CS458: Introduction to Information Security

Notes 7: Message Authentication Codes (MACs)

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Outline

- Message Authentication Functions
- The principle behind MACs
- The security properties that can be achieved with MACs
- How MACs can be realized with hash functions and with block ciphers

Message Authentication

- Receiver wants to verify:
  1. Contents of the message have not been modified (data authentication)
  2. Source of message is who they claim to be (source authentication)
- Possible attacks on message authentication:
  - Content modification
  - Sequence modification
    - Any modification to a sequence of messages between parties, including insertion, deletion, and reordering.
  - Timing modification
    - Delay or replay of messages
- In summary
  - Message authentication is a procedure to verify that received messages come from the alleged source and have not been altered.
  - Message authentication may also verify sequencing and timeliness.

Message Authentication Functions

Any message authentication or DS mechanism has two levels of functionality:

- Lower level
  - There must be some sort of function that produces an authenticator
  - authenticator: a value to be used to authenticate a message.
- Higher-level
  - Uses the lower-level function as a primitive in a higher-level authentication protocol that enables a receiver to verify the authenticity of a message
- There are types of functions that may be used to produce an authenticator:
  - Message encryption
    - The ciphertext of the entire message serves as its authenticator
  - Hash function
    - A function that maps a message of arbitrary length into a fixed-length hash value which serves as the authenticator

  Message authentication code (MAC)
    - A function of the message and a secret key that produces a fixed-length value that serves as the authenticator

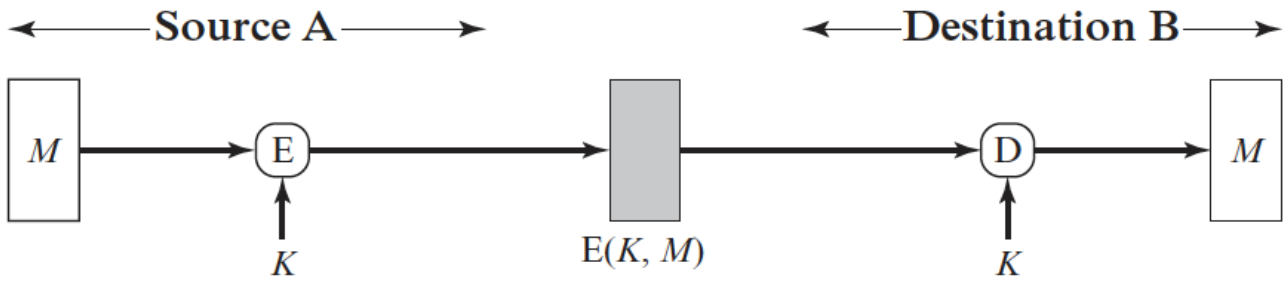
      - This does not provide a digital signature because both sender and receiver share the same key

Message Encryption as Authentication

- Message encryption (either symmetric or public-key) by itself can provide a measure of authentication.
- The ciphertext of the entire message serves as its authenticator
  - The message must have come from the sender because the ciphertext can be decrypted using the sender key.
  - None of the bits in the message have been altered because an opponent does not know how to manipulate the bits of the ciphertext to induce meaningful changes to the plaintext.
- The analysis differs for symmetric and public-key encryption schemes.

Symmetric Key Encryption

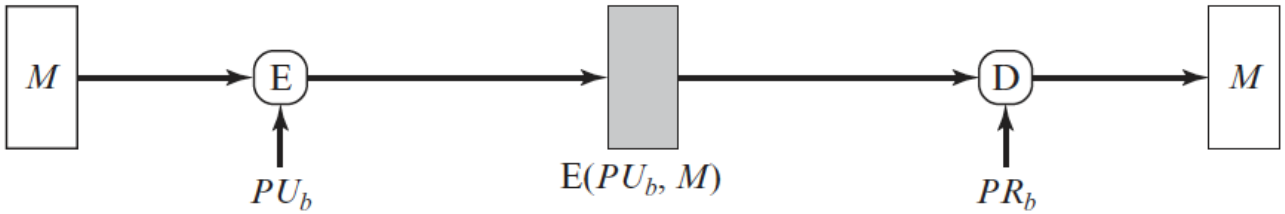
- Assumption:
  - Decryption using wrong key or modified ciphertext will produce unintelligible output
- Symmetric key encryption can provide: data authentication and source authentication (as well as confidentiality)



- However, typically authentication is performed separately to encryption for confidentiality
  - Avoid overhead of using encryption when not needed
- Q) How to make sure the message is correct?
  - There must be some internal structure to the plaintext so that the receiver can distinguish between well-formed plaintext and random bits.
- *Although the symmetric key provides message authentication, we would often to use other techniques to provide authentication.*

Public-Key Encryption

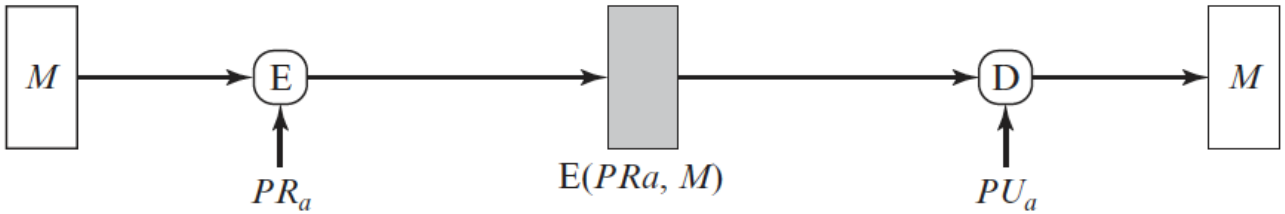
- The straightforward use of public-key encryption provides confidentiality but not authentication.
- `A` encrypts `M` using `B`'s public key, which provides confidentiality



- There must be some internal structure to the plaintext so that the receiver can distinguish between well-formed plaintext and random bits.
- Q) Do we have message authentication (data integrity/authenticity)?

