ECE 443/518 – Computer Cyber Security
Lecture 10 Diffie-Hellman and Man-in-the-Middle Attack

Professor Jia Wang
Department of Electrical and Computer Engineering
Illinois Institute of Technology

September 26, 2022

Outline

Reading Assignment

- This lecture: UC 8.1,8.5,13.3.1
- Next lecture: UC 10.1 – 10.3

Midterm Exam

- Lecture 1 $\sim$ Lecture 13
- Students registered for main campus section: Wed. 10/12, 11:25 AM – 12:40 PM, in class.
  - A physical calculator is allowed. Laptop or any other electronic device or calculator apps running on them are not allowed.
  - Closed book/notes. A letter-size page of cheat sheet is allowed.
- Students registered for online sections: contact Charles Scott, scott@iit.edu, from the Center of Learning Innovation to make arrangement, and confirm with me.
  - No make-up exam will be offered if you fail to do so.
  - You may confirm with me directly if you plan to take the exam with the main campus section as mentioned above.
- 100+20 points
  - See Homework 2 and 3 for sample questions.
  - You are required to show steps of calculations.
  - Points may be deducted if key steps are missing even if the answers are correct.
- Emergency/extraordinary reasons for make-up midterm exams are accepted only with documented proof like docter's notes.

Outline

Diffie-Hellman Key Exchange

Man-in-the-Middle Attack

Perfect Forward Secrecy (PFS)

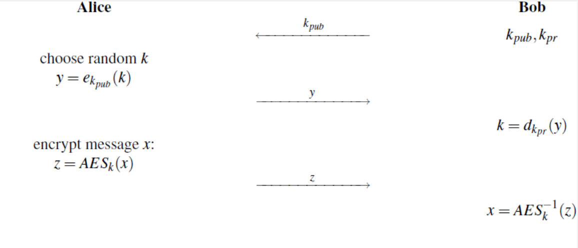

Fig. 6.5 Basic key transport protocol with AES as an example of a symmetric cipher

(Paar and Pelzl)

- Oscar, realizing there is no hope to factor every n for RSA, decided to build a machine to factor a few n's he/she might be interested of.
  - Oscar has recorded all communications encrypted using the simple hybrid protocol.
- How could Bob could protect k's if k_{pr} is compromised?
  - Will it help if Alice/Bob generates another RSA key-pair randomly per communication?

History of Diffie-Hellman Key Exchange

- 1976: created by Whitfield Diffie and Martin Hellman
  - First public-key algorithm in open literature.
- 1977: patent granted in US
- 2005: variants are included in NSA Suite B Cryptography
  - Together with AES and SHA-2

DHKE

Diffie–Hellman Key Exchange

Alice		Bob
choose $a = k_{pr,A} \in \{2, \ldots, p-2\}$		choose $b = k_{pr,B} \in \{2, \ldots, p-2\}$
compute $A = k_{pub,A} \equiv \alpha^a \bmod p$		compute $B = k_{pub,B} \equiv \alpha^b \bmod p$
	$\xrightarrow{k_{pub,A}=A}$	
	$\xleftarrow{k_{pub,B}=B}$	
$k_{AB} = k_{pub,B}^{k_{pr,A}} \equiv B^a \bmod p$		$k_{AB} = k_{pub,A}^{k_{pr,B}} \equiv A^b \bmod p$

(page 207, Paar and Pelzl)

- DHKE setup
  - A large prime p and an integer α chosen from $2, 3, \ldots, p-2$.
  - Usually chosen/published by a well-known entity and used by a large group of people.
- Key exchange: upon completion, a shared secret k_{AB} is established between Alice and Bob.
  - Assume one of the public key is sent over an authentic channel.
- Time complexity: $O(N^3)$.

