CS458: Introduction to Information Security

Notes 6: Cryptographic Hash Functions

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Outline

- Hash Functions and Cryptographic Hash Functions
- Requirements and Security of Cryptographic Hash Functions
- Popular Hash Functions (MD5 and SHA)

Hash Functions

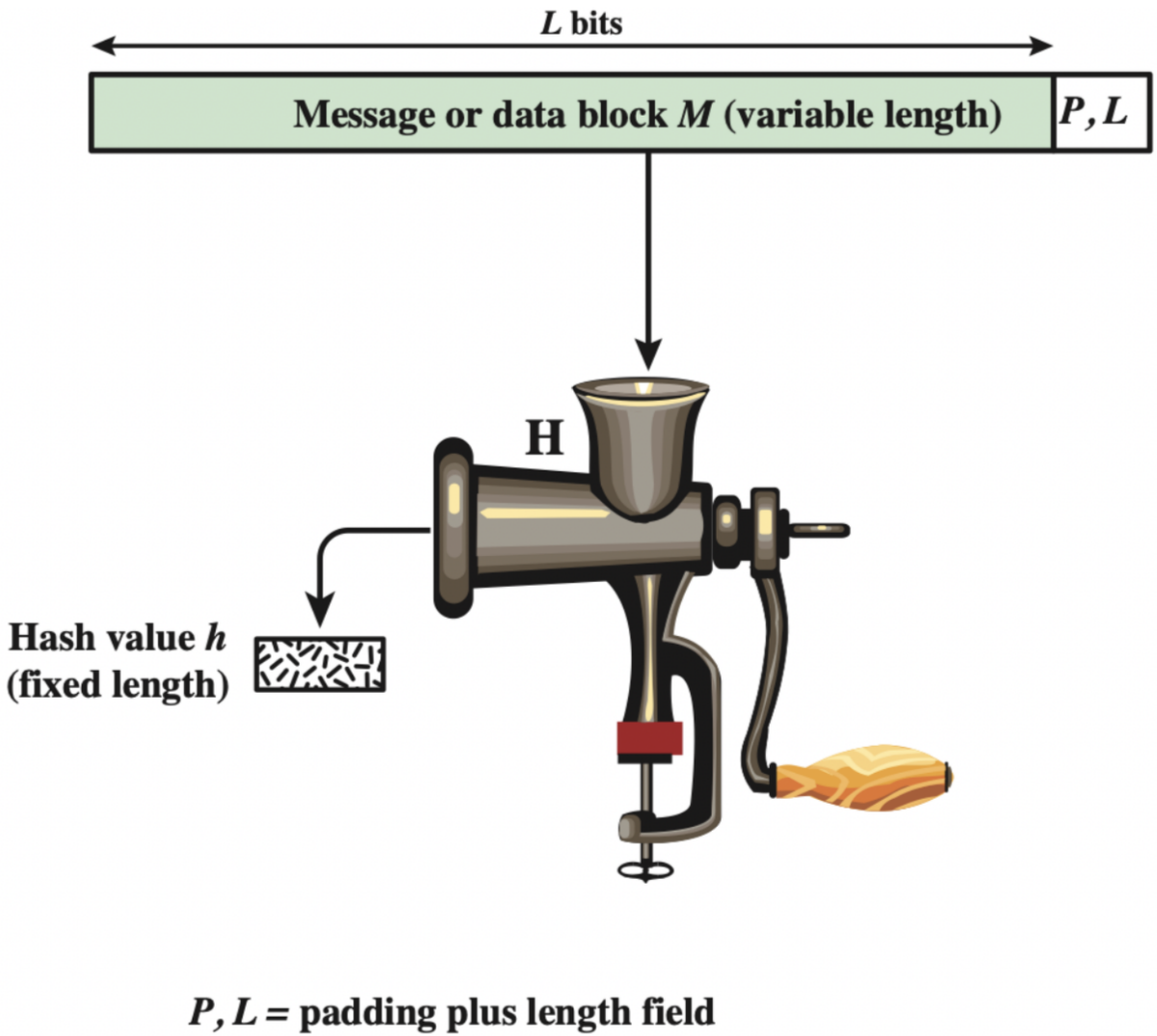
- *Hash functions are mathematical algorithms that convert input data of "arbitrary size" into a fixed-size output, typically represented as a string of characters.*

Hash Functions

- Hash Functions H
  - **Input**: variable-length block of data M
  - **Output**: fixed-size hash value $h = H(M)$
  - Applying H to large set of inputs should produce evenly distributed and random looking outputs
  - Values returned by a hash function are called *message digest* or simply *hash values*.
- Cryptographic hash function:
  - An algorithm for which it is computationally infeasible[1] to find either:
    1. a data object that maps to a pre-specified hash result (*the one-way property*)
       - *i.e., it should be computationally hard to reverse a hash function*
    2. two data objects that map to the same hash result (*the collision-free property*)
       - *i.e., it should be hard to find two different inputs messages that produce the same hash value*
  - Used to determine whether or not data has changed
    - Examples: message authentication, digital signatures, one-way password file, intrusion/virus detection, PRNG

[1] *infeasible means it would take too long to do that.*

Cryptographic Hash Function: $h = H(M)$



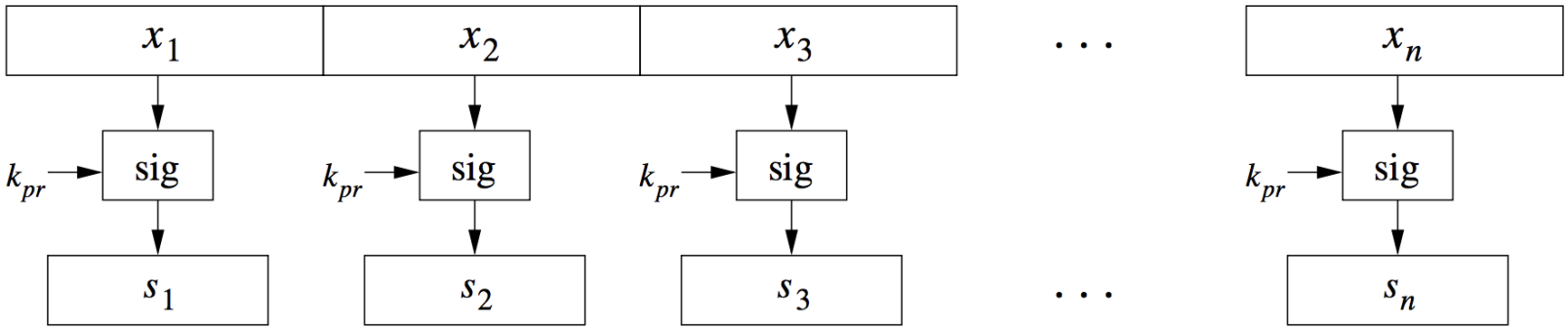
Hash function maps from input of some length L bits and produce a fixed small length output

Motivation: Signing Long Messages

- Suppose Bob signs x
- Bob sends x and $s = sig_{K_{pr,B}}(x)$ to Alice.
- Alice verifies that $ver_{K_{pub,B}}(x, s)$.
- Problem:
  - x is restricted in length, e.g., $|x| < 256$ Bytes (N is 2048 bits)
  - In practice the plaintext x will often be large.
- *Q: How can we efficiently compute signatures of large messages?*
  - Divide the message x into blocks x_i of size less than the allowed input size of the signature algorithm, and sign each block separately

