Message authentication

-- Reminder on hash functions
-- MAC functions
hash based
block cipher based
-- Digital signatures

Hash functions

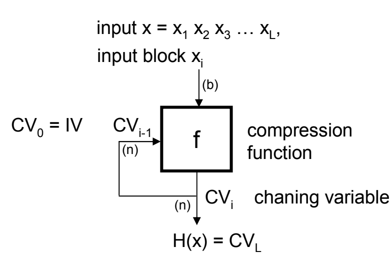
- a hash function is a function H: $\{0, 1\}^* \rightarrow \{0, 1\}^n$ that maps arbitrary long messages into a fixed length output
- notation and terminology:
  - x – (input) message
  - y = H(x) – hash value, message digest, fingerprint
- typical application:
  - the hash value of a message can serve as a compact representative image of the message (similar to fingerprints)
    - H is a many-to-one mapping → collisions are unavoidable
    - however, finding collisions are very difficult (practically infeasible)
  - increase the efficiency of digital signatures by signing the hash instead of the message (expensive operation is performed on small data)
- examples:
  - (MD5,) SHA-1, SHA-256

Desired properties of hash functions

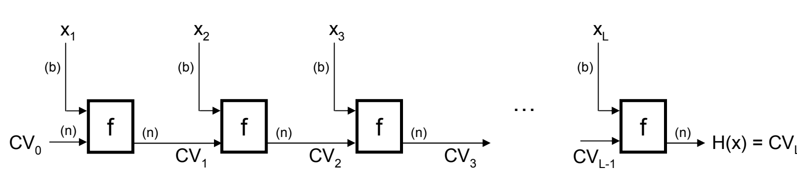
- ease of computation
  – given an input x, the hash value H(x) of x is easy to compute
- weak collision resistance (2^{nd} preimage resistance)
  – given an input x, it is computationally infeasible to find a second input x' such that H(x') = H(x)
- strong collision resistance (collision resistance)
  – it is computationally infeasible to find any two distinct inputs x and x' such that H(x) = H(x')
- one-way hash function (preimage resistance)
  – given a hash value y (for which no preimage is known), it is computationally infeasible to find any input x such that H(x) = y
- collision resistant hash functions are similar to block ciphers in the sense that they can be modeled as a random function

Iterative hash functions

- operation:
  – input is divided into fixed length blocks
  – last block is padded if necessary
  – each input block is processed according to the following scheme



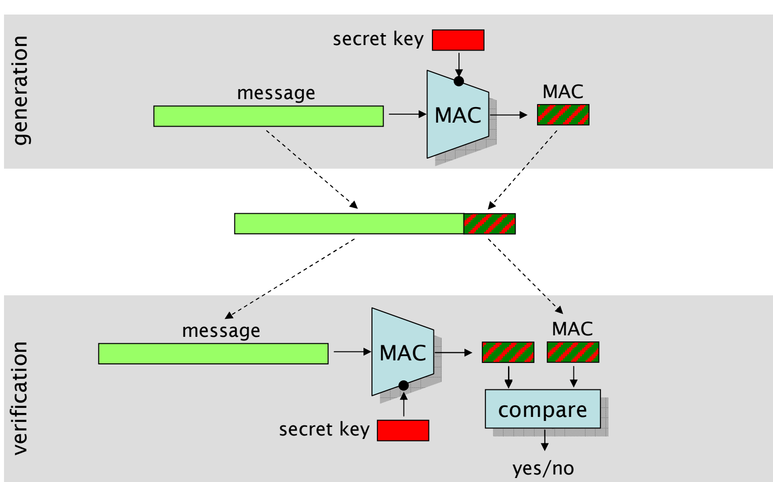
alternative illustration:



