Analysis of Security APIs (part I)

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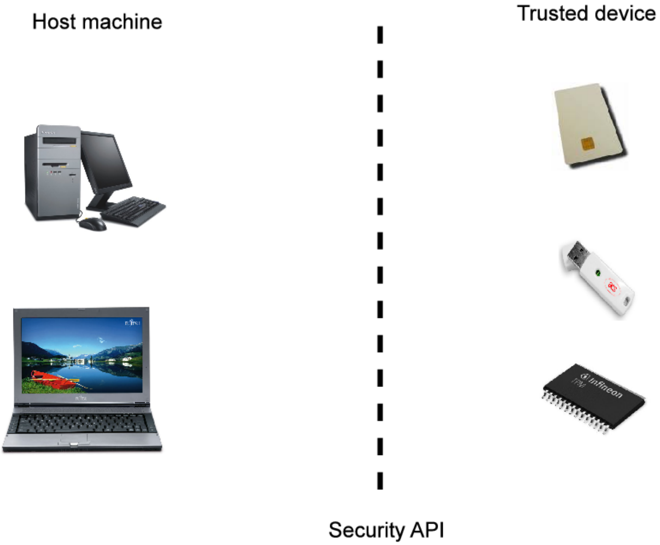
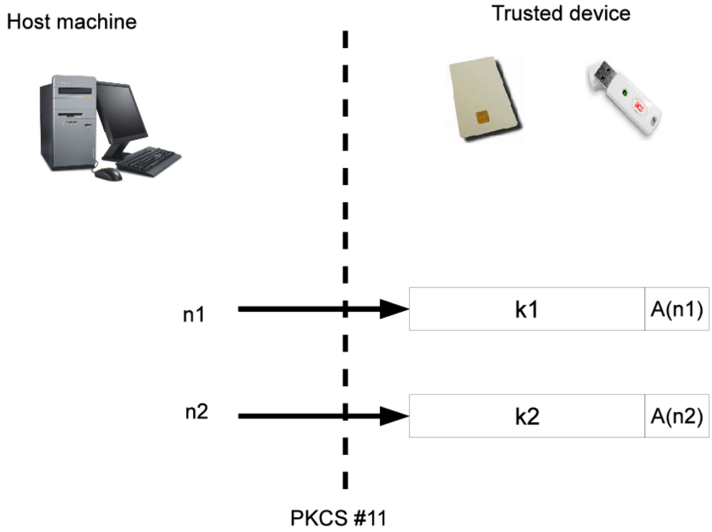
Security APIs



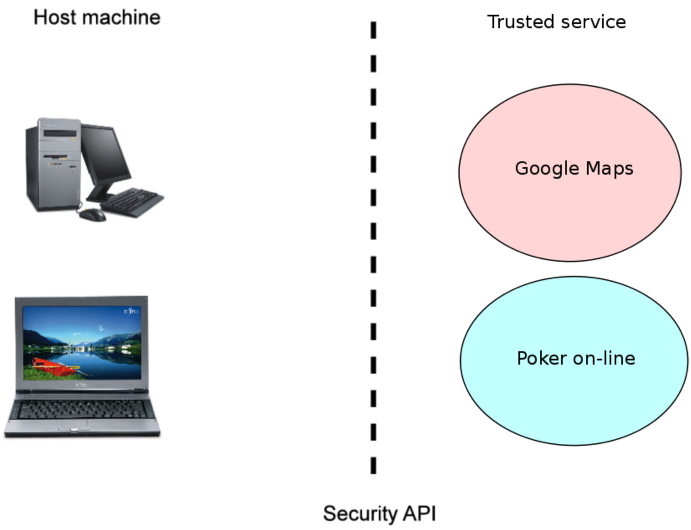
Example 1: Hardware Security Module (HSM)

- Used in the ATM Bank network
- Tamper resistant
- Security API for
  - Managing cryptographic keys
  - Decrypting/re-encrypting the PIN
  - Checking the validity of the PIN

Example 2: PKCS#11 API for tokens/smarcards



Example 3: API to a service or on-line game



Outline of the course

- Today: PIN processing APIs
  - Attacks to guess bank PINs
  - Best strategies to break PINs
  - Language-based analysis and fixes
- Tomorrow: PKCS#11 devices
  - Attacks to compromise a sensitive key
  - A formal model of PKCS#11
  - How to secure PKCS#11: a software token
  - Tookan: Analysis of real tokens