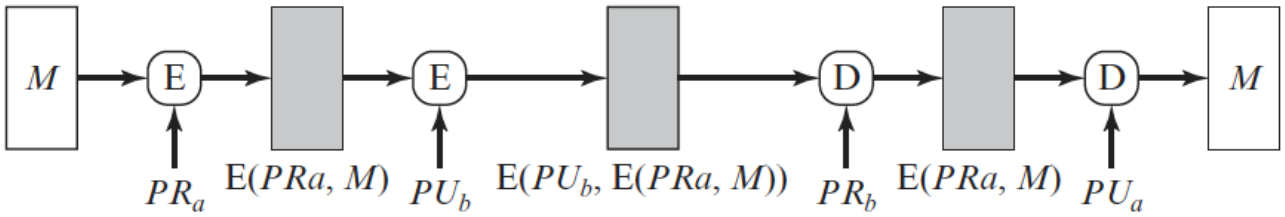
Public-Key Encryption

- To provide authentication, `A` uses its private key to encrypt the message, and `B` uses `A`'s public key to decrypt.
  - use the keys of sender not the receiver



Public-Key Encryption

- To provide both confidentiality and authentication, `A` can encrypt `M` first using its private key which provides the digital signature, and then using `B`'s public key, which provides confidentiality



- Disadvantage is that the public-key algorithm must be exercised four times rather than two in each communication
  - too costly, too slow

More to authentication than simple encryption?

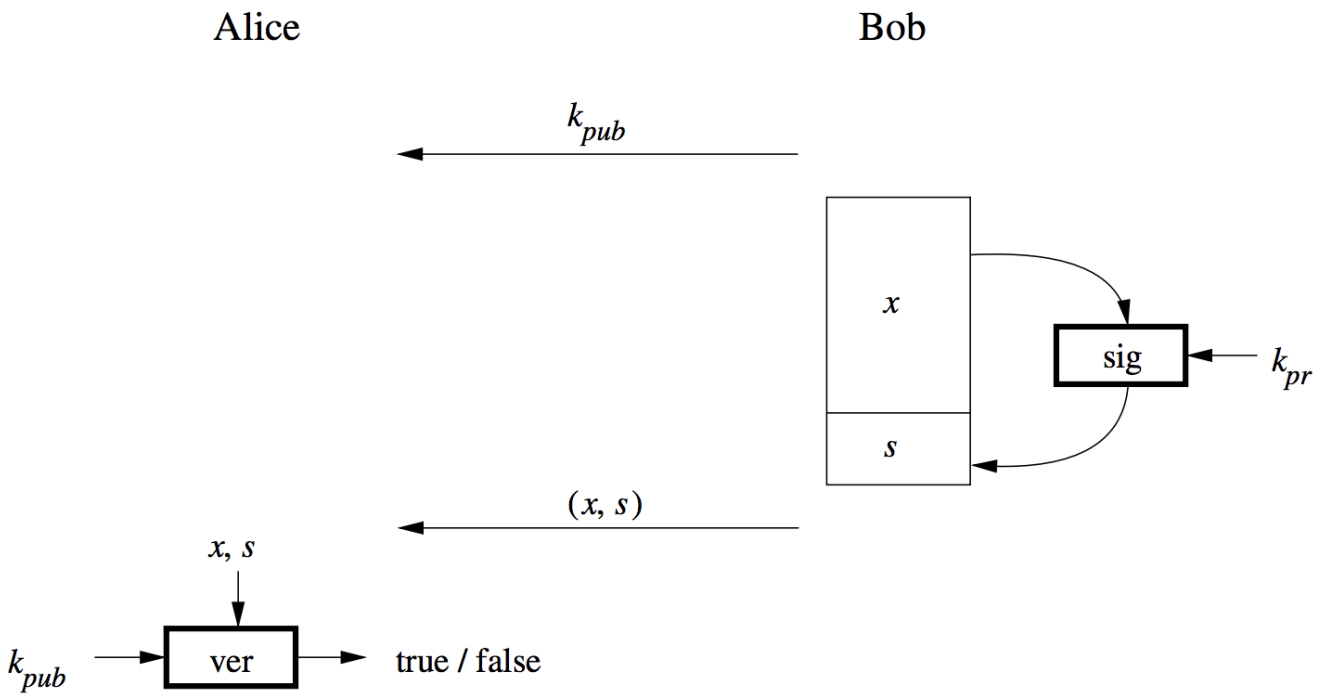
- Often one needs alternative authentication schemes than just encrypting the message
  - Encryption and authentication may be separated in the system architecture
  - If a message is broadcast to several destinations in a network (such as an alarm signal in a military control center), then it is cheaper and more reliable to have just one node responsible to evaluate the authenticity
    - Thus, the message will be sent in plain with an attached authenticator.
    - The responsible system performs authentication.
    - If a violation occurs, the other destination systems are alerted by a general alarm.
  - If one side has a heavy load, it cannot afford to decrypt all messages.
    - It will just check the authenticity of some randomly selected messages
  - If the message is sent encrypted, it is of course protected over the network. However, once the receiver decrypts the message, it is no longer secure. Using a different type of authentication protects the message also on the local computer
  - Authentication of a computer program in plaintext is an attractive service

Introduction to Message Authentication Codes (MACs)

- Message Authentication Codes (MACs) are also called "cryptographic checksums"
  - Is small piece of information used to authenticate a message, in other words, to confirm that the message came from the stated sender (its authenticity) and has not been changed.
- Similar to digital signatures, MACs append an authentication tag to a message

Introduction to Message Authentication Codes (MACs)

- Recall motivation for digital signatures
  - "message authentication"
  - How to do that?



