Dedicated Attacks on Popular Hash Functions

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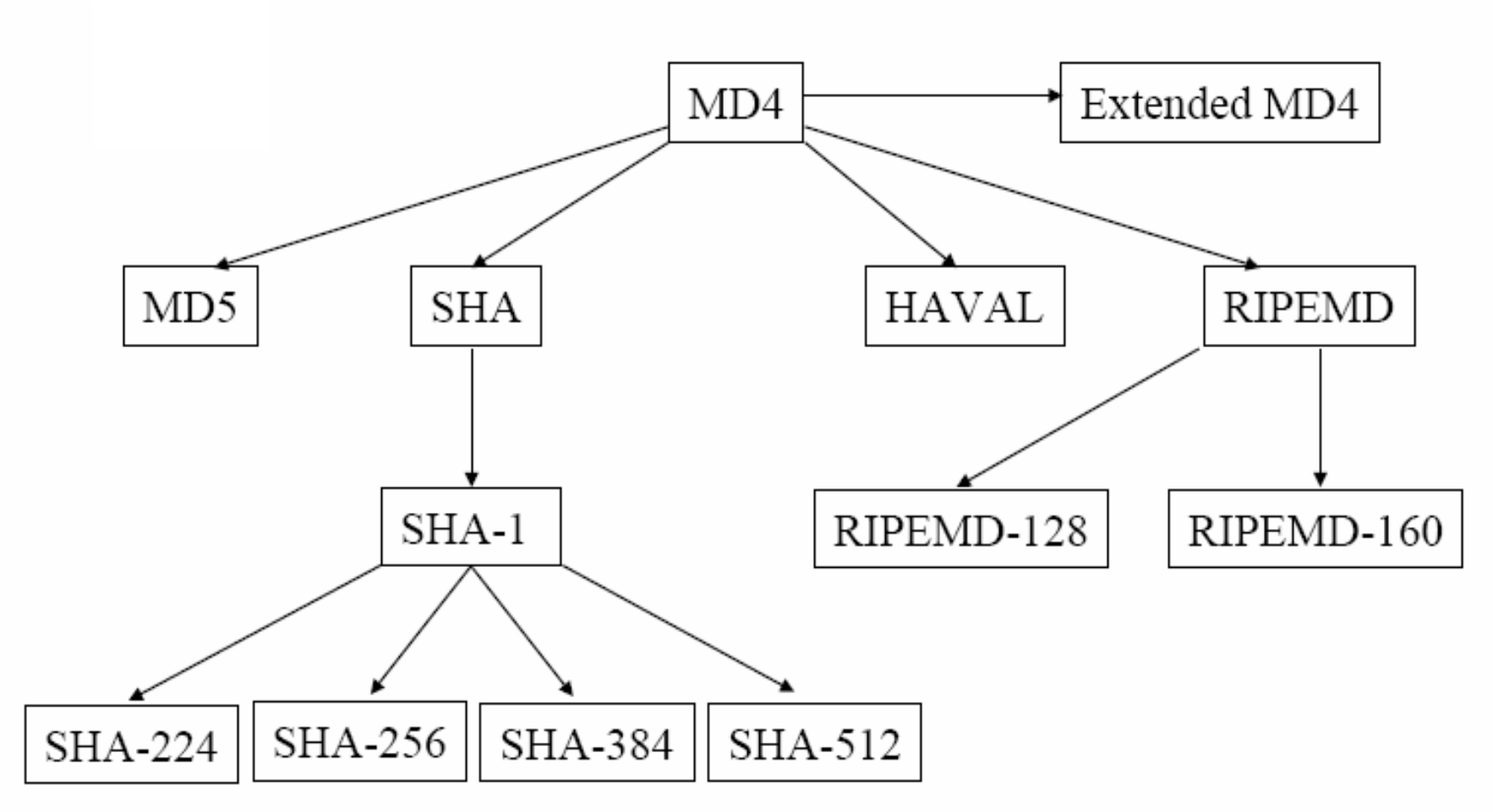
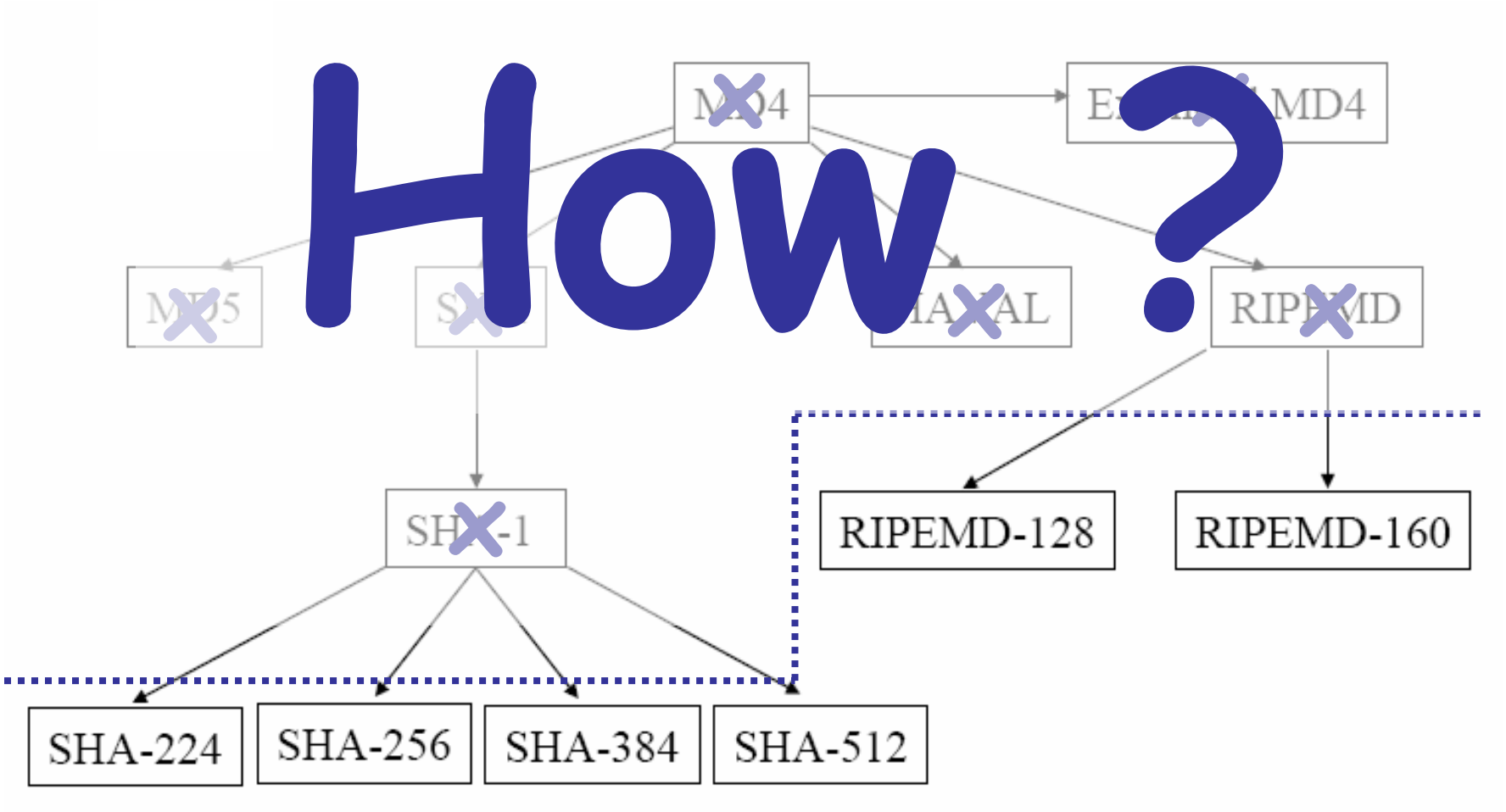
Motivation


MD4
Extended MD4
MD5
SHA
HAVAL
RIPEMD
SHA-1
RIPEMD-128
RIPEMD-160
SHA-224
SHA-256
SHA-384
SHA-512

Motivation


How?
MD4
MD4
MD5
SHA-1
HAVAL
RIPEMD
RIPEMD-128
RIPEMD-160
SHA-224
SHA-256
SHA-384
SHA-512

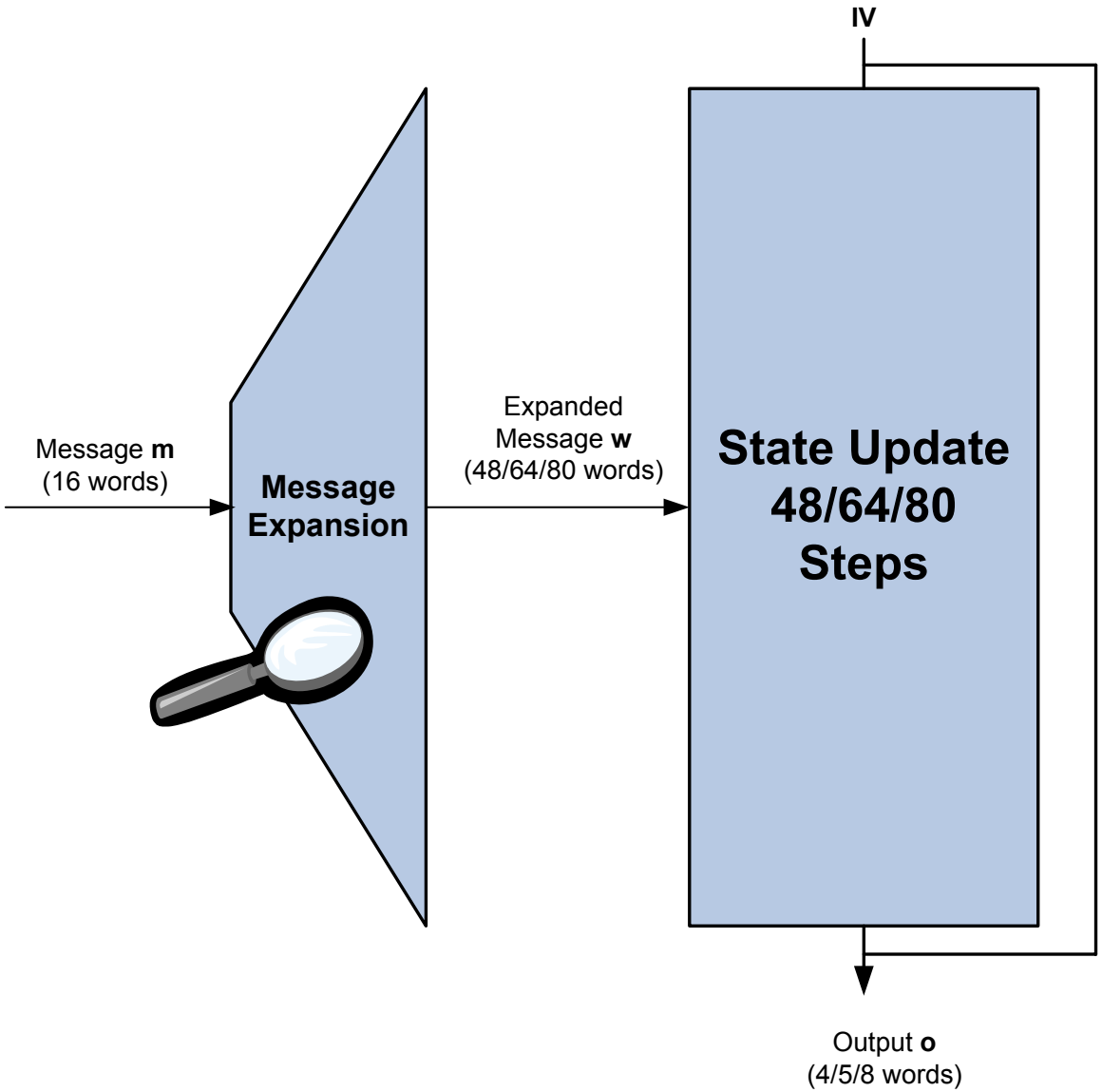
Agenda

- The MD4 “family”

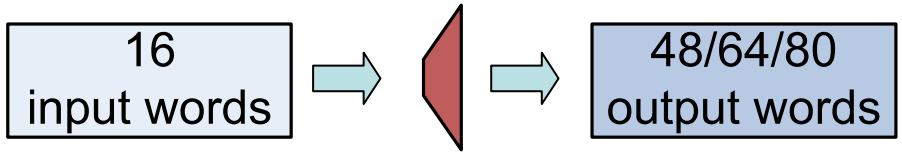
- Basic attack on SHA
- Advanced methods for fast collision search (example SHA-1) and applications
- SHA-2?