PIN processing infrastructure

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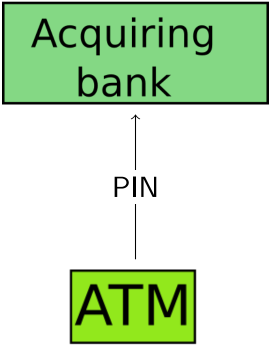

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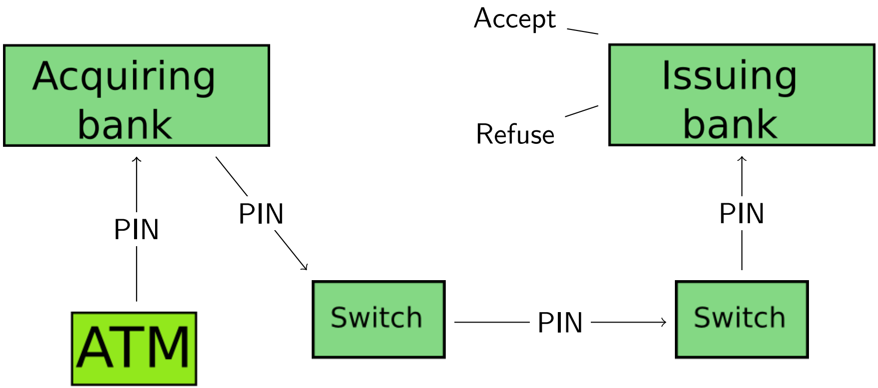

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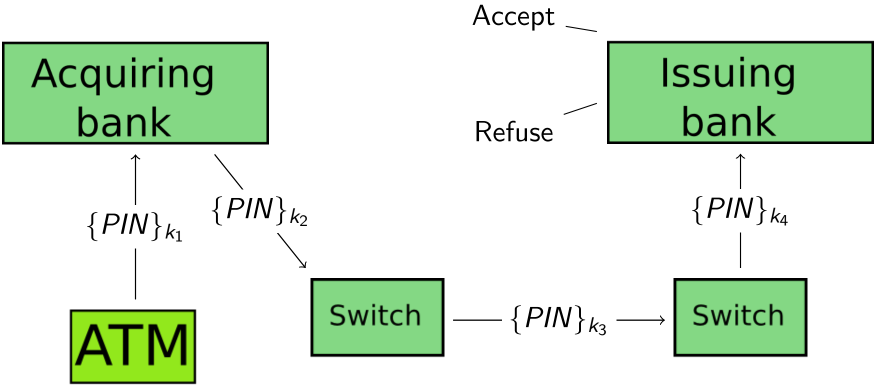

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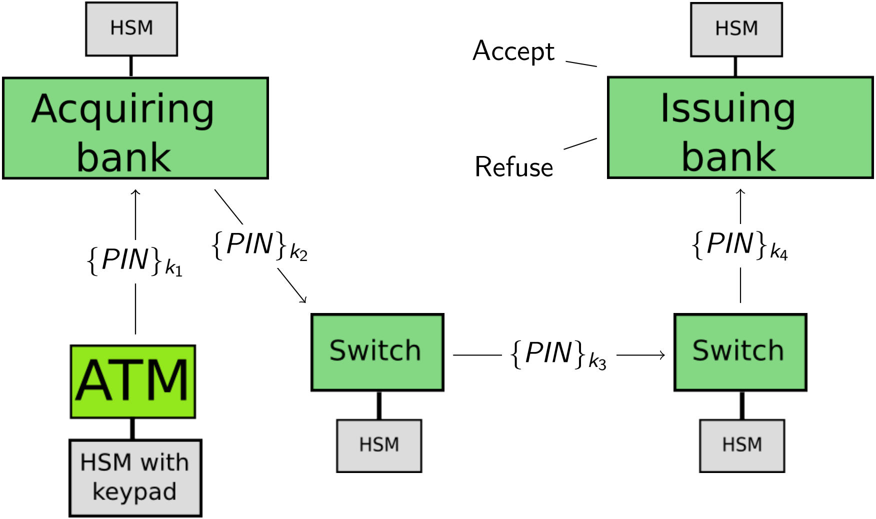

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The PIN verification API

- *Encrypted PIN Block* : contains the PIN at the ATM

PIN_V(EPB , vdata,len,dectab,offset)

