SECURITY 2013

21. ročník konference o bezpečnosti v ICT

Discovering PIN Prints In Mobile Applications

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ATA Scenario

Definition (ATA). *Let the After-Theft Attack (ATA) be any attacking scenario that assumes the attacker has unlimited physical access to the user's smart phone.*

- Imagine somebody steals your mobile phone…
- Despite being really obvious threat, it is often neglected in contemporary applications.
- By a robbery, the attacker can even get access to unlocked screen or a synced computer, hence receiving another considerable favor!

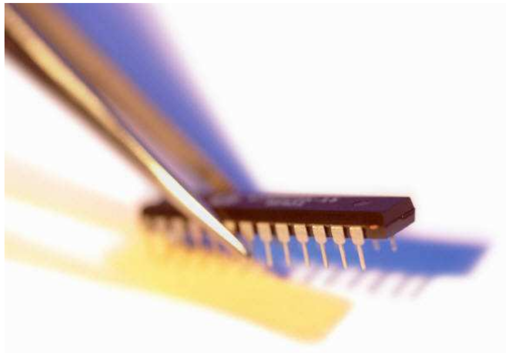
Forensic Techniques Lessons

- Hackers conferences are not the only place to look for an inspiration.

- There are also forensic experts who publish very interesting results.
  - Actually, they often take hacking techniques and refine them to another level of maturity.
  - The main purpose is to prosecute criminals, of course.
  - But it is just a question of who is holding the gun…
  - Anyway, security experts shall definitely consider looking into forensic publications, at least time to time.

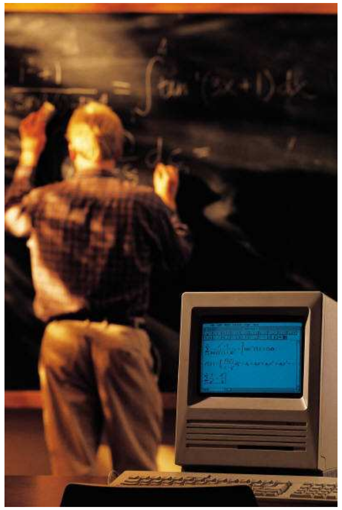
Memento ATA

- We shall assume that:
  - once having unlimited physical access to the mobile device,
  - the attacker can read any binary data stored in its FLASH memory.
  - This also applies to certain encryption keys!
- Despite not being trivial, we shall further assume this also applies to the content of the volatile RAM.



PIN Prints

- This can be <u>any direct or indirect function value </u>that:
  - once gained by the attacker,
  - leads to a successful brute force attack on the PIN,
  - under the particular attack scenario.
- Principally, the same applies to general passwords, too.
  - However, we can mitigate the risk by enforcing strong password policy here.

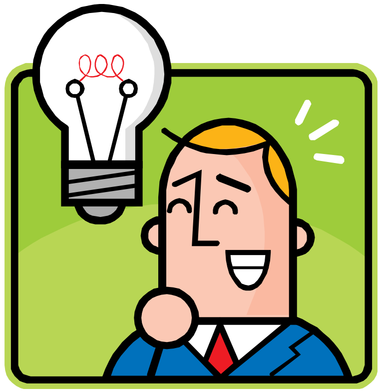


No PIN Prints Postulate

- **Postulate (NP3).** *In the time the application process is closed (from the client perspective)…*
  - *…there is not enough information stored in the whole mobile device that would allow an attacker to disclose the client's PIN successfully.*

Once Upon a Time

- There was a PKI based approach…
  - …and there was RSA private key encrypted by a derivative of a decimal PIN.
  - First factor: mobile device with the encrypted RSA key
  - Second factor: the PIN
  - Idea: gorgeous PKI and RSA take care about the rest…



Correct PIN

- So, this was the plaintext obtained from the ciphertext under the correct PIN value:

```
RSAPrivateKey ::= SEQUENCE {
    version           Version,
    modulus           INTEGER,    -- N, N = p*q*other_factors_if_any
    publicExponent    INTEGER,    -- e
    privateExponent   INTEGER,    -- d, d*e ≡ 1 (mod λ(N))
    prime1            INTEGER,    -- p, p | N
    prime2            INTEGER,    -- q, q | N
    exponent1         INTEGER,    -- d_p, d_p = d mod (p – 1)
    exponent2         INTEGER,    -- d_q, d_q = d mod (q – 1)
    coefficient       INTEGER,    -- q_inv, q_inv*q ≡ 1 (mod p)
    -- ...
}
```

