Applied Cryptography and Computer Security
CSE 664 Spring 2020

Lecture 19: Key Distribution and Agreement

Department of Computer Science and Engineering
University at Buffalo

Key Distribution Mechanisms

- Secret-key encryption is much faster than public-key encryption
  - to have efficiency, we are to deal with distribution of the shared keys
- Recall that public-key cryptography can bootstrap communication with symmetric keys
  - suppose Alice knows Bob's public key pk_B
  - Alice chooses a session key s and sends Bob $E_{pk_B}(s)$
  - Bob decrypts it and now they share the same key
  - this simple solution can work in some cases, but has disadvantages

Key Distribution Mechanisms

- There are many possibilities for key distribution
  - assume that we have an insecure network of n users
  - there is also a trusted authority (TA)
    - the TA's responsibilities could include checking user identities, issuing certificates, transmitting keys, etc.
- We divide all approaches in 3 categories
  - key predistribution
    - a TA distributes keying information during the setup phase using a secure channel
    - a pair of users is then able to compute a key known only to them

Key Distribution Mechanisms

- Types of key distribution (cont.)
  - session key distribution
    - on request, an online TA chooses a session keys and distributes it to two users
    - the TA communicates the new keys by encrypting them using previously distributed secret keys
    - session keys are used for a fixed, rather short period of time
  - key agreement (a.k.a. key establishment or key exchange)
    - network users employ an interactive protocol to construct a session key
    - no TA's help is used
    - can be based on secret-key or public-key schemes

Key Distribution Mechanisms

- The difference between key distribution and key agreement:
  - in key distribution, one party (e.g., a TA) chooses a key and transmits it to one or more parties
    - key transmission is performed in an encrypted form
  - in key agreement, two or more parties jointly establish a secret key
    - communication is performed over a public channel
    - each participant contributes to the value of the resulting key
    - the key is not sent from one party to another

Key Distribution Mechanisms

- In the network, users may have long-lived keys
  - they can be precomputed and stored securely
  - they could be secret keys known to a pair of users or to a user and the TA
  - they also could be private keys corresponding to public keys stored in users' certificates
- Pairs of users often employ short-lived session keys
  - a session key is used for a particular session and is discarded at the end of it
  - session keys are normally secret keys for a symmetric encryption scheme or MAC

Key Distribution Mechanisms

- Since the network is insecure, we need to protect against attackers
  - the adversary might be one of the users in the network
- An active adversary can:
  - modify messages being transmitted on the network
  - save messages for later use
  - try to masquerade as another user in the network
- Adversary's goal might be:
  - fool someone into accepting an invalid key as valid
  - learn some information about the key being established
  - use another user's identity to establish a shared key with someone

Key Distribution Mechanisms

- In real life applications, the adversary can have even more power
  - suppose that a session key has been exposed
    - we prefer to see no impact on the security of the long-lived key
  - suppose that an attacker gets ahold of your long-lived key
    - ideally this should not compromise the security of past session keys
    - this property is called perfect forward secrecy
- Often we also want parties to authenticate during the key agreement protocol
  - this is called authenticated key exchange

Diffie-Hellman Key Predistribution

- The following key predistribution scheme is a modification of the Diffie-Hellman key exchange protocol
  - its security is based on the hardness of the Decision Diffie-Hellman (DDH) problem
- The setup
  - the public domain parameters consist of a group $(G, \cdot)$ and an element $g \in G$ of some order q
  - every user U in the network has a long-lived private key x_U $(0 < x_U \leq q - 1)$ and the corresponding public key $y_U = g^{x_U}$
  - the users' public keys are certified (signed) by the TA to guarantee their authenticity

Diffie-Hellman Key Predistribution

- Diffie-Hellman key predistribution
  - A and B would like to setup a joint key
  - A computes the key $k_{A,B}$ using B's (signed) public key y_B and A's private key x_A:

$$k_{A,B} = y_B^{x_A} = g^{x_A x_B}$$

  - likewise, B, using A's (signed) public key y_A and B's private key x_B, computes:

$$k_{A,B} = y_A^{x_B} = g^{x_A x_B}$$

- Each pair of users performs the same computation to obtain the key known only to them