- Data for computing the user PIN
- Returns the equality of the two PINs

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The code for PIN verification

$$
\begin{array}{l}
\mathrm{PIN\_V}(\mathit{EPB}, \mathit{vdata}, \mathit{len}, \mathit{dectab}, \mathit{offset})\ \{ \\
\quad x_1 := \mathrm{enc}_{pdk}(\mathit{vdata}); \\
\quad x_2 := \mathrm{left}(\mathit{len}, x_1); \\
\quad x_3 := \mathrm{decimalize}(\mathit{dectab}, x_2); \\
\quad \mathit{u\_pin} := \mathrm{sum\_mod10}(x_3, \mathit{offset}); \\
\\
\quad x_4 := \mathrm{dec}_k(\mathit{EPB}); \\
\quad \mathit{t\_pin} := \mathrm{fcheck}(x_4); \\
\\
\quad \text{if } (\mathit{t\_pin} = \bot) \text{ then return}(''\mathit{format\ wrong}''); \\
\quad \text{if } (\mathit{t\_pin} = \mathit{u\_pin}) \text{ then return}(''\mathit{PIN\ is\ correct}''); \\
\qquad \text{else return}(''\mathit{PIN\ is\ wrong}'') \\
\}
\end{array}
$$

Secure? Against who ... ?

Security property

- Confidentiality: PIN should never be disclosed
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Worst case scenario

the attacker works inside the bank

- breaks into the system and have direct access to the HSM
- can perform any sequence of API calls
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- ... but no direct access to HSM keys, memory or resources

- But, how can we break PIN secrecy by just calling the API?
  ... have you ever played Mastermind?

The Mastermind Game

- Invented by the Israeli postmaster and telecommunications expert Mordecai Meirowitz in 1970;
- 4 pegs from 6 possible colors, duplicates are allowed.
- The *codemaker* chooses a sequence of 4 pegs, the *codebreaker* has to guess it
- Goal: Minimize the number of guesses

The Mastermind 'API'

- The codebreaker 'calls'

  MasterMind(guess)

  where 'guess' is a sequence of 4 pegs
- The return value is a set of 4 markers:
  - red marker: right color and position;
  - white marker: right color and wrong position.
- Partial information about the secret sequence ...

Can we 'play mastermind' on this API?

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The 'decimalization' attack on PIN_V [Bond, Zielinski '03]

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- Has this kind of attack been tried on real bank systems?
- How long does it take to discover the whole PIN?

Reports suggest something has been going on ...

Verizon Breach Report 2008

"Were seeing entirely new attacks that a year ago were thought to be only academically possible"
"What we see now is people going right to the source [..] and stealing the encrypted PIN blocks and using complex ways to un-encrypt the PIN blocks."
(Quotes from Wired Magazine interview with report author, Bryan Sartin)

How many API calls are needed?

For a four digit PIN:

- [Bond, Zielinski '03] Average 16.5 API calls
- [Steel, TCS06] Average 16.145 API calls
- [Focardi, Luccio, FUN'10] Average 14.47 API calls (as instance of Mastermind)
- Lower-bound of 13.362 API calls

The Extended Mastermind Game

- Colors: $\mathcal{C} = \{0, 1, \ldots, N-1\}$
- Secret sequence: $(c_1, c_2, \ldots, c_k)$, with $c_1, \ldots, c_k \in \mathcal{C}$
- Extended guess: $(S_1, S_2, \ldots, S_k)$, with $S_1, \ldots, S_k \subseteq \mathcal{C}$

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Example

- 6 colors: $\mathcal{C} = \{0, 1, \ldots, 5\}$
- Secret: $(1, 2, 3, 1)$
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- what's the answer?

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2 red and 1 white markers

Red Markers

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Example

- Secret: $(1, 2, 3, 1)$
- Extended guess: $(\{1\}, \{3\}, \{1\}, \{1, 3\})$
- $r = |\{i \in [1, k] \mid c_i \in S_i\}| = 2$

White Markers

- Secret : $(c_1, c_2, \ldots, c_k)$, Extended guess: $(S_1, S_2, \ldots, S_k)$

- $p_j = |\{i \in [1, k] \mid j = c_i\}|$ occurrences of a color j in the secret
- $q_j = |\{i \in [1, k] \mid j \in S_i\}|$ occurrences of a color j in the guess

Definition (White markers)

The number w of white markers is computed as $w = \sum_{j=1}^{N} min(p_j, q_j) - r$.