MAC functions

- MAC = Message Authentication Code
- a MAC function is a function MAC: $\{0, 1\}^* \times \{0, 1\}^k \rightarrow \{0, 1\}^n$ that maps an arbitrary long message and a key into a fixed length output
  - can be viewed as a hash function with an additional input (the key)
- terminology and usage:
  - the sender computes the MAC value M = MAC(m, K), where m is the message, and K is the MAC key
  - the sender attaches M to m, and sends them to the receiver
  - the receiver receives (m', M')
  - the receiver computes M" = MAC(m', K) and compares it to M'; if they are the same, then the message is accepted, otherwise rejected
- services:
  - **message authentication and integrity protection:** after successful verification of the MAC value, the receiver is assured that the message has been generated by the sender and it has not been altered
- examples:
  - HMAC, CBC-MAC schemes

MAC generation and verification illustrated



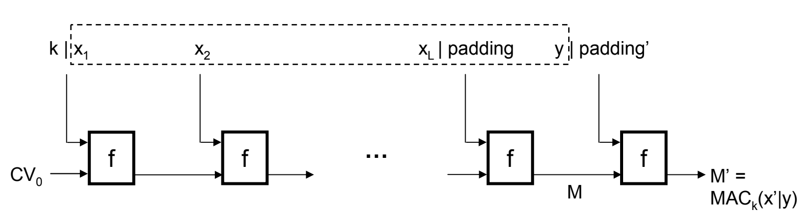
Desired properties of MAC functions

- ease of computation
- key non-recovery
  - it is computationally infeasible to recover the secret key K, given one or more message-MAC pairs (m_i, M_i) for that K
- computation resistance
  - given zero or more message-MAC pairs (m_i, M_i), it is computationally infeasible to find a valid message-MAC pair (m, M) such that $m \neq m_i$
  - computation resistance implies key non-recovery but the reverse is not true in general

Secret prefix method

$MAC_k(x) = H(k|x)$

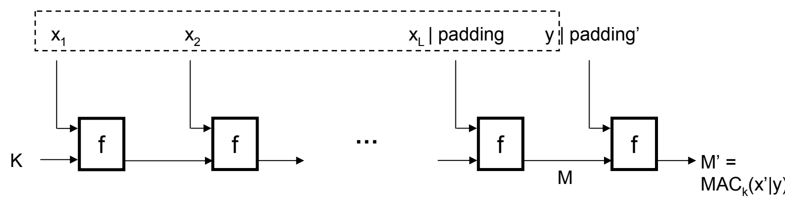
- insecure !
  - assume an attacker knows the MAC on x: M = H(k|x)
  - he can produce the MAC on x'|y as M' = f(M,y), where x' is x with padding and f is the compression function of H



A similar mistake

$MAC_k(x) = H_k(x)$

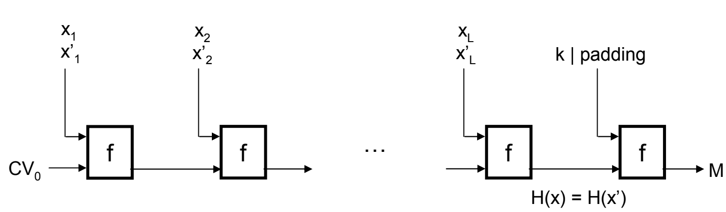
where $H_k(.)$ is $H(.)$ with $CV_0 = k$



Secret suffix method

$MAC_k(x) = H(x|k)$

- insecure if H is not collision resistant
  - using a birthday attack, the attacker finds two inputs x and x' such that H(x) = H(x') (can be done off-line without the knowledge of k)
  - then obtaining the MAC M on one of the inputs, say x, allows the attacker to forge a text-MAC pair (x', M)
- weaknesses
  - MAC depends only on the last chaining variable
  - key is involved only in the last step

