Practical Collisions for EnRUPT

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Fast Software Encryption 2009

Outline

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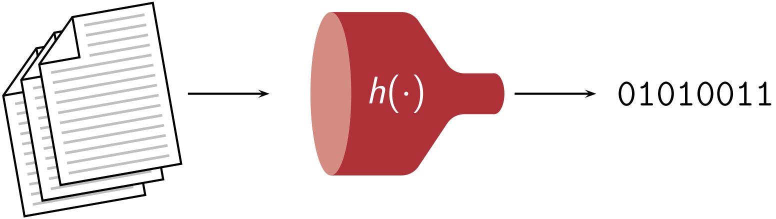
1. Introduction
2. Description of EnRUPT
3. Attacking EnRUPT
4. Results
5. Conclusion

Cryptographic Hash Functions



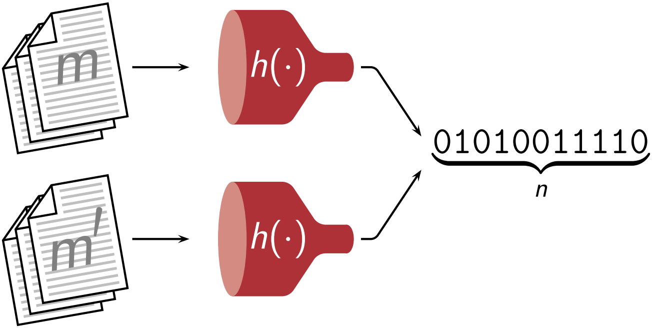
$$h : \{0,1\}^* \mapsto \{0,1\}^w$$

Desired properties

- Collision resistance, (Second) preimage resistance, . . .
- Efficiently computable, *i.e.*, fast!

Cryptographic Hash Functions

Collision Resistance



- "Hard" to find $m \neq m'$ s.t. $h(m) = h(m')$.
- Birthday paradox $\mathcal{O}(2^{n/2})$

EnRUPT

EnRUPT

- SHA-3 round 1 candidate
- Sean O'Neil, Karsten Nohl, Luca Henzen [ONH08]
- Many parameters, **7 concrete proposals**

This talk

None of the 7 proposed EnRUPT variants is collision resistant

Outline

Description of EnRUPT

EnRUPT variant	digest length h	word size w	parallelisation level P	security parameter s	number of state words H
EnRUPT-128	128 bits	32 bits	2	4	8
EnRUPT-160	160 bits	32 bits	2	4	10
EnRUPT-192	192 bits	32 bits	2	4	12
EnRUPT-224	224 bits	64 bits	2	4	8
EnRUPT-256	256 bits	64 bits	2	4	8
EnRUPT-384	384 bits	64 bits	2	4	12
EnRUPT-512	512 bits	64 bits	2	4	16

Description of EnRUPT

1. **Initialisation**
   - Set internal state $\langle \mathbf{d[P], x[H], r} \rangle$
2. **Message Processing**
   - Process each or w-bit message word just once
   - No message expansion, message block schedule, ...
   - Uses the **round function**
3. **Finalisation**
   - Generate message digest from internal state

Round Function

function round $(\langle d[P], x[H], r\rangle, m)$

  for $i = 0$ to $s \cdot P - 1$ **do**

    $\alpha \leftarrow r + (i + 1 \bmod P) \bmod H$

    $\beta \leftarrow r + i + 2P \bmod H$

    $\gamma \leftarrow r + i + P \bmod H$

    $\xi \leftarrow r + i \bmod H$

    $e \leftarrow ((x[\alpha] \lll 1) \oplus x[\beta] \oplus d[i \bmod P] \oplus \mathrm{uint}_w(r + i)) \ggg w/4$

    $f \leftarrow (e \lll 3) \boxplus e$

    $x_\gamma \leftarrow x_\gamma \oplus f$

    $d[i \bmod P] \leftarrow d[i \bmod P] \oplus x[\xi] \oplus f$

  end for

  $d_{P-1} \leftarrow d_{P-1} \oplus m$

  $r \leftarrow r + s \cdot P$

  return $\langle d[P], x[H], r\rangle$

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Outline

Attacking EnRUPT

Observation

- EnRUPT is **GF(2)-linear** except $\begin{cases} f & \leftarrow & e \boxplus (e \lll 3) \\ & \text{or} & \\ f & \leftarrow & e \times 9 \end{cases}$

Attack strategy

1. Find a **linear approximation**
2. Find a **differential characteristic**
3. Find a **conforming pair**

Similar to [CJ98] on SHA-0 and [RO05, PRR05] on SHA-1

Linear Approximation of EnRUPT

EnRUPT-$\mathcal{L}$

- Replace all non-linear $\boxplus$ by linear $\oplus$
  - i.e., ignore the carries

- Restrict to some fixed message length $t \cdot w$

$$\text{EnRUPT-}\mathcal{L}(m) = [o]_{1\times h} = [m]_{1\times tw} \cdot [\mathbf{O}]_{tw\times h}$$

- Differentials?

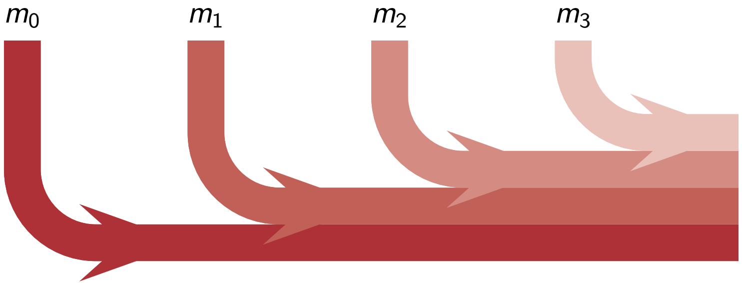
$$[\Delta o]_{1\times h} = [\Delta m]_{1\times tw} \cdot [\mathbf{O}]_{tw\times h}$$

“Good” Differential Characteristic, pt. I

- What is a **“good”** differential characteristic?
- Let’s skip this for now. . .

