CSCI-GA.3205 Applied Cryptography & Network Security

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Public key encryption
ElGamal encryption
Digital signatures

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Asymmetric encryption

- Public-key encryption is sometimes called *asymmetric encryption* to denote the fact that the encryptor uses one key, pk, and the decryptor uses a different key, sk.
- The basic idea of public-key encryption is that the receiver, Bob in this case, runs a key generation algorithm G, obtaining a pair of keys:

$$(pk, sk) \xleftarrow{R} G()$$

- The key pk is Bob's public key, and sk is Bob's secret key. As their names imply, Bob should keep sk secret, but may publicize pk.

Asymmetric encryption

- To send Bob an encrypted email message, Alice needs two things: Bob's email address, and Bob's public key pk.
- So let us assume now that Alice has Bob's email address and public key pk. To send Bob an encryption of her email message m, she computes the ciphertext:

$$c \xleftarrow{R} E(pk, m)$$

- She then sends c to Bob, using his email address. At some point later, Bob receives the ciphertext c, and decrypts it, using his secret key:

$$m \leftarrow D(sk, c)$$

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Public-key encryption scheme

Definition 11.1. *A public-key encryption scheme $\mathcal{E} = (G, E, D)$ is a triple of efficient algorithms: a* ***key generation algorithm*** *G, an* ***encryption algorithm*** *E, a* ***decryption algorithm*** *D.*

- *G is a probabilistic algorithm that is invoked as $(pk, sk) \xleftarrow{R} G()$, where pk is called a* ***public key*** *and sk is called a* ***secret key.***
- *E is a probabilistic algorithm that is invoked as $c \xleftarrow{R} E(pk, m)$, where pk is a public key (as output by G), m is a message, and c is a ciphertext.*
- *D is a deterministic algorithm that is invoked as $m \leftarrow D(sk, c)$, where sk is a secret key (as output by G), c is a ciphertext, and m is either a message, or a special* reject *value (distinct from all messages).*

Attack Game (semantic security)

Attack Game 11.1 (semantic security). For a given public-key encryption scheme $\mathcal{E} = (G, E, D)$, defined over $(\mathcal{M}, \mathcal{C})$, and for a given adversary $\mathcal{A}$, we define two experiments.

Experiment b $\quad (b = 0, 1)$:

- The challenger computes $(pk, sk) \xleftarrow{R} G()$, and sends pk to the adversary.
- The adversary computes $m_0, m_1 \in \mathcal{M}$, of the same length, and sends them to the challenger.
- The challenger computes $c \xleftarrow{R} E(pk, m_b)$, and sends c to the adversary.
- The adversary outputs a bit $\hat{b} \in \{0, 1\}$.

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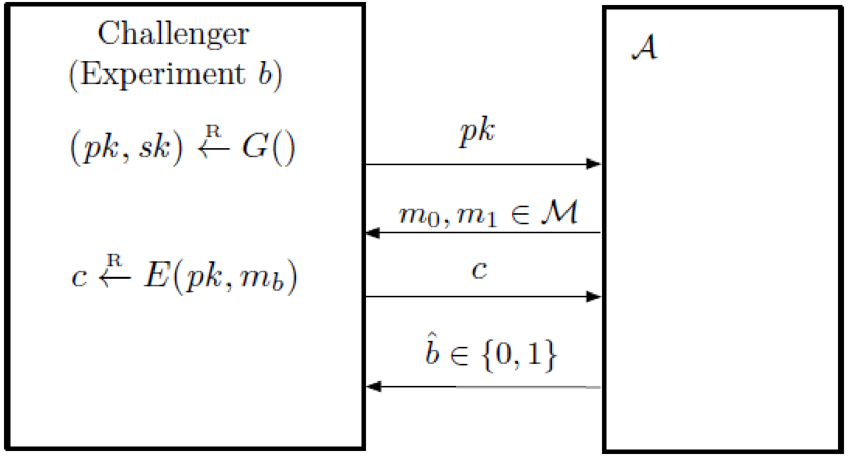
Experiment b of Attack Game (semantic security)

If W_b is the event that $\mathcal{A}$ outputs 1 in Experiment b, we define $\mathcal{A}$'s **advantage** with respect to $\mathcal{E}$ as

$$\mathrm{SSadv}[\mathcal{A}, \mathcal{E}] := \Big|\Pr[W_0] - \Pr[W_1]\Big|. \quad \square$$



Definition 11.2 (semantic security). *A public-key encryption scheme $\mathcal{E}$ is* **semantically secure** *if for all efficient adversaries $\mathcal{A}$, the value $\mathrm{SSadv}[\mathcal{A}, \mathcal{E}]$ is negligible.*

Implications of semantic security

- We first show that any semantically secure public-key scheme must use a randomized encryption algorithm.
- We also show that in the public-key setting, semantic security implies CPA security.
    - This was not true for symmetric encryption schemes: the one-time pad is semantically secure, but not CPA (Chosen Plaintext Attack) secure.