Diffie-Hellman Key Predistribution

- Hardness assumptions
  - Computational DH: given g, g^a and g^b, it is hard to compute g^{ab}
  - Decision DH: given g, g^a, g^b, and g^c, it is hard to decide whether $g^c = g^{ab}$
- Security of DH key predistribution
  - since there is no interaction, an active adversary cannot do much
  - if CDH problem is hard, recovery of any key $k_{U,V}$ is infeasible
  - if DDH problem is hard, the keys are indistinguishable from random

Session Key Distribution Schemes

- Assume that the TA has a shared key with each user on the network
  - k_A is the key shared with Alice, k_B is the key shared with Bob, etc.
- The TA chooses session keys and distributes them in encrypted form upon user requests
- How do we do this?
  - the simplest solution is for Alice to send a session key request for users A, B
  - the TA chooses a key k at random and sends $E_{k_A}(k||B)$ to Alice and $E_{k_B}(k||A)$ to Bob
  - each of them decrypt and start communicating using k
  - is this enough?

Session Key Distribution Schemes

- Needham-Schroeder SKDS was designed in 1978
  - uses fresh nonces, but still doesn't provide adequate security
- Denning and Sacco discovered an attack on Needham-Schroeder SKDS
  - it is called known session key attack because it assumes the attacker obtains one of the past session keys k
- Kerberos is a series of related SKDSs developed at MIT in the 80-90s
  - it additionally uses validity period in security tokens
  - this limits the time period during which a Denning-Sacco type of attack can be carried out
- Neither solution has a security proof and both have security weaknesses

Bellare-Rogaway SKDS

- Bellare and Rogaway proposed an SKDS in 1995 that has a proof of security
  - it has a different flow structure than the earlier schemes
- Bellare-Rogaway SKDS
  - Alice chooses random r_A and sends A, B, and r_A to Bob
  - Bob chooses random r_B and sends A, B, r_A, and r_B to the TA
  - the TA chooses a random session key k and computes
    $y_B = (E_{k_B}(k), MAC_B(A||B||r_B||E_{k_B}(k)))$ and
    $y_A = (E_{k_A}(k), MAC_A(B||A||r_A||E_{k_A}(k)))$
  - the TA sends y_B to Bob and y_A to Alice

Bellare-Rogaway SKDS

- Alice and Bob need to verify that the messages have a correct form, the MAC is valid, and the proper values r_A and r_B were used
- No explicit key confirmation is provided
  - if Alice accepts, she believes that she has received a new session key from the TA
  - she doesn't know if Bob received everything as well, but she is confident that noone other than Bob can compute the session key
- We arrive at (informal) definition of a secure session key distribution scheme
  - if a protocol participant "accepts," then the probability that someone other than the intended peer knows the session key is negligible

Bellare-Rogaway SKDS

- To show security, we make certain assumptions
  - Alice and Bob are honest
  - r_A, r_B, and k are chosen perfectly at random
  - the encryption scheme and MAC are secure
  - secret keys are known only to their intended owners
- Possibilities for an adversary
  - Mallory is a passive adversary
  - Mallory is an active adversary
    - she may impersonate Alice, Bob, or the TA; intercept and modify messages

Bellare-Rogaway SKDS

- If Mallory is passive, Alice and Bob compute the same key and accept
  - Mallory cannot compute the key because encryption is secure
- Now assume that Alice is a legitimate user and Mallory is active
  - Alice doesn't know if she is really communicating with Bob or the TA
  - when Alice receives y_A, she checks that the MAC contains her r_A, the identities are A and B
    - this convinces her that the response is fresh and came from the TA
    - using r_A prevents replay attacks
    - also, including $E_{k_A}(k)$ under the MAC prevents its replacement by the attacker
- Similar reasoning applies to Bob's side

Key Distribution and Agreement

- Recall that setting up a shared key between two users can be done by
  - predistributing keys to them
  - using a session key distribution scheme
  - engaging them in a key agreement protocol
- We next cover key agreement (or key exchange) schemes
  - a key exchange is an interactive protocol between two users without active participation of a TA
  - this is achieved by means of public-key cryptography

