MANCHESTER 1824

The University of Manchester

Topic 6: Secret Key Management

Understand crypto secret key management issues and their distribution methods

Source: Main textbook: 20.6, 21.5

Some slides are based on the slides by Lawrie Brown prepared for the text book

Overview

- Key Management Issues
- Symmetric Key Establishment
  - Symmetric Key Agreement: Diffie-Hellman (DH) algorithm/protocol
  - Symmetric Key Distribution
    - using symmetric key encryption
    - using public-key encryption
- Conclusion

Key Management Issues

- Key management is the hardest part of cryptography
  - How should keys be generated so that they can not be easily guessed?
  - How to securely store keys so that they can not be easily stolen?
  - How could keys be delivered to their intended recipients securely?
  - How could two entities agree on, or establish, a key securely?
  - How are keys revoked and replaced?
  - ‘People’ and ‘management’ are at the centre of some of these issues
- For symmetrical ciphers - how to keep keys **secret**?
- For public-key ciphers - how to ensure private key secret and public keys **trust-worthy**?

Key Management Issues - Keys spaces

- Number of possible keys (key space) given various constraints:

	6-bytes	8-bytes
Lowercase letters(26)	$3.1*10^8$	$2.1*10^{11}$
Lowercase letters & digits (36)	$2.2*10^9$	$2.8*10^{12}$
Alphanumeric characters (62)	$5.7*10^{10}$	$2.2*10^{14}$
Printable characters (95)	$7.4*10^{11}$	$6.6*10^{15}$
ASCII characters (128)	$4.4*10^{12}$	$7.2*10^{16}$

Key Management Issues - Keys spaces

- Exhaustive search (assume 10^6 attempts/second):

	6-bytes	8-bytes
Lowercase letters(26)	5 minutes	2.4 days
Lowercase letters & digits (36)	36 minutes	33 days
Alphanumeric characters (62)	16 hours	6.9 years
Printable characters (95)	8.5 days	210 years
ASCII characters (128)	51 days	2300 years

Key Management Issues - Keys spaces

- **Main points**
  - Giving various constraints on the input string can greatly reduce the number of possible keys (key space), making ciphertexts much easier to break!
  - Computer power increases all the time ...
    - If you expect your keys to stand up against brute-force attacks for 10 years, plan accordingly.

Key Management Issues – Key generation

- Good keys are random numbers.
- Users tend to choose less random keys.
- Which of these keys is more random (more difficult to guess) - *Barney1* or **9(hH/A*?
- Remember: a smart brute-force attacker doesn't try all possible keys in numeric order; he will try the obvious ones first.

- What is a random number?
  - Given an integer, k>0, and a sequence of numbers, n_1, n_2, …, an observer can not predict n_k even if all of n_1, …, n_{k-1} are known.

Key Management Issues - Key generation

- Ordinary random number generation functions, e.g. `java.util.Random`, is <u>not</u> good enough for this purpose.
- Use a cryptographically secure pseudo-random-number generator, e.g. `SecureRandom` class in `java.security` package, or a reliably random source.

- Physical sources of random numbers
  - Based on nondeterministic physical phenomena, e.g. atmospheric noise,
  - stock market data, etc.

Key Management Issues - Key generation

- Some pseudo-random numbers are generated from a strong mixing function
  - that takes two or more inputs having some randomness (e.g. CPU load, arrival times of network packets), but produces an output each bit of which depends on some nonlinear function of all the bits of the inputs.
  - Cryptographic hashing functions and encryption algorithms (e.g. MD5, SHA3 and AES) are examples of the strong mixing function.

- For example, in a UNIX system, you may use the process state at a given time (date ; ps gaux) as the input to a MD5 function to generate a pseudorandom number, where ‘ps gaux’ lists all the information about all the processes on the system.

Key Management Issues - Key storage

- You must protect the key to the same degree as all the data it encrypts.
  - Why would one bother to go through all the trouble of trying to break the cipher system if he can recover the key because of sloppy key storage procedures?
  - Why would one spend $10 million building a cryptanalysis machine if he could spend $1000 bribing a clerk?