White Markers

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Example

- Secret $(1,2,3,1)$ and extended guess $(\{1\},\{3\},\{1\},\{1,3\})$:
- $p_1 = |\{1,4\}| = 2,\ q_1 = |\{1,3,4\}| = 3, min(p_1, q_1) = 2$
- $p_2 = 1,\ q_2 = 0, min(p_2, q_2) = 0;\ p_3 = 1,\ q_3 = 2, min(p_3, q_3) = 1$
- $w = \sum_{j=1}^{N} min(p_j, q_j) - r = 2 + 0 + 1 - 2 = 1$

We can still play Mastermind

Proposition

The Mastermind game is an instance of the Extended game

Proof.

Trivial: just restrict the sets in the estended guesses to singletons. □

Cracking a PIN by playing extended Mastermind

Theorem

PIN cracking is an instance of the Extended Mastermind game

Proof.

Intuition: Restrict to cases in which guesses $(S_1, S_2, \ldots, S_k)$ minus offset provide either equal or disjoint sets.

1. Modify the dectab mapping of all elements of the i-th set from d to $d + i \pmod{10}$
2. Compensate by $-i \pmod{10}$ the offset in the corresponding positions to find out whether those PIN digits are in the set.

The answer is four red markers if and only if PIN verification succeeds. □

Example

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- We play: $(\{4, 5, 6, 7, 8\}, \{0, 1, 7, 8, 9\}, \{0, 1\}, \{2, 3, 4, 5, 6\})$

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- We play: $(\{4,5,6,7,8\},\{0,1,7,8,9\},\{0,1\},\{2,3,4,5,6\})$
- Subtract the offset: $(\{0,1,2,3,4\},\{0,1,2,3,4\},\{7,8\},\{0,1,2,3,4\})$
- Two disjoint sets: $\{0,1,2,3,4\},\{7,8\}$, change the dectab

Example

Example: PIN_V($\{4104, r\}_k$,vdata,4, 0123456789012345,4732)

1. $\text{dec}_k(\{4104, r\}_k) = 4104, r$
   4104
2. $\text{enc}_{pdk}(\text{vdata}) = A47295FDE32A48B1$
   $0472 \oplus 4732 \bmod 10 = 4104$

- We play: $(\{4, 5, 6, 7, 8\}, \{0, 1, 7, 8, 9\}, \{0, 1\}, \{2, 3, 4, 5, 6\})$
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Example: PIN_V($\{4104, r\}_k$,vdata,4, 1234556909123455,4732)

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Example

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- Two disjoint sets: $\{0, 1, 2, 3, 4\}, \{7, 8\}$, change the dectab
- Compensate the offset
- PIN_V returns ‘true’ iff PIN digits are in the sets

An algorithm for the Extended Mastermind Problem

Based on [Knuth JRM76]: an algorithm for the solution of the standard Mastermind problem (quasi optimal solutions).

1. Tries all the possible guesses. For each guess, computes the number of 'surviving' solutions related to each possible outcome of the guess;
2. Picks the guess from the previous step which minimizes the maximum number of surviving solutions among all the possible outcomes and performs the guess.

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Focus on two kinds of guesses:

- $(\{0,1,2,3,4,5\},\{0,1,2,3,4,5\},\{0,1,2,3,4,5\},\{0,1,2,3,4,5\})$, the same set repeated: checks if 6,7,8,9 are in the PIN
- $(\{1,3\},\{0,2,4,5,6,7,8,9\},\{0,2,4,5,6,7,8,9\},\{1,3\})$, one set and its complementary
- perform very well and still find a complete strategy

Summary of results for PIN cracking

Four digit PINs

- [Bond, Zielinski '03] Average 16.5 API calls
- [Steel, TCS06] Average 16.145 API calls
- [Focardi, Luccio, FUN'10] Average 14.47 API calls
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Lower bounds

- The lower bounds for 4 and 5 digit PINs are 13.362 and 16.689, for the average case

The ‘lunch-break’ attack

A realistic scenario

gaining access to the HSM and intercepting incoming data an insider might disclose thousands of PINs in a lunch-break!

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How to prevent the attack?

- low-impact CVV-based fix [Focardi, Luccio, Steel, NORDSEC’09]
  - **mitigates** the attack (50000 times slower)
- point-to-point MAC-based fix and type-based proof of security [Centenaro, Focardi, Luccio, Steel, ESORICS’09]
  - **prevents** the attack but requires modifying each HSM
- efficient HSM upgrading strategies [Focardi, Luccio, ARSPA-WITS’10]
  - **securing subnetworks** while keeping service up

What kind of attack?

