Cryptanalysis of Stream-Based Hashes

ECRYPT II
Hash^3: Proofs, Analysis, and Implementation

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Ingenico

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Outline

Stream-based hash functions

- What is a stream-based hash function ?
- Some examples
- A perfect example: CubeHash

Generic attacks

- Meet-in-the-middle attacks
- Slide attacks

Differential attacks

- Linear differential paths
- Truncated differential paths
- Symmetric differential paths

Using the freedom degrees

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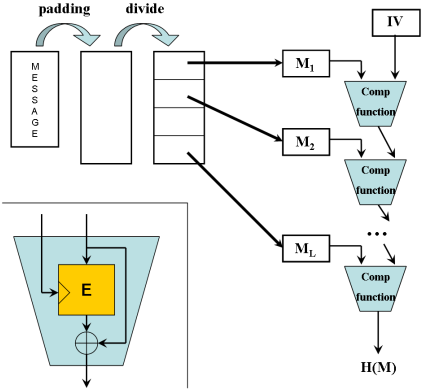
How to build a hash function (usually) ?

Merkle-Damgård algorithm + Davies-Meyer



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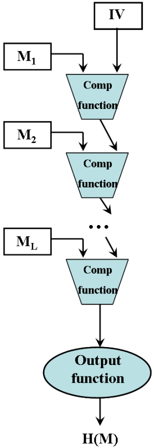
Generalization



- use an output function (for example truncation in double pipe construction)
- use another method for introducing message chunks
- **c** represents the capacity.
- **r** represents the bit-rate.
- **R** represents the number of rounds.

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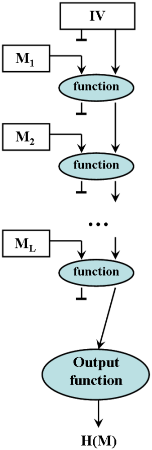

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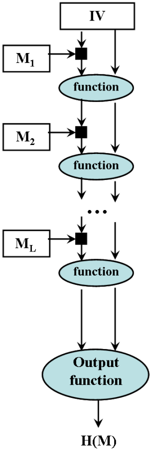

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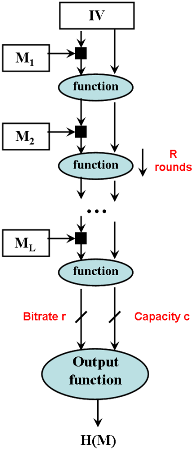

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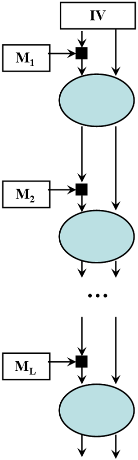
Block/stream-based hash functions



- **block-based hash:**
  r is bigger or at least the same size than c
- **stream-based hash:**
  r is small compared to c
- increasing c/r improves security: less control to the attacker
- increasing R improves security: less good differential paths
- stream-based hashes internal function is in general a permutation

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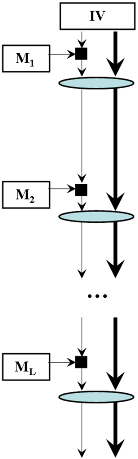

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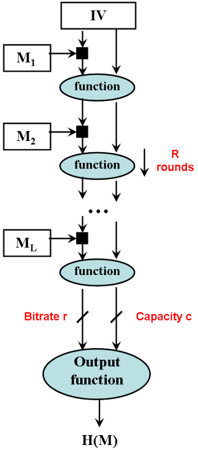

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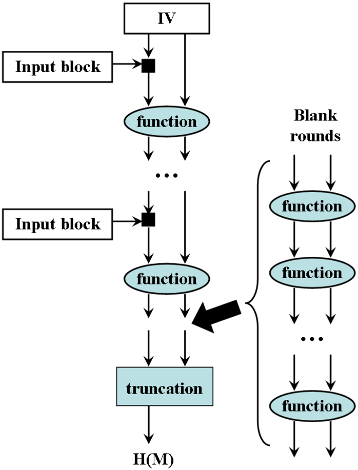

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- **option 1:** just truncate the internal state to obtain the hash value (Grindahl, CubeHash, ...)
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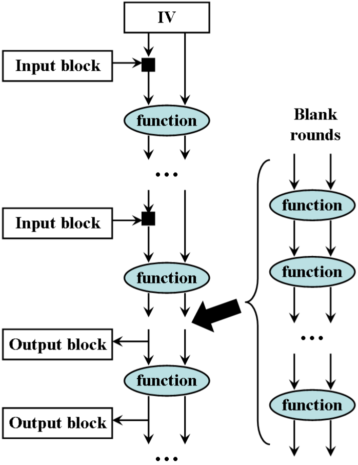

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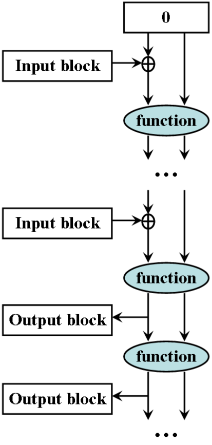
The sponge functions [BDPV-ECRYPTHW07]



