Collision Attacks on the Reduced Dual-Stream Hash Function RIPEMD-128

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Outline

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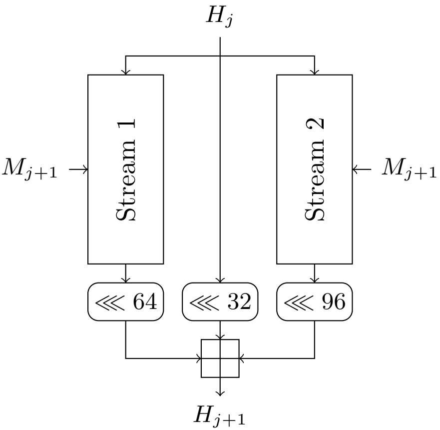
Motivation

- Cryptanalysis of ARX based designs is still important
- Very difficult without the right tools
- Even more for dual-stream hash functions
- Do the results on SHA-2 help to improve attacks on other designs?
- RIPEMD-128: shares some similarities with SHA-2

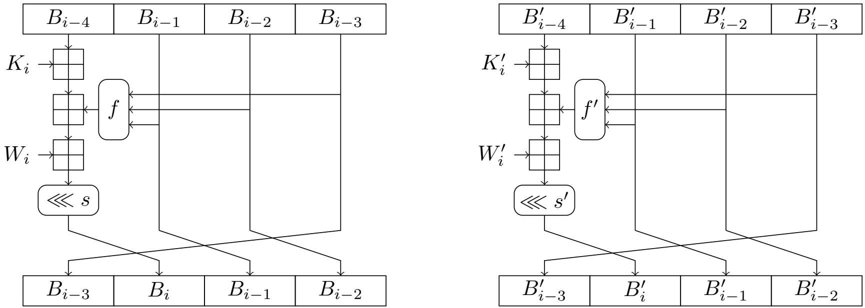
Outline

Description of RIPEMD-128



- ISO/IEC standard [DBP96]
- designed by Dobbertin, Bosselaers and Preneel
- iterated, Merkle-Damgård hash function
- dual stream compression function
- no output transformation
- 128-bit hash output

Step Update Transformation of RIPEMD-128



- one message word updates two state variables
- different message word permutations
- different rotation values and Boolean functions
- no interaction between streams (SHA-2: with interaction)
- 4 rounds of 16 steps

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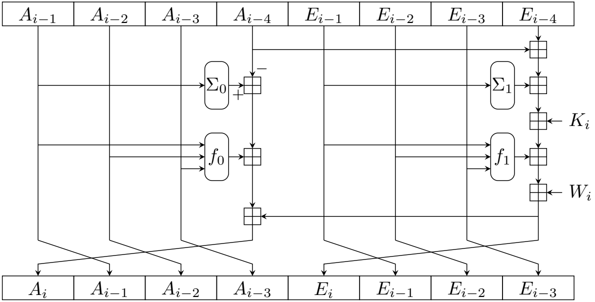

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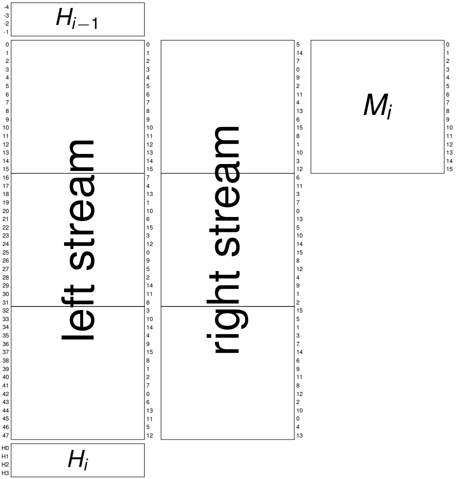
Overview of the Attack



