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Network Security

Chapter 2 Cryptography
2.2 Cryptographic Hash Functions

- Motivation
- Cryptographic Hash Functions
    - SHA-1, SHA-3, Skein
- Message Authentication Codes (MACs)

Acknowledgments

This course is based to a significant extend on slides provided by Günter Schäfer, author of the **book "Netzsicherheit - Algorithmische Grundlagen und Protokolle"**, available in German from **dpunkt Verlag**. The English version of the book is entitled "Security in Fixed and Wireless Networks: An Introduction to Securing Data Communications" and is published by Wiley is also available. We gratefully acknowledge his support.

The slides by Günter Schäfer have been partially reworked by Heiko Niedermayer, Ali Fessi, Ralph Holz and Georg Carle.

Motivation (1)

- *Data integrity* is an essential security service

  ➔ Upon receiving a message *m*, we need to detect whether *m* has been modified intentionally by an attacker

- Common practice in data communications: *error detection code* over messages, to identify if errors were introduced during transmission
  - Examples: Parity, Bit-Interleaved Parity, Cyclic Redundancy Check (CRC)

➔ Underlying idea of these codes: add redundancy to a message for being able to *detect*, or even *correct* transmission errors

➔ The error detection/correction code of choice and its parameters: trade-off between

  - computational overhead
  - increase of message length
  - Probability/characteristics of errors on the transmission medium

Motivation (2)

- It is a different (and much harder!) problem to determine if *m* has been *modified on purpose!*
- Consequently, we need to add a *Modification Detection Code* (MDC) that fulfills some additional properties which should make it *computationally infeasible* for an attacker to tamper with messages
- This property is fulfilled by so-called “cryptographic hash functions”

Overview

- **Cryptographic Hash Function**
- MAC and other applications
- Common Structures and SHA-1
- Birthday Phenomenon
- CBC-MACs / CMAC
- SHA-3 and Skein
- Integrity Check and Digital Signature

Cryptographic Hash Functions: Definition

- Definition: **hash function**
  - A *hash function* is a function *h* which has the following two properties:
    - *Compression: h* maps an input *x* of arbitrary finite bit length to an output *h(x)* of fixed bit length *n*:

      $$h: \{0,1\}^* \rightarrow \{0,1\}^n$$

    - *Ease of computation:* Given *h* and *x* it is *easy* to compute *h(x)*

- Definition: one-way function
  - A *hash function* is a function *h* which has the following property
  - for essentially all pre-specified outputs *y*, it is *computationally infeasible* to find an *x* such that $h(x) = y$
  - e.g. given *p* a large prime number and *g* a primitive root in Z^*_p

    Let $h(x) = g^x \bmod p$

    Then *h* is a one-way function

Cryptographic Hash Functions: Definition

- Definition: **cryptographic hash function**
  - A *cryptographic hash function h* is a hash function which additionally satisfies the following properties:

    (1) h is a one-way function

    This property is also called *(First) Pre-image resistance*

    ("Unbestimmbarkeit von Urbildern"):
    For essentially all pre-specified outputs *y*, it is *computationally infeasible* to find an *x* such that $h(x) = y$

    (2) 2nd pre-image resistance ("Unbestimmbarkeit eines zweiten Urbildes"):
    given *x* it is *computationally infeasible* to find any second input *x'* with $x \neq x'$ such that $h(x) = h(x')$

    Note: This property is very important for digital signatures.

    (3) Collision resistance ("Kollissionsfreiheit"):
    it is *computationally infeasible* to find any pair (x, x') with $x \neq x'$ such that $h(x) = h(x')$

    (4) Random oracle property:

    It is computationally infeasible to distinguish $h(m)$ from random *n*-bit value

General Remarks (1)

- Computational infeasibility
  - In a mathematical sense, the notion of *computational infeasibility* is directly related to complexity theory.
  - It means that no polynomial complexity algorithm for the given problem exists
  - However, cryptographic hash functions, which are actually used in practice, e.g. SHA-1 or MD5, are not directly based on such mathematical problems
- Random output
  - The algorithm for calculating the hash value of a string is deterministic
  - However, the output of a cryptographic hash function should "look" random [Ferg03]
  - In particular, a cryptographic hash function should map two "similar" strings to completely uncorrelated outputs (similar in the sense of a small Hamming distance) [Cos06]
  - In particular, a cryptographic hash function should not be additive
    - If $x' = x \oplus \Delta$, then $H(x')$ should be different from $H(x) \oplus H(\Delta)$

General Remarks (2)

- In networking there are codes for error detection.
- Cyclic redundancy checks (CRC)
  - CRC is commonly used in networking environments
  - CRC is based on binary polynomial division with Input / CRC divisor (divisor depends on CRC variant).
  - The remainder of the division is the resulting error detection code.
  - CRC is a fast compression function.
- Why not use CRC?
  - CRC is <u>not</u> a cryptographic hash function
  - CRC does not provide 2nd pre-image resistance and collision resistance
  - CRC is additive
    - If $x' = x \oplus \Delta$, then $CRC(x') = CRC(x) \oplus CRC(\Delta)$
  - CRC is useful for protecting against noisy channels
  - But not against intentional manipulation

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Case:
No attacker

Alice (A)

m, h(m)

Bob (B)

ok

Case:
With attacker

Alice (A)

m, h(m)

m‘, h(m‘)

Bob (B)

ok

- Applying a hash function is not sufficient to secure a message.
- h(m) needs to be protected.

Application of Cryptographic Hash Functions for Data Integrity

- Cryptographic hash functions are used to detect whether a message has been modified by an attacker
- As seen on the last slide:
  - However, the use of a cryptographic hash function is *not sufficient* to detect whether a message has been modified.
  - if Alice sends a message (x, $H(x)$) to Bob, with H a cryptographic hash function, it holds:
    - The computation of H(x) is usually based on a well-known algorithm
    - The computation of H(x) does not include a secret key or anything else bound to the identity of Alice

    ➔ An attacker can modify x to x‘, calculate H(x‘) easily and sends (x‘, H(x‘)) to Bob pretending that this message would be originating from Alice

Application of Cryptographic Hash Functions for Data Integrity

- Potential workarounds:
  - Alice might send the cryptographic hash value via an out-of-band (trusted) channel to Bob. Examples:
    - by phone call
    - by a letter
    - the hash value may be published on a (trusted) web server.
    - Alice and Bob might use a physically-protected channel where attackers can only listen, but not send.
  - Use cryptography and secret keys
    - Message Authentication Code (MAC) that depends on key k and message m.