  - Let's try the same with symmetric algorithm

Principle of Message Authentication Codes

- MACs use a symmetric key k for generation and verification
- When A has a message to send to B, it calculates the MAC as a function of the message and the key:
  - Append small, fixed-size block of data to message: cryptographic checksum or MAC

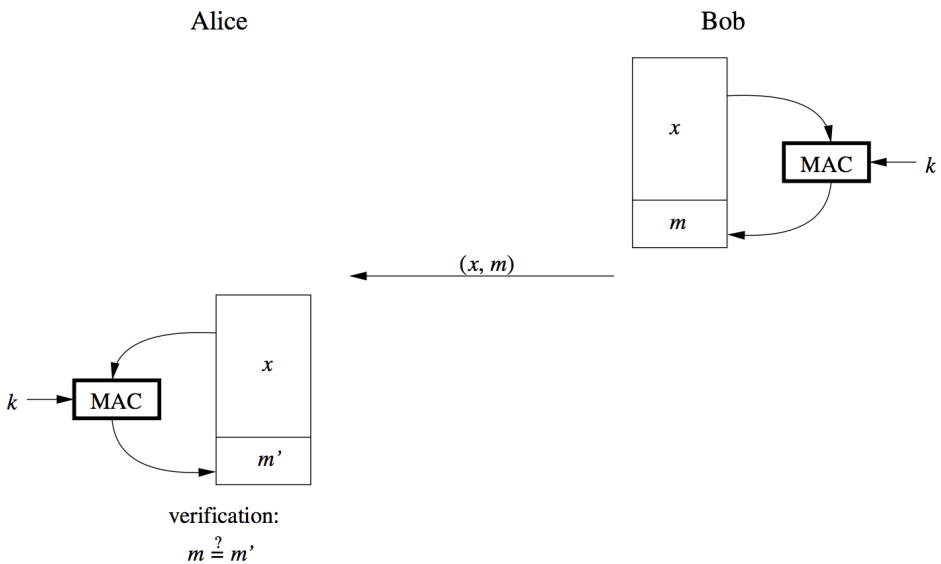
$$MAC = F(K, M)$$

where
M = input message
F = MAC function
K = shared secret key
MAC = message authentication code

- The message plus MAC are transmitted to the intended recipient
- The recipient performs the same calculation on the received message, using the same secret key, to generate a new MAC.
- The received MAC is compared to the calculated MAC, if the received MAC matches the calculated MAC
  - The receiver is assured that the message has not been altered
  - The receiver is assured that the message is from the alleged sender

Principle of Message Authentication Codes

- MACs use a symmetric key k for generation and verification
- MAC function similar to encryption, but does not need to be reversible
  - Easier to design stronger MAC functions than encryption functions
- Computation of a MAC:
  - A MAC is generated by a function $m = MAC_k(x)$ that can be computed by anyone knowing the secret key k
- `Bob` computes $m = MAC_k(x)$ and sends (x, m) to `Alice`.
- `Alice` receives (x, m') and verifies that $m' = m$.



Properties of Message Authentication Codes

1. Cryptographic checksum: A MAC generates a cryptographically secure authentication tag for a given message.
2. Symmetric: MACs are based on secret symmetric keys. The signing and verifying parties must share a secret key.
3. Arbitrary message size: MACs accept messages of arbitrary length.
4. Fixed output length: MACs generate fixed-size authentication tags.
5. Message integrity: MACs provide message integrity: Any manipulations of a message during transit will be detected by the receiver.
6. Message (data origin) authentication: The receiving party is assured of the origin of the message.
7. No nonrepudiation: Since MACs are based on symmetric principles, they do not provide nonrepudiation

Requirements for Message Authentication Codes

- MAC is a many-to-one function
  - Messages are arbitrarily long and the MAC has fixed length, thus there will be more than one message with the same MAC
  - But finding these needs to be very difficult
- Computationally easy to compute the MAC
- It is infeasible to find another message with same MAC
  - Knowing x and $m = MAC_k(x)$, it is computationally infeasible to construct another message x' with $MAC_k(x) = MAC_k(x')$
- MACs should be uniformly distributed in the sense that for randomly chosen messages, x and x', the probability that is $MAC_k(x) = MAC_k(x')$ is 2^{-n}
  - If the attacker chooses a random bit pattern of length n, the chances of it being the correct signature is 2^{-n}
- MAC should depend equally on all bits of the message
  - If x' is obtained from x by certain transformations (even switching one bit), then the probability that the two have the same MAC is 2^{-n}

Security of MACs

- Security Requirement
  - Key is secret and difficult to find from pairs of (x, `MAC`)
  - Given pairs of (x, `MAC`), difficult to find the MAC of another message
- Brute Force Attacks on MACs
- Cryptanalysis

Brute Force Attacks on MACs

- A brute force attack in MAC is more difficult undertaking than a brute-force attack on a hash function because it requires known message-tag pairs
  - To attack hash code: Given a fixed message x with n-bit hash code $H(x)$, a brute-force method of finding a collision is to pick a random bit string y and check if $H(y)=H(x)$
- Two lines of attack:
  - Attack the key space
    - If an attacker can determine the MAC key then it is possible to generate a valid MAC value for any input x
    - Effort $\approx 2^k$
  - Attack the MAC value
    - The attacker can also work on the tag without attempting to recover the key.
    - Objective:
      - to generate a valid tag for a given message or
      - to find a message that matches a given tag.
    - Effort $\approx 2^n$
- Effort to break MAC: $\min(2^k, 2^n)$