- Conclusions

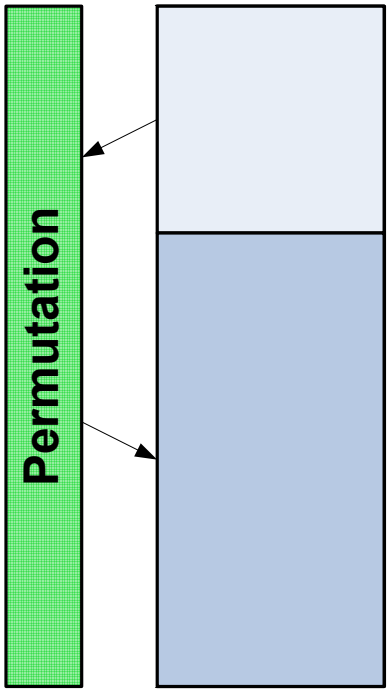
Outline of MD4-style Hash Functions



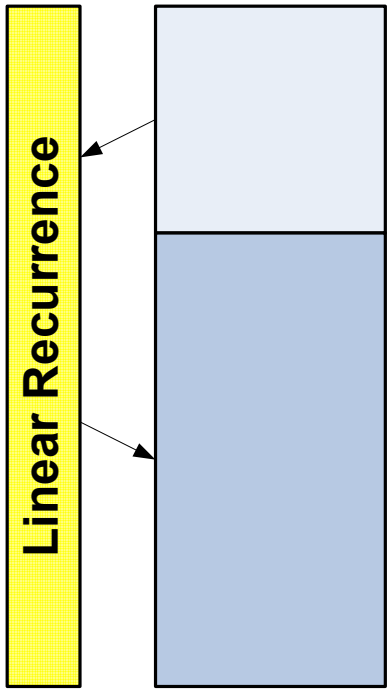
Message Expansions in the MD4 family



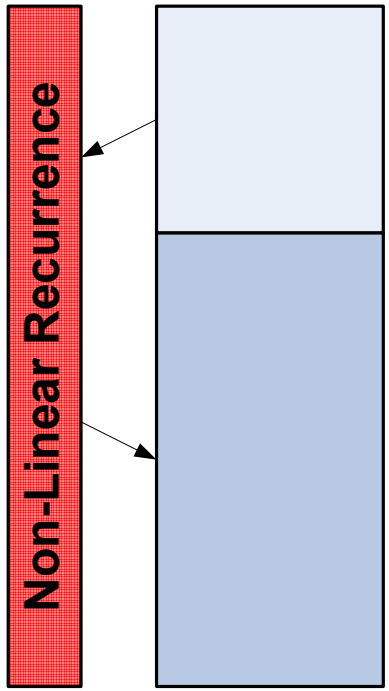
MD4/5, RIPEMD



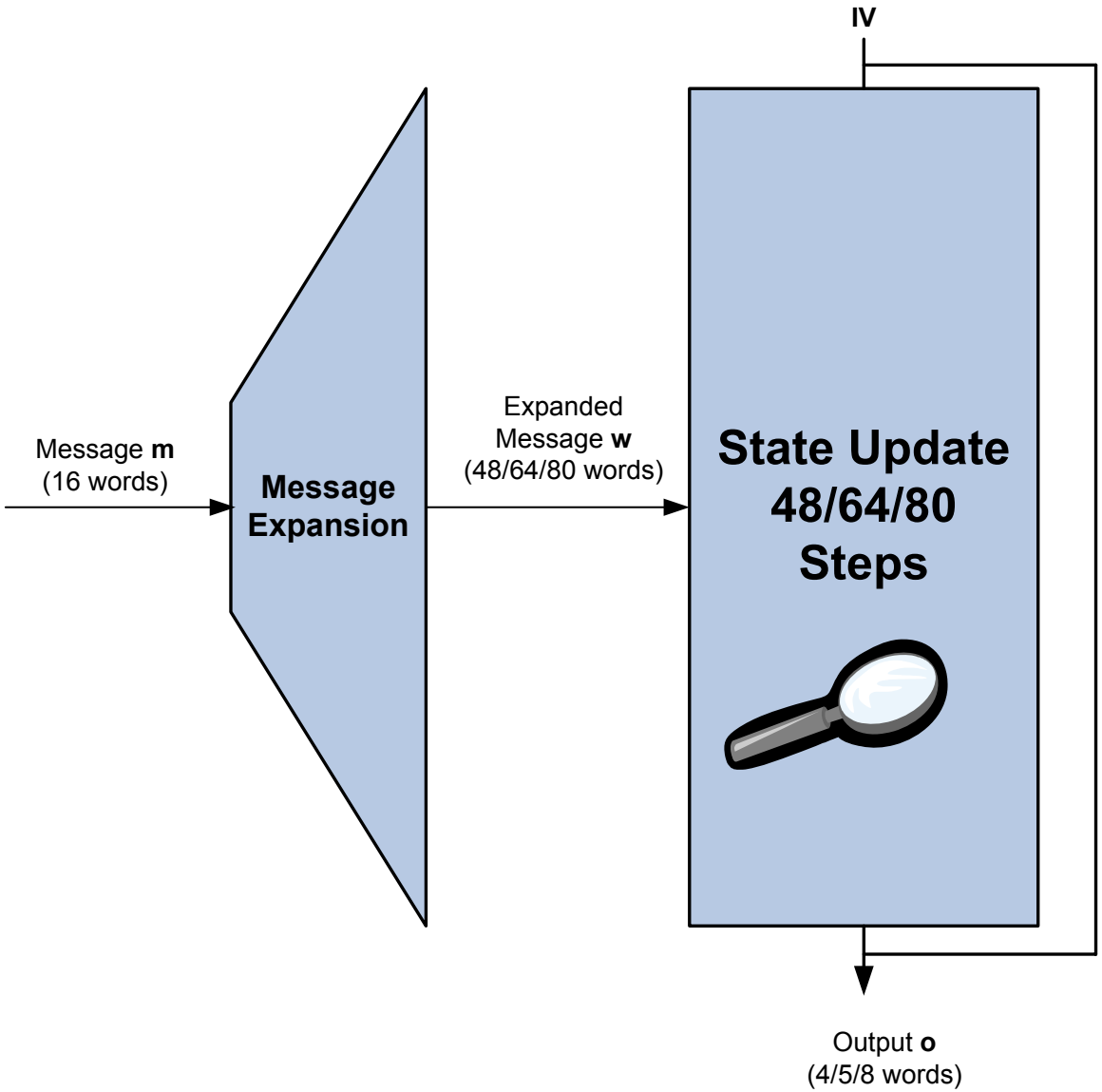
SHA / SHA-1



SHA-2 members

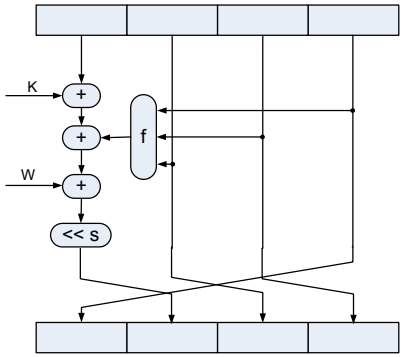


Outline of MD4-style Hash Functions

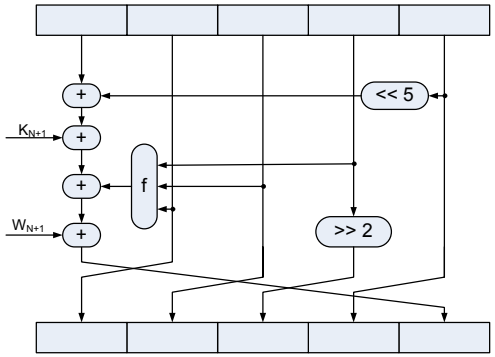


Evolution of the State Updates in the MD4 Family

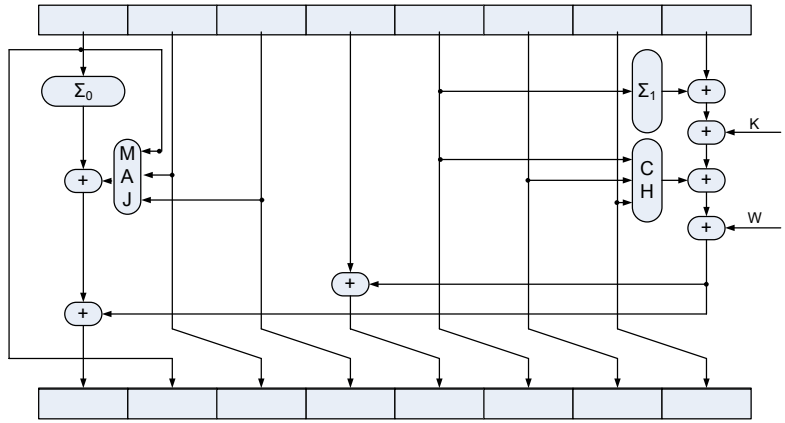
MD4



SHA/SHA-1



SHA-2 members



Design Complexity

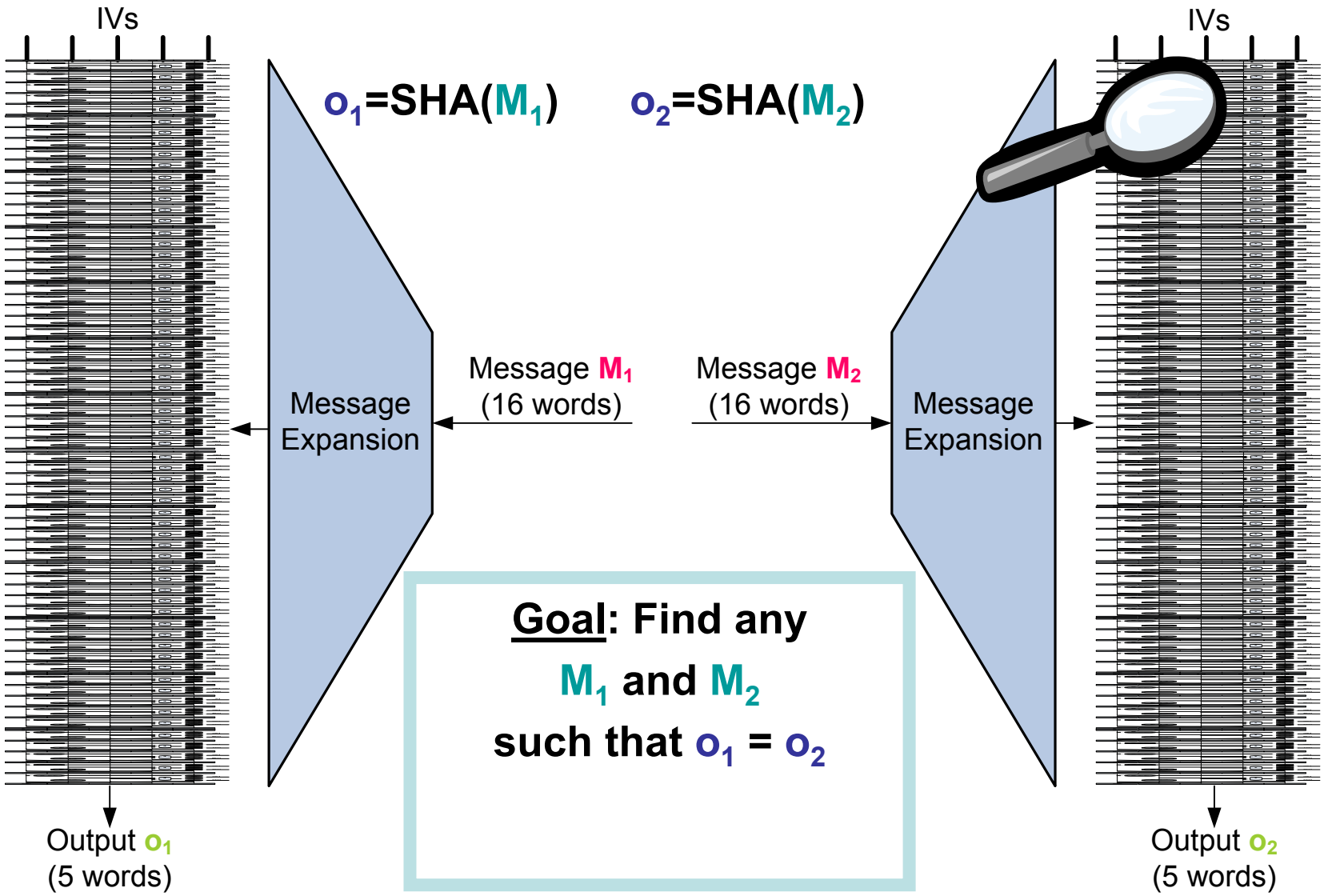
Cryptanalysis of MD4

- Several people have shown weaknesses in the compression function of MD4
  - Merkle [Mer90]
  - Bosselaers and den Boer [BB91]
  - Vaudenay [Vau94]
  - Dobbertin [Dob96]
- Dobbertin's techniques received the most attention in the scientific community [Dob98]
  - Lead to a fast collision-producing algorithm
  - Even (partially) meaningful collisions can be produced

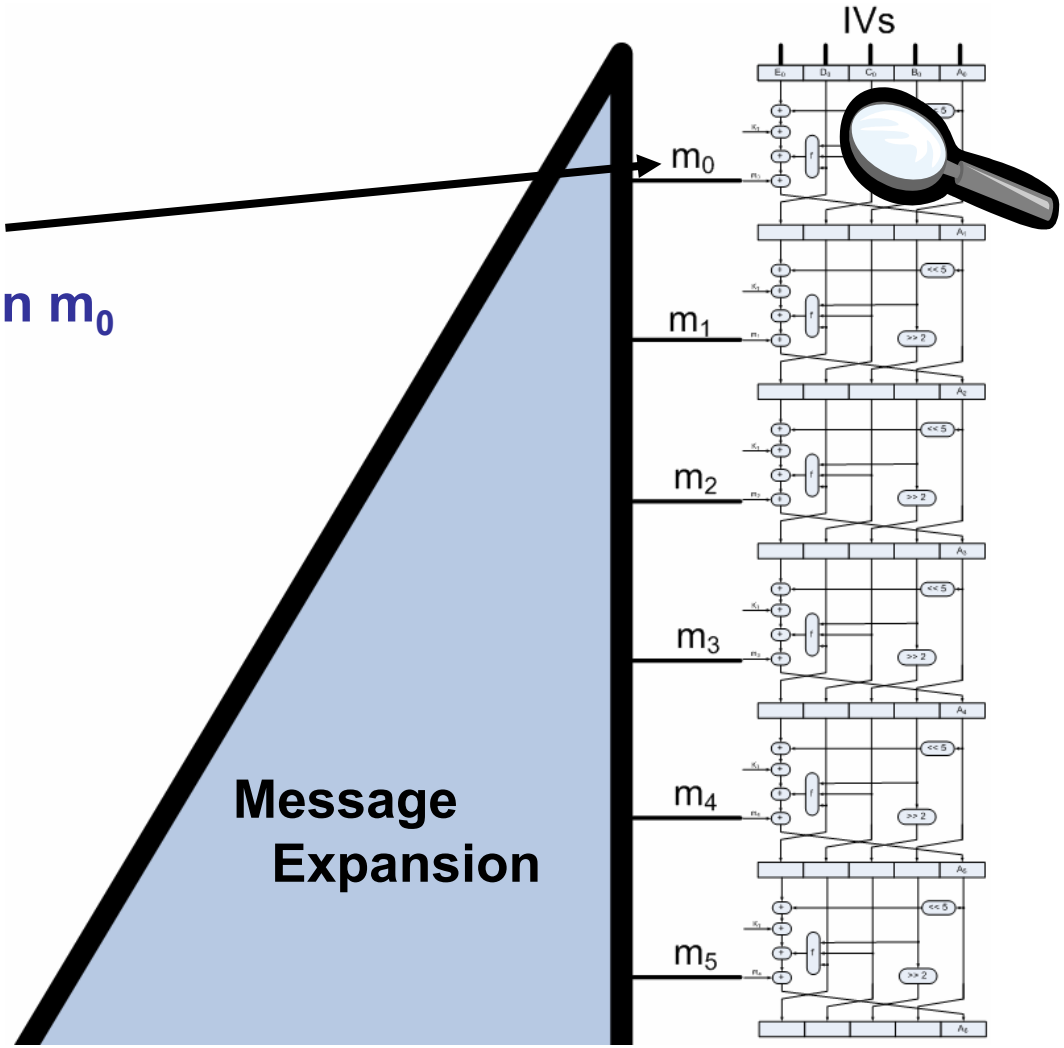
Cryptanalysis of SHA

- SHA
  - Chabaud and Joux [CJ98]
  - Biham and Chen [BC04]
  - Joux et al. [BCJ+05]
  - Wang et al. [WYY05a]
- SHA-1
  - Rijmen and Oswald [RO05]
  - Biham and Chen [BCJ+05]
  - Wang et al. [WYY05b]
  - De Cannière and Rechberger [DR06]

How to produce a collision?

