Cryptography
Lecture 3

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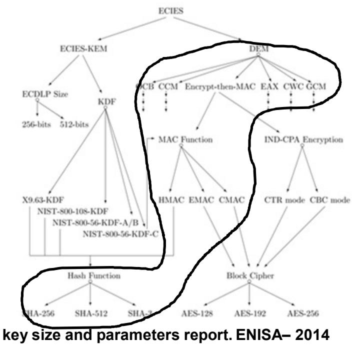
Agenda

- Hash functions

OVERVIEW

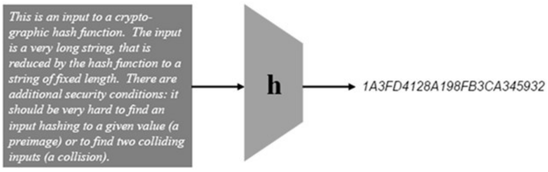


*** Algorithms, key size and parameters report. ENISA– 2014**

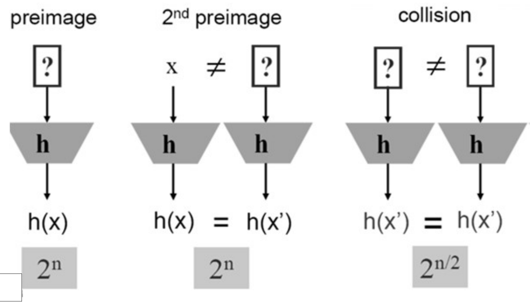
Hash functions

HASH FUNCTIONS

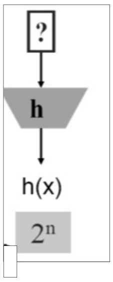
- ✓ no secret parameters
- ✓ input string x of arbitrary length ⇒ output h(x) of fixed length n (bits)
- ✓ computation "easy"
- ✓ One-way functions



CRYPTOGRAPHIC PROPERTIES



PREIMAGE



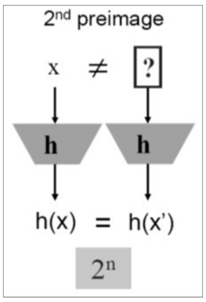
A password file must not store the passwords!
i.e. (username, password) pairs

Instead it must store:
(username,hash(password))

✓this is sufficient to verify a password
✓an attacker with access to the password file has to find a preimage

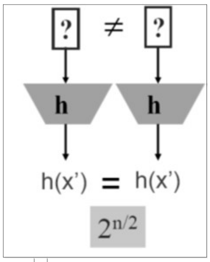
✓Still, do not use it!!!

SECOND PREIMAGE



- Can be used to protect the integrity of data x
- A secure channel is needed to send h(x) to the verifier.
- The attacker wants to modify x and remain undetected
- The attack is successful if the attacker can find a second preimage of x

COLLISION



The hacker prepares two versions of a software Let
1. x be the correct code
2. x' contain a backdoor that gives hacker access to a machine

The hacker submits x for inspection to Bob

If Bob is satisfied, he digitally signs h(x) with his private key
The hacker distributes x';
The users verify the signature with Bob's public key
This signature works for x and for x',
since h(x) = h(x')!

Birthday paradox

- the birthday problem or birthday paradox concerns the probability that, in a set of *n* randomly chosen people, some pair of them will have the same birthday.

Example: lets assume that we have a group of 23 people.

$$\binom{23}{2} = \frac{23!}{21!2!} = 253\ pairs$$

We can show that the birthday paradox is larger than 50%!

Birthday paradox

$$p(n) = 1 - \frac{n!\binom{365}{n}}{365^n}$$

n	*p*(*n*)
10	11.7%
20	41.1%
23	50.7%
30	70.6%
50	97.0%
57	99.0%
100	99.99997%
200	99.9999999999999999999999999998%
300	$(100 - (6\times10^{-80}))\%$
350	$(100 - (3\times10^{-129}))\%$
365	$(100 - (1.45\times10^{-155}))\%$
367	100%

Birthday Attack

- A birthday attack is a name used to refer to a class of brute-force attacks. More precisely,

"If some function, when supplied with a random input, returns one of |k| equally-likely values, then by repeatedly evaluating the function for different inputs, we expect to obtain the same output after about $1.2|k|^{1/2}$."