Incorrect PIN

- The plaintext obtained for a wrong PIN can be considered as a pseudorandom sequence.
  - The ASN.1 format rules as well as the algebraic relations are probably corrupted.
  - PIN searching hint – do you remember TV tuning? *Just turn the tunning knob until you get any plausible picture and sound…*

NP3 Failure

- We have seen that…
  - …according to PKCS#1, there is a huge redundancy based on the ASN.1 structure syntax.
  - …furthermore, there is a terrible amount of algebraic-based redundancy.
- So, the decimal PIN was in fact packed together with the encrypted key store.
  - …as a bonus gift to the diligent attacker!

Another Example

- This time, there was a PIN-encrypted symmetric authentication key.
  - Great, there is a chance to eliminate the algebraic redundancy!
  - First factor: device with the encrypted auth. key
  - Second factor: the PIN
  - Idea: HOTP and OCRA-based verification of the symmetric key (with implicit PIN check)

Looking Inside

- PIN key derivation

$$K = \text{SHA-1}(Salt_A \,||\, PIN \,||\, Salt_B)[0..15],$$

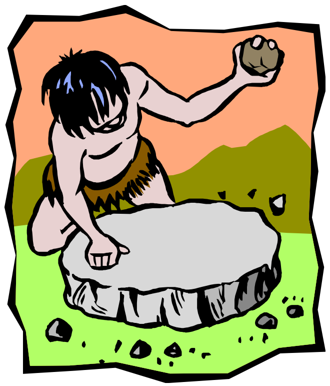
  where $Salt_{A,B}$ are device-dependent static strings.
  - We shall assume $Salt_{A,B}$ is accessible under ATA.
  - Anyway, this is OK.
- HOTP/OCRA key generation and encryption
  - (P)RNG used for key generation.
  - No usable algebraic redundancy inside. OK.
  - Encrypted using AES-ECB_K.
  - OK. But… wait a minute – what is the padding?

Randomized Padding Structure

- L-byte message: $M = M_1 \,||\, M_2 \,||\, \ldots \,||\, M_L$
- Pad to N bytes: $OT = M \,||\, PS_1 \,||\, \ldots \,||\, PS_{N-L}$
- Padding string construction:

For each PS_i, $1 \le i \le N\text{-}L$, choose $j \in_R \{1, 2, \ldots, L\}$ randomly, and set $PS_i = M_j$.

In other words, the padding string consists of randomly indexed bytes from the original message.



Incorrect PIN

- Again, the obtained plaintext OT' can be regarded as a pseudorandom sequence.
  - The better the encryption algorithm is, the closer to ideal random noise OT' is… (sad, but true).
- The probability of accidentally correct padding structure can be estimated as

$$p_{\text{padding}} < (L/256)^{N-L}.$$

Proof. $PS_i = M_j$ for particular i and some j holds with $p < L/256$. To be a valid padding, all N-L independent equations must hold.

Practical Configuration

- In one setup, we had $N = 32$, $L = 20$.
  - So, there were in total 12 bytes of padding string.

$$p_{padding} < (L/256)^{N-L} = (20/256)^{12} < \underline{\underline{2^{-44}}}$$

  - In other words, if we try Q incorrect PIN guesses, we can expect, in mean value,

$$E = Q * p_{padding} < Q * 2^{-44}$$

accidentally correct padding structures.

  - This directly corresponds with the number of false positives in a brute force searching for PIN.

Information Needed

- Let the PIN be any value with a variable length of *r* to *s* digits.

  There are

  $$W = \sum_{i=r}^{s} 10^i < \frac{10^{s+1}}{9} < 10^{s+0,05}$$

  possible PIN values.

  For instance, $r = 4$, $s = 8$ gives $W = 111\,110\,000$.

  Note that “1234” is not the same as “<u>0</u>1234”.

Information Conveyed

- When brute forcing *r*-to-*s*-digit PIN, we need to verify no more than *W* incorrect PIN values.