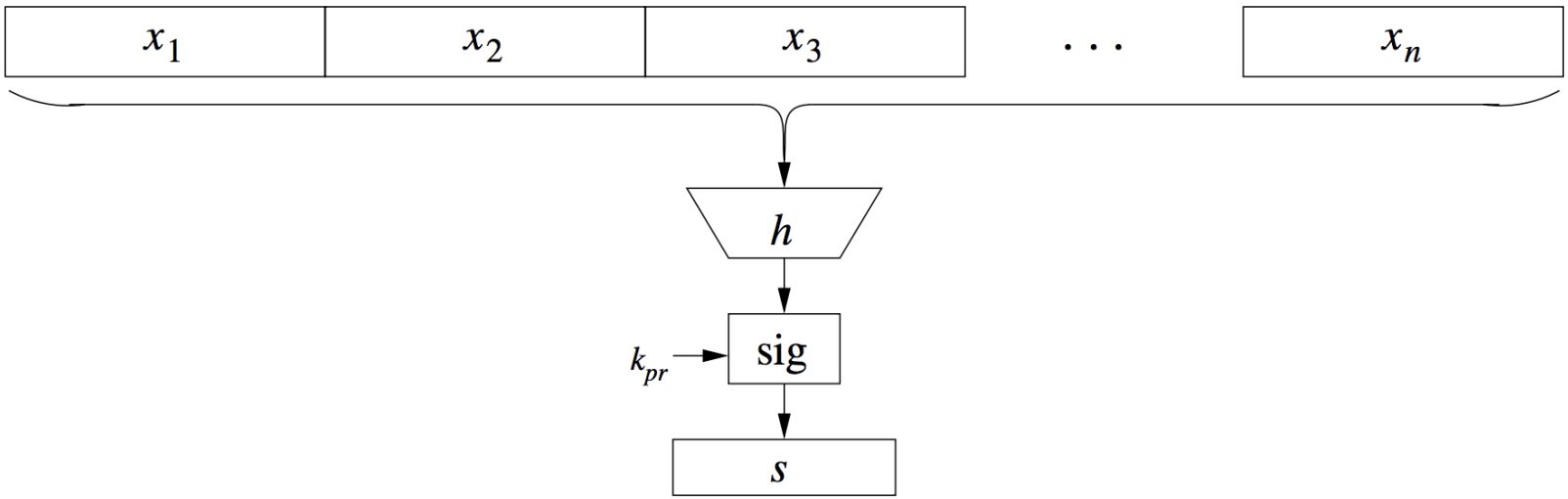
Motivation: Signing Long Messages: Problem

- Naïve signing of long messages generates a signature of same length.



- This is Bad. Three Problems
  - **Computational overhead**
    - DSs are based on computationally intensive asymmetric operations
  - **Message overhead**
    - Double the message overhead
  - **Security limitations**
    - Attacker can remove individuals messages/signatures, reorder messages/signatures, or reassemble new messages/signatures, etc
- **Solution**: *Instead of signing the whole message, sign only a digest (hash).* Also secure, but much faster
  - i.e., somehow "compress" the message $\boldsymbol{x}$ prior to signing
- **Needed**: Hash Functions

Signing of long messages with a hash function



Message Authentication

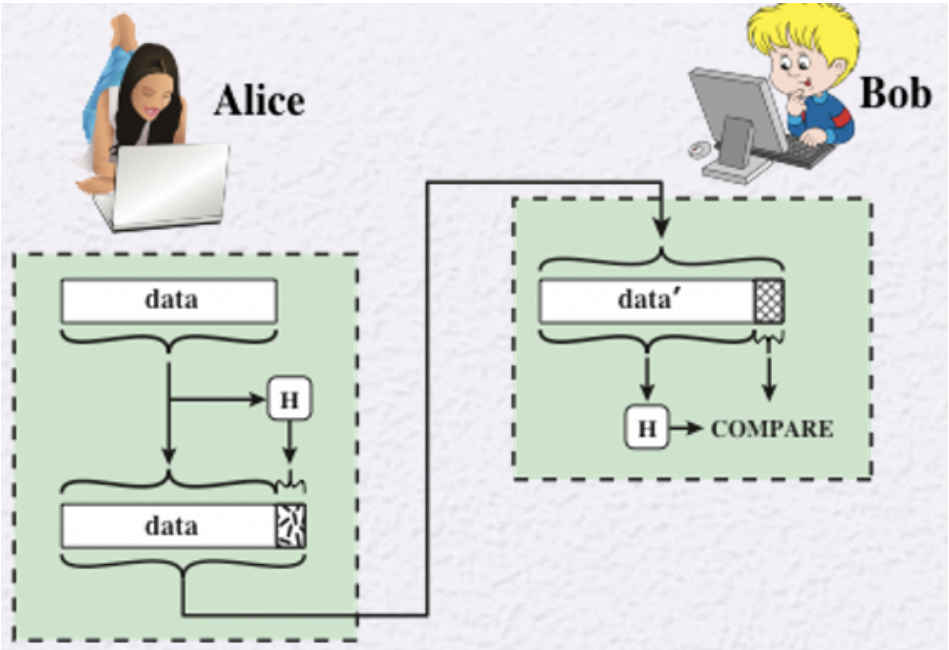
- Protects against active attacks
- Provide services to ensure the integrity of a message.
  - Ensure data received are exactly as sent (data Integrity)
    - i.e., contain no modification, insertion, deletion, or replay
  - Assure identity of the sender is valid (authentic)
- When a hash function is used to provide message authentication, the hash function value is often referred to as a message digest[1]

[1] *Message digest is a fixed size numeric representation of the contents of a message, computed by a hash function. A message digest can be encrypted forming a digital signature.*

Use Hash Function to Check Data Integrity

- The essence of the use of a hash function for message authentication is as follows.
  1. `Alice` computes a hash value as a function of the bits in the message
  2. `Alice` transmits both the hash value and the message.
  3. `Bob` performs the same hash calculation on the message bits
  4. `Bob` compares this value with the incoming hash value.
     - If there is a mismatch, `Bob` knows that the message (or possibly the hash value) has been altered

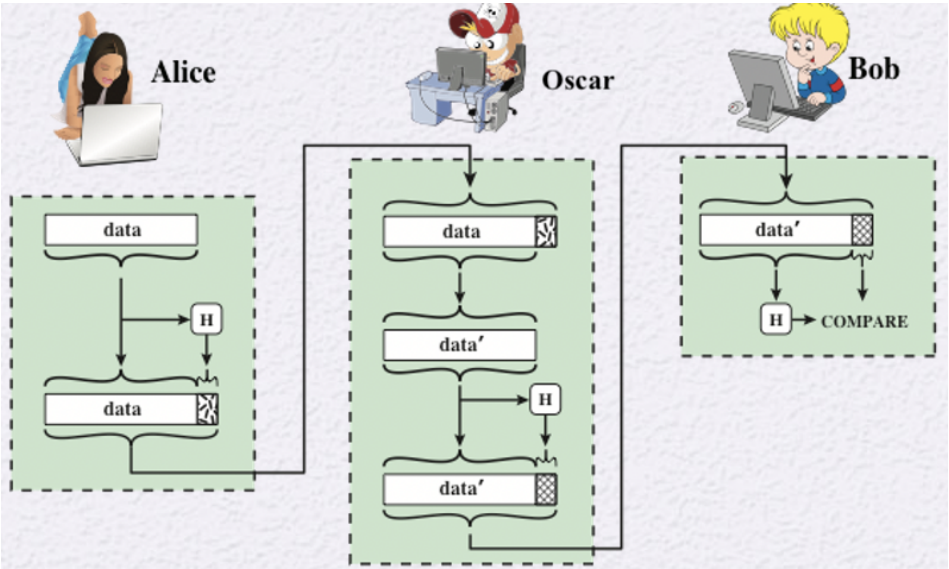
Use Hash Function to Check Data Integrity



Attack against Hash Function

- The hash function must be transmitted in a secure fashion.
- The hash function must be protected so that if an adversary alters or replaces the message, it is not feasible to also alter the hash value to fool the receiver
- Man-in-Middle Attack
  1. `Alice` transmits a data block and attaches a hash value.
  2. `Oscar` intercepts the message, alters or replaces the data block, and calculates and attaches a new hash value.
  3. `Bob` receives the altered data with the new hash value and does not detect the change.
- *To prevent this attack, the hash value generated by `Alice` must be protected.*

Attack against Hash Function

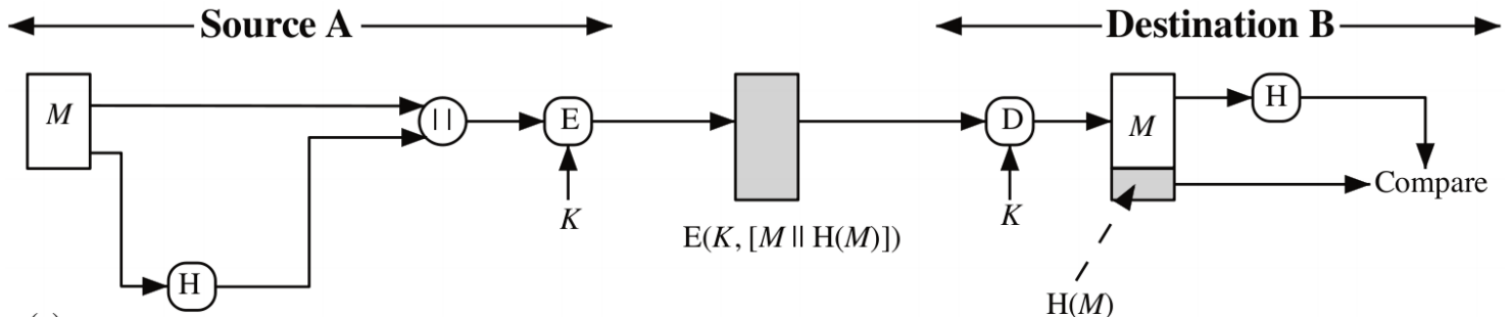


Message Authentication using Hash Function

- Hash function does not take a secret key as input.
- To authenticate a message, the message digest is sent with the message in such a way that the message digest is authentic.
- Next: illustrate different ways in which the message can be authenticated using a hash code