Key Agreement Schemes

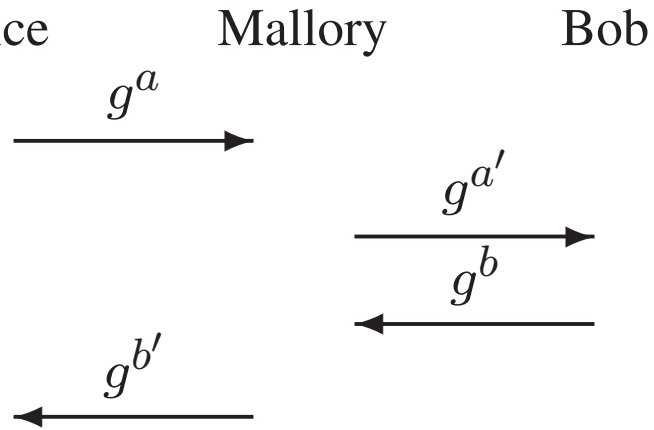
- The best-known key exchange protocol is due to Diffie and Hellman
  - recall that Alice and Bob want to establish a shared key
    - the common parameters are (G, q, g)
    - Alice chooses a random number a from $\mathbb{Z}_q$, computes g^a, and sends g^a to Bob
    - Bob chooses a random number b from $\mathbb{Z}_q$, computes g^b, and sends g^b to Alice
    - Alice computes the shared key as $(g^b)^a = g^{ab}$
    - Bob computes the shared key as $(g^a)^b = g^{ab}$

Diffie-Hellman Key Exchange

- Diffie-Hellman key exchange
  - Alice and Bob compute the same key, but it is computationally difficult for someone else to compute their key
  - the security property holds only against a passive attacker
  - the protocol has a serious weakness in the presence of an active adversary
    - this is called a man-in-the-middle attack
    - Mallory will intercept messages between Alice and Bob and substitute her own
    - Alice establishes a shared key with Mallory and Bob also establishes a shared key with Mallory

Diffie-Hellman Key Exchange

- Man-in-the-middle attack on Diffie-Hellman key exchange



  - Alice shares the key $g^{ab'}$ with Mallory
  - Bob shares the key $g^{a'b}$ with Mallory
  - Alice and Bob do not share any key
  - what is Mallory capable of doing?

Diffie-Hellman Key Exchange

- Alice and Bob need to make sure they are exchanging messages with each other
  - there is a need for authentication
  - preceding this protocol with an authentication scheme is not guaranteed to solve the problem
    - after they authenticate, the same attack can be carried out
- We need a protocol that authenticates the participants at the same time the key is being established
  - such a protocol is called an authenticated key agreement scheme
  - it should simultaneously guarantee secure mutual authentication and secure key computation

Diffie-Hellman Key Exchange

- Authenticated Diffie-Hellman key exchange
  - each user U has a private signing key sk_U and the corresponding public verification key pk_U
  - there is a trusted authority TA that signs keys
  - user U holds a certificate $\mathsf{cert}(U)$ issued by the TA

$$\mathsf{cert}(U) = (U, pk_U, \sigma_{TA}(U, pk_U))$$

  - the protocol is also known as station-to-station key agreement
  - it combines the key exchange with a mutual authentication scheme

Diffie-Hellman Key Exchange

- Authenticated Diffie-Hellman key exchange (simplified)
  - public parameters are as before (G, q, g)
  - Alice chooses random a, computes $x_A = g^a$, and sends $\mathsf{cert}(A)$ and x_A to Bob
  - Bob chooses random b, computes

    $$x_B = g^b,\ k = (x_A)^b = g^{ab}\ \text{, and}\ \ y_B = \sigma_B(A||x_B||x_A)$$

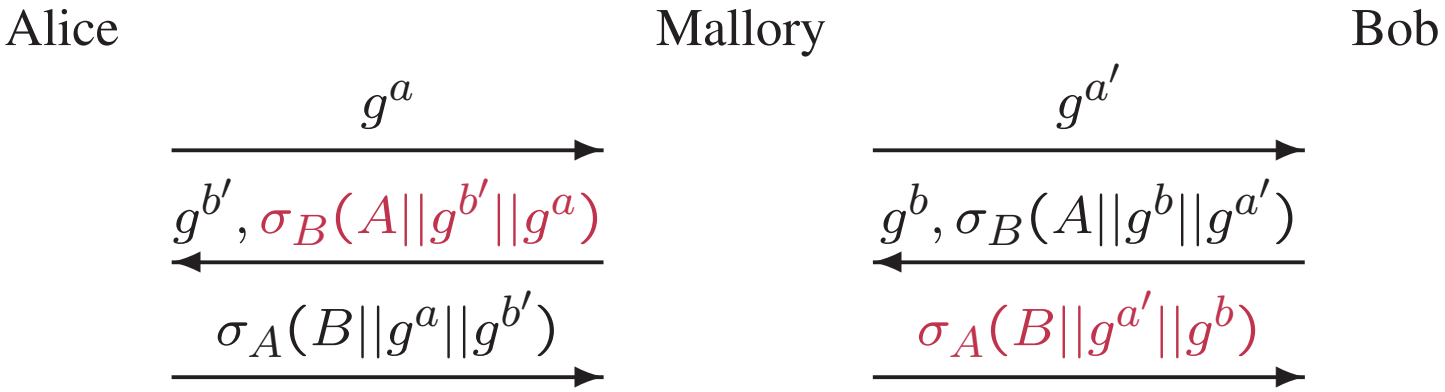
    and sends $\mathsf{cert}(B)$, x_B, and y_B to Alice
  - Alice verifies y_B; if the signature is valid, she computes