Key Management Issues - Key storage

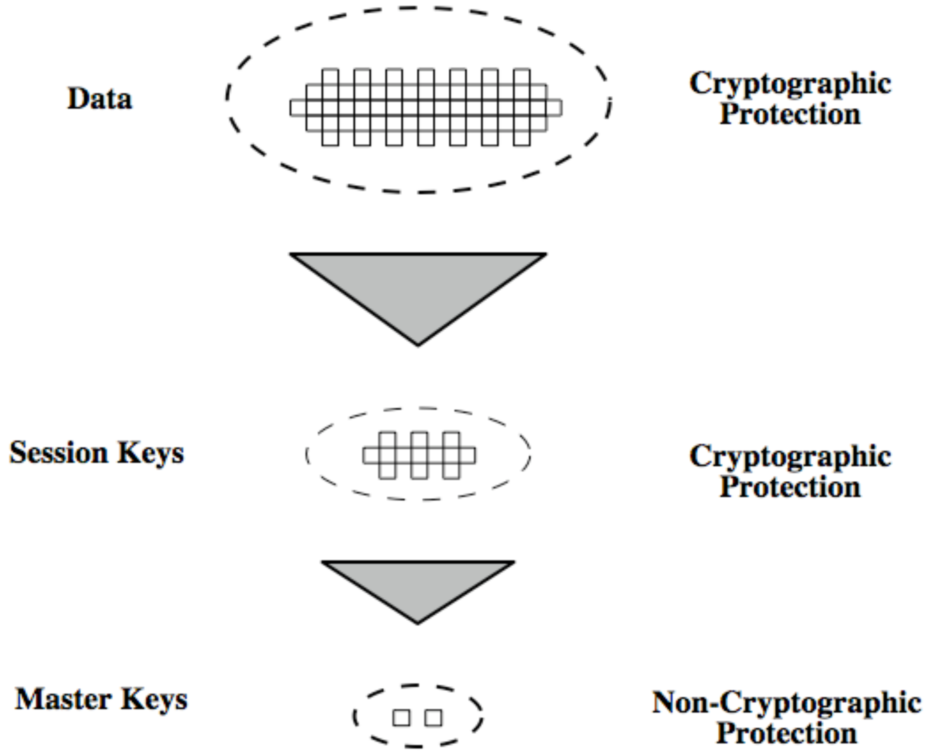
- Attackers may defeat access control mechanisms, so should always encrypt the file containing keys.
- If possible, a key should not come out of the device generating the key.
- A key should never appear unencrypted outside the encryption device.
- Try not to store your key on a medium connected to the network.
- Key may be resident in memory, and attackers may be able to access it via, e.g. malware
  - Use a physical token to store the key (e.g. a smart card) and protect the token with a PIN number.
  - Card can be stolen, so splitting a key into two halves, store
    - one half in the machine, and
    - another half in the card.
- Splitting a key, K, into two halves (k_1, k_2): $k_2 = k_1$ xor K

Key Management Issues – more issues

- Key access to make sure only authorized users could gain access to some specific keys.
- Key updates to ensure key freshness (forward secrecy).
- Key deletions to discard any unrequired keys securely.
- Key usage auditing to ensure keys are used properly and securely.

Key Hierarchy

- Usually there is a key hierarchy
  - Master key/secret (key encryption key)
    - used to establish/distribute session keys
  - Session key (data encryption key)
    - used to encrypt data/message
    - for one logical session only



The University of Manchester

MANCHESTER 1824

Session Keys

- More often a symmetric key is used, more likely it may be compromised.
- Generate and use a symmetric (secret) key for one session only → session key.
- Using different session keys in different sessions can
  - limit available ciphertexts for cryptanalysis.
  - limit exposure (both in time period and amount of data) in an event of key compromise.
- To avoid long-term storage of a large number of secret keys, we only generate them when they are needed.

Session Key Establishment

- Session key establishment solutions
  - Key agreement (exchange) protocols
    - A shared secret (master or session secret) is derived by the parties as a function of information contributed by each, such that no party can predetermine the resulting value - Diffie-Hellman (DH) protocol.
  - Key transportation/distribution protocols
    - Without any use of a public-key cipher (PKC)
      - Session keys are generated and distributed using symmetric-key cipher and with the help of a third party - the Needham-Schroeder protocol.
    - With the use of a public-key cipher
      - One party creates a secret value (session key), and securely transfers it to the other party using the recipient's public key.

MANCHESTER 1824

The University of Manchester

Session Key Establishment

- There are other issues that should be considered
  - Key secrecy and entity/key authentication
    - Assurance: no other party (outsiders - apart from the entities involved) could gain access to the established session key.
    - The session key is established with the intended entities.
    - Key confirmation: asking the other entity (possibly unidentified) to demonstrate that he has the knowledge of the key by
      - producing a one-way hash value of the key; or
      - encrypting some known data (e.g. nonce) with the key.
  - Key freshness
    - Assurance: the key is fresh, i.e. not used before.

Diffie-Hellman Algorithm/Protocol

- DH was the 1st public-key algorithm ever invented - back in 1976.
- DH key exchange protocol allows two parties who have never met before to exchange messages in public and collectively generate a key that is private to them, and none of the parties could predetermine the key.
- Its security is based on the difficulty of calculating discrete logarithms in a finite field.
  - Given integers y and g and prime number n, compute x such that $y = g^x \bmod n$.
  - This is computationally infeasible if n is sufficiently large.

Diffie-Hellman Algorithm/Protocol

- Assuming two parties, *Alice* and *Bob,* take part in the exchange.
- Initial condition
  - *Alice* and *Bob* agree on two large integers, ***g*** and ***n***;
  - *n* - prime number that serves as the modulus.
  - *g* - random number that serves as the basis, with $1<g<n$.
  - *g* and *n* do not have to be secret.
- Definition
  - *Alice* has private key $\boldsymbol{X_a}$, and public key Y_a.
  - *Bob* has private key $\boldsymbol{X_b}$, and public key Y_b.

