Cryptographic Hash

BMEVITMAV52

Information and Network Security

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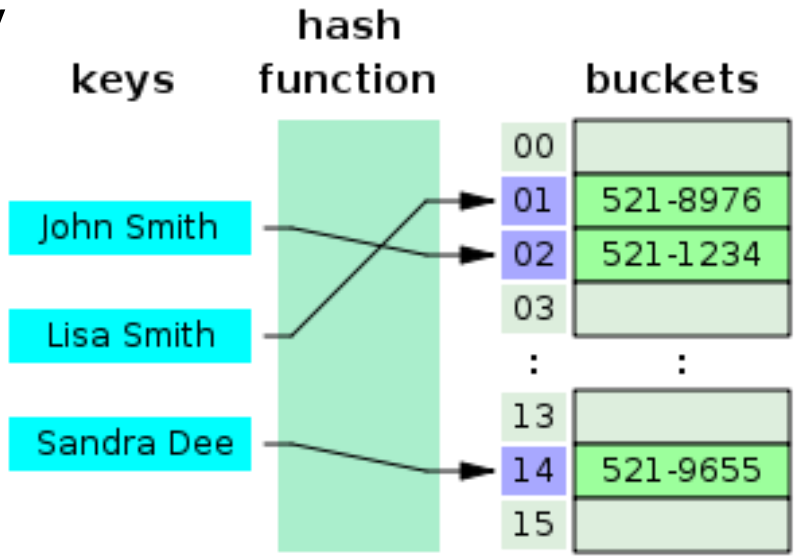
Conventional hashing

- Conventional hash functions (bucket hashing)
  - Larger domains are mapped to smaller ranges
    - Speed up data retrieval
    - Reduce memory footprint
    - Collisions reduce efficiency



Cryptographic hashing

- Cryptographic hash functions
  - Creating a representative image
    - Compact representative image
      - Imprint, digital fingerprint, message digest
    - Used for data integrity protection and authentication
    - Collisions make the hash unsecure
  - Message -> hash (hash-code, hash-result, hash-value)

Hash functions

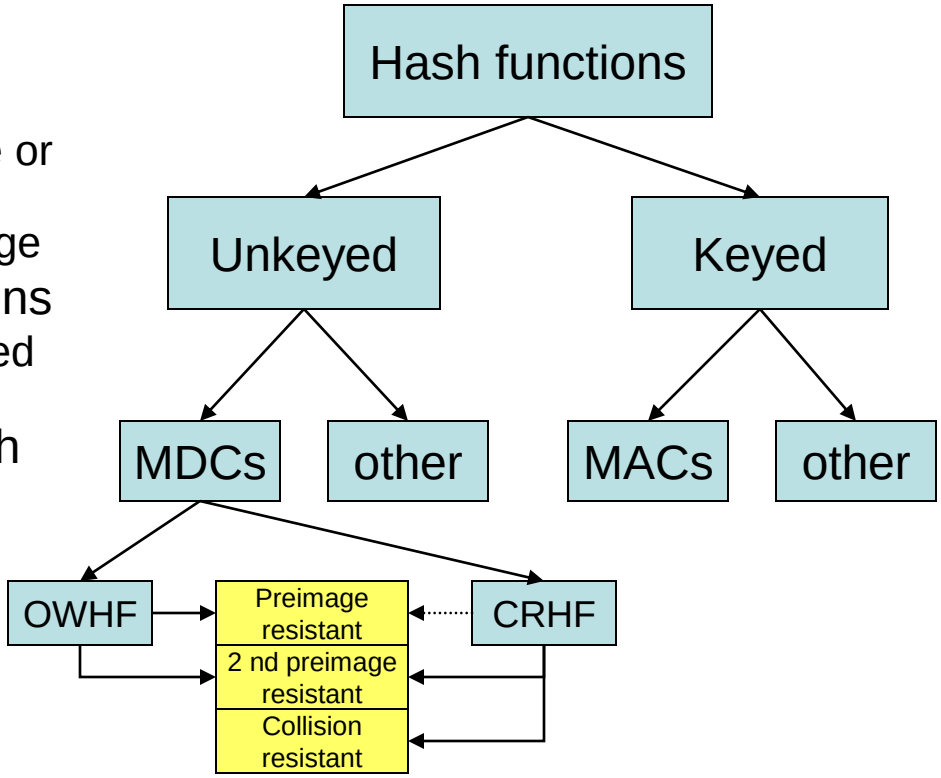
- From any sized input, provide a fixed length string
- Many-to-one function
  - There are collisions
    - Two input has the same output with the probability of 2^{-n}
      - Independent of the size of the input (it should be!)
- Minimum requirements
  - Compression
    - Arbitrary length -> finite length
  - Ease of computation