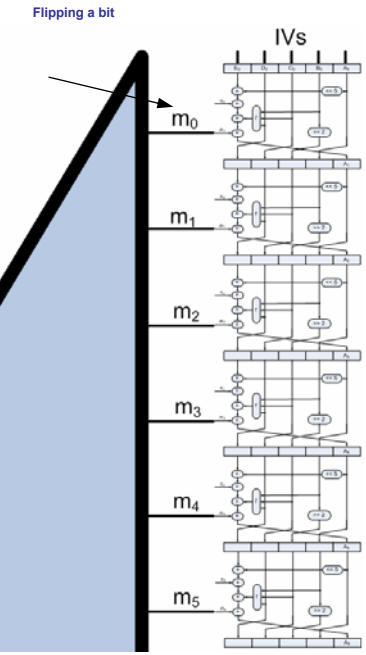


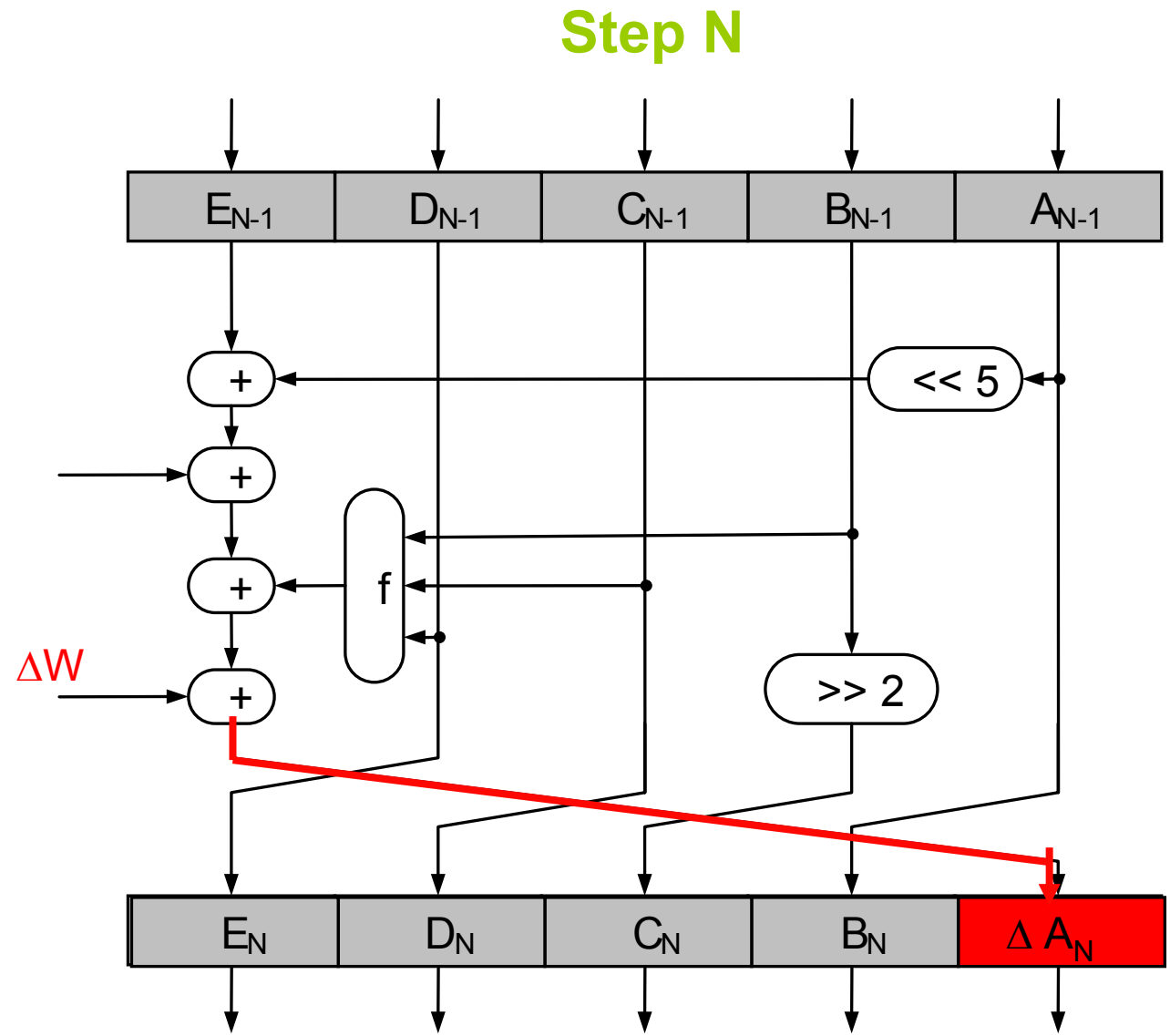
Propagation of a small difference



Flip a bit in m_0

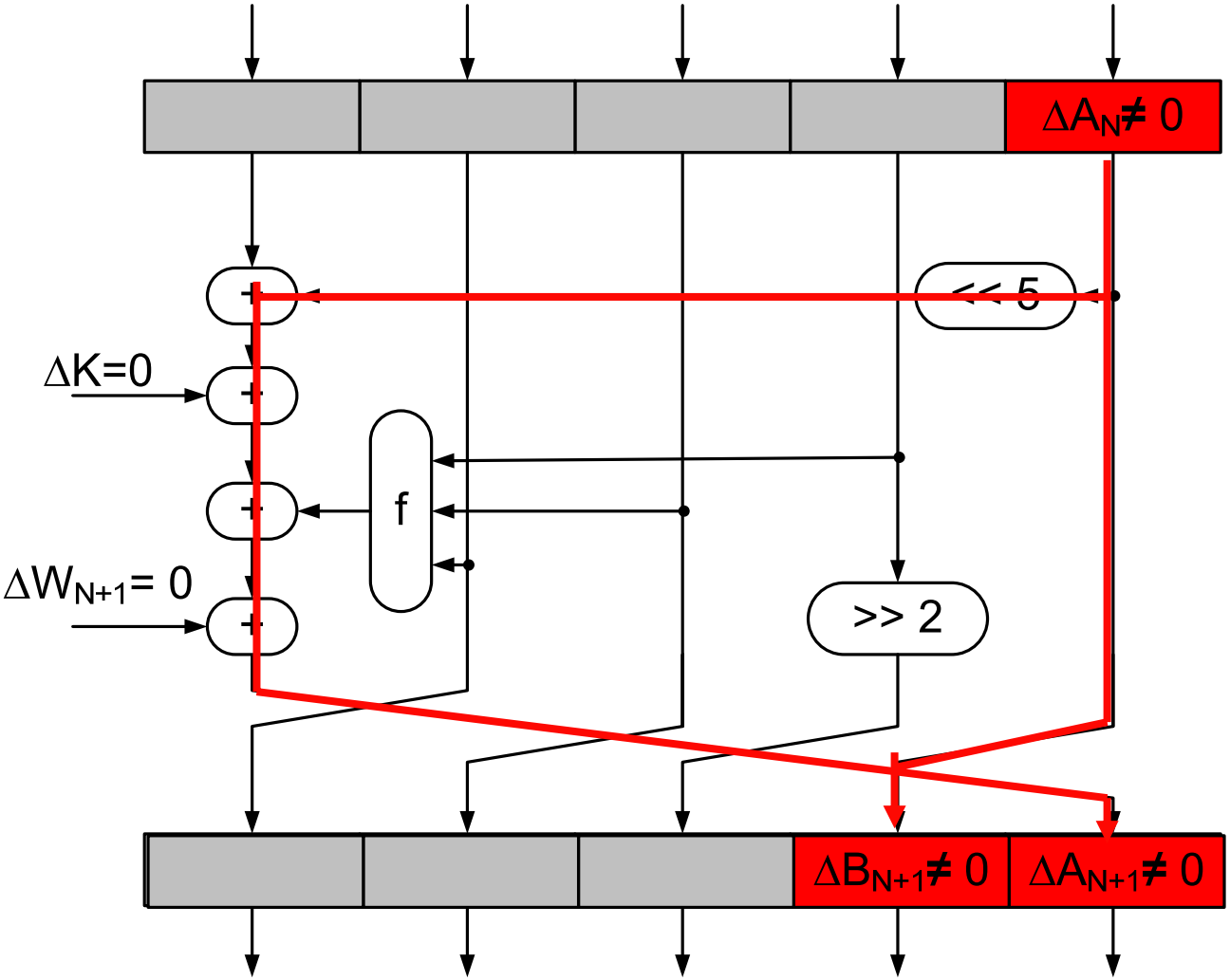
Propagation of a small difference





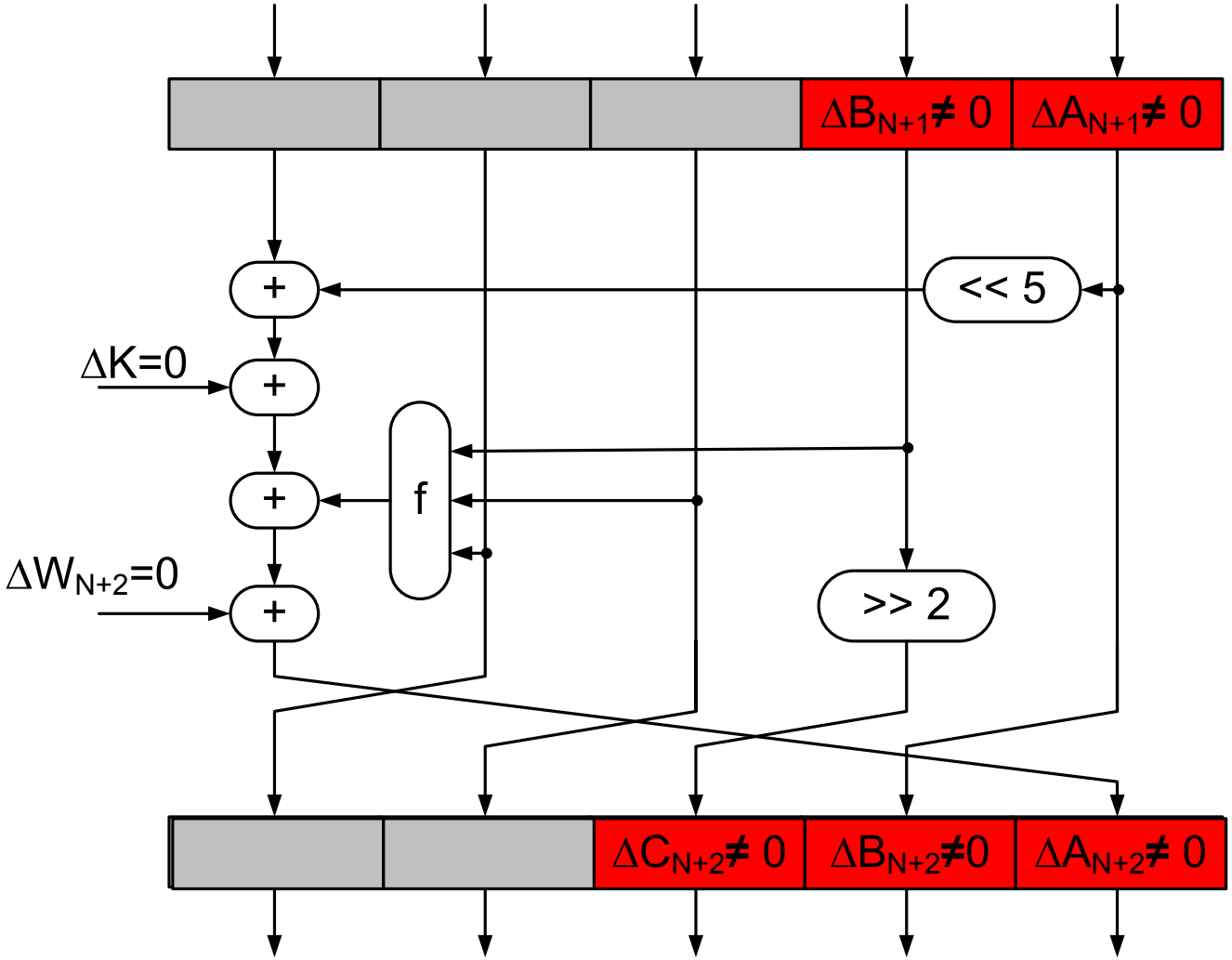
Propagation of a small difference

Step N+1



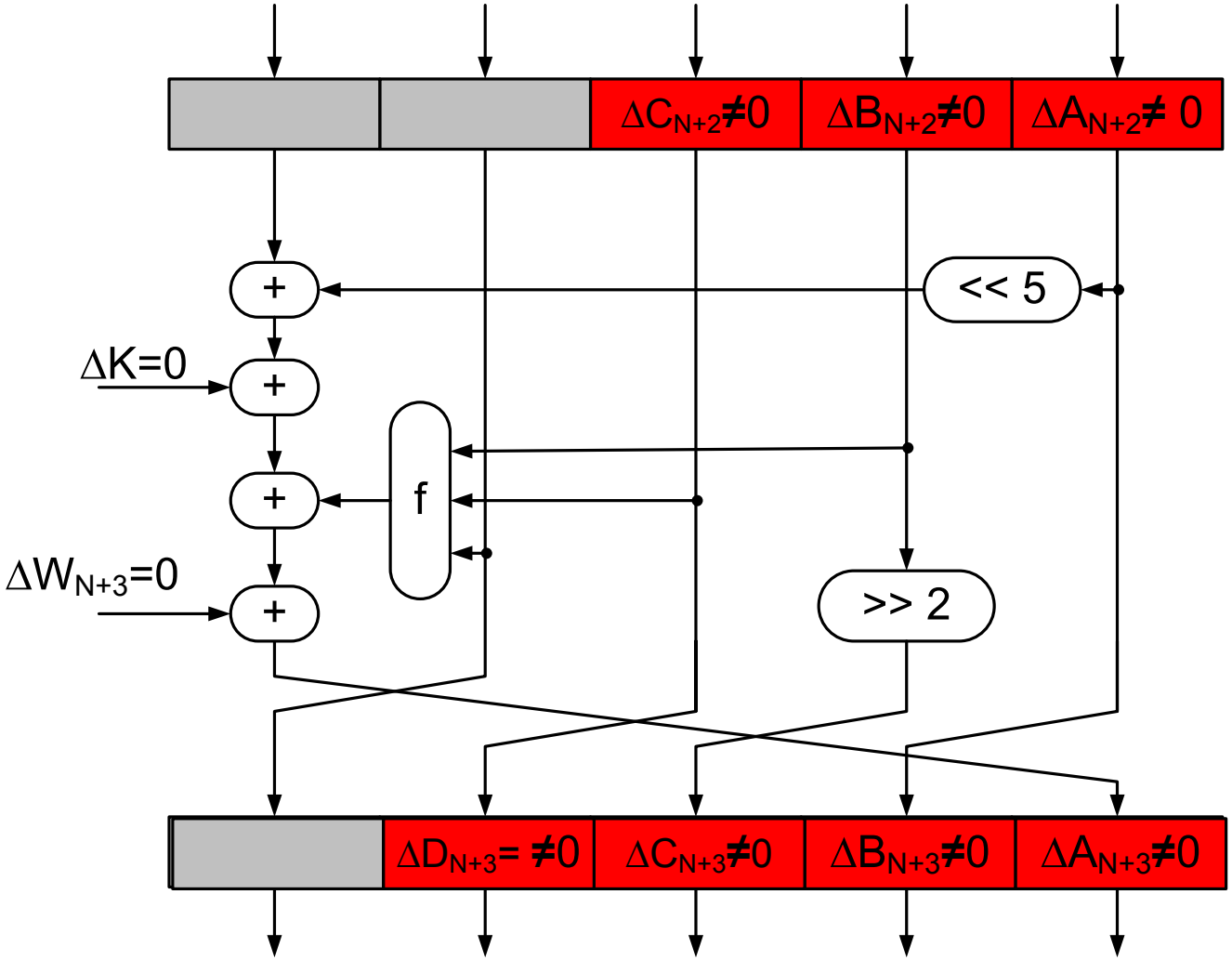
Propagation of a small difference

Step N+2

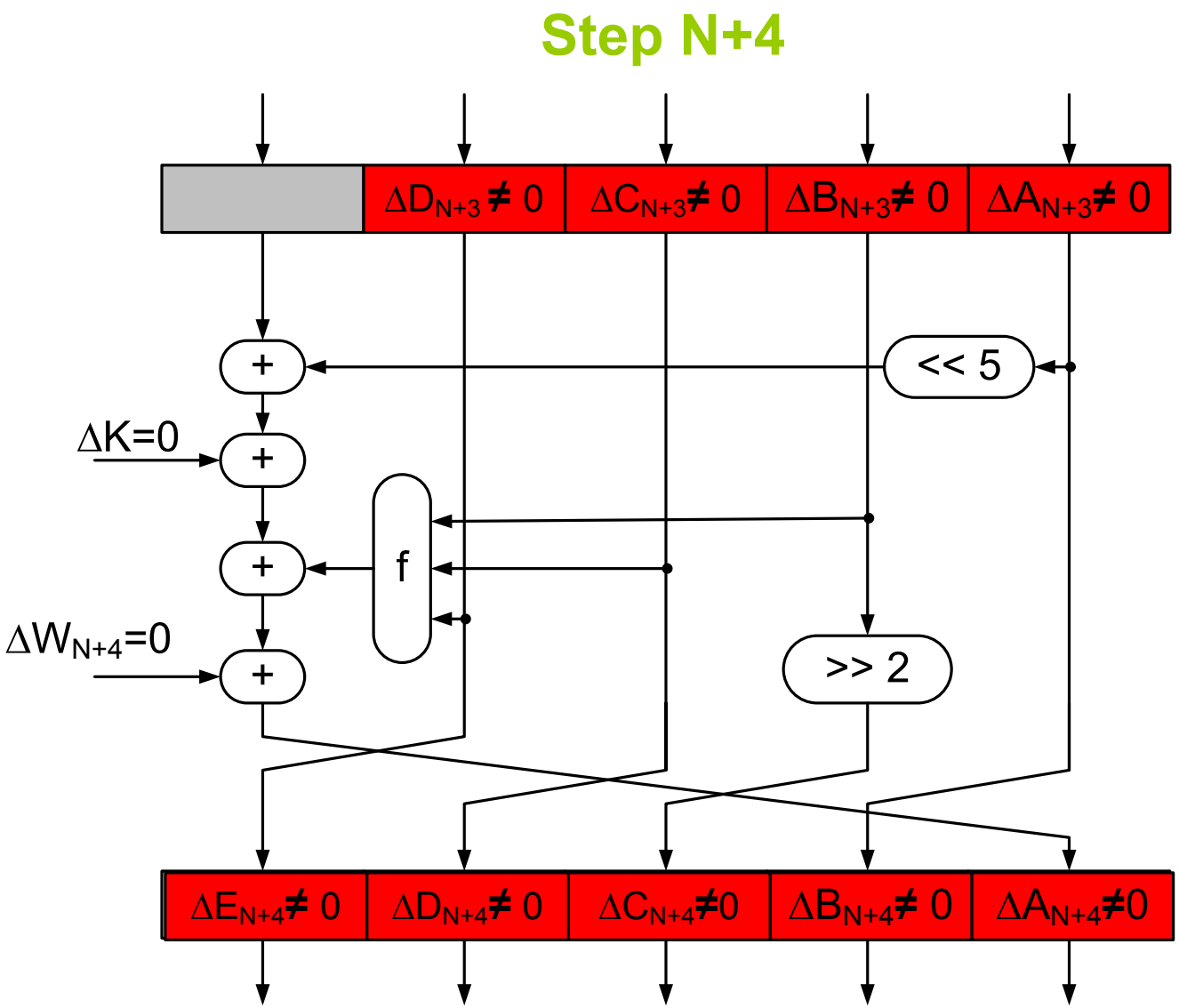


Propagation of a small difference

Step N+3



Propagation of a small difference



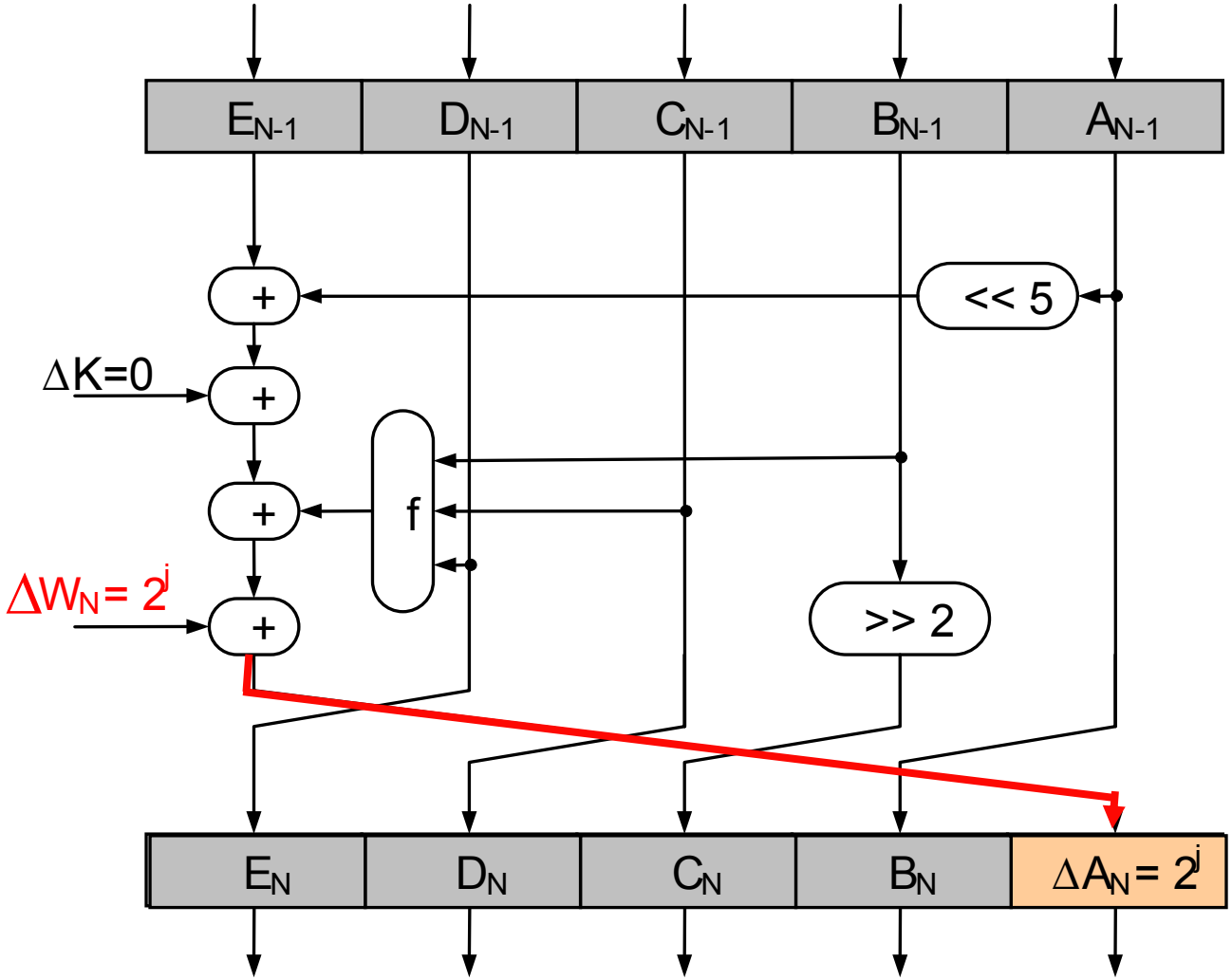
Differential cryptanalysis of SHA

- Small differences quickly expand
- Approach by Chabaud & Joux [CJ98]
  - Perturbations and corrections
  - Theoretical attack on SHA
  - Later on improved to practical attack [BCJ+05]