Incorrect use of a Trapdoor Function (TDF)

Never encrypt by applying F directly to plaintext:

E(pk, m) :	**D(sk, c) :**
output $c \leftarrow F(pk, m)$	output $F^{-1}(sk, c)$

Problems:

- Deterministic functions will not be semantically secure if used for public-key encryption from TDFs! Why?

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The need for randomized encryption

Let $\mathcal{E} = (G, E, D)$ be a semantically secure public-key encryption scheme defined over $(\mathcal{M}, \mathcal{C})$ where $|\mathcal{M}| \geq 2$. We show that the encryption algorithm E must be randomized, otherwise the scheme cannot be semantically secure.

To see why, suppose E is deterministic. Then the following adversary $\mathcal{A}$ breaks semantic security of $\mathcal{E} = (G, E, D)$:

The need for randomized encryption

- $\mathcal{A}$ receives a public key pk from its challenger.
- $\mathcal{A}$ chooses two distinct messages m_0 and m_1 in $\mathcal{M}$ and sends them to its challenger. The challenger responds with $c := E(pk, m_b)$ for some $b \in \{0, 1\}$.
- $\mathcal{A}$ computes $c_0 := E(pk, m_0)$ and outputs 0 if $c = c_0$. Otherwise, it outputs 1.

Because E is deterministic, we know that $c = c_0$ whenever $b = 0$. Therefore, when $b = 0$ the adversary always outputs 0. Similarly, when $b = 1$ it always outputs 1. Therefore

$$\mathsf{SSadv}[\mathcal{A}, \mathcal{E}] = 1$$

Random oracles

- The idea is that we simply model a hash function H *as if* it were a truly random function O. The random oracle is implemented using an associative array Map : $G^2 \rightarrow K$.
- If H maps M to T , then O is chosen uniformly at random from the set Funs[M; T].
- We can translate any attack game into its random oracle version:
- The function O is called a **random oracle** and security in this setting is said to hold in the random oracle model.

Attack Game (PRF in the random oracle model)

- We have a PRF F that uses a hash function H as an oracle,
- We denote by F^O the function that uses the random oracle O in place of H.

Definition 8.5. *We say that a PRF F is secure in the random oracle model if for all efficient adversaries $\mathcal{A}$, the value* $\mathrm{PRF^{ro}}\mathsf{adv}[\mathcal{A}, F]$ *is negligible.*

- Let F be a PRF defined over (K; X; Y) that uses a hash function H defined over (M; T) as an oracle.
- For a given adversary A, we define two experiments, Experiment 0 and Experiment 1. For b = 0; 1, we define:

Attack Game (PRF in the random oracle model)

- Experiment b:

  - $\mathcal{O} \xleftarrow{R} \text{Funs}[\mathcal{M}, \mathcal{T}]$.
  - The challenger selects $f \in \text{Funs}[\mathcal{X}, \mathcal{Y}]$ as follows:

    if $b = 0$: $k \xleftarrow{R} \mathcal{K}$, $f \leftarrow F^{\mathcal{O}}(k, \cdot)$;
    if $b = 1$: $f \xleftarrow{R} \text{Funs}[\mathcal{X}, \mathcal{Y}]$.

  - The adversary submits a sequence of queries to the challenger.
    - F-query: respond to a query $x \in \mathcal{X}$ with $y = f(x) \in \mathcal{Y}$.
    - $\mathcal{O}$-query: respond to a query $m \in \mathcal{M}$ with $t = \mathcal{O}(m) \in \mathcal{T}$.
  - The adversary computes and outputs a bit $\hat{b} \in \{0, 1\}$.

For $b = 0, 1$, let W_b be the event that $\mathcal{A}$ outputs 1 in Experiment b. We define $\mathcal{A}$'s **advantage** with respect to F as

$$\text{PRF}^{\text{ro}}\text{adv}[\mathcal{A}, F] := \Big|\Pr[W_0] - \Pr[W_1]\Big|. \quad \Box$$

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Semantic security against chosen plaintext attack

- In the public-key setting, the adversary can encrypt any message he likes, without knowledge of any secret key material.
- The adversary does so by using the given public key and never needs to issue encryption queries to the challenger.
- In contrast, in the symmetric key setting, the adversary cannot encrypt messages on his own.

Attack Game (CPA security)

Attack Game 11.2 (CPA security). For a given public-key encryption scheme $\mathcal{E} = (G, E, D)$, defined over $(\mathcal{M}, \mathcal{C})$, and for a given adversary $\mathcal{A}$, we define two experiments.