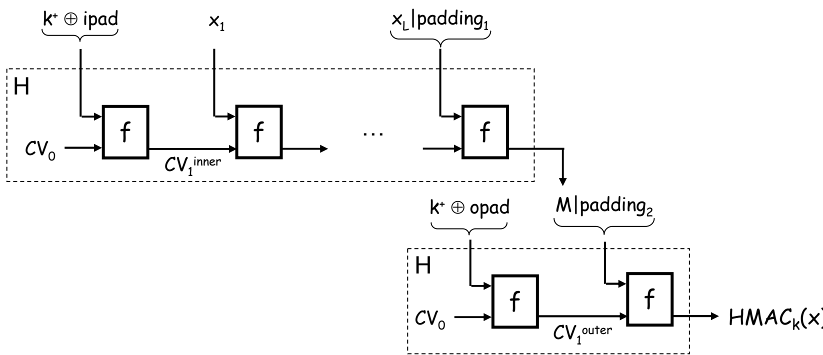


HMAC

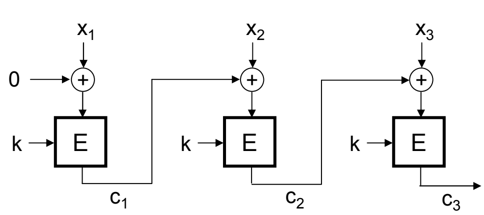
$\mathrm{HMAC}_k(x) = H(\,(k^+ \oplus \mathrm{opad}) \mid H(\,(k^+ \oplus \mathrm{ipad}) \mid x\,)\,)$

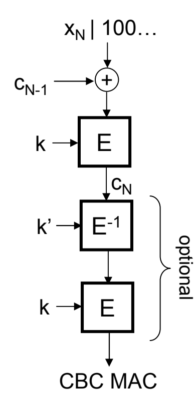
where

- h is a hash function with input block size b and output size n
- k^+ is k padded with 0s to obtain a length of b bits
- ipad is 00110110 repeated b/8 times
- opad is 01011100 repeated b/8 times



CBC-MAC





- CBC MAC is secure for messages of a fixed number of blocks
- forgery is possible if variable length messages are allowed

How to use CBC-MAC in practice?

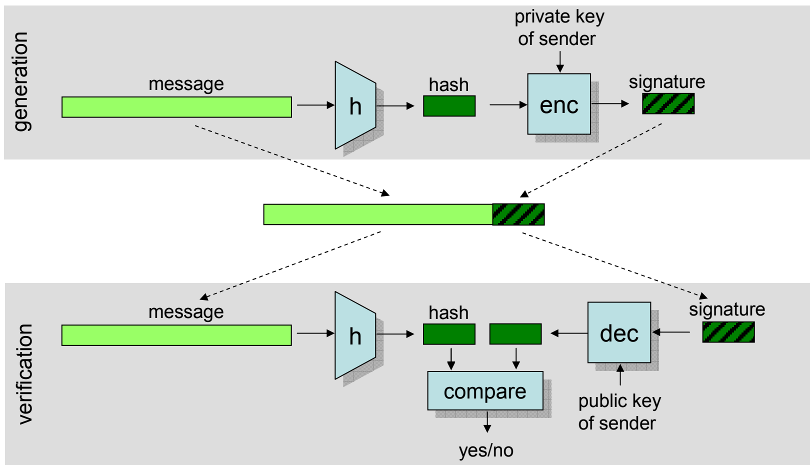
- use the optional final encryption
  - reduces the threat of exhaustive key search (key is (k, k') → key length is doubled)
  - prevents known existential forgeries
  - has marginal overhead (only last block is encrypted multiple times)
- prepend the message with a block containing the length of the message before the MAC computation
- use k to encrypt the length and obtain k' = E_k(length), and use k' as the MAC key (i.e., use message dependent MAC keys)

Digital signature schemes

- functions (algorithms) and terminology:
  - key-pair generation function G() = (K^+, K^-)
    - K^+ – public key
    - K^- – private key
  - signature generation function S(K^-, m) = s
    - m – message
    - s – signature
  - signature verification function V: V(K^+, m, s) = accept or reject
- services:
  - **message authentication and integrity protection:** after successful verification of the signature, the receiver is assured that the message has been generated by the sender and it has not been altered
  - **non-repudiation of origin:** the receiver can prove this to a third party (hence the sender cannot repudiate)
- examples: RSA, DSA, ECDSA (shorter key and signature length!)