Cryptanalysis

- Cryptanalytic attacks seek to exploit some property of the algorithm to perform some attack other than an exhaustive search
- An ideal MAC algorithm will require a cryptanalytic effort greater than or equal to the brute-force effort
- There is much more variety in the structure of MACs than in hash functions, so it is difficult to generalize about the cryptanalysis of MACs

MACs Based on Hash Functions: HMAC

- MAC is realized with cryptographic hash functions
- Motivations
  - Cryptographic hash functions such as MD5 and SHA generally execute faster in software than symmetric block ciphers
  - Library code for cryptographic hash functions is widely available
- Hash values not intended for MAC. They are not protected by secret keys
  - Some protection needs to be built on top of the hash value
- **Basic idea**: Key is hashed together with the message

  $m = MAC_k(x) = h(k, x)$
- Q: How exactly do we mix k and x?
- Two possible constructions:
  - secret prefix MAC: $m = MAC_k(x) = h(k||x)$
  - secret suffix MAC: $m = MAC_k(x) = h(x||k)$
- There have been a number of proposals for the incorporation of a secret key into an existing hash algorithm.
- The approach that has received the most support is HMAC

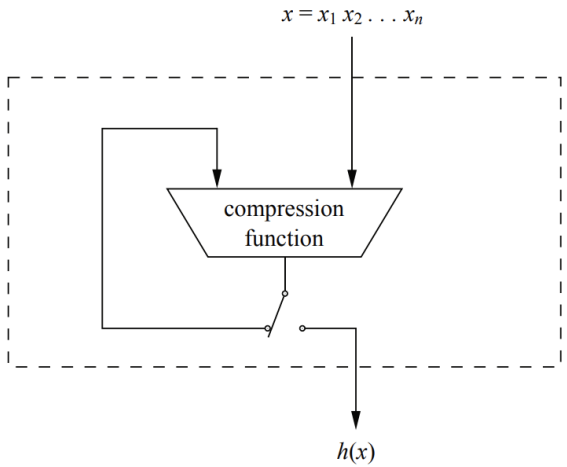
Length Extension Attack

- Type of attack where an attacker can use $H(x)$ and the length of x to calculate $H(x||y)$ for an attacker-controlled y, without needing to know the content of x.
- Algorithms like MD5, SHA-1 and most of SHA-2 that are based on the Merkle-Damgård construction[1] are susceptible to this kind of attack.
  - You take the message and break it up into fixed-size blocks.
  - You start with an initialization vector (IV), which you feed into a compression function along with the first block.
  - Take the output (it will be the same length as the IV), and feed it into the compression function along with the second message block, and so on.
  - *To make the construction secure, the messages are padded with a padding that encodes the length of the original message. This is called length padding or Merkle-Damgård strengthening.*

[1] *Merkle-Damgård hash function/ construction is a method of building collision-resistant cryptographic hash functions from collision-resistant one-way compression functions.*