Message Authentication Example (a)

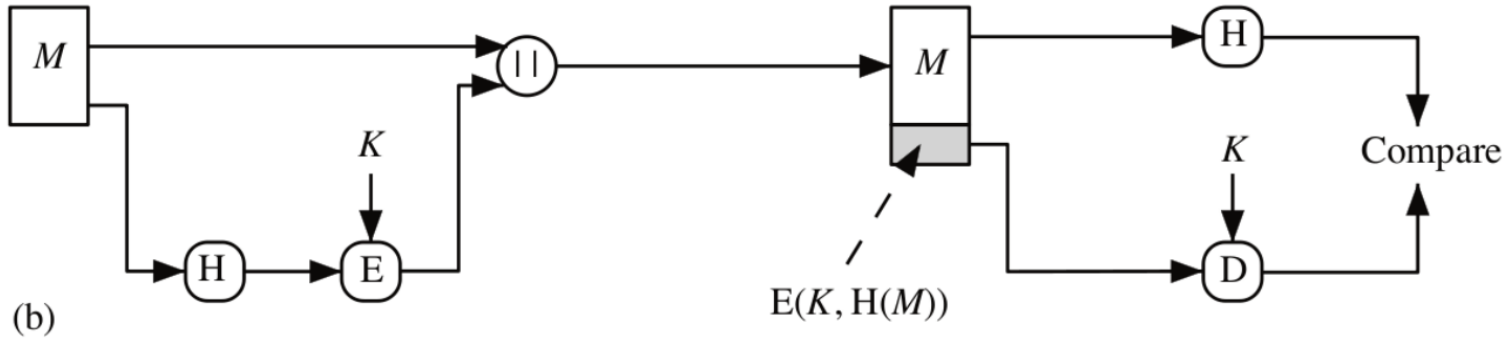
- Encrypt the message and hash code using symmetric encryption



- || denotes concatenation.
- The hash code provides the structure or redundancy required to achieve authentication.
- Confidentiality is also provided
- *Q) Do we have nonrepudiation here?*

Message Authentication Example (b)

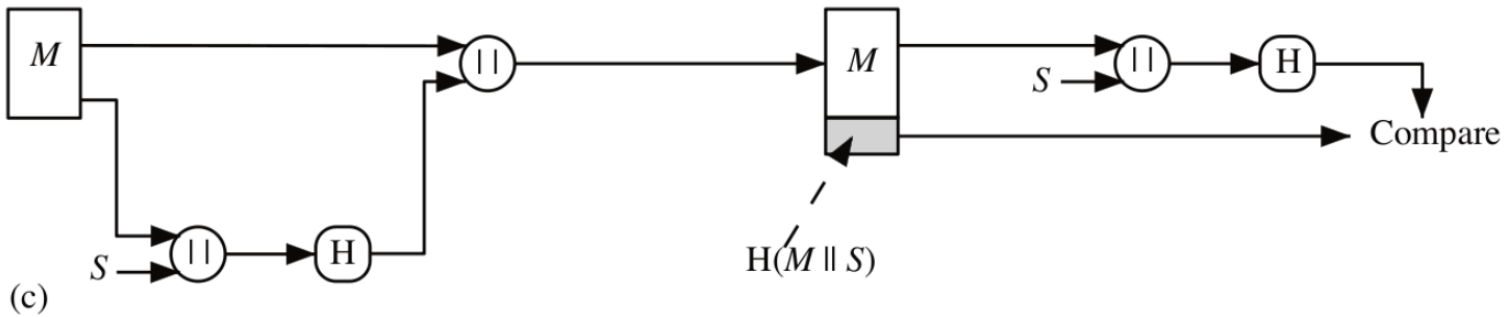
- Encrypt only hash code using symmetric encryption
- Reduces computation overhead when confidentiality not required



- *Desired property of the Hash Function: two different messages produce different hash values.*

Message Authentication Example (c)

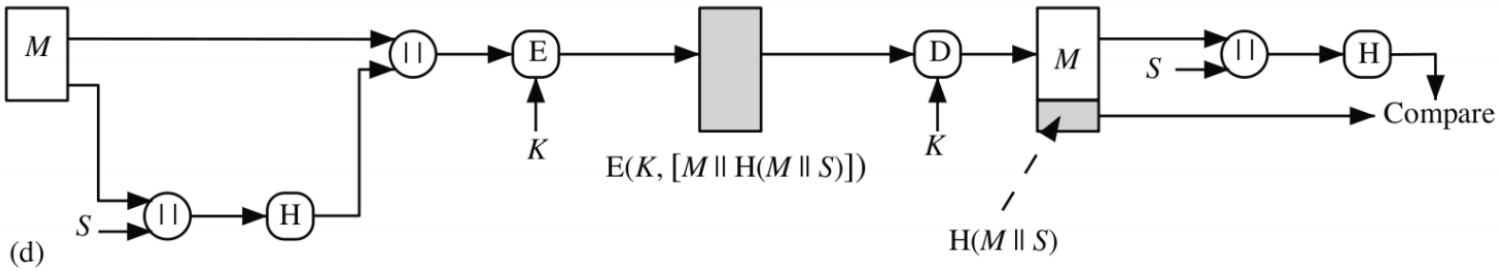
- It is possible to use a hash function but no encryption for message authentication
  - Shared secret S is hashed
  - No encryption needed



- *Q) Can attacker find the shared secret S?*

Message Authentication Example (d)

- Confidentiality can be added to the approach of method `(c)` by encrypting the entire message plus the hash code
  - Shared secret combined with confidentiality



Message Authentication Without Confidentiality

- It is possible to combine authentication and confidentiality in a single algorithm by encrypting a message plus its authentication tag
- Typically message authentication is provided as a separate function from message encryption
- Situations in which message authentication without confidentiality may be preferable include:
  - There are a number of applications in which the same message is broadcast to a number of destinations
  - An exchange in which one side has a heavy load and cannot afford the time to decrypt all incoming messages
  - Authentication of a computer program in plaintext is an attractive service
- Thus, there is a place for both authentication and encryption in meeting security requirements

Authentication and Encryption

- Sometimes desirable to avoid encryption when performing authentication due to various reasons:
  - Encryption in software can be slow
    - *This can lead to slower processing times, which may not be ideal for certain applications where speed is crucial.*
  - Encryption in hardware can provide faster encryption speeds but has financial costs
    - *The cost of specialized encryption hardware and its integration into systems may not be justifiable for certain use cases, particularly when dealing with small amounts of data.*
  - Encryption hardware can be inefficient for small amount of data
  - Encryption algorithms may be patented, need to pay license to use it, increasing costs to use
    - *RSA encryption algorithm was patented in the United States until September 20, 2000. After the patent expired, it became widely adopted as a standard for secure communication.*
- More commonly, message authentication is achieved using a Message Authentication Codes (MAC)

Message Authentication Codes (MAC)

- Message Authentication Codes (or keyed hash function)
- Typically used between two parties that share a secret key to authenticate information exchanged between those parties
  - Take secret key K and a data block M as input; produce hash value (or MAC) which is associated with the protected message as output
    - If the integrity of the message needs to be checked, the MAC function can be applied to the message and the result compared with the associated MAC value
    - An attacker who alters the message will be unable to alter the associated MAC value without knowledge of the secret key
  - Combining hash function and encryption produces same result as MAC; but MAC algorithms can be more efficient than encryption algorithms
  - MAC covered in next topic

Digital Signatures

- Another important application, which is similar to the message authentication application, is the digital signature
- Hash value of message encrypted with user's private key
- Anyone who knows the user's public key can verify integrity of message and author
- An attacker who wishes to alter the message would need to know the user's private key
- Implications of digital signatures go beyond just message authentication

Digital Signature Operations (Concept)