    $$k = (x_B)^a = g^{ab}\ \text{ and }\ y_A = \sigma_A(B||x_A||x_B)$$

    and sends y_A to Bob
  - Bob verifies y_A; if the signature is valid, he accepts

Diffie-Hellman Key Exchange

- Security of authenticated Diffie-Hellman
  - the man-in-the-middle attack on DH key exchange no longer works
  - what happens now is:



  - Mallory cannot forge Alice's and Bob's signature, so she cannot be successful

Diffie-Hellman Key Exchange

- Security of authenticated Diffie-Hellman
  - this protocol is a secure mutual identification scheme
    - this can be proven using the security definitions for mutual authentication
  - if an adversary is active, this will be detected by the participants
  - if the adversary is passive, both parties will accept with the same key
    - the adversary cannot compute any information about the key assuming that the DDH problem is hard

Diffie-Hellman Key Exchange

- Let's look at the level of assurance Alice and Bob receive
  - Alice accepts after sending g^a and receiving $\sigma_B(A||g^b||g^a)$ back
    - Alice is confident that she is really communicating with Bob
    - if Bob followed the instructions, he will be able to compute the key
    - Alice is confident that Bob can compute g^{ab} because g^a and g^b were in Bob's signature
  - Bob accepts after sending $\sigma_B(A||g^b||g^a)$ to Alice and receiving $\sigma_A(B||g^a||g^b)$ back
    - the analysis is similar for Bob, except that he knows that Alice already accepted
  - when Alice accepts, she doesn't know whether Bob will accept

Key Agreement Schemes

- We can define different levels of assurance that Alice (or Bob) obtain during a key exchange protocol
  - implicit key authentication is provided if A is assured that noone other than B can compute the key
  - implicit key confirmation is provided if A is assured that B can compute the key and noone else can
  - explicit key confirmation is provided if A is assured that B computed the key and noone else can compute it
- Authenticated Diffie-Hellman provides implicit key confirmation to both parties
- Kerberos and Needham-Schroeder provide explicit key confirmation

Key Agreement Schemes

- We might want to consider possible influence that different sessions can have on each other in real life usage
- We'll next look at security under a known session key attack
  - Mallory observes several sessions with different users (which can involve Mallory as well) of her choice
  - Mallory is able to compromise session keys associated with some of the observed sessions of her choice
  - Mallory is then asked to recover the key for a challenge session

Key Agreement Schemes

- Consider the authenticated Diffie-Hellman protocol
  - Mallory observes values g^a and g^b (and signatures)
  - Mallory is also allowed to ask for $k = g^{ab}$
  - we allow Mallory to ask for a key even if she cheats in a protocol
    - suppose Mallory is engaging in a key exchange with Bob
    - Mallory picks a random h sends it to Bob (i.e., $h = g^x$ s.t. Mallory doesn't know x)
    - Bob sends g^b back (and they send signatures)
    - Mallory is still allowed to ask for the key $k = h^b$

Key Agreement Schemes

- Known session key attack on authenticated Diffie-Hellman
  - this key exchange protocol is secure against the known session key attack
  - intuition:
    - the values g^a, g^b are chosen anew for each session
    - they are not related to previous sessions or the long-term keys of the participants
  - it is computationally infeasible, given g^a and g^b, to compute any information about g^{ab}

Key Agreement Schemes

- Perfect forward secrecy
  - this property means that compromise of long-term key does not compromise past session keys
  - suppose Mallory records sessions between Alice and Bob and somehow gets ahold of Alice's secret signing key
  - this property requires that Mallory cannot recover session keys for Alice's expired session
    - an expired session is a session for which Alice erased all information used to generate the session key k
    - what is this information in authenticated Diffie-Hellman?

