Functional Graph Revisited: Updates on (Second) Preimage Attacks on Hash Combiners

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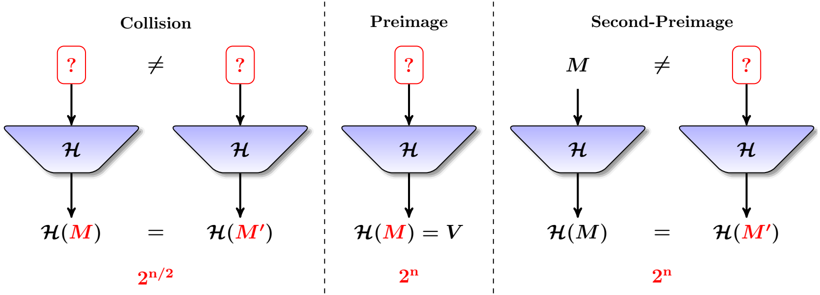
Security Requirements for Hash Functions

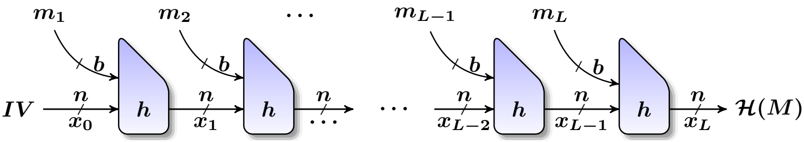
1. **Collision resistance**: It should be computationally difficult to find two messages M and M' such that $\mathcal{H}(M) = \mathcal{H}(M')$.
2. **Preimage resistance**: Given a target V, it should be computationally difficult to find a message M such that $\mathcal{H}(M) = V$.
3. **Second-preimage resistance**: Given a message M, it should be computationally difficult to find another message $M' \neq M$ such that $\mathcal{H}(M') = \mathcal{H}(M)$.



Underlying Construction - Iterative Hash Functions

1. The Merkle-Damgård construction (MD) [Mer90; Dam90]: Padding and dividing $M = m_1 \| m_2 \| \ldots \| m_L$, where m_L is encoded with the length the message $|M|$:

$$x_0 = IV \quad x_i = h(x_{i-1}, m_i) \quad \mathcal{H}(M) = h(x_{L-1}, m_L)$$



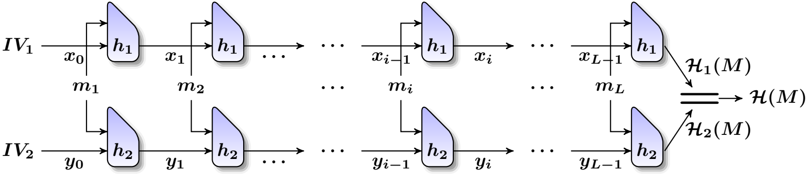
An Approach to Construct a Secure Hash Function - Hash Combiner

Hash Combiner

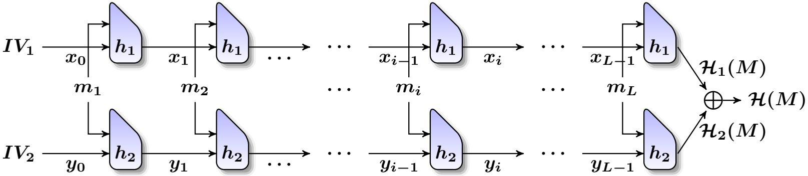
- Security amplification
  the combiner is more secure than its underlying hash functions;
- Security robustness
  the combiner is secure as long as any one of its underlying hash functions is secure

Hash Combiners - Parallel

- Concatenation combiner: $\mathcal{H}(M) = \mathcal{H}_1(M) \| \mathcal{H}_2(M)$

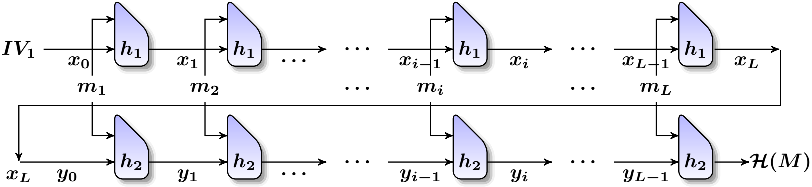


- XOR combiner: $\mathcal{H}(M) = \mathcal{H}_1(M) \oplus \mathcal{H}_2(M)$

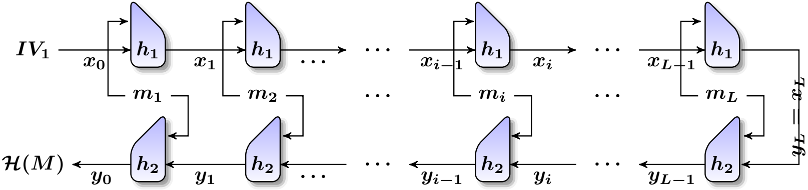


Hash Combiners - Cascade

- Hash Twice: $\mathcal{H}(M) = \mathcal{H}_2(\mathcal{H}_1(IV, M), M)$



- Zipper Hash [Lis07]: $\mathcal{H}(M) = \mathcal{H}_2(\mathcal{H}_1(IV, M), \overleftarrow{M})$



Research on Hash Combiners

Security of classical hash combiners

- Generic attacks: upper bound;
- Security proofs: lower bound;

Research on Hash Combiners

Security of classical hash combiners

- Generic attacks: upper bound; the main focus of this work
- Security proofs: lower bound;

Expected Security of Hash Combiners Before 2004

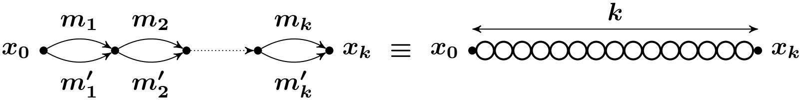
	Digest Size	Collision Resistance	Preimage Resistance	Second Preimage Resistance
Ideal $\mathcal{H}$	n	$2^{n/2}$	2^n	2^n
Ideal $\mathcal{H}_1 \| \mathcal{H}_2$	$2n$	2^n	2^{2n}	2^{2n}
Ideal $\mathcal{H}_1 \oplus \mathcal{H}_2$	n	$2^{n/2}$	2^n	2^n

$\Uparrow$
birthday bound
half of digest size

$\Uparrow$
full digest size

Joux's Multi-collisions (JM [Jou04])

- Get 2^k-multicollision by successively applying birthday attack k times.

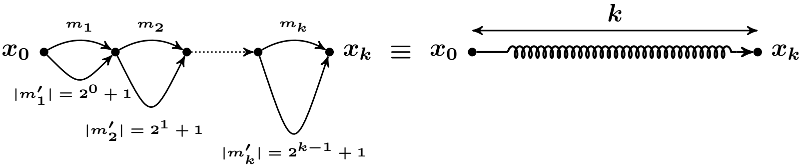


Security Status of MD Hash Combiners in 2004

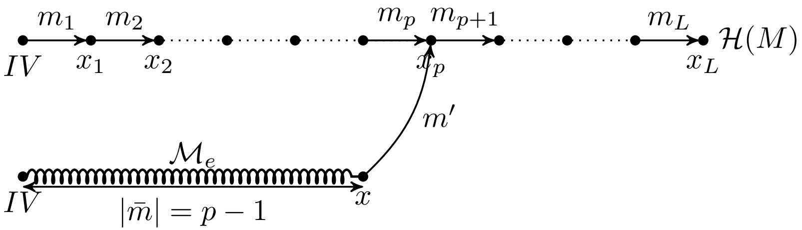
	Collision Resistance	Preimage Resistance	Second Preimage Resistance
Ideal $\mathcal{H}$	$2^{n/2}$	2^n	2^n
MD $\mathcal{H}$	$2^{n/2}$	2^n	2^n
Ideal $\mathcal{H}_1 \| \mathcal{H}_2$	2^n	2^{2n}	2^{2n}
MD $\mathcal{H}_1 \| \mathcal{H}_2$	([Jou04] JM) $\cancel{2^n}$ $\approx 2^{n/2}$	([Jou04] JM) $\cancel{2^{2n}}$ $\approx 2^n$	([Jou04] JM) $\cancel{2^{2n}}$ $\approx 2^n$
Ideal $\mathcal{H}_1 \oplus \mathcal{H}_2$	$2^{n/2}$	2^n	2^n
MD $\mathcal{H}_1 \oplus \mathcal{H}_2$	$2^{n/2}$	2^n	2^n

Kelsey-Schneier's Expandable Message (EM [KS05])

- Get 2^k-multicollision with length cover the whole range of $[k, k + 2^k - 1]$ by successively applying birthday attack k times.