- Example: for the birthday paradox, we have |k|=365.

Brute force

- multiple target second preimage (1 out of many):
- – if one can attack 2^t simultaneous targets, the effort to find a single preimage is 2^{n-t}
- multiple target second preimage (many out of many):
  - time-memory trade-off with $\Theta(2^n)$ precomputation and storage $\Theta(2^{2n/3})$ time per (2nd) preimage: $\Theta(2^{2n/3})$ [Hellman'80]
- answer: randomize hash function with a parameter S

(salt, key, spice,…)

Brute force attacks in practice

- (2nd) preimage search
  - n = 128: 23 B$ for 1 year if one can attack **240 targets in** parallel
- parallel collision search: small memory using cycle finding algorithms (distinguished points)

  – n = 128: 1 M$ for 8 hours (or 1 year on 100K PCs)

  – n = 160: 90 M$ for 1 year

  – need 256-bit result for long term security (30 years or more)

Quantum era

- in principle exponential parallelism
  - inverting a one-way function: 2^n reduced to $2^{n/2}$ [Grover'96]
- collision search:

– $2^{n/3}$ computation + hardware [Brassard-Hoyer-Tapp'98]

– [Bernstein'09] classical collision search requires $2^{n/4}$ computation and hardware (= standard cost of $2^{n/2}$)

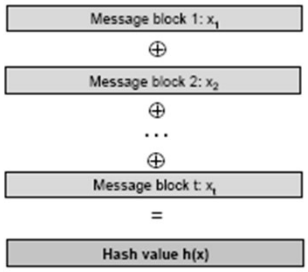
Properties in practice

- collision resistance is not always necessary
- other properties are needed:
  - PRF: pseudo-randomness if keyed (with secret key)
  - PRO: pseudo-random oracle property (formalization of security properties when there is no key)
  - near-collision resistance
  - partial preimage resistance (most of input known)
  - multiplication freeness
- how to formalize these requirements and the relation between them?

Basic Constructions

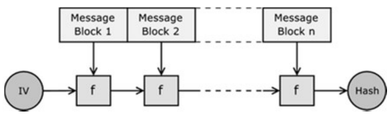
A simple approach

Divide the message into t blocks x_i of n bits each



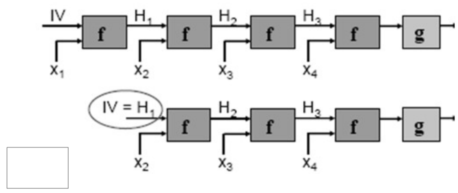
MERKLE–DAMGÅRD CONSTRUCTION

- f is a compression function
- How to choose the function
- - ad hoc
- - based on a block cipher



Iterated structure -attack

- iterating f can degrade its security
  - trivial example: 2nd preimage



Merkle-Damgard strengthening

Algorithm MD-strengthening

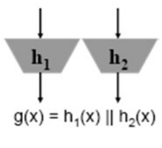
Before hashing a message $x = x_1 x_2 \dots x_t$ (where x_i is a block of bitlength r appropriate for the relevant compression function) of bitlength b, append a final length-block, x_{t+1}, containing the (say) right-justified binary representation of b. (This presumes $b < 2^r$.)

