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On Randomizing Hash Functions to Strengthen the Security of Digital Signatures

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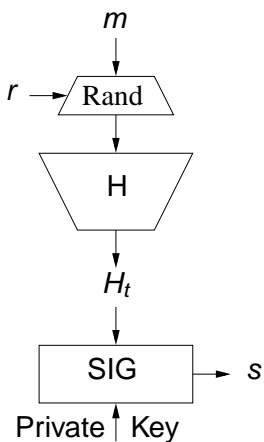
Outline

- 1 Strengthening digital signatures via randomized hashing
- 2 Generic forgery attack on RMX-hash-then-sign schemes
- 3 Forging some randomize-hash-then-sign schemes

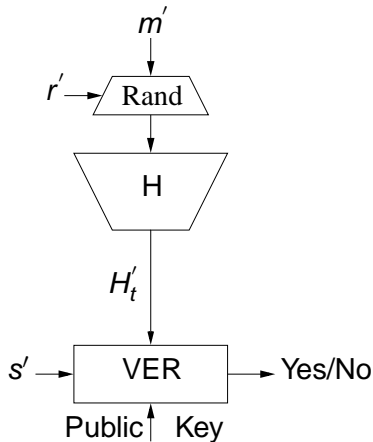
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Randomize-hash-then-sign signatures



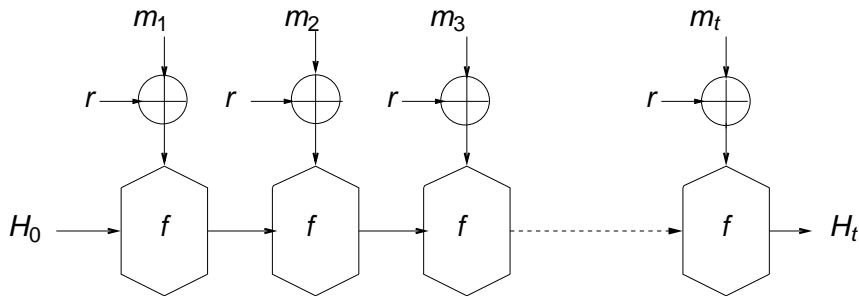
SIGNATURE GENERATION



SIGNATURE VERIFICATION

Randomized hashing (Halevi and Krawczyk-Crypto'06)

$H_r(m) = H((m_1 \oplus r) || (m_2 \oplus r) || \dots || (m_t \oplus r))$ where H is an n -bit hash function.

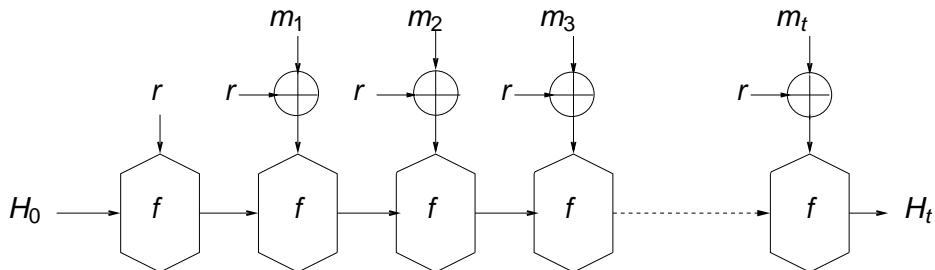


Properties

- Target collision resistance (TCR): Difficulty in finding $m^* \neq m$ after committing to m and receiving r , such that $H_r(m) = H_r(m^*)$.
- If f is c-SPR or e-SPR then H_r is TCR.
- Signing using H_r :
 - Use SIG algorithm to sign the pair $(r, H_r(m))$.
 - Certain signature schemes either do not accommodate signing of both r and $H_r(m)$ (DSA) or requires implementation changes (RSA).

RMX Hash function mode

$$\tilde{H}_r(m) = H(r \parallel (m_1 \oplus r) \parallel (m_2 \oplus r) \parallel \dots \parallel (m_t \oplus r))$$



Properties

- Enhanced target collision resistance (eTCR): Difficulty in finding $(r^*, m^*) \neq (r, m)$ after committing to m and receiving r , such that $\tilde{H}_r(m) = \tilde{H}_{r^*}(m^*)$.
- If f is c-SPR or e-SPR then \tilde{H}_r is eTCR
- Signing using \tilde{H}_r :
 - Use SIG algorithm to sign just $\tilde{H}_r(m)$

Known results on randomize-hash-then-sign schemes

Forging signatures based on H_r and \tilde{H}_r (via off-line) requires:

- Solving a cryptanalytical problem which is related to finding second preimages in H .
 - Kelsey-Schneier second preimage attack on H for a message of 2^k blocks in 2^{n-k} work.
- Breaking c-SPR or e-SPR property of f .

To forge randomize-hash-then-sign signatures:

- How many queries to the signer are required?
- What properties of f or H can we exploit?
- For how many times we need to play the game of TCR/eTCR?