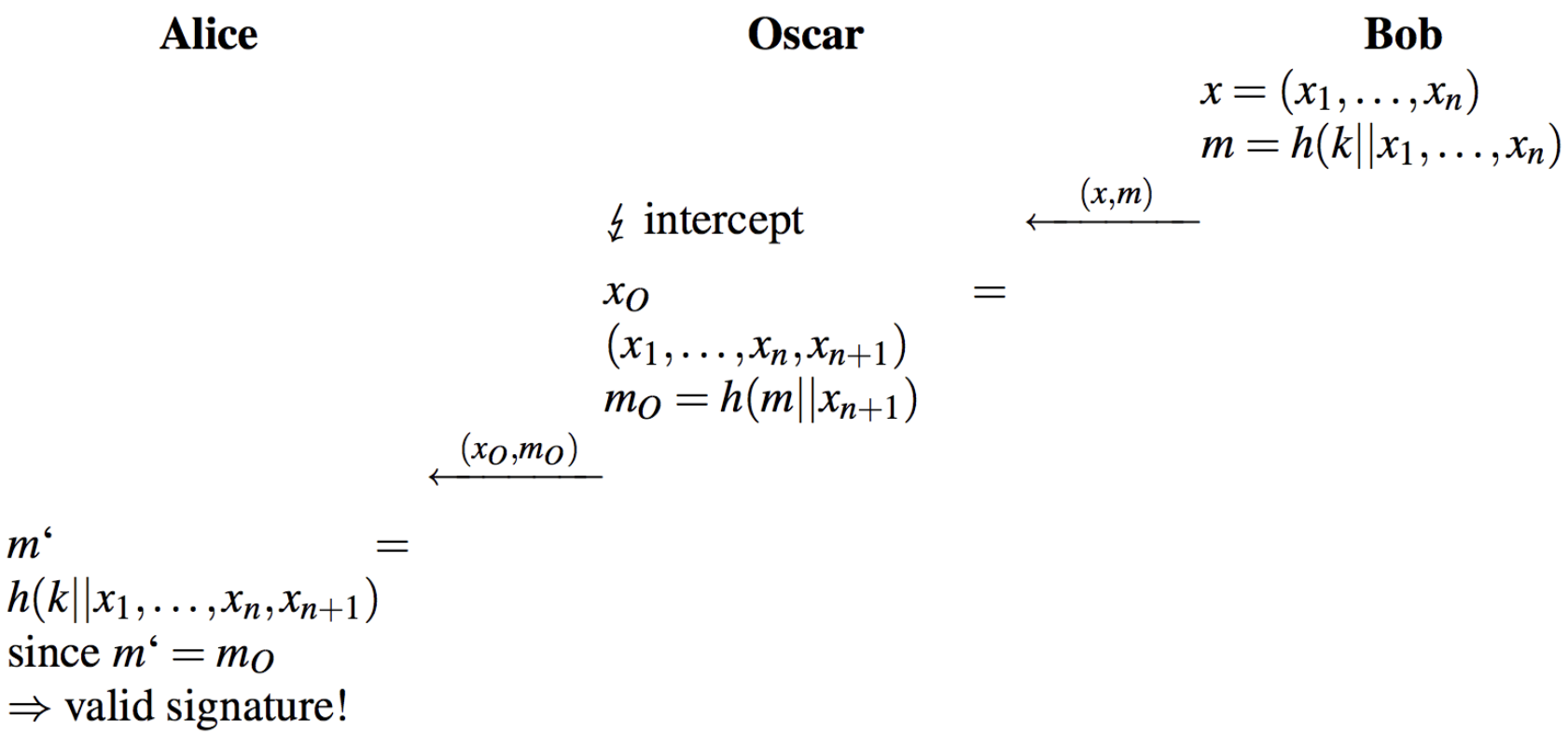
Attack Against Secret Prefix MACs

- Assume $x = (x_1, x_2, \ldots, x_n)$



- $m = MAC_k(x) = h(k||x_1||x_2||\ldots||x_n)$ is computed using Merkle-Damgård hash function/construction.
  - This iterated approach is used in the majority of today's hash functions
- Attack MAC for the message $x = (x_1, x_2, \ldots, x_n, x_{n+1})$, where x_{n+1} is an arbitrary additional block, can be constructed from m without knowing the secret key.

Attack Against Secret Prefix MACs



- Oscar intercepts $x = (x_1, x_2, \ldots, x_n)$ and m
- Adds x_{n+1}, and calculates $m_o = h(m \,||\, x_{n+1})$
- Sends $x = (x_1, x_2, \ldots, x_n, x_{n+1})$ and m_o

Attack Against Secret Suffix MACs

- Assume $x = (x_1, x_2, \ldots, x_n)$
- $m = MAC_k(x) = h(x||k) = h(x_1||x_2||\ldots||x_n||k)$
- **Attack**:
  - Assume Oscar can find collisions, x and x_o such that $h(x) = h(x_o)$, then $m = h(x||k) = h(x_o||k)$
  - Can replace x with x_o
- Q: Is this a problem, i.e., does Oscar gain anything?

  It depends on the parameters used in the construction

  $\Rightarrow$ Compare brute-force effort with collision-finding effort:
  - Example: $h()$ $\rightarrow$ SHA-1 (160 bit output)
    $|K| = 128$-bit $\rightarrow$ we expect attacker complexity of 2^{128}
  - but collision search takes $\approx \sqrt{2^{160}} = 2^{80}$ steps (birthday paradox)
  - $\Rightarrow$ cryptographically, make MAC attackable by birthday attack.
    i.e., the secret suffix method also does not provide the security one would like to have from a MAC construction

HMAC Design Objectives

- There have been a number of proposals for the incorporation of a secret key into an existing hash algorithm.
- The one approach that gained wide support is HMAC (RFC 2104) included in IP security and SSL
- RFC 2104[2] lists the following objectives for HMAC:
  - To use, without modifications, available hash functions
  - To allow for easy replaceability of the embedded hash function in case faster or more secure hash functions are found or required
  - To preserve the original performance of the hash function without incurring a significant degradation
  - To use and handle keys in a simple way
  - To have a well understood cryptographic analysis of the strength of the authentication mechanism based on reasonable assumptions about the embedded hash function
    - Main advantage of of HMAC over other proposed hash-based scheme:
      - *HMAC can be proven secure provided that the embedded hash function has some reasonable cryptographic strengths.*

[2] HMAC: Keyed-Hashing for Message Authentication

HMAC Construction

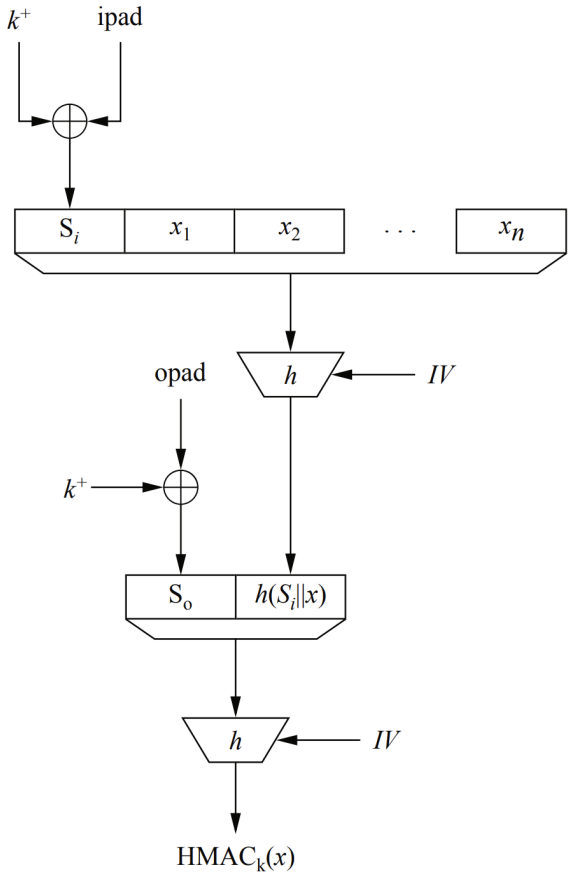
- Hash-based message authentication code
- Proposed by Bellare, Canetti and Krawczyk in 1996
- Widely used in practice, e.g., SSL/TLS
- **idea**:
  - Append a secret key to the message and compute the hash value
    - To avoid a brute-force attack, apply the hash twice to mangle thoroughly the bits of the key with those of the message
    - i.e., use two nested secret prefix MACs
  - Roughly, $h(k \,||\, h(k \,||\, x))$
  - HMAC uses two passes of hash computation (scheme consists of an inner and outer hash)
  - The secret key is first used to derive two keys (inner and outer).