- Difference = XOR operation

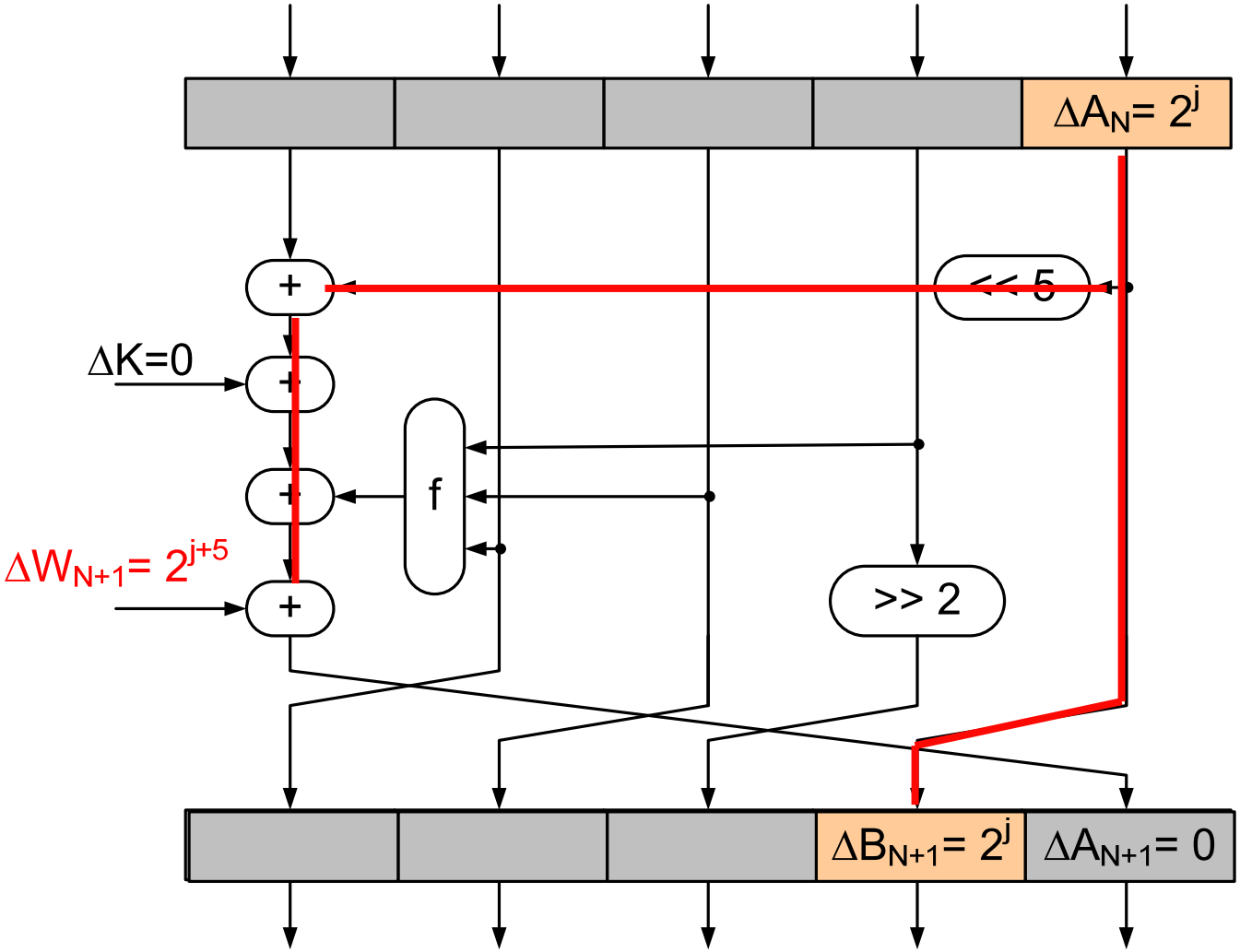
Perturbation

Step N



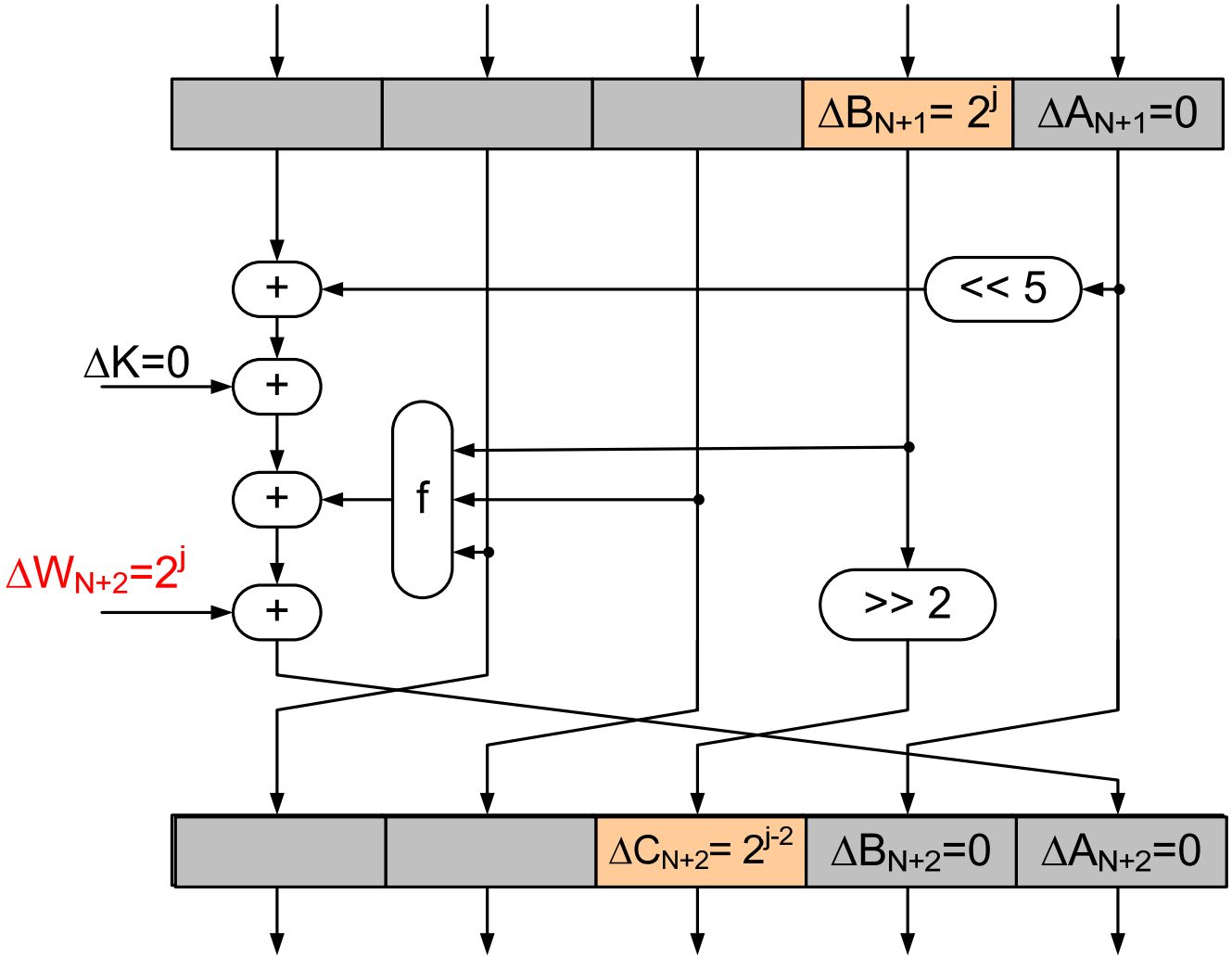
Correction 1

Step N+1



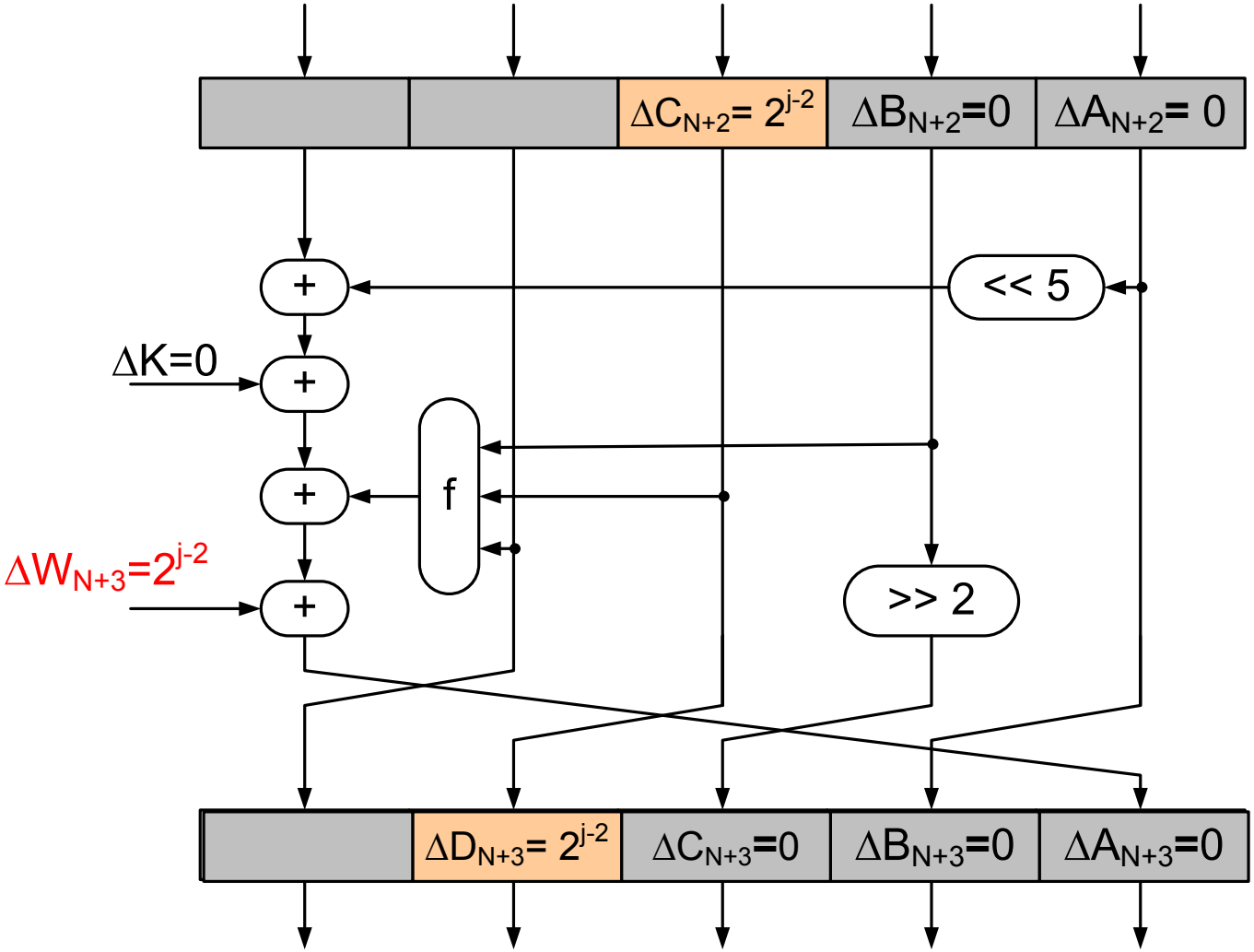
Correction 2

Step N+2



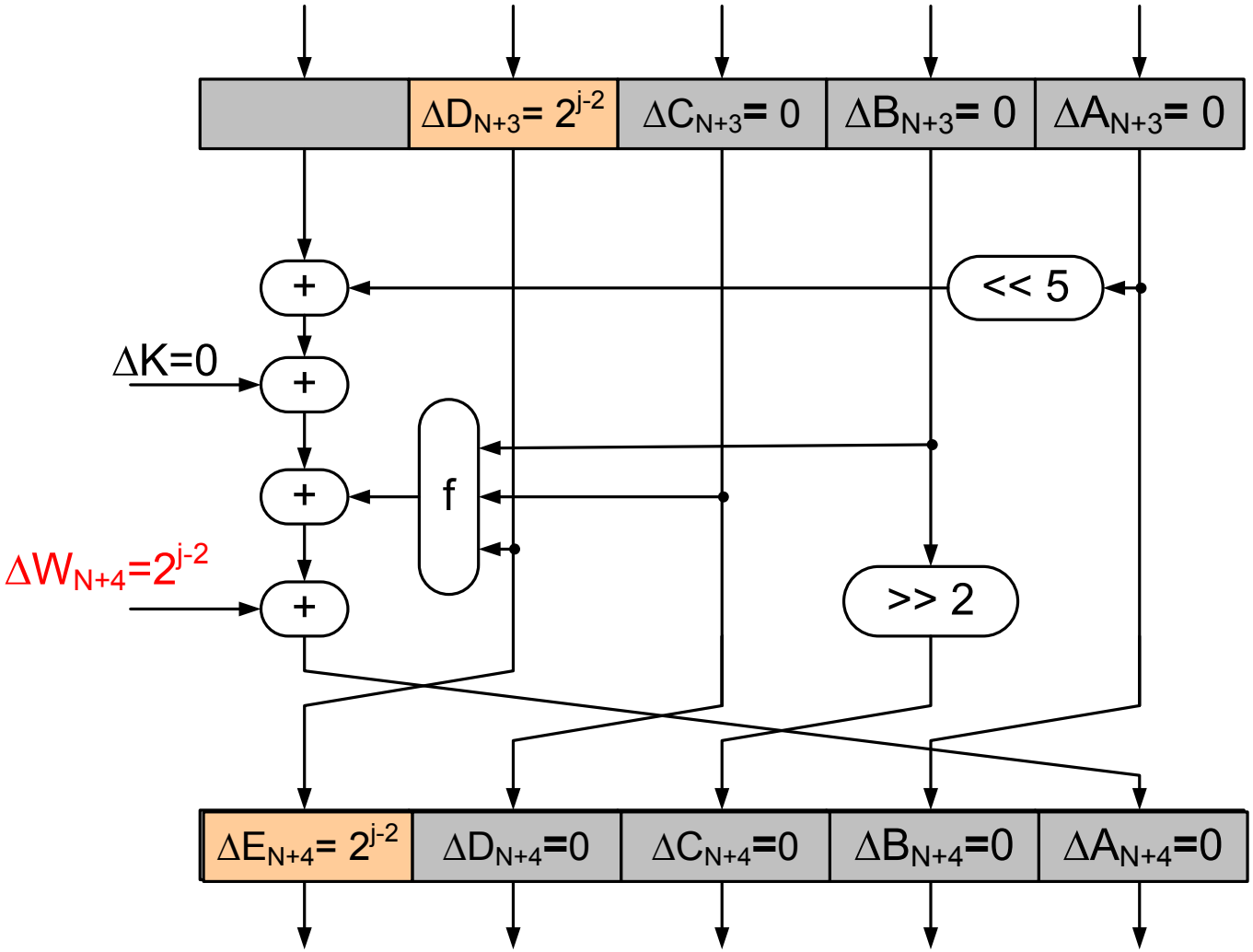
Correction 3

Step N+3



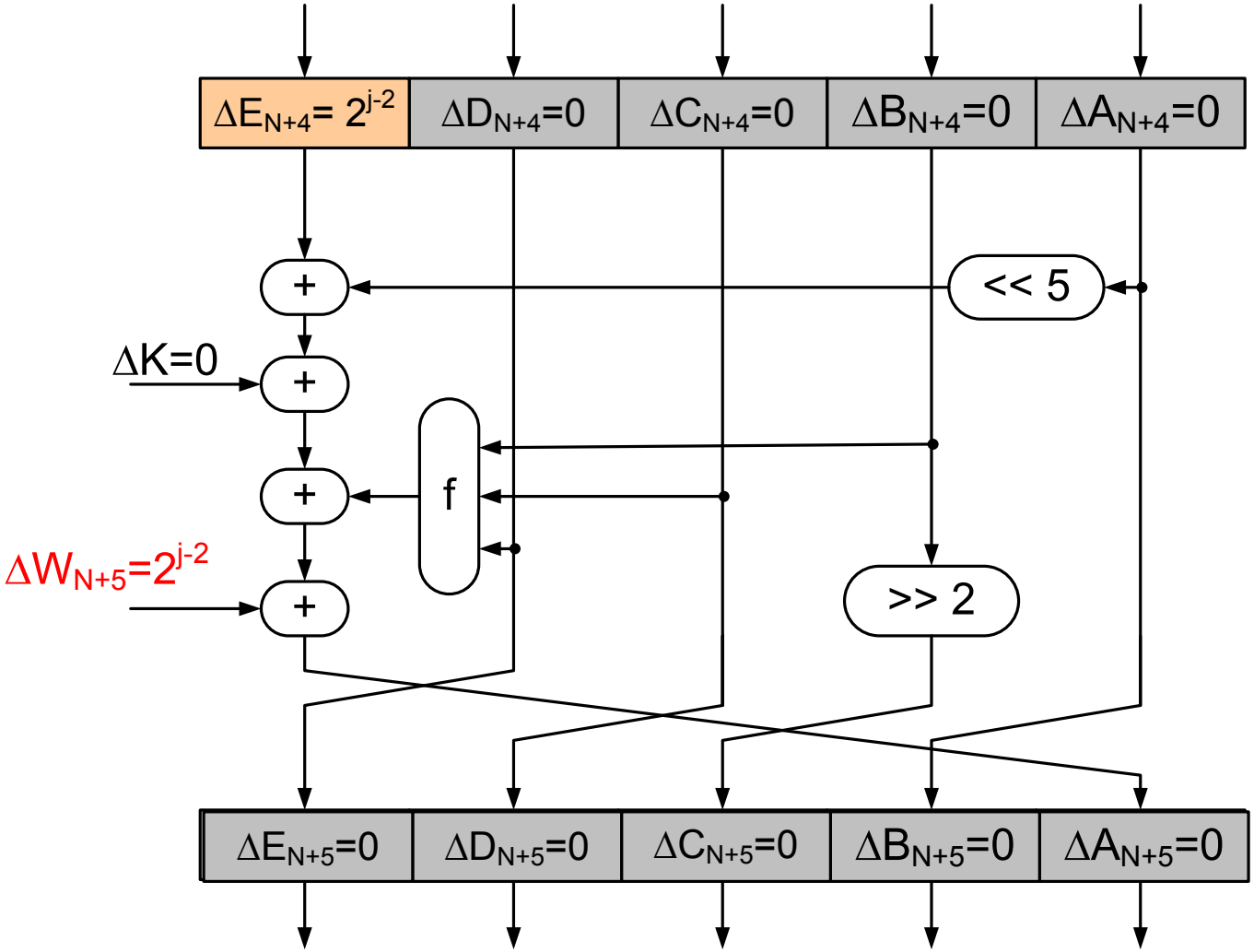
Correction 4

Step N+4



Correction 5

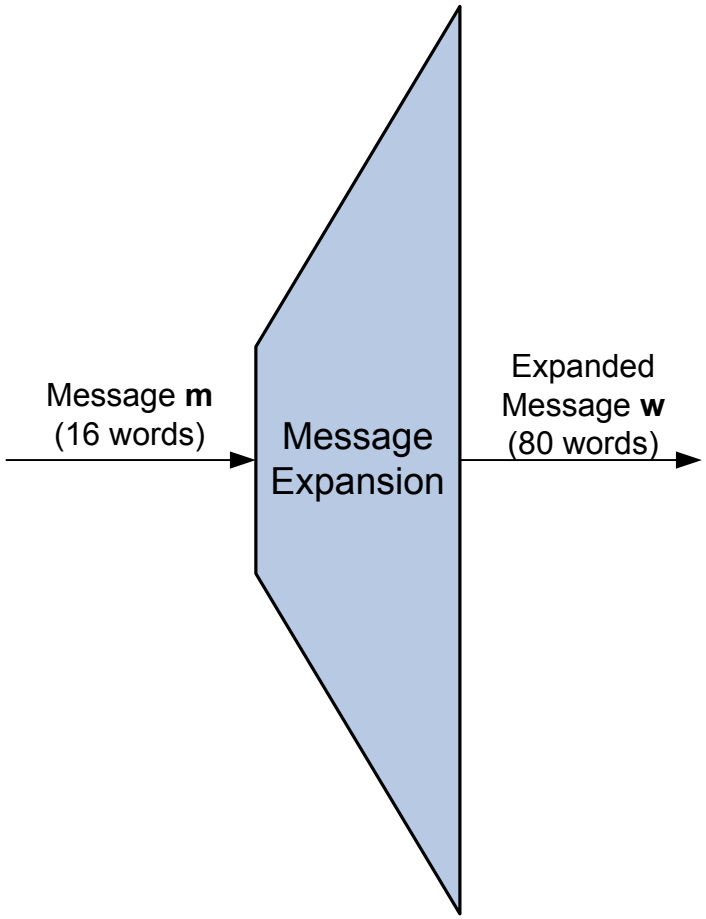
Step N+5



Local collision

- Resynchronisation of internal state
- One perturbation and 2-5 corrections
- Creating local collisions is not so difficult
- Problem: message expansion

Outline of SHA – Message Expansion



SHA

$$W_t = \begin{cases} M_t & for\,(0 \le t \le 15) \\ W_{t-3} \oplus W_{t-8} \oplus W_{t-14} \oplus W_{t-16} & for\,(16 \le t \le 79) \end{cases}$$

SHA-1

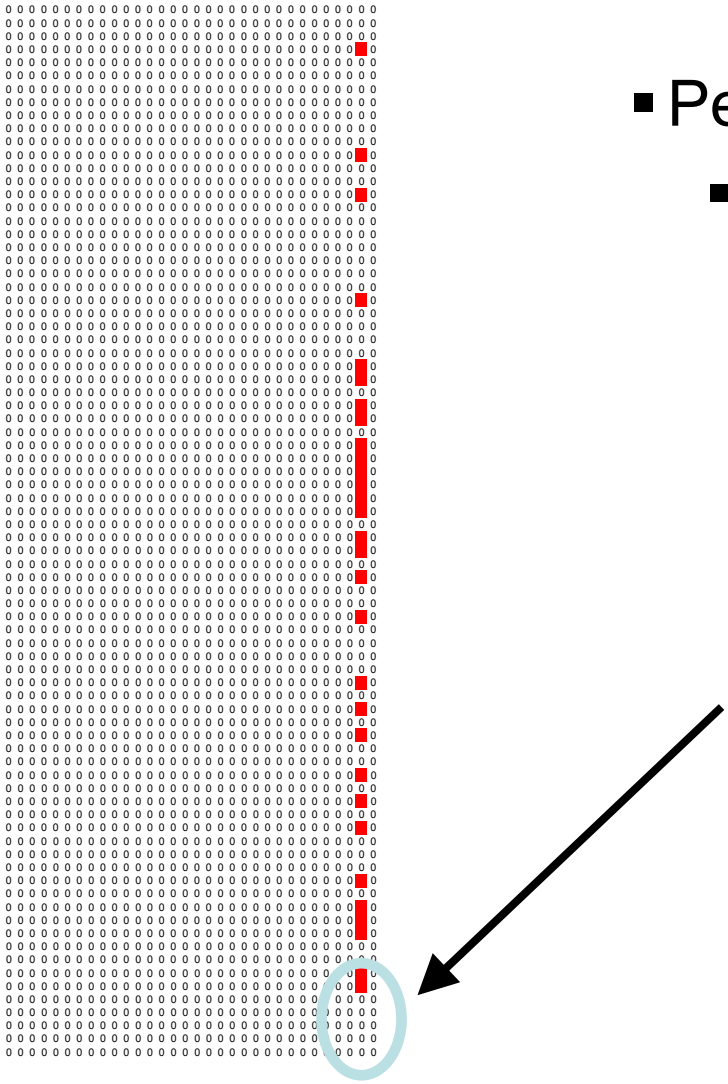
$$W_t = \begin{cases} M_t & for\,(0 \le t \le 15) \\ (W_{t-3} \oplus W_{t-8} \oplus W_{t-14} \oplus W_{t-16}) <<1 & for\,(16 \le t \le 79) \end{cases}$$

Message expansion

- Every bit changed influences other bits
- Impossible to find m_1, m_2 such that ME(m_1), ME(m_2) differ in 3-6 bits only

- Constructing a global collision = finding good characteristic

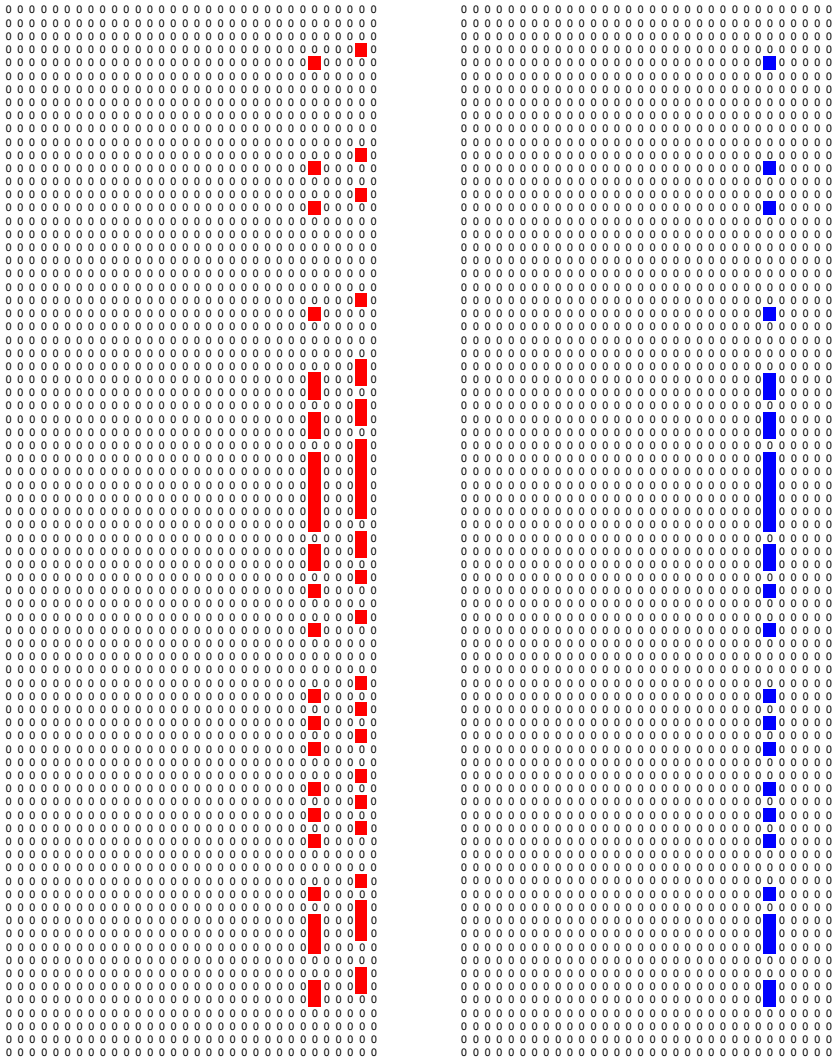
Building a collision for SHA



- Perturbation pattern