Size of the hash output

- Hash collision: 2^{-n}
  - Collision should be less than $1:2^{64}$ n = 64 ??? **no!**
- Birthday attack
  - The birthday paradox states that if there are 23 people in a room then there is a chance of more than 50% that at least two of them will have birthday on the same day (For 60 or more people, the probability is greater than 99%)
    - Paradox, since 23 seems to be too small
  - Using it on hash functions, generating N bit hash values there is a chance that there is a collision among $2^{N/2}$ randomly chosen messages
  - n should be 128 or 160 to defeat birthday attack

Hash function groups

- MDC
  - Modification detection code
    - Manipulations detection code or message integrity code
    - Provide a representative image
  - OWHF: One way hash functions
    - Find and input for the specified hash value is difficult
  - CRHF: Collision resistant hash function
    - Find two input that have the same hash value is difficult
- MAC
  - Message authentication code
    - The Integrity and source authentication



Unkeyed hash functions

- h(x)=y and h(x')=y'

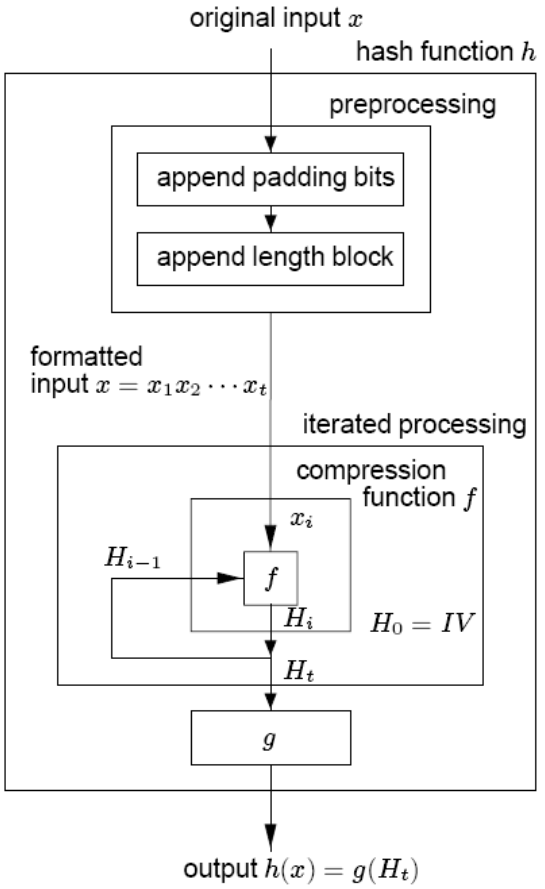
- Preimage resistance (one-way)
  - Computationally infeasible to find preimage x' that h(x')=y for a **given y**
- 2nd preimage resistance (weak collision resistant)
  - Computationally infeasible to find a second preimage that has the same output. For a **given x**, where h(x)=y, find x' where h(x')=y
- Collision resistance (strong collision resistant)
  - Computationally infeasible to find **any two** distinct input which have the same output h(x) = h(x')

Collision resistance

- Collision resistance implies 2nd preimage resistance
  - Proof: Assume h is collision resistant but not 2nd preimage resistant
    - For a given x one can find x' , where h(x)=h(x')
    - x and x' a collision pair
- Collision resistance does not guarantee preimage resistance
  - Proof: assume g is collision resistant with output of n bit
    - Output of the h hash function is n+1 bit:
      - If x is n bit long: h(x) =1|x
      - Otherwise: o|g(x)
    - h is also collision resistant
    - h is not preimage resistant