- Signing
  - `Bob` signs a message by encrypting with own private key
    - $s = E_{k_{pr,B}}(x)$
  - `Bob` attaches signature to message

- Verification
  - `Alice` verifies a message by decrypting signature with signer's (`Bob`) public key
    - $x' = D_{k_{pub,B}}(s)$
  - `Alice` then
    - compares received message x with decrypted x'
    - if identical, signature is verified

Digital Signature Operations (Practice)

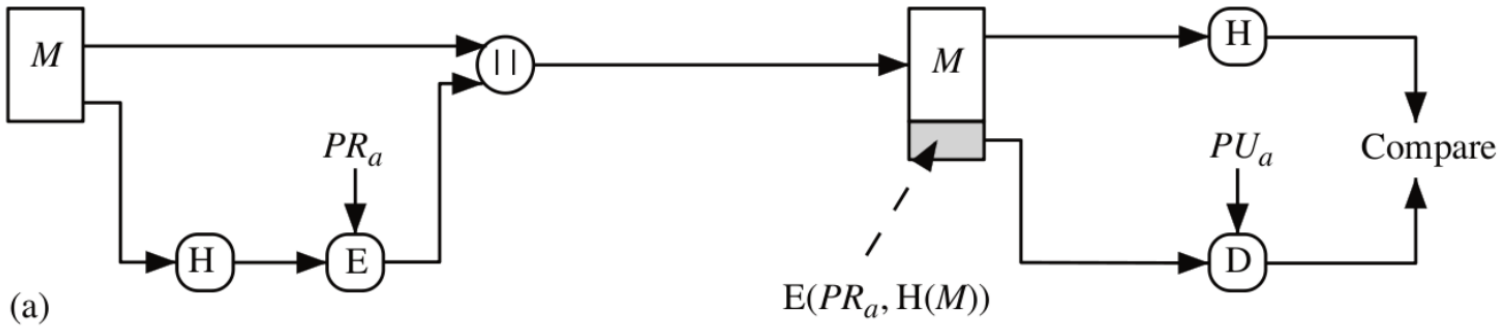
No need to encrypt entire message; encrypt hash of message

- Signing
  - `Bob` signs a message by encrypting hash of message with own private key
    - $s = E_{k_{pr,B}}(H(x))$
  - `Bob` attaches signature to message

- Verification
  - `Alice` verifies a message by decrypting signature with signer's (`Bob`) public key
    - $h' = D_{k_{pub,B}}(s)$
  - `Alice` then
    - compares hash of received message, $H(x)$, with decrypted h';
    - if identical, signature is verified

Simplified Examples of Digital Signatures

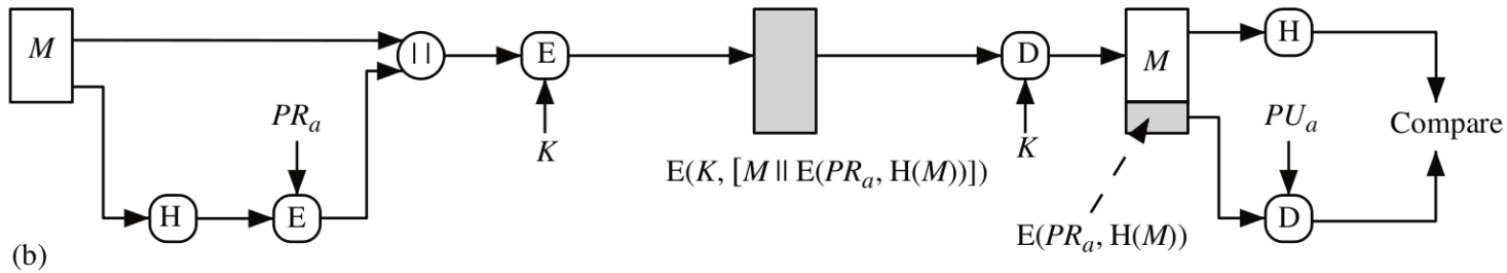
- The hash code is encrypted, using public-key encryption with the sender's private key.



- *Q) Can the attacker have the hash value?*

Simplified Examples of Digital Signatures

- If confidentiality as well as a digital signature is desired, then the message plus the private-key-encrypted hash code can be encrypted using a symmetric secret key.
- This is a common technique.



- *Using this approach, the message is encrypted for confidentiality, and the digital signature provides authenticity and integrity*

Other Hash Function Uses

- Commonly used to create a one-way password file
  - When a user enters a password, the hash of that password is compared to the stored hash value for verification
  - This approach to password protection is used by most operating systems
- Can be used for intrusion and virus detection
  - For each file on the system, a hash function is applied to its contents to produce a unique hash value (`H(F)`)
  - Store `H(F)` for each file on a system and secure the hash values
    - *This ensures that the stored hash values cannot be easily tampered with or modified.*
  - One can later determine if a file has been modified by recomputing `H(F)`
    - *By comparing these computed hash values with the stored hash values, it can determine if any files have been modified or tampered with*
  - An intruder would need to change `F` without changing `H(F)`
  - This method is called *File integrity checking/monitoring*

Simple Hash Functions

- All hash functions operate using the following general principles.
  - The input (message, file, etc.) is viewed as a sequence of n-bit blocks.
  - The input is processed one block at a time in an iterative fashion to produce an n-bit hash function.
- One of the simplest hash functions is the bit-by-bit exclusive-OR (XOR) of every block.

Bit-by-Bit Exclusive OR

- $C_i = b_{i1} \oplus b_{i2} \oplus \ldots \oplus b_{im}$
  - C_i is i^{th} bit of hash code, $1 \leq i \leq n$
  - m is number of n-bit blocks in input
  - b_{ij} is i^{th} bit in j^{th} block

	Bit 1	**Bit 2**	• • •	**Bit n**
Block 1	b_{11}	b_{21}		b_{n1}
Block 2	b_{12}	b_{22}		b_{n2}
	•	•	•	•
	•	•	•	•
	•	•	•	•
Block m	b_{1m}	b_{2m}		b_{nm}
Hash code	C_1	C_2		C_n

Requirements and Security

- Preimage[1]
  - For a hash value $z = H(x)$, x is the pre-image of z
    - That is, x is a data block whose hash function, using the function H, is z
  - Because H is a many-to-one mapping, for any given hash value z, there will in general be multiple pre-images
- Collision
  - Occurs if we have $x_1 \neq x_2$ and $H(x_1) = H(x_2)$
  - Because we are using hash functions for data integrity, collisions are clearly undesirable
  - How many pre-images for given hash value?
    - If H takes $b\text{-}bit$ input block, 2^b possible messages
    - For $n\text{-}bit$ hash code, where $b > n$, 2^n possible hash codes
    - On average, if uniformly distributed hash values, then each hash value has 2^{b-n} pre-images

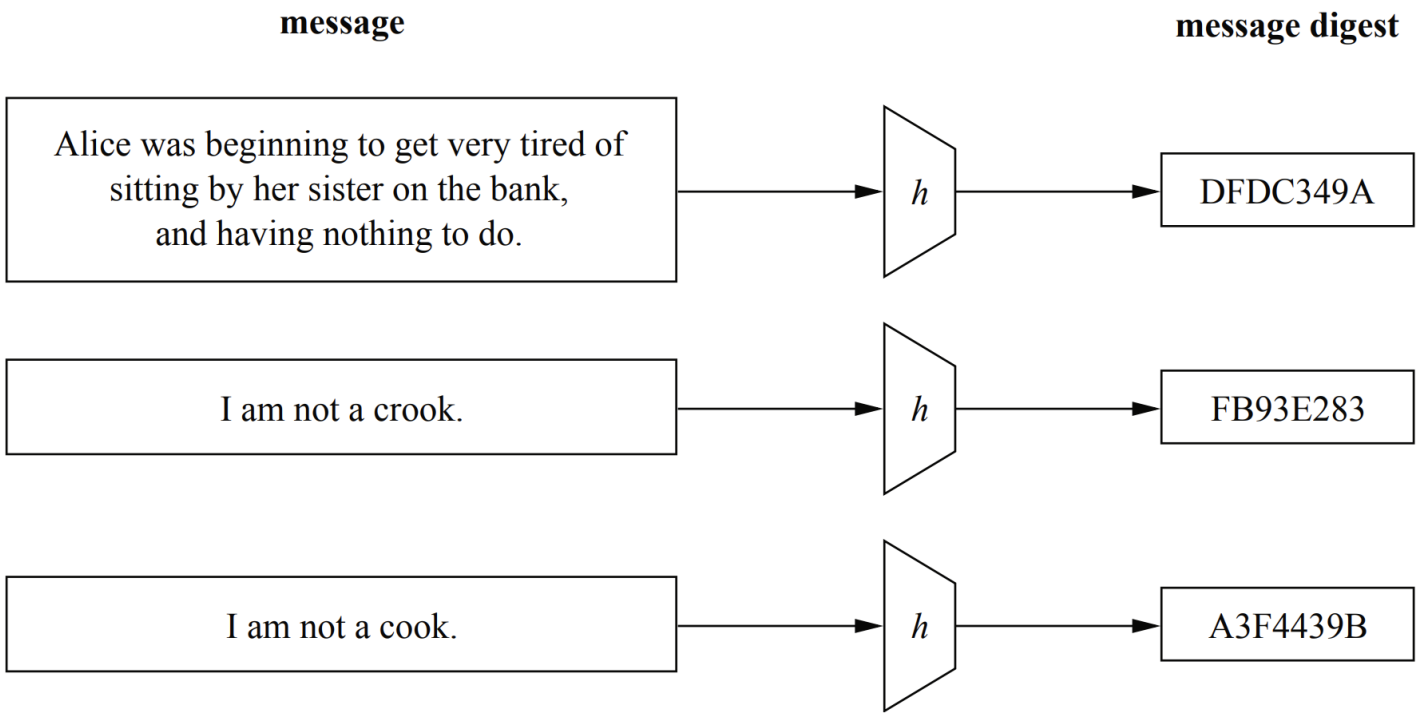
[1] *The preimage of a hash value in cryptography refers to the original input message or data that has been hashed using a specific hash function to produce that hash value.*