“Hash-and-sign” paradigm

- public/private key operations are slow
- increase efficiency by signing the hash of the message instead of the message
- it is essential that the hash function is collision resistant (why?)



Security of digital signature schemes

- as in the case of public-key encryption, security is usually related to the difficulty of solving the underlying hard problems
- attack objectives:
  - existential forgery
    - attacker is able to compute a valid signature for at least one message
  - selective forgery
    - attacker is able to compute valid signatures for a particular class of messages
  - total break
    - the attacker is able to forge signatures for all messages or he can deduce the private key
- attack models:
  - key-only attack
  - known-message attack
  - (adaptive) chosen-message attack

RSA signature scheme

- key pair generation
  - same as for RSA encryption: public key is (n, e), private key is d
- signature generation (input: m, d; output: σ)
  - compute $\mu = h(m)$
  - (PKCS #1 formatting)
  - compute $\sigma = \mu^d \bmod n$
- signature verification (input: m, σ, (n, e); output: yes/no)
  - compute $\mu' = \sigma^e \bmod n$
  - (PKCS #1 processing, reject if μ' is not well formatted)
  - compute $\mu = h(m)$
  - compare μ and μ'
    - if they match, then output yes (accept)
    - otherwise, output no (reject)

Management requirements for key pairs

- RSA has the interesting property that the same key pair can be used for both encryption and digital signature
- however, such double use of key-pairs is not advisable; users should have different key-pairs for different applications
- the main reason is in the difference in key management requirements
  - digital signature
    - private key should never leave the key owner's system
    - private key doesn't need back up and archive (why?)
    - public key (certificate) needs to be archived
  - encryption
    - private key often needs to be backed up and archived (why?)
    - public key usually doesn't need to be archived

  → the two applications have conflicting requirements

Session key establishment protocols

-- Motivations and design objectives
-- Basic concepts and techniques
-- Key transport and key agreement protocols
-- Password based key exchange

Motivation

- communicating parties must share a secret key in order to use symmetric key cryptographic algorithms (e.g., block ciphers, stream ciphers, and MAC functions)
- it is desired that a different shared key is established for each communication session → session key
  - to ensure independence across sessions
  - to avoid long-term storage of a large number of shared keys
  - to limit the number of ciphertexts available for cryptanalysis
- we need mechanisms that allow two (or more) remote parties to set up a shared secret in a dynamic (on-demand) manner → session key establishment protocols

Design objectives

at the end of the protocol

- Alice and Bob should learn the value of the session key K (**effectiveness**)
- no other parties (with the possible exception of a trusted third party) should know the value of K (**implicit key authentication**)
- Alice and Bob should believe that K is freshly generated (**key freshness**)
- optionally, Alice should believe that Bob knows the key K, and vice versa (**key confirmation**)

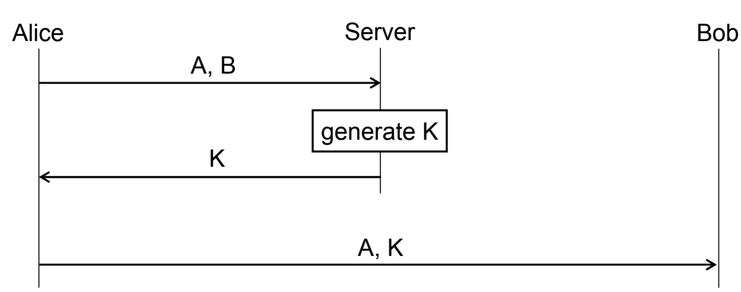
Adversary model

- the underlying cryptographic primitives used in the protocol are secure
- however, the adversary may obtain old session keys
- the adversary has full control over the communications of the honest parties
  - can eavesdrop, modify, delete, inject, and replay messages
  - can coerce honest parties to engage into protocol runs
- the adversary may be a legitimate protocol participant (an insider), or an external party (an outsider), or the combination of both