Case:
No attacker

Alice (A)

share symmetric key k

Bob (B)

m, MAC(k,m)

ok

Case:
With attacker

Alice (A)

m, MAC(k,m)

m‘, MAC(k,m)

Bob (B)

not ok

- Since the secret key k is unknown to the attacker, the attacker cannot compute MAC(k,m’).

Message Authentication Codes (MACs)

- Definition: **message authentication code**
  - A *message authentication code algorithm* is a family of functions h_k parameterized by a ***secret key k*** with the following properties:
    - *Compression:*
      h_k maps an input x of arbitrary finite bitlength to an output $h_k(x)$ of fixed bitlength, called the MAC
    - *Ease of computation:*
      given k, x and a known function family h_k the value $h_k(x)$ is easy to compute
    - *Computation-resistance:*
      for every fixed, allowed, but unknown value of k, given zero or more text-MAC pairs $(x_i, h_k(x_i))$ it is computationally infeasible to compute a text-MAC pair $(x, h_k(x))$ for any new input $x \neq x_i$

- Please note that *computation-resistance* implies the property of *key non-recovery*
  - k can not be recovered from pairs $(x_i, h_k(x_i))$,
  - but computation-resistance can not be deduced from key non-recovery, as the key k needs not always to be recovered to forge new MACs (as shown in subsequent example)

A Simple Attack Against an Insecure MAC

- For illustrative purposes, consider the following MAC definition:
  - Input: message $m = (x_1, x_2, ..., x_n)$ with x_i being 128-bit values, and key k
  - Compute $\Delta(m) := x_1 \oplus x_2 \oplus ... \oplus x_n$ with $\oplus$ denoting bitwise exclusive-or
  - Output: MAC $C_k(m) := E_k(\Delta(m))$ with $E_k(x)$ denoting AES encryption
- The key length is 128 bit and the MAC length is 128 bit, so we would expect an effort of about 2^{127} operations to obtain the key k and break the MAC (= being able to forge messages).
- Unfortunately the MAC definition is insecure:
  - Assume an attacker Eve who wants to forge messages exchanged between Alice and Bob obtains a message $(m, C_k(m))$ which has been "protected" by Alice using the secret key k shared with Bob
  - Eve can construct a message m' that yields the same MAC:
    - Let $y_1, y_2, ..., y_{n-1}$ be arbitrary 128-bit values
    - Define $\boldsymbol{y_n} := y_1 \oplus y_2 \oplus ... \oplus y_{n-1} \oplus \Delta(m)$
    - This $\boldsymbol{y_n}$ allows to construct the new message m' := $(y_1, y_2, ..., \boldsymbol{y_n})$
    - Therefore, $C_k(m') = E_k(\Delta(m')) = E_k(y_1 \oplus y_2 \oplus ... \oplus y_{n-1} \oplus \boldsymbol{y_n}))$

$$
\begin{aligned}
&= E_k(y_1 \oplus y_2 \oplus ... \oplus y_{n-1} \oplus y_1 \oplus y_2 \oplus ... \oplus y_{n-1} \oplus \Delta(m)))\\
&= E_k(\Delta(m)))\\
&= C_k(m)
\end{aligned}
$$

  - Therefore, $C_k(m)$ is a valid MAC for m'
  - When Bob receives $(m', C_k(m))$ from Eve, he will accept it as being originated

Applications of Cryptographic Hash Functions

- Principal application which led original design:
  - Message integrity:
    - Using a shared secret key:
      - A MAC over a message *m* directly certifies that the sender of the message possesses the secret key *k* and the message could not have been modified without knowledge of that key
    - Using public key cryptography:
      - The cryptographic hash value represents a *digital fingerprint*, which can be signed with a private key using public key cryptography (like RSA, ECC, ElGamal)
      - Given a cryptographic hash function it is computationally infeasible to construct two messages with the same fingerprint. Therefore, a given signed fingerprint can not be re-used by an attacker.
      - Note: Signatures in public key cryptography are often used in settings where the security has to be guaranteed a long time, e.g. digitalling signing a contract.

Other Applications which require some Caution (1)

- Pseudo-random number generation
  - The output of a cryptographic hash function is assumed to be uniformly distributed
  - Although this property has not been proven in a mathematical sense for common cryptographic hash functions, such as MD5, SHA-1, it is often used
  - Start with random seed, then hash
    - b_0 = seed
    - $b_{i+1} = H(b_i \mid seed)$

- Encryption
  - Remember: Output Feedback Mode (OFB) – encryption performed by generating a pseudo random stream, and performing XOR with plain text
  - Generate a key stream as follow:
    - $k_0 = H(K_{A,B} \mid IV)$
    - $k_{i+1} = H(K_{A,B} \mid k_i)$
  - The plain text is XORed with the key stream to obtain the cipher text.

Other Applications of Cryptographic Hash Functions

- Authentication with a *challenge-response* mechanism
  - Alice → Bob: random number "r_A"
  - Bob → Alice: "$H(K_{A,B}, r_A)$"
  - Based on the assumption that only Alice and Bob know the shared secret $K_{A,B}$, Alice can conclude that an attacker would not be able to compute $H(K_{A,B}, r_A)$, and therefore that the response is actually from Bob
  - Mutual authentication can be achieved by a 2nd exchange in opposite direction
  - This authentication is based on a well-established authentication method called „*challenge-response*"
  - This type of authentication is used, e.g., by HTTP digest authentication
    - It avoids transmitting the transport of the shared key (e.g. password) in clear text
  - Another type of a challenge-response would be, e.g., if Bob signs the challenge "r_A" with his private key
  - Note that this kind of authentication does not include negotiation of a session key.
  - Protocols for key negotiation will be discussed in subsequent chapters.

