Understanding Cryptography

by Christof Paar and Jan Pelzl

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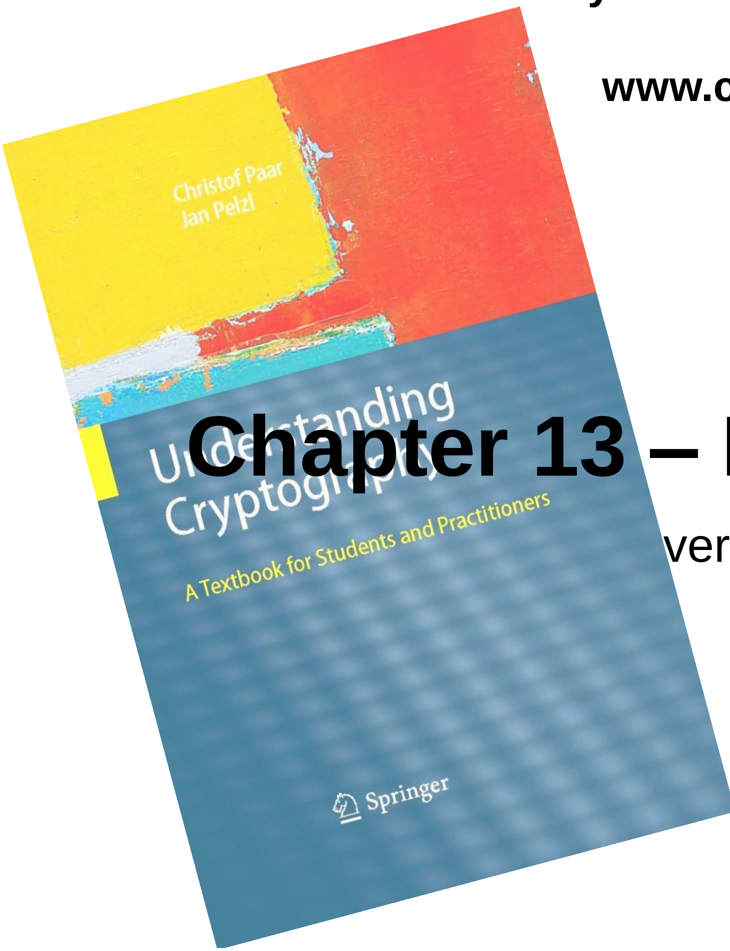

Chapter 13 – Key Establishment

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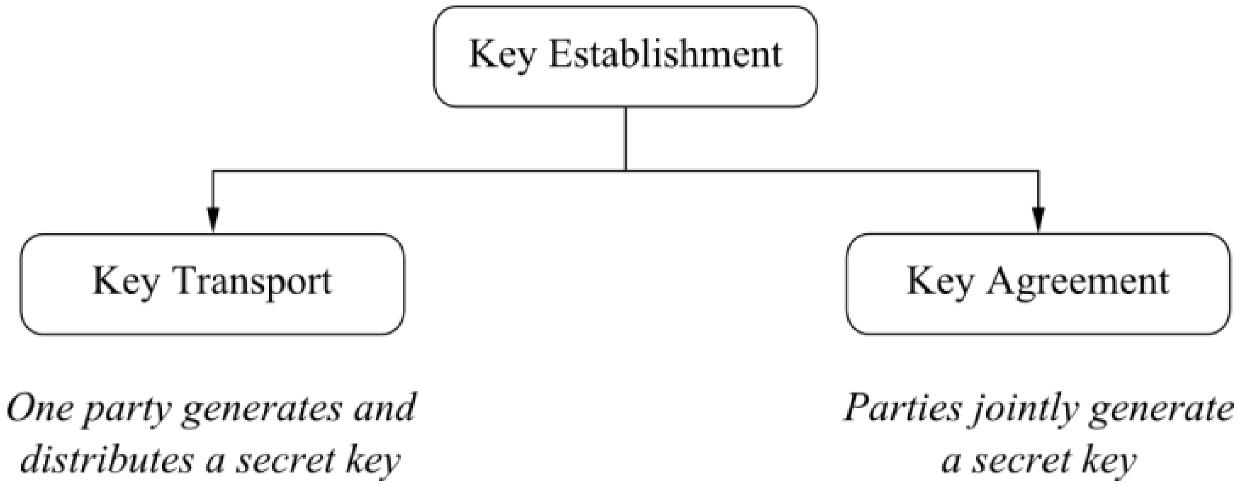
Content of this Chapter