Second Preimage Attack Using Expandable Message [KS05]



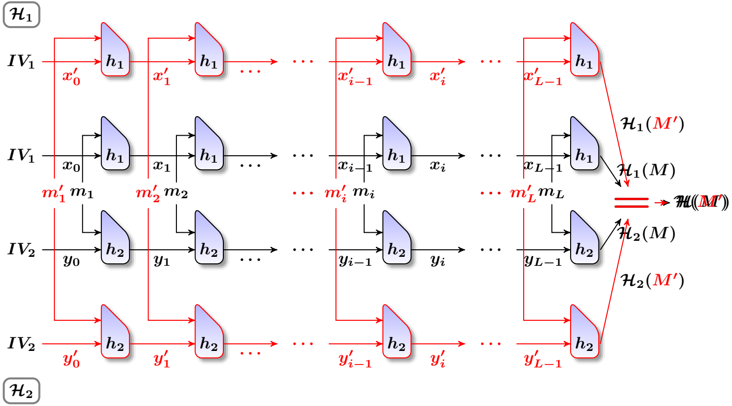
- Step 1: Start from IV, build an expandable message and end up at arbitrary state x.
- Step 2: Start from x and try different m' until $h(x, m') = x_p$ (for each trail $\Pr(succeed) = L/2^n$).
- Step 3: Select message $\bar{m}$ of appropriate length $p-1$ and output $M' = \bar{m}||m'||m_{p+1}|| \ldots ||m_L$.

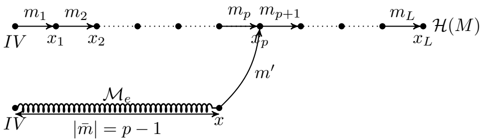
Security Status of MD Hash in 2005

	Collision Resistance	Preimage Resistance	Second Preimage Resistance
Ideal $\mathcal{H}$	$2^{n/2}$	2^n	2^n
MD $\mathcal{H}$	$2^{n/2}$	2^n	([KS05] EM) $\cancel{2^n}$ $2^n/L$
Ideal $\mathcal{H}_1 \| \mathcal{H}_2$	2^n	2^{2n}	2^{2n}
MD $\mathcal{H}_1 \| \mathcal{H}_2$	([Jou04] JM) $\cancel{2^n}$ $\approx 2^{n/2}$	([Jou04] JM) $\cancel{2^{2n}}$ $\approx 2^n$	([Jou04] JM) $\cancel{2^{2n}}$ $\approx 2^n$
Ideal $\mathcal{H}_1 \oplus \mathcal{H}_2$	$2^{n/2}$	2^n	2^n
MD $\mathcal{H}_1 \oplus \mathcal{H}_2$	$2^{n/2}$	2^n	2^n

A Primary Second Preimage Attack Against Concatenation Combiner

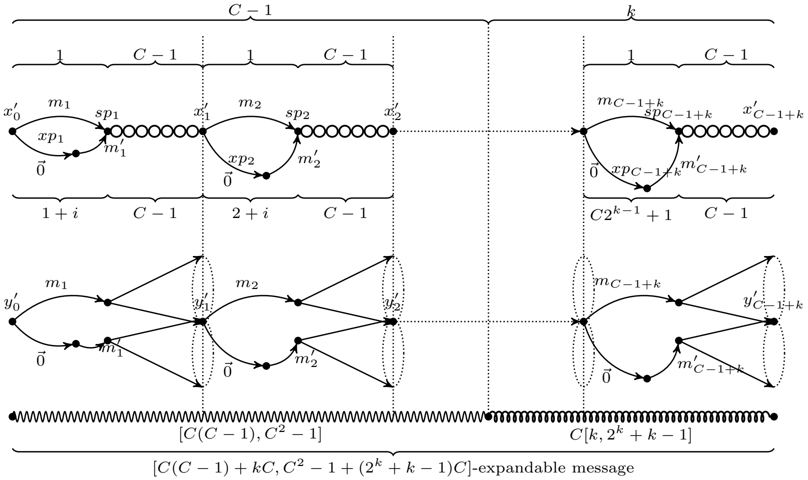
Goal:





Simultaneous Expandable Message (Parallel) (SEM [Din16])

$$T : n \cdot 2^k + n^2 \cdot 2^{\frac{n}{2}}, M : n^2 + k \cdot n, D : 2^{\frac{n}{2}}(n + k)$$



Functional Graph

The Functional Graph (FG) of Random Mapping:
Let $f \in \mathcal{F}_N$, $x \to f(x)$, FG of f is a directed graph, nodes are $[0 \ldots N-1]$ and edges are $\langle x, f(x) \rangle$

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- Starting from a random point x_0

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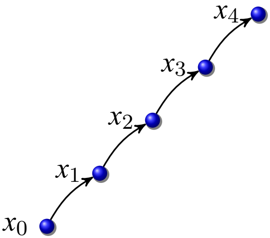

- Starting from a random point x_0
- Iterate: $x_1 = f(x_0)$, $x_2 = f(x_1), \ldots$

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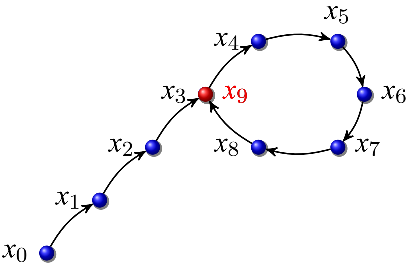

- Starting from a random point x_0
- Iterate: $x_1 = f(x_0),\ x_2 = f(x_1), \ldots$
- Before N and $\approx \sqrt{N}$ iterations, we will find a value x_j equal to one of $x_0, x_1, \ldots, x_{j-1}$.

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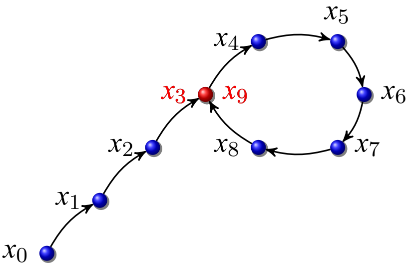

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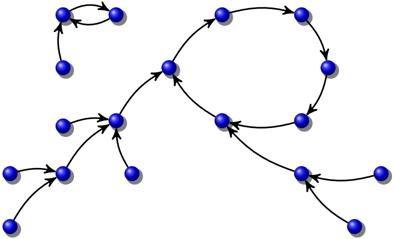
- Before N and $\approx \sqrt{N}$ iterations, we will find a value x_j equal to one of $x_0, x_1, \ldots, x_{j-1}$.
- We say collision x_j is an α-node and the path $x_0 \to x_1 \to \cdots \to x_{j-1} \to x_j$ connects to a cycle.