Other Applications of Cryptographic Hash Functions

- Authentication with One-Time Passwords (OTP):
  - The basic idea of one-time-passwords authentication is to transmit a “password”, that can only be used for one run of an authentication dialogue
  - Initial Setup:
    - The authenticator A sends a seed value r_A and the peer entity B concatenates it with his password and computes a hash value: $PW_N = H^N(r_A, password_B)$
    - The pair (N, PW_N) is transmitted to the authenticator and stored at the authenticator
  - Authentication dialogue:
    - $A \rightarrow B$: $N - 1$
    - $B \rightarrow A$: $PW_{N-1} := H^{N-1}(r_A, password_B)$
    - A checks if $H(PW_{N-1}) = PW_N$, and stores $(N - 1, PW_{N-1})$ as the new authentication information for B
  - Security: In order to break this scheme, an attacker would have to eavesdrop one PW_N and compute $H^{-1}(PW_N)$ which is impractical
  - Note: One-time-passwords must not be confused with one-time-pads

Other Applications of Cryptographic Hash Functions

- Cryptographic hash values can also be used for error detection, but they are generally computationally more expensive than simple error detection codes such as CRC

Constructing a MAC from a Cryptographic Hash Functions (1)

- Reasons for constructing MACs from cryptographic hash functions :
  - Cryptographic hash functions generally execute faster than symmetric block ciphers (Note: with AES this isn't much of a problem today)
  - There are no export restrictions to cryptographic hash functions
- Basic idea: "mix" a secret key *K* with the input and compute a hash value
- The assumption that an attacker needs to know *K* to produce a valid MAC nevertheless raises some cryptographic concern:
  - The construction $H(K \mid m)$ is not secure
  - The construction $H(m, K)$ is not secure
  - The construction $H(K, p, m, K)$ with *p* denoting an additional padding field does not offer sufficient security

Constructing a MAC from a Cryptographic Hash Functions (2)

- The construction *H(K | m | K),* called prefix-suffix mode, has been used for a while.
  - See for example [RFC 1828]
  - It has been also used in earlier implementations of the Secure Socket Layer (SSL) protocol (until SSL 3.0)
  - However, it is now considered vulnerable to attack by the cryptographic community.

- The most used construction is **HMAC**:

$$H(K \oplus opad \mid H(K \oplus ipad \mid m))$$

  - The length of the key *K* is first extended to the block length required for the input of the hash function *H* by appending zero bytes.
  - Then it is xor'ed respectively with two constants *opad* and *ipad*
  - The hash function is applied twice in a nested way.
  - Currently no attacks have been discovered on this MAC function. (see note 9.67 in [Men97a])
  - It is standardized in RFC 2104 [Kra97a] and is called ***HMAC***

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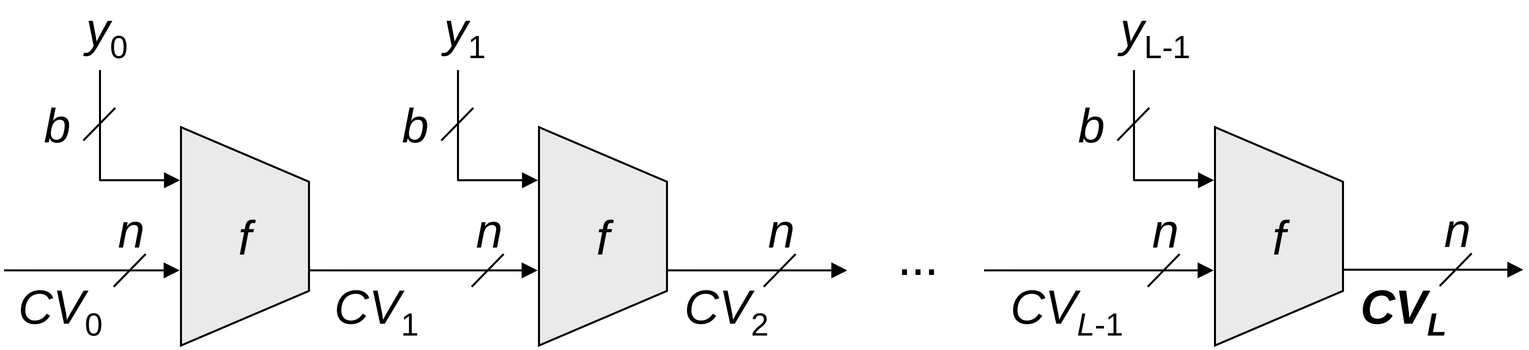
Overview of Commonly Used Cryptographic Hash Functions and Message Authentication Codes

- Cryptographic Hash Functions:
  - Message Digest 5 (MD5):
    - Invented by R. Rivest, Successor to MD4. Considered to be broken.
  - Secure Hash Algorithm 1 (SHA-1):
    - Old NIST standard.
    - Invented by the National Security Agency (NSA). Inspired by MD4.
  - Secure Hash Algorithm 3 (SHA-3):
    - Current NIST standard (since October 2012).
    - Keccak algorithm by G. Bertoni, J. Daemen, M. Peeters und G. Van Assche.

- Message Authentication Codes:
  - MACs constructed from cryptographic hash functions:
    - Example HMAC: $H(K, p_1, H(K, p_2, m))$, RFC 2104, details later
  - CBC-MAC, CMAC
    - Uses blockcipher in Cipher Block Chaining mode
      (Encryption: XOR plain text with cipher text of previous block, then encrypt)
    - CMAC better than pure CBC-MAC, details later

Merkle-Damgård construction (1)

- Like many of today's block ciphers follow the general structure of a Feistel network, cryptographic hash functions like SHA-1 and MD5 follow the **Merkle-Damgård construction**:
  - Let y be an arbitrary message. Usually, the length of the message is appended to the message and padded to a multiple of some block size b. Let $(y_0, y_1, ..., y_{L-1})$ denote the resulting message consisting of L blocks of size b
  - The general structure is as depicted below:



  - CV is a *chaining value*, with $CV_0 := IV$ and $H(y) := CV_L$
  - f is a specific compression function which compresses $(n + b)$ bit to n bit

Merkle-Damgård construction (2)