- **Introduction**
- The n^2 Key Distribution Problem
- Symmetric Key Distribution
- Asymmetric Key Distribution
  - Man-in-the-Middle Attack
  - Certificates
  - Public-Key Infrastructure

Classification of Key Establishment Methods



In an ideal key agreement protocol, no single party can control what the key value will be.

Key Freshness

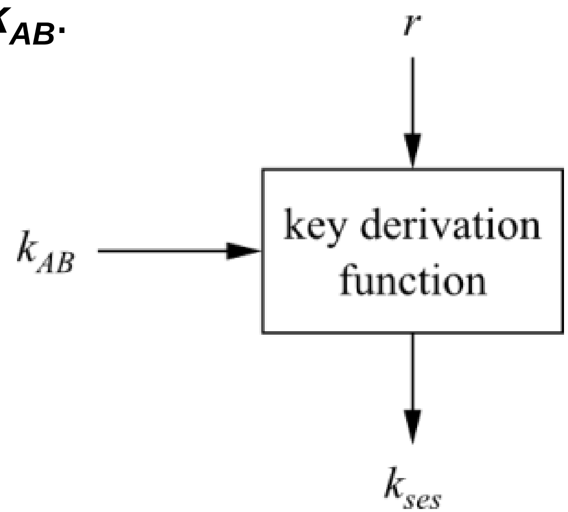
It is often desirable to frequently change the key in a cryptographic system.

Reasons for key freshness include:

- If a key is exposed (e.g., through hackers), there is limited damage if the key is changed often
- Some cryptographic attacks become more difficult if only a limited amount of ciphertext was generated under one key
- If an attacker wants to recover long pieces of ciphertext, he has to recover several keys which makes attacks harder

Key Derivation

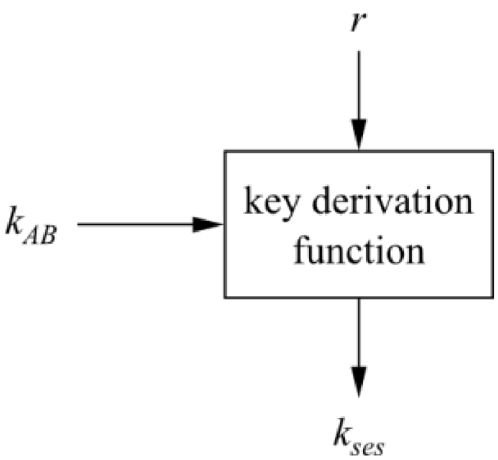
- In order to achieve key freshness, we need to generate new keys frequently.
- Rather than performing a full key establishment every time (which is costly in terms of computation and/or communication), we can **derive multiple session keys k_{ses} from a given key k_{AB}.**



- The key k_{AB} is fed into a key derivation function together with a nonce r („number used only once“).
- Every different value for r yields a different session key

Key Derivation

- The key derivation function is a computationally simple function, e.g., a block cipher or a hash function



- Example for a basic protocol:

Alice		**Bob**
		generate nonce r
	$\xleftarrow{\quad r \quad}$	
derive session key $K_{ses} = e_{kAB}(r)$		derive session key $K_{ses} = e_{kAB}(r)$

