTING

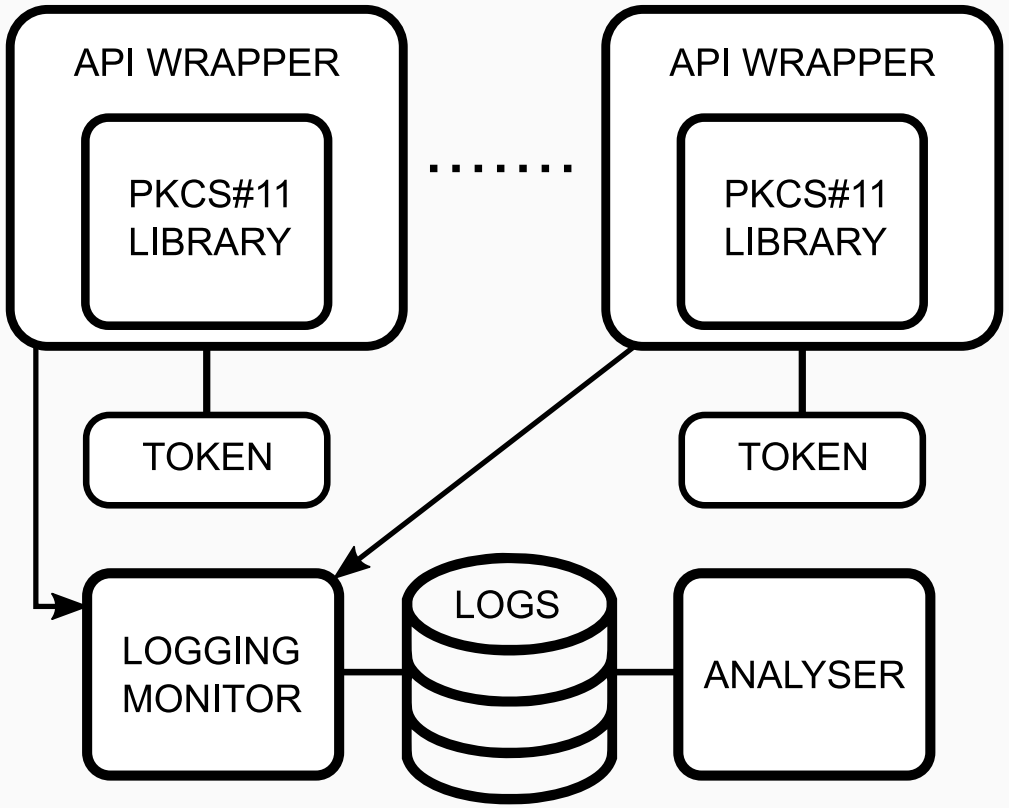
Given logs and handles of sensitive keys:

1. Collect all the fingerprints of sensitive keys
2. For each wrap call
   - if a sensitive key is wrapped under an insecure one → ATTACK
3. For each decrypt call
   - if the decryption key is sensitive
   - compute the fingerprint of the result and compare it against the set of fingerprints collected at step 1
   - if a match is found → ATTACK

Implementation

LOG ANALYSIS TOOL FOR PKCS#11

The tool is able to detect all the key-management attacks found in the literature [DKS10, FLS10] involving symmetric encryption operations



LOG ANALYSIS TOOL FOR PKCS#11

Instrumented API functions

- `C_WrapKey`
- `C_Decrypt`
- `C_GetAttributeValue`
- `C_GenerateKey`
- `C_Login`

LOG ANALYSIS TOOL FOR PKCS#11

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- `C_GenerateKey`
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Possible fingerprints for a key depending on its attributes

- encrypt $\rightarrow \mathrm{kf}(\mathrm{k})_E = \langle \mathrm{r}, \mathrm{E}_\mathrm{k}(\mathrm{r}) \rangle$
- decrypt $\rightarrow \mathrm{kf}(\mathrm{k})_D = \langle \mathrm{r}, \mathrm{D}_\mathrm{k}(\mathrm{r}) \rangle$
- wrap $\rightarrow \mathrm{kf}(\mathrm{k})_W = \langle \mathrm{E}_\mathrm{k}(\mathrm{k}) \rangle$

Conclusions

CONTRIBUTIONS

- Provided a model for distributed run-time detection of crypto APIs attacks
- Devised a sound and complete characterization of attacks
- Proved that the problem of offline attack detection is unsolvable
- ...but key fingerprinting mechanism enables feasible and efficient analysis
- Developed a proof-of-concept log analysis tool for PKCS#11

FUTURE WORKS

- Reason about practical implementations of key fingerprint
- Cover a more extensive fragment of PKCS#11 with the tool and implement a key fingerprint call the API using software emulators
- Characterize other crypto APIs and study formally which are the problematic rules that should be tracked in the logs
- Formally devise a logging policy to prevent logs to grow indefinitely

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Thank you!

Questions?

Bonus Slides

Algorithm 1 Log Analysis using Key Fingerprinting

```
1:  procedure LogAnalysis(σ̄, H)
2:      FSK = [ ]
3:      for (a, ret) ∈ σ̄ do
4:          if a == KeyFprint(h) and h ∈ H then
5:              FSK ← FSK + [ret]
6:          end if
7:      end for
8:      for (a, ret) ∈ σ̄ do
9:          if a == Wrap_*(h_1, h_2) and h_1 ∉ H and h_2 ∈ H then
10:             return a
11:         end if
12:         if a == Decrypt_*(h, t) and h ∈ H and kf(ret) ∈ FSK then
13:             return a
14:         end if
15:     end for
16:     return None
17: end procedure
```

API RULES

$$\xrightarrow[\text{new } n, k]{\text{KeyGen}} \quad h_k$$

$$\xrightarrow[\text{new } n, s]{\text{KeyPairGen}} \quad h_{\text{priv}(s)},\ \text{pub}(s)$$

$$h_{y_1},\ h_{y_2} \xrightarrow{\text{Wrap}} E_{y_1}(y_2)$$

$$h_{\text{priv}(z)},\ h_{y_2} \xrightarrow{\text{Wrap}_{sa}} \text{aenc}(y_2,\ \text{pub}(z))$$

$$h_{y_1},\ h_{\text{priv}(z)} \xrightarrow{\text{Wrap}_{as}} E_{y_1}(\text{priv}(z))$$

$$h_{y_2}, E_{y_2}(y_1) \xrightarrow[\text{new } n_1]{\text{Unwrap}} h_{y_1}$$

$$h_{\text{priv}(z)}, \text{aenc}(y_1,\ \text{pub}(z)) \xrightarrow[\text{new } n_1]{\text{Unwrap}_{sa}} h_{y_1}$$

$$h_{y_2}, E_{y_2}(\text{priv}(z)) \xrightarrow[\text{new } n_1]{\text{Unwrap}_{as}} h_{\text{priv}(z)}$$

$$h_{y_1}, y_2 \xrightarrow{\text{Encrypt}} E_{y_1}(y_2)$$

$$h_{y_1}, E_{y_1}(y_2) \xrightarrow{\text{Decrypt}} y_2$$

$$h_{\text{priv}(z)}, y_1 \xrightarrow{\text{Encrypt}_a} \text{aenc}(y_1,\ \text{pub}(z))$$

$$h_{\text{priv}(z)}, \text{aenc}(y_2,\ \text{pub}(z)) \xrightarrow{\text{Decrypt}_a} y_2$$