Example

- $p = 29, \alpha = 2$.
- Alice: $k_{pr,A} = 5$
  - $k_{pub,A} = 2^5 \bmod 29 = 3$
- Bob: $k_{pr,B} = 12$
  - $k_{pub,B} = 2^{12} \bmod 29 = 7$
- Alice: $k_{AB} = (k_{pub,B})^{k_{pr,A}} \bmod p = 7^5 \bmod 29 = 16$
  Bob: $k_{AB} = (k_{pub,A})^{k_{pr,B}} \bmod p = 3^{12} \bmod 29 = 16$

The Discrete Logarithm Problem

Given a prime number p, an integer $\alpha \in \{2, 3, \ldots, p-2\}$, and an integer B, solve for an integer b,

$$\alpha^b \equiv B \pmod{p}.$$

- A passive adversary may obtain $k_{pr,B}$ and then k_{AB}.
- Brute-force: compute $\alpha^k \bmod p$ for $k = 1, 2, \ldots, p-1$
  - Time complexity: $O(2^N N^2)$.
- Better algorithm exists, but still of exponential time.
- The Diffie-Hellman problem: compute $\alpha^{ab} \bmod p$ given $\alpha^a \bmod p$ and $\alpha^b \bmod p$ with α and p known.
  - It is unknown if this could be done without solving discrete logarithm first.
  - DHKE is believed to be secure for large enough N.
- Will Alice be able to learn Bob's private key?

The Elgamal Encryption Scheme

- An extension of DHKE for encryption.
- After successfully completing DHKE, Alice sends $y = k_{AB}x \bmod p$ to Bob.
  - Plaintext $x \in \{1, 2, \ldots, p-1\}$
  - Ciphertext $y \in \{1, 2, \ldots, p-1\}$
- Bob decrypts y by solving $k_{AB}x \equiv y \pmod{p}$ for x via EEA or other algorithms.
- Ephemeral keys: k_{AB} should be used only once.
  - A passive adversary who learned a pair of x and y could solve $k_{AB}x \equiv y \pmod{p}$ for k_{AB} and decrypts all other ciphertext with the same k_{AB}.

Elgamal Encryption Protocol

Elgamal Encryption Protocol

Alice		**Bob**
		choose large prime p choose primitive element $\alpha \in \mathbb{Z}_p^*$ or in a subgroup of $\mathbb{Z}_p^*$ choose $k_{pr} = d \in \{2, \ldots, p-2\}$ compute $k_{pub} = \beta = \alpha^d \bmod p$
	$\xleftarrow{k_{pub}=(p,\alpha,\beta)}$	
choose $i \in \{2, \ldots, p-2\}$ compute ephemeral key $k_E \equiv \alpha^i \bmod p$ compute masking key $k_M \equiv \beta^i \bmod p$ encrypt message $x \in \mathbb{Z}_p^*$ $y \equiv x \cdot k_M \bmod p$		
	$\xrightarrow{(k_E,y)}$	
		compute masking key $k_M \equiv k_E^d \bmod p$ decrypt $x \equiv y \cdot k_M^{-1} \bmod p$

(page 228, Paar and Pelzl)

- Rearrange messages: Elgamal looks very similar to RSA
  - Assume Bob's public key is sent over an authentic channel.
  - Alice's message could be sent over an insecure channel.
  - Need padding for similar reasons as RSA.

DHKE vs. RSA

- Good alternatives of each other.
  - Their security depends on different problems that we don't know how to solve efficiently yet.
  - While DHKE was originally designed for key exchange, its variants can match with the functionalities provided by RSA.
- Both DHKE and RSA may need an authentic channel for communicating a public key.
- In practice, both DHKE and RSA use keys a few thousand bits long to be secure.
- DHKE can be generalized to other mathematical structures.
  - E.g. elliptic-curve cryptography (ECC), which requires much less bits to achieve same level of security as DHKE, and is widely adopted currently.