Security relation between f and h

- solution: Merkle-Damgård (MD) strengthening
  - fix IV, use unambiguous padding and insert length at the end
- f is collision resistant $\Rightarrow$ h is collision resistant [Merkle'89-Damgård'89]
- f is ideally 2nd preimage resistant $\overset{?}{\Leftarrow}$ h is ideally 2nd preimage resistant [Lai-Massey'92]
- property preservation has been a heavily studied topic since 2005

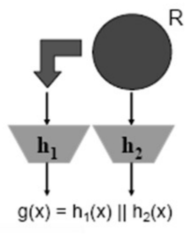
How (NOT) to strengthen a hash function?[Joux'04]

- answer: concatenation
- h_1 (n1-bit result) and h_2 (n2-bit result)
- intuition: the strength of g against collision/(2nd) preimage attacks is the product of the strength of h_1 and h_2
  - if both are "independent"
- but…. for iterated hash functions only the strongest function matters



Multi-collisions [Joux '04]

- finding multi-collisions for an iterated hash function is not much harder than finding a single collision (if the size of the internal memory is n bits)
  - algorithm
    - generate R = $2^{n1/2}$-fold multi-collision for h_2
    - in R: search by brute force for h_1
  - time: $n1 . 2^{n2/2} + 2^{n1/2} << 2^{(n1+n2)/2}$



Multi-collisions [Joux '04]

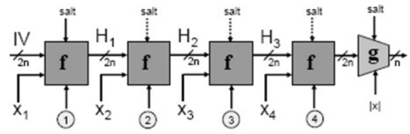
consider h_1 (n1-bit result) and h_2 (n2-bit result), with n1 ≥ n2.

concatenation of 2 iterated hash functions ($g(x)= h_1(x) \| h_2(x)$) is as most as strong as the strongest of the two (even if both are independent)

- cost of collision attack against g at most
  $n1 \,.\, 2^{n2/2} + 2^{n1/2} \ll 2^{(n1+n2)/2}$
- cost of (2nd) preimage attack against g at most
  $n1 \,.\, 2^{n2/2} + 2^{n1} + 2^{n2} \ll 2^{n1+n2}$
- if either of the functions is weak, the attacks may work better

Improving MD iteration

salt + output transformation + counter + wide pipe



Improving MD iteration

- degradation with use: salting (family of functions, randomization)

– or should a salt be part of the input?

- PRO: strong output transformation g

– also solves length extension

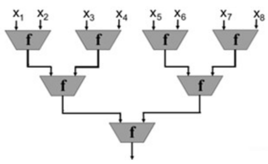
- long message 2nd preimage: preclude fix points

– counter f → fi [Biham-Dunkelman'07]

- multi-collisions, herding: avoid breakdown at $2^{n/2}$ with larger internal memory: known as wide pipe

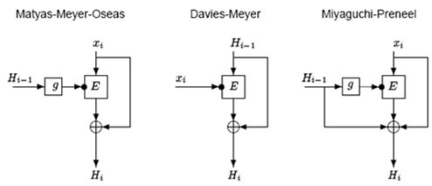
– e.g., extended MD4, RIPEMD, [Lucks'05]

Tree structure: parallelism



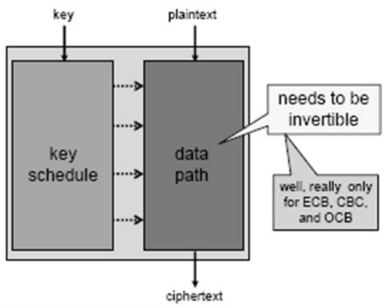
Compression Functions

Block cipher based



Motivation for use of a larger permutation

block cipher internals



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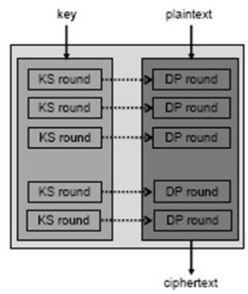

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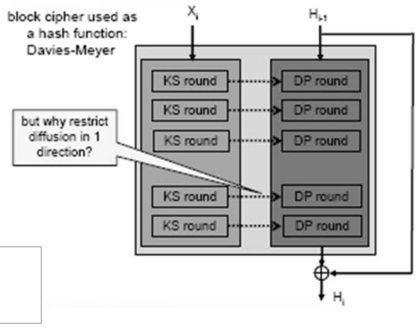