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- no cryptoanalysis and no broken protocols

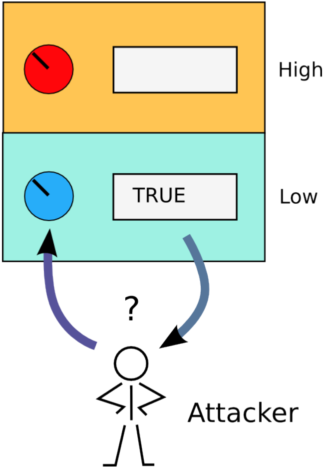
What kind of attack?

- no cryptoanalysis and no broken protocols
- Information-flow: variations on the input produce unintended *information leakage*

Absence of information leakage [Goguen, Meseguer'82]

Noninterference

High behaviour is not observable by the Low attacker



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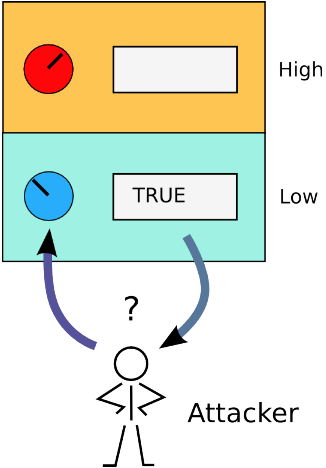

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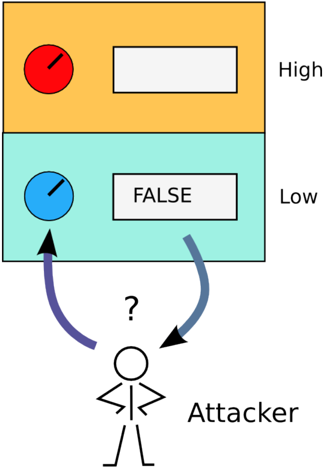

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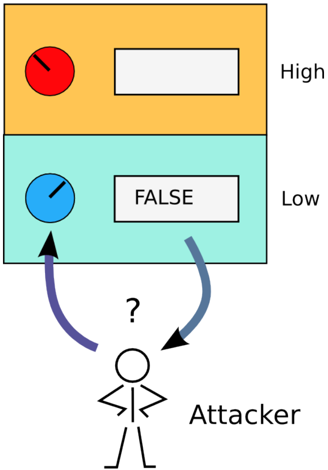
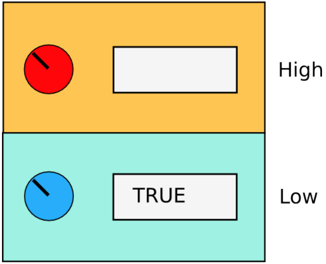


Noninterference is too much

$$\text{PIN\_V}(\{\,4104\,, r\}_k, \text{vdata}, 4, 0123456789012345, 4732)$$

- PIN_V intentionally 'leaks' the correctness of the PIN



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PIN_V($\{$ 5832 $, r\}_k$,vdata, 4, 0123456789012345, 4732)

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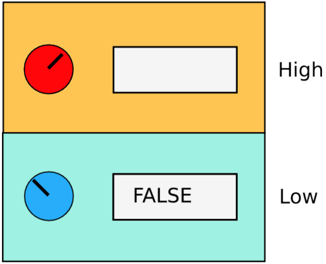

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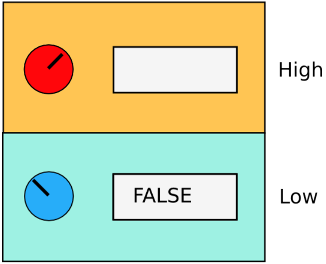
PIN_V($\{$5832$, r\}_k$,vdata, 4, 0123456789012345, 4732)

- PIN_V intentionally 'leaks' the correctness of the PIN
- PIN correctness is *declassified*

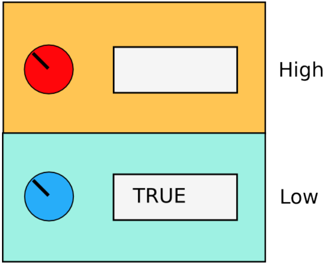


Robust declassification [Myers, Sabelfeld, Zdancewic '06]