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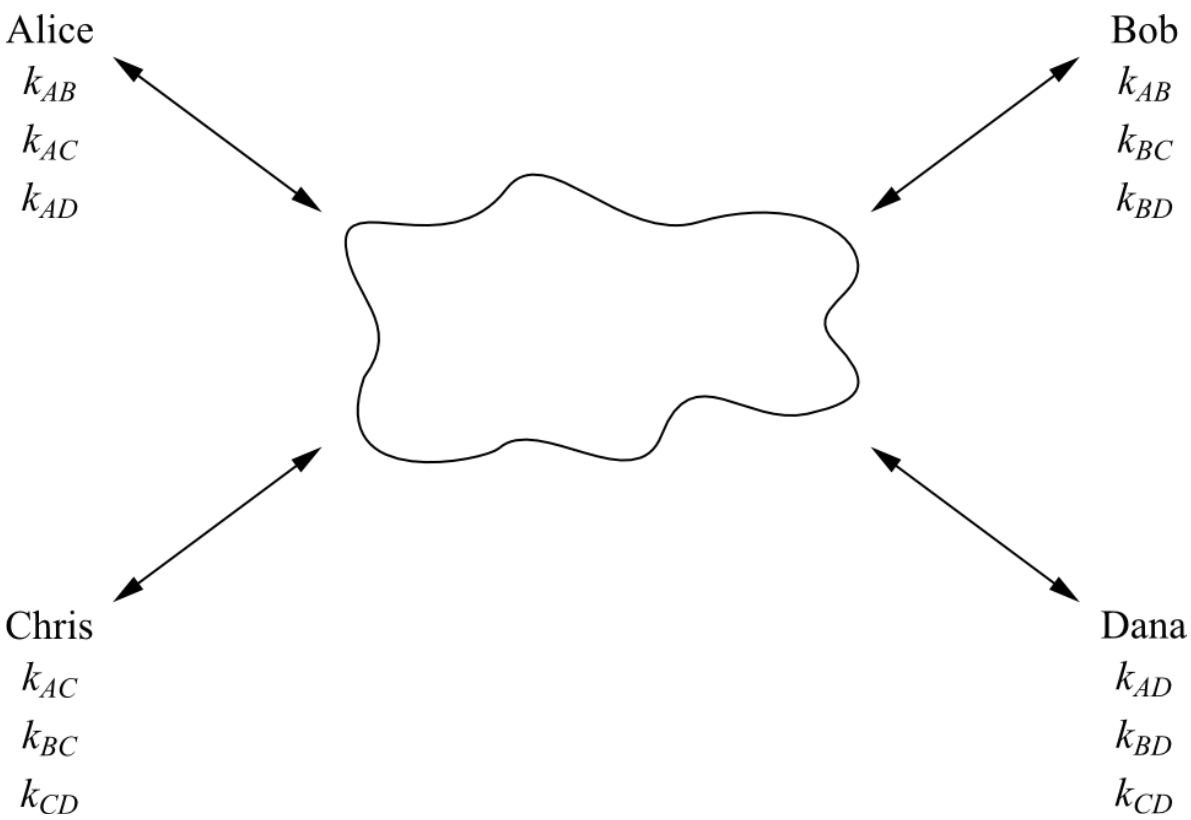
The n^2 Key Distribution Problem

- Simple situation: Network with n users. Every user wants to communicate securely with every of the other n-1 users.
- Naïve approach: Every pair of users obtains an individual key pair