Round	Step	Δe	$\rightarrow$	Δf
inject message word difference $\Delta m_{-1} = 0000000008000000_x$				
0	0	0000000000000000_x	$\rightarrow$	0000000000000000_x
	1	0000000000000800_x	$\rightarrow$	0000000000004800_x
	2	9000000000000000_x	$\rightarrow$	1000000000000000_x
	3	4800000000000800_x	$\rightarrow$	0800000000004800_x
	4	9000000000000000_x	$\rightarrow$	1000000000000000_x
	5	4800280000000800_x	$\rightarrow$	0801680000004800_x
	6	$90000002d0000000_x$	$\rightarrow$	1000001450000000_x
	7	0000280168000800_x	$\rightarrow$	$0001680a28004800_x$
inject message word difference $\Delta m_0 = 0000002280000000_x$				
1	0	$90000002d0000000_x$	$\rightarrow$	1000001450000000_x
	1	0000280168000000_x	$\rightarrow$	$0001680a28000000_x$
	2	$90000002d0000000_x$	$\rightarrow$	1000001450000000_x

Finding a Conforming Pair
Observation

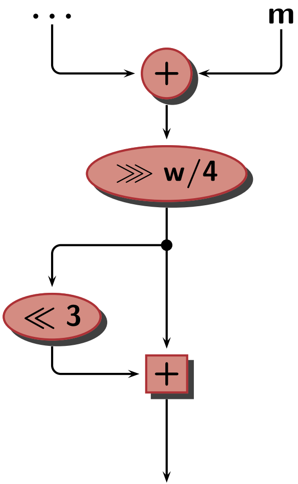


Observation

- Each message word is used only once
- New freedom in every round
- Search **round per round**

Finding a Conforming Pair

Finding it Faster



Message modification

- First step of a round **for free**!

Finding a Conforming Pair

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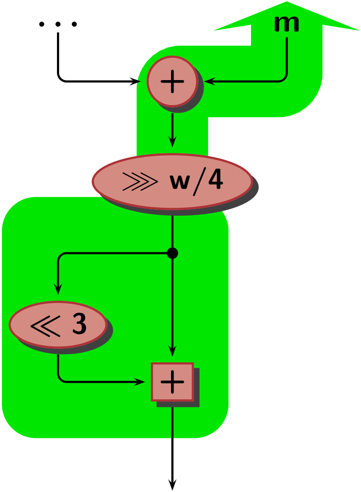

Message modification

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Finding a Conforming Pair
Round Complexities?

Need to estimate/compute $\mathrm{DP}^{\times 9}$

First Attempt

- $\mathbf{x \times 9 = x \boxplus (x << 3)}$
- Could use [LM01] to estimate $\mathrm{DP}^{\times 9}$:

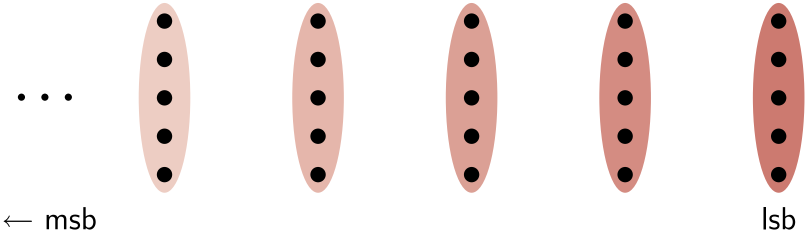
$$\mathrm{DP}^{\times 9}(\Delta) \approx 2^{-\mathrm{wt}\left(\left(\Delta \vee (\Delta \ll 3)\right) \wedge \mathrm{bin}\, 01\cdots 1000\right)}$$

(after simplification)

Finding a Conforming Pair

Round Complexities?

- Compact representation of $\mathbf{x} + (\mathbf{x} \lll 3)$ and $\mathbf{x}' + (\mathbf{x}' \lll 3)$ where $\mathbf{x}' = \mathbf{x} \oplus \mathbf{\Delta}$ in a **trellis**
- 2^5 nodes per segment $(c_i, c'_i, x_{i-2}, x_{i-1}, x_i)$



- Can quickly count paths, and thus compute $\mathbf{DP}^{\times 9}$ **exactly** using the Viterbi algorithm (modified)

Finding a Conforming Pair

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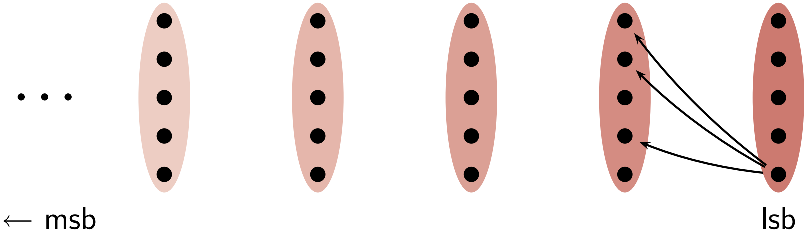

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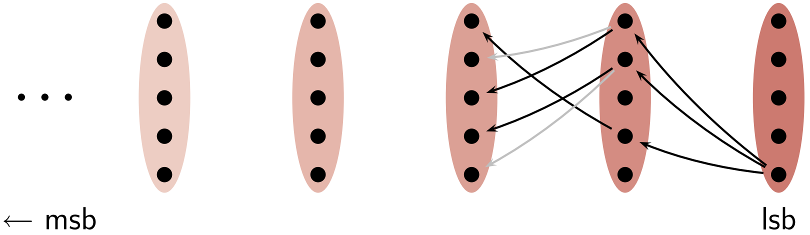

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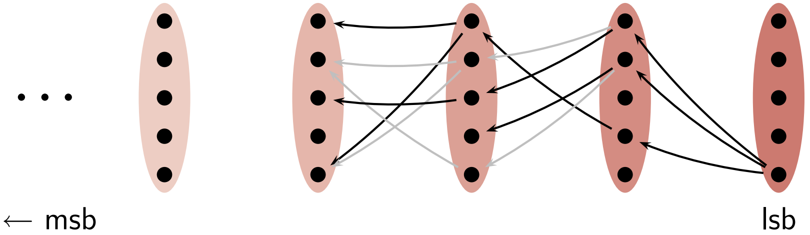

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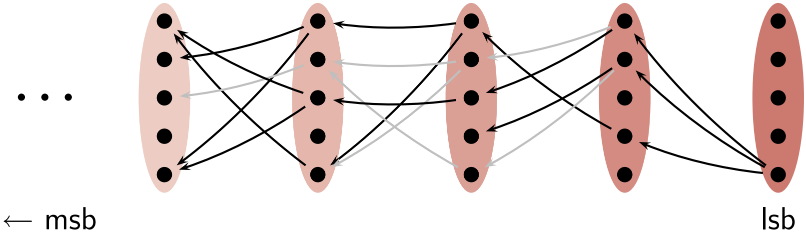