Diffie-Hellman Algorithm/Protocol

Alice

Generate
Random & private $X_a < n$;
Calculate
Public $Y_a = g^{Xa} \bmod n$

Y_a

Y_b

Calculate
$\mathbf{K_{ab}} = Y_b^{\ Xa} \bmod n$
$= g^{XaXb} \bmod n$

Bob

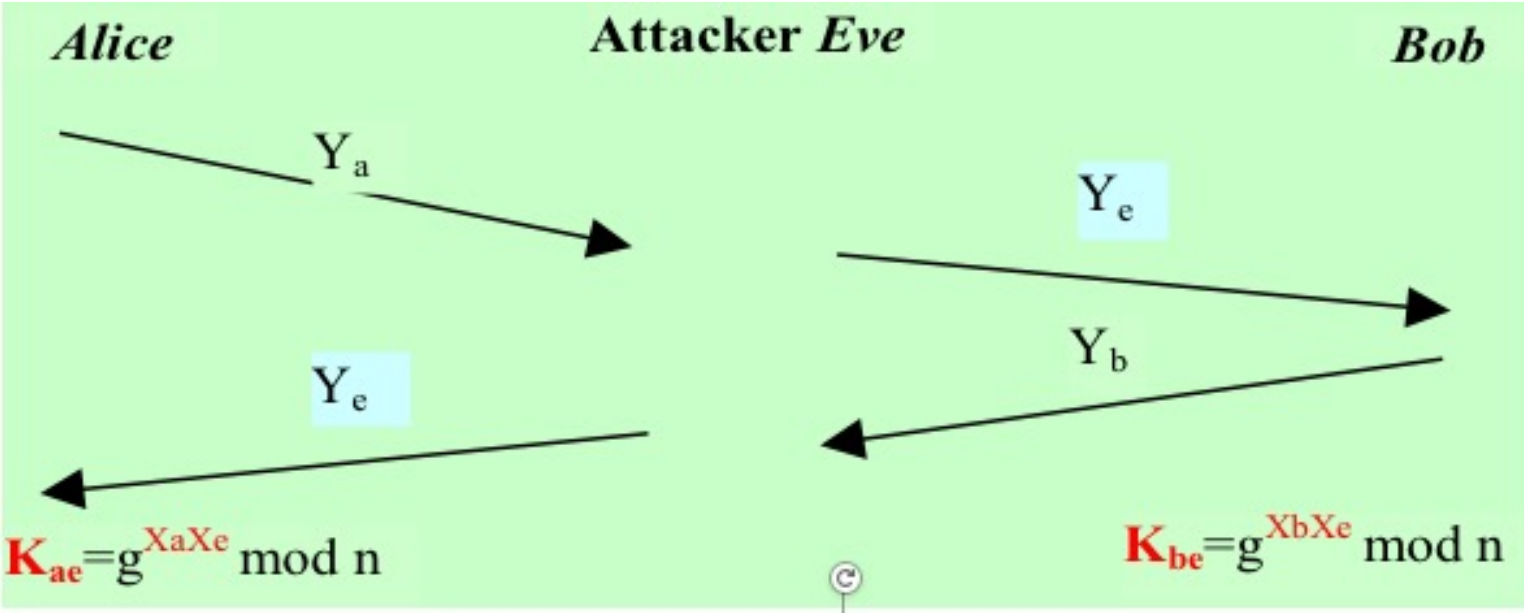
Generate
Random & private $X_b < n$;
Calculate
Public $Y_b = g^{Xb} \bmod n$

Calculate
$\mathbf{K_{ab}} = Y_a^{\ Xb} \bmod n$
$= g^{XaXb} \bmod n$

Diffie-Hellman Protocol

- It resists passive attacks such as eavesdropper, as calculating a discrete logarithm is a computationally hard problem.
- There is one problem - neither party knows who it shares the secret with! So it is vulnerable to active, man-in-the-middle attacks, as to be illustrated shortly.

Diffie-Hellman Protocol - Man-in-the-middle attack



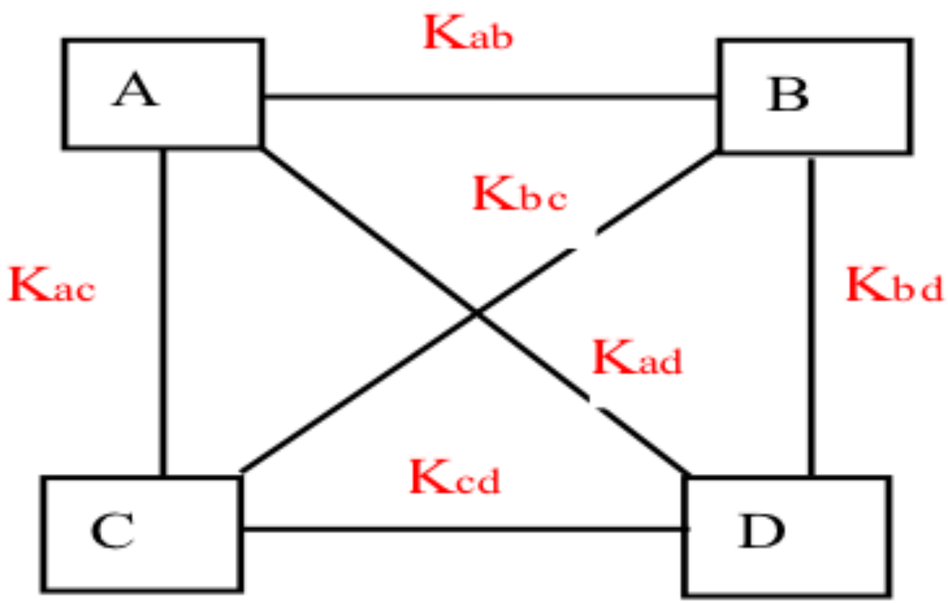
- *Alice* (*Bob*) thought she shares a key with *Bob* (*Alice*), but actually with *Eve*.
- So the attacker *Eve* can intercept and read any messages encrypted without been detected by *Alice* and *Bob* .