- sponge functions: introduced by Bertoni, Daemen, Peeters and Van Assche in 2007.
- Example: Keccak.
- **Particularities:**
  - special padding rule (that implies last message block $\neq 0$)
  - insert message chunks with a XOR
  - use squeezing process as output function (with the same internal state words than insertion): allows to be very flexible on the hash output size, with the same internal function ... can be used as a stream cipher.
  - the round function should presents no structural property (hermetic sponge)

Security proofs for sponge functions [BDPV-EC08]

- **white box model**: the attacker has access to the internal round function. Use the indifferentiability framework from Maurer *et al.* [MRH-TCC04].
- assume the internal function is a random permutation
- **Theorem:** a random sponge can be differentiated from a random oracle only with probability $\simeq N(N+1)/2^{c+1}$, with $N < 2^c$, where N is the total number of calls to the internal round function.
- generic attacks require $2^{c/2}$.
- as long as you can't say anything on the actual internal permutation (i.e. structural properties), the sponge looks like a random oracle (resistant to multicollisions, long 2nd preimage, length-extension attacks, ...)

Examples

name	capacity c	bit-rate r	nb rounds R	insert function	output function
Panama	8480	256	1	XOR	BR + trunc
RadioGatun	1760	96	1	XOR	BR + squeeze
Keccak	512	1088	24	XOR	squeeze
Grindahl	384	32	1	ERASE	BR + trunc
Fugue	928	32	1	XOR	BR + trunc
LUX	736	32	1	XOR	BR + squeeze
HAMSI	256	32	3	special	BR + trunc
Luffa	512	256	1	special	BR + squeeze
CubeHash	768	256	16	XOR	BR + trunc
EnRupt	576	64	8	XOR	BR + squeeze
SHABAL	896	512	3	MIX	BR + squeeze

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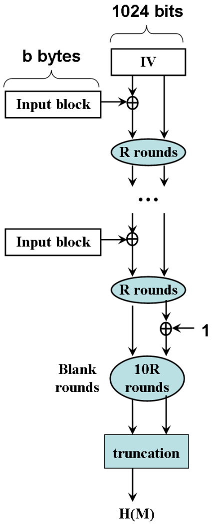
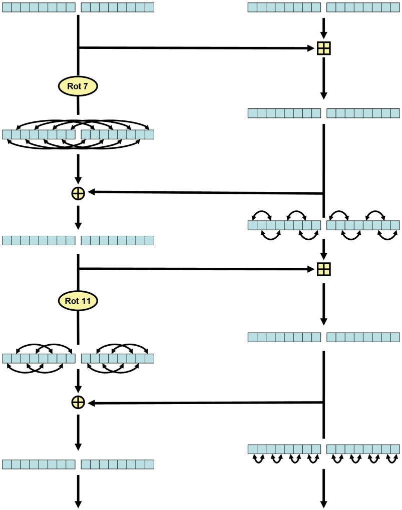
CubeHash-R/b



- SHA-3 candidate of Dan Bernstein
- internal state of 1024 bits (32 words of 32 bits each)
- insert b bytes of message (with xor) each iteration
- process R rounds of the permutation each iteration
- xor 1 and execute 10R blank rounds
- truncate the internal state to the appropriate hash size
- capacity = 1024 - 8b.

CubeHash round function



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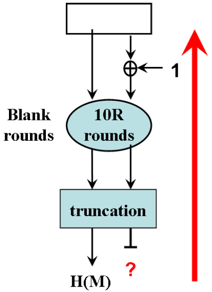

- assume we use an internal permutation, let's try to find a preimage
- invert the output function
- compute $2^{c/2}$ candidates forward and backward ...
- ... and meet-in-the-middle
- to be preimage resistant, the capacity should be $c \geq 2n$
- in the case of CubeHash, we need $2^{(1024-8b)/2} = 2^{512-4b}$ operations to find a preimage

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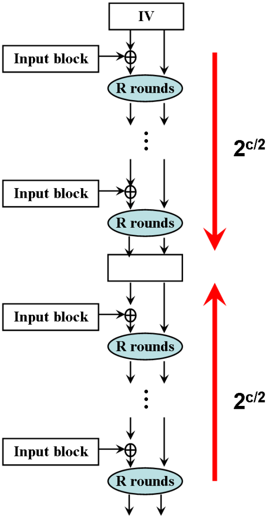

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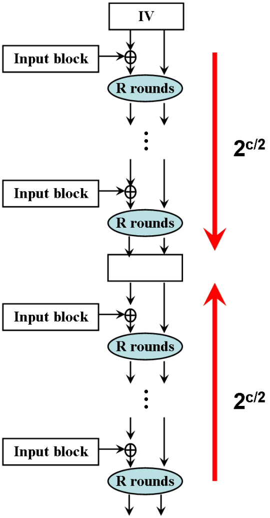