Basic classification of protocols

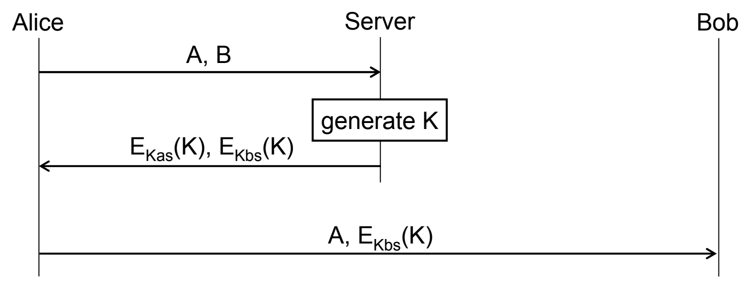
- key transport protocols
  - one party (typically a trusted third party) creates a new session key, and securely transfers it to the other parties
- key agreement protocols
  - the session key is derived by the parties as a function of information contributed by each, such that no party can predetermine the resulting value of the key

First attempt for a key transport protocol



most obvious problem:
- the adversary can eavesdrop K
- implicit key authentication is not provided

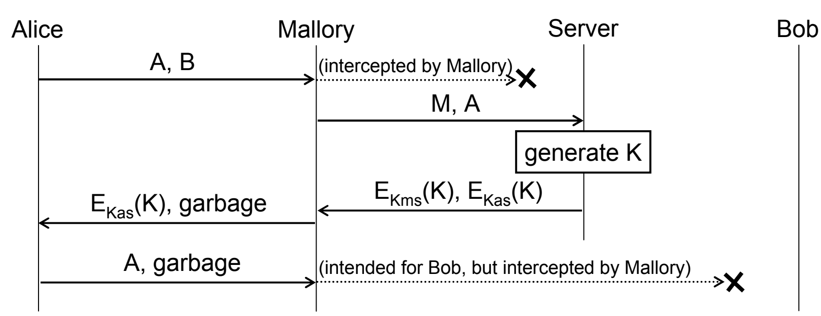
Second attempt



problems:

– Alice cannot be sure that K has been created for the session between herself and Bob
– similarly, Bob cannot be sure that he shares K with Alice
– implicit key authentication is still not provided
– …

An attack against the second attempt



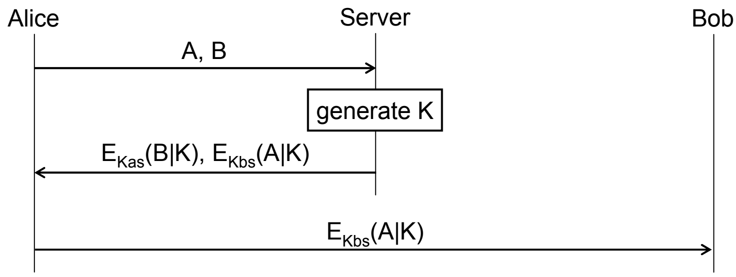
notes:

– typical *man-in-the-middle (MitM) attack*
– Alice believes that she shares K with Bob, but she shares it with the adversary

derived design principle:

– ***if the name of a party is essential to the meaning of a message, then it must be mentioned explicitly in the message***

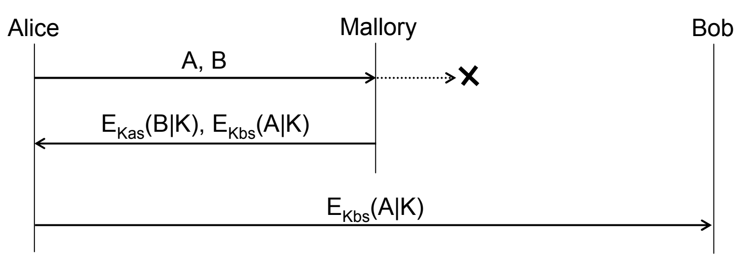
Third attempt



problem:

- neither Alice nor Bob can be sure that K is fresh
- no key freshness is provided

An attack against the third attempt



notes:

- typical *replay attack*
- if K is compromised by the adversary, then she can decrypt follow-up communications between Alice and Bob
- even if K is not compromised, the adversary can replay encrypted messages to Alice and Bob from the past session where K was used

How to achieve freshness?