Iterated hash functions

- Input is divided into fixed length blocks
  - Use padding
    - Padding with 0s
    - Padding with 1 then 0s
- f is the compression function
  - $H_i=f(H_{i-1},x_i)$
  - n bit chaining variable
  - H_0 is the IV
    - Should be known at the other side
- g is an optional transformation
  - From n bit produces m bit



Merkle-Damgård strengthening

- MD-strengthening
  - Before hashing, append length block, containing the binary representation of the input's length
    - Presumes length < $2^{\text{block size}}$
  - Any collision resistant compression function can be extended to a collision resistant hash function
    - Using the iterated approach

Cascading hash functions

- If $h_1(x)$ and $h_2(x)$ are collision resistant hash functions then $h(x) = h_1(x)||h_2(x)$ is also a collision resistant hash function
  - Increase the strength of the hash function

Block cipher based hash functions

- Usually block cipher is present (SW or HW)
- h is an iterated hash function. In each iteration f perform s block encryptions to get the successive n-bit block
  - The rate of h is 1/s

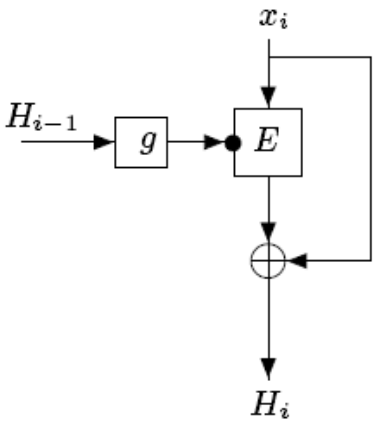
  - k: key size
  - n: block size
  - m: hash size

Hash function	(n, k, m)	Rate
Matyas-Meyer-Oseas	(n, k, n)	1
Davies-Meyer	(n, k, n)	k/n
Miyaguchi-Preneel	(n, k, n)	1
MDC-2 (with DES)	$(64, 56, 128)$	$1/2$
MDC-4 (with DES)	$(64, 56, 128)$	$1/4$

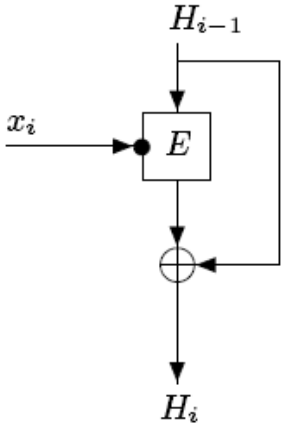
Single-length MDCs

- Components:
  - n-bit Block cipher
  - Function g that maps n-bit blocks to the key
  - Fixed initial value (IV) for the block cipher