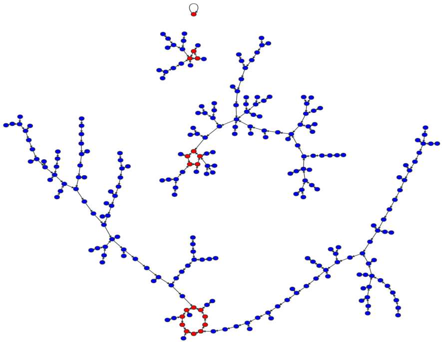
Functional Graph

The Functional Graph (FG) of Random Mapping:
Let $f \in \mathcal{F}_N$, $x \to f(x)$, FG of f is a directed graph, nodes are $[0 \ldots N-1]$ and edges are $\langle x, f(x) \rangle$



- Starting from a random point x_0
- Iterate: $x_1 = f(x_0),\ x_2 = f(x_1), \ldots$
- Before N and $\approx \sqrt{N}$ iterations, we will find a value x_j equal to one of $x_0, x_1, \ldots, x_{j-1}$.
- We say collision x_j is an α-node and the path $x_0 \to x_1 \to \cdots \to x_{j-1} \to x_j$ connects to a cycle.
- Starting from all possible points, paths confluence and form into trees; trees grafted on cycles form components; components forms a functional graph.

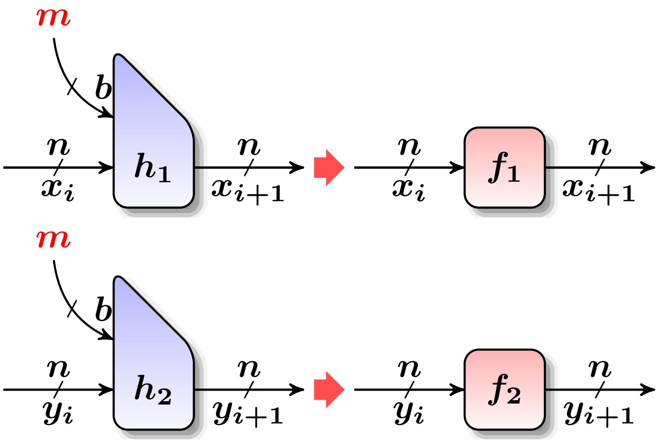
Properties of Functional Graph [FO90]



[PSW12; LPW13; PW14; Guo+14; DL14]

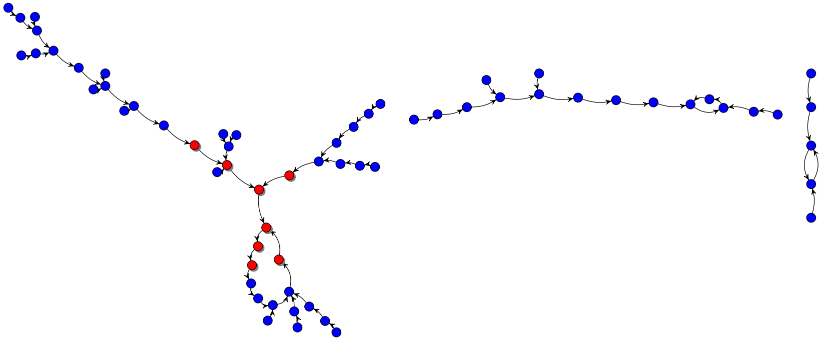
1. # Components: $\frac{1}{2}\log N = 0.5 \cdot n$
2. # Cyclic nodes: $\sqrt{\pi N/2} = 1.2 \cdot 2^{n/2}$
3. # Terminal nodes: $e^{-1}N = 0.37 \cdot 2^n$
4. # Image points: $(1 - e^{-1})N = 0.62 \cdot 2^n$
5. # k-th iterate image points: $(1 - \tau_k)N$, where the τ_k satisfy the recurrence $\tau_0 = 0$, $\tau_{k+1} = e^{-1+\tau_k}$.
6. Maxinum cycle length: $0.78 \cdot 2^{n/2}$.
7. Maxinum tail length: $1.74 \cdot 2^{n/2}$.
8. Maxinum rho length: $2.41 \cdot 2^{n/2}$.
9. Largest tree size: $0.48 \cdot 2^n$.
10. Largest component size: $0.76 \cdot 2^n$.

Functional Graph Corresponding to Underlying Compression Functions

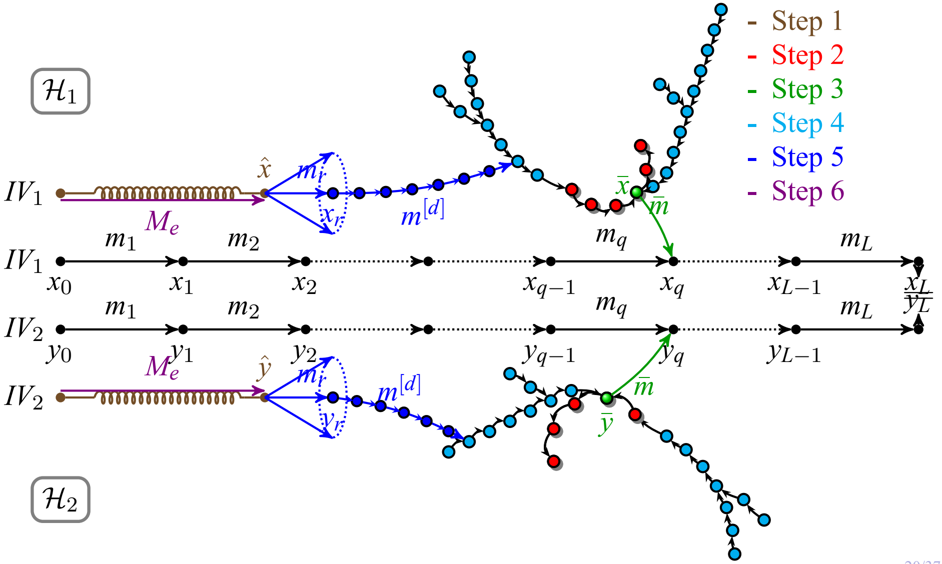


Deep Iterates in Functional Graph (FGDI [Din16])

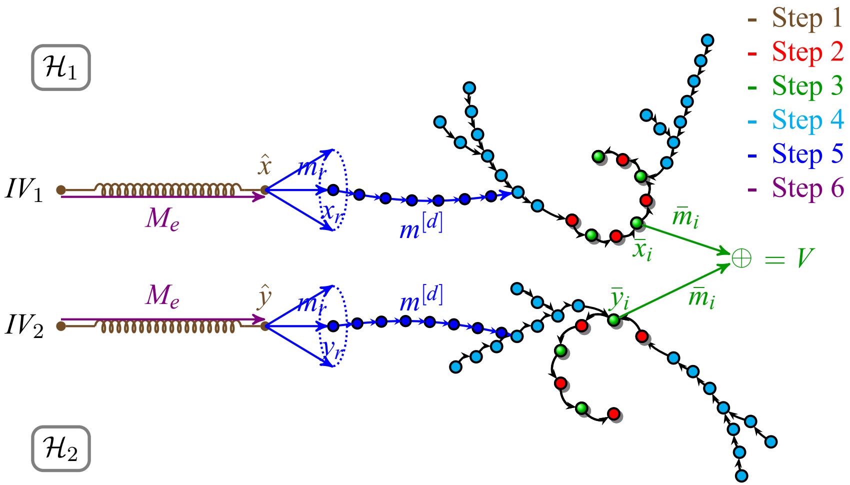
- It is easy to get a large set of deep iterates: $T : 2^k, M : 2^k, D : 2^k$
- A deep iterate has a relatively high probability to be reached from a randomly selected starting node.