Requirements of Cryptographic Hash Function

- Crypto hash function H must provide:
  1. Variable input size: H can be applied to input block of "varying size".[1]
     Fixed output size: H produces fixed length output.
  2. Deterministic: Same input data should always produce same hash output.
  3. Efficiency of operation
     - $H(x)$ is relatively easy/fast to compute for any given x
     - Computationally hash functions are much faster than a symmetric encryption.
  4. Pre-image resistance (*One-way property*)
     - For a given hash value z, it is computationally infeasible to find any input x such that $H(x) = z$, i.e., $H(x)$ is one-way
  5. Second pre-image resistance (*Weak collision resistance*)
     - For any given block x_1, and thus $H(x_1)$, it is computationally infeasible to find any $x_2 \neq x_1$ with $H(x_1)=H(x_2)$.
  6. Collision resistance (*Strong collision resistance*)
     - It is computationally infeasible to find any pairs $x_1 \neq x_2$, s.t., $H(x_1) = H(x_2)$.
- *Actually, lots of collisions exist, but hard to find any*

[1] *while hash functions are designed to handle input messages of varying sizes, there are practical limits to the maximum size of the input that a hash function can handle.*

Principal input-output behavior of hash functions

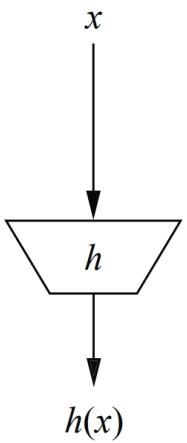


- Able to apply a hash function to messages $\boldsymbol{x}$ of any size
- Output of a hash function must be of fixed length, independent of the input size
- Computed hash value should be highly sensitive to all input bits.

  $\Rightarrow$ *minor modifications to the input* $\boldsymbol{x}$*, hash value should look very different*

1st Security properties of hash functions

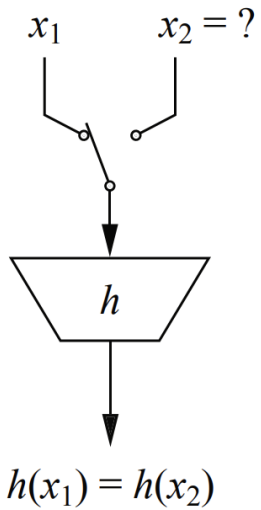
1. Preimage resistance (*One-way property*)
   - For a given output z, it is impossible to find any input x such that $h(x)=z$, i.e., $h(x)$ is one-way
     - *This property protects against an attacker who only has a hash value and is trying to find the input.*
   - Bob sends $(E_K(x), sig_{K_{pr,B}}(z))$
     - Encrypts with AES and signs with RSA: $s = sig_{K_{pr,B}}(z) \equiv z^d \bmod n$
   - Oscar uses Bob's public key to calculate $s^e \equiv z \bmod n$
   - If $h(x)$ is not one-way then $x = h^{-1}(z)$
     - Thus, the symmetric encryption of x is circumvented by the signature, which leaks the plaintext. $\Rightarrow$ $h(x)$ should be a one-way function



preimage resistance

2nd Security properties of hash functions

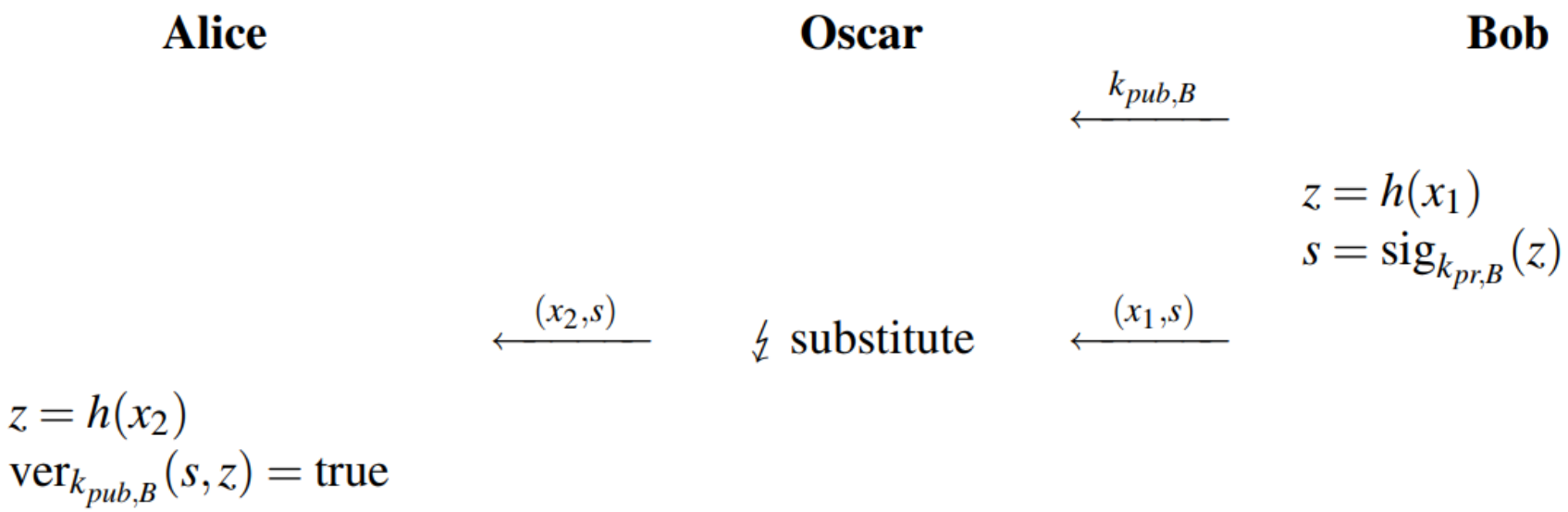
2. Second preimage resistance (*Weak collision resistance*)
   - Given x_1, and thus $h(x_1)$, it is computationally infeasible to find any other input value x_2 s.t., $h(x_1) = h(x_2)$.
     - *This property protects against an attacker who has an input value and its hash, and wants to substitute a different value as legitimate value in place of the original input value.*



second preimage resistance

2nd Preimage Attack

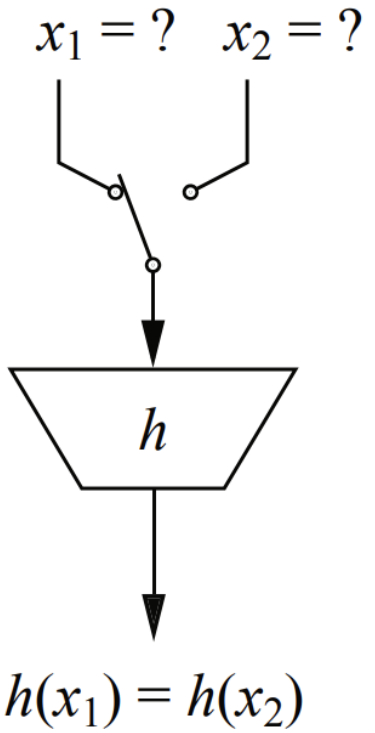
- Assume Bob hashes and signs a message x_1.
- If Oscar is capable of finding a second message x_2 such that $h(x_1)=h(x_2)$, he can run the following substitution attack