Key Agreement Schemes

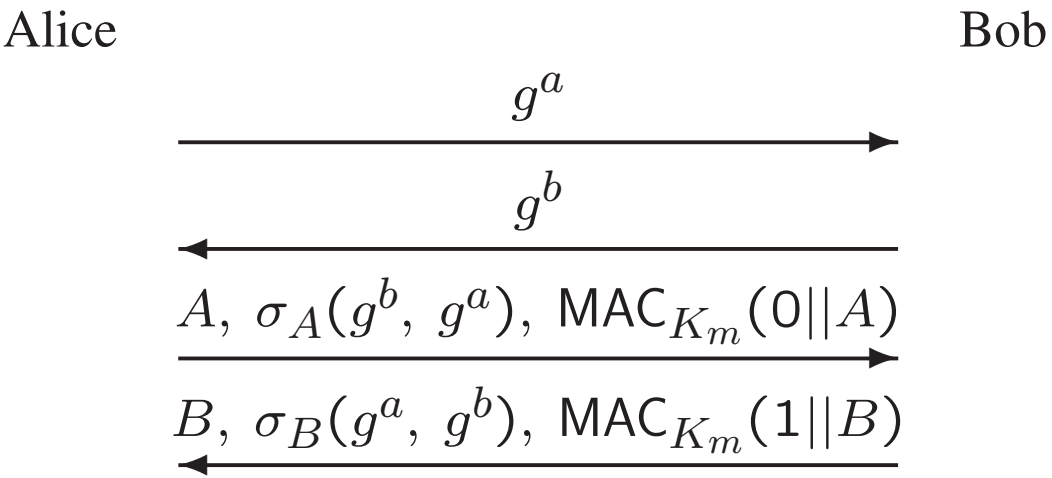
- Perfect forward secrecy (cont.)
  - where do we stand with respect to authenticated Diffie-Hellman key exchange?
  - in authenticated Diffie-Hellman protocol, session keys are independent of long-term keys
  - it achieves perfect forward secrecy
- We arrive at the following conclusion:
  - authenticated Diffie-Hellman key agreement scheme is an authenticated key agreement scheme secure against known session key attacks and achieving perfect forward secrecy
  - now this is the standard security requirement for key exchange protocols

Key Agreement Schemes

- There are different versions of authenticated DH key exchange
- We'll study SIGMA next
  - SIGMA is signature-based authenticated key exchange
  - it stands for SIGn-and-MAc
  - it has been formally analyzed and proven secure
  - it has been standardized as the main protocol in Internet Key Exchange (IKE) version 1 and 2 (RFCs 2409 and 4306, respectively)
- As before, assume that Alice and Bob want to agree on a session key
- Each of them hold a private signing and a public verification key

SIGMA Key Exchange

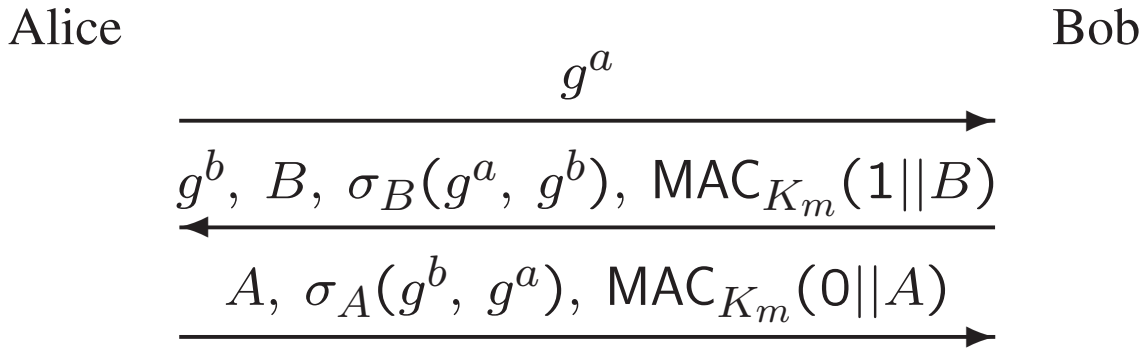
- SIGMA key exchange



  - here $K_m = h(g^{ab})$ is a hash of g^{ab}
  - the sender includes 0 in the MAC, and the responder includes 1
  - the purpose of the MAC is to prevent the identity misbinding attack
  - also notice that the identity of the peer is never signed

