Network Security

Chapter 2 Cryptography

2.2 Cryptographic Hash Functions

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

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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 \textit{modified on purpose}!

- Consequently, we need to add a \textit{Modification Detection Code} (MDC) that fulfills some additional properties which should make it \textit{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 $\mathbb{Z}_p^*$
    - Let $h(x) = g^x \mod p$
    - Then $h$ is a one-way function
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. **2$^{nd}$ 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 **not** a cryptographic hash function
  - CRC does not provide 2\textsuperscript{nd} pre-image resistance and collision resistance
  - CRC is additive
    - If $x' = x \oplus \Delta$, then $\text{CRC}(x') = \text{CRC}(x) \oplus \text{CRC}(\Delta)$
  - CRC is useful for protecting against noisy channels
  - But not against intentional manipulation
Overview

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- **MAC and other applications**
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- Birthday Phenomenon
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Applying a hash function is not sufficient to secure a message.

- $h(m)$ needs to be protected.
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
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 $m$. 
Since the secret key $k$ is unknown to the attacker, the attacker cannot compute $\text{MAC}(k,m')$. 
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 $y_n := y_1 \oplus y_2 \oplus ... \oplus y_{n-1} \oplus \Delta(m)$
    - This $y_n$ allows to construct the new message $m' := (y_1, y_2, ..., y_n)$
    - Therefore, $C_k(m') = E_k(\Delta(m')) = E_k(y_1 \oplus y_2 \oplus ... \oplus y_{n-1} \oplus y_n))$
      $$= E_k(y_1 \oplus y_2 \oplus ... \oplus y_{n-1} \oplus y_1 \oplus y_2 \oplus ... \oplus y_{n-1} \oplus \Delta(m)))$$
      $$= E_k(\Delta(m)))$$
      $$= C_k(m)$$

  - 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. digital 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
    - $b_0 = \text{seed}$
    - $b_{i+1} = H(b_i \mid \text{seed})$

- 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 2\(^{nd} \) 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:
      $$PW_N = H^N(r_A, \text{password}_B)$$
    - The pair $(N, PW_N)$ is transmitted to the authenticator and stored at the authenticator
  - Authentication dialogue:
    - $A \rightarrow B$: $N - 1$
    - $B \rightarrow A$: $PW_{N-1} := H^{N-1}(r_A, \text{password}_B)$
    - $A$ 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
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
The construction $H(K \mid m \mid K)$, 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 \((y_0, y_1, \ldots, y_{L-1})\) denote the resulting message consisting of \( L \) blocks of size \( b \).
  - The general structure is as depicted below:

\[
\begin{array}{c}
\text{CV}_0 \\
\downarrow b \\
f \\
\downarrow n \\
y_0 \\
\end{array} \\
\begin{array}{c}
\text{CV}_1 \\
\downarrow b \\
f \\
\downarrow n \\
y_1 \\
\end{array} \\
\begin{array}{c}
\text{CV}_2 \\
\downarrow b \\
f \\
\downarrow n \\
y_{L-1} \\
\end{array} \\
\begin{array}{c}
\text{CV}_L \\
\downarrow b \\
f \\
\downarrow n \\
\end{array}
\]

- \( CV \) 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:
  \[
  CV_0 = IV = \text{initial n-bit value} \\
  CV_i = f(CV_{i-1}, y_{i-1}) \quad 1 \leq i \leq L \\
  H(y) = CV_L
  \]

- Security proofs by the authors [Mer89a] have 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.
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:  
    \[
    \begin{align*}
    A &= 0x\ 67\ 45\ 23\ 01 & B &= 0x\ EF\ CD\ AB\ 89 \\
    C &= 0x\ 98\ BA\ DC\ FE & D &= 0x\ 10\ 32\ 54\ 76 \\
    E &= 0x\ C3\ D2\ E1\ F0 \\
    \end{align*}
    \]
    - 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:
  - \( t \in \{0, \ldots, 15\} \Rightarrow W_t := y_i[t] \)
  - \( t \in \{16, \ldots, 79\} \Rightarrow W_t := CLS_1(\underbrace{W_{t-16} \oplus W_{t-14} \oplus W_{t-8} \oplus W_{t-3}}) \)
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 $P(n, k) := \Pr[\text{at least one duplicate in } k \text{ items, with each item able to take one of } n \text{ equally likely values between 1 and } n]$
- Define $Q(n, k) := \Pr[\text{no duplicate in } k \text{ items, each item between 1 and } n]$
  - $P(n, k) = 1 - Q(n, k)$
  - 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: $N = n \times (n - 1) \times \ldots \times (n - k + 1) = n! / (n - k)!$
  - 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)