- The hash function H according to Merkle-Damgård construction can be summarized as follows:

$$CV_0 = IV \qquad = \text{initial n-bit value}$$

$$CV_i = f(CV_{i-1}, y_{i-1}) \qquad 1 \leq i \leq L$$

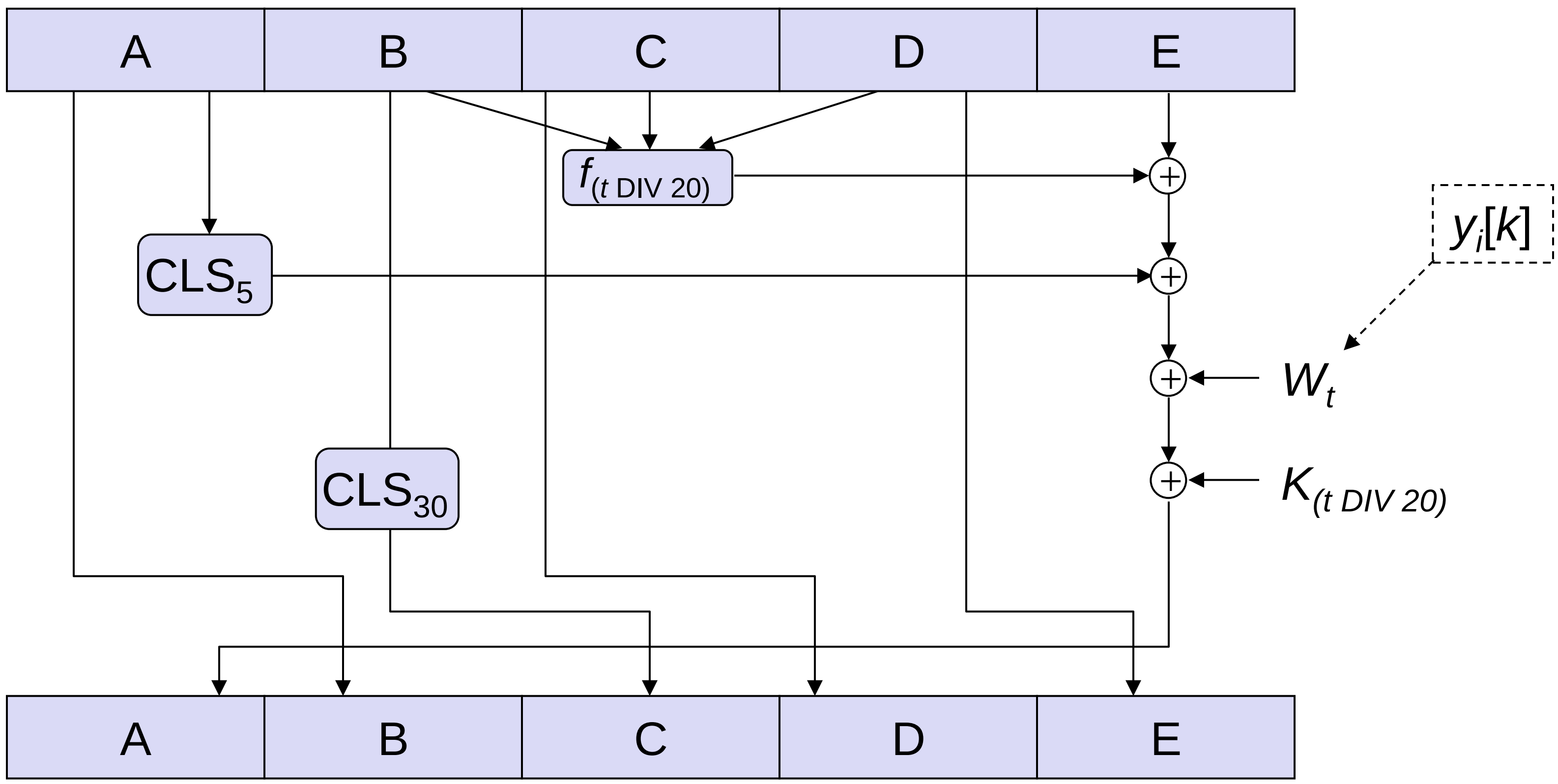
$$H(y) = CV_L$$

- Security proofs by the authors [Mer89a] have shown shown that if the compression function *f* is collision resistant, then the resulting iterated hash function *H* is also collision resistant.
- However, the construction has undesirable properties like length extension attacks. The Merkle-Damgård construction can be strengthened:
  - by adding a block with the length of the message (length padding).
  - by using a wide pipe construction where the hash output has less bits than the intermediate chaining values CV_i with $i < L$.
    - Hash shorter than state good as less info leaked to attacker (e.g. against length extension). However, less search space for other attacks like brute force.

The Secure Hash Algorithm SHA-1 (1)

- Also SHA-1 follows the common structure as described above:
  - SHA-1 works on 512-bit blocks and produces a 160-bit hash value
  - Initialization
    - The data is padded, a length field is added and the resulting message is processed as blocks of length 512 bit
    - The chaining value is structured as five 32-bit registers A, B, C, D, E
    - Initialization: **`A = 0x 67 45 23 01  B = 0x EF CD AB 89`**
`C = 0x 98 BA DC FE  D = 0x 10 32 54 76`
`E = 0x C3 D2 E1 F0`
    - The values are stored in big-endian format
  - Each block y_i of the message is processed together with CV_i in a module realizing the compression function f in four rounds of 20 steps each.
    - The rounds have a similar structure but each round uses a different primitive logical function f_1, f_2, f_3, f_4
    - Each step makes use of a fixed additive constant K_t, which remains unchanged during one round
  - The text block y_i which consists of 16 32-bits words is „stretched" with a recurrent linear function in order to make 80 32-bits out of it, which are required for the 80 steps:
    - $t \in \{0, ..., 15\} \quad \Rightarrow W_t := y_i[t]$
    - $t \in \{16, ..., 79\} \quad \Rightarrow W_t := \mathrm{CLS}_1(W_{t-16} \oplus W_{t-14} \oplus W_{t-8} \oplus W_{t-3})$

The Secure Hash Algorithm SHA-1 (2) - One Step



- After step 79 each register A, B, C, D, E is added modulo 2^{32} with the value of the corresponding register before step 0 to compute CV_{i+1}

The Secure Hash Algorithm SHA-1 (3)

- The SHA-1 value over a message is the content of the chaining value CV after processing the final message block
- Security of SHA-1:
  - As SHA-1 produces a hash value of length 160 bit, it offers better security than MD5 with its 128 bits.
  - In February 2005, 3 Chinese Scientists published a paper where they break SHA-1 collision resistance within 2^{69} steps, which is much less than expected from a cryptographic hash function with an output of 160 bits (2^{80}).
  - Meanwhile down to 2^{52} steps (EuroCrypt 2009 Rump Session).
  - Up to now, no attacks on the pre-image resistance of SHA-1 have been published.