- There is always x_2 such that $h(x_1) = h(x_2)$ but it should be difficult to find
- "weak" collision, requires exhaustive search

3rd Security properties of hash functions

3. Collision resistance (*Strong collision resistance*)
   - It is computationally infeasible to find any pairs $x_1 \neq x_2$ such that $h(x_1) = h(x_2)$.
   - *This property makes it very difficult for an attacker to find two input values with the same hash.*



collision resistance

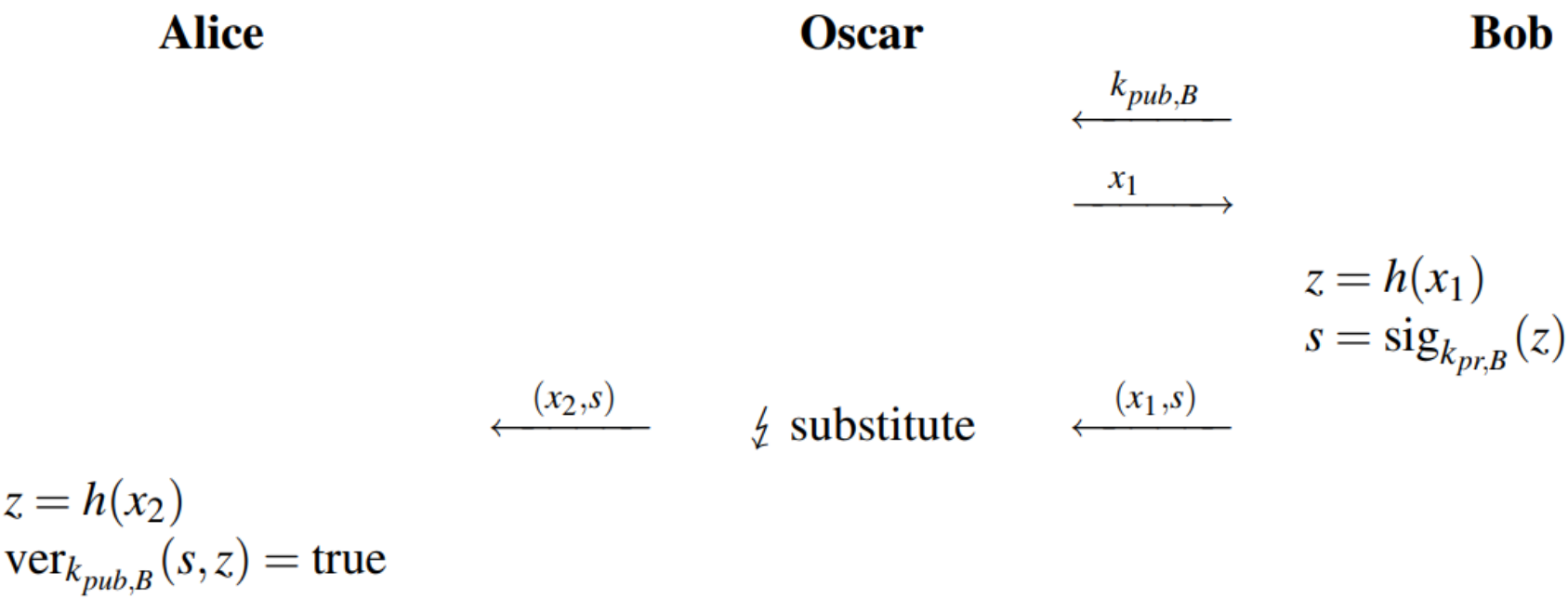
Collision Attack

- Oscar starts with two messages:

  x_1 = `Transfer $10 into Oscar's account`

  x_2 = `Transfer $10,000 into Oscar's account`

- He alters x_1 and x_2 at "non-visible" locations and continues until the condition $h(x_1) = h(x_2)$ is fulfilled.
- With the two messages, he can launch the following attack



Required Hash Properties for Different Applications

- Weak hash function: Satisfies 5 requirements listed in *slide 31* (but not collision resistant)
- Strong hash function: Also collision resistant
- Hash Function Resistance Properties Required for Various Data Integrity Applications

	Preimage Resistant	**Second Preimage Resistant**	**Collision Resistant**
Hash + digital signature	yes	yes	yes*
Intrusion detection and virus detection		yes	
Hash + symmetric encryption			
One-way password file	yes		
MAC	yes	yes	yes*

* Resistance required if attacker is able to mount a chosen message attack

Security of Hash Functions

- There are two approaches to attacking a secure hash function:

1. Cryptanalysis
   - An attack based on weaknesses in a particular cryptographic algorithm
   - Seek to exploit some property of the algorithm to perform some attack other than an exhaustive search
2. Brute-force attack
   - Does not depend on the specific algorithm, only depends on bit length
   - In the case of a hash function, attack depends only on the bit length of the hash value
   - Method is to pick values at random and try each one until a collision occurs
   - *Strength of hash function depends solely on the length of the hash code produced by the algorithm.*

Brute Attacks on Hash Functions

- Pre-image and Second Pre-image Attack
  - Find a x that gives specific z; try all possible values of x
  - With $n\text{-}bit$ hash code, effort required proportional to 2^n
- Collision Resistant Brute Attack
  - Find any two messages that have same hash values
  - Effort required is proportional to $2^{n/2}$
  - Due to birthday paradox, easier than pre-image attacks

- Brute force attack can be applied against any hash algorithm, but its practicality depends on the size of the input space and the computational resources available to the attacker.
- Practical Effort (other attacks take advantage of the algorithm design)
  - Cryptanalysis attacks:
    - Take advantage of weaknesses in the algorithm design and are typically more efficient than brute force attacks.
    - However, can be complex and may require advanced knowledge and skills to execute successfully.
  - Collision resistance desirable for general hash algorithms
  - MD5 uses `128-bits`: collision attacks possible (2^{60}) (not much better than brute force attack)

Collision Attacks and the Birthday Paradox

- It turns out that collision resistance causes most problems and more difficult
- Collision attacks are much harder to prevent than 2^{nd} preimage attack.
- Q: Can we have hash function without collisions?
  - Since $|X| >> |Z| \Rightarrow$ collision must exist. ("Pigeonhole Principle")
    $\Rightarrow$ We must make collision very hard to find!
- Q: How difficult it is to find collisions?

2^{nd} preimage attack with brute-force

- Q: How difficult it is to find collisions?
- Probably this is as difficult as finding second preimages
- If $|Z| = 2^{80}$, where $|h(x)| = n = 80$

  $\Rightarrow$ attack requires $\approx 2^{80}$ steps until to find a collision

Birthday Attacks

- For a collision resistant attack, an adversary wishes to find two messages or data blocks that yield the same hash function
  - The effort required is explained by a mathematical result referred to as the birthday paradox
- The Birthday Attack exploits the birthday paradox[1]
  - The chance that in a group of people two will share the same birthday
  - Only `23` people are needed for a `Probability` $>$ `0.5` of this.
  - Can generalize the problem to one wanting a matching pair from any two sets, and show need $2^{\frac{n}{2}}$ in each to get a matching n-bit hash.