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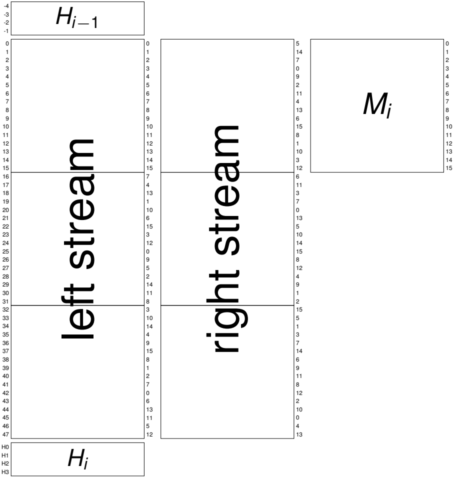
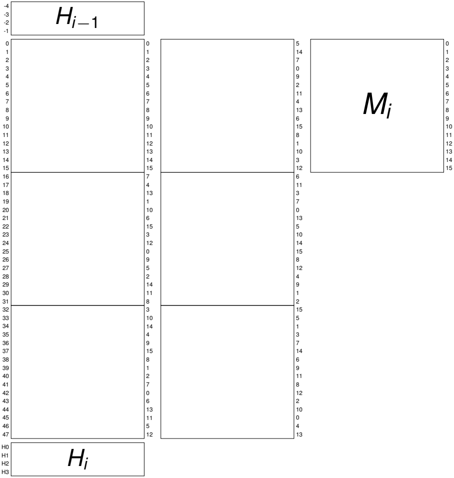


1. choose a good starting point
   - few message word differences
   - high probability characteristic
2. search for a characteristics
   - very sparse in R2 and R3
   - sparse in one stream in R1
3. determine message pair
   - message modification in R1
   - exhaustive search for R2, R3

$\Rightarrow$ iterations between phases

Choosing a Starting Point



- which message words should contain differences?
  - as few words as possible
  - only words used late in R3
  - short local collisions in R2

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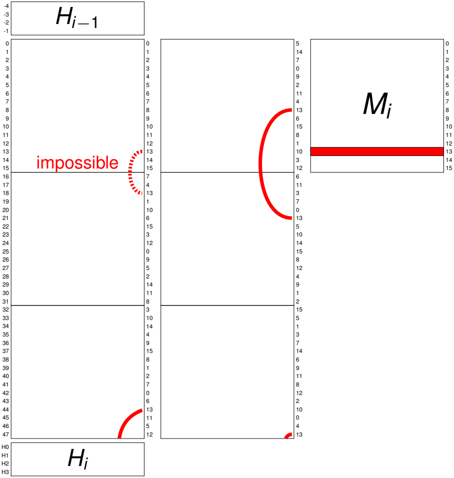

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- message word 13
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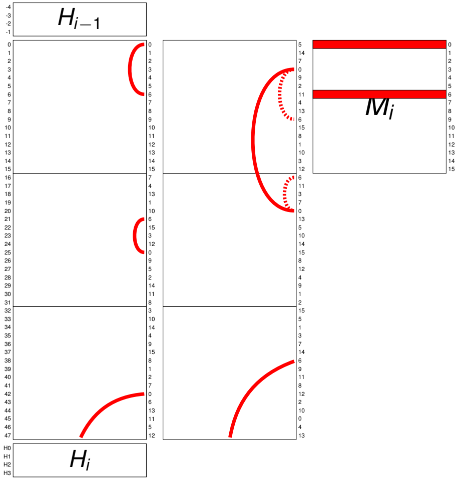

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- message word 0 and 6
  - left: two short local collisions
  - right: one long local collision
  - avoid overlapping of LCs
  - collision for 38 steps

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Differences and Conditions

Generalized Conditions [DR06]

- take all 16 possible conditions on a pair of bits into account

(X_i, X_i^*)	(0,0)	(1,0)	(0,1)	(1,1)	(X_i, X_i^*)	(0,0)	(1,0)	(0,1)	(1,1)
?	✓	✓	✓	✓	3	✓	✓	-	-
-	✓	-	-	✓	5	✓	-	✓	-
x	-	✓	✓	-	7	✓	✓	✓	-
0	✓	-	-	-	A	-	✓	-	✓
u	-	✓	-	-	B	✓	✓	-	✓
n	-	-	✓	-	C	-	-	✓	✓
1	-	-	-	✓	D	✓	-	✓	✓
#	-	-	-	-	E	-	✓	✓	✓