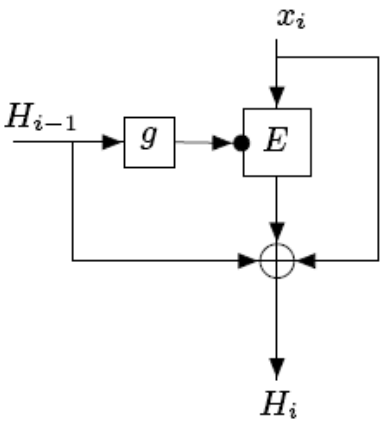
Matyas-Meyer-Oseas



Davies-Meyer

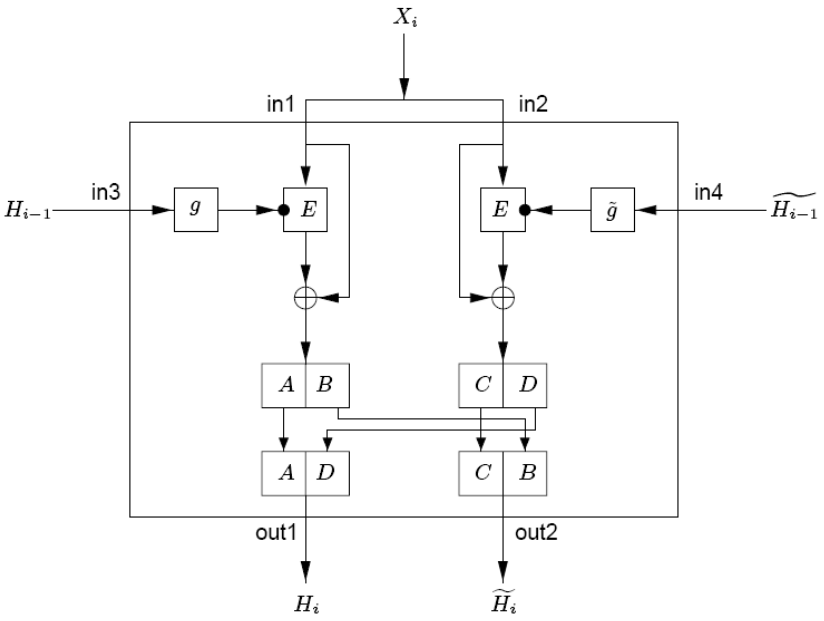


Miyaguchi-Preneel



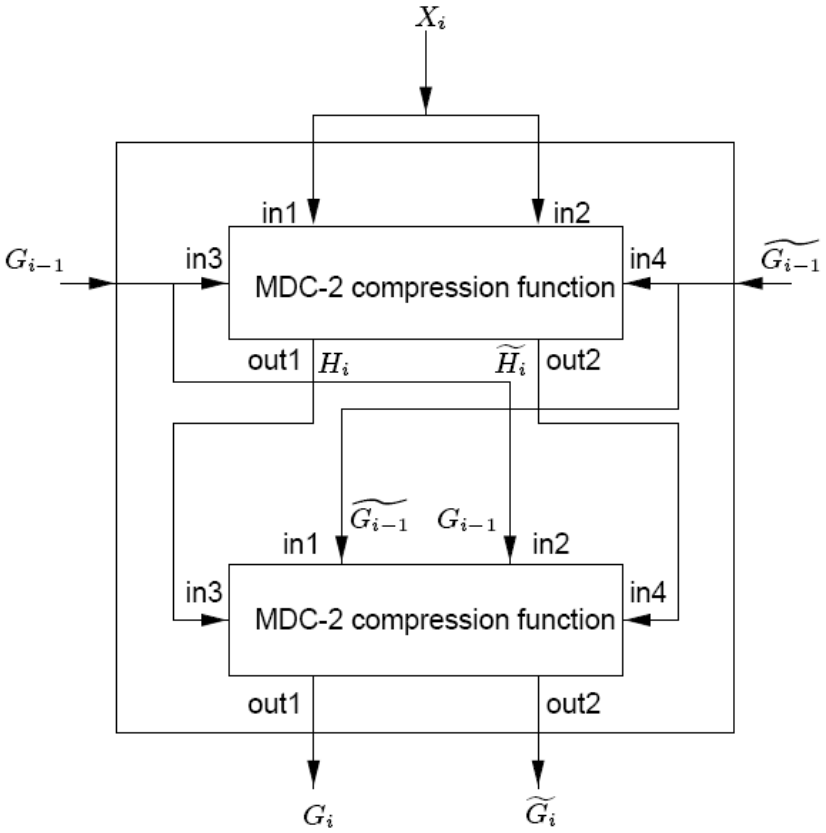
Double-length MDCs (MDC-2)

- More encryption operation during one iteration
- MDC-2:
  - Use DES
  - Combination of Matyas-Meyer-Oseas
  - Key generation:
    - $g(U)=u_1\mathbf{10}u_4u_5u_6u_7u_9u_{10}..u_{63}$
    - $g'(U)=u_1\mathbf{01}u_4u_5u_6u_7u_9u_{10}..u_{63}$



Double-length MDCs (MDC-4)