- use timestamps
- use random nonces (nonce = n̲umber used o̲n̲c̲e̲)
- use a key agreement protocol

Timestamps

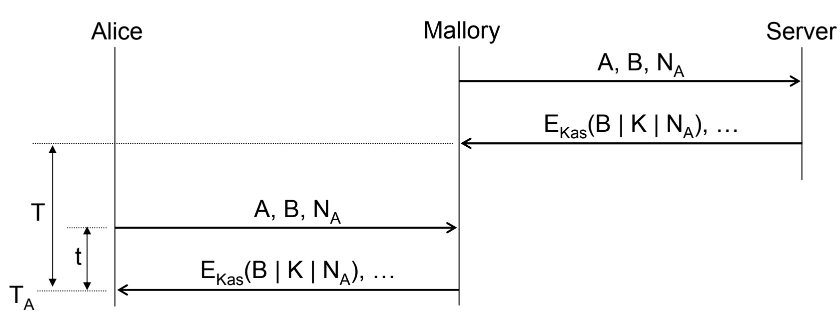
- $E_{Kas}(B \mid K \mid T_s)$, where T_s is the current time on the clock of S
- key is accepted only if the timestamp is within an acceptable window of the current time at the receiver
- can provide strong assurances, but requires synchronized clocks
- important warning:
  if a party's clock is advanced, then (s)he may generate messages that will be considered fresh *in the future* (although they may be dropped near the time of their generation)

Random nonces

- $E_{Kas}(B \mid K \mid N_A)$, where N_A is a fresh and *unpredictable* random number generated by A (and sent to S beforehand)
- key is accepted only if the time that elapsed between sending the nonce and receiving the message containing the nonce is acceptably short
- less precise than a timestamp (exact time of key generation is not known), but it provides sufficient guarantees of freshness in most practical cases
- it requires an extra message to send the nonce, and some temporary state to store the nonce for verification purposes

Random nonces

- important warning:
  if nonces were predictable, the adversary could obtain a message containing a future nonce of Alice, which would later be considered as fresh by Alice



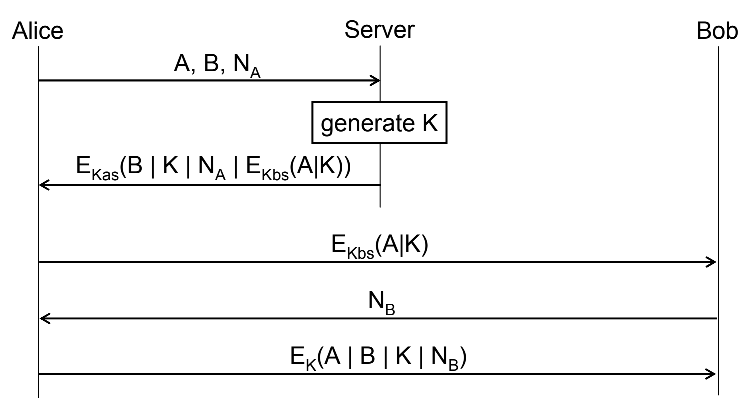
Alice believes that the key is younger than T_A-t, while in fact, it is older than T_A-T

Key freshness in key agreement protocols

- $K = f(k_A, k_B)$, where k_A and k_B are the contributions of Alice and Bob, respectively
- if $f(x, .)$ is a one-way function (for any x), then once Alice has chosen k_A, Bob cannot find any k_B, such that $f(k_A, k_B)$ has a pre-specified value (e.g., an old session key)
- similarly, if $f(., y)$ is a one-way function (for any y), then once Bob has chosen k_B, Alice cannot find any k_A, such that $f(k_A, k_B)$ has a pre-specified value

→ if the contribution of a party is fresh, then (s)he can be sure that the resulting session key is fresh too