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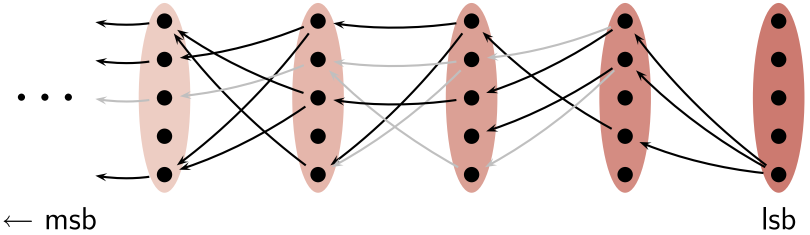

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“Good” Differential Characteristic, pt. II

Let’s Summarise

- Low Hamming weight in Δe is good
- Can easily compute attack complexity, incl. *tricks*

A Different View: Coding Theory

- All linearised differentials are **codewords** of a linear code.

$$\mathbf{G} = \left[\ \mathbf{I}_{tw \times tw} \ \middle| \ \mathbf{E}_{tw \times tsPw} \ \middle| \ \mathbf{O}_{tw \times h} \ \right]$$

- Low weight codewords [RO05, PRR05]

“Good” Differential Characteristic, pt. II

- But low weight is just a **heuristic**
- Use the **actual attack complexity** in an algorithm for finding low weight codewords (similar to [CC98])
- Simplified:

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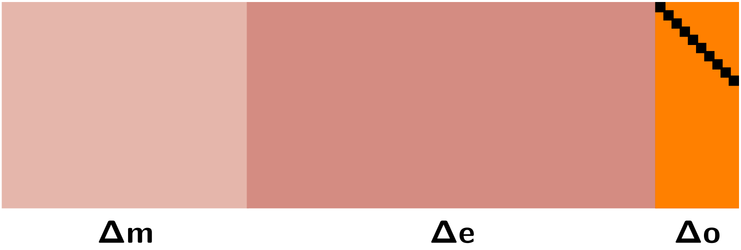
G = 

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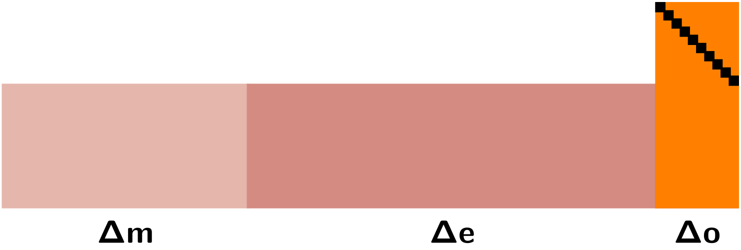
$\mathbf{G} =$ 

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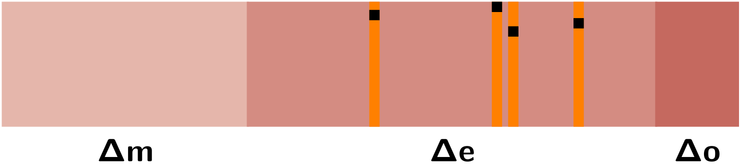
$\mathbf{G} =$ 

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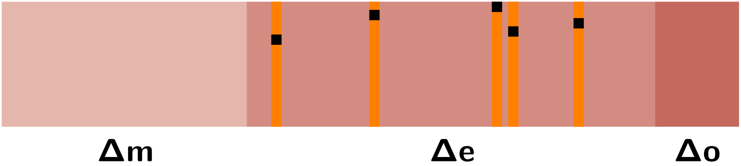
$\mathbf{G} =$ 

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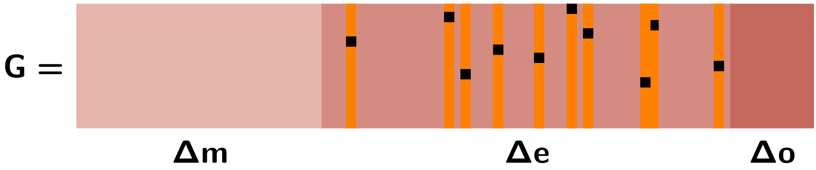

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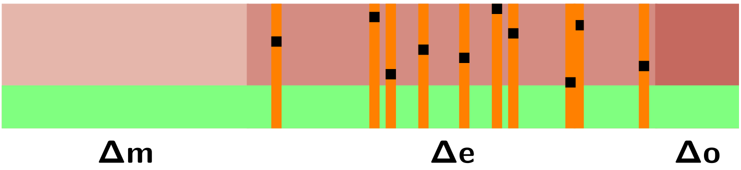
G = 

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Results

variant	time complexity	message length
EnRUPT-128	$2^{36.04}$	6
EnRUPT-160	$2^{37.78}$	7
EnRUPT-192	$2^{38.33}$	8
EnRUPT-224	$2^{37.02}$	6
EnRUPT-256	$2^{37.02}$	6
EnRUPT-384	$2^{39.63}$	8
EnRUPT-512	$2^{38.46}$	10

Example: EnRUPT-256

Round	Step	Δe	$\rightarrow$	Δf	$\mathrm{DP}^{\times 9}$	totals
inject message word difference $\Delta m_{-1} = 0000000008000000_x$						
0	0	0000000000000000_x	$\rightarrow$	0000000000000000_x	$2^{-0.00}$	$\mathbf{2^{-0.00}}$
	1	0000000000000800_x	$\rightarrow$	0000000000004800_x	$\star$	
	2	9000000000000000_x	$\rightarrow$	1000000000000000_x	$2^{-0.85}$	
	3	4800000000000800_x	$\rightarrow$	0800000000004800_x	$2^{-3.70}$	
	4	9000000000000000_x	$\rightarrow$	1000000000000000_x	$2^{-0.85}$	
	5	4800280000000800_x	$\rightarrow$	0801680000004800_x	$2^{-7.28}$	
	6	$90000002d0000000_x$	$\rightarrow$	1000001450000000_x	$2^{-6.43}$	
	7	0000280168000800_x	$\rightarrow$	$0001680a28004800_x$	$2^{-11.02}$	
inject message word difference $\Delta m_0 = 0000002280000000_x$						
1	0	$90000002d0000000_x$	$\rightarrow$	1000001450000000_x	$2^{-6.43}$	$\mathbf{2^{-36.56}}$
	1	0000280168000000_x	$\rightarrow$	$0001680a28000000_x$	$\star$	
	2	$90000002d0000000_x$	$\rightarrow$	1000001450000000_x	$2^{-6.43}$	
	3	4800280000000000_x	$\rightarrow$	0801680000000000_x	$2^{-5.43}$	
	4	$90000002d0000000_x$	$\rightarrow$	1000001450000000_x	$2^{-6.43}$	
	5	0000080000000000_x	$\rightarrow$	0000480000000000_x	$2^{-1.85}$	