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

- 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:

\[
P(n, k) > 1 - \left[ \left( e^{-\frac{1}{n}} \right) \times \left( e^{-\frac{2}{n}} \right) \times \ldots \times \left( e^{-\frac{k-1}{n}} \right) \right] = 1 - e^{-\left[ \frac{1}{n} + \frac{2}{n} + \ldots + \frac{k-1}{n} \right]} = 1 - e^{-\frac{k \times (k-1)}{2n}}
\]
Attacks Based on the Birthday Phenomenon (3)

- In the last step, we used the equality: \( 1 + 2 + \ldots + (k - 1) = \frac{(k^2 - k)}{2} \)
  - 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 \( \geq 0.5 \)?
  - So, we want to solve:
    
    \[
    \frac{1}{2} = 1 - e^{-\frac{k \times (k-1)}{2n}}
    \]
    
    \( \Leftrightarrow \)
    
    \[
    2 = e^{\frac{k \times (k-1)}{2n}}
    \]
    
    \( \Leftrightarrow \ln(2) = \frac{k \times (k-1)}{2n} \)
  - 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 \( \geq 0.5 \), is in the order of \( \sqrt{n} \).

- Now, consider the “Yuval’s square root attack” [Yuv79a]:
  - Eve wants Alice to sign a message \( m_1 \) 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 \( m_1 \). If she would now compute \( H(m_1) \) and then try to find a second harmless message \( m_2 \) 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 \( m_2 \) and starts producing variations \( m_1' \) and \( m_2' \) of the two messages, e.g. by adding \(<\text{space}>\) and \(<\text{backspace}>\) combinations or varying with semantically identical words.
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 $m_1'$ and $m_2'$ 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 $m_1'$ and $m_2'$ with $H(m_1') = H(m_2')$ she asks Alice to sign $m_2'$. Eve can then take this signature and claim that Alice signed $m_1'$. 

$$r \approx 22$$
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 $m_1'$ and $m_2'$ 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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- 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:

  ![Diagram](image)

  - 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 $k_1$ and $k_2$ from shared key $k$.
  - Within the CBC processing
    - XOR complete blocks before encryption with $k_1$
    - XOR incomplete blocks before encryption with $k_2$
    - $k$ 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 $k_1$ and $k_2$ are input to XCBC-MAC algorithm and not derived from $k$. 
Overview

- Introduction
- MAC and other applications
- Common Structures and SHA-1
- 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 competition
- Requirement: fast and secure!
- Round1: 51 candidates accepted, 13 rejected. (December 2008)
- Round2: 14 candidates survived. (July 2009)
- Round3 (final): 5 candidates (BLAKE, Grostl, JH, Keccak, Skein) (December 2010)
- Winner (October 2012): Keccak
- **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 $f(r+mi \mid ci)$ (= Absorbing phase)
  - In squeezing phase concatenate the $ri$ until output length reached.
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 prominent 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 \((\text{mod } 2^{64})\), 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
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 / final block

- **UBI in Skein**
  - type field
    - Config
      - 32 byte configuration string containing fields like output length
    - Message
      - Plaintext
    - Out
      - Generates final output, input is 0.
- Increase the output size by applying a counter mode for the output computation

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).
Overview

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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 \( H(K \oplus opad | H(K \oplus ipad | m)) \)
- CBC-MAC / CMAC
- Encrypt(kab, h(m))
Integrity check with hash function / MAC

- 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 \( \text{MAC}_h(k_ab, m) \)
  - He can check if his \( \text{MAC}_h(k_ab, m) \) matches the one Alice signed.
  - Only Alice and Bob who know key \( k_ab \) can do this.

Take home message: for integrity checks the receiver needs to know \( m \) and a modification check value that it can compare.
- Think about it: Why is \( E(k_ab, m) \) usually not sufficient?
Additional References I

(Beyond the scope of examination)


Additional References II