Experiment b $\quad (b = 0, 1)$:

- The challenger computes $(pk, sk) \xleftarrow{R} G()$, and sends pk to the adversary.
- The adversary submits a sequence of queries to the challenger.

  For $i = 1, 2, \ldots,$ the ith query is a pair of messages, $m_{i0}, m_{i1} \in \mathcal{M}$, of the same length.

  The challenger computes $c_i \xleftarrow{R} E(pk, m_{ib})$, and sends c_i to the adversary.
- The adversary outputs a bit $\hat{b} \in \{0, 1\}$.

If W_b is the event that $\mathcal{A}$ outputs 1 in Experiment b, then we define $\mathcal{A}$'s **advantage** with respect to $\mathcal{E}$ as

$$\mathrm{CPAadv}[\mathcal{A}, \mathcal{E}] := \Big|\Pr[W_0] - \Pr[W_1]\Big|. \quad \Box$$

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Semantic security against chosen plaintext attack

Definition 11.4 (CPA security). *A public-key encryption scheme $\mathcal{E}$ is called* ***semantically secure against chosen plaintext attack****, or simply* ***CPA secure****, if for all efficient adversaries $\mathcal{A}$, the value $\mathrm{CPAadv}[\mathcal{A}, \mathcal{E}]$ is negligible.*

Theorem 11.1. *If a public-key encryption scheme $\mathcal{E}$ is semantically secure, then it is also CPA secure.*

In particular, for every CPA adversary $\mathcal{A}$ that plays Attack Game 11.2 with respect to $\mathcal{E}$, and which makes at most Q queries to its challenger, there exists an SS adversary $\mathcal{B}$, where $\mathcal{B}$ is an elementary wrapper around $\mathcal{A}$, such that

$$\mathrm{CPAadv}[\mathcal{A}, \mathcal{E}] = Q \cdot \mathrm{SSadv}[\mathcal{B}, \mathcal{E}].$$

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Encryption based on a trapdoor function scheme

Our encryption scheme is called $\mathcal{E}_{\mathrm{TDF}}$, and is built out of several components:

- a trapdoor function scheme $\mathcal{T} = (G, F, I)$, defined over $(\mathcal{X}, \mathcal{Y})$,
- a symmetric cipher $\mathcal{E}_{\mathrm{s}} = (E_{\mathrm{s}}, D_{\mathrm{s}})$, defined over $(\mathcal{K}, \mathcal{M}, \mathcal{C})$,
- a hash function $H : \mathcal{X} \to \mathcal{K}$.

Encryption based on a trapdoor function scheme

The message space for $\mathcal{E}_{\text{TDF}}$ is $\mathcal{M}$, and the ciphertext space is $\mathcal{Y} \times \mathcal{C}$. We now describe the key generation, encryption, and decryption algorithms for $\mathcal{E}_{\text{TDF}}$.

- The key generation algorithm for $\mathcal{E}_{\text{TDF}}$ is the key generation algorithm for $\mathcal{T}$.
- For a given public key pk, and a given message $m \in \mathcal{M}$, the encryption algorithm runs as follows:

$$
\begin{aligned}
E(pk, m) := \quad & x \xleftarrow{\text{R}} \mathcal{X}, \quad y \leftarrow F(pk, x), \quad k \leftarrow H(x), \quad c \xleftarrow{\text{R}} E_{\text{s}}(k, m) \\
& \text{output } (y, c).
\end{aligned}
$$

- For a given secret key sk, and a given ciphertext $(y, c) \in \mathcal{Y} \times \mathcal{C}$, the decryption algorithm runs as follows:

$$
\begin{aligned}
D(sk,\ (y, c)\ ) := \quad & x \leftarrow I(sk, y), \quad k \leftarrow H(x), \quad m \leftarrow D_{\text{s}}(k, c) \\
& \text{output } m.
\end{aligned}
$$

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Encryption based on a trapdoor function with RSA

- This scheme is parameterized by two quantities: the length l of the prime factors of the RSA modulus, and the encryption exponent e, which is an odd, positive integer.
- Let us assume that X is a fixed set into which we may embed $\mathbb{Z}_N$, for every RSA modulus n generated by RSAGen(l; e) (for example, we could take X = $\{0, 1\}^{2l}$).
- The scheme also makes use of a symmetric cipher $\xi = (E_s; D_s)$ defined over (**K; M; C**), as well as a hash function **H : X → K**.