Example: EnRUPT-256

inject message word difference $\Delta m_{-1} = 0000000008000000_x$						
0	0	0000000000000000_x	$\rightarrow$	0000000000000000_x	$2^{-0.00}$	$\mathbf{2^{-0.00}}$
	1	0000000000000800_x	$\rightarrow$	0000000000004800_x	$\star$	
	2	9000000000000000_x	$\rightarrow$	1000000000000000_x	$2^{-0.85}$	
	3	4800000000000800_x	$\rightarrow$	0800000000004800_x	$2^{-3.70}$	
	4	9000000000000000_x	$\rightarrow$	1000000000000000_x	$2^{-0.85}$	
	5	4800280000000800_x	$\rightarrow$	0801680000004800_x	$2^{-7.28}$	
	6	$90000002d0000000_x$	$\rightarrow$	1000001450000000_x	$2^{-6.43}$	
	7	0000280168000800_x	$\rightarrow$	$0001680a28004800_x$	$2^{-11.02}$	
inject message word difference $\Delta m_0 = 0000002280000000_x$						
1	0	$90000002d0000000_x$	$\rightarrow$	1000001450000000_x	$2^{-6.43}$	$\mathbf{2^{-36.56}}$
	1	0000280168000000_x	$\rightarrow$	$0001680a28000000_x$	$\star$	
	2	$90000002d0000000_x$	$\rightarrow$	1000001450000000_x	$2^{-6.43}$	
	3	4800280000000000_x	$\rightarrow$	0801680000000000_x	$2^{-5.43}$	
	4	$90000002d0000000_x$	$\rightarrow$	1000001450000000_x	$2^{-6.43}$	
	5	0000080000000000_x	$\rightarrow$	0000480000000000_x	$2^{-1.85}$	
	6	9000000240000000_x	$\rightarrow$	1000001040000000_x	$2^{-3.70}$	
	7	4800080120000000	$\rightarrow$	0800480820000000	$2^{-6.54}$	

Example: EnRUPT-256

	1	0000000000000800$_x$	$\longrightarrow$	0000000000004800$_x$	$\star$	
	2	9000000000000000$_x$	$\longrightarrow$	1000000000000000$_x$	$2^{-0.85}$	
	3	4800000000000800$_x$	$\longrightarrow$	0800000000004800$_x$	$2^{-3.70}$	
	4	9000000000000000$_x$	$\longrightarrow$	1000000000000000$_x$	$2^{-0.85}$	
	5	4800280000000800$_x$	$\longrightarrow$	0801680000004800$_x$	$2^{-7.28}$	
	6	90000002d0000000$_x$	$\longrightarrow$	1000001450000000$_x$	$2^{-6.43}$	
	7	0000280168000800$_x$	$\longrightarrow$	0001680a28004800$_x$	$2^{-11.02}$	
inject message word difference $\Delta m_0 =$ 0000002280000000$_x$						
1	0	90000002d0000000$_x$	$\longrightarrow$	1000001450000000$_x$	$2^{-6.43}$	$\mathbf{2^{-36.56}}$
	1	0000280168000000$_x$	$\longrightarrow$	0001680a28000000$_x$	$\star$	
	2	90000002d0000000$_x$	$\longrightarrow$	1000001450000000$_x$	$2^{-6.43}$	
	3	4800280000000000$_x$	$\longrightarrow$	0801680000000000$_x$	$2^{-5.43}$	
	4	90000002d0000000$_x$	$\longrightarrow$	1000001450000000$_x$	$2^{-6.43}$	
	5	0000080000000000$_x$	$\longrightarrow$	0000480000000000$_x$	$2^{-1.85}$	
	6	9000000240000000$_x$	$\longrightarrow$	1000001040000000$_x$	$2^{-3.70}$	
	7	4800080120000000$_x$	$\longrightarrow$	0800480820000000$_x$	$2^{-6.54}$	
inject message word difference $\Delta m_1 =$ 0000002288000000$_x$						
2	0	9000000240000000$_x$	$\longrightarrow$	1000001040000000$_x$	$2^{-3.70}$	$\mathbf{2^{-34.08}}$

Example: EnRUPT-256

	3	4800000000000800$_x$	$\rightarrow$	0800000000004800$_x$	2	
	4	9000000000000000$_x$	$\rightarrow$	1000000000000000$_x$	$2^{-0.85}$	
	5	4800280000000800$_x$	$\rightarrow$	0801680000004800$_x$	$2^{-7.28}$	
	6	90000002d0000000$_x$	$\rightarrow$	1000001450000000$_x$	$2^{-6.43}$	
	7	0000280168000800$_x$	$\rightarrow$	0001680a28004800$_x$	$2^{-11.02}$	
inject message word difference Δm_0 = 0000002280000000$_x$						
1	0	90000002d0000000$_x$	$\rightarrow$	1000001450000000$_x$	$2^{-6.43}$	$\mathbf{2^{-36.56}}$
	1	0000280168000000$_x$	$\rightarrow$	0001680a28000000$_x$	$\star$	
	2	90000002d0000000$_x$	$\rightarrow$	1000001450000000$_x$	$2^{-6.43}$	
	3	4800280000000000$_x$	$\rightarrow$	0801680000000000$_x$	$2^{-5.43}$	
	4	90000002d0000000$_x$	$\rightarrow$	1000001450000000$_x$	$2^{-6.43}$	
	5	0000080000000000$_x$	$\rightarrow$	0000480000000000$_x$	$2^{-1.85}$	
	6	9000000240000000$_x$	$\rightarrow$	1000001040000000$_x$	$2^{-3.70}$	
	7	4800080120000000$_x$	$\rightarrow$	0800480820000000$_x$	$2^{-6.54}$	
inject message word difference Δm_1 = 0000002288000000$_x$						
2	0	9000000240000000$_x$	$\rightarrow$	1000001040000000$_x$	$2^{-3.70}$	$\mathbf{2^{-34.08}}$
	1	0000080048000000$_x$	$\rightarrow$	0000480208000000$_x$	$\star$	
	2	9000000240000000$_x$	$\rightarrow$	1000001040000000$_x$	$2^{-3.70}$	