Symmetric Key Distribution without using PKC

- Symmetric key distribution using symmetric key encryption - Needham-Schroeder Protocol.
- This protocol is widely used in single sign on (SSO) solutions, e.g. window domain authentication, Kerberos.

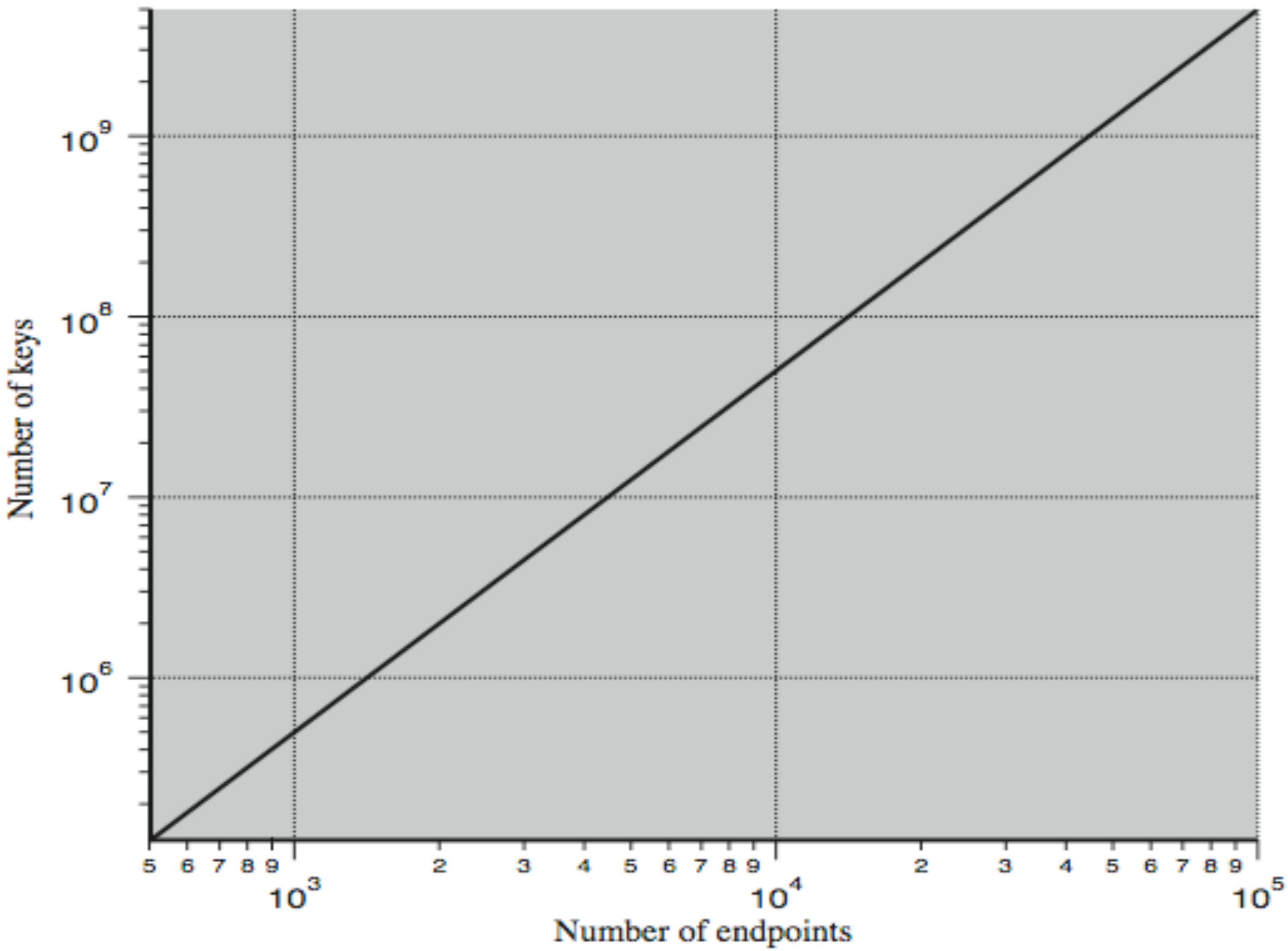
Distribution without using PKC – Approach-One

- *Approach One*: Given n users (parties/nodes) to communicate with each other, the system needs $n(n-1)/2$ keys.
- As n increases, the number of keys becomes untenable for everyone.
- The n^2 problem!