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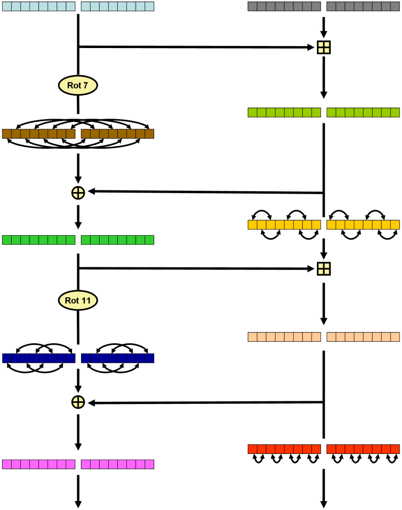
CubeHash round function structural property [ABMNP-ACISP09]



Improving meet-in-the-middle attacks with structural property

- find all symmetry classes in CubeHash internal function
- 16 classes of 2^{512} elements each, a total of 2^{516} symmetric states
- **let's find a preimage:**
    - invert the output function
    - from this internal state, compute backward and reach a symmetric state ($2^{1024-516-8b} = 2^{508-8b}$ operations)
    - from the IV, compute forward and reach a symmetric state ($2^{1024-516-8b} = 2^{508-8b}$ operations)
    - do a meet-in-the-middle while remaining in the symmetry class $S_F \cap S_B$ ($2^{512/2} = 2^{256}$ operations)
- total complexity $2^{512-8b} < 2^{512-4b}$

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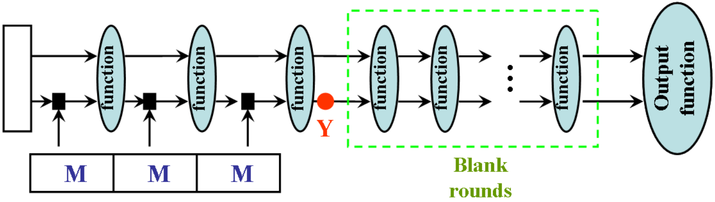
Slide attacks on stream-based hash functions

If the addition of X is neutral, then $output1 = round(output2)$.



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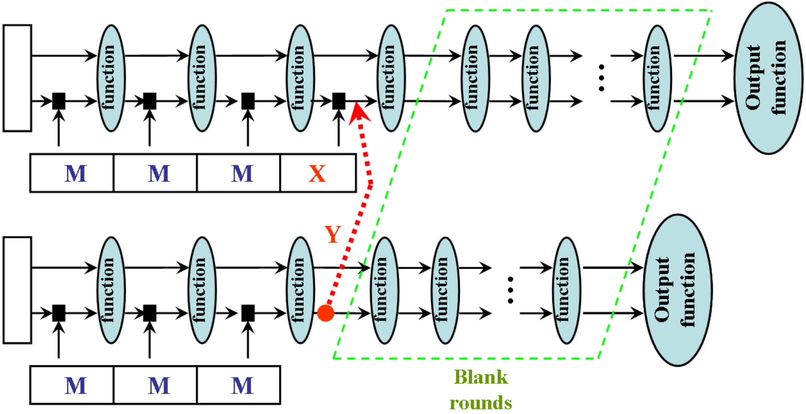

Slide attacks for hash functions

What can we obtain from slide attacks ?

- slide attacks are a typical block cipher cryptanalysis technique.
- doesn't seem useful for collision or preimage attacks ...
- ... but we can "distinguish" the hash function from a random oracle.
- the key recovery attack may also be useful if some secret is used in the hash function: we can attack a MAC construction using a hash function.

We'll try to attack the following MAC construction:

$$\mathrm{MAC}(K, M) = H(K||M).$$

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We'll try to attack the following MAC construction:

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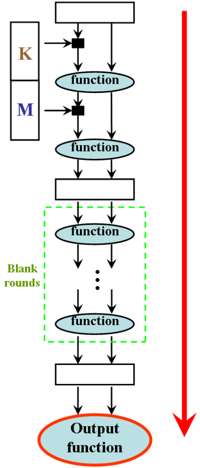
- **... which is secure if the hash function is modeled as a random oracle.**
- **Merkle-Damgård already known to be weak against this construction**: given $\mathrm{MAC}(K, M) = H(K||M)$, compute $\mathrm{MAC}(K, M||Y) = H(K||M||Y)$ without knowing the secret key K.
- patch provided in Coron *et al.*'s paper [CDMP-CRYPTO05].

Slide attacks on stream-based hash functions

The Attack Scenario: the attacker makes queries M_i and receive replies $H(K||M)$. He then tries to get some non trivial information from the secret K or manage to forge another MAC with good probability.



The attack will be in three steps:

- Find and detect slid pairs of messages.
- Recover the internal state.
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The padding must also be taken in account !