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Attacks Based on the Birthday Phenomenon (1)

- Attack against collision resistance of cryptographic hash functions
- The Birthday Phenomenon:
  - How many people need to be in a room such that the possibility that there are at least two people with the same birthday is greater than 0.5?
  - For simplicity, we don't care about February, 29, and assume that each birthday is equally likely
- Define $P(n, k)$:= Pr[at least one duplicate in k items, with each item able to take one of n equally likely values between 1 and n]
- Define $Q(n, k)$:= Pr[no duplicate in k items, each item between 1 and n]
  - $P(n, k) = 1 - Q(n, k)$
  - We are able to choose the first item from n possible values, the second item from n - 1 possible values, etc.
  - Hence, the number of different ways to choose k items out of n values with no duplicates is: $N = n \times (n - 1) \times ... \times (n - k + 1) = n! / (n - k)!$
  - The number of different ways to choose k items out of n values, with or without duplicates is: n^k
  - So, $Q(n, k) = N / n^k = n! / ((n - k)! \times n^k)$

Attacks Based on the Birthday Phenomenon (2)

- *P(n, k)* := Pr[at least one duplicate in *k* items, with each item able to take one of n equally likely values between 1 and *n*]
- We have:

$$P(n,k) = 1 - Q(n,k) = 1 - \frac{n!}{(n-k)! \times n^k}$$

$$= 1 - \frac{n \times (n-1) \times \ldots \times (n-k+1)}{n^k}$$

$$= 1 - \left[\frac{n-1}{n} \times \frac{n-2}{n} \times \ldots \times \frac{n-k+1}{n} \right]$$

$$= 1 - \left[\left(1 - \frac{1}{n}\right) \times \left(1 - \frac{2}{n}\right) \times \ldots \times \left(1 - \frac{k-1}{n}\right) \right]$$

- We will use the following inequality: $(1 - x) \leq e^{-x}$ for all $x \geq 0$
- So:

$$P(n,k) > 1 - \left[\left(e^{-1/n}\right) \times \left(e^{-2/n}\right) \times \ldots \times \left(e^{-(k-1)/n}\right) \right]$$

$$= 1 - e^{-\left[\left(1/n\right) + \left(2/n\right) + \ldots + \left(k-1/n\right)\right]}$$

$$= 1 - e^{-k \times (k-1) / 2n}$$

Attacks Based on the Birthday Phenomenon (3)

- In the last step, we used the equality: 1 + 2 + ... + (k - 1) = (k^2 - k) / 2
  - Exercise: proof the above equality by induction
- Let's go back to our original question: how many people *k* have to be in one room such that there are at least two people with the same birthday (out of *n* = 365 possible) with probability ≥ 0,5?
  - So, we want to solve:

$$\frac{1}{2} = 1 - e^{-k\times(k-1)/2n}$$

$$\Leftrightarrow \quad 2 = e^{k\times(k-1)/2n}$$

$$\Leftrightarrow \ln(2) = \frac{k\times(k-1)}{2n}$$

  - For large *k* we can approximate $k \times (k - 1)$ by k^2, and we get:

$$k = \sqrt{2\ln(2)n} \approx 1.18\sqrt{n}$$

  - For *n* = 365, we get *k* = 22.54 which is quite close to the correct answer 23

Attacks Based on the Birthday Phenomenon (4)

- What does this have to do with cryptographic hash functions?
- We have shown, that if there are *n* possible different values, the number *k* of values one needs to randomly choose in order to obtain a pair of identical values with probability ≥ 0.5, is in the order of $\sqrt{n}$
- Now, consider the "*Yuval's square root attack*" [Yuv79a]:
  - Eve wants Alice to sign a message *m1* which Alice normally never would sign. Eve knows that Alice uses the function H to compute a cryptographic hash value of *m.* The hash value has length *r* bit before she signs it with her private key yielding her digital signature
  - First, Eve produces her message *m1*. If she would now compute H(*m*1) and then try to find a second harmless message *m2* which leads to the same hash value her search effort in the average case would be on the order of $2^{(r-1)}$
  - Instead she takes any harmless message *m2* and starts producing variations *m1'* and *m2'* of the two messages, e.g. by adding <space> <backspace> combinations or varying with semantically identical words

Attacks Based on the Birthday Phenomenon (5)

- As we learned from the birthday phenomenon, Eve will just have to produce about $\sqrt{2^r} = 2^{r/2}$ variations of each of the two messages such that the probability that she obtains two messages *m1'* and *m2'* with the same hash value is at least 0.5
- As she has to store the messages together with their hash values in order to find a match, the memory requirement of her attack is on the order of $2^{r/2}$ and its computation time requirement is on the same order
- After she has found *m1'* and *m2'* with *H*(*m1'*) = *H*(*m2'*) she asks Alice to sign *m2'*. Eve can then take this signature and claim that Alice signed *m1'*

Attacks Based on the Birthday Phenomenon (6)

- Attacks following this method are called *birthday attacks*
- Consider now, that Alice uses RSA with keys of length 2048 bit and a cryptographic hash function which produces hash values of length 96 bit.
  - Eves average effort to produce two messages *m1’* and *m2’* as described above is on the order of 2^{48}, which is feasible today. Breaking RSA keys of length 2048 bit is far out of reach with today's algorithms and technology