- 2 MDC-2 blocks

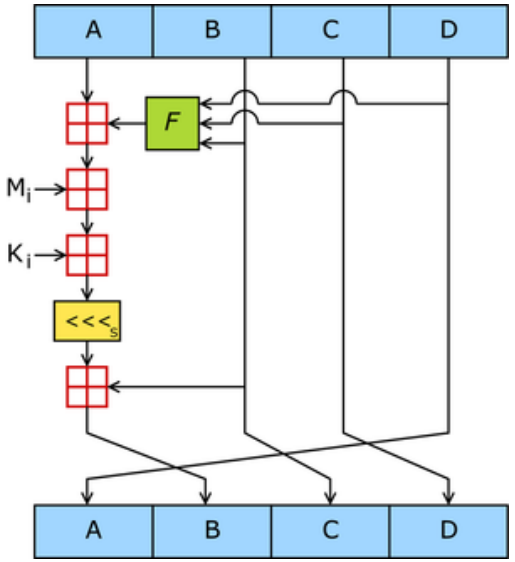


MD4 and MD5

- Designed “from scratch”
  - Optimized performance
- Message Digest 4 – MD4
  - Ron Rivest – 1990
  - 128 bit hash function (512 bit internal blocks)
  - Designed for 32 bit architectures
  - Goal: breaking would require roughly brute-force effort – FAILED (1991)
- Message Digest 5 – MD5
  - Ron Rivest – 1991
  - Strengthened MD4
  - Widespread use
  - 128 bit hash function (512 bit internal blocks)
  - Flaws:
    - 1996: design flaw found (not fatal)
    - 2004: collision using a cluster computer
    - 2006: collision within one minute on a notebook (tunneling)

MD5 algorithm

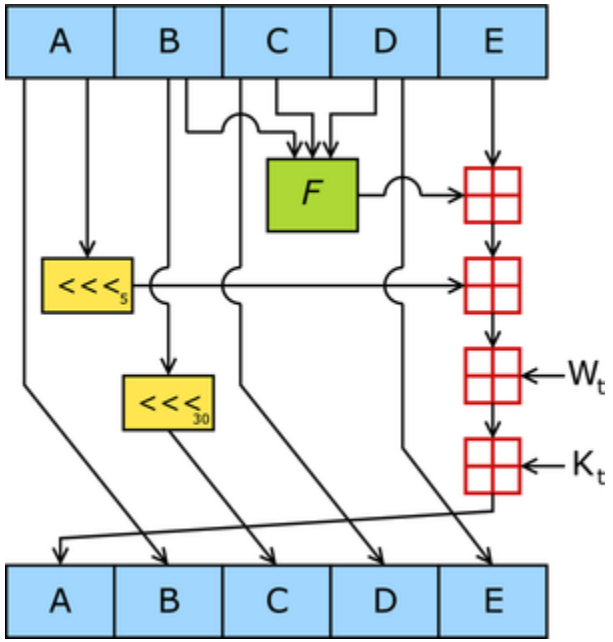
- Padding to 512 bit blocks
  - Bit 1, followed by 0s
  - The last 64 bit is the message length
- Iterations
  - 4 rounds, 16 repetition
  - 128 output: 4 states (32 bit)
  - Nonlinear function F
  - M: message in 32 bits
  - K: operation dependant key



$$F(X,Y,Z) = (X \wedge Y) \vee (\neg X \wedge Z)$$
$$G(X,Y,Z) = (X \wedge Z) \vee (Y \wedge \neg Z)$$
$$H(X,Y,Z) = X \oplus Y \oplus Z$$
$$I(X,Y,Z) = Y \oplus (X \vee \neg Z)$$

SHA algorithms

- SHA (SHA-0) was published in 1993
  - Flaw: collision in 2^{39} steps (2005)
- Secure Hash Algorithm – SHA-1
  - U.S. National Security Agency – 1995
  - Based on MD4
  - NIST proposal
  - 160 bit hash function (512 bit internal blocks)
  - Flaw: collision in 2^{69} steps (2005), 2^{61} steps (2012)
- SHA-2: SHA-224, 256, SHA-384, SHA-512
  - Same Merkle-Damgarg engine as SHA-1
  - Still considered secure
- SHA-3: Keccak from 2015
  - Alternative engine