Second Preimage Attacks on Concatenation Combiner Using Deep Iterates in FG [Din16]



Preimage Attacks on XOR Combiner Using Deep Iterates in FG [Din16]



(Second) Preimage Attack on Concatenation and XOR Combiner [Din16]

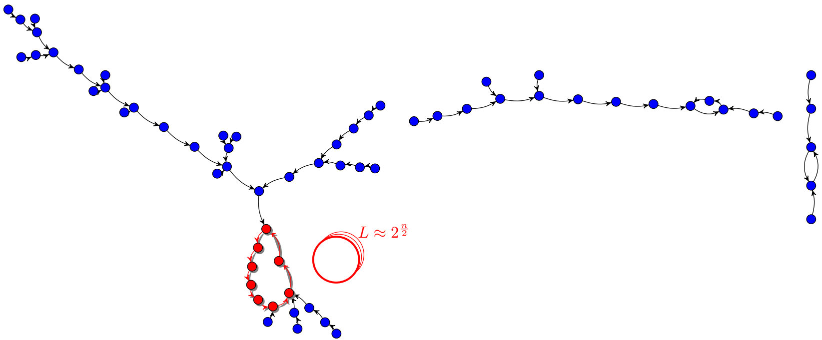
Simultaneous Expandable Message and Deep Iterates in FG (SEM+FGDI [Din16])

	Collision Resistance	Preimage Resistance	Second Preimage Resistance
Ideal $\mathcal{H}$	$2^{n/2}$	2^n	2^n
MD $\mathcal{H}$	$2^{n/2}$	2^n	$\cancel{2}^n$ $2^n/L$
Ideal $\mathcal{H}_1 \| \mathcal{H}_2$	2^n	2^{2n}	2^{2n}
MD $\mathcal{H}_1 \| \mathcal{H}_2$	$\cancel{2}^n$ $\approx 2^{n/2}$	$\cancel{2}^{2n}$ $\approx 2^n$	$\cancel{2}^{2n}$ $\approx 2^{3n/4}$
Ideal $\mathcal{H}_1 \oplus \mathcal{H}_2$	$2^{n/2}$	2^n	2^n
MD $\mathcal{H}_1 \oplus \mathcal{H}_2$	$2^{n/2}$	$\cancel{2}^n$ $\approx 2^{2n/3}$	$\cancel{2}^n$ $\approx 2^{2n/3}$

Functional Graph Multi-cycles (FGMC [Our's])

Cyclic Node and Multi-cycles in Functional Graph:

- It is easy to locate the largest cycle: Repeat the cycle search algorithm a few times $T : 2^{\frac{n}{2}}, M : 1, D : 2^{\frac{n}{2}}$
- It is effortless to loop around the cycles to correct differences between the distances to the target nodes.



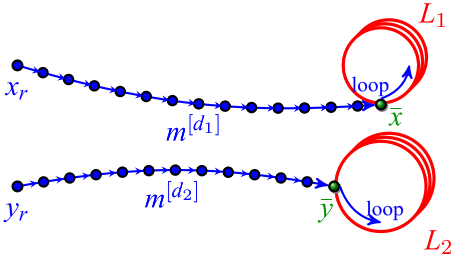
Functional Graph Multi-cycles (FGMC [Our's])

$$f_1^{d_1}(x_r) = \bar{x},\ f_1^{L_1}(\bar{x}) = \bar{x} \quad \Rightarrow \quad f_1^{d_1+i\cdot L_1}(x_r) = \bar{x} \text{ for } \forall\, i$$

$$f_2^{d_2}(y_r) = \bar{y},\ f_2^{L_2}(\bar{y}) = \bar{y} \quad \Rightarrow \quad f_2^{d_2+j\cdot L_2}(y_r) = \bar{y} \text{ for } \forall\, j$$

$$\Downarrow$$

$$\exists\,(i, j) \text{ s.t. } d_1 - d_2 = j\cdot L_2 - i\cdot L_1 \quad \Rightarrow \quad \exists\, d \text{ s.t. } f_1^{d}(x_r) = \bar{x},\, f_2^{d}(y_r) = \bar{y}$$



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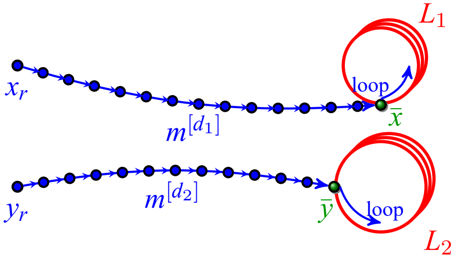
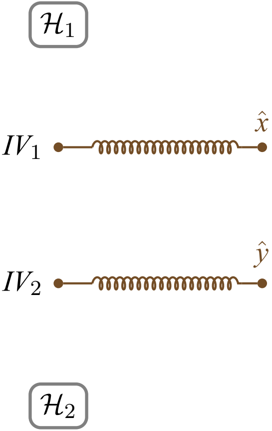
correctable distance bias



Preimage Attacks on XOR Combiner Using Multiple Cycles in FG

- Step 1



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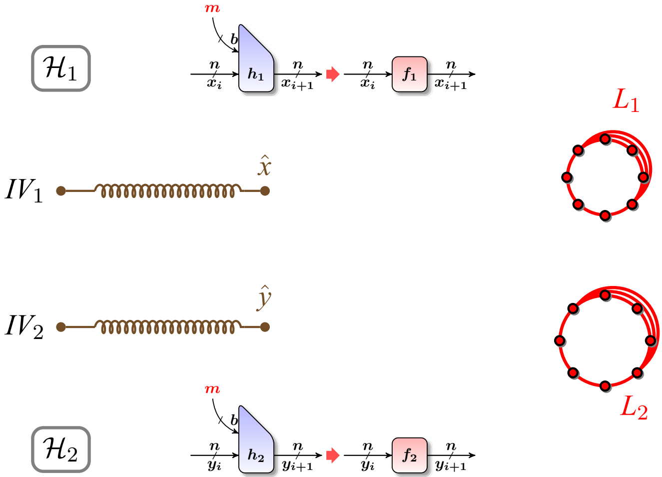
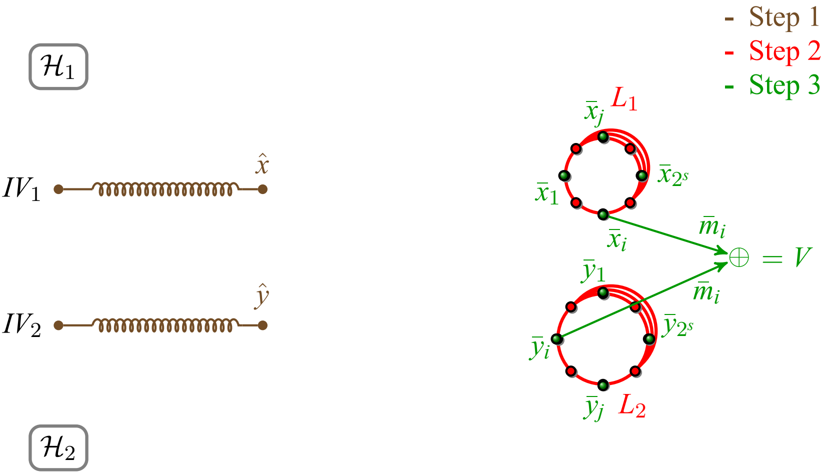


- Step 1
- Step 2

Preimage Attacks on XOR Combiner Using Multiple Cycles in FG



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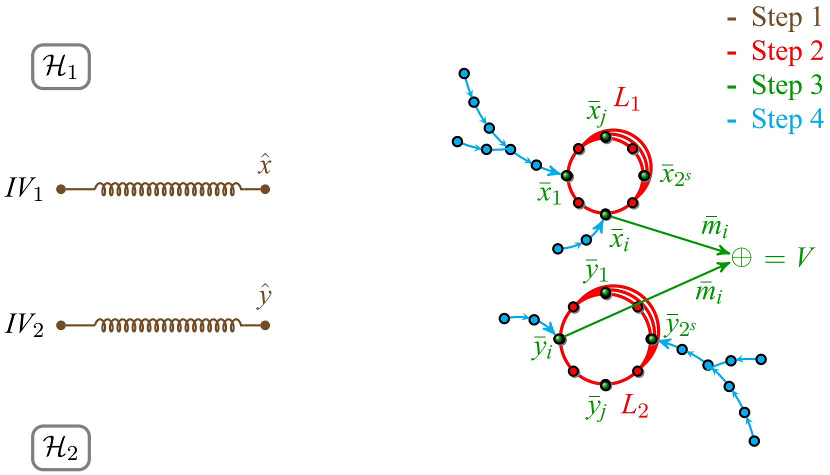