HMAC Construction

- In reality: $HMAC_k(x) = h[(k^+ \oplus opad) || h((k^+ \oplus ipad) || x)]$
  - *The key k is padded with zeros to the block size of the hash function, and ipad and opad are constants of that block size.*
  - k^+ is expanded key k
    - If the length of the key its is greater than hash block size, then it will be given as input to the hash function.
    - If the original length of key is smaller than hash block size, zero extended on the left to match hash block size ($k^+ = 00...00||k$).
  - Expanded key k^+ is XORed with inner and outer pads
  - Padding[3]:
    - Let B be the block length of hash in bytes.
    - $0x36$ repeated B times for $ipad$
    - $0x5c$ repeated B times for $opad$
      e.g., $B = 64$ for MD5 and SHA-1
- The first pass of the algorithm produces an internal hash derived from the message and the inner key.
- The second pass produces the final HMAC code derived from the inner hash result and the outer key.
- Thus the algorithm provides better immunity against length extension attacks.

[3] *The values of ipad and opad are not critical to the security of the algorithm, but were defined in such a way to have a large Hamming distance from each other and so the inner and outer keys will have fewer bits in common.*

HMAC Construction



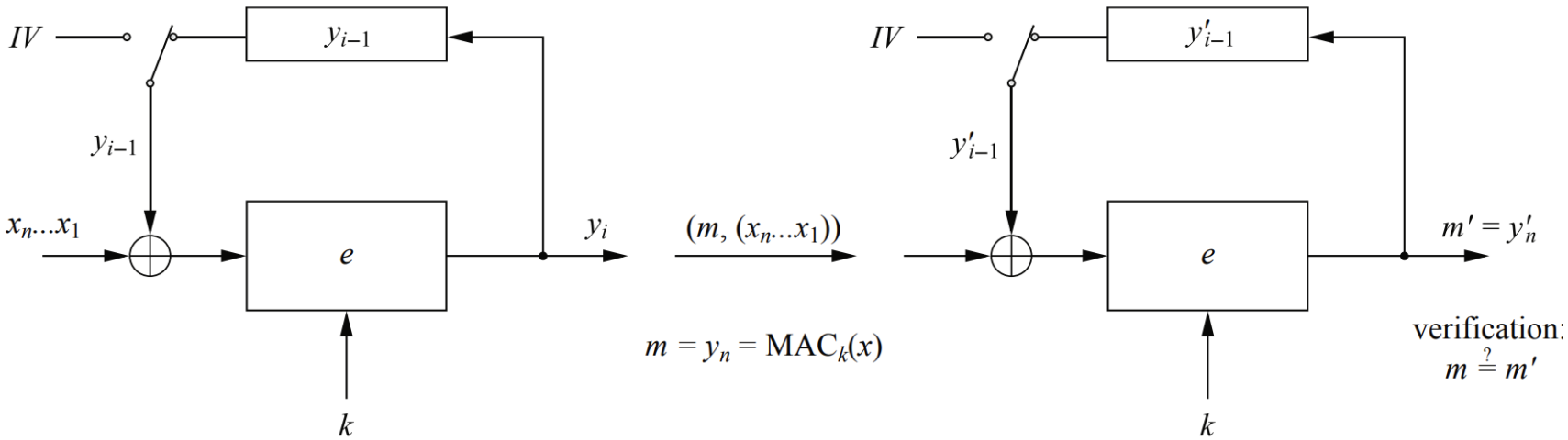
- Note: Message is only processed in inner hash!.
- HMAC is provable secure which means (informally speaking): The MAC can only be broken if a collision for the hash function can be found.

HMAC and Strong Collisions

- Birthday attacks don't make sense in HMAC scenario
  - Attacker would need to know k to generate candidate message/hash pairs

MACs from Block Ciphers

- We can construct a secure message authentication code for short fixed length messages. Based on any sort of random function.
- An alternative method is to construct MACs from block ciphers (e.g., AES)
- Popular: Use AES in CBC (cipher block chaining) mode
- Cipher block chaining message authentication code (CBC-MAC)



CBC-MAC

- MAC Generation
  - Divide the message x into blocks x_i
  - Compute first iteration $y_1 = E_k(x_1 \oplus IV)$
  - Compute $y_i = E_k(x_i \oplus y_{i-1})$ for the next blocks
  - Final block is the MAC value: $m = MAC_k(x) = y_n$
- MAC Verification
  - Repeat MAC computation (m')
  - Compare results:
    - If $m' = m$, the message is verified as correct
    - If $m' \neq m$, the message and/or the MAC value m have been altered during transmission