Keyed hash funcitons

- Primary purpose: message authentication
  - MAC: Message Authentication Code
  - Hash function with two input: the key and the message
    - y = h(x, k)
  - Ease of computation
  - Compression
  - Key non-recovery
    - From one or more message-MAC pairs it is unfeasible to get the key
  - Computation resistance
    - Form one or more message-MAC pairs it is unfeasible to get a new message-MAC pair

Secret prefix method

- $MAC_k(x) = hash(k|x)$

- Insecure with iterated hash functions!
  - x and M are known (M=h(k|x))
  - Producing MAC on x|y is possible:
    - M’ = f(M,y), where f is the compression function

Secret suffix method

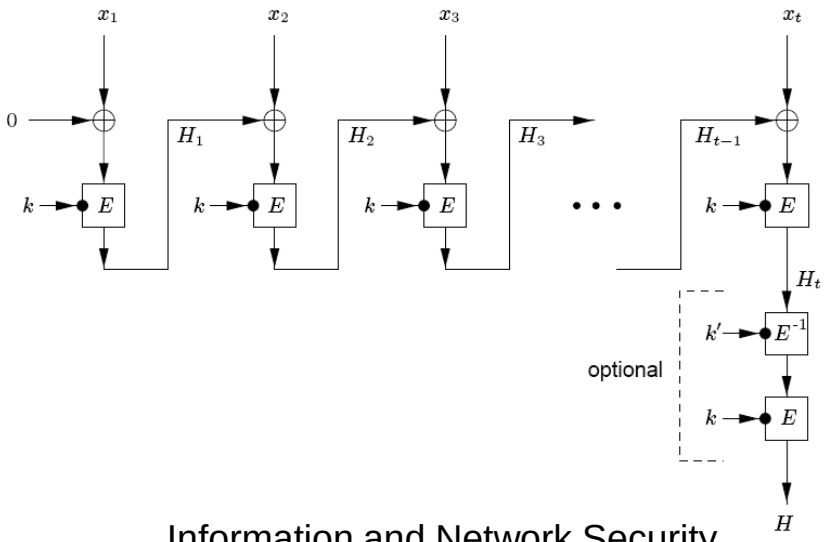
- $MAC_k(x) = hash(x|k)$
  - May be insecure if collision is found
  - If $h(x)=h(x')$ then $MAC_k(x) = MAC_k(x')$
  - Weakness
    - MAC depends on the last chaining variable

HMAC

- Keyed-hash message authentication code
- Mihir Bellare, Ran Canetti, and Hugo Krawczyk (1996)
  - HMAC(h,k,m) = h((k ⊗ opad) || h((k ⊗ ipad) || m))
  - ipad (inner)= 0x363636…36 (a whole block)
  - opad (outer) = 0x5c5c5c…5c (a whole block)
- HMAC-SHA1
  - 512 bit block size, 160 bit hash size
- HMAC-MD5
  - 512 bit block size, 128 bit hash size

CBC-MAC

- Based on cipher block chaining
  - Block cipher: DES
    - Block size: 64 bit
  - MAC key: DES key (56 bit)
  - Padding and blocking
  - Additional security: Use an other key and play 3DES
  - The final output is the hash value (64 bit)



CBC-MAC weakness

- Existential forgery of CBC-MAC
  - x_1 and MAC_1 pair is known
  - Request CBC-MAC for MAC_1: $MAC_2=E_k(E_k(x_1))$
  - MAC_2 is a MAC for $x_1|000\ldots0$ as well !