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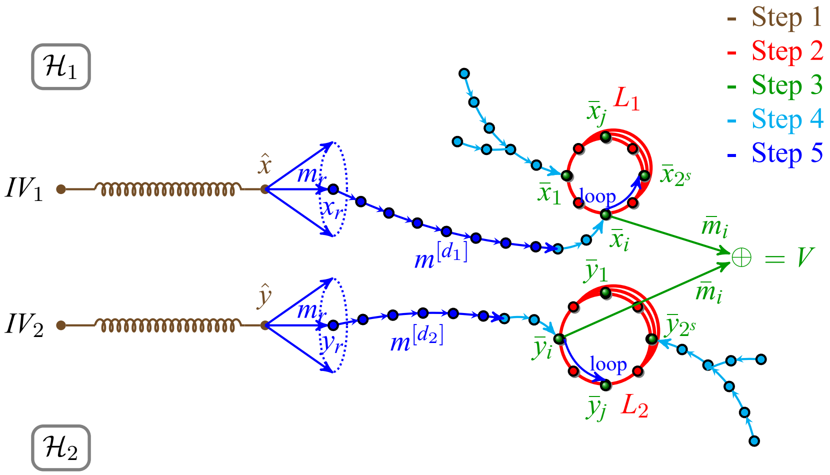

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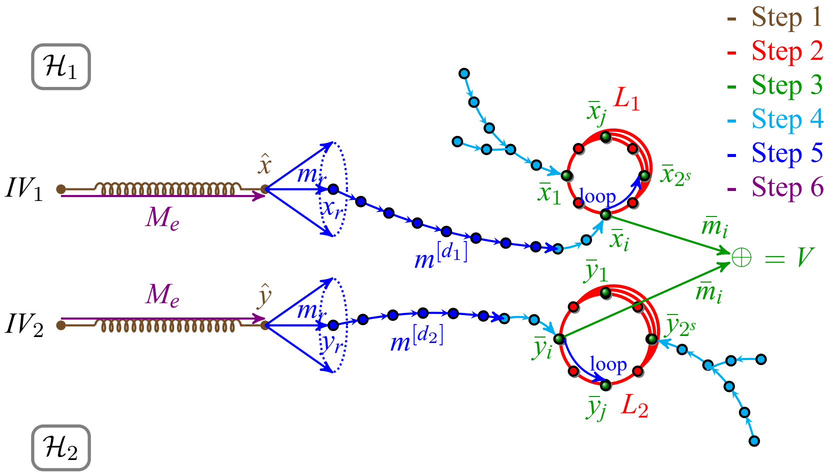

Hash Combiners - Cascade

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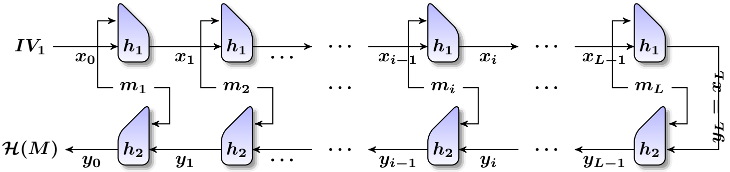
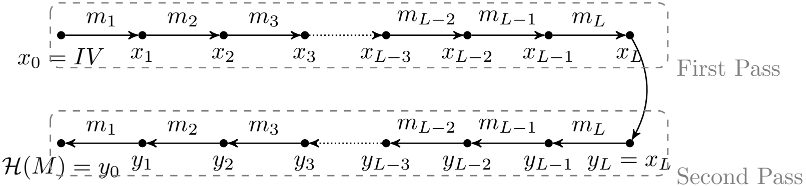
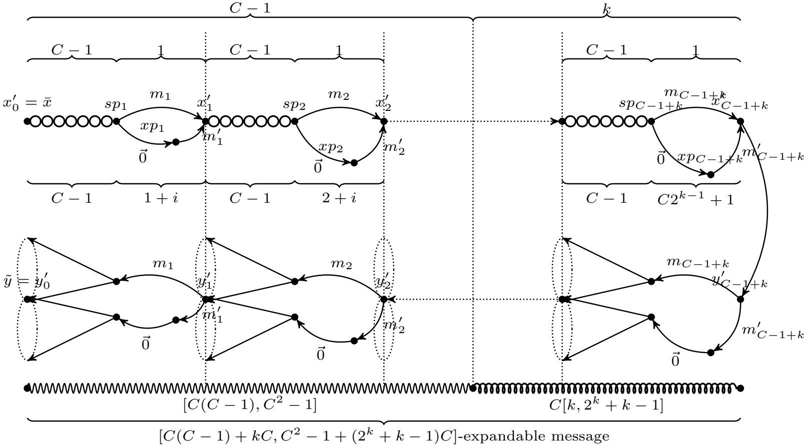




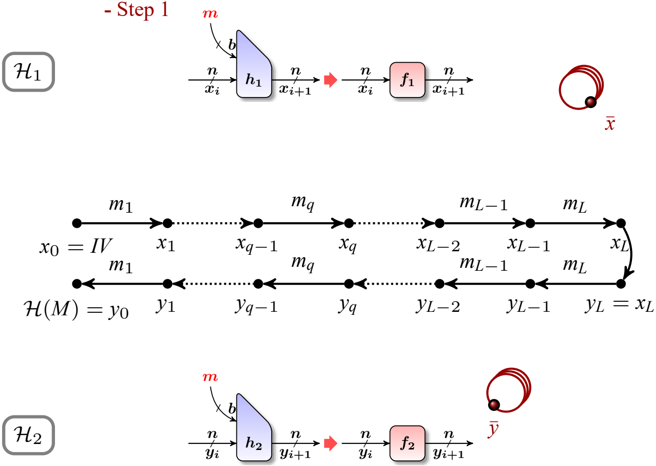
Simultaneous Expandable Message (Cascade)

$$T: n \cdot 2^k + n^2 \cdot 2^{\frac{n}{2}}, M: n^2 + k \cdot n, D: 2^{\frac{n}{2}}(n+k)$$



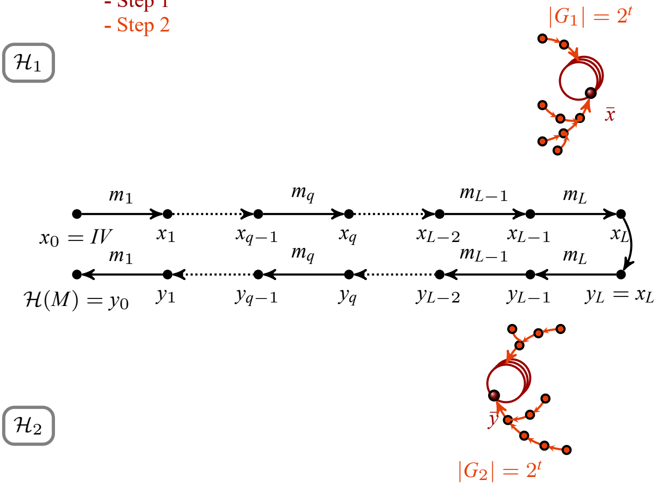
Second Preimage Attacks on Zipper Hash

- Step 1



Second Preimage Attacks on Zipper Hash

- Step 1
- Step 2



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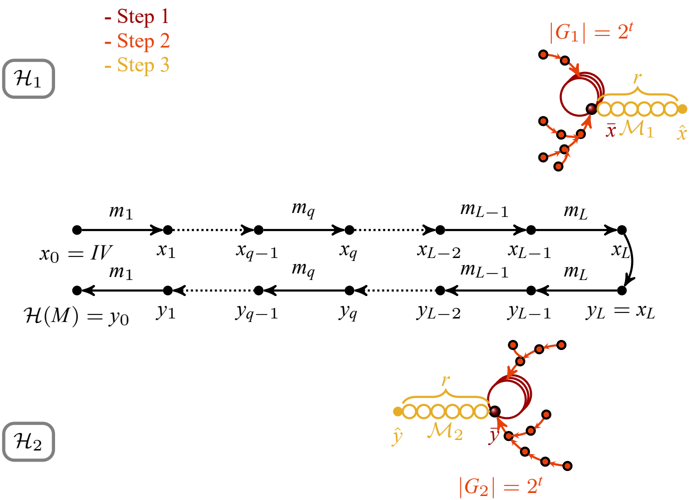

