A Cautionary Note: Side-Channel Leakage Implications of Deterministic Signature Schemes

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Motivation

- ElGamal-like digital signature schemes (e.g. ECDSA) require a random number for the ephemeral (short-term) key
- Security depends on the quality of this random number
  - Designers are not always aware of this (e.g. PS3 hack in 2010)
  - Embedded systems cannot always guarantee this
- Idea: remove need for high-quality randomness
- Solution: deterministic generation of ephemeral key from message and private key
- Problem: derivation of ephemeral may reveal private key through a side-channel

Recap: ECDSA Digital Signature Generation

Signing message m using private key d where n is the order of the base point P

(a) choose cryptographically secure random $k \in \{1, 2, \dots, n-1\}$

(b) $(x_1, y_1) = k \cdot P$

(c) $r = x_1 \bmod n$, if $r = 0$ go back to (a)

(d) $s = k^{-1} \cdot (\mathrm{H}(m) + d \cdot r) \bmod n$, if $s = 0$ go back to (a)

(e) signature for m is the pair (r, s)

Attacks Exploiting bad Randomness

Trivial case: two signatures (r, s) and (r, s') of different messages m, m' using the same private key (d) and ephemeral key (k)

$$s = k^{-1} \cdot (\mathrm{H}(m) + d \cdot r) \bmod n \tag{1}$$

$$d = \frac{s \cdot k - \mathrm{H}(m)}{r} \bmod n \tag{2}$$

$$s - s' = k^{-1} \cdot (\mathrm{H}(m) - \mathrm{H}(m')) \bmod n \tag{3}$$

$$k = \frac{\mathrm{H}(m) - \mathrm{H}(m')}{s - s'} \bmod n \tag{4}$$

More sophisticated attacks known, e.g. Nguyen and Shparlinsky only require some bits of k [NS03]

RFC6979: Scheme by Thomas Pornin [Por13]

Based on HMAC-DRBG (deterministic random bit generator) [KBC97][BK12]

$$HMAC(K, m) = H\left((K \oplus opad)|H((K \oplus ipad)|m)\right) \tag{5}$$

The first step of the HMAC-DRBG updates K_i in the following way

$$K_1 = HMAC(K_0 = 0, m = (V_0|0x00|d|H(m))) \tag{6}$$

After substitution Equ.6 in Equ.5:

$$K_1 = H\left(opad|\color{red}{H(ipad|V_0|0x00|d|H(m))}\right) \tag{7}$$

Side-Channel Vulnerability of RFC6979

$$\boxed{H(\underbrace{ipad|V_0|0x00|}_{\text{fixed, known}}\overbrace{d}^{\text{fixed, unknown}}\underbrace{|H(m)}_{\text{variable, known}})}$$

Differential side-channel attacks possible!

EdDSA: Scheme by Bernstein et al. [BDL+12]

Signing message m using private key d

(a) The private key is hashed $\mathrm{H}(d) = (h_0, h_1, \ldots, h_{2b-1})$

(b) The first half of the hash value is used to derive $a = 2^{b-2} + \sum_{3 \leq i \leq b-3} 2^i h_i$ and public key $A = a \cdot P$

(c) Deterministic ephemeral key $r = \mathrm{H}(h_b, h_{b+1}, \ldots, h_{2b-1} | m)$

(d) $R = r \cdot P$

(e) $S = (r + \mathrm{H}(R, A, m)a) \bmod n$

(f) The signature for m is the pair (R, S)

Side-Channel Vulnerability of EdDSA

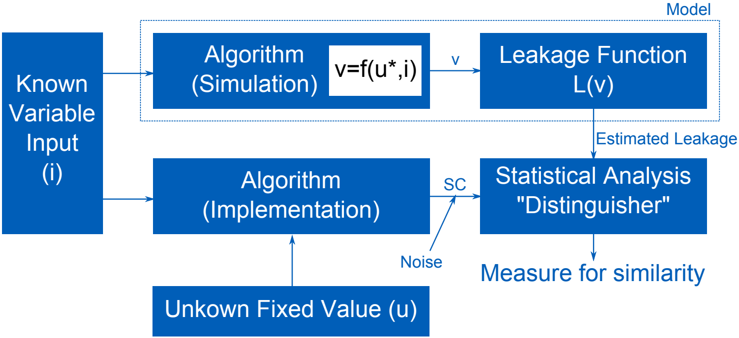
$$\boxed{r = H(\overbrace{h_b, h_{b+1}, \ldots, h_{2b-1}}^{\text{fixed, unknown}} \mid \underbrace{m}_{\text{variable, known}})}$$

Differential side-channel attacks possible!

Long-term key d not directly observable, but r and a are revealed

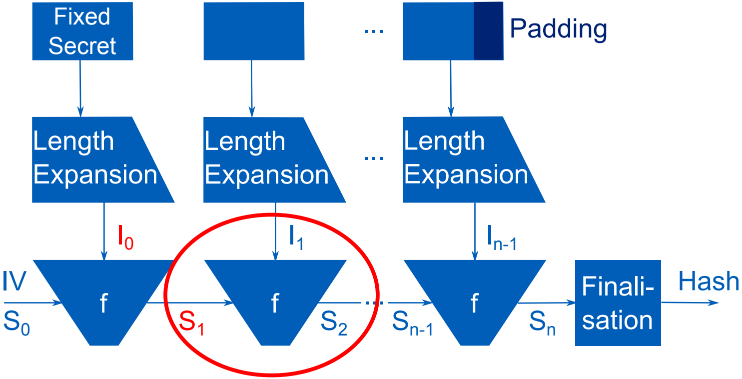
$$S = (r + \mathrm{H}(R, A, m)a) \bmod n \Rightarrow a = \frac{S - r}{\mathrm{H}(R, A, m)} \bmod n$$

Differential Side-Channel Attacks



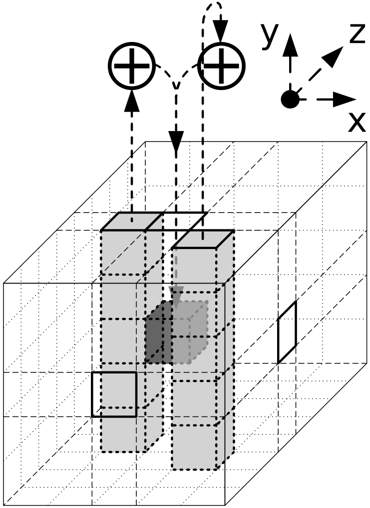
Differential Side-Channel Attacks on SHA-2

- McEvoy et al. [MTMM07] presented a successful side-channel attack on HMAC-SHA-256
- Attack targets the compression function and reveals S_1



Differential Side-Channel Attacks on SHA-3

- 1600 bit state initially zero
- State absorbs block of data
- State XORed with previous one and applied to Keccak function
- Keccak function: 24 rounds of 5 sequential operations
- Attack on θ-operation by Taha et al.[TS13]
- Attack directly reveals secret input



Source: http://keccak.noekeon.org/ (CC BY 3.0)

Conclusion and Future Work

- Deterministic ephemeral keys bear side-channel risks
- System parameters influence the success rate for attacks
- Open Topics:
  - Perform actual attacks
  - Propose countermeasures (which again need randomness!)

Thank You!
Any Questions?

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