[1] *Statistical phenomenon that states in a group of randomly chosen people, the probability that at least two people have the same birthday becomes greater than 50% when the number of people reaches 23.*

Collision Attack

- It turns out that collision resistance causes most problems and more difficult to achieve
  - How hard is it to find a collision with a probability of 0.5?
  - Related Problem: How many people are needed such that two of them have the same birthday with a probability of 0.5?

$$P(\text{no collision among 2 people}) = 1-\frac{1}{365}$$
$$P(\text{no collision among 3 people}) = (1-\frac{1}{365})(1-\frac{2}{365})$$
$$\ldots$$
$$P(\text{no collision among } t \text{ people}) = \prod_{i=1}^{t-1} (1-\frac{i}{365})$$

    - for $t = 23$, $\prod_{i=1}^{22} (1-\frac{i}{365}) = 0.507 \approx 50\%$
  - No! Not $\frac{365}{2} = 183.$ 23 are enough! This is called the **birthday paradox** (Search takes $\approx \sqrt{2^n}$ steps for 50% probability collision)
  - To deal with this paradox, hash functions need a output size of at least 224 bits

How Long Should Hash Be

- Many input messages yield the same hash
  - e.g., `1024-bit` message, `128-bit` hash
  - On average, 2^{896} messages map into one hash
- With `n=64`, it takes 2^{32} trails to find a collision (doable in very little time)
- Today, need at least `n=160`, requiring about 2^{80} trails

Popular Crypto Hashes

- MD5: message-digest algorithm 5
  - MD5 was most popular and widely used hash function for quite some years.
  - The MD family comprises of hash functions `MD2`, `MD4`, `MD5` and `MD6`.
  - Developed by Ron Rivest in 1991
  - Generates `128-bit` hash
  - Was commonly used by applications, passwords, file integrity; no longer recommended
    - e.g., file servers often provide a pre-computed `MD5 checksum` for the files, so that a user can compare the checksum of the downloaded file to it.
  - Collision and other attacks possible; tools publicly available to attack `MD5`, *so it's broken*.

- *In particular, it is vulnerable to collision attacks, where an attacker can find two different inputs that produce the same hash value. This makes it possible for an attacker to create a fake file or message with the same hash value as the original, which can be used to bypass file integrity checks or other security measures.*

Secure Hash Algorithm (SHA)

- Family of SHA comprise of four SHA algorithms; SHA-0, SHA-1, SHA-2, and SHA-3.
- SHA-0:
  - Produces 160-bit hash values.
  - It had few weaknesses and did not become very popular.
  - Was revised in 1995 as SHA-1.
- SHA-1:
  - Most widely used of the existing SHA hash functions.
  - Employed in several widely used applications and protocols.
  - No longer considered secure against well-funded opponents[1]
- SHA-2:
  - In 2002, NIST produced a revised version of the standard that defined three new versions of SHA with hash value lengths of 224, 256, 384, and 512.
    - Collectively known as SHA-2
  - No successful attacks have yet been reported.

[1] *While a cryptographic algorithm may provide a certain level of security against attacks, it may not be able to withstand attacks from well-funded attackers who have access to significant resources, such as advanced hardware, software, or expertise.* *Announcing the first SHA1 collision*

SHA-3

- SHA-2 shares same structure and mathematical operations as its predecessors and causes concern
- Due to time required to replace SHA-2 should it become vulnerable, NIST announced in 2007 a competition to produce SHA-3
- SHA-3 Requirements:
  - Must support hash value lengths of 224, 256, 384, and 512 bits
  - Algorithm must process small blocks at a time instead of requiring the entire message to be buffered in memory before processing it
- SHA-3 standard was released by NIST as FIPS 202 (SHA-3 Standard: Permutation-Based Hash and Extendable-Output Functions)[2] on August 5, 2015
- Like SHA-2, SHA-3 is designed to provide strong collision resistance and resistance against other attacks, such as preimage attacks and length extension attacks.
- It is also designed to be faster and more efficient than SHA-2 in some applications, such as software implementations on small devices.

[2] SHA-3 Standard: Permutation-Based Hash and Extendable-Output Functions

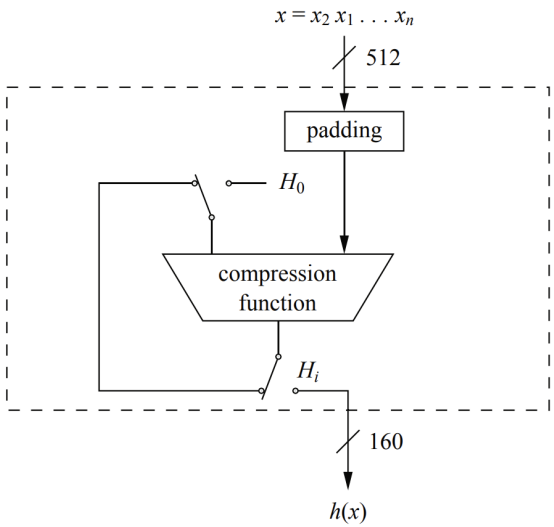
Comparison of SHA Parameters

	SHA-1	SHA-224	SHA-256	SHA-384	SHA-512	SHA-512/224	SHA-512/256
Message size	$< 2^{64}$	$< 2^{64}$	$< 2^{64}$	$< 2^{128}$	$< 2^{128}$	$< 2^{128}$	$< 2^{128}$
Word size	32	32	32	64	64	64	64
Block size	512	512	512	1024	1024	1024	1024
Message digest size	160	224	256	384	512	224	256
Number of steps	80	64	64	80	80	80	80
Security	80	112	128	192	256	112	128

- Notes:
  1. All sizes are measured in bits.
  2. Security refers to the fact that a birthday attack on a message digest of size n produces a collision with a work factor of approximately $2^{n/2}$.

SHA-1 High Level Diagram

- Compression function consists of *80* rounds which are divided into four stages of *20* rounds each

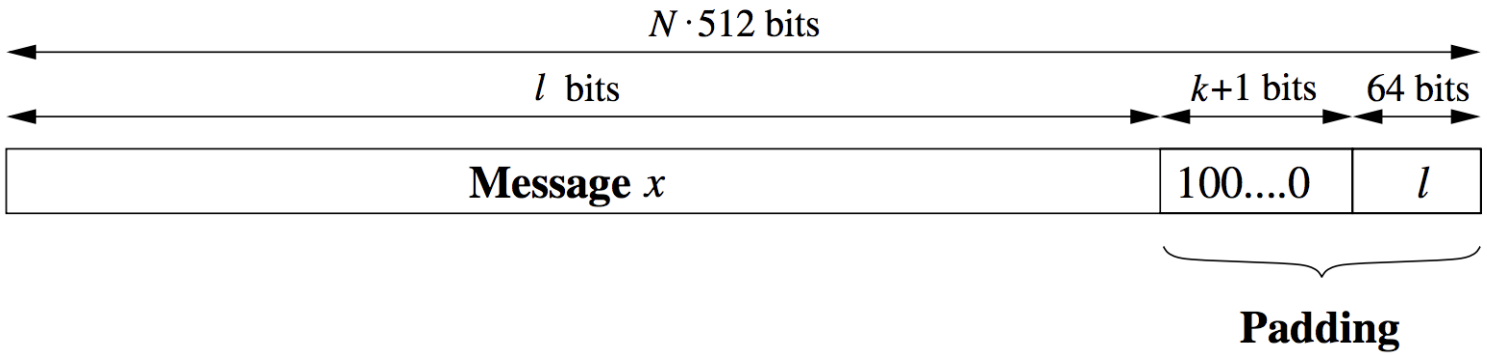


Merkle-Damgård Construction for Hash Functions

- Message is divided into fixed-size blocks and padded.
  - The input is viewed as a sequence of *512-bit* blocks
- The initial value H_0 is set to a predefined constant.
- The input is processed one block at a time in an iterative fashion to produce an *160-bit* hash function.

Example: SHA-1: Padding

- Message x has to be padded to fit a size of a multiple of 512 bit.
  - Let x with a length of l bit
  - To obtain an overall message size of a multiple of 512 bits
    - Append a single 1 followed by k zero bits and the binary 64-bit representation of l.
    - Consequently, the number of required zeros k is given by $k \equiv 512 - 64 - 1 - l = 448 - (l + 1) \bmod 512$
- *The single 1-bit is appended to indicate the end of the message and to ensure that the message can be uniquely padded.*



SHA-1: Padding: Example

- Given is the message `abc` consisting of three 8-bit ASCII characters with a total length of $l = 24$ bits:

$$\underbrace{01100001}_{\texttt{a}} \quad \underbrace{01100010}_{\texttt{b}} \quad \underbrace{01100011}_{\texttt{c}}.$$