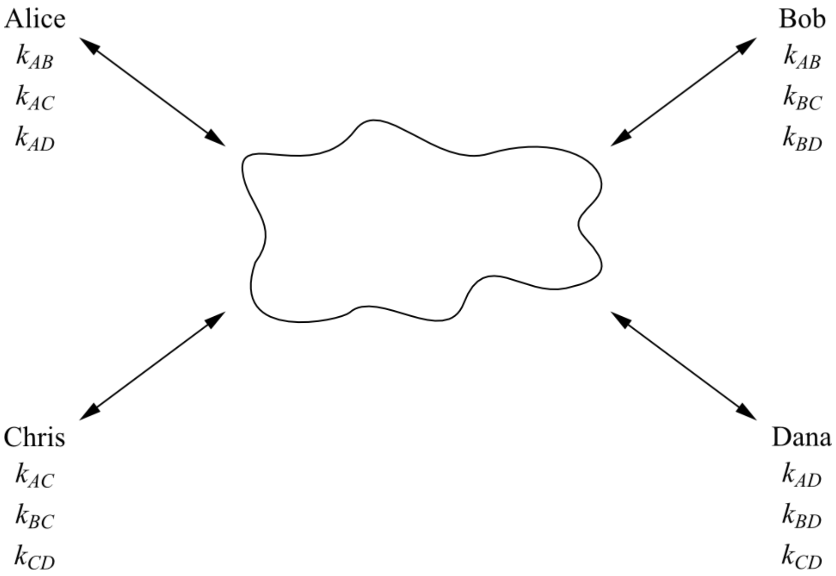


The n^2 Key Distribution Problem

Shortcomings

- There are $n\ (n-1) \approx n^2$ keys in the system
- There are $n\ (n-1)/2$ key pairs
- If a new user Esther joins the network, new keys k_{XE} have to be transported via secure channels (!) to each of the existing usersa

$\Rightarrow$ Only works for small networks which are relatively static



Example: mid-size company with 750 employees

- 750 x 749 = 561,750 keys must be distributed securely

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Key Establishment with Key Distribution Center

- Key Distribution Center (KDC) = Central party, trusted by all users
- KDC shares a **key encryption key (KEK)** with each user
- Principle: KDC sends session keys to users which are encrypted with KEKs

Alice		**KDC**		**Bob**
KEK: k_A		KEKs: k_A , k_B		KEK: k_B
	$\xrightarrow{RQST\ (ID_A\ ,ID_B)}$	*generate session key* k_{ses}		
		$y_A = e_{KA}\ (k_{ses})$		
		$y_B = e_{KB}\ (k_{ses})$		
	$\xleftarrow{y_A}$		$\xrightarrow{y_B}$	
derive session key $K_{ses}= e_{KA}\ (y_A)$				derive session key $K_{ses}= e_{KB}\ (y_B)$

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message *y*		
$y= e_{Kses}\ (x)$	$\xrightarrow{y}$	$x= e^{-1}_{Kses}\ (y)$

Key Establishment with Key Distribution Center

- Advantages over previous approach:
  - Only *n* long-term key pairs are in the system
  - If a new user is added, a secure key is only needed between the user and the KDC (the other users are not affected)
  - Scales well to moderately sized networks

- *Kerberos* (a popular authentication and key distribution protocol) is based on KDCs
- More information on KDCs and Kerberos: Section 13.2 of *Understanding Cryptography*

Key Establishment with Key Distribution Center

Remaining problems:

- **No *Perfect Forward Secrecy***: If the KEKs are compromised, an attacker can decrypt past messages if he stored the corresponding ciphertext
- **Single point of failure**: The KDC stores all KEKs. If an attacker gets access to this database, all past traffic can be decrypted.
- **Communication bottleneck**: The KDC is involved in every communication in the entire network (can be countered by giving the session keys a long life time)
- For more advanced attacks (e.g., key confirmation attack): Cf. Section 13.2 of *Understanding Cryptography*

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Recall: Diffie–Hellman Key Exchange (DHKE)

Public parameters α, p

Alice		**Bob**
Choose random private key $k_{prA} = a \in \{1, 2, \ldots, p\text{-}1\}$		Choose random private key $k_{prB} = b \in \{1, 2, \ldots, p\text{-}1\}$
Compute public key $k_{pubA} = A = \alpha^a \bmod p$	$\xrightarrow{\quad A \quad}$	Compute public key $k_{pubB} = B = \alpha^b \bmod p$
	$\xleftarrow{\quad B \quad}$	
Compute common secret $k_{AB} = B^a = (\alpha^a)^b \bmod p$		Compute common secret $k_{AB} = A^b = (\alpha^b)^a \bmod p$