2-bit Conditions [MNS11]

- linear relation between closely related bits: $X_i \oplus X_j = 0/1$
- 2-bit conditions on any generalized condition (-,x,?,...)
- used to determine critical bits (those with many relations)

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  - Boolean functions
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  - even on carries (sign of carry)
- Efficiency
  - not all conditions in every iteration/phase
  - use table lookups when possible

Search Strategy

Search Algorithm [DR06, MNS11]

(1) Start with an unrestricted characteristic ('?' and '-')

(2) Successively impose new conditions on the characteristic
- path search: replace '?' by '-' and 'x' by 'n' or 'u'
- message search: replace '-' by '1' or '0'

(3) Propagate the conditions in a bitslice manner and check for consistency
- if a contradiction occurs then backtrack
- else proceed with step 2

(4) Repeat steps 2 and 3 until all bits of the characteristic are determined

Search Strategy

The difficulties are in the details...

- Which information to propagate (and when)?
  - path search: generalized conditions
  - message search: generalized conditions and 2-bit conditions
- Which bits (which area) to guess?
  - dedicated to hash function
  - bits with many 2-bit conditions (in message search)
  - lots of trial and error needed to find best strategy
- How to backtrack?
  - if a contradiction occurs on a bit, backtrack until bit can be set
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$\Rightarrow$ Dedicated for every hash function (unfortunately)

Searching for a Differential Characteristic

i	∇B_i	$\nabla B'_i$	∇m_i
-4	--------------------------------		
-3	--------------------------------		
-2	--------------------------------		
-1	--------------------------------		
0	????????????????????????????????	--------------------------------	???????????????????????????????x
1	????????????????????????????????	--------------------------------	--------------------------------
2	????????????????????????????????	--------------------------------	--------------------------------
3	--------------------------------	????????????????????????????????	--------------------------------
4	--------------------------------	????????????????????????????????	--------------------------------
5	--------------------------------	????????????????????????????????	--------------------------------
6	--------------------------------	????????????????????????????????	????????????????????????????????
7	--------------------------------	????????????????????????????????	--------------------------------
8	--------------------------------	????????????????????????????????	--------------------------------
9	--------------------------------	????????????????????????????????	--------------------------------
10	--------------------------------	????????????????????????????????	--------------------------------
11	--------------------------------	????????????????????????????????	--------------------------------
12	--------------------------------	????????????????????????????????	--------------------------------
13	--------------------------------	????????????????????????????????	--------------------------------
14	--------------------------------	????????????????????????????????	--------------------------------
15	--------------------------------	????????????????????????????????	--------------------------------
16	--------------------------------	????????????????????????????????	
17	--------------------------------	--------------------------------	
18	--------------------------------	--------------------------------	
19	--------------------------------	--------------------------------	
20	--------------------------------	--------------------------------	
21	????????????????????????????????	--------------------------------	
22	--------------------------------	--------------------------------	
23	--------------------------------	--------------------------------	
24	--------------------------------	--------------------------------	
25	--------------------------------	--------------------------------	
26	--------------------------------	--------------------------------	
27	--------------------------------	--------------------------------	
28	--------------------------------	--------------------------------	
29	--------------------------------	--------------------------------	
30	--------------------------------	--------------------------------	
31	--------------------------------	--------------------------------	
32	--------------------------------	--------------------------------	
33	--------------------------------	--------------------------------	
34	--------------------------------	--------------------------------	
35	--------------------------------	--------------------------------	
36	--------------------------------	--------------------------------	
37	--------------------------------	--------------------------------	

- Start characteristic
  - ? in words with difference
  - - in words without differences
  - x in LSB of word 0