  So, we can expect to encounter, in mean value, at most

  $$E = W^*p_{\text{padding}} < W^*2^{-44} < W^*10^{-13,2}$$

  false positives.

  In particular, **4-to-13-digit PIN** gives

  $$W < 10^{13,05},$$

  still leading to

  $$\boldsymbol{E < 1.}$$

NP3 Failure

- We have seen that…
  - …given one particular encrypted authentication key, we could successfully brute force any PIN in the range of 4 to 13 decimal digits.
- So, the PIN was again gracefully packed right with the encrypted authentication key.
  - …and the diligent attacker was happy again!

Be Aware of OTPs

- If the PIN is involved in OTP generation, then <u>any OTP itself is a valuable PIN print.</u>
  - This is true even if the OTP is also based on some symmetric key stored in the mobile device.
  - Or, we have to prove the key cannot be retrieved by respective forensic techniques.
- Therefore, we shall:
  - not store OTPs in permanent memory,
  - wipe OTPs out of the volatile memory as soon as possible,
  - <u>regardless whether they were already used or not.</u>

Wiping Issues

- Consider the HOTP according to RFC 4226.
  - This is a popular OTP generator based on HMAC-SHA-1.
  - Its reference Java implementation (cf. RFC 4226), however, contains a security flaw.
  - OK, it is a reference design in the sense of test vectors, which are correct.
    - On the other hand, the RFC does not warn clearly that this code shall not be used for real implementations.
    - Especially on Android, it is probably tempting to simply copy-paste the code. Do not do that!

OTP Formatting by RFC 4226

```
result = Integer.toString(otp);
while (result.length() < digits) {
  result = "0" + result;
}
return result;
```

Secret Life of OTP Instances

- With each iteration, there are two new instances created:
  - (“+”) `java.lang.StringBuffer` or `StringBuilder` to perform the concatenation,
  - (“=”) `java.lang.String` to hold the result.
- However, the references to the previous iteration `result` and to the concatenation instance are lost.
  - So, we cannot wipe them even if we want to…

Android Proof-Of-Concept

- We have compiled the original HOTP padding procedure for Gingerbread.
  - To exhibit the faulty behavior, we have deliberately shortened the input integer, so we were able to see the zero-padding in action.
  - In particular, we set:
    - `otp = 755224,`
    - `digits = 9.`