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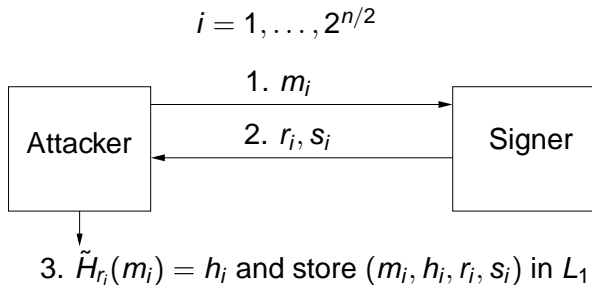
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Generic forgery of RMX-hash-then-sign schemes (Dang-Perlner)



4. Choose some r^* , do $\tilde{H}_{r^*}(m_i^*) = h_i^*$ and store (h_i^*, m_i^*) in L_2 .
5. Find $(r, m) \in L_1$ and $m^* \in L_2$ such that $\tilde{H}_r(m) = \tilde{H}_{r^*}(m^*)$.
6. Signature on m is also valid on m^* .

Limitations

Attack does not succeed when:

- Same salt r is used for both hashing and signing (DSA, ECDSA, RSA-PSS).
- Signatures are based on TCR hashing H_r .

We can overcome these limitations when f has fixed points. Davies-Meyer compression function used in many popular hashes such as MD5 and SHA family has this property.

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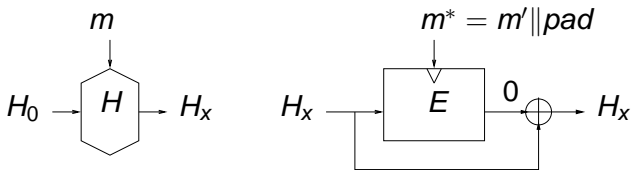
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Forging H -SIG scheme using Dean's method

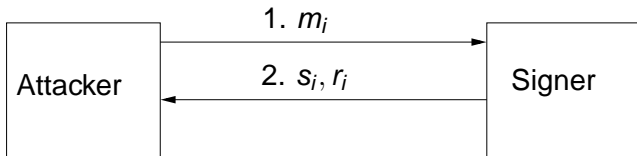
Exploit the fixed point property of Davies-Meyer.

- 1 Find $2^{n/2}$ hash values of H for equal length messages m_i . Store (H_i, m_i) in L_1 .
- 2 Find $2^{n/2}$ fixed points (H_i, m_i^*) for f . Store them in L_2 .
- 3 Find $(H_x, m) \in L_1$ and $(H_x, m^*) \in L_2$ such that $H(m) = H_x = f(H_x, m^*)$.
- 4 $H(m) = H(m||m^*) \Rightarrow \text{SIG}(H(m)) = \text{SIG}(H(m||m^*))$.



Forging RMX-hash-then-sign schemes

- On-line phase:
Ask the signer for the signatures s_i on $2^{n/2}$ equal length messages m_i . Store (r_i, m_i, s_i) in L_1 .

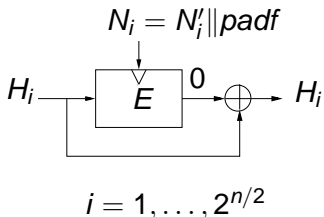


Note that $s_i = \text{SIG}(\tilde{H}_{r_i}(m_i))$ and $i = 1, \dots, 2^{n/2}$.

- Off-line phase: Compute $\tilde{H}_{r_i}(m_i)$ and add to L_1 .

Forging RMX-hash-then-sign schemes

- Off-line phase:
Compute $2^{n/2}$ fixed points (H_i, N_i) for f . Store them in L_2 .



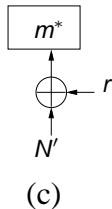
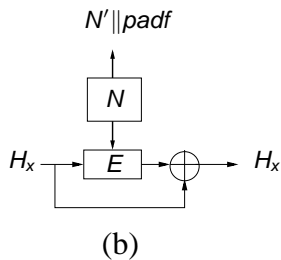
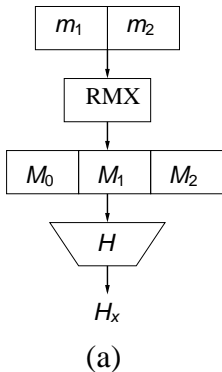
Forging RMX-hash-then-sign schemes

- Off-line phase:

- 1 Find $(m, r, \tilde{H}_r(m)) \in L_1$ and $(N, \tilde{H}_r(N)) \in L_2$ such that $\tilde{H}_r(m) = H_x = f(H_x, N)$.
- 2 This implies $\tilde{H}_r(m) = H_x = \tilde{H}_r(m \| m^*)$ where $m^* = N \oplus r$.
- 3 $\text{SIG}(\tilde{H}_r(m)) = \text{SIG}(\tilde{H}_r(m \| m^*))$.
- 4 Output $m \| m^*$ as the forgery of m .

Complexity: $2^{n/2}$ chosen messages, $2^{n/2+1}$ evaluations of f and $2^{n/2}$ memory

Forging RMX-hash-then-sign schemes



Applications of the approach

- Independent of the size of r .
- RMX-hash-then-sign scheme in NIST's SP 800-106.
- Applies to signatures based on $H_r(m)$, $H(r\|H_r(m))$ and $RO(H_r(m))$.
- Many others (please see article).

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Summary of our analysis

- 1 Complements previous analysis:
 - Off-line birthday attacks do not help.
 - Attacks must be online but not much over birthday complexity.
 - Worth investigating SPR properties of compression functions in the SHA-3 competition.
- 2 Security of RMX-hash-then-sign schemes is similar to that of HMAC.

Nitpick in Conclusion: “Our research shows that randomized hashing is not easy to implement safely.”

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Thank You