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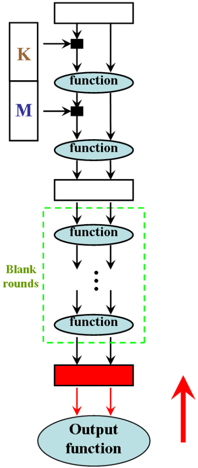

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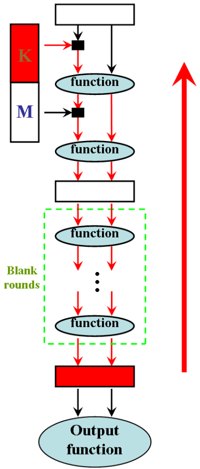

Find and detect slid pairs of messages.

If you are inserting message blocks with XOR:

- very easy to slide, just use 0
- you don't need to detect it, you know it will slide
- impossible in the original sponge framework (in which the last inserted word must be different from 0) ...
- ... but possible if a different padding is used !

If you are inserting message blocks with ERASE:

- you can slide if you replace exactly what you erased
- happens with probability $P = 2^{-r}$
- detection depends on the output function:
  - very easy with the squeezing process (all the output words are shifted by one iteration).
  - more complicated with a direct truncation.

Recovering the internal state and **uncovering the secret key** both depend on the whole hash function (require a case by case analysis).

Patches

This attacks works against:

- Grindahl [GLP-AC08]
- LUX [P-SHA3list09] (with chosen salt)

It is very easy (and costless) for the designers to protect themselves against slide attacks:

- add a constant to the internal state just before the blank rounds to clearly separate them from the normal rounds (CubeHash).
- use a different transformation during the blank rounds (Panama, SHABAL).
- **If you're inserting message blocks with a XOR:** just use exactly the sponge framework and make sure that the last inserted message work is different from zero (RadioGatun, Keccak, EnRupt).

Outline

General principles

- **internal collisions:** the collision occurs on the whole internal state, before the blank rounds or the output function.
  - **advantages:** you can use the freedom degrees MUCH more efficiently
  - **drawbacks:** you have to collide on the entire big internal state
- **external collisions:** the internal state before the blank rounds or the output function contains some differences:
  - **advantages:** you only have to collide on the (small) hash output size.
  - **drawbacks:** you have no freedom degree to use
- Finding internal near collisions is useless (the output function is often strong because it doesn't affect the efficiency for long messages)
- Finding free-start collisions is useless in practice (and very easy since one can invert the internal function)

General principles

Situation different for stream-cipher based and block-based hash functions (not a rule, just a general observation):

- **block-based:**
    - finding a differential path is not the most difficult part (e.g. we know very good differential paths for SHA-1)
    - using the freedom degrees is hard, because they are all located at the same place while the conditions are everywhere (many freedom degrees are wasted in SHA-1 attacks) you may find good differential characteristics for the internal functions used in stream-based hashes ...
    - ... but the problem is how to link them
- **stream-based:**
    - finding a differential path is hard, because the internal state is really big (many conditions to take care of). Moreover, you often need several iterations in order to get a collision.
    - using the freedom degrees is rather easy, because you only have a few incoming each iteration: it is easy to use each of them to take care of a condition.

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Linear differential paths

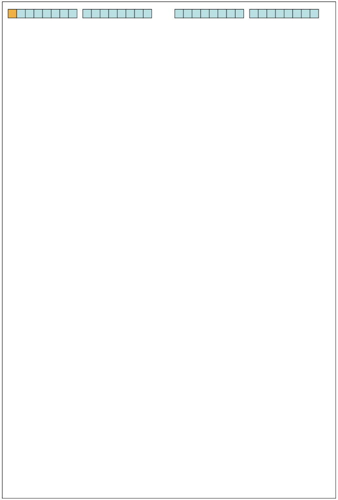
- try to **linearize** the scheme ... for example, simply replace additions by XORs
- solve the set of linear equations and try to find a good differential trail (in general, good = low weight)

Complexity computation:

- **two situations** have to be considered in order to compute the success probability of the differential path in the non-linearized case (both with probability 1/2):
  - **move:** a perturbation at a certain bit position is added to another bit containing no difference.
  - **correction:** a perturbation at a certain bit position is added to another bit containing a difference.
- for the addition of two words $A + B$, the probability of a linear behavior is $\mathrm{HW}((\Delta_A \vee \Delta_B) \wedge \mathtt{0x7fffffff})$.

Works rather well for (32 or 64-bit)-word oriented primitives (ex: EnRupt [IP-FSE09], CubeHash [D-SHA3list09] [BP-ACNS09] [BKMP-AC09])

Linear differential paths: example for CubeHash-2/4



- add a one bit difference on X_0 (at position i).
- do one iteration (2 rounds).
- erase all the differences in X_0 (at positions i+4, i+14, i+22).
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- 46 bit conditions in total.