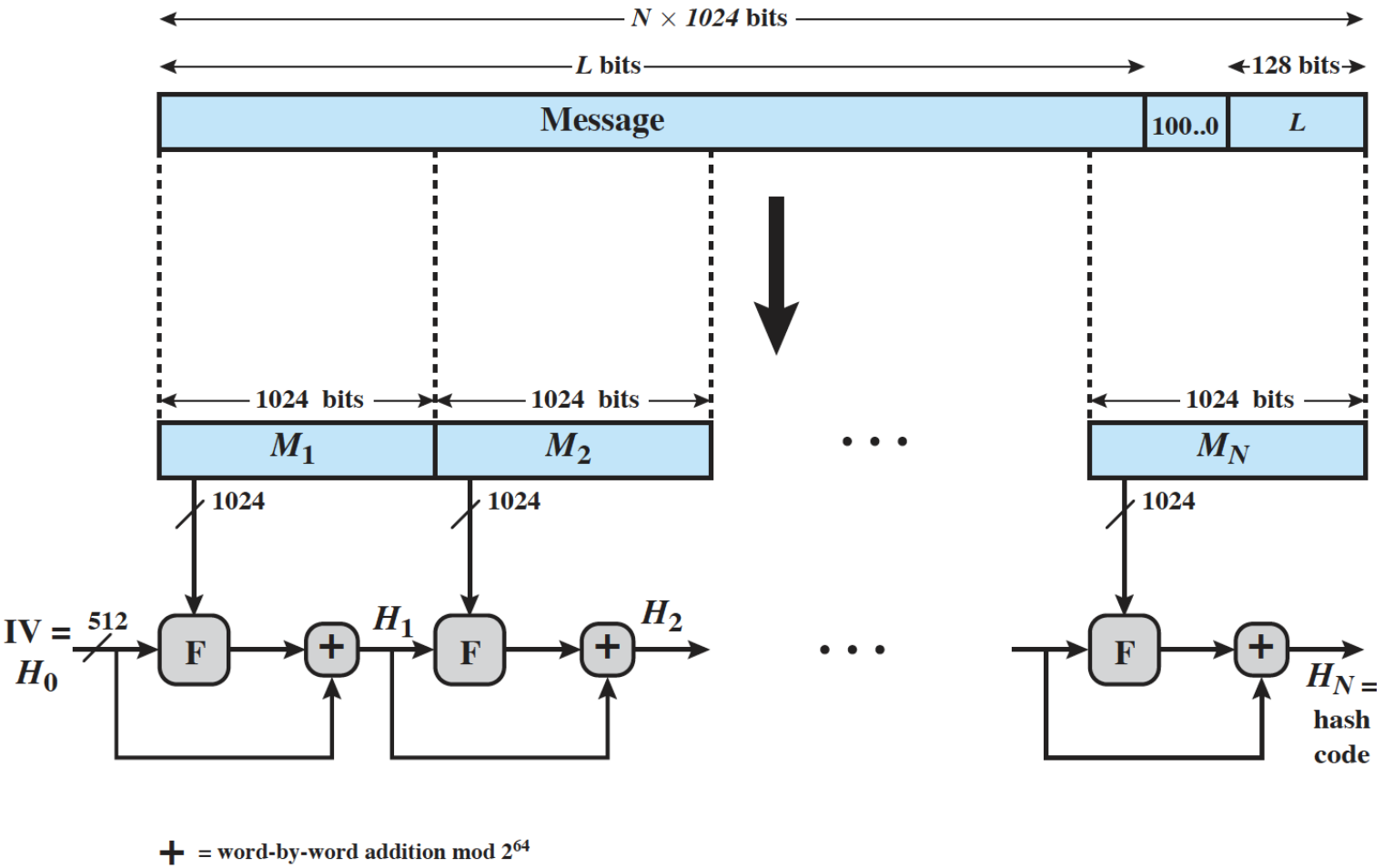
We append a "1" followed by $k = 423$ zero bits, where k is determined by

$$k \equiv 448 - (l+1) = 448 - 25 = 423 \bmod 512.$$

Finally, we append the 64-bit value which contains the binary representation of the length $l = 24_{10} = 11000_2$. The padded message is then given by

$$\underbrace{01100001}_{\texttt{a}} \quad \underbrace{01100010}_{\texttt{b}} \quad \underbrace{01100011}_{\texttt{c}} \quad 1 \quad \underbrace{00\ldots0}_{423\text{ zeros}} \quad \underbrace{00\ldots011000}_{l=24}.$$

Message Digest Generation Using SHA-512



Message Digest Generation Using SHA-512

- **Step 1: Append padding bits**: message length is congruent to *896 modulo 1024*
- **Step 2: Append length**: as a block of *128* bits being an unsigned *128*-bit integer length of the original message (before padding).
- **Step 3: Initialize hash buffer**: *512*-bit buffer is used to hold intermediate and final results of the hash function. The buffer can be represented as eight *64*-bit registers
- **Step 4: Process the message in *1024-bit* (*128-word*) blocks**: The heart of the algorithm is a module that consists of *80* rounds; this module is labeled *F* in Figure in next slide.
- **Step 5: Output**: After all *N 1024-bit* blocks have been processed, the output from the N^{th} stage is the *512-bit* message digest.

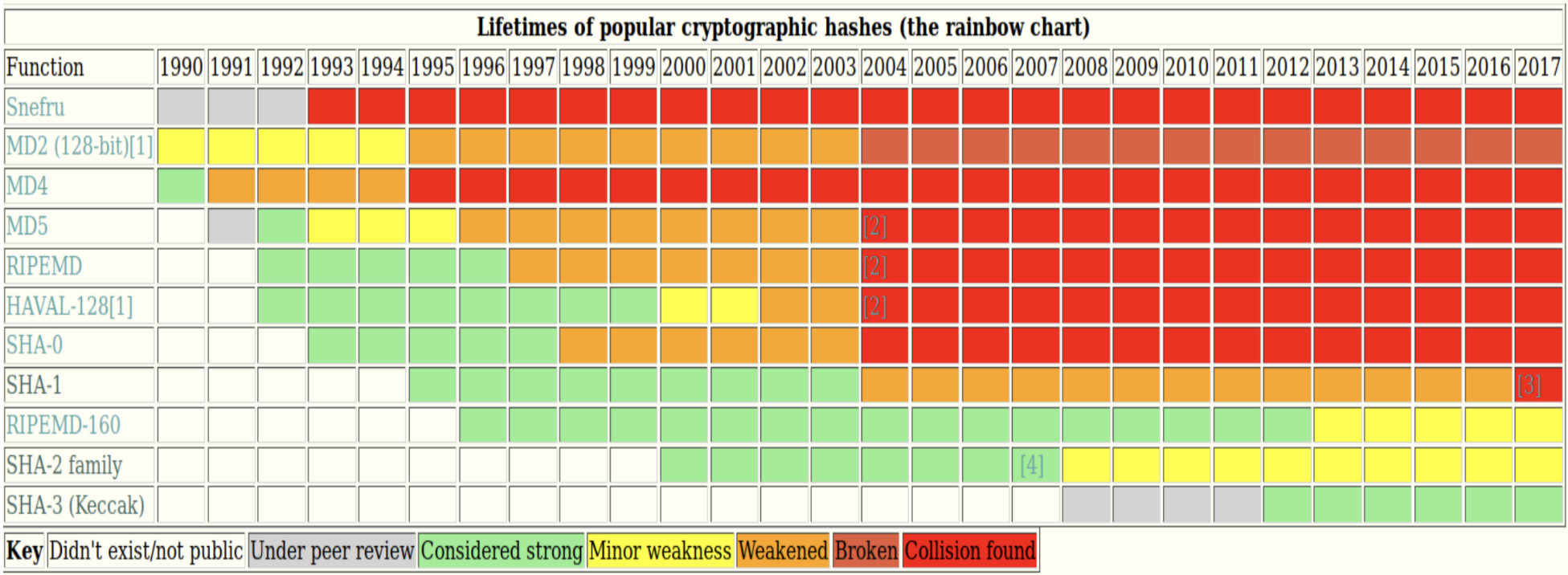
Choosing the length of Hash outputs

- The Weakest Link Principle:
  - A system is only as secure as its weakest link.
- Hence all links in a system should have similar levels of security.
- Because of the birthday attack, the length of hash outputs in general should double the key length of block ciphers
  - SHA-224 matches the 112-bit strength of triple-DES (encryption 3 times using DES)
  - SHA-256, SHA-384, SHA-512 match the new key lengths (128,192,256) in AES

Summary

- Hash functions are keyless.
- Applications of cryptographic hash functions
  - Message authentication
  - Digital signatures
  - Other applications
- Requirements and security
  - Security requirements for cryptographic hash functions
  - Brute-force attacks
  - Cryptanalysis
- Secure hash algorithm (SHA)

Hash function life cycles[1]



- Historically, popular cryptographic hash functions have a useful lifetime of around 10 years

[1] Jan-aeke Larsson, Linkoepings Universitet

Reading

- `Computer Security: Principles and Practice`
  - Chapters 2 and 21
- `Understanding Cryptography: A Textbook for Students and Practitioners` - *available online*
  - Chapter 11: Hash Functions