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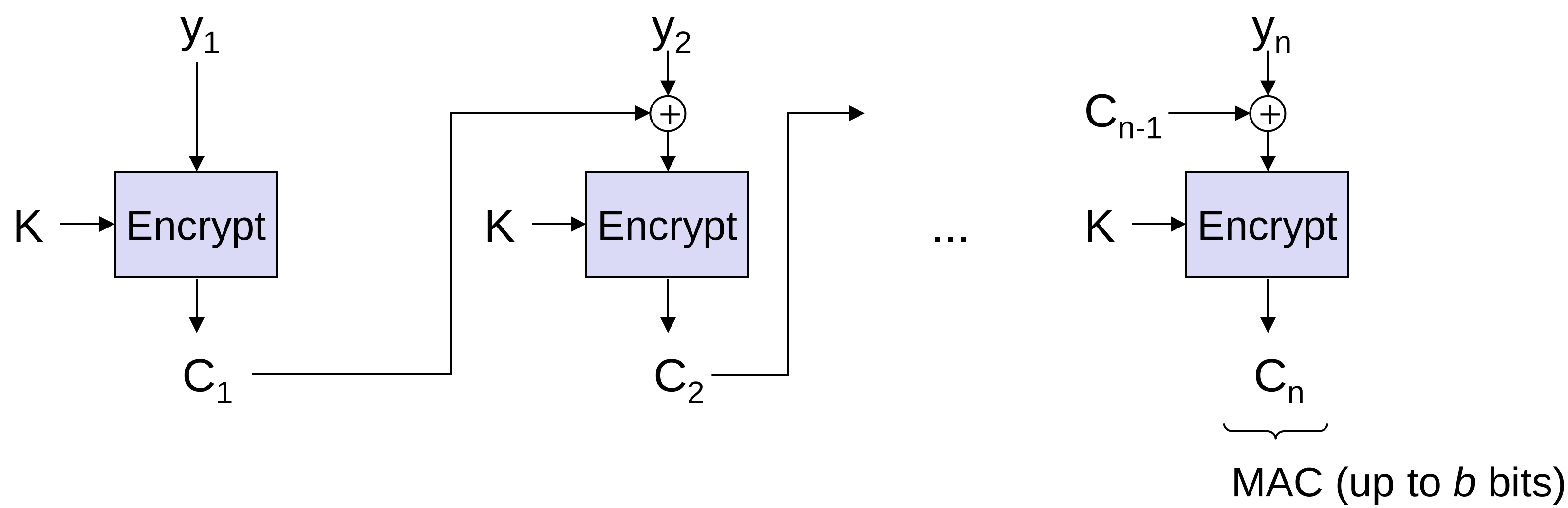
Cipher Block Chaining Message Authentication Codes (1)

- A CBC-MAC is computed by encrypting a message in CBC Mode and taking the last ciphertext block or a part of it as the MAC:



- This MAC needs not to be signed any further, as it has already been produced using a shared secret K.
- This scheme works with any block cipher (AES, Twofish, 3DES, ...)
- It is used, e.g., for IEEE 802.11 (WLAN) WPA2, many modes in SSL / IPSec use some CBC-MAC construction.

Cipher Block Chaining Message Authentication Codes (2)

- CBC-MAC security
  - CBC-MAC must NOT be used with the same key as for the encryption
  - In particular, if CBC mode is used for encryption, and CBC-MAC for integrity with the same key, the MAC will be equal to the last cipher text block
  - If the length of a message is unknown or no other protection exists, CBC-MAC can be prone to length extension attacks. CMAC resolves the issue.
- CBC-MAC performance
  - Older symmetric block ciphers (such as DES) require more computing effort than dedicated cryptographic hash functions, e.g. MD5, SHA-1 therefore, these schemes are considered to be slower.
  - However, newer symmetric block ciphers (AES) is faster than conventional cryptographic hash functions.
  - Therefore, AES-CBC-MAC is becoming popular.

Cipher-based MAC (CMAC)

- CMAC is a modification of CBC-MAC
  - Compute keys k1 and k2 from shared key k.
  - Within the CBC processing
    - XOR complete blocks before encryption with k1
    - XOR incomplete blocks before encryption with k2
    - k is used for the block encryption
  - Output is the last encrypted block or the l most significant bits of the last block.
  - AES-CMAC is standardized by IETF as RFC 4493 and its truncated form in RFC 4494.
- XCBC-MAC (e.g. found in TLS) is similar to CMAC but k1 and k2 are input to XCBC-MAC algorithm and not derived from k.

Overview

- Introduction
- MAC and other applications
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- Birthday Phenomenon
- CBC-MACs / CMAC
- **SHA-3 and Skein**
- Integrity Check and Digital Signature

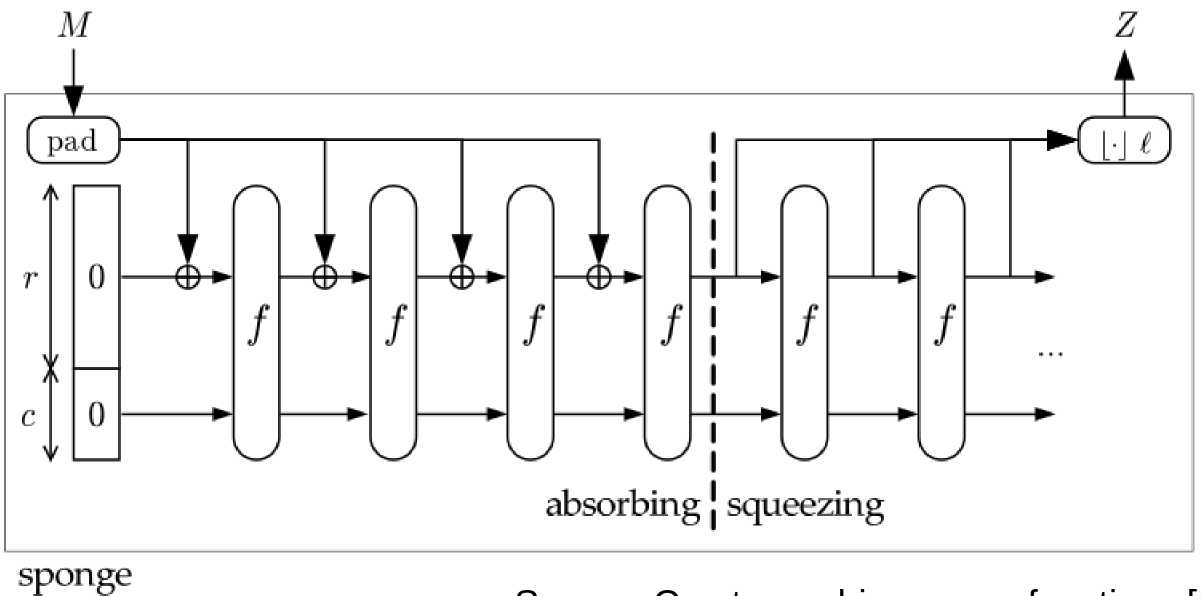
SHA-3 – a new hash standard

- MD5 is considered to be broken and SHA-1 is under heavy attack.
- Performance of SHA-1 worse than performance of up-to-date symmetric ciphers like AES or Twofish.

➔ NIST startet a competition for a new hash function standard that will be called SHA-3 in 2007.