- Widely used in practice
- If the parameters are chosen carefully (especially a prime p > 2^{1024}), the DHKE is secure against *passive* (i.e., listen-only) attacks
- However: If the attacker can *actively* intervene in the communciation, the man-in-the-middle attack becomes possible

Man-in-the-Middle Attack

Alice	**Oscar**	**Bob**
$k_{prA} = a$		$k_{prB} = b$
$k_{pubA} = A = \alpha^a \bmod p$	$\xrightarrow{A}$ substitute $A' = \alpha^o \bmod p$ $\xrightarrow{A'}$	$k_{pubB} = B = \alpha^b \bmod p$
	$\xleftarrow{B'}$ substitute $B' = \alpha^o \bmod p$ $\xleftarrow{B}$	
$k_{AO} = (B')^a \bmod p$	$k_{AO} = A^o \bmod p$	$k_{BO} = (A')^b \bmod p$
	$k_{BO} = B^o \bmod p$	

- Oscar computes a session key k_{AO} with Alice, and k_{BO} with Bob
- However, Alice and Bob think they are communicationg with each other !
- The attack efficiently performs 2 DH key-exchanges: Oscar-Alice and Oscar-Bob
- Here is why the attack works:

Alice computes: $k_{AO} = (B')^a = (\alpha^o)^a$

Oscar computes: $k_{AO} = A^o = (\alpha^a)^o$

Bob computes: $k_{BO} = (A')^b = (\alpha^o)^b$

Oscar computes: $k_{BO} = B^o = (\alpha^b)^o$

Implications of the Man-in-the-Middle Attack

Alice		**Oscar**		**Bob**
$k_{prA} = a$				$k_{prB} = b$
$k_{pubA} = A = \alpha^a \bmod p$	$\xrightarrow{A}$	substitute $A' = \alpha^o \bmod p$	$\xrightarrow{A'}$	$k_{pubB} = B = \alpha^b \bmod p$
	$\xleftarrow{B'}$	substitute $B' = \alpha^o \bmod p$	$\xleftarrow{B}$	
$k_{AO} = (B')^a \bmod p$		$k_{AO} = A^o \bmod p$		$k_{BO} = (A')^b \bmod p$
		$k_{BO} = B^o \bmod p$		

- Oscar has no complete control over the channel, e.g., if Alice wants to send an encrypted message x to Bob, Oscar can read the message:

$y = AES_{kA,O}(x)$	$\xrightarrow{y}$	decrypt $x = AES^{-1}_{kA,O}(y)$		
		re-encrypt $y' = AES_{kB,O}(x)$	$\xrightarrow{y'}$	$x = AES^{-1}_{kB,O}(y')$

Very, very important facts about the Man-in-the-Middle Attack

- **The man-in-the-middle-attack is not restricted to DHKE; it is applicable to any public-key scheme, e.g. RSA encryption. ECDSA digital signature, etc. etc.**
- The attack works always by the same pattern: Oscar replaces the public key from one of the parties by his own key.
- The attack is also known as MIM attack or Janus attack

- Q: What is the underlying problem that makes the MIM attack possible?
- A: The public keys are not authenticated: When Alice receives a public key which is allegedly from Bob, she has no way of knowing whether it is in fact his. (After all, a key consists of innocent bits; it does not smell like Bob‘s perfume or anything like that)

Even though public keys can be sent over unsecure channels, they require authenticated channels.