Example: EnRUPT-256

	[illegible]	[illegible]	→	[illegible]	[illegible]	
	6	$90000002d0000000_x$	→	1000001450000000_x	$2^{-6.43}$	
	7	0000280168000800_x	→	$0001680a28004800_x$	$2^{-11.02}$	
inject message word difference $\Delta m_0 = 0000002280000000_x$						
1	0	$90000002d0000000_x$	→	1000001450000000_x	$2^{-6.43}$	$\mathbf{2^{-36.56}}$
	1	0000280168000000_x	→	$0001680a28000000_x$	⋆	
	2	$90000002d0000000_x$	→	1000001450000000_x	$2^{-6.43}$	
	3	4800280000000000_x	→	0801680000000000_x	$2^{-5.43}$	
	4	$90000002d0000000_x$	→	1000001450000000_x	$2^{-6.43}$	
	5	0000080000000000_x	→	0000480000000000_x	$2^{-1.85}$	
	6	9000000240000000_x	→	1000001040000000_x	$2^{-3.70}$	
	7	4800080120000000_x	→	0800480820000000_x	$2^{-6.54}$	
inject message word difference $\Delta m_1 = 0000002288000000_x$						
2	0	9000000240000000_x	→	1000001040000000_x	$2^{-3.70}$	$\mathbf{2^{-34.08}}$
	1	0000080048000000_x	→	0000480208000000_x	⋆	
	2	9000000240000000_x	→	1000001040000000_x	$2^{-3.70}$	
	3	4800080168000000_x	→	$0800480a28000000_x$	$2^{-9.28}$	
	4	9000000240000000_x	→	1000001040000000_x	$2^{-3.70}$	

Example: EnRUPT-256

inject message word difference $\Delta m_0 = 0000002280000000_x$						
1	0	$90000002d0000000_x$	$\rightarrow$	1000001450000000_x	$2^{-6.43}$	$\mathbf{2^{-36.56}}$
	1	0000280168000000_x	$\rightarrow$	$0001680a28000000_x$	$\star$	
	2	$90000002d0000000_x$	$\rightarrow$	1000001450000000_x	$2^{-6.43}$	
	3	4800280000000000_x	$\rightarrow$	0801680000000000_x	$2^{-5.43}$	
	4	$90000002d0000000_x$	$\rightarrow$	1000001450000000_x	$2^{-6.43}$	
	5	0000080000000000_x	$\rightarrow$	0000480000000000_x	$2^{-1.85}$	
	6	9000000240000000_x	$\rightarrow$	1000001040000000_x	$2^{-3.70}$	
	7	4800080120000000_x	$\rightarrow$	0800480820000000_x	$2^{-6.54}$	
inject message word difference $\Delta m_1 = 0000002288000000_x$						
2	0	9000000240000000_x	$\rightarrow$	1000001040000000_x	$2^{-3.70}$	$\mathbf{2^{-34.08}}$
	1	0000080048000000_x	$\rightarrow$	0000480208000000_x	$\star$	
	2	9000000240000000_x	$\rightarrow$	1000001040000000_x	$2^{-3.70}$	
	3	4800080168000000_x	$\rightarrow$	$0800480a28000000_x$	$2^{-9.28}$	
	4	9000000240000000_x	$\rightarrow$	1000001040000000_x	$2^{-3.70}$	
	5	0000200000000000_x	$\rightarrow$	0001200000000000_x	$2^{-1.85}$	
	6	9000000000000000_x	$\rightarrow$	1000000000000000_x	$2^{-0.85}$	

Example: EnRUPT-256

	1	0000280168000000_x	$\longrightarrow$	$0001680a28000000_x$	$\star$	
	2	$90000002d0000000_x$	$\longrightarrow$	1000001450000000_x	$2^{-6.43}$	
	3	4800280000000000_x	$\longrightarrow$	0801680000000000_x	$2^{-5.43}$	
	4	$90000002d0000000_x$	$\longrightarrow$	1000001450000000_x	$2^{-6.43}$	
	5	0000080000000000_x	$\longrightarrow$	0000480000000000_x	$2^{-1.85}$	
	6	9000000240000000_x	$\longrightarrow$	1000001040000000_x	$2^{-3.70}$	
	7	4800080120000000_x	$\longrightarrow$	0800480820000000_x	$2^{-6.54}$	
inject message word difference $\Delta m_1 = 0000002288000000_x$						
2	0	9000000240000000_x	$\longrightarrow$	1000001040000000_x	$2^{-3.70}$	$\mathbf{2^{-34.08}}$
	1	0000080048000000_x	$\longrightarrow$	0000480208000000_x	$\star$	
	2	9000000240000000_x	$\longrightarrow$	1000001040000000_x	$2^{-3.70}$	
	3	4800080168000000_x	$\longrightarrow$	$0800480a28000000_x$	$2^{-9.28}$	
	4	9000000240000000_x	$\longrightarrow$	1000001040000000_x	$2^{-3.70}$	
	5	0000200000000000_x	$\longrightarrow$	0001200000000000_x	$2^{-1.85}$	
	6	9000000000000000_x	$\longrightarrow$	1000000000000000_x	$2^{-0.85}$	
	7	4800200000000000_x	$\longrightarrow$	0801200000000000_x	$2^{-3.70}$	
inject message word difference $\Delta m_2 = 0000000208000000_x$						