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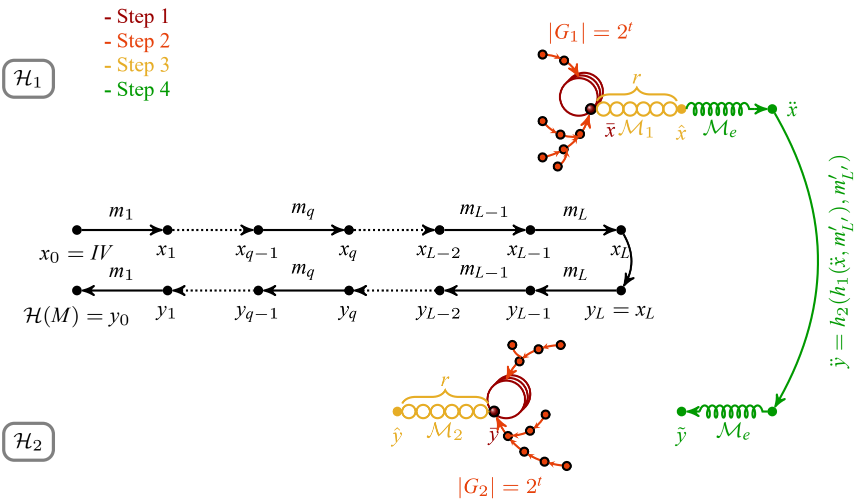
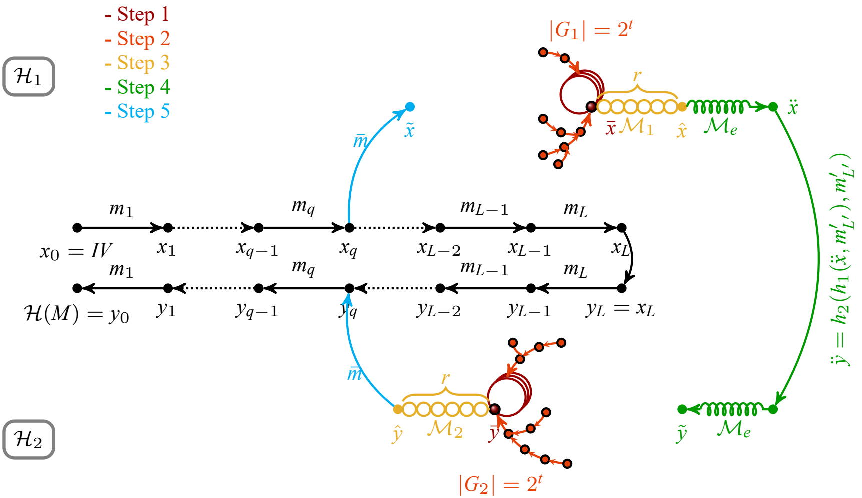
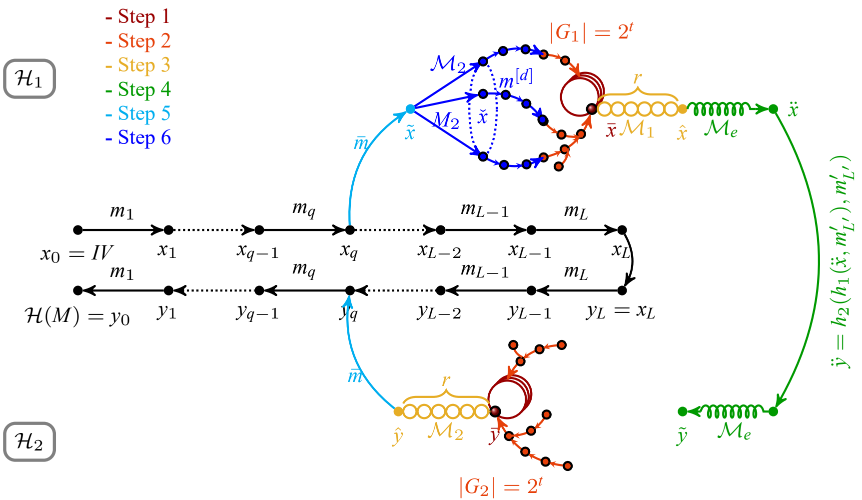


Second Preimage Attacks on Zipper Hash

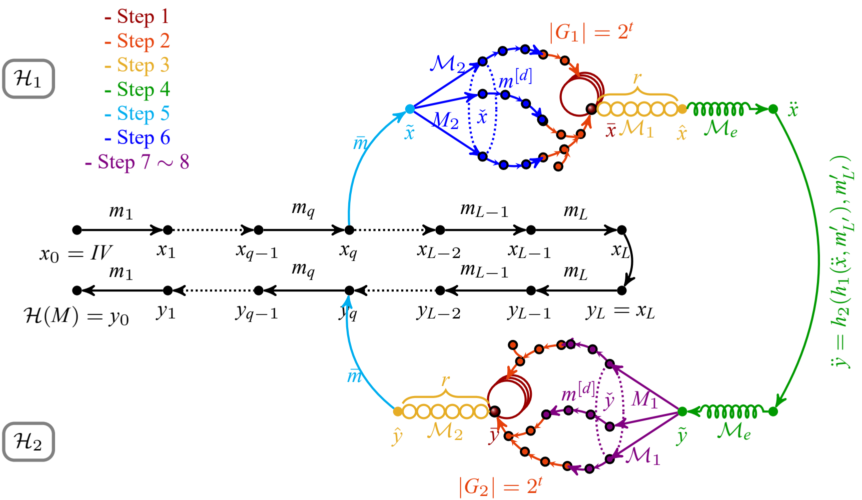


Second Preimage Attacks on Zipper Hash

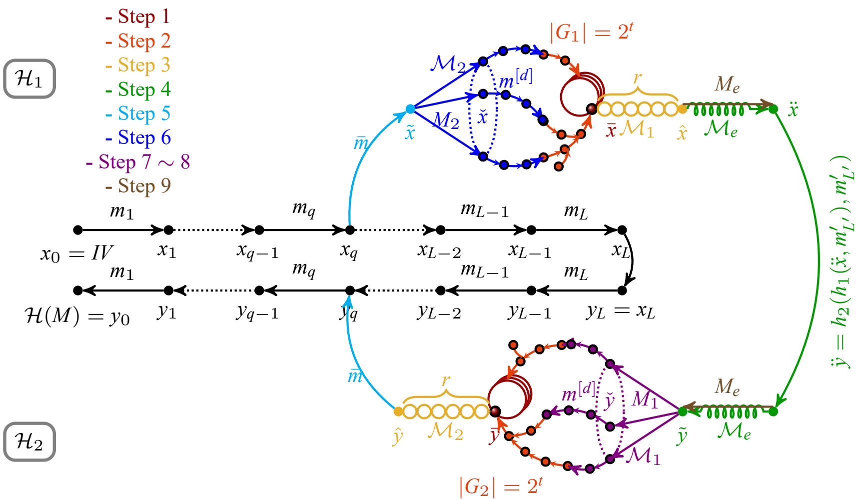


28/37

Second Preimage Attacks on Zipper Hash



Second Preimage Attacks on Zipper Hash



Upper Bounds vs Lower Bounds (Ignoring the factor n)