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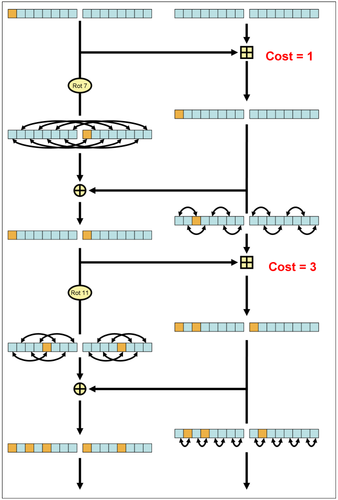

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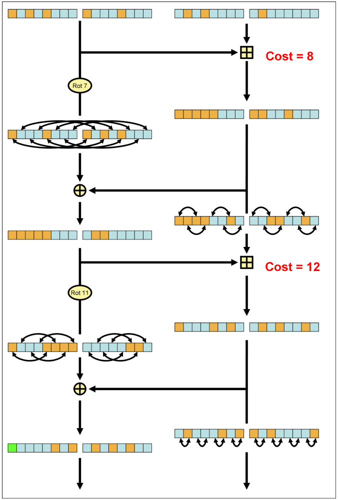

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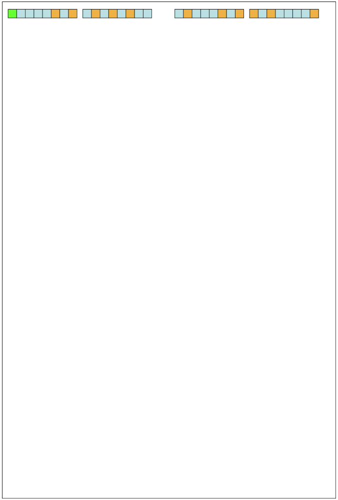

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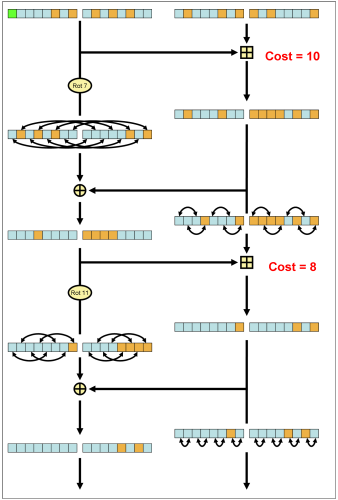

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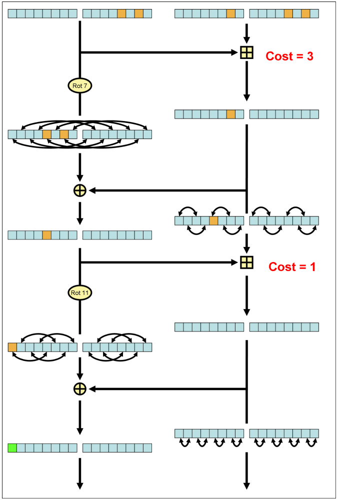

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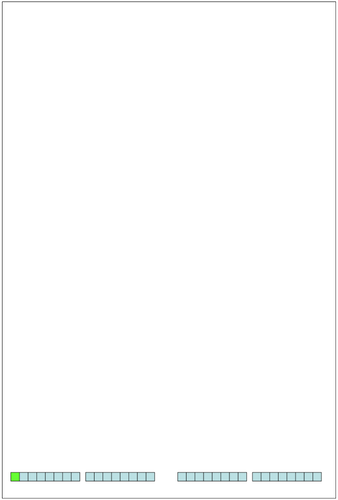

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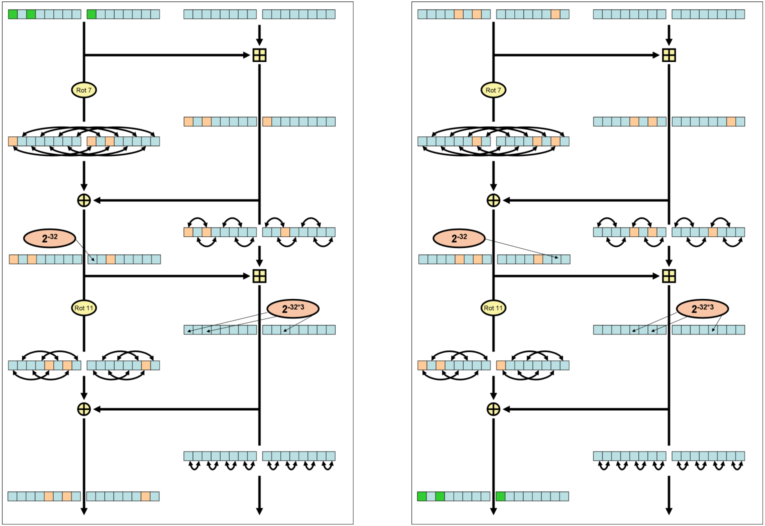
Outline