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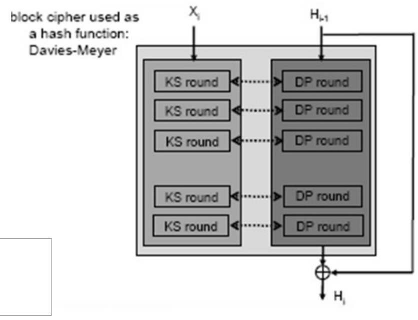

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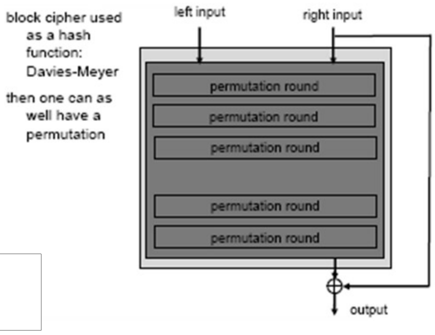

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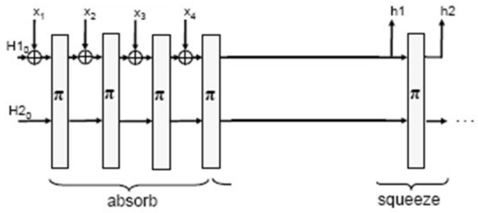
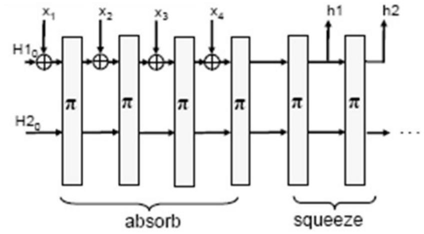


example: Keccak (no buffer)

generalization called Parazoa

JH, Cubehash, Fuge, Grindahl, Hamsi, Luffa

Motivation for use of a larger permutation



If H1 has r bits (rate) and H2 has c bits (capacity) and the permutation π is "ideal", then a sponge function has security $O(2^c)$ against (2nd) preimage attacks and $O(2^{c/2})$ against collision attacks

Iteration modes and compression functions

- security of simple modes well understood
  - powerful tools available
- analysis of slightly more complex schemes very difficult
  - which properties are meaningful?
  - which properties are preserved?
  - MD versus sponge is still open debate

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Constructions

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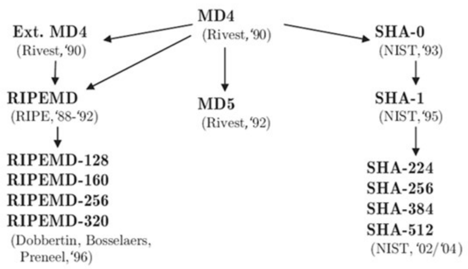
MD4 family



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TIMELINE

1990: MD4 by Ron Rivest

1991: MD5 by Ron Rivest (RFC 1321, 1992)

1992: RIPEMD by H. Dobbertin, A. Bosselaers and B. Preneel

1993: SHA-0 by U.S. Government (FIPS PUB 180)

1995: SHA-1 by U.S. Government (FIPS PUB 180-1)

2000: Whirlpool by V. Rijmen and P. Barreto

2001: SHA-2 by U.S. Government (FIPS PUB 180-2)

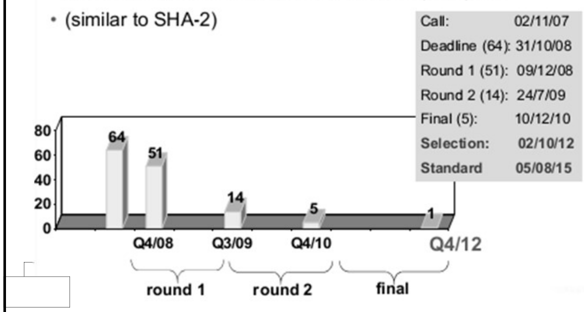
2005: First attacks against SHA-1

2015: SHA-3 by the Keccak team (FIPS 202)