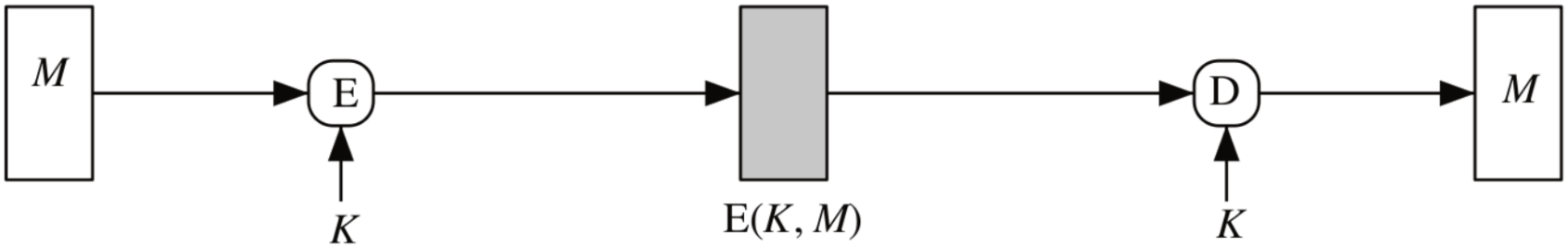
Summary: Protecting messages

- Encryption protects message confidentiality.
  - prevents unauthorized disclosure
- We also wish to protect message integrity and authenticity.
  - Integrity means that the message has not been altered.
    - detect unauthorized writing (i.e., modification of data)
  - Authenticity (Source Authentication) means that the message is genuine.
- Encryption alone does **not** provide integrity.
- Q: When data integrity is more important than confidentiality?
  - Example: Inter-bank fund transfers
    Confidentiality may be nice, integrity is **critical**

Summary: Protecting integrity and authenticity

- Integrity and authenticity are protected using symmetric or asymmetric methods.
- A digital signature or a message authentication code (MAC) is a string s that binds an individual or other entity `Alice` with a message x.
  - The recipient of the message verifies that s is a valid signature of `Alice` for message x.
  - It should be hard for `Oscar` to create a valid signature s' for a message x' without knowledge of `Alice`'s secret information.

Summary: Symmetric Encryption: Confidentiality and Authentication



- Confidentiality: only `Bob` (and `Alice`) can recover plaintext
- Source Authentication: `Alice` is only other user with key; must have come from `Alice`
- Data Authentication (integrity): successfully decrypted; data has not been modified
- Assumption: decryptor can recognize correct plaintext

Recognizing Correct Plaintext

- Example 1:
  - `Bob` receives ciphertext (supposedly from `Alice`, using shared secret key `K`)

    `DPNFCTEJLYONCJAEZRCLASJTDQFY`

  - `Bob` decrypts with key `K` to obtain plaintext:

    `SECURITYANDCRYPTOGRAPHYISFUN`

    - Was the plaintext encrypted with key `K` (and hence sent by `Alice`)?
    - Is the ciphertext received the same as the ciphertext sent by `Alice`?

  - *The typical answer for above is yes, the plaintext was sent by Alice and nothing has been modified. This is because the plaintext "makes sense". Our knowledge of most ciphers (using the English language) is that if the wrong key is used or the ciphertext has been modified, then decrypting will produce an output that does not make sense (not a combination of English words).*

Recognizing Correct Plaintext

- Example 2:
  - `Bob` receives ciphertext (supposedly from `Alice`, using shared secret key `K`)

    `QEFPFPQEBTOLKDJBPPXDBPLOOVX`

  - `Bob` decrypts with key `K` to obtain plaintext:

    `FTUEUEFTQIDAZSYQEEMSQEADDKM`

    - Was the plaintext encrypted with key `K` (and hence sent by `Alice`)?
    - Is the ciphertext received the same as the ciphertext sent by `Alice`?

  - *Based on the previous argument, the answer is no. Or more precise, either the plaintext was not sent by Alice, or the ciphertext was modified along the way. This is because the plaintext makes no sense, and we were expected it to do so.*

Recognizing Correct Plaintext

- Example 3:
  - `Bob` receives ciphertext (supposedly from `Alice`, using shared secret key `K`)

    `01101001101011010101101110000 10`

  - `Bob` decrypts with key `K` to obtain plaintext:

    `01011101000011010010101001011 10`

    - Was the plaintext encrypted with key `K` (and hence sent by `Alice`)?
    - Is the ciphertext received the same as the ciphertext sent by `Alice`?

  - *This is harder. We cannot make a decision without further understanding of the expected structure of the plaintext. What are the plaintext bits supposed to represent? A field in a packet header? A portion of a binary file? A random key? Without further information, the receiver does not know if the plaintext is correct or not. And therefore does not know if the ciphertext was sent by Alice and has not been modified.*

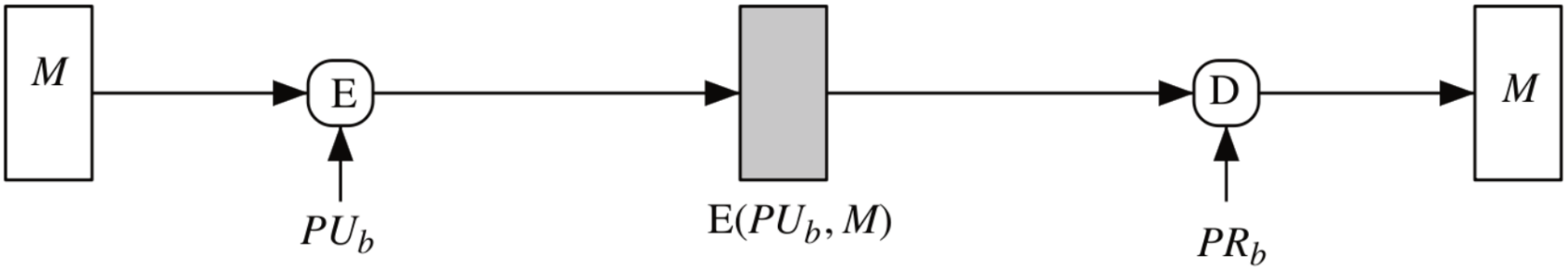
Recognizing Correct Plaintext

- Example 1:
  - Assume the message is English
  - Plaintext had expected structure; assume the plaintext is correct
    - Sent by `Alice` and has not been modified
- Example 2:
  - Assume the message is English
  - Plaintext had no structure in expected language; assume plaintext is incorrect
    - Either not sent by `Alice` or modified
- Example 3:
  - Binary data, e.g. image, compressed file
  - Cannot know whether correct or incorrect