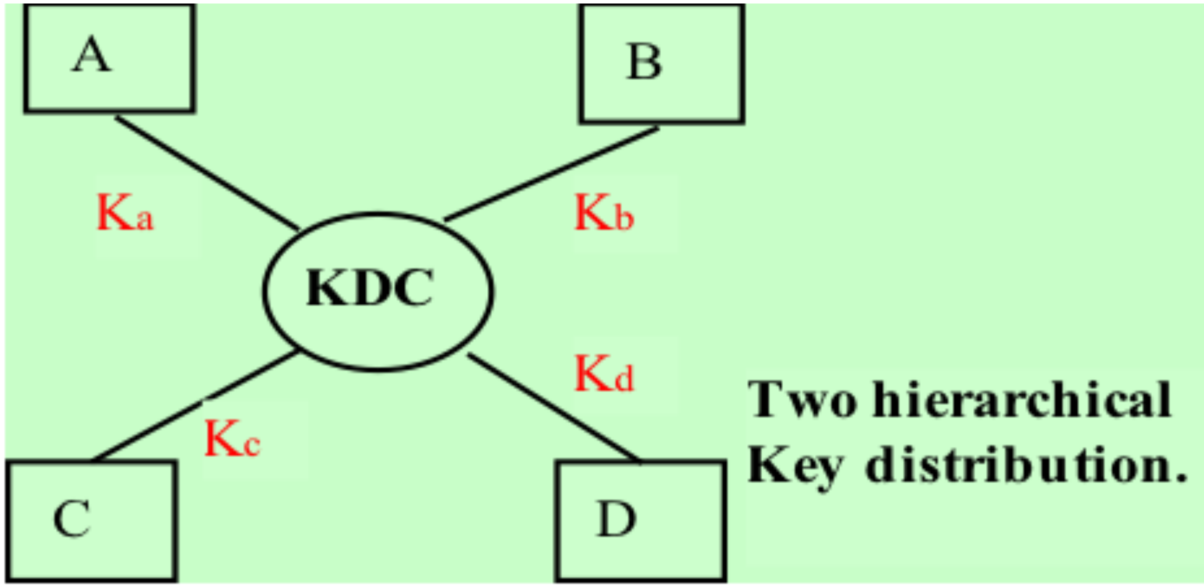
One hierarchical Key distribution.

Distribution without using PKC - Scalability problem



Distribution without using PKC – Approach-Two

- *Approach Two:* use a key distribution centre (*KDC*) or security server.
  - A key hierarchy, e.g. two hierarchical approach - *master keys* (*long-term keys*) and *session keys* (*valid just for one session*).



Distribution without using PKC – Approach-Two

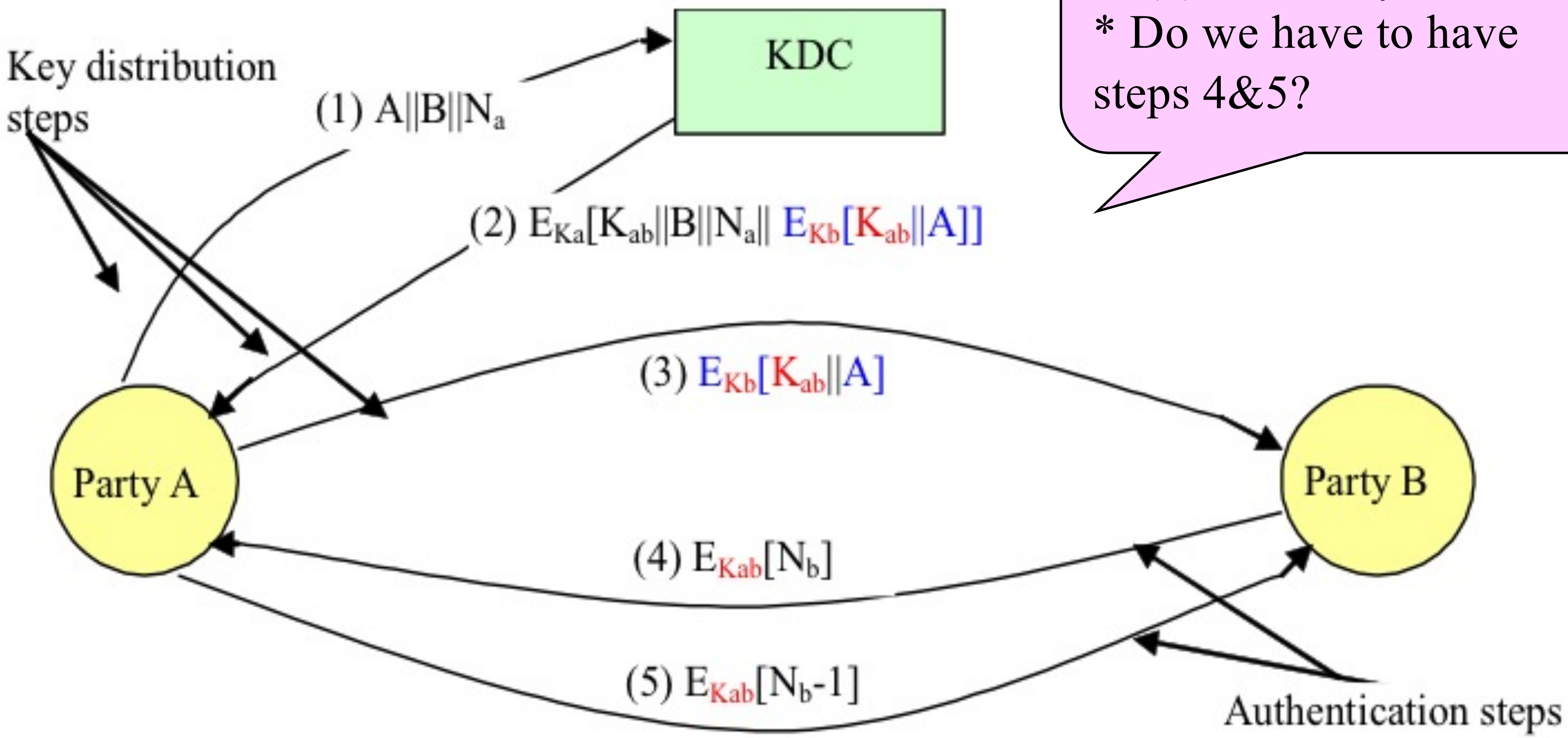
- A unique master key, shared between a pair of user/*KDC*, is for session key distribution.
- A session key is to secure a particular session.
- Benefit of using Approach Two
  - Reduces the scale of the problem - reduces the n^2 problem to an n problem, thus making the system more scalable.
- But:
  - The need to trust the intermediaries - KDC.
    - KDC has enough information to impersonate anyone to anyone. If it is compromised, all the resources in the system are vulnerable.
  - KDC is a single point of failure.
  - KDC may be a performance bottleneck.