Robustness

Declassification is independent of the attacker behaviour

- the attacker cannot cause to release more information than intended



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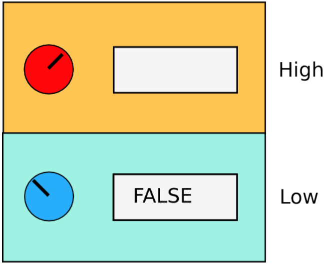

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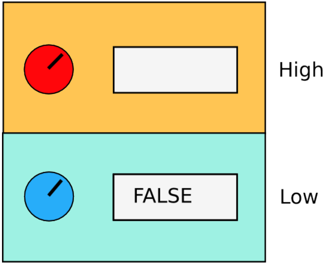

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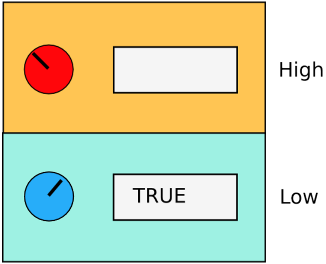

PIN_V is not robust!

PIN_V($\{$ 4104 $, r\}_k$,vdata, 4, 0123456789012345 , 4732)

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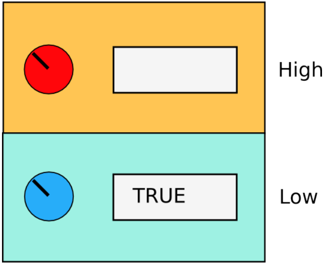

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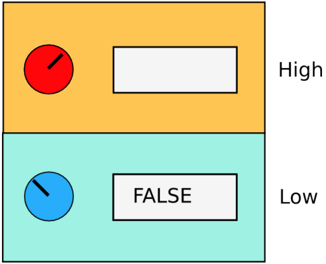

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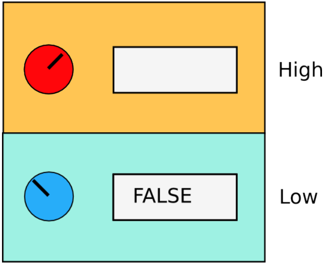

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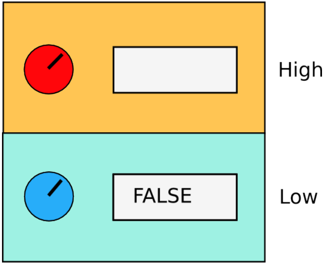

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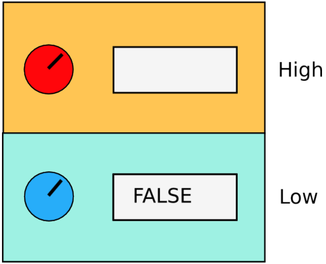

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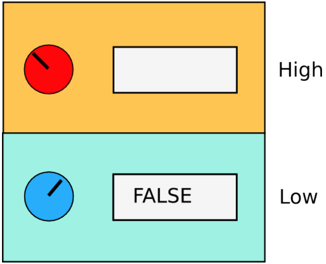

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PIN_V($\{$ 4104 , $r\}_k$,vdata, 4, 1123456789112345 , 4732)

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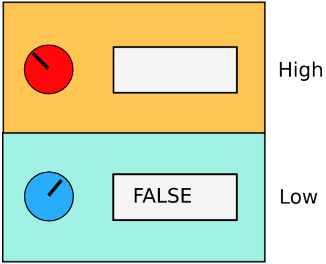
- PIN_V now fails in both cases
- the attacker has influenced declassification



The code for PIN verification, what is wrong ... ?

$PIN\_V(EPB, vdata, len, dectab, offset)$ {

$x_1 := enc_{pdk}(vdata)$;

$x_2 := left(len, x_1)$;

$x_3 := decimalize(dectab, x_2)$;

$u\_pin := sum\_mod10(x_3, offset)$;

$x_4 := dec_k(EPB)$;

$t\_pin := fcheck(x_4)$;

if $(t\_pin = \perp)$ then return("*format wrong*");

if $(t\_pin = u\_pin)$ then return("*PIN is correct*");

else return("*PIN is wrong*")

}

How to be robust?