$\mathcal{H}_1 \Vert \mathcal{H}_2$	Collision Resistance	Preimage Resistance	2nd Preimage Resistance
Ideal	2^n	2^{2n}	2^{2n}
MD $\top$	([Jou04] JM) $2^{n/2}$	([Jou04] JM) 2^n	([Din16] SEM+FGDI) $2^{3n/4}$
MD $\perp$	$2^{n/2}$ [HS08]	$2^{n/2}$ [HS08]	$2^{n/2}$ [HS08]
HAIFA $\top$	([Jou04] JM) $2^{n/2}$	([Jou04] JM) 2^n	([Jou04] JM) 2^n
HAIFA $\perp$	$2^{n/2}$ [HS08]	$2^{n/2}$ [HS08]	$2^{n/2}$ [HS08]

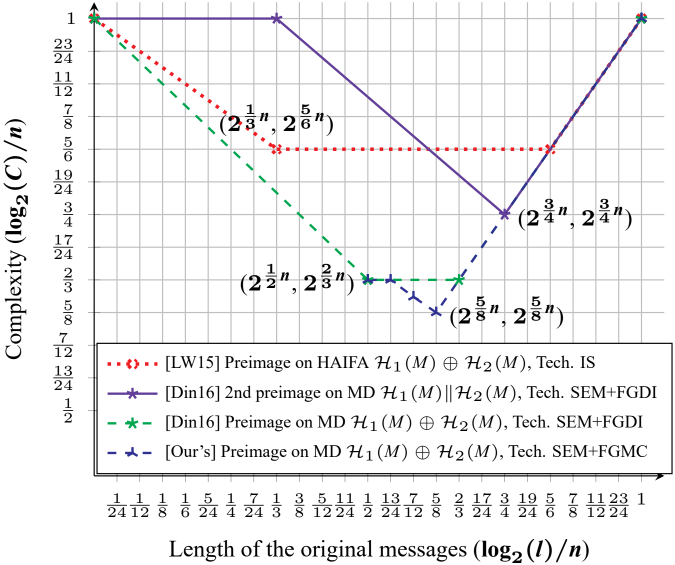
$\mathcal{H}_1 \oplus \mathcal{H}_2$	Collision Resistance	Preimage Resistance	2nd Preimage Resistance
Ideal	$2^{n/2}$	2^n	2^n
MD $\top$	Birthday $2^{n/2}$	([Din16] SEM+FGDI) $2^{2n/3}$ ([Our's] SEM+FGMC) $2^{5n/8}$	([Din16] SEM+FGDI) $2^{2n/3}$ ([Our's] SEM+FGMC) $2^{5n/8}$
MD $\perp$	$2^{n/2}$ [HS08]	$2^{n/2}$ [HS08]	$2^{n/2}$ [HS08]
HAIFA $\top$	Birthday $2^{n/2}$	([LW15] IS) $2^{5n/6}$	([LW15] IS) $2^{5n/6}$
HAIFA $\perp$	$2^{n/2}$ [HS08]	$2^{n/2}$ [HS08]	$2^{n/2}$ [HS08]

Upper Bounds vs Lower Bounds (Ignoring the factor n)

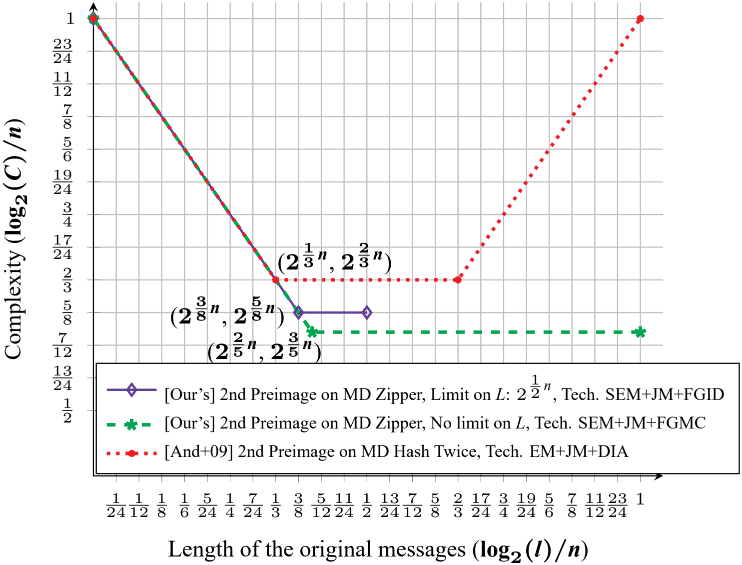
Hash Twice	Collision Resistance	Preimage Resistance	2nd Preimage Resistance
Ideal $\top$	$2^{n/2}$	2^n	2^n
MD $\top$	$2^{n/2}$	2^n	([And+09] EM+JM+DIA) $2^{2n/3}$
MD $\perp$	$2^{n/2}$	$2^{n/2}$	$2^{n/2}$
HAIFA $\top$	$2^{n/2}$	2^n	2^n
HAIFA $\perp$	$2^{n/2}$	$2^{n/2}$	$2^{n/2}$

Zipper Hash	Collision Resistance	Preimage Resistance	2nd Preimage Resistance
Ideal $\top$	$2^{n/2}$	2^n	2^n
MD $\top$	$2^{n/2}$	2^n	([Our's] SEM+JM+FGMC) $2^{3n/5}$
MD $\perp$	$2^{\min(m,n)}$	$2^{\min(m,n)}$ [Lis07]	$2^{\min(m,n)}$ [Lis07]
HAIFA $\top$	$2^{n/2}$	2^n	2^n
HAIFA $\perp$	$2^{\min(m,n)}$	$2^{\min(m,n)}$ [Lis07]	$2^{\min(m,n)}$ [Lis07]

Trade-offs Between the Message Length and the Attack Complexity



Trade-offs Between the Message Length and the Attack Complexity



Thanks for your attention!

References I

[Mer90] Ralph C. Merkle. "One Way Hash Functions and DES". In: *Advances in Cryptology — CRYPTO' 89 Proceedings*. Ed. by Gilles Brassard. Vol. 435. Lecture Notes in Computer Science. New York, NY: Springer New York, 1990, pp. 428–446. ISBN: 978-0-387-34805-6. DOI: 10.1007/0-387-34805-0_40. URL: http://dx.doi.org/10.1007/0-387-34805-0_40.

[Dam90] Ivan Bjerre Damgård. "A Design Principle for Hash Functions". In: *Advances in Cryptology — CRYPTO' 89 Proceedings*. Ed. by Gilles Brassard. Vol. 435. Lecture Notes in Computer Science. New York, NY: Springer New York, 1990, pp. 416–427. ISBN: 978-0-387-34805-6. DOI: 10.1007/0-387-34805-0_39. URL: http://dx.doi.org/10.1007/0-387-34805-0_39.

[Lis07] Moses Liskov. "Constructing an Ideal Hash Function from Weak Ideal Compression Functions". In: *Selected Areas in Cryptography: 13th International Workshop, SAC 2006, Montreal, Canada, August 17-18, 2006 Revised Selected Papers*. Ed. by Eli Biham and Amr M. Youssef. Vol. 4356. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer Berlin Heidelberg, 2007, pp. 358–375. ISBN: 978-3-540-74462-7. DOI: 10.1007/978-3-540-74462-7_25. URL: http://dx.doi.org/10.1007/978-3-540-74462-7_25.