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Certificates

- In order to authenticate public keys (and thus, prevent the MIM attack) , all public keys are digitally signed by a central trusted authority.
- Such a construction is called *certificate*

certificate = public key + ID(user) + digital signature over public key and ID

- In its most basic form, a certificate for the key k_{pub} of user Alice is:

$$\mathbf{Cert(Alice) = (}\boldsymbol{k_{pub}, ID(Alice), sig_{K_{CA}}}\mathbf{(}\boldsymbol{k_{pub}}\mathbf{,ID(Alice)\ )}$$

- Certificates bind the identity of user to her public key
- The trusted authority that issues the certificate is referred to as ***certifying authority (CA)***
- „Issuing certificates“ means in particular that the CA computes the signature $sig_{K_{CA}}(k_{pub})$ using its (super secret!) private key k_{CA}
- The party who receives a certificate, e.g., Bob, verifies Alice‘s public key using the public key of the CA

Diffie–Hellman Key Exchange (DHKE) with Certificates

CA

Cert(Alice) → **Alice**

Cert(Bob) → **Bob**

Alice		Bob
$k_{prA} = a$		$k_{prB} = b$
$k_{pubA} = A$		$k_{pubB} = B = \alpha^b \bmod p$
$Cert(Alice) = ((A, ID_A), sig_{K_{CA}}(A, ID_A))$		$Cert(Bob) = ((B, ID_B), sig_{K_{CA}}(B, ID_B))$
	$\xrightarrow{Cert(Alice)}$	
	$\xleftarrow{Cert(Bob)}$	
verify certificate $ver_{K_{pub,CA}}(Cert(Bob))$		verify certificate $ver_{K_{pub,CA}}(Cert(Alice))$
if verification is correct: Compute common secret $k_{AB} = B^a = (\alpha^a)^b \bmod p$		if verification is correct: Compute common secret $k_{AB} = A^b = (\alpha^b)^a \bmod p$

Certificates

- Note that verfication requires the public key of the CA for $ver_{Kpub,CA}$
- In principle, an attacker could run a MIM attack when $k_{pub,CA}$ is being distributed

  $\Rightarrow$ The public CA keys must also be distributed via an authenticated channel!

- Q: So, have we gained anything?

  After all, we try to protect a public key (e.g., a DH key) by using yet another public-key scheme (digital signature for the certificate)?

- A: YES! The difference from before (e.g., DHKE without certificates) is that **we only need to distribute the public CA key *once***, often at the set-upt time of the system

- Example: Most web browsers are shipped with the public keys of many CAs. The „authenticated channel" is formed by the (hopefully) correct distribution of the original browser software.

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Certificates in the Real World

- In the wild certificates contain much more information than just a public key and a signature.
- X509 is a popular signature standard. The main fields of such a certificate are shown to the right.
- Note that the „Signature“ at the bottom is computed over all other fields in the certifcate (after hashing of all those fields).
- It is important to note that there are **two** public-key schemes involved in every certificate:
    1. The public-key that actually is protected by the signature („Subject‘s Public Key“ on the right). This was the public Diffie-Hellman key in the earlier examples.
    2. The digital signature algorithm used by the CA to sign the certificate data.
- For more information on certificates, see Section 13.3 of *Understanding Cryptography*

Serial Number
Certificate Algorithm: - Algorithm - Parameters
Issuer
Period of Validity: - Not Before Date - Not After Date
Subject
Subject’s Public Key: - Algorithm - Parameters - Public Key
Signature

Remaining Issues with PKIs

There are many additional problems when certificates are to be used in systems with a large number of participants. The more pressing ones are:

1. Users communicate which other whose certificates are issued by different CAs
   - This requires cross-certification of CAs, e.g.. CA1 certifies the public-key of CA2. If Alice trusts „her" CA1, cross-certification ensures that she also trusts CA2. This is called a „chain of trust" and it is said that „trust is delegated".
2. Certificate Revocation Lists (CRLs)
   - Another real-world problem is that certificates must be revoced, e.g., if a smart card with certificate is lost or if a user leaves an organization. For this, CRLs must be sent out periodically (e.g., daily) which is a burden on the bandwidth of the system.

More information on PKIs and CAs can be found in Section 13.3 of *Understanding Cryptography*