Recognizing Correct Plaintext

- Valid plaintexts should be small subset of all possible messages
  - E.g. 26^n possible messages of length n; only small subset are valid English phrases
- Plaintext messages have structure
  - *Recognizing correct plaintext is possible if there is some structure in the original plaintext.*
- BUT automatically detecting structure can be difficult
- Authentication should be possible without decryptor having to know context of the information being transferred
- Authentication purely via symmetric key encryption is insufficient
- Solutions
  - Add structure to information, such as error detecting code
  - Use other forms of authentication, e.g. MAC

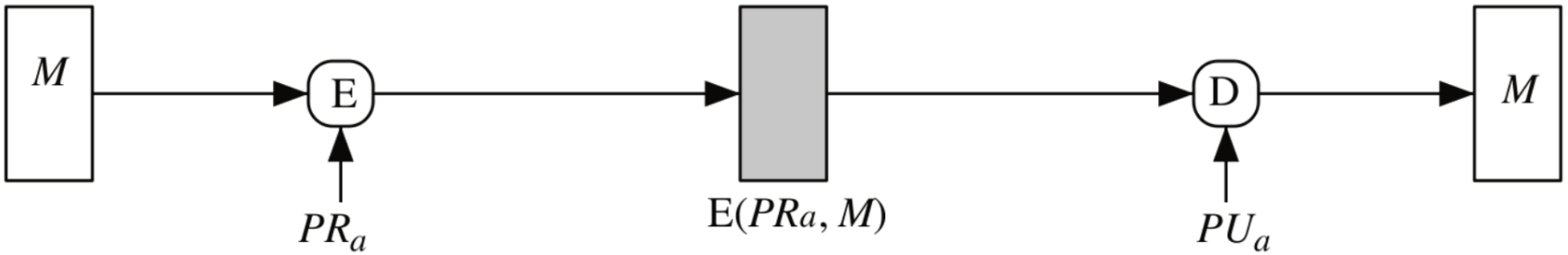
Summary: Public-Key Encryption: Confidentiality



- Only provides confidentiality
- Same assumption as before: plaintext must have structure so can be recognized as correct or incorrect

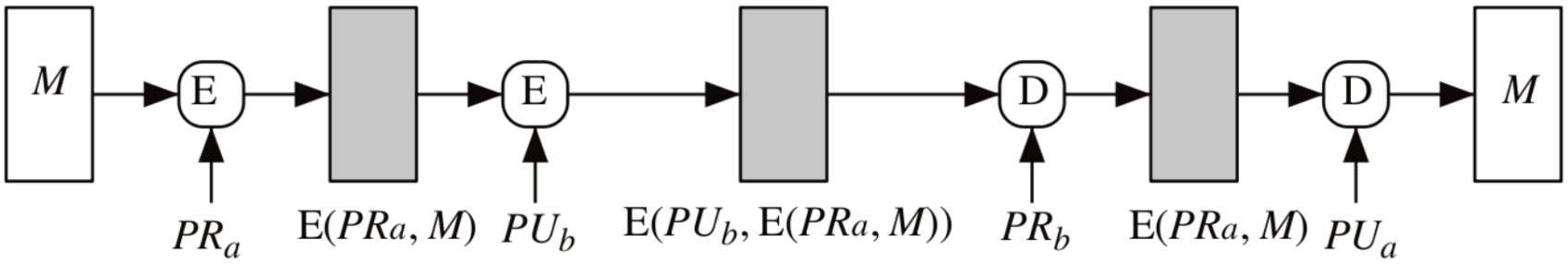
Summary: Public-Key Encryption: Authentication and Signature

- Data authentication: (data has not been modified)
- Source authentication: proof that message came from `Alice`



Summary: Public-Key Encryption for Authentication

- Confidentiality, authentication and signature



Summary: Non-non-repudiation

- `Alice` orders *100* shares of stock from `Bob`.
- `Alice` computes MAC using symmetric key.
- Stock drops, `Alice` claims she did not order.
- Q: Can `Bob` prove that `Alice` placed the order?
  - **No!** `Bob` also knows the symmetric key, so he could have forged the MAC.
- Problem: `Bob` knows `Alice` placed the order, but he can't prove it.

Summary: Non-repudiation

- **Can an asymmetric scheme help?**
- `Alice` orders *100* shares of stock from `Bob`.
- `Alice` signs order with her private key.
- Stock drops, `Alice` claims she did not order.
- Q: Can `Bob` prove that Alice placed the order?
  - **Yes!** `Alice`'s private key used to sign the order - only `Alice` knows her private key.
  - Of course, this assumes `Alice`'s private key has not been lost/stolen.

Summary: Non-repudiation

- Non-repudiation refers to a state where the author of a statement will not be able to successfully challenge the authorship of the statement.
- What is the relationship between authenticity and non-repudiation?
  - Authenticity: `Alice` interacts with `Bob` and convinces him that a message x truly came from her.
  - Non-repudiation: Same as above but now `Bob` can convince `Charlie` too.

Summary

- Message authentication requirements
- MACs provide two security services, message and source authentication using symmetric ciphers.
- MACs are widely used in protocols.
- Both of these services are also provided by digital signatures, but MACs are much faster
- MACs do not provide non-repudiation.
- In practice, MACs are either based on block ciphers or on hash functions.
- HMAC is a popular MAC used in many practical protocols such as Transport Layer Security (TLS) - indicated by a small lock in the browser.

Reading

- Understanding Cryptography: A Textbook for Students and Practitioners *available online*
  - Chapter 12: Message Authentication Codes (MACs)