Distribution without using PKC - Needham-Schroeder Protocol

- The Needham-Schroeder is a key distribution protocol.
- It uses Approach-Two. That is:
  - both parties, *A* and *B*, shares a secret key with the KDC, K_a and K_b ;
  - *A* and *B* wishes to establish a secure communication channel, i.e. establish a shared one-time session key K_{ab}, for use between *A* and *B* in this session.
- N_a, N_b are nonces (random challenges), generated by *A* and *B* respectively, to keep messages fresh.

Distribution without using PKC - Needham-Schroeder Protocol

*Is the nested encryption in (2) necessary?
* Do we have to have steps 4&5?



MANCHESTER 1824

The University of Manchester

Distribution without using PKC - Needham-Schroeder Protocol

(1) A sends a request to *KDC* for a session key to establish a secure channel with *B*.

(2) KDC generate a random number K_{ab}, and replies with the response containing

- session key K_{ab}.
- original request enables A matching the response with the request.
- an item (the session key and A's identity) which only *B* can view.

(3) A forwards the item to *B*.

At this point, the session key is securely delivered to A and B, and they may begin secure communication.

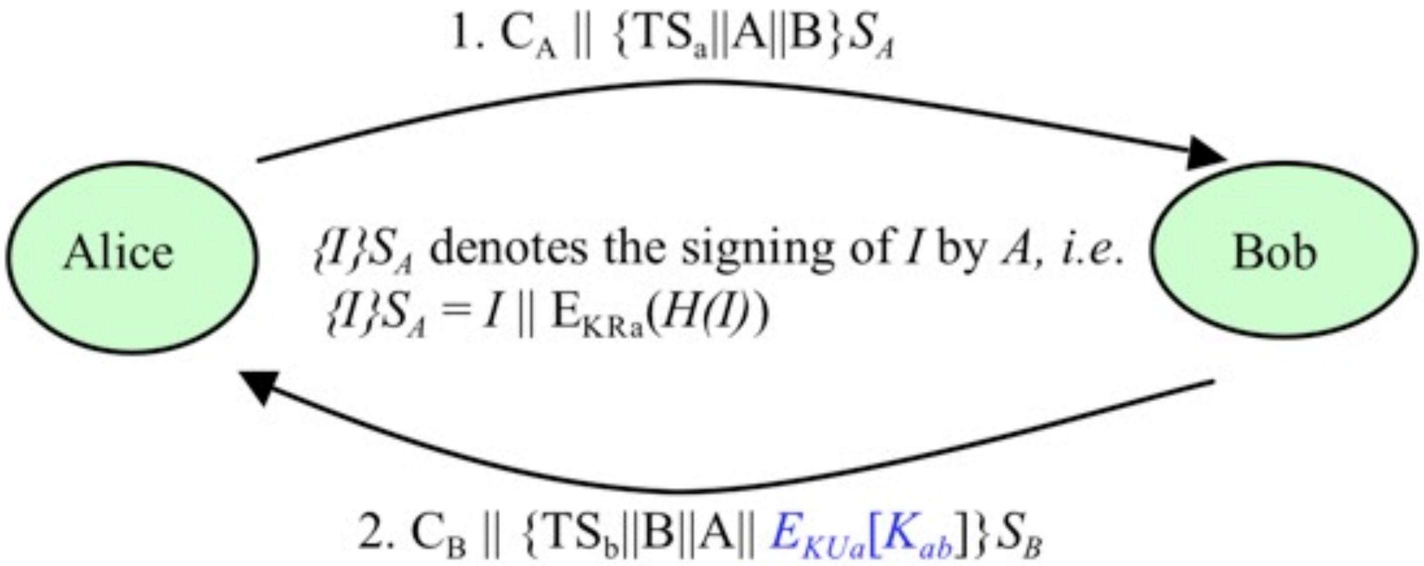
(4) B sends a nonce N_b to *A* encrypted using the new session key.