- NIST SHA-3 comptetition
  - Requirement: fast and secure!
  - Round1: 51 candidates accepted, 13 rejected. (December 2008)
  - Round2: 14 candidates survivided. (July 2009)
  - Round3 (final): 5 candidates (BLAKE, Grostl, JH, Keccak, Skein) (December 2010)
  - **Winner (October 2012): Keccak**

SHA-3 / Keccak / Sponge Construction



Source: Cryptographic sponge functions [CSF], January 2011, http://sponge.noekeon.org/ by Keccak authors

- SHA-3 (Keccak)
  - Follows the sponge construction
  - M is padded to a multiple of the block length r
  - r=0, c=0
  - For each block i, compute f(r+mi | ci) (= Absorbing phase)
  - In squeezing phase concatenate the ri until output length reached.

SHA-3 / Keccak / Sponge Construction

- The function f follows a block cipher-like concept.
- Internal state:
  - 3d state space, 5x5 64-bit words (400 Bits)
- 256 Bit and 512 Bit blocks, 24 rounds with each 5 subrounds
- Round operations include
  - Parity in columns of the state space
  - Bitwise rotation in words
  - Permutation of words
  - A non-linear bitwise combination operation
  - XOR with round constant
- Authenticated Encryption and Tree Hash support proposed, not standardized.

SHA-3 candidate Skein

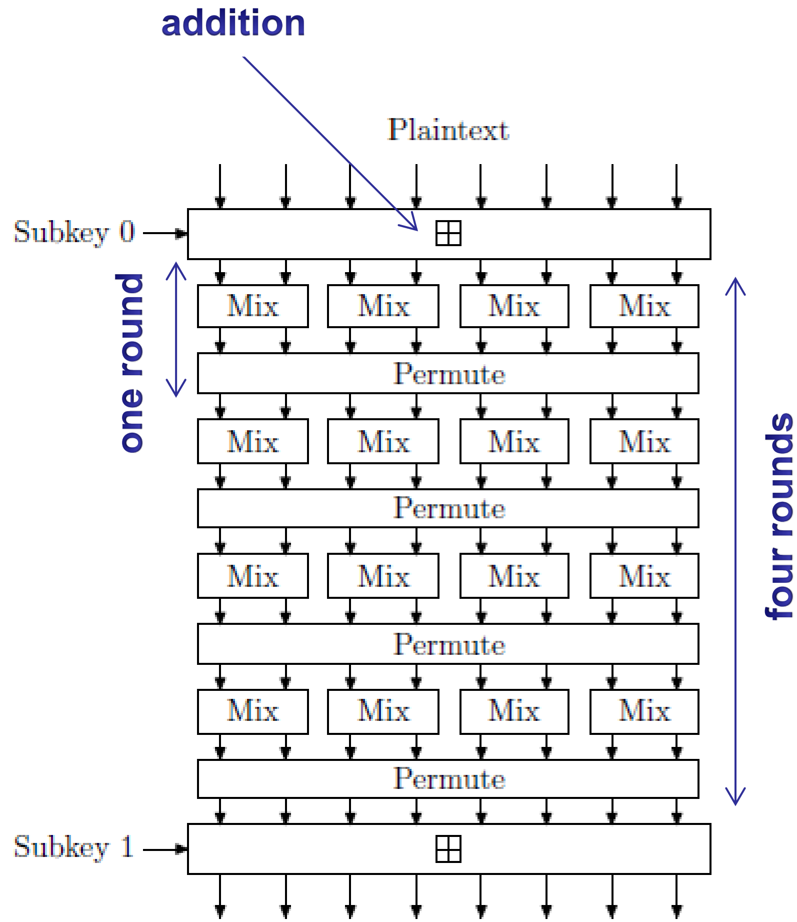
- In addition to SHA-3 finalist Skein might also get wide support in libraries and protocols due to its prominant authors .
- Variants Skein-n / Skein-n-m
  - n = size of internal state (relates to the strength of the hash function)
    - n = 512 (default), n = 1024 (conservative), n = 256 (low memory)
  - m = size of hash output
- Concept
  - Build hash function out of tweakable block cipher
  - Uses block cipher Threefish
    - 512, 1024, 256 bits key length and block length (depending on variant)
  - Unique Block Iteration (UBI) as chaining mode
    - Variable input and fixed (configurable) output size
  - Optional Argument System
    - Key, Configuration, Personalization, Public Key, Key Derivation Identifier, Nonce, Message, Output
  - Support for Tree Hashing
    - Option to process large plaintexts on parallel CPUs / machines in a tree rather than linear processing (cannot be parallelized)

Tweak

- Tweak in Skein
  - Overall size = 128 bits
  - 96 bits counter for message length
    - Incremented for each block
  - 6 bits type information
  - Bit indicates padding
  - Bit indicates first block
  - Bit indicates last block
  - Makes hash result for a plaintext subsequence position-dependent
    - E.g. harder to insert blocks that do not change chaining value to next block
    - E.g. harder to extend message and compute new MAC
    - Etc.

Threefish

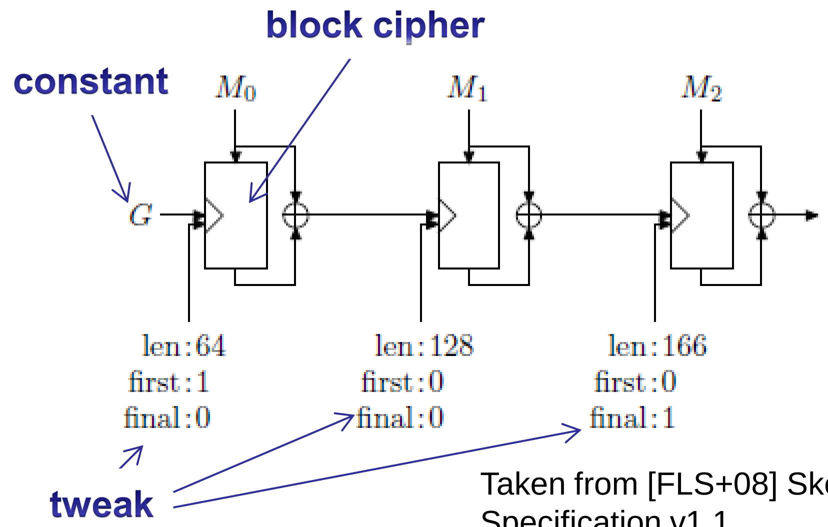
- Block size 256, 512, or 1024 bits
- Key size = block size
- Tweak size = 128 bits
- All operations on 64 bit words
- Mix operation uses
  - XOR, addition (mod 2^64), constant rotation (round and word-specific)
- 72 rounds (80 rounds for 1024 bit version)
- Subkeys
  - Are round-specific and derived from key (4, 8, or 16 words) and tweak (128 bits = 2 words)