Example: EnRUPT-256

	3	4800280000000000_x	$\rightarrow$	0801680000000000_x	$2^{-5.43}$	
	4	$90000002d0000000_x$	$\rightarrow$	1000001450000000_x	$2^{-6.43}$	
	5	0000080000000000_x	$\rightarrow$	0000480000000000_x	$2^{-1.85}$	
	6	9000000240000000_x	$\rightarrow$	1000001040000000_x	$2^{-3.70}$	
	7	4800080120000000_x	$\rightarrow$	0800480820000000_x	$2^{-6.54}$	
inject message word difference $\Delta m_1 = 0000002288000000_x$						
2	0	9000000240000000_x	$\rightarrow$	1000001040000000_x	$2^{-3.70}$	$\mathbf{2^{-34.08}}$
	1	0000080048000000_x	$\rightarrow$	0000480208000000_x	$\star$	
	2	9000000240000000_x	$\rightarrow$	1000001040000000_x	$2^{-3.70}$	
	3	4800080168000000_x	$\rightarrow$	$0800480a28000000_x$	$2^{-9.28}$	
	4	9000000240000000_x	$\rightarrow$	1000001040000000_x	$2^{-3.70}$	
	5	0000200000000000_x	$\rightarrow$	0001200000000000_x	$2^{-1.85}$	
	6	9000000000000000_x	$\rightarrow$	1000000000000000_x	$2^{-0.85}$	
	7	4800200000000000_x	$\rightarrow$	0801200000000000_x	$2^{-3.70}$	
inject message word difference $\Delta m_2 = 0000000208000000_x$						
3	0	9000000000000000_x	$\rightarrow$	1000000000000000_x	$2^{-0.85}$	$\mathbf{2^{-23.91}}$
	1	0000280120000000_x	$\rightarrow$	0001680820000000_x	$\star$	

Example: EnRUPT-256

	5	0000080000000000_x	$\rightarrow$	0000480000000000_x	$2^{-1.85}$	
	6	9000000240000000_x	$\rightarrow$	1000001040000000_x	$2^{-3.70}$	
	7	4800080120000000_x	$\rightarrow$	0800480820000000_x	$2^{-6.54}$	
inject message word difference $\Delta m_1 = 0000002288000000_x$						
2	0	9000000240000000_x	$\rightarrow$	1000001040000000_x	$2^{-3.70}$	$\mathbf{2^{-34.08}}$
	1	0000080048000000_x	$\rightarrow$	0000480208000000_x	$\star$	
	2	9000000240000000_x	$\rightarrow$	1000001040000000_x	$2^{-3.70}$	
	3	4800080168000000_x	$\rightarrow$	$0800480a28000000_x$	$2^{-9.28}$	
	4	9000000240000000_x	$\rightarrow$	1000001040000000_x	$2^{-3.70}$	
	5	0000200000000000_x	$\rightarrow$	0001200000000000_x	$2^{-1.85}$	
	6	9000000000000000_x	$\rightarrow$	1000000000000000_x	$2^{-0.85}$	
	7	4800200000000000_x	$\rightarrow$	0801200000000000_x	$2^{-3.70}$	
inject message word difference $\Delta m_2 = 0000000208000000_x$						
3	0	9000000000000000_x	$\rightarrow$	1000000000000000_x	$2^{-0.85}$	$\mathbf{2^{-23.91}}$
	1	0000280120000000_x	$\rightarrow$	0001680820000000_x	$\star$	
	2	9000000090000000_x	$\rightarrow$	1000000410000000_x	$2^{-3.70}$	
	3	4800280168000000_x	$\rightarrow$	$0801680a28000000_x$	$2^{-11.02}$	

Example: EnRUPT-256

	7	4800080120000000_x	$\longrightarrow$	0800480820000000_x	$2^{-6.54}$	
inject message word difference $\Delta m_1 = 0000002288000000_x$						
2	0	9000000240000000_x	$\longrightarrow$	1000001040000000_x	$2^{-3.70}$	$\mathbf{2^{-34.08}}$
	1	0000080048000000_x	$\longrightarrow$	0000480208000000_x	$\star$	
	2	9000000240000000_x	$\longrightarrow$	1000001040000000_x	$2^{-3.70}$	
	3	4800080168000000_x	$\longrightarrow$	$0800480a28000000_x$	$2^{-9.28}$	
	4	9000000240000000_x	$\longrightarrow$	1000001040000000_x	$2^{-3.70}$	
	5	0000200000000000_x	$\longrightarrow$	0001200000000000_x	$2^{-1.85}$	
	6	9000000000000000_x	$\longrightarrow$	1000000000000000_x	$2^{-0.85}$	
	7	4800200000000000_x	$\longrightarrow$	0801200000000000_x	$2^{-3.70}$	
inject message word difference $\Delta m_2 = 0000000208000000_x$						
3	0	9000000000000000_x	$\longrightarrow$	1000000000000000_x	$2^{-0.85}$	$\mathbf{2^{-23.91}}$
	1	0000280120000000_x	$\longrightarrow$	0001680820000000_x	$\star$	
	2	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	
	3	4800280168000000_x	$\longrightarrow$	$0801680a28000000_x$	$2^{-11.02}$	
	4	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	
	5	0000080048000000_x	$\longrightarrow$	0000480208000000_x	$2^{-4.70}$	
	6	[illegible]	$\longrightarrow$	[illegible]	$2^{-3.70}$	

Example: EnRUPT-256

2	0	9000000240000000_x	$\longrightarrow$	1000001040000000_x	$2^{-3.70}$	$\mathbf{2^{-34.08}}$
	1	0000080048000000_x	$\longrightarrow$	0000480208000000_x	$\star$	
	2	9000000240000000_x	$\longrightarrow$	1000001040000000_x	$2^{-3.70}$	
	3	4800080168000000_x	$\longrightarrow$	$0800480a28000000_x$	$2^{-9.28}$	
	4	9000000240000000_x	$\longrightarrow$	1000001040000000_x	$2^{-3.70}$	
	5	0000200000000000_x	$\longrightarrow$	0001200000000000_x	$2^{-1.85}$	
	6	9000000000000000_x	$\longrightarrow$	1000000000000000_x	$2^{-0.85}$	
	7	4800200000000000_x	$\longrightarrow$	0801200000000000_x	$2^{-3.70}$	
inject message word difference $\Delta m_2 = 0000000208000000_x$						
3	0	9000000000000000_x	$\longrightarrow$	1000000000000000_x	$2^{-0.85}$	$\mathbf{2^{-23.91}}$
	1	0000280120000000_x	$\longrightarrow$	0001680820000000_x	$\star$	
	2	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	
	3	4800280168000000_x	$\longrightarrow$	$0801680a28000000_x$	$2^{-11.02}$	
	4	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	
	5	0000080048000000_x	$\longrightarrow$	0000480208000000_x	$2^{-4.70}$	
	6	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	
	7	4800080000000000_x	$\longrightarrow$	0800480000000000_x	$2^{-3.70}$	
inject message word difference [illegible]						