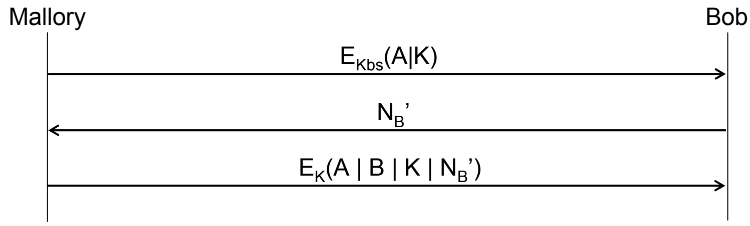
Fourth attempt



notes:

- nested encryption provides key confirmation for Bob
- this protocol is similar to the well-known Needham-Schroeder protocol (symmetric key)
- seemingly correct, but …

An attack against the fourth attempt



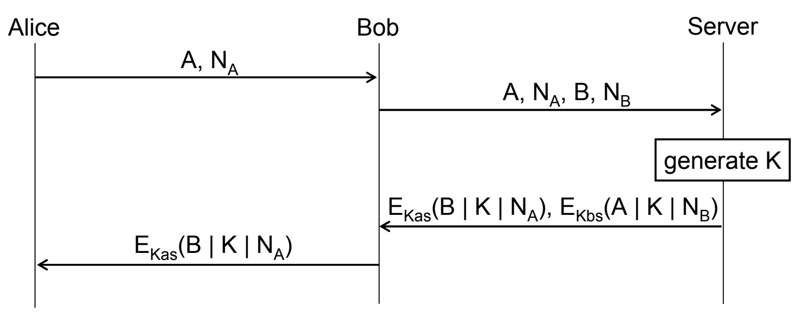
notes:

- K is an old session key that is compromised by the adversary
- $E_{Kbs}(A|K)$ is replayed from the old protocol run (where K was established as the session key)
- Bob will believe that he established a session with A, but A is not present

derived design principles:

- ***the fact that a key K is used recently to encrypt a message does not mean that K is fresh***
- ***when proving the freshness of a key K by binding it to some fresh data (timestamp or nonce), don't use K itself for the binding***

Fifth attempt



- any problems?

Protocol engineering checklist

- be explicit
  – interpretation of messages shouldn't depend on context information, but it should be based solely on the content of the messages
  – include **names** that are needed to correctly interpret the message
  – consider including protocol type, run identifier, and message number to avoid protocol interference, interleaving, and message reflection attacks, respectively

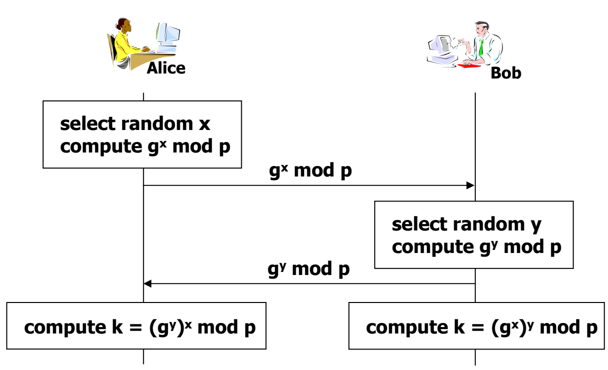
- think twice about key freshness
  – decide on how you want to ensure key freshness for the different participants
  – consider the advantages and disadvantages of nonces and timestamps in a given application environment

- state assumptions
  – explicitly state all the assumptions on which the security of your protocol depends so that someone who wants to use your protocol can verify if they hold in a given application environment

Key agreement with the Diffie-Hellman protocol

summary: a key agreement protocol based on one-way functions; in particular, security of the protocol is based on the hardness of the discrete logarithm problem and that of the Diffie-Hellman problem