Truncated differential paths: CubeHash-1/36 example



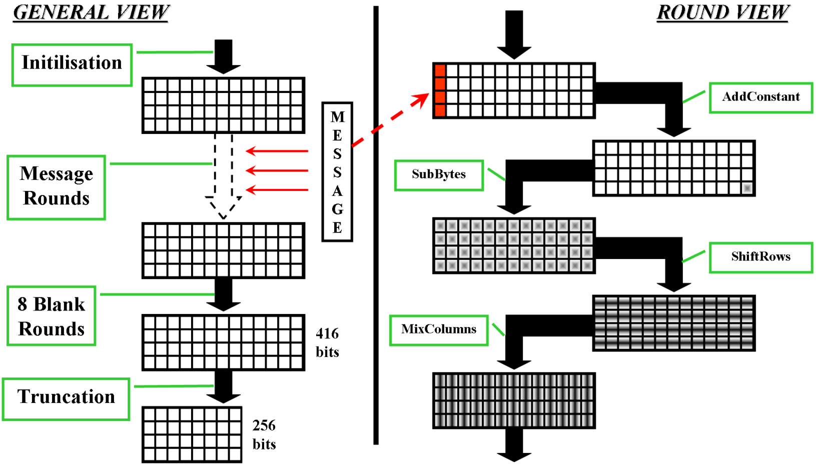
Truncated differential paths: CubeHash-1/36 results

Results (using freedom degrees):

- a collision for CubeHash-1/36 in 2^{32} operations.
- a collision for CubeHash-2/36 in 2^{96} operations.
- ... seems hard to go further !

Truncated differential paths don’t work well for CubeHash.

Truncated differential paths: Grindahl



Truncated differential paths: attacking Grindahl [P-AC07]

- Building a differential path is really hard because of the two security properties:
  - a collision requires intermediate states with at least half of the bytes active.
  - an internal collision requires at least 5 rounds.
- **idea - take the all-difference state as a check point:**
  - from a no-difference state to an all-difference state: hopefully very easy ! No need for a differential path here.
  - from an all-difference state to a no-difference state: harder ! Build the differential path backward and search for a collision onward.
- the costly part when searching for a collision is obviously the second stage !

Very unintuitive strategy (letting all the differences spread), this is surely not the best path one could find for Grindahl. However, it is a very handy method in order to find a rather good candidate trail.

Truncated differential paths

Reducing the ”zoom” with truncated differentials allows to simplify the path search, but also decrease the probability that a good path exist in the search space. In general truncated differentials works well for byte-oriented primitives, not against bit-oriented, 32-bit or 64-bit hash functions.

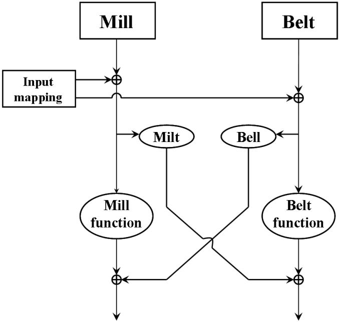
- **bit-oriented schemes** (e.g. RadioGatun): bit-wise diffusion will make the truncated differential analysis fail
- **byte-oriented schemes** (e.g. Grindahl): simplifies the path search while not reducing too much the search space
- **word-oriented schemes** (e.g. CubeHash): simplifies the path search too much, only very costly trails are likely to be found

Fugue presents security arguments regarding this kind of attacks.

Outline

Symmetric differences: RadioGatun-32

- **initialize** the state with zeros.
- **for each round** do (while all the padded message hasn't been processed):
  - **XOR** 3 words of the Mill and 3 of the Belt to 3 new message words.
  - do **Milt**.
  - do **Bell**.
  - do **Mill function**.
  - do **Belt function**.
- do **16 blank rounds**.
- **do** (until we reach the good output size): a blank iteration and output 2 words from the Mill.



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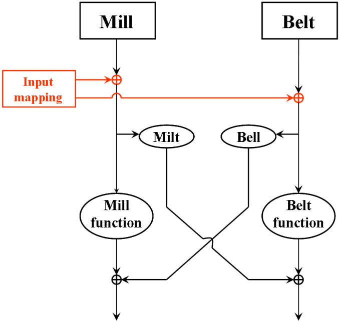

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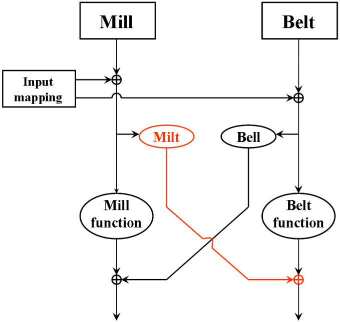

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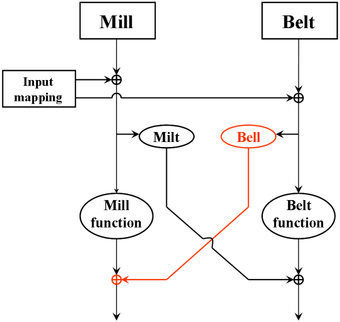