[Jou04] Antoine Joux. "Multicollisions in Iterated Hash Functions. Application to Cascaded Constructions". In: *Advances in Cryptology – CRYPTO 2004: 24th Annual International Cryptology Conference, Santa Barbara, California, USA, August 15-19, 2004. Proceedings*. Ed. by Matt Franklin. Vol. 3152. Lecture Notes in Computer Science (LNCS). Berlin, Heidelberg: Springer Berlin Heidelberg, 2004, pp. 306–316. ISBN: 978-3-540-28628-8. DOI: 10.1007/978-3-540-28628-8_19. URL: http://dx.doi.org/10.1007/978-3-540-28628-8_19.

[KS05] John Kelsey and Bruce Schneier. "Second Preimages on n-Bit Hash Functions for Much Less than 2^n Work". In: *Advances in Cryptology – EUROCRYPT 2005: 24th Annual International Conference on the Theory and Applications of Cryptographic Techniques, Aarhus, Denmark, May 22-26, 2005. Proceedings*. Ed. by Ronald Cramer. Vol. 3494. Lecture Notes in Computer Science (LNCS). Berlin, Heidelberg: Springer Berlin Heidelberg, 2005, pp. 474–490. ISBN: 978-3-540-32055-5. DOI: 10.1007/11426639_28. URL: http://dx.doi.org/10.1007/11426639_28.

[Din16] Itai Dinur. "New Attacks on the Concatenation and XOR Hash Combiners". In: *Advances in Cryptology – EUROCRYPT 2016: 35th Annual International Conference on the Theory and Applications of Cryptographic Techniques, Vienna, Austria, May 8-12, 2016, Proceedings, Part I*. Ed. by Marc Fischlin and Jean-Sébastien Coron. Vol. 9665. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer Berlin Heidelberg, 2016, pp. 484–508. ISBN: 978-3-662-49890-3. DOI: 10.1007/978-3-662-49890-3_19. URL: http://dx.doi.org/10.1007/978-3-662-49890-3_19.

[PSW12] Thomas Peyrin, Yu Sasaki, and Lei Wang. "Generic Related-Key Attacks for HMAC". In: *Advances in Cryptology – ASIACRYPT 2012: 18th International Conference on the Theory and Application of Cryptology and Information Security, Beijing, China, December 2-6, 2012. Proceedings*. Ed. by Xiaoyun Wang and Kazue Sako. Vol. 7658. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer Berlin Heidelberg, 2012, pp. 580–597. ISBN: 978-3-642-34961-4. DOI: 10.1007/978-3-642-34961-4_35. URL: http://dx.doi.org/10.1007/978-3-642-34961-4_35.

[LPW13] Gaëtan Leurent, Thomas Peyrin, and Lei Wang. "New Generic Attacks against Hash-Based MACs". In: *Advances in Cryptology - ASIACRYPT 2013: 19th International Conference on the Theory and Application of Cryptology and Information Security, Bengaluru, India, December 1-5, 2013, Proceedings, Part II*. Ed. by Kazue Sako and Palash Sarkar. Vol. 8270. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer Berlin Heidelberg, 2013, pp. 1–20. ISBN: 978-3-642-42045-0. DOI: 10.1007/978-3-642-42045-0_1. URL: http://dx.doi.org/10.1007/978-3-642-42045-0_1.

[PW14] Thomas Peyrin and Lei Wang. "Generic Universal Forgery Attack on Iterative Hash-Based MACs". In: *Advances in Cryptology – EUROCRYPT 2014: 33rd Annual International Conference on the Theory and Applications of Cryptographic Techniques, Copenhagen, Denmark, May 11-15, 2014. Proceedings*. Ed. by Phong Q. Nguyen and Elisabeth Oswald. Vol. 8441. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer Berlin Heidelberg, 2014, pp. 147–164. ISBN: 978-3-642-55220-5. DOI: 10.1007/978-3-642-55220-5_9. URL: http://dx.doi.org/10.1007/978-3-642-55220-5_9.

References III

[Guo+14] Jian Guo et al. "Updates on Generic Attacks against HMAC and NMAC". In: *Advances in Cryptology – CRYPTO 2014: 34th Annual Cryptology Conference, Santa Barbara, CA, USA, August 17-21, 2014, Proceedings, Part I*. Ed. by Juan A. Garay and Rosario Gennaro. Vol. 8616. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer Berlin Heidelberg, 2014, pp. 131–148. ISBN: 978-3-662-44371-2. DOI: 10.1007/978-3-662-44371-2_8. URL: http://dx.doi.org/10.1007/978-3-662-44371-2_8.

[DL14] Itai Dinur and Gaëtan Leurent. "Improved Generic Attacks against Hash-Based MACs and HAIFA". In: *Advances in Cryptology – CRYPTO 2014: 34th Annual Cryptology Conference, Santa Barbara, CA, USA, August 17-21, 2014, Proceedings, Part I*. Ed. by Juan A. Garay and Rosario Gennaro. Vol. 8616. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer Berlin Heidelberg, 2014, pp. 149–168. ISBN: 978-3-662-44371-2. DOI: 10.1007/978-3-662-44371-2_9. URL: http://dx.doi.org/10.1007/978-3-662-44371-2_9.

[FO90] Philippe Flajolet and Andrew M. Odlyzko. "Random Mapping Statistics". In: *Advances in Cryptology — EUROCRYPT '89: Workshop on the Theory and Application of Cryptographic Techniques Houthalen, Belgium, April 10–13, 1989 Proceedings*. Ed. by Jean-Jacques Quisquater and Joos Vandewalle. Vol. 434. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer Berlin Heidelberg, 1990, pp. 329–354. ISBN: 978-3-540-46885-1. DOI: 10.1007/3-540-46885-4_34. URL: http://dx.doi.org/10.1007/3-540-46885-4_34.

[HS08] Jonathan J. Hoch and Adi Shamir. "On the Strength of the Concatenated Hash Combiner When All the Hash Functions Are Weak". In: *Automata, Languages and Programming: 35th International Colloquium, ICALP 2008, Reykjavik, Iceland, July 7-11, 2008, Proceedings, Part II*. Ed. by Luca Aceto et al. Vol. 5126. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer Berlin Heidelberg, 2008, pp. 616–630. ISBN: 978-3-540-70583-3. DOI: 10.1007/978-3-540-70583-3_50. URL: http://dx.doi.org/10.1007/978-3-540-70583-3_50.

References IV

[LW15] Gaëtan Leurent and Lei Wang. "The Sum Can Be Weaker Than Each Part". In: *Advances in Cryptology – EUROCRYPT 2015: 34th Annual International Conference on the Theory and Applications of Cryptographic Techniques, Sofia, Bulgaria, April 26-30, 2015, Proceedings, Part I*. Ed. by Elisabeth Oswald and Marc Fischlin. Vol. 9056. Lecture Notes in Computer Science. Berlin, Heidelberg: Springer Berlin Heidelberg, 2015, pp. 345–367. ISBN: 978-3-662-46800-5. DOI: `10.1007/978-3-662-46800-5_14`. URL: `http://dx.doi.org/10.1007/978-3-662-46800-5_14`.

[And+09] Elena Andreeva et al. "Herding, Second Preimage and Trojan Message Attacks beyond Merkle-Damgård". In: *Selected Areas in Cryptography: 16th Annual International Workshop, SAC 2009, Calgary, Alberta, Canada, August 13-14, 2009, Revised Selected Papers*. Ed. by Michael J. Jacobson, Vincent Rijmen, and Reihaneh Safavi-Naini. Vol. 5867. Lecture Notes in Computer Science (LNCS). Berlin, Heidelberg: Springer Berlin Heidelberg, 2009, pp. 393–414. ISBN: 978-3-642-05445-7. DOI: `10.1007/978-3-642-05445-7_25`. URL: `http://dx.doi.org/10.1007/978-3-642-05445-7_25`.