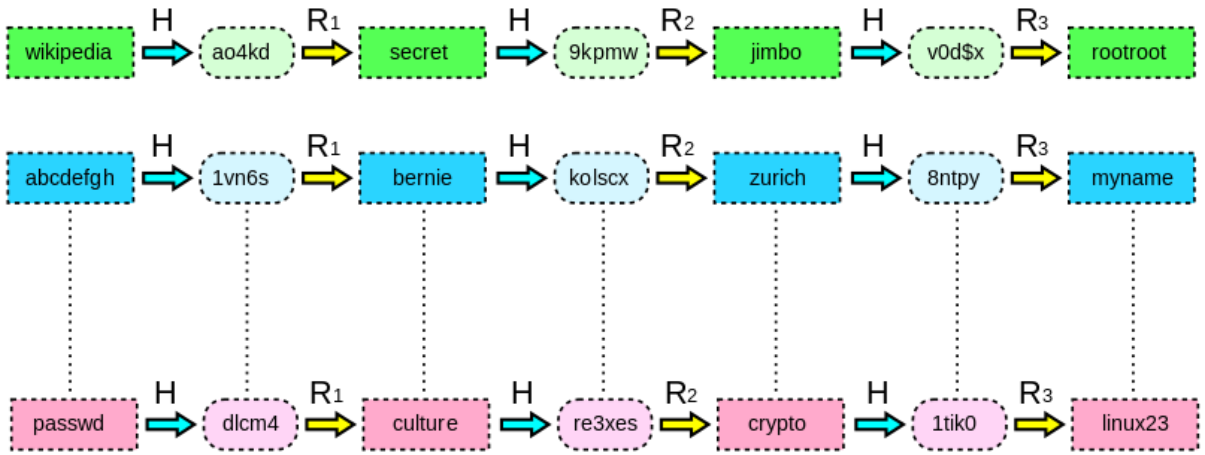
  - x_1,MAC_1 and x_2,MAC_2 are known <u>one block</u> messages + hashes
  - Request CBC-MAC for $x_1|z$: $MAC_z=E_k(E_k(x_1)\oplus z)$
  - MAC_z is also MAC for $x_2|MAC_1\oplus z\oplus MAC_2$
- Use fixed number of blocks
- MD-strengthening might help

Rainbow tables

- Inverse hash function is theoretically possible with stored hash inputs and outputs
  - Huge tables, not feasible
- Storing just some of these values, which are the inputs and outputs of hash chains
  - Ideally the chains are loop free and not merging to each other
  - TB large tables for given input sets, but now it is already feasible!

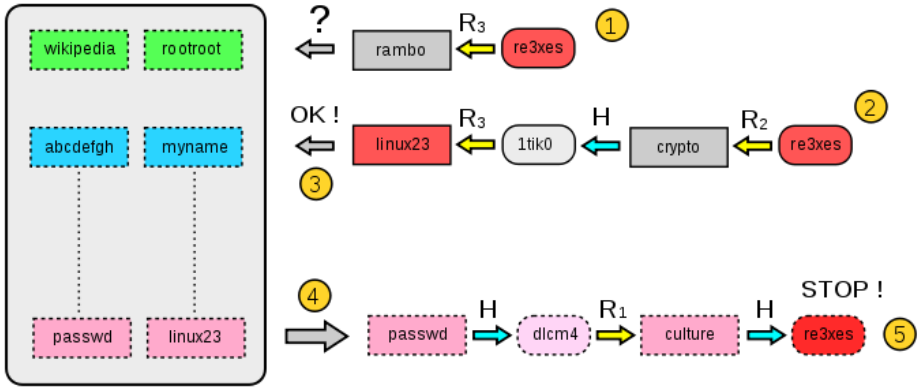
Rainbow table construction

- Reduction function: R
  - Convert hash output into an possible input
  - Multiple reduction functions in order to avoid loops and merges: R_1, R_2, … R_k



Rainbow tables

- Attacking with rainbow tables
- Example
  - Find input for hash output re3xes



1-2. Test with the end of the chains (k tests)
3. Find a match in the table
4. Start the chain from the table's input word
5. Hash until a we found the input

Defense against rainbow tables

- Make the input larger
  - Slating
    - `saltedhash(password) = hash(password || salt)`
    - Makes the input larger
    - Salt is not secret! But different for each hash
  - Key stretching
    - Use iterations to make the computation longer
    - Reduces brute force rate and increase the time to build a rainbow table

References

- Alfred J. Menezes, Paul C. van Oorschot and Scott A. Vanstone, “Handbook of Applied Cryptography”, CRC Press, ISBN: 0-8493-8523-7
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