Example: EnRUPT-256

	2	9000000240000000_x	$\longrightarrow$	1000001040000000_x	$2^{-3.70}$	
	3	4800080168000000_x	$\longrightarrow$	$0800480a28000000_x$	$2^{-9.28}$	
	4	9000000240000000_x	$\longrightarrow$	1000001040000000_x	$2^{-3.70}$	
	5	0000200000000000_x	$\longrightarrow$	0001200000000000_x	$2^{-1.85}$	
	6	9000000000000000_x	$\longrightarrow$	1000000000000000_x	$2^{-0.85}$	
	7	4800200000000000_x	$\longrightarrow$	0801200000000000_x	$2^{-3.70}$	
inject message word difference $\Delta m_2 = 0000000208000000_x$						
3	0	9000000000000000_x	$\longrightarrow$	1000000000000000_x	$2^{-0.85}$	$\mathbf{2^{-23.91}}$
	1	0000280120000000_x	$\longrightarrow$	0001680820000000_x	$\star$	
	2	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	
	3	4800280168000000_x	$\longrightarrow$	$0801680a28000000_x$	$2^{-11.02}$	
	4	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	
	5	0000080048000000_x	$\longrightarrow$	0000480208000000_x	$2^{-4.70}$	
	6	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	
	7	4800080000000000_x	$\longrightarrow$	0800480000000000_x	$2^{-3.70}$	
inject message word difference $\Delta m_3 = 0000000200000000_x$						
4	0	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	$\mathbf{2^{-34.19}}$
	1	0000080000000800_x	$\longrightarrow$	0000480000004800_x	$\star$	

Example: EnRUPT-256

	4	9000000240000000_x	$\longrightarrow$	1000001040000000_x	$2^{[illegible]}$	
	5	0000200000000000_x	$\longrightarrow$	0001200000000000_x	$2^{-1.85}$	
	6	9000000000000000_x	$\longrightarrow$	1000000000000000_x	$2^{-0.85}$	
	7	4800200000000000_x	$\longrightarrow$	0801200000000000_x	$2^{-3.70}$	
inject message word difference $\Delta m_2 = 0000000208000000_x$						
3	0	9000000000000000_x	$\longrightarrow$	1000000000000000_x	$2^{-0.85}$	$\mathbf{2^{-23.91}}$
	1	0000280120000000_x	$\longrightarrow$	0001680820000000_x	$\star$	
	2	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	
	3	4800280168000000_x	$\longrightarrow$	$0801680a28000000_x$	$2^{-11.02}$	
	4	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	
	5	0000080048000000_x	$\longrightarrow$	0000480208000000_x	$2^{-4.70}$	
	6	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	
	7	4800080000000000_x	$\longrightarrow$	0800480000000000_x	$2^{-3.70}$	
inject message word difference $\Delta m_3 = 0000000200000000_x$						
4	0	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	$\mathbf{2^{-34.19}}$
	1	0000080000000800_x	$\longrightarrow$	0000480000004800_x	$\star$	
	2	0000000000000000_x	$\longrightarrow$	0000000000000000_x	$2^{-0.00}$	
	3	0000080000000800_x	$\longrightarrow$	0000480000004800_x	$2^{-3.70}$	

Example: EnRUPT-256

	6	9000000000000000_x	$\longrightarrow$	1000000000000000_x	2	
	7	4800200000000000_x	$\longrightarrow$	0801200000000000_x	$2^{-3.70}$	
inject message word difference $\Delta m_2 = 0000000208000000_x$						
3	0	9000000000000000_x	$\longrightarrow$	1000000000000000_x	$2^{-0.85}$	$\mathbf{2^{-23.91}}$
	1	0000280120000000_x	$\longrightarrow$	0001680820000000_x	$\star$	
	2	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	
	3	4800280168000000_x	$\longrightarrow$	$0801680a28000000_x$	$2^{-11.02}$	
	4	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	
	5	0000080048000000_x	$\longrightarrow$	0000480208000000_x	$2^{-4.70}$	
	6	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	
	7	4800080000000000_x	$\longrightarrow$	0800480000000000_x	$2^{-3.70}$	
inject message word difference $\Delta m_3 = 0000000200000000_x$						
4	0	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	$\mathbf{2^{-34.19}}$
	1	0000080000000800_x	$\longrightarrow$	0000480000004800_x	$\star$	
	2	0000000000000000_x	$\longrightarrow$	0000000000000000_x	$2^{-0.00}$	
	3	0000080000000800_x	$\longrightarrow$	0000480000004800_x	$2^{-3.70}$	
	4	0000000000000000_x	$\longrightarrow$	0000000000000000_x	$2^{-0.00}$	
	5	4800080048000800_x	$\longrightarrow$	0800480208004800_x	$2^{-8.39}$	

Example: EnRUPT-256

inject message word difference Δm_2

3	0	9000000000000000_x	$\longrightarrow$	1000000000000000_x	$2^{-0.85}$	$\mathbf{2^{-23.91}}$
	1	0000280120000000_x	$\longrightarrow$	0001680820000000_x	$\star$	
	2	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	
	3	4800280168000000_x	$\longrightarrow$	$0801680a28000000_x$	$2^{-11.02}$	
	4	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	
	5	0000080048000000_x	$\longrightarrow$	0000480208000000_x	$2^{-4.70}$	
	6	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	
	7	4800080000000000_x	$\longrightarrow$	0800480000000000_x	$2^{-3.70}$	
inject message word difference $\Delta m_3 = 0000000200000000_x$						
4	0	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	$\mathbf{2^{-34.19}}$
	1	0000080000000800_x	$\longrightarrow$	0000480000004800_x	$\star$	
	2	0000000000000000_x	$\longrightarrow$	0000000000000000_x	$2^{-0.00}$	
	3	0000080000000800_x	$\longrightarrow$	0000480000004800_x	$2^{-3.70}$	
	4	0000000000000000_x	$\longrightarrow$	0000000000000000_x	$2^{-0.00}$	
	5	4800080048000800_x	$\longrightarrow$	0800480208004800_x	$2^{-8.39}$	
	6	0000000000000000_x	$\longrightarrow$	0000000000000000_x	$2^{-0.00}$	
	7	4800080048000800_x	$\longrightarrow$	0800480208004800_x	$2^{-8.39}$	