  - Low weight

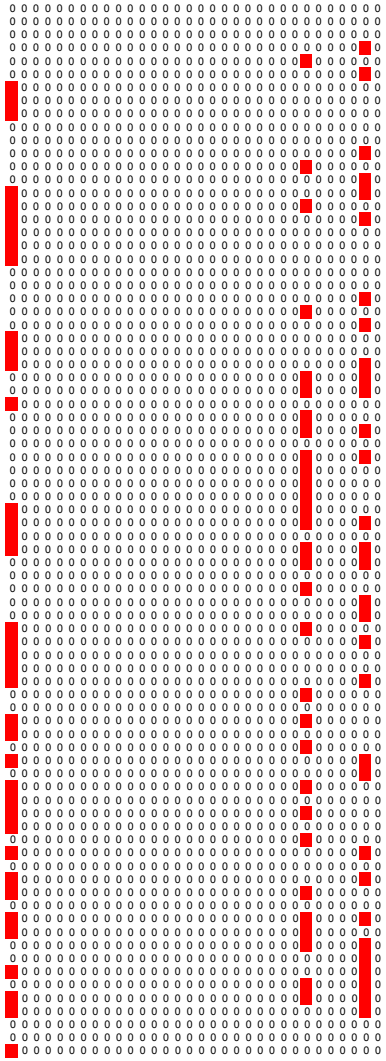
$$W_t = W_{t-3} \oplus W_{t-8} \oplus W_{t-14} \oplus W_{t-16}$$

A collision-producing difference pattern



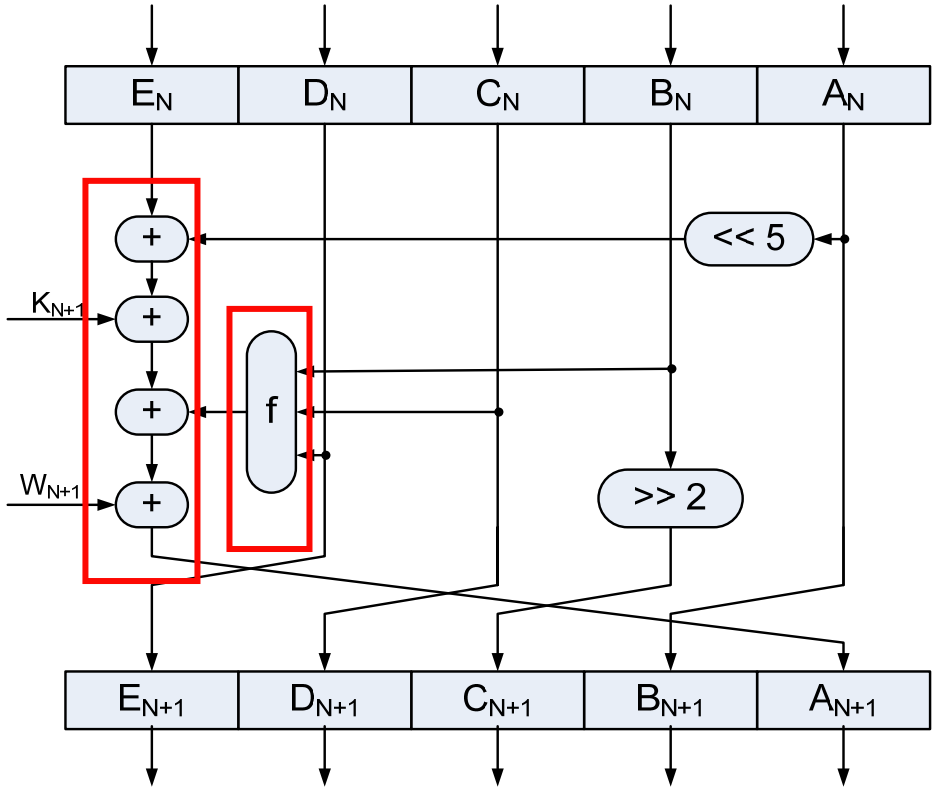
- Apply 5 corrections with the same pattern
  - displaced over steps
  - rotated over bit positions

A collision-producing expanded-message difference pattern



- Completed difference pattern consisting of
  - 1 perturbation pattern
  - 5 correction patterns

Conditions imposed by nonlinear elements



- Boolean function f
- Modular addition

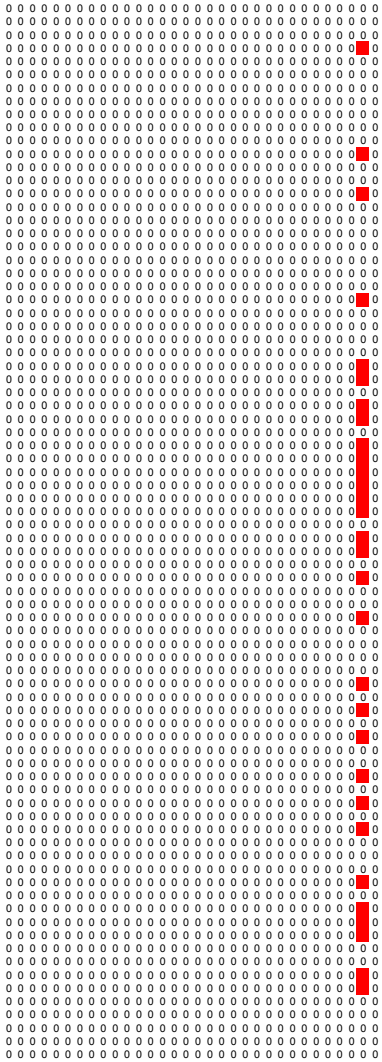
Modular addition

- Linear except for carry effects
  - Carry = 0 with probability 1/2
  - Carry moves upwards only
  - No carry from MSB
- Requirement: difference propagation as with XOR

Boolean functions

- Linear in 40 out of 80 steps
- Bitwise parallel: every input bit affects 1 output bit
- We set as requirement: difference propagations as with XOR
  - High probability
  - Easy to find good characteristics

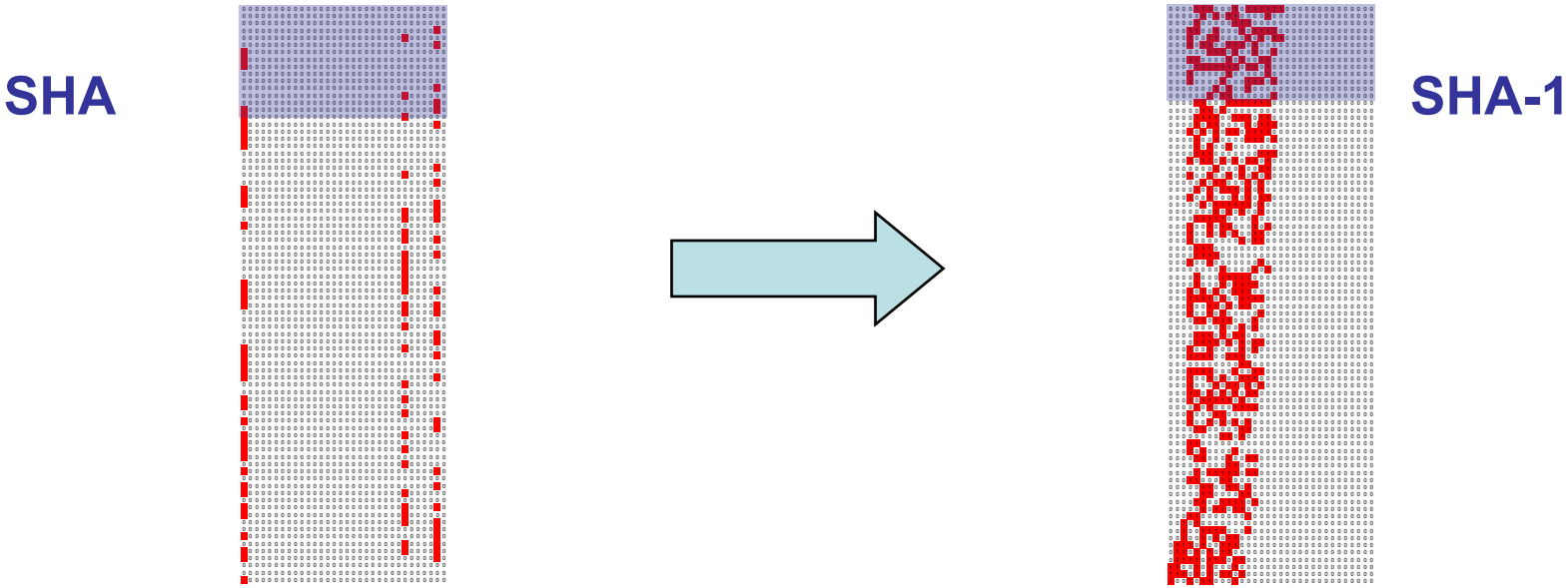
Conditions



- Every perturbation gives 2-5 conditions on the message
- Most conditions are nonlinear and complicated to express in terms of the input message
- Goal is to minimize these conditions (to make final search easier)