(5) A responds with N_b-1.

Steps (4) & (5) assure B that the message received in (3) was not a replay, i.e. to authenticate A.

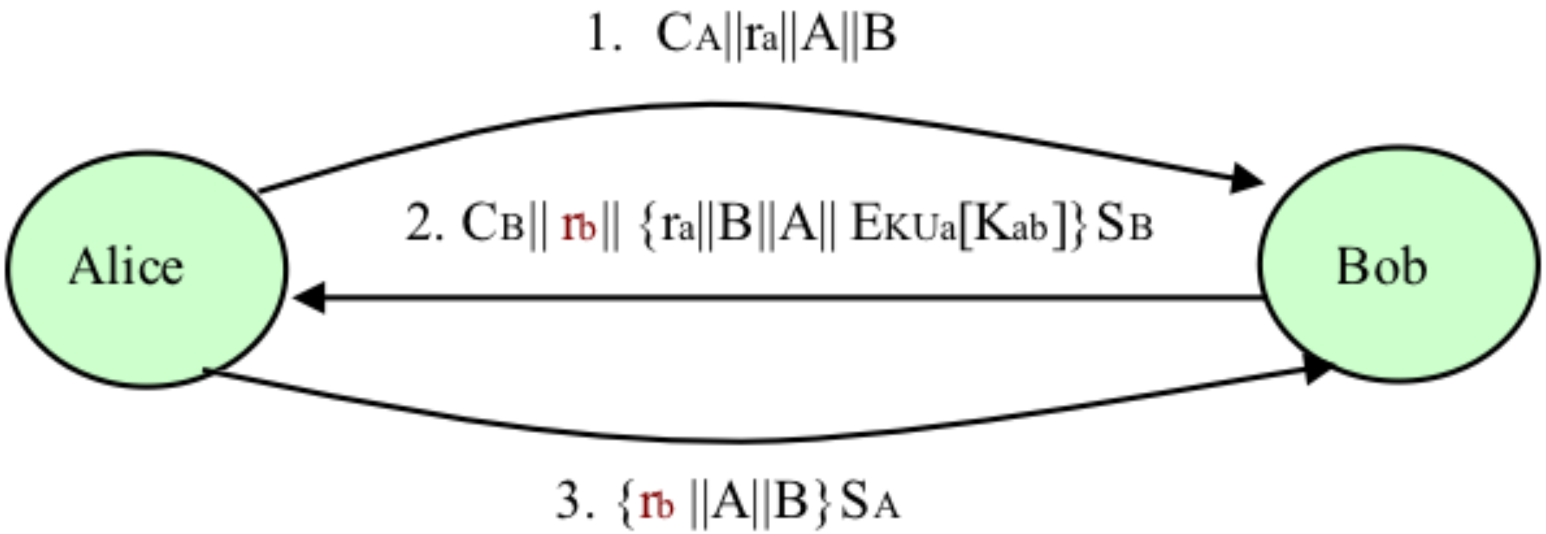
Symmetric Key Distribution using PKC – Two passes

- Secret key distribution with mutual authentication using public key cipher + timestamps. C_A and C_B are, respectively, Alice's and Bob's certificates.



Symmetric Key Distribution using PKC - Three passes

- Symmetrical key distribution with mutual authentication using public key cipher + nonces (random numbers).
- In both of these two protocols, entity authentication is done by using digital signatures.



