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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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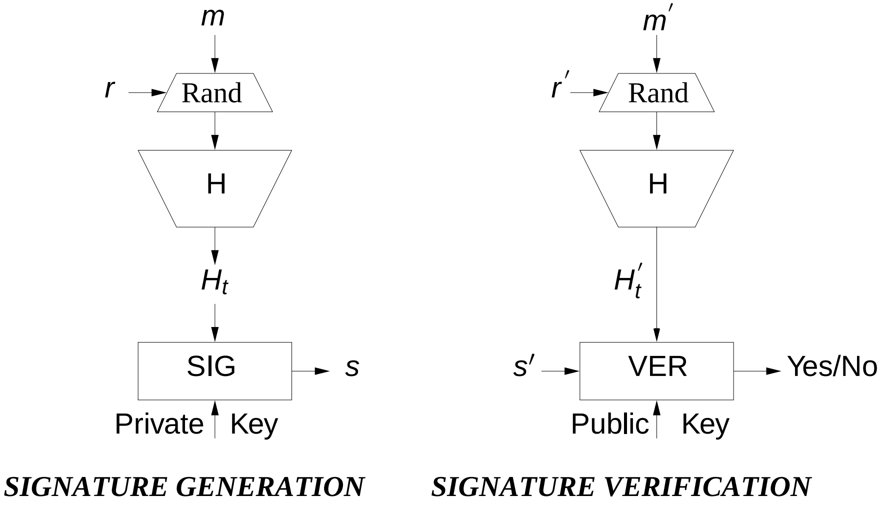
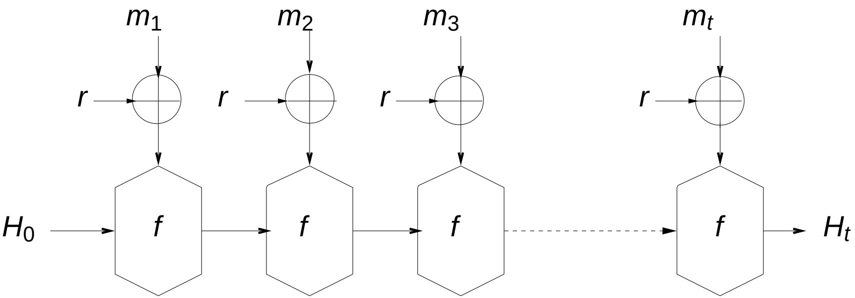
# Randomize-hash-then-sign signatures



# Randomized hashing (Halevi and Krawczyk-Crypto'06)

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

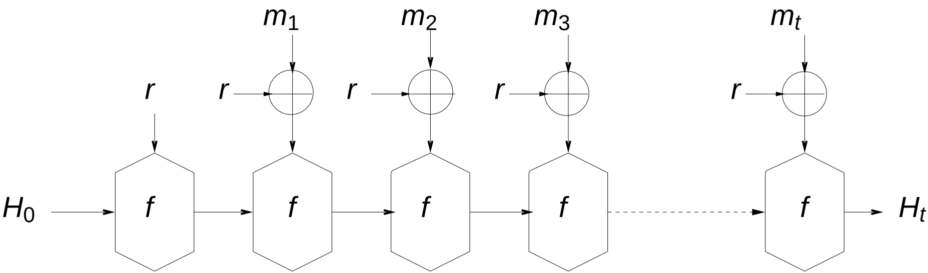


# Properties

- 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 $\mathrm{SIG}$ 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

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



# 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 $\mathrm{SIG}$ 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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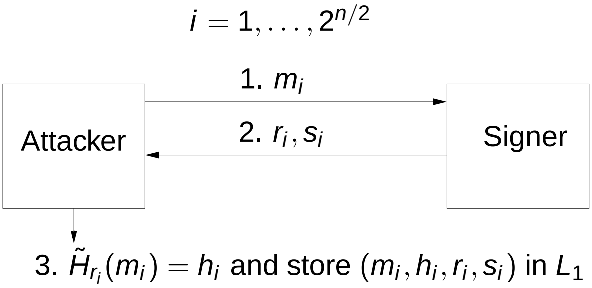
# Generic forgery of RMX-hash-then-sign schemes (Dang-Perlner)




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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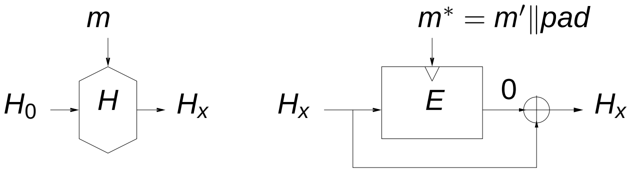
# Forging $H$-SIG scheme using Dean's method

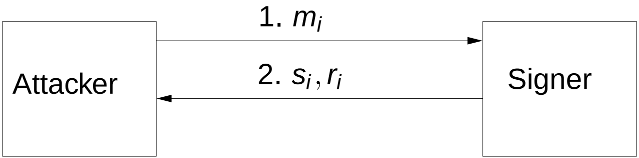
Exploit the fixed point property of Davies-Meyer.

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. $H(m) = H(m \| m^*) \Rightarrow SIG(H(m)) = SIG(H(m \| m^*))$.



# 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 $L_1$.

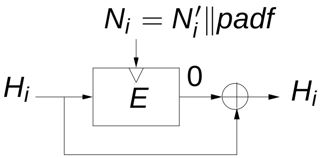



Note that $s_i = \mathrm{SIG}(\tilde{H}_{r_i}(m_i))$ and $i = 1, \ldots, 2^{n/2}$.

- 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 $L_2$.



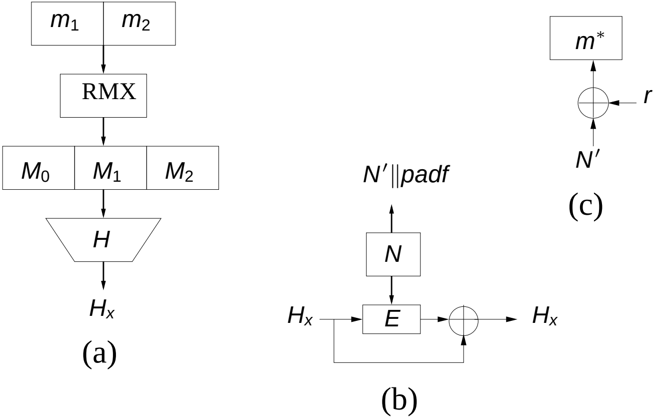

$$i = 1, \ldots, 2^{n/2}$$

# 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 $\mathrm{RO}(H_r(m))$.
- 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**