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i	∇B_i	$\nabla B'_i$	∇m_i
-4	--------------------------------		
-3	--------------------------------		
-2	--------------------------------		
-1	--------------------------------		
0	-------unnnnunnnnnnnn-----------	--------------------------------	----------------------u--------u
1	------n--------------nuuuunnnnnn	--------------------------------	--------------------------------
2	------unnunnnnnnnnnnnnnnnnnnnnnn	--------------------------------	--------------------------------
3	--------------------------------	-----------u--------u-----------	--------------------------------
4	--------------------------------	????????-----------?????????????	--------------------------------
5	--------------------------------	????????????????????????????????	--------------------------------
6	--------------------------------	????????????????????????????????	--------n----------------------n
7	--------------------------------	????????????????????????????????	--------------------------------
8	--------------------------------	????????????????????????????????	--------------------------------
9	--------------------------------	????????????????????????????????	--------------------------------
10	--------------------------------	????????????????????????????????	--------------------------------
11	--------------------------------	????????????????????????????????	--------------------------------
12	--------------------------------	????????????????????????????????	--------------------------------
13	--------------------------------	????????????????????????????????	--------------------------------
14	--------------------------------	????????????????????????????????	--------------------------------
15	--------------------------------	----------------------x--------x	--------------------------------
16	--------------------------------	----------------------n--------n	
17	--------------------------------	--------------------------------	
18	--------------------------------	--------------------------------	
19	--------------------------------	--------------------------------	
20	--------------------------------	--------------------------------	
21	----------------------n--------n	--------------------------------	
22	----------------------0--------0	--------------------------------	
23	----------------------1--------1	--------------------------------	
24	--------------------------------	--------------------------------	
25	--------------------------------	--------------------------------	
26	--------------------------------	--------------------------------	
27	--------------------------------	--------------------------------	
28	--------------------------------	--------------------------------	
29	--------------------------------	--------------------------------	
30	--------------------------------	--------------------------------	
31	--------------------------------	--------------------------------	
32	--------------------------------	--------------------------------	
33	--------------------------------	--------------------------------	
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37	--------------------------------	--------------------------------	

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  1. high probability in R2
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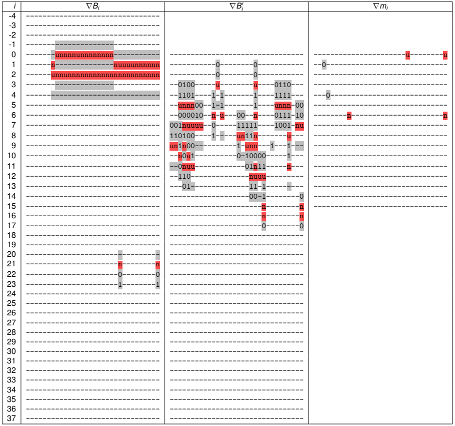

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  - x in LSB of word 0
- Separate search (phases)
  1. high probability in R2
  2. left stream in R1
  3. find first block M_0
  4. right stream in R1

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Finding a Colliding Message Pair

- Message modification
  - many dedicated techniques published
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- Automatic message search
  - continue guessing '-' bits to '0' or '1'
  - guess on words (state, message) in order they appear
- Amortize costs
  - automatic message modification until word 13
  - brute-force with message words 14,15
  - complexity $2^?$

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Results

previous results:

component	attack	steps	complexity	generic	reference
hash	preimage	33	$2^{124.5}$	2^{128}	[OSS10]
hash	preimage	interm. 35	2^{121}	2^{128}	[OSS10]
hash	preimage	interm. 36	$2^{126.5}$	2^{128}	[WSK$^+$11]

our results:

component	attack	steps	complexity	generic
hash	collision	38	example, 2^{14}	2^{64}
hash	near-collision	44	example, 2^{32}	$2^{47.8}$
hash	non-randomness	48	2^{70}	2^{76}
compression	collision	48	example, 2^{40}	2^{64}

Summary

- Strategy to analyze dual stream hash functions
- Automatic path search and automatic message modification
- Time consuming to find the right settings
- Once settings are found, collision can be found in minutes
- Still lots of work to be done for other (ARX based) hash functions
- Remember: it took 5 years to get from SHA-1 to SHA-2

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