SIGMA Key Exchange

- There is a 3-message variant of the protocol
  - the 4-message SIGMA is called SIGMA-R and the 3-message variant is called SIGMA-I
  - SIGMA-I can be obtained by reverting the order of the 3rd and 4th messages



  - this has advantage of identity protection if the last two messages are encrypted
    - g^a and g^b are then used to compute such an encryption key

Key Agreement Schemes

- Another rather new standardized key exchange protocol is SKEME
  - it is based on public-key encryption instead of signatures
  - it also uses MAC
  - it was introduced because of its deniability property
- Deniability provides a way to deny participation in a key exchange (and the consecutive encrypted conversation)
  - authenticated Diffie-Hellman is not deniable
  - SIGMA provides limited deniability
  - SKEME is fully deniable

Key Agreement Schemes

- All protocols so far relied on the use of public keys and certificates
- What happens if there is no public-key infrastructure and instead two users share a password?
  - a password can often be shared between a user and a server
  - the password is likely to be too short to be used as a good cryptographic key
- How can we establish a session key then?
  - one suggestion is to encrypt the session key with the password
  - i.e., Alice chooses a new key k and sends $\mathsf{Enc}_{pwd}(k)$ to Bob
  - Bob decrypts and they start sending messages encrypted with k

Key Agreement Schemes

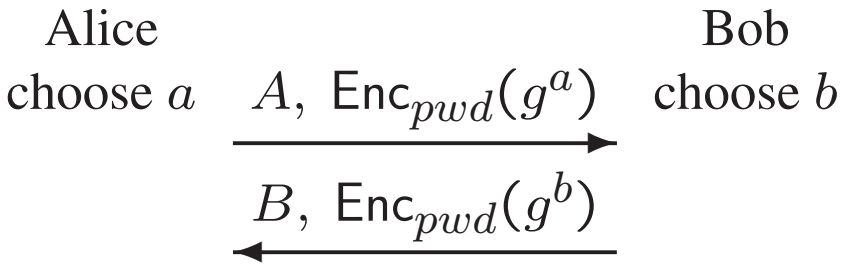
- Password-based key establishment
  - unfortunately, since the password is short, Mallory can try all possibilities
  - Mallory saves $x = \mathsf{Enc}_{pwd}(k)$ and $y = \mathsf{Enc}_k(m)$
  - she computes $k' = \mathsf{Dec}_{pwd}(x)$ and $m' = \mathsf{Dec}_{k'}(y)$ for each possible password pwd
  - since m normally contains redundancy, Mallory will be able to tell when a match is found
  - Mallory now can impersonate the user or read all communication
- It is still possible to securely encrypt data during the key agreement
  - such schemes are called Encrypted Key Exchange (EKE)

Key Agreement Schemes

- We'll look at the simplified Bellovin-Merritt protocol obtained from DH key exchange
- Bellovin-Merritt EKE2
  - public parameters consist of a group G and element $g \in G$
  - Alice and Bob share a secret password pwd
  - Alice picks a and Bob picks b, and the session key is $k = g^{ab}$
  - the difference from previous solutions is that values g^a and g^b are encrypted using the password during the transmission

Bellovin-Merritt EKE

- Bellovin-Merritt EKE2



  - each of them decrypt the messages received and compute the shared key $k = g^{ab}$
  - authentication is not used, but encryption prevents an adversary from carrying out a successful attack
    - Alice knows that knowledge of g^a is required to construct the key
    - the only person who knows the decryption key is Bob

Bellovin-Merritt EKE

- Bellovin-Merritt EKE2
  - the above analysis assumes that the password is not known to other parties
  - it is also assumed that an adversary cannot compute any information about the password
  - consider the previous brute force search attack
    - before attacker could test all possible passwords because he would know when a match occurred
    - now the password is used to encrypt g^a and g^b, while a different value g^{ab} is used for encryption of messages themselves
  - even if the value of a past session key is known to the attacker, the password remains secure

Summary

- There are many key exchange protocols, many of which are based off of the Diffie-Hellman key exchange
- The properties that are essential
  - secure mutual authentication
  - secure key computation
  - resilience to known session key attack
  - perfect forward secrecy
- Deniability can be important as well