Results of CJ98

- Low- weight patterns exist for SHA => break

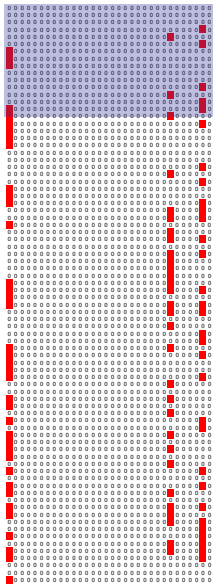


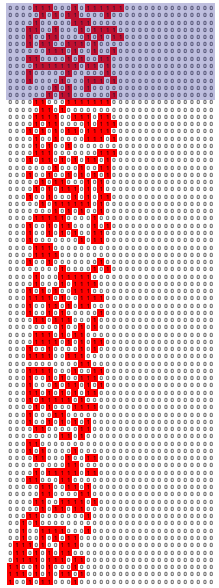
- For SHA-1: weight is too high

Results of CJ98

- Low- weight patterns exist for SHA => break

SHA





SHA-1

- For SHA-1: weight is too high

Improvements

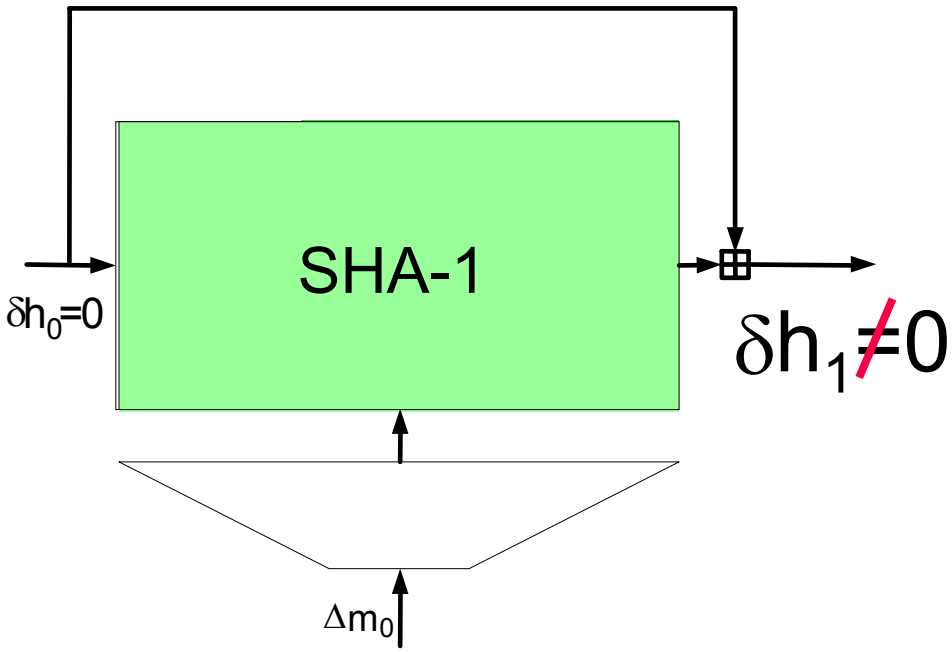
- Better characteristics
  - 1-block ➔ multi-block
  - Better suited for hash functions

- Better ways to construct right pairs
  - Message modification

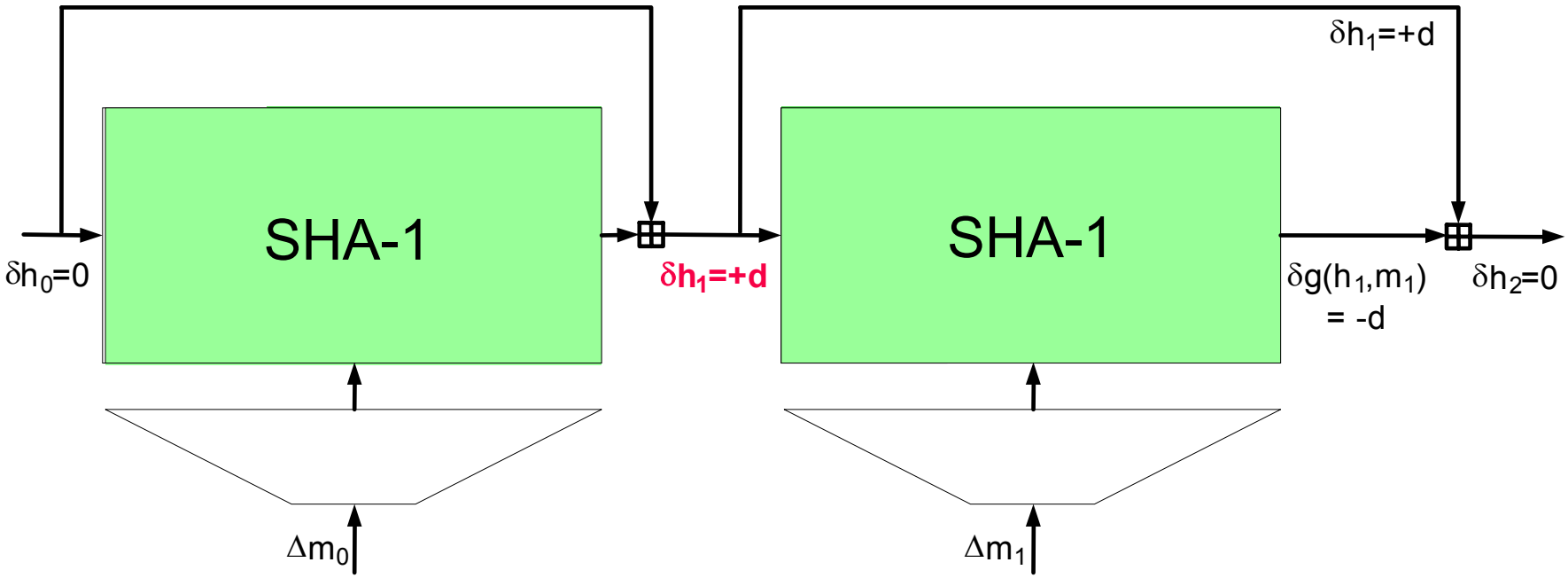
Multi-block collisions

- Near-collision: outputs differ in only a few bits
- Observation: much easier than collisions
  - Characteristics with higher probability

Use of near-collisions



Use of near-collisions

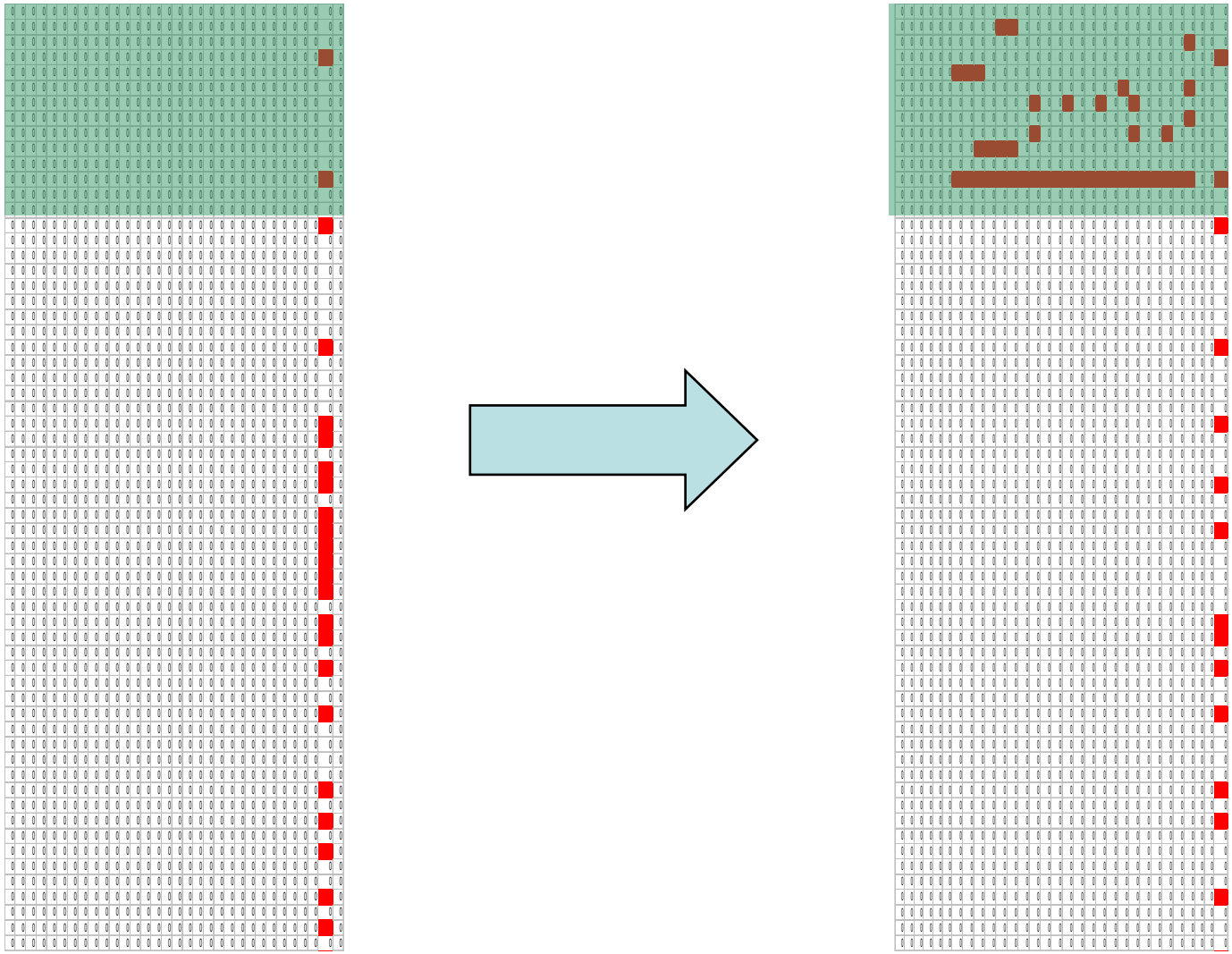


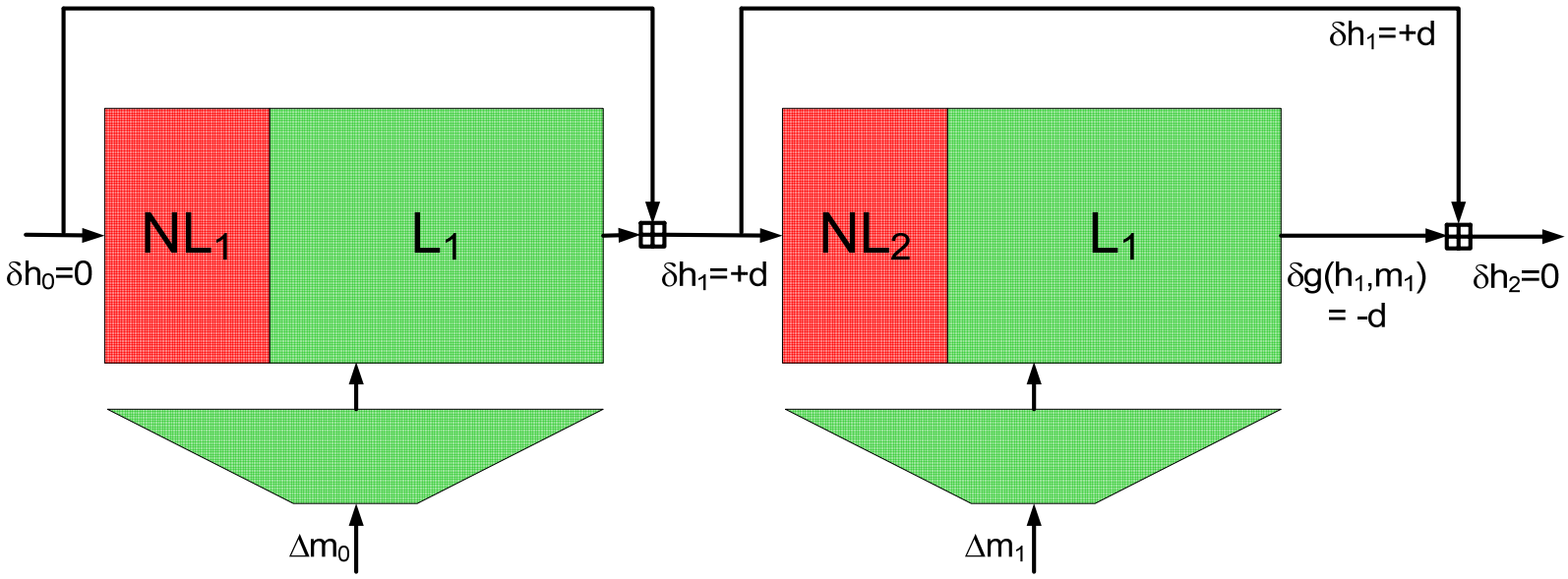
- Two related near-collisions give a 2-block collision
- Work effort of two blocks is only double of one block

Differential attacks on hash functions

- Good characteristics for block ciphers:
  - Optimise probability
  - Minimise number of chosen plaintexts
- Good characteristics for hash functions
  - Optimise probability
  - Minimise effort to solve equations
  - Equations in first steps are always easy
    - Only a small part of the message involved
    - Inputs are known
    - Late start / Early stop

Good characteristics





- Two key techniques of Wang et al.:
  - Manually find suitable complex characteristic NL_1 and NL_2
  - Advanced message modification to improve work factor

- Methods are rather ad hoc (manual)
- Optimization?

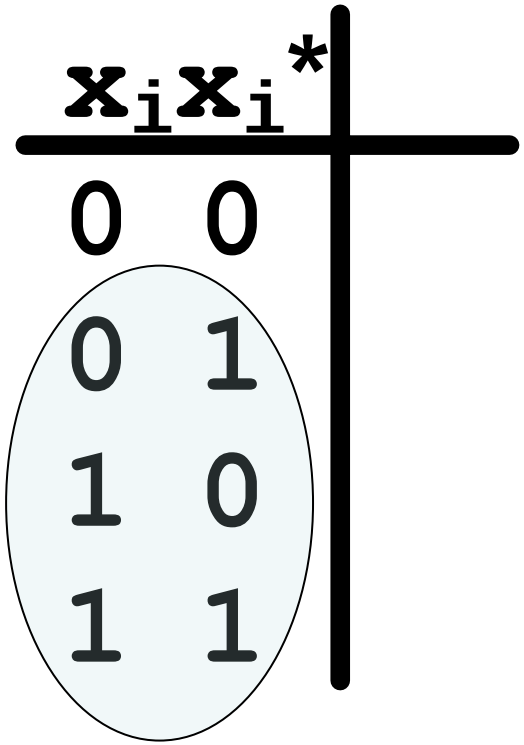
Optimising characteristic

- Optimise probability after step 16
- Before step 16
  - Concentrate low probability in few steps
  - More difficult search problem
    - Manual construction [WYY05b]
    - Automatic tools [DR06]

How does it work?