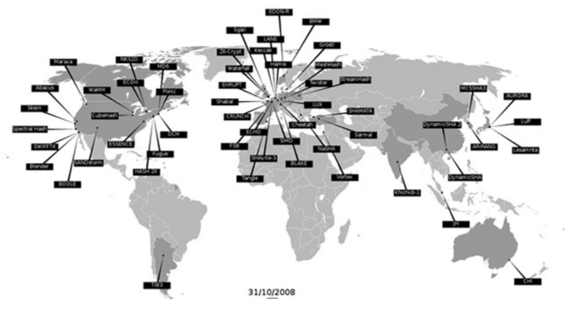
2017: February 2017, CWI Amsterdam and Google announced they had performed a collision attack against SHA-1

SHA-3 COMPETITION

- SHA-3: 224, 256, 384, and 512-bit message digests
- (similar to SHA-2)



THE CANDIDATES



From B. Preneel slides
Slides credits: Christophe De Cannière

ROUND-2 CANDIDATES

SHA-3 FINALISTS

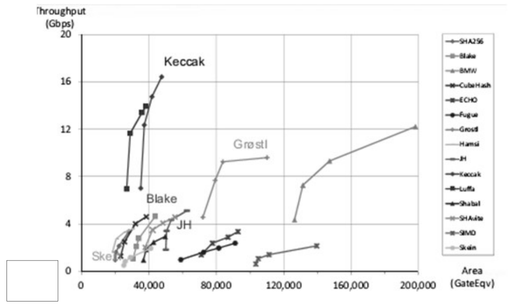
- ✓ BLAKE (Aumasson et al.)
- ✓ Grøstl (Knudsen et al.)
- ✓ JH (Hongjun Wu)
- ✓ Keccak (Keccak team, Daemen et al.)
- ✓ Skein (Schneier et al.)

Geography: 3 from Europe, 1 from Asia, 1 from America

Team members also AES finalist: 3

Hardware: post-place & route results ASIC 130nm

- [Guo-Huang-Nazhandali-Schaumont'10]



Keccak: FIPS 202 (published: 5 August 2015)

- append 2 extra bits for domain separation to allow
  - flexible output length (XOFs or eXtendable Output Functions)
  - tree structure (Sakura) allowed by additional encoding
- 6 versions
  - SHA3-224: n=224; c = 448; r = 1152 (72%)
  - SHA3-256: n=256; c = 512; r = 1088 (68%)
  - SHA3-384: n=384; c = 768; r = 832 (52%)
  - SHA3-512: n=512; c = 1024; r = 576 (36%)
  - SHAKE128: n=x; c = 256; r = 1344 (84%)
  - SHAKE256: n=x; c = 512; r = 1088 (68%)
- if result has n bits, H1 has r bits (rate), H2 has c bits (capacity) and the permutation π is "ideal":
  - collisions: min ($2^{c/2}$, $2^{n/2}$)
  - 2nd preimage: min ($2^{c/2}$, 2^{n})
  - Preimage: min (2^{c}, 2^{n})

SHA3 WINNER: KECCAK

- ✓ Not an MD construction
- ✓ Based on a new design: sponge

- ✓ Design team: Guido Bertoni, Joan Daemen, Michaël Peeters, Gilles Van Assche
- ✓ FIPS PUB 202: SHA-3 Standard: Permutation-Based Hash and
- Extendable-Output Functions
- ✓ **https://nvlpubs.nist.gov/nistpubs/FIPS/NIST.FIPS.202.pdf**

STATE OF THE ART

Primitive	Output Length	Classification Legacy	Classification Future
SHA-2	256, 384, 512	✓	✓
SHA3	256,384,512	✓	✓
Whirlpool	512	✓	✓
SHA3	224	✓	✗
SHA-2	224	✓	✗
RIPEMD-160	160	✓	✗
SHA-1	160	X	✗
MD-5	128	✗	✗
RIPEMD-128	128	✗	✗

OTHER HASH FUNCTIONS

- **BLAKE2**
  - Since 2012
  - high efficiency that it offers on modern CPUs
- **Whirlpool**
  - Since 2000
  - designed by Vincent Rijmen and Paulo S. L. M. Barreto
  - 512 bits