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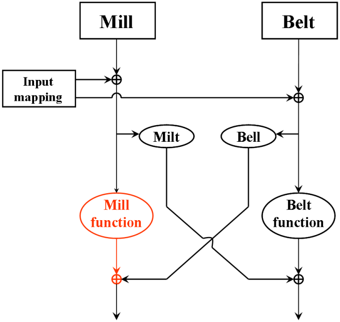

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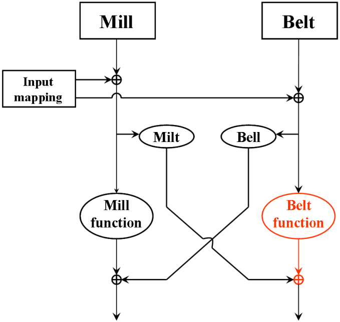
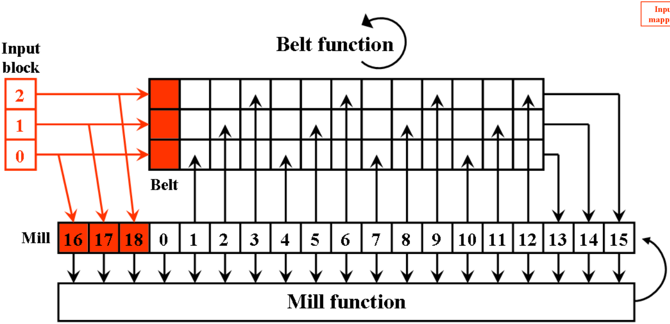
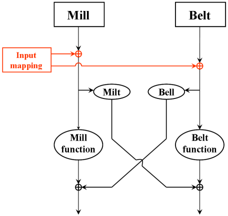


Symmetric differences: RadioGatun-32





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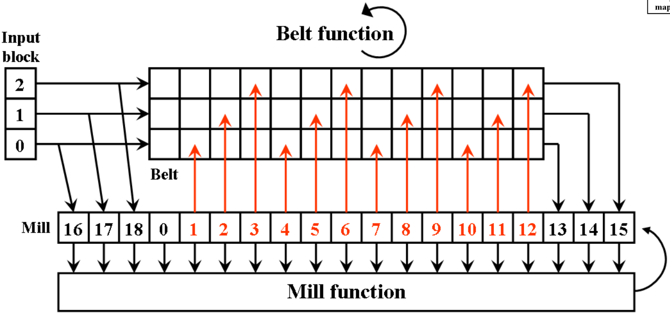

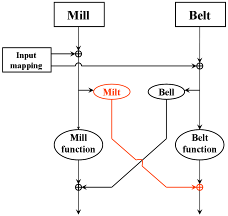

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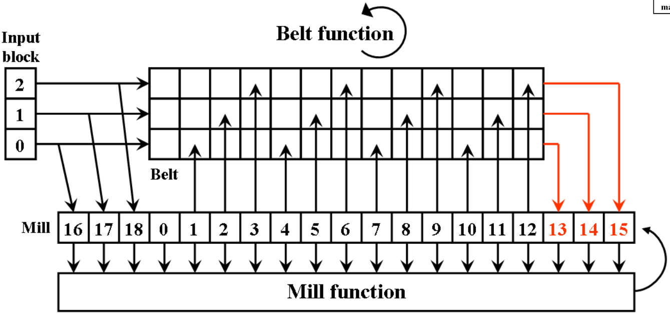

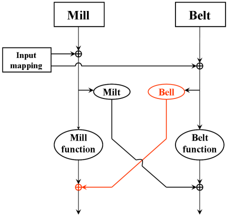

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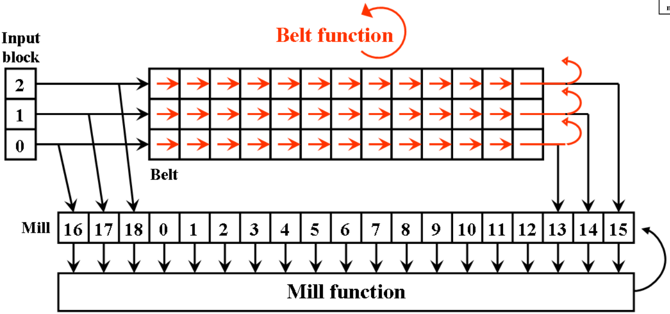

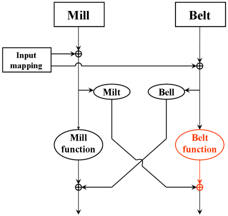

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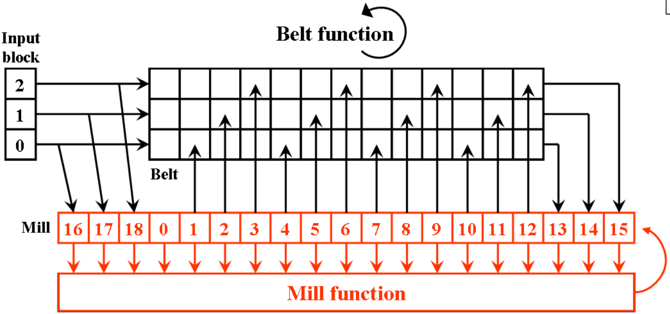