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PIN_V({t_pin, r}$_k$, vdata,len,dectab,offset)

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PIN_V($\{$t_pin, r$\}_k$, vdata,len,dectab,offset)

- 👎 declassify(t_pin = u_pin)

Fixing PIN_V

- add a *Message Authentication Code*

$$m = \langle \{\text{t\_pin}, r\}_k, \text{vdata}, \text{len}, \text{dectab}, \text{offset} \rangle_j$$

```
PIN_V+( {t_pin, r}_k, vdata,len,dectab,offset, m ) {
    if mac_j( {t_pin, r}_k, vdata,len,dectab,offset ) = m
        ... old PIN_V code ...
    else
        FAIL
}
```

- MAC guarantees that data come from a specific user

Integrity representatives

- MAC creation has to be regulated
- with these three MACs the attacker can get the first PIN digit

$$\langle\ \{4104, r\}_k,\ \text{vdata}, 4, 0123456789012345, 4732\ \rangle_j$$
$$\langle\ \{4104, r\}_k,\ \text{vdata}, 4, 1123456789112345, 4732\ \rangle_j$$
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vdata is the *integrity representative*: len, dectab, offset and the PIN are 'determined' by vdata

More precisely, in the two MACs

$$\langle\{pin_1, r_1\}_k, \boxed{\text{vdata}}, len_1, dectab_1, offset_1\rangle_j$$
$$\langle\{pin_2, r_2\}_k, \boxed{\text{vdata}}, len_2, dectab_2, offset_2\rangle_j$$

we require $len_1 = len_2$, $dectab_1 = dectab_2$, $offset_1 = offset_2$, $pin_1 = pin_2$

... still not robust!

user 1 has inserted the correct PIN:

$$PIN\_V^{+}(EPB_1, vdata_1, len_1, dectab_1, offset_1, m_1) \rightarrow \text{true}$$

user 2 has typed a wrong PIN:

$$PIN\_V^{+}(EPB_2, vdata_2, len_2, dectab_2, offset_2, m_2) \rightarrow \text{false}$$

- the attacker affects declassification by calling PIN_V^{+} with data from completely different users

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- the attacker affects declassification by calling PIN_V^{+} with data from completely different users
- ... he only gets the expected outputs

... still not robust!

user 1 has inserted the correct PIN:

$$\text{PIN\_V}^{+}(\text{EPB}_1, \text{vdata}_1, \text{len}_1, \text{dectab}_1, \text{offset}_1, \text{m}_1) \rightarrow \text{true}$$

user 2 has typed a wrong PIN:

$$\text{PIN\_V}^{+}(\text{EPB}_2, \text{vdata}_2, \text{len}_2, \text{dectab}_2, \text{offset}_2, \text{m}_2) \rightarrow \text{false}$$

- the attacker affects declassification by calling PIN_V^{+} with data from completely different users
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disallow changes to vdata

PIN_V$^+$ is robust, for each user

$$\text{PIN\_V}^+(\ \{\text{pin, r}\}_k, \text{vdata, len, dectab, offset,} \\ \langle\ \{\text{pin, r}\}_k, \text{vdata, len, dectab, offset}\ \rangle_j\ )$$

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1. vdata cannot be manipulated (focus on one user)

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1. vdata cannot be manipulated (focus on one user)
2. vdata in the MAC must correspond

PIN_V$^+$ is robust, for each user

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- vdata : [VDATA] , dectab : [DTAB$\hookleftarrow$VDATA]

The ISO0 PIN block format

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$\Rightarrow$ noninterference holds

Summary: fixing PIN management APIs

- robustness in a non-randomized cryptographic setting: existing PIN processing APIs are not robust
- a MAC-based fix of PIN_V (and PIN_T in the paper)
  - low-impact CVV-based fix [Focardi, Luccio, Steel, NORDSEC'09]
- integrity w.r.t. a representative, e.g., dectab : [DTAB↩VDATA]
- a type system to type-check APIs

Theorem

1. $\Gamma \vdash P$ *then* P *is robust*
2. *if* P *does not declassify data, then* P *satisfies noninterference, too*

- More detail in [Centenaro, Focardi, Luccio, Steel, ESORICS'09]

Conlusion

- ✓ API-level attacks to guess bank PINs
(much more can be found in [Bond, Zielinski '03, Clulow '03])
- ✓ How to become rich by playing Mastermind:
almost-optimal strategies to break PINs [Focardi, Luccio, FUN'10]
- ✓ Language-based analysis and fixes
[Centenaro, Focardi, Luccio, Steel, ESORICS'09,
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- Tomorrow we will see why some smarcard and crypto-tokens can be easily cloned

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