Outline

Diffie-Hellman Key Exchange

Man-in-the-Middle Attack

The Authentic Channel

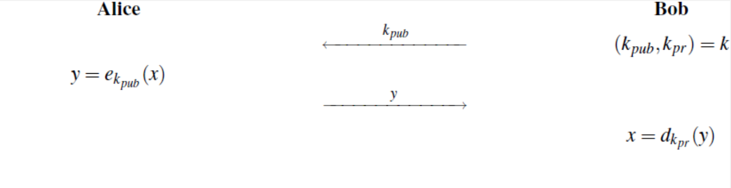

Fig. 6.4 Basic protocol for public-key encryption

(Paar and Pelzl)

- We do see how RSA and DHKE (Elgamal) both use the above protocol for public key encryption.
- Both require Alice to receive Bob's public key on an authentic channel.
  - What if not?

Man-in-the-Middle Attack

- Assume Bob's public key $k_{pub,B}$ is sent through an insecure channel.
- Oscar the active adversary replaces $k_{pub,B}$ that Alice receives.
  - With Oscar's public key $k_{pub,O}$.
- Alice receives $k_{pub,O}$ and encrypts x as $y = e_{k_{pub,O}}(x)$.
- Oscar replaces y that Bob receives.
  - With $y' = e_{k_{pub,B}}(x)$.
  - Note that Oscar simply decrypts y to obtain x since y is encrypted with $k_{pub,O}$: $x = d_{k_{pr,O}}(y)$.
- Man-in-the-Middle: Oscar sits between Alice and Bob, and replaces all messages on either direction.
  - Neither Alice and Bob will be able to detect it!

Man-in-the-Middle and DHKE

Man-in-the-Middle Attack Against the DHKE

Alice	**Oscar**	**Bob**
choose $a = k_{pr,A}$		choose $b = k_{pr,B}$
$A = k_{pub,A} \equiv \alpha^a \bmod p$		$B = k_{pub,B} \equiv \alpha^b \bmod p$
$\xrightarrow{A}$	$\lightning$ substitute $\tilde{A} \equiv \alpha^o$	$\xrightarrow{\tilde{A}}$
$\xleftarrow{\tilde{B}}$	$\lightning$ substitute $\tilde{B} \equiv \alpha^o$	$\xleftarrow{B}$
$k_{AO} \equiv (\tilde{B})^a \bmod p$	$k_{AO} \equiv A^o \bmod p$ $k_{BO} \equiv B^o \bmod p$	$k_{BO} \equiv (\tilde{A})^b \bmod p$

(Paar and Pelzl)

- This attack also applies to the original DHKE assuming both Alice and Bob's public keys are not sent via an authentic channel.
  - Oscar then have two secret keys, one with Alice and one with Bob, that can be used for any following communications.
- What if, as originally assumed, one of Alice and Bob's public keys is sent via an authentic channel?
- Does man-in-the-middle attack apply to symmetric ciphers?

Identity

- The problem of man-in-the-middle attack is with identity.
  - Alice sees Oscar as Bob.
  - Bob sees Oscar as Alice.
- The authentic channel authenticates that a public key belongs to a particular identity.
  - To create an authentic channel, we need to study how to establish identity – who is Bob?
- Can we establish identity without the authentic channel?
  - Yes if the public key is the identity, but how?
  - Note that in a successful man-in-the-middle attack, communications between Alice and Oscar is secure against any third party including Bob, and communications between Oscar and Bob is secure against any third party including Alice.

Summary

- DHKE
  - Setup: prime p, $\alpha \in \{2, 3, \ldots, p-2\}$.
  - Alice: $k_{pr,A}$, publish $k_{pub,A} = \alpha^{k_{pr,A}} \bmod p$
  - Bob: $k_{pr,B}$, publish $k_{pub,B} = \alpha^{k_{pr,B}} \bmod p$
  - Alice and Bob: $k_{AB} \equiv (k_{pub,B})^{k_{pr,A}} \equiv (k_{pub,A})^{k_{pr,B}} \pmod{p}$
  - Assumption: Oscar cannot solve $\alpha^b \equiv B \pmod{p}$ for b in polynomial time.
- Man-in-the-Middle attack