Principles

- Generalized conditions



Type	Possibilities
XOR	2
Signed-bit	4-6
Generalized:	**16**

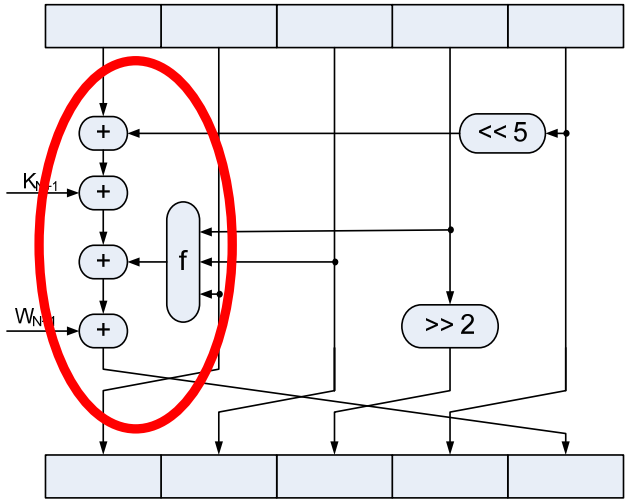
Generalized Conditions - Notation

(x_i, x_i^*)	$(0,0)$	$(1,0)$	$(0,1)$	$(1,1)$
?	✓	✓	✓	✓
-	✓	-	-	✓
x	-	✓	✓	-
0	✓	-	-	-
u	-	✓	-	-
n	-	-	✓	-
1	-	-	-	✓
#	-	-	-	-

Principles

- Generalized conditions

- Use “bit-sliced design” to efficiently
  - Propagate conditions *within one* step transformation
  - Propagate conditions *among all* step transformations



Animated Illustration

Key properties of new approach [DR06]

- Looks for (parts of) the colliding pair and characteristic at the same time
- *Precise* calculation of probabilities
  instead of approx. by HW and counting conditions
- Available degrees of freedom can be used to
  - Direct improvements of probability (Greedy approach)
  - Facilitate final search method for a right pair
  - Fix part of the colliding message on beforehand and/or during final search (meaningful)

Constructing right pairs

- Equations following from nonlinear operations
  - Every step increases the complexity
- First 15 steps: easily solvable
- Next steps: mostly guess and verify
- Solving of eqs. in steps 16 and ff.
  - Neutral-bit technique [Biham and Chen]
  - Advanced message modification [Wang et al.]
  - Symbolic computation [Sugita et al.]
  - Greedy method [De Cannière and Rechberger]
  - Boomerang method [Joux and Peyrin]

Neutral bits

- Weak diffusion
- After small number of steps, not all output bits depend on all input bits

- When trying pairs, only vary bits that don't change the outputs which are already right

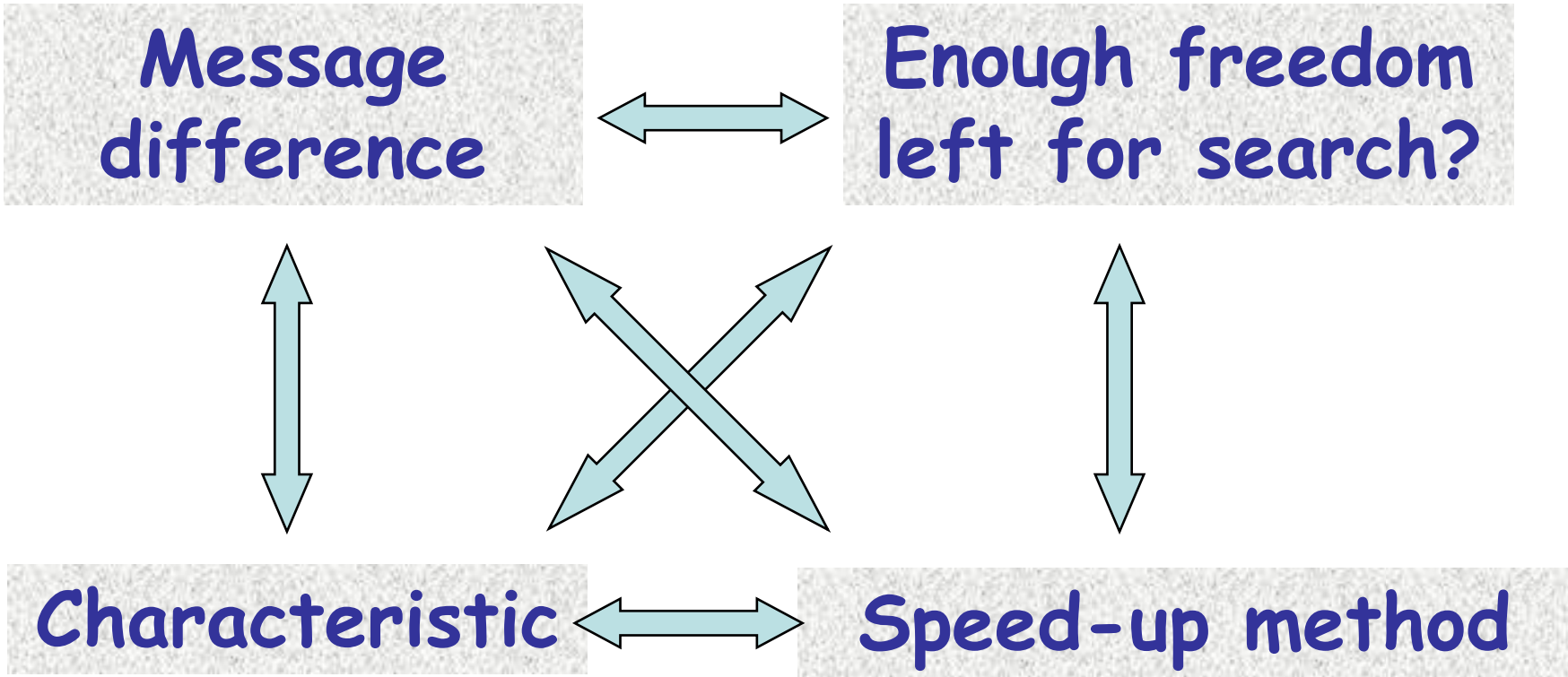
Advanced message modification

- Solve equations deterministically
  - Iterative solving strategy
- Again helped by weak diffusion

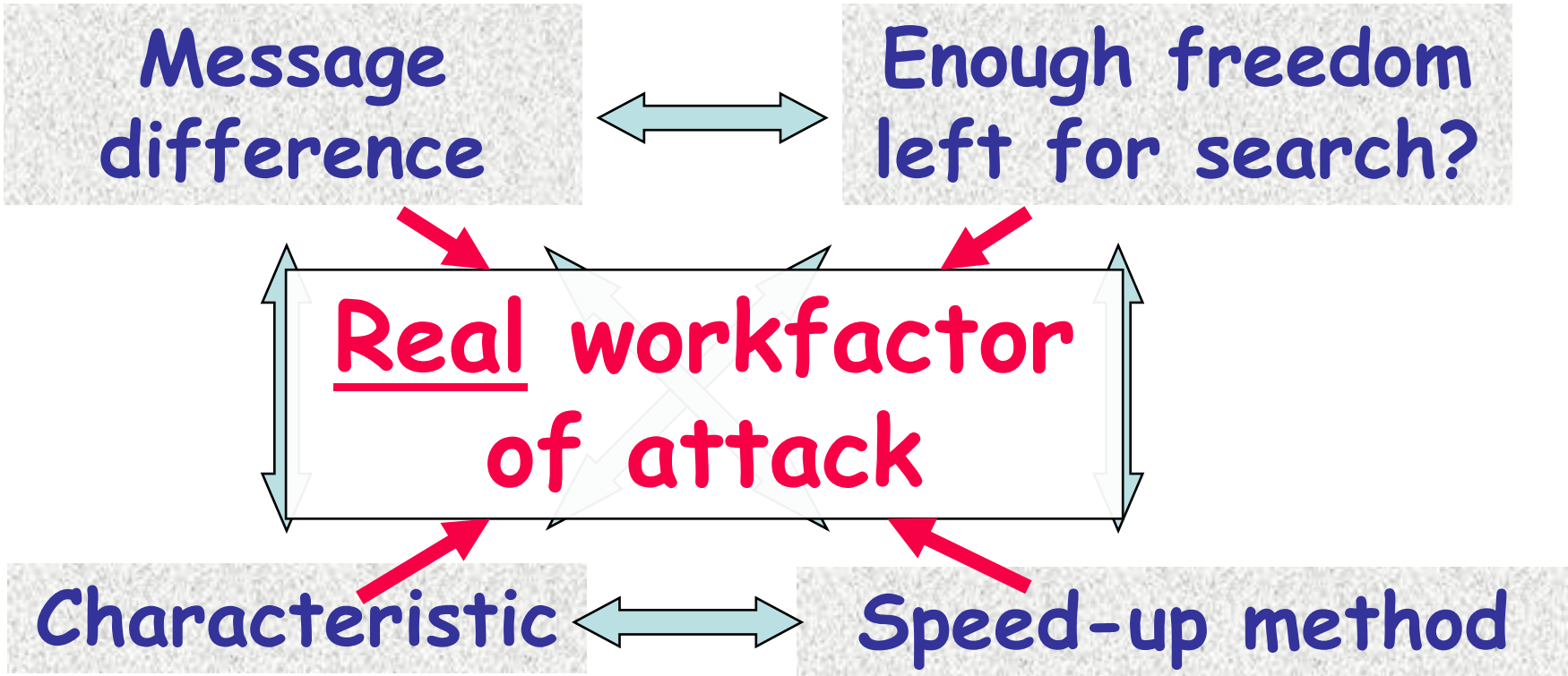
- Results for SHA/SHA-1
  - Up to 25 steps with manual optimization of characteristic (Wang et al., unpublished)
  - Up to 31 steps with especially restricted computer generated characteristic (ongoing work)

- Boundary: we need to leave some degrees of freedom for last phase

Problem of optimization



Problem of optimization



Some results

- SHA
  - 1998: 2^{61} [CJ98]
  - 2004: 2^{51} [BCJ+05]
  - 2005: 2^{39} [WYY05a]
  - 2006: 2^{36} [N+06]
- SHA-1
  - 2005: 58 steps 2^{33} [WYY05b]
  - 2006: 64 steps 2^{35} [DR06]
  - 2007: 70 steps 2^{44} [DMR07]

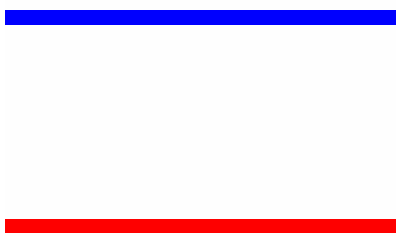
Meaningful Collisions - Motivation

- Setting: Collisions for a hash function can be constructed

- Cryptanalyst perspective: Some more interesting things to find out w.r.t. collision resistance?
  - Constructing collisions **faster**
  - Finding and exploiting degrees of freedom to construct (partially) **meaningful** collisions

  Practically relevant if hash function is widely deployed

Color Code



Under control, attacker can freely choose → meaningful

Not under direct control, determined by the collision search algorithm → not meaningful

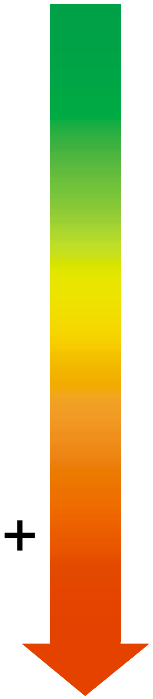
Meaningful Collisions: Challenges for MD4-style Hash Functions

I. One Commonly Chosen Prefix

II. One Commonly Chosen Prefix +
Partial Control over Colliding Blocks

III. Two Arbitrary Different Chosen Prefixes

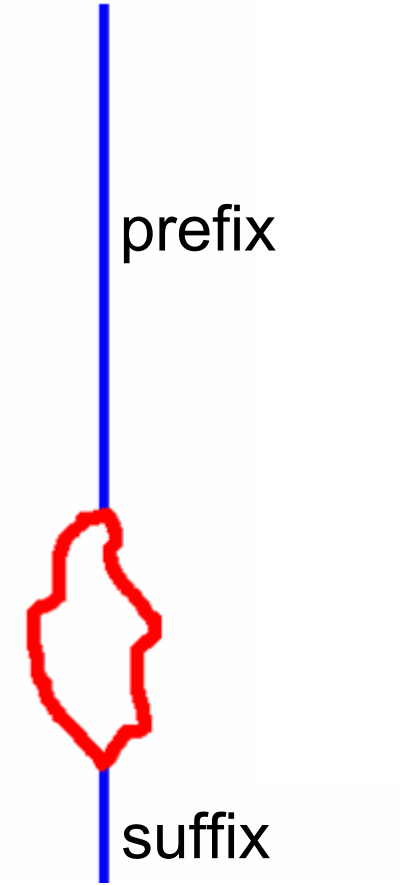
IV. Two Arbitrary Different Chosen Prefixes +
Partial Control over Colliding Blocks



"easier"

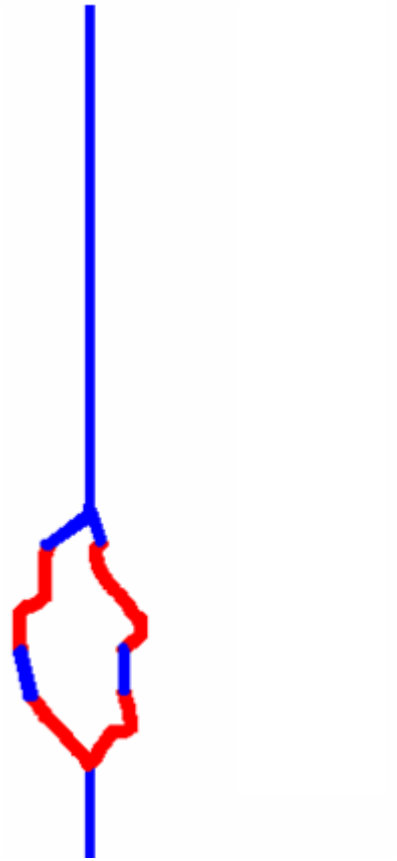
"harder"

I. One Commonly Chosen Prefix



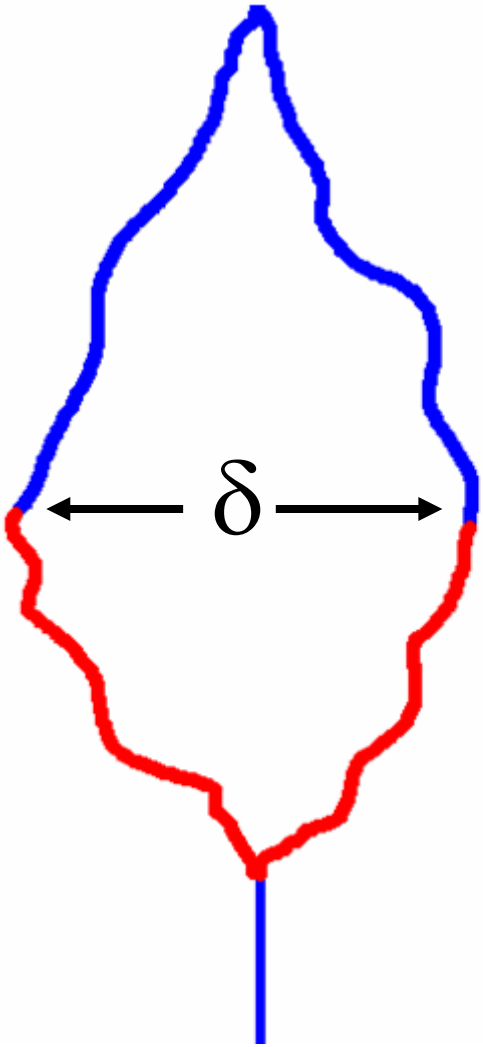
- Small number of colliding blocks
- Enough for colliding meaningful postscript files, etc… (see demo of Lars)

II. One Commonly Chosen Prefix + Partial Control over Colliding Blocks



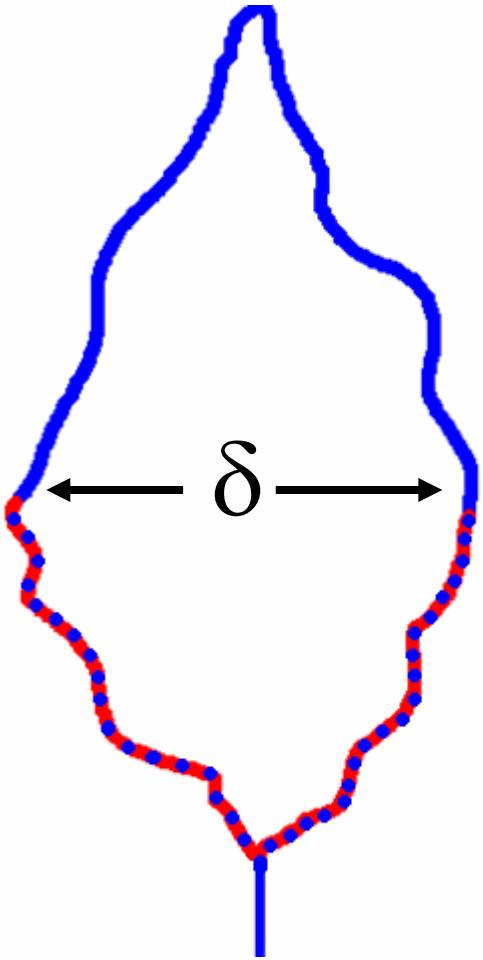
- Small number of colliding blocks
- Application in areas where format restrictions apply
- Example for 64-step SHA-1 in [DR06b]

III. Two Arbitrary Different Chosen Prefixes



- Using feed-forward operation, iteratively cancel out chaining differences with selected near-collision paths
- Usually much more than two message blocks needed
- Speedup: birthday phase before
- Example for MD5: see [SLdW07]

IV. Two Arbitrary Different Chosen Prefixes + Partial Control over Colliding Blocks



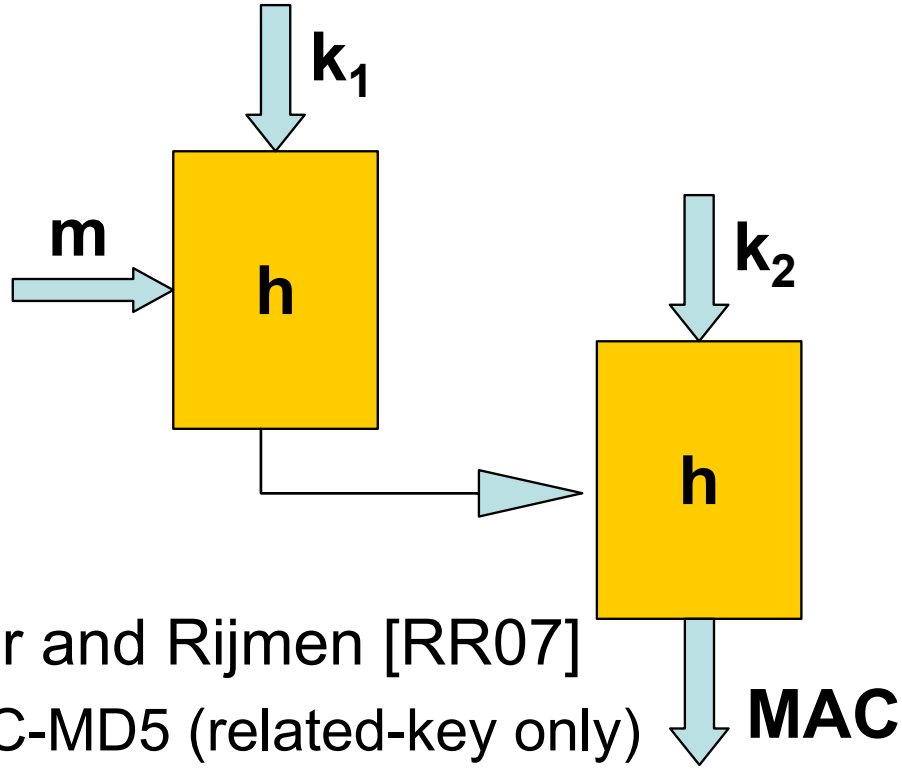
- Using feed-forward operation, iteratively cancel out chaining differences with selected near-collision paths
- Combination of methods