Example: EnRUPT-256

	2	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	
	3	4800280168000000_x	$\longrightarrow$	$0801680a28000000_x$	$2^{-11.02}$	
	4	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	
	5	0000080048000000_x	$\longrightarrow$	0000480208000000_x	$2^{-4.70}$	
	6	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	
	7	4800080000000000_x	$\longrightarrow$	0800480000000000_x	$2^{-3.70}$	
inject message word difference $\Delta m_3 = 0000000200000000_x$						
4	0	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	$\mathbf{2^{-34.19}}$
	1	0000080000000800_x	$\longrightarrow$	0000480000004800_x	$\star$	
	2	0000000000000000_x	$\longrightarrow$	0000000000000000_x	$2^{-0.00}$	
	3	0000080000000800_x	$\longrightarrow$	0000480000004800_x	$2^{-3.70}$	
	4	0000000000000000_x	$\longrightarrow$	0000000000000000_x	$2^{-0.00}$	
	5	4800080048000800_x	$\longrightarrow$	0800480208004800_x	$2^{-8.39}$	
	6	0000000000000000_x	$\longrightarrow$	0000000000000000_x	$2^{-0.00}$	
	7	4800080048000800_x	$\longrightarrow$	0800480208004800_x	$2^{-8.39}$	
inject message word difference $\Delta m_3 = 0000000200000000_x$						
5	0	0000000000000000_x	$\longrightarrow$	0000000000000000_x	$2^{-0.00}$	$\mathbf{2^{-20.49}}$

Example: EnRUPT-256

	4	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	
	5	0000080048000000_x	$\longrightarrow$	0000480208000000_x	$2^{-4.70}$	
	6	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	
	7	4800080000000000_x	$\longrightarrow$	0800480000000000_x	$2^{-3.70}$	
inject message word difference $\Delta m_3 = 0000000200000000_x$						
4	0	9000000090000000_x	$\longrightarrow$	1000000410000000_x	$2^{-3.70}$	$\mathbf{2^{-34.19}}$
	1	0000080000000800_x	$\longrightarrow$	0000480000004800_x	$\star$	
	2	0000000000000000_x	$\longrightarrow$	0000000000000000_x	$2^{-0.00}$	
	3	0000080000000800_x	$\longrightarrow$	0000480000004800_x	$2^{-3.70}$	
	4	0000000000000000_x	$\longrightarrow$	0000000000000000_x	$2^{-0.00}$	
	5	4800080048000800_x	$\longrightarrow$	0800480208004800_x	$2^{-8.39}$	
	6	0000000000000000_x	$\longrightarrow$	0000000000000000_x	$2^{-0.00}$	
	7	4800080048000800_x	$\longrightarrow$	0800480208004800_x	$2^{-8.39}$	
inject message word difference $\Delta m_3 = 0000000200000000_x$						
5	0	0000000000000000_x	$\longrightarrow$	0000000000000000_x	$2^{-0.00}$	$\mathbf{2^{-20.49}}$
	1	0000000000000000_x	$\longrightarrow$	0000000000000000_x	$\star$	
	⋮	⋮	$\longrightarrow$	⋮	⋮	

Example: EnRUPT-256

	6	9000000090000000_x	$\rightarrow$	1000000410000000_x	$2^{-3.70}$	
	7	4800080000000000_x	$\rightarrow$	0800480000000000_x	$2^{-3.70}$	
inject message word difference $\Delta m_3 = 0000000200000000_x$						
4	0	9000000090000000_x	$\rightarrow$	1000000410000000_x	$2^{-3.70}$	$\mathbf{2^{-34.19}}$
	1	0000080000000800_x	$\rightarrow$	0000480000004800_x	$\star$	
	2	0000000000000000_x	$\rightarrow$	0000000000000000_x	$2^{-0.00}$	
	3	0000080000000800_x	$\rightarrow$	0000480000004800_x	$2^{-3.70}$	
	4	0000000000000000_x	$\rightarrow$	0000000000000000_x	$2^{-0.00}$	
	5	4800080048000800_x	$\rightarrow$	0800480208004800_x	$2^{-8.39}$	
	6	0000000000000000_x	$\rightarrow$	0000000000000000_x	$2^{-0.00}$	
	7	4800080048000800_x	$\rightarrow$	0800480208004800_x	$2^{-8.39}$	
inject message word difference $\Delta m_3 = 0000000200000000_x$						
5	0	0000000000000000_x	$\rightarrow$	0000000000000000_x	$2^{-0.00}$	$\mathbf{2^{-20.49}}$
	1	0000000000000000_x	$\rightarrow$	0000000000000000_x	$\star$	
	$\vdots$	$\vdots$	$\rightarrow$	$\vdots$	$\vdots$	
	7	0000000000000000_x	$\rightarrow$	0000000000000000_x	$2^{-0.00}$	$\mathbf{2^{-0.00}}$

Collision Example for EnRUPT-256

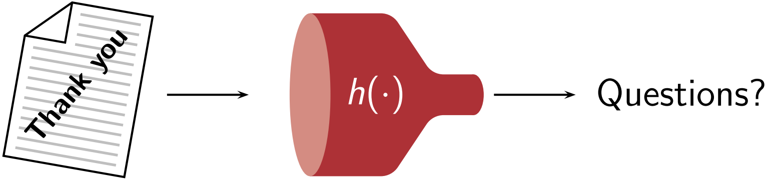
```
Example collision pair for EnRUPT-256
2008-11-06, Sebastiaan Indesteege, COSIC, Katholieke Universiteit Leuven

m1 = 13c84b456270176e04f9317ec36ce7d3e121786a347411197f64a3c940077576a14f9086fdc7334a413a769196062ca1
EnRUPT-256(m1) = bd67517ca6c0412082e03b745ffc4a64e9f092c258c398b8449afecb7fc86f72

m2 = 13c84b456a70176e04f9315c436ce7d3e1217848bc7411197f64a3cb48077576a14f9084fdc7334a413a769396062ca1
EnRUPT-256(m2) = bd67517ca6c0412082e03b745ffc4a64e9f092c258c398b8449afecb7fc86f72

m1 and m2 collide!
```

- http://homes.esat.kuleuven.be/~sindeste/enrupt.html (or see SHA-3 Zoo)

Outline

Conclusion

- Collision attacks on EnRUPT
- Breaks **all seven** proposed EnRUPT variants
- **Mitigation:** increase s-parameter to 8 [O'Neil] (i.e., double # steps per round)



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