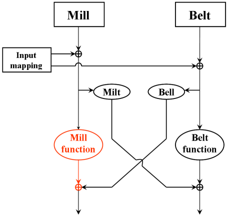

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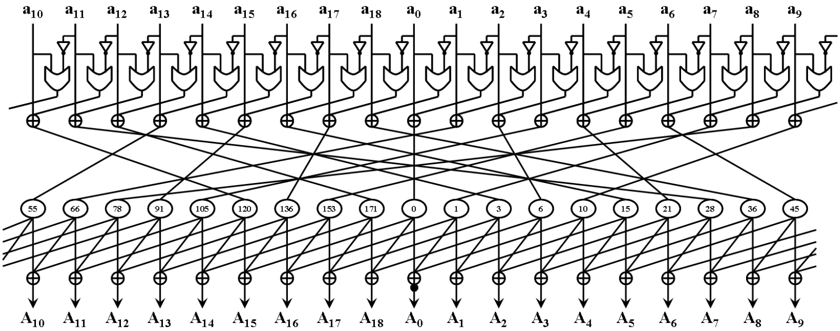


Symmetric differences

Consider **symmetric differences** for each word: only "all-different" or "equal".

- analysis REALLY simplified: you only have to study RadioGatun with w=1 (internal state of 58 bits).
- but each uncontrolled event cost a lot: all the complexity comes from the non-linear part in the Mill function.
- each event you want to force costs you one word of message freedom.
- the conditions can sometime be compressed (two same conditions on the same word).
- there may be contradicting conditions.

This techniques works well for bit-oriented primitives (RadioGatun [BDPV-RG06] [FP-FSE09] or PANAMA [RRPV-FSE01] [DV-FSE07])

Outline

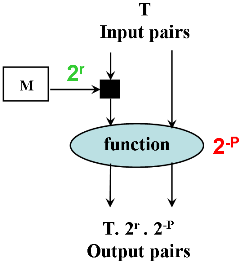
Using the freedom degrees

- **The techniques used are similar to the block-based hash functions: message modification, neutral bits, etc.** For example the control words used for attacking Grindahl ([P-AC07]) can be seen as byte-level message modifications.
- they lead to HUGE improvements. For example, from 2^{440} to 2^{112} for Grindahl [P-AC07].
- but because many freedom degrees can be used, and because the paths sometimes requires a few hundreds steps (RadioGatun [FP-FSE09]), one very often uses **automated tools** (Grindahl [P-AC07], RadioGatun [FP-FSE09], CubeHash [BKMP-AC09])
- Those tools are generally integrated directly during the path search (avoid the problem of ”good raw probability, but no freedom degrees possibility”)
- you can use structures (Grindahl or RadioGatun [K-SAC09]) or algebraic techniques (RadioGatun [BF-SAC08])

Using the freedom degrees: the trail backtracking cost

Trail backtracking [BDPV-RG06] is a method for estimating the cost of staying in a differential path when searching for collisions in hash functions.

- find a t-round trail starting and ending with no difference
- **Idea:**
  - start with T pairs at the beginning of the trail
  - each round i you go through, you have to ”pay” a probability P_i
  - each round i, you get r bits of freedom degrees



Using the freedom degrees: the trail backtracking cost

- The **number of valid pairs** at the end of a k-round trail is

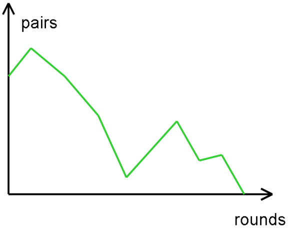
$$N(k) = T \times 2^{k \cdot r} \times 2^{-\sum_{i=1}^{k} P_i}$$

- at each round, you must have that the number of valid pairs is always ≥ 1 (can be removed if considering average cost), thus

$$T \geq \max_{0<k\leq t} \{2^{(\sum_{i=1}^{k} P_i) - k \cdot r}\}$$

- **total cost for the trail** is the sum of the number of pairs entering the rounds

$$cost = \sum_{j=1}^{t} N(j)$$



Using the freedom degrees: improving the trail backtracking

- Improvement: **find a good differential trail and define how you will use the freedom degrees at the same time.**
- **Search paths with a meet-in-the-middle tracking technique** (RadioGatun [FP-FSE09]):
  - keep track of the cost for forward paths (and cut off costly branches)
  - keep track of the cost for backward paths (and cut off costly branches)
  - meet-in-the-middle the two sets
  - adjust the costs during the meeting phase
- **Example:** for RadioGatun, with trail backtracking best attack found $2^{46 \cdot w}$ operations, with meet-in-the-middle tracking $2^{11 \cdot w}$ operations.
- to simplify the search, instead of randomly meeting in the middle, you can meet to a fixed difference (all-difference state for Grindahl [P-AC07]).

That’s all folks !

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