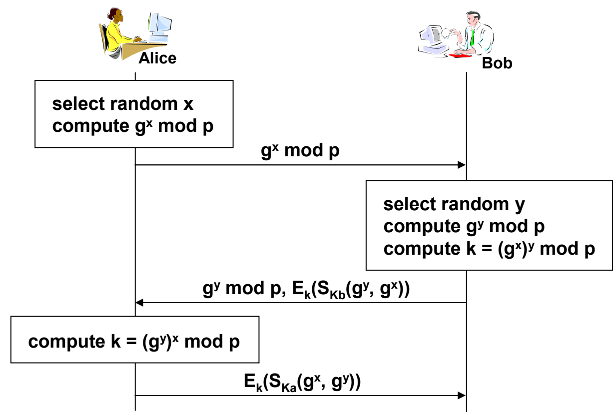
assumptions: p is a large prime, g is a generator of Z_p^*, both are publicly known system parameters



characteristics: NO AUTHENTICATION, key freshness with randomly selected exponents, no party can control the key, no need for a trusted third party

The Station-to-Station protocol

summary: three-pass variation of the basic Diffie-Hellman protocol; it uses digital signatures to provide mutual entity authentication and mutual explicit key authentication



characteristics: mutual entity authentication, mutual explicit key authentication, key freshness with random exponents, no party can control the key, off-line third party for issuing public key certificates may be required, initial exchange of public keys between the parties may be required

Password based key exchange

- assume that two parties (e.g., a user and a server) share a password (relatively weak secret)
- how to set up a cryptographic key (strong secret) with the help of this password?

A naïve solution

- Alice can generate a key K and encrypt it with the password pwd (or its hash value):

$$A \rightarrow B: \; A, E_{H(pwd)}(K)$$

- Bob can use the hash of the password to obtain K from $E_{H(pwd)}(K)$, and then use K to encrypt messages for Alice
- for example:

$$B \rightarrow A: \; E_K(\text{“Last login at 16:34, Monday”})$$

The problem

- (key freshness is not provided by the naïve protocol, but it could be added by including a timestamp)

- if a weak password is used, then the naïve solution is vulnerable to an **off-line dictionary attack**:
  - assume that the attacker eavesdropped a protocol run
  - for each candidate password pwd?, compute the candidate key $K? = D_{H(pwd?)}(E_{H(pwd)}(K))$
  - test K? by checking if $D_{K?}(E_K(\text{“Last login …”}))$ is a meaningful message
  - if so, then pwd? is Alice’s password, otherwise throw away pwd? and try a new candidate password from the dictionary

Encrypted Key Exchange (EKE) – the basic idea

- Alice generates a public key / private key pair K^+ and K^-, and encrypts K^+ with the (hash of the) password pwd:

$$A \rightarrow B : \; A, E_{H(pwd)}(K^+)$$

- Bob uses the (hash of the) password to obtain K^+, then generates a (symmetric) key K, and encrypts it with K^+ in the public key cryptosystem; the result is further encrypted with the (hash of the) password:

$$B \rightarrow A : \; E_{H(pwd)}(AE_{K+}(K))$$

- Alice uses the (hash of the) password and K^- to obtain K from $E_{H(pwd)}(AE_{K+}(K))$; then she can use K to send messages to Bob:

$$A \rightarrow B : \; E_K(\text{“Last login at 16:34, Monday”})$$

Why is this good?

- for a candidate password pwd?, the attacker can compute a candidate public key $K^+?$ as $D_{H(pwd?)}(E_{H(pwd)}(K^+))$
- but $K^+?$ cannot really be tested
  - the attacker needs to find a key K? such that
    - $AE_{K+?}(K?) = D_{H(pwd?)}(E_{H(pwd)}(AE_{K+}(K)))$
    - $D_{K?}(E_K(\text{“Last login …”}))$ makes sense
  - both would require an exhaustive search over the key space from which K is chosen (or breaking the symmetric or the asymmetric cipher)

→ the relatively small space of passwords is thus multiplied by the large key space from which K is chosen (privacy amplification effect)

What about key freshness?

- as Bob generates K, key freshness is provided for Bob
- for Alice K^+ is fresh, and this guarantees freshness of K through the encryption $AE_{K+}(K)$ (assuming that Alice trusts Bob for generating fresh session keys)
  - Alice can conclude that someone who knows the password (which can only be Bob) has recently sent K to the other holder of the password (which can only be Alice)