Even that is possible: Example Characteristic for type IV

i	∇A_i	∇W_i
-4:	0000uuu1nu001n1u100nn111u1nn00u1	
-3:	01000n0n110nunnun1nu00n1u1n1un00	
-2:	0uu0nn10uu1nunu10111n01uu1u11n1n	δ
-1:	1u1n1111110n11n110101n1u1n001001	
0:	01u0nu1unu0n01010n10001un0n0n00u	n0n00000000000000000000000000nn
1:	u001uuu1u011n1nn1001un0nu0u10n1u	10n0100010001100000011011 0un0011
2:	uuu0nu0uuu0nu1uuu11u0001n0u0001u	0uu11111010100----------------0
3:	101nn110n1un00nn1uu-0un1uu0-10-1	nnn11010101011-10------1--u1n1u1
4:	1011u01u00n11111n000u0-n0100011n	00u00101100110------100--n1001un
5:	00n111uu101111nn1u0u10u0-1n00010	x1un010010-110--011--0101u-11-10
6:	0nn01n0nn0-1uu--01n1-11u0--u0n0n	xu-n0-11------0-00-0-----x-u--uu
7:	n0-nu-0110n0--1101-0u10-00-011nu	xu1u010-------1-------1---x---u0
8:	00n10001n0u10u101--u0n01u1n--0u1	-1n0------0----1---------1-0----
9:	-11111n---100n-10----0n0u0001---	-nn-------0---------------uu--u-
10:	0--n1-1-0-010n-0--u--1-01u1n0---	-nu----------------------n----uu
11:	1---110-0--11n------1---0-01nu0-	--n--------------------1-n------
12:	--nu-1n-n-n--uun--n-1--nu-u1u010	xnu----------------------u----u-
13:	u---01--0-0-0--100--1-------0-10	-nn--------------------------n-
14:	x-0-11--1-1-1--011--1-----0-1-1-	x----------------------------u
15:	------------------------------	------------------------x-----

Attacks on NMAC/HMAC

Earlier results by
Kim et al. [KBPH06]
Contini and Yin [CY06]

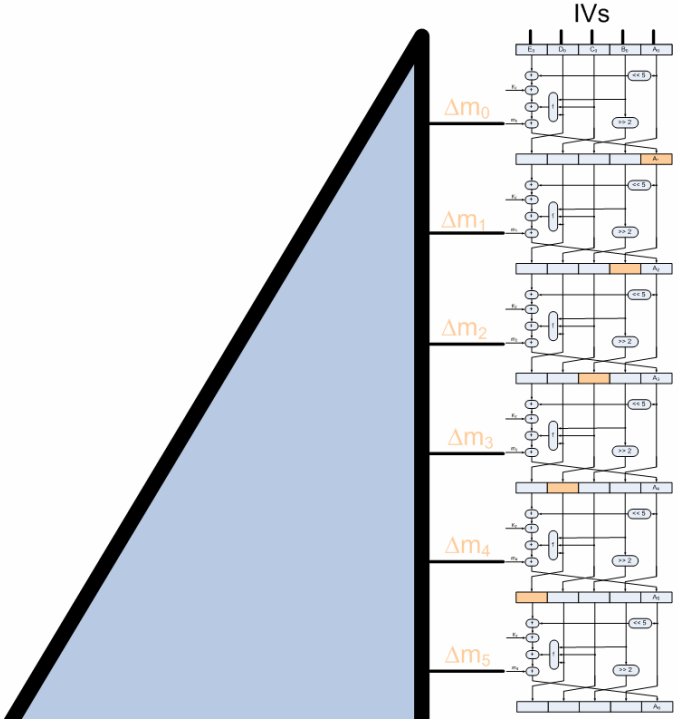


Recent Results by Rechberger and Rijmen [RR07]

- **Full** Key-Recovery for NMAC-MD5 (related-key only)
- **Full** Key-Recovery for NMAC-SHA-1 for 34/80 steps
- Distinguisher and Partial-Key recovery for NMAC/HMAC-SHA-1 for up to **62**/80 steps

What about SHA-2 members?

Probabilities of local collisions

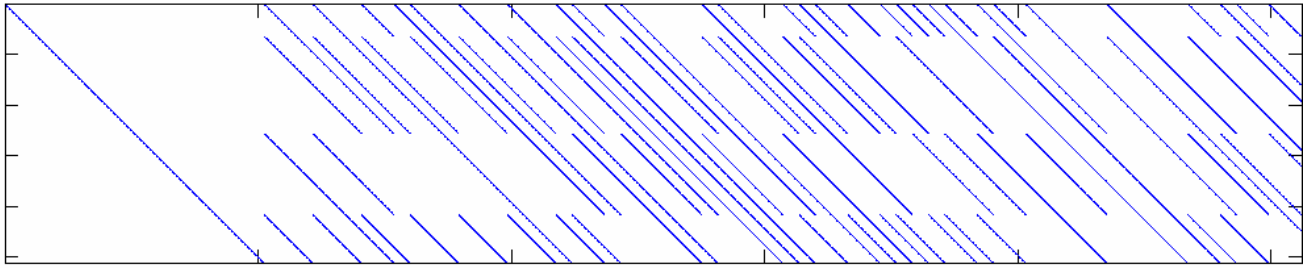


SHA/SHA-1: 2^{-2} to 2^{-5}

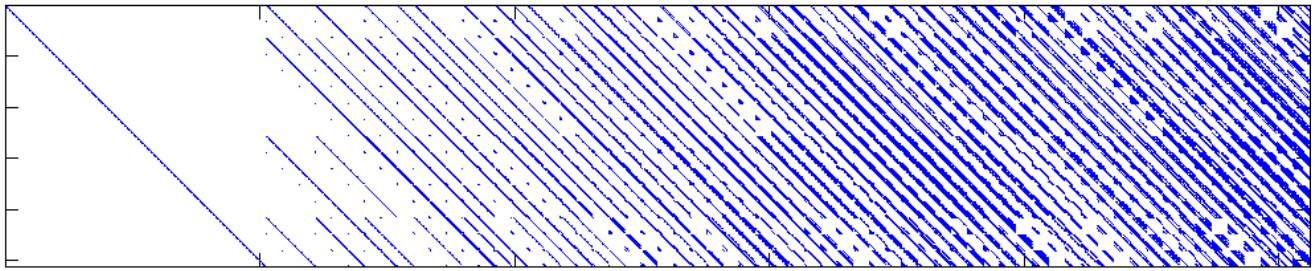
SHA-2: 2^{-38} to 2^{-41}

Comparing the message expansions of the SHA family

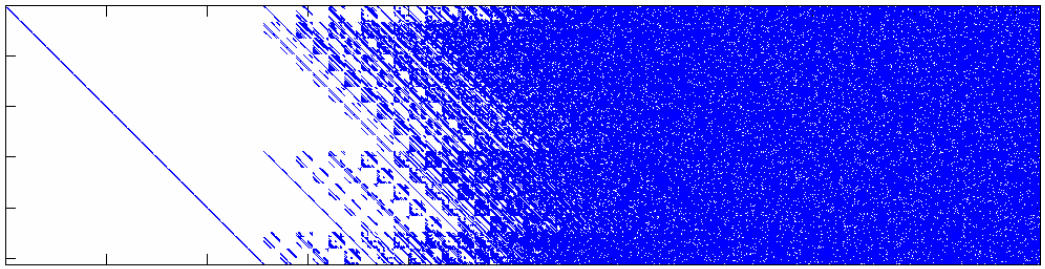
SHA



SHA-1



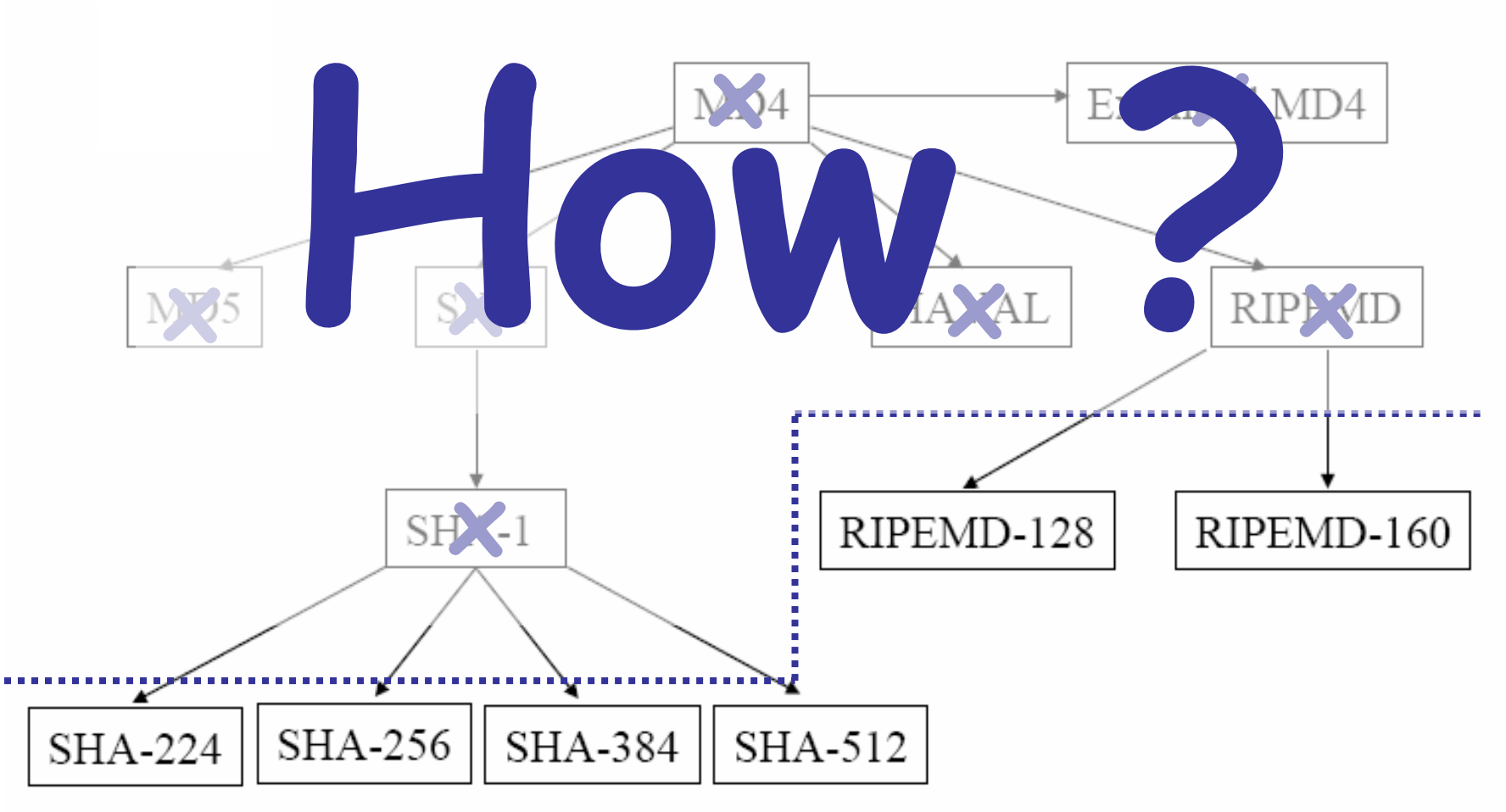
SHA-256
(linearized)



What about SHA-2 members?

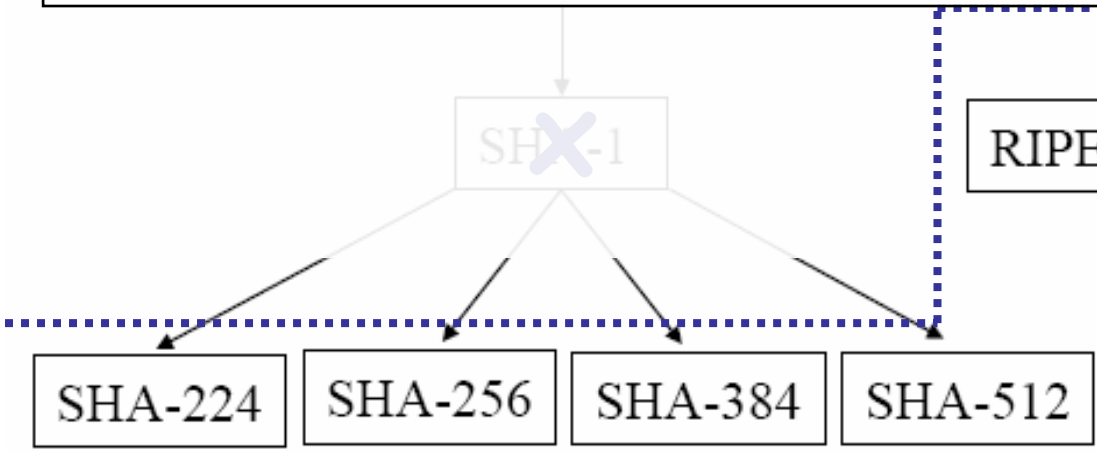
- Collision characteristic for 19-step SHA-224 [MPRR06]
- All publicly known attacks on SHA/SHA-1 since 1997 are not directly applicable to any SHA-2 member
- Message modification more difficult – cyclic dependencies
- New methods for characteristic search not applied yet

Conclusions



Conclusions

1) Special characteristics
2) Clever ways of solving equations (fast)



Conclusions

- Collisions for MD4, MD5, SHA
- Collision for full (80-step) SHA-1 is getting closer
- Optimization is ongoing
  - 2006: 2^{62} * x (unpublished work, estimates)
  - Advanced techniques as used for partial meaningful collisions can also be turned into **faster** collision search
  - 2007: ?

- Apply new insights to other hash functions like RIPEMD-160, SHA-2, new proposals?
- Improved Attacks on NMAC/HMAC?
- Results on (2nd-)preimage resistance?

Some References for MD4/MD5

[BB91] Den Boer, Booselaers, “An Attack on the Last Two Rounds of MD4”, CRYPTO 1991

[Dob98] Dobbertin: “Cryptanalysis Of MD4”, JoC, 1998

[Mer90] Merkle: “Note on MD4”, unpublished, 1990

[SLdW07] Stevens, Lenstra, De Weger, “Chosen-prefix Collisions for MD5 and Colliding X.509 Certificates for Different Identities”, EUROCRYPT 2007

[Vod94] Vaudenay, “On the Need for Multipermutations: Cryptanalysis of MD4 and SAFER”, FSE 1994

[WY05] Wang, Yu, “How to Break MD5 and Other Hash Functions”, EUROCRYPT 2005

Some References for SHA/SHA-1/SHA-256

[BC04] Biham, Chen: “Near-Collisions for SHA-0”, CRYPTO 2004

[BCJ+05] Biham, Chen, Joux et al.: “Collisions of SHA-0 and Reduced SHA-1”, EUROCRYPT 2005

[CJ98] Chabaud, Joux: “Differential Collisions in SHA-0”, CRYPTO 1998

[DR06] De Cannière, Rechberger: “Finding SHA-1 Characteristics: General Results and Applications”, ASIACRYPT 2006

[DR06b] De Cannière, Rechberger: “Meaningful Collisions for SHA-1 at no extra cost?”, CRYPTO 2006 Rump Session

[MPRR06] Mendel, Pramstaller, Rechberger, Rijmen: “Analysis of Step-Reduced SHA-256”, FSE 2006

[RO05] Rijmen, Oswald: “Update on SHA-1”, CT-RSA 2005

[WYY05a] Wang, Yu, Yin: “Efficient Collision Search Attacks on SHA-0”, CRYPTO 2005

[WYY05b] Wang, Yin, Yu: “Finding Collisions in the Full SHA-1”, CRYPTO 2005

Dedicated Attacks on NMAC/HMAC

[KBPH06] Kim, Biryukov, Preneel, Hong: “On the Security of HMAC and NMAC Based on HAVAL, MD4, MD5, SHA-0 and SHA-1”, SCN 2006

[CY06] Contini, Yin: “Forgery and Partial Key-Recovery Attacks on HMAC and NMAC Using Hash Collisions”, ASIACRYPT 2006

[RR07] Rechberger, Rijmen: “On Authentication with HMAC and Non-Random Properties”, Financial Cryptography 2007

Credits

Some slides are by curtsey of

Christophe De Cannière
Florian Mendel
and Vincent Rijmen

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events.iaik.tugraz.at/hashworkshop07

Dedicated Attacks on Popular Hash Functions

Q&A

Christian.Rechberger@iaik.tugraz.at
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ECRYPT Summer School, May 02, 2007

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