The University of Manchester

MANCHESTER 1824

A summary of symmetric key (session key, secret key) establishment protocols

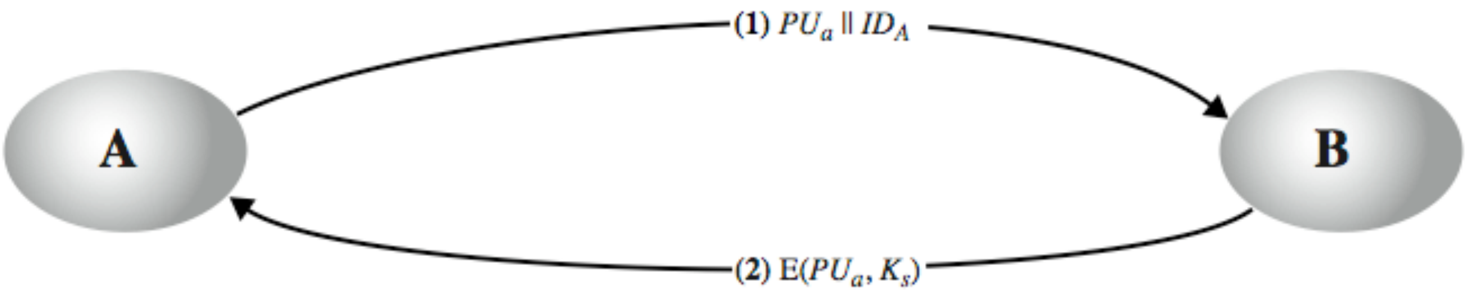
Protocols	ThirdParty	Timestamps	EntityAuth	messages
Diffie-Hellman	No	No	None	2
Needham-Schroeder protocol	KDC (online)	No	Symmetric encryption	5
X.509 (2 pass)	CA (offline)	Yes	mutual	2
X.509 (3 pass)	CA (offline)	No, but with nonce	mutual	3

Exercise Question – E6.1

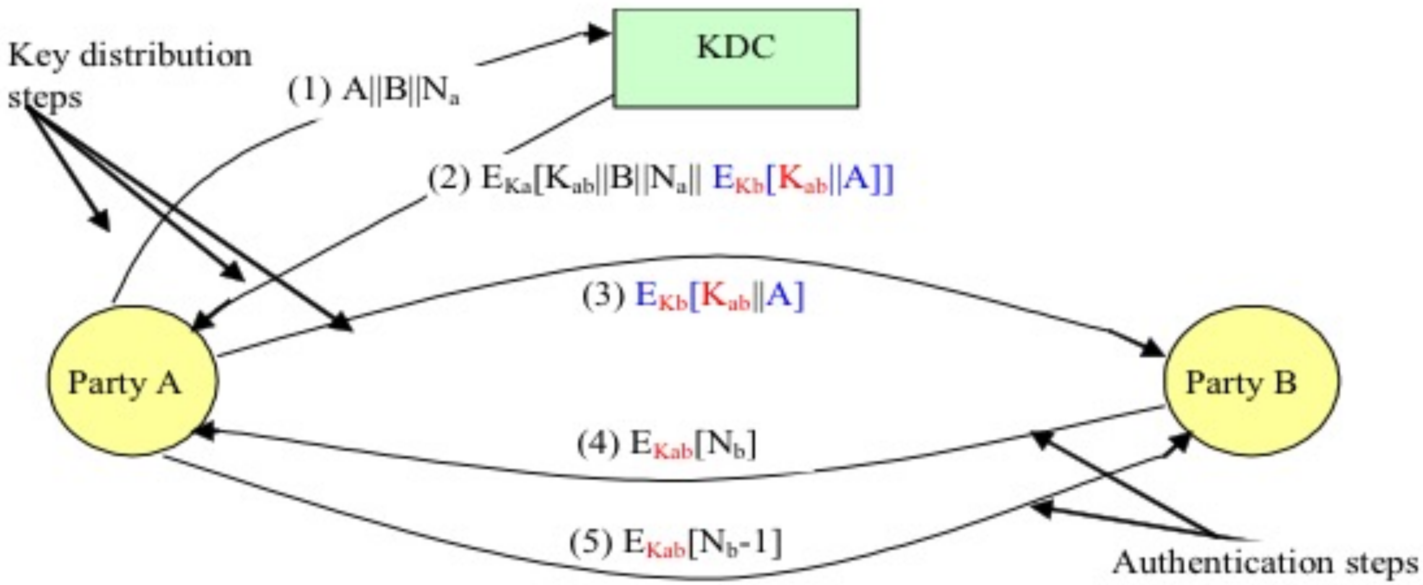
Assuming that Alice is to send a message, *M*, to Bob. *M* is encrypted with a shared key established using the DH protocol. Explain whether Eve could access this message *M*. If so, explain how, and propose a solution to address this vulnerability.

Exercise Question – E6.2

- The following is an extremely simple protocol proposed for symmetric key distribution. It is assumed that A and B has never met before (or there is no key established prior to this communication).
  - Identify as many problems/flaws as you can.
  - Modify the protocol to fix the problems/flaws you have identified.



Exercise Question – E6.3



This is the Needham-Schroeder protocol. Answer the following questions:

i. What are the benefits for A to forward the session key to B (i.e. step 3), rather than letting KDC to directly send the session key to B?

ii. TRY to identify two application areas of the Needham-Schroeder protocol and to elaborate the benefits of using the Needham-Schroeder protocol in these application areas.

MANCHESTER
1824

The University of Manchester

Conclusions

- Key management encompasses a number of critical issues to the effective use of cryptosystems.
- A number of protocols exist to support symmetrical key distribution and agreement.
  - Key transport protocols
    - One party creates or otherwise obtains a secret value, and securely transfers it to the other party.
  - Key agreement protocols
    - A shared secret is derived by the parties using information contributed by each, such that no party can predetermine the resulting value.
- Key agreement/distribution protocols can be vulnerable to security attacks, such as the man-in-the-middle and replay attacks, so they should be used with care.