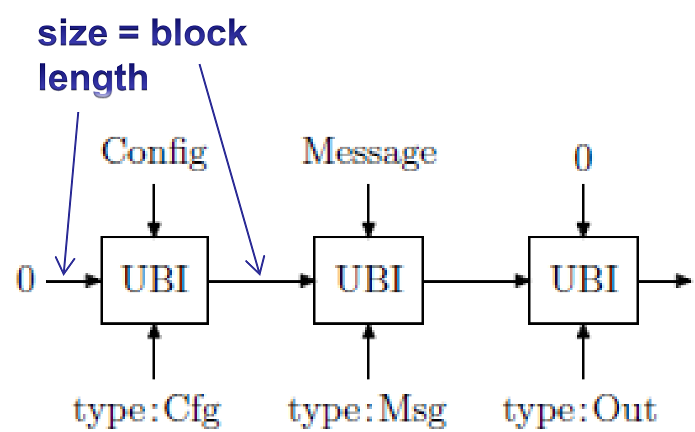
Taken from [FLS+08] Skein Specification v1.1
http://www.skein-hash.info/sites/default/files/skein1.1.pdf

Unique Block Iteration (UBI) Chaining Mode

- Unique Block Iteration (UBI)
  - Block cipher
    - Input: Message Blocks
    - Key: Tweak and chaining value
  - Chaining Value
    - XOR of output and input of block cipher
  - Tweak
    - „Counts bytes until now“ (len field)
    - Indicates first block / finalblock
- UBI in Skein
  - type field
    - Config
      - 32 byte configuration string containing fields like output length
    - Message
      - Plaintext
    - Out
      - Generates final output, input is 0.



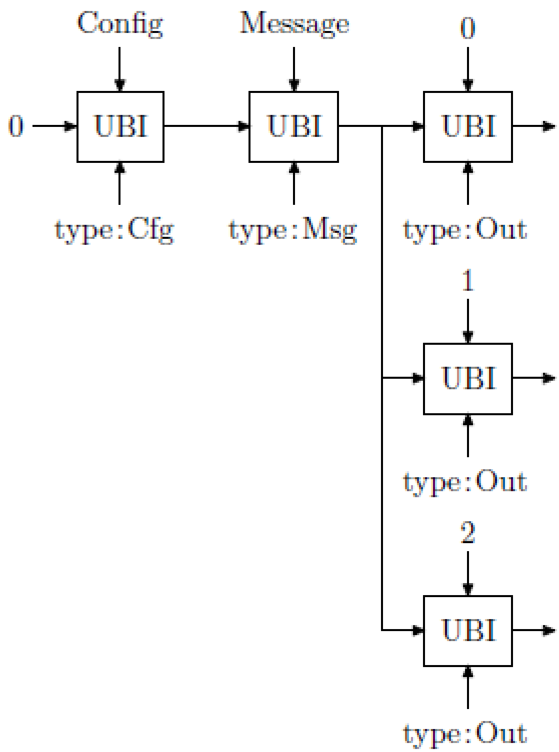
Taken from [FLS+08] Skein Specification v1.1



Taken from [FLS+08] Skein Specification v1.1
http://www.skein-hash.info/sites/default/files/skein1.1.pdf

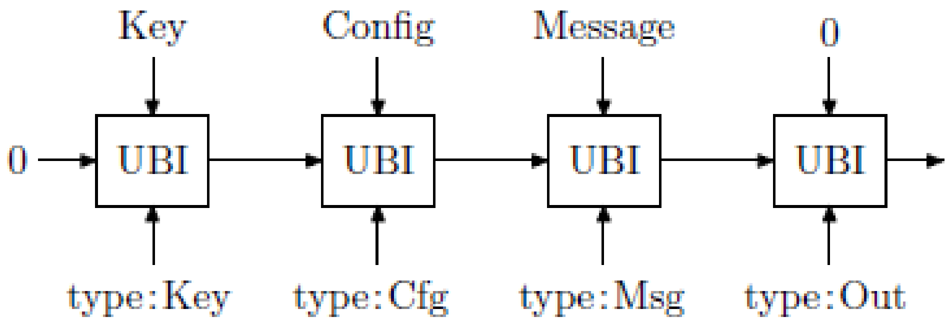
UBI in Skein – Output Generation

- Increase the output size by applying a counter mode for the output computation



Taken from [FLS+08] Skein Specification v1.1

Skein-MAC



Taken from [FLS+08] Skein Specification v1.1

- MAC usage
  - Skein can be used with HMAC and similar functions, requires two hashes
  - Faster option: use Skein with optional argument „key"
    - The key input are processed by an UBI block with the key as input, 0 as constant / initial chaining value and the tweak type information „Key"
    - This does not suffer the same weaknesses mentioned before like adding a key to the plaintext as in some weaker MAC contructions like H(k,m,k).

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Integrity check with hash function / MAC

Alice (A)

share symmetric key kab

Bob (B)

m, MAC_h(kab, m)

- Alice protects her message m with a MAC function which is based on
  - Some hash function: h
    - h can be a cryptographic hash function or a symmetric cipher or both
  - The shared key between Alice and Bob: kab
- Alice has to send m and the MAC value to Bob.
- Examples for potential MAC constructions:
  - HMAC $H(K \oplus opad \mid H(K \oplus ipad \mid m))$
  - CBC-MAC / CMAC
  - Encrypt(kab, h(m))

Integrity check with hash function / MAC

Alice (A)

share symmetric key kab

Bob (B)

m, MAC_h(kab, m)

- Alice „signs“ her data m with the Message Authentication Code.
- Bob can verify the MAC code by using the shared key.
  - He reads Alice‘s MACh(kab, m)
  - He can check if his MACh(kab, m) matches the one Alice signed.
  - Only Alice and Bob who know key kab can do this.

Take home message: for integrity checks the receiver needs to know m <u>and</u> a modification check value that it can compare.

- Think about it: Why is E(kab, m) usually not sufficient?

Additional References I

(Beyond the scope of examination)

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