Dalvík Code View by IDA Pro

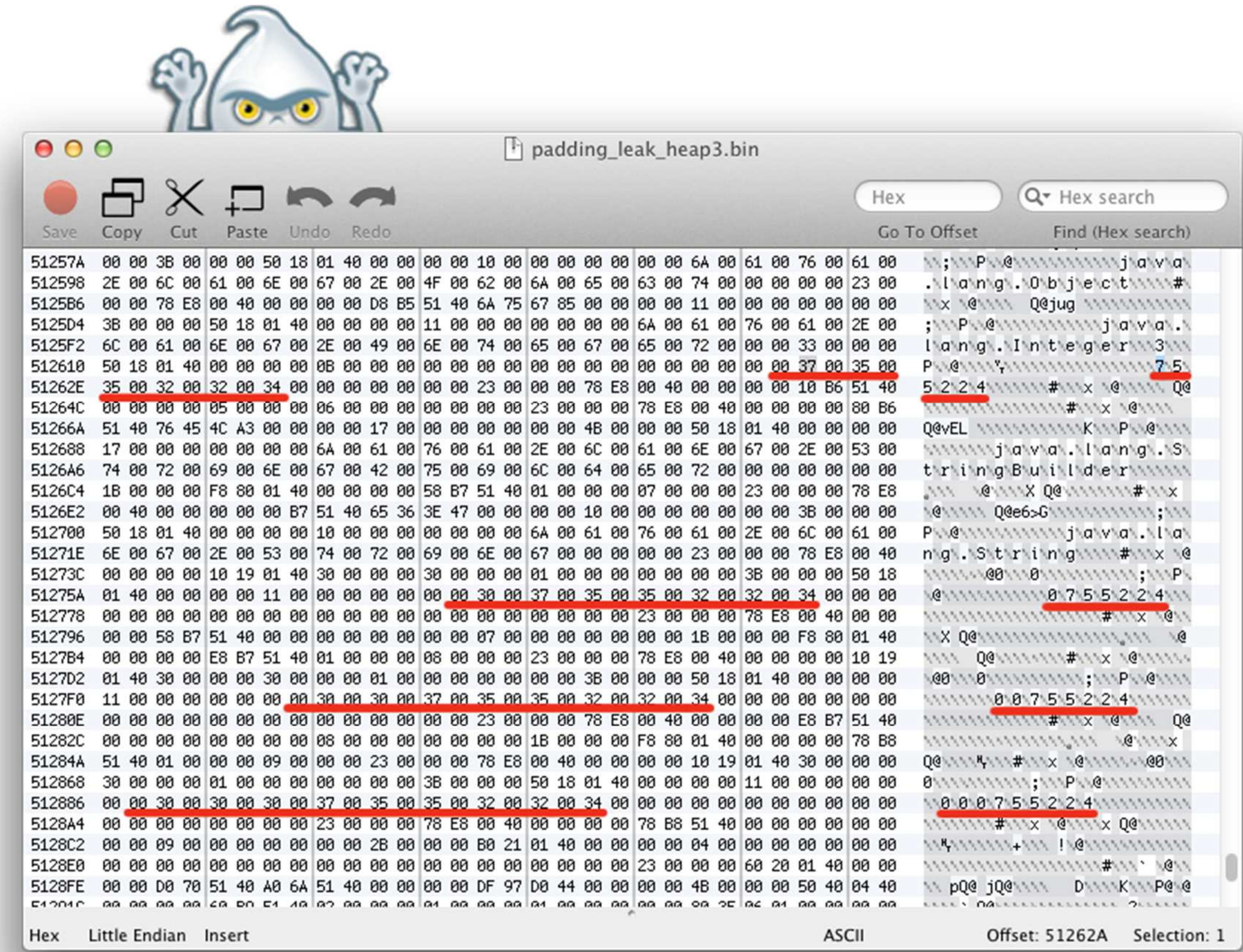
```
                invoke-static           {p0}, <ref Integer.toString(int) imp. @ _def_Integer_toString@LI>
                move-result-object      v0

loc_4A0:                          # CODE XREF: PaddingLeak_doPad@LII+3C↓j
                invoke-virtual          {v0}, <int String.length() imp. @ _def_String_length@I>
                move-result             v1
                if-lt                   v1, p1, loc_4AE

locret:
                return-object           v0
# ---------------------------------------------------------------------------

loc_4AE:                          # CODE XREF: PaddingLeak_doPad@LII+10↑j
                new-instance            v1, <t: StringBuilder>
                const/16                v2, 0x30
                invoke-static           {v2}, <ref String.valueOf(char) imp. @ _def_String_valueOf@LC>
                move-result-object      v2
                invoke-direct           {v1, v2}, <void StringBuilder.<init>(ref) imp. @ _def_StringBuilder__init_@V
                invoke-virtual          {v1, v0}, <ref StringBuilder.append(ref) imp. @ _def_StringBuilder_append@LL
                move-result-object      v1
                invoke-virtual          {v1}, <ref StringBuilder.toString() imp. @ _def_StringBuilder_toString@L>
                move-result-object      v0
                goto                    loc_4A0
```

Android Leakage Illustration



1-2-3 Countermeasure

1. Avoid encrypting keys with intrinsic algebraic redundancy.
   - If you want RSA, think twice. In principle, RSA key can be wrapped by other protocol (e.g. secret sharing), but is it really worth it? Be careful about the public key – it can also break NP3!
2. Avoid adding any “technical” redundancy.
   - ASN.1, XML, padding, …
3. Avoid storing any PIN-based OTP.
   - Regardless whether it was already used!

Conclusion

- Two-factor authentication resistant against After-Theft Attack is a doable adventure.
  - *It is a pity that ATA is still often ignored in practice.*
- The key idea is a distributed implicit PIN verification.
  - *Seems to be well-known approach.*
- We shall, however, carefully verify the No PIN Prints Postulate holds.
  - *Seems to be somehow lesser known in practice.*

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Děkujeme za pozornost.

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