Encryption based on a trapdoor function with RSA

- The basic RSA encryption scheme is $\xi_{\text{RSA}} = (G; E; D)$, with message space **M** and ciphertext space X × C, where
  - the key generation algorithm runs as follows:

$$\begin{aligned} G() := \quad & (n,d) \xleftarrow{R} \mathrm{RSAGen}(\ell, e), \quad pk \leftarrow (n,e), \quad sk \leftarrow (n,d) \\ & \text{output } (pk, sk); \end{aligned}$$

  - for a given public key $pk = (n, e)$, and message $m \in \mathcal{M}$, the encryption algorithm runs as follows:

$$\begin{aligned} E(pk, m) := \quad & x \xleftarrow{R} \mathbb{Z}_n, \quad y \leftarrow x^e, \quad k \leftarrow H(x), \quad c \xleftarrow{R} E_s(k, m) \\ & \text{output } (y, c) \in \mathcal{X} \times \mathcal{C}; \end{aligned}$$

  - for a given secret key $sk = (n, d)$, and a given ciphertext $(y, c) \in \mathcal{X} \times \mathcal{C}$, where y represents an element of $\mathbb{Z}_n$, the decryption algorithm runs as follows:

$$\begin{aligned} D(sk, \ (y,c)\ ) := \quad & x \leftarrow y^d, \quad k \leftarrow H(x), \quad m \leftarrow D_s(k, c) \\ & \text{output } m. \end{aligned}$$

Public-key encryption from TDFs

(G, F, F^{-1}): secure TDF $X \longrightarrow Y$

(E_s, D_s) : symmetric auth. encryption defined over (K,M,C)

$H: X \longrightarrow K$ a hash function

E(pk, m) :

$x \leftarrow X$, $y \leftarrow F(pk, x)$

$k \leftarrow H(x)$, $c \leftarrow E_s(k, m)$

output (y, c)

D(sk, (y,c)) :

$x \leftarrow F^{-1}(sk, y)$,

$k \leftarrow H(x)$, $m \leftarrow D_s(k, c)$

output m

$$\underbrace{F(pk, x)}_{\text{header}}\ \underbrace{E_s(\,H(x),\ m\,)}_{\text{body}}$$

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ElGamal encryption

The encryption scheme is a variant of a scheme first proposed by ElGamal, and we call it $\mathcal{E}_{\mathrm{EG}}$. It is built out of several components:

- a cyclic group $\mathbb{G}$ of prime order q with generator $g \in \mathbb{G}$,
- a symmetric cipher $\mathcal{E}_{\mathrm{s}} = (E_{\mathrm{s}}, D_{\mathrm{s}})$, defined over $(\mathcal{K}, \mathcal{M}, \mathcal{C})$,
- a hash function $H : \mathbb{G}^2 \to \mathcal{K}$.

The message space for $\mathcal{E}_{\mathrm{EG}}$ is $\mathcal{M}$, and the ciphertext space is $\mathbb{G} \times \mathcal{C}$. We now describe the key generation, encryption, and decryption algorithms for $\mathcal{E}_{\mathrm{EG}}$.

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Diffie-Hellman protocol (1977) in ElGamal pub-key encryption (1984)

Fix a finite cyclic group G $\left(\text{e.g } G = (Z_p)^*\right)$ of order n

Fix a generator g in G $\left(\text{i.e. } G = \{1, g, g^2, g^3, \ldots, g^{n-1}\}\right)$

Alice | **Bob**

choose random **a** in {1,…,n} | choose random **b** in {1,…,n}

$A = g^a$ $\longrightarrow$

$\longleftarrow$ $B = g^b$

$$\mathbf{B^a} = (g^b)^a = \mathbf{k_{AB} = g^{ab}} = (g^a)^b = \mathbf{A^b}$$

To encrypt: compute $g^{ab} = A^b$, derive symmetric key k , encrypt message m with k
To decrypt: compute $g^{ab} = B^a$, derive k, and decrypt

ElGamal encryption

- the key generation algorithm runs as follows:

$$G() := \quad \alpha \xleftarrow{\text{R}} \mathbb{Z}_q, \quad u \leftarrow g^\alpha$$
$$pk \leftarrow u, \quad sk \leftarrow \alpha$$
$$\text{output } (pk, sk);$$

- for a given public key $pk = u \in \mathbb{G}$ and message $m \in \mathcal{M}$, the encryption algorithm runs as follows:

$$E(pk, m) := \quad \beta \xleftarrow{\text{R}} \mathbb{Z}_q, \quad v \leftarrow g^\beta, \quad w \leftarrow u^\beta, \quad k \leftarrow H(v, w), \quad c \leftarrow E_{\text{s}}(k, m)$$
$$\text{output } (v, c);$$

- for a given secret key $sk = \alpha \in \mathbb{Z}_q$ and a ciphertext $(v, c) \in \mathbb{G} \times \mathcal{C}$, the decryption algorithm runs as follows:

$$D(sk,\ (v, c)\ ) := \quad w \leftarrow v^\alpha, \quad k \leftarrow H(v, w), \quad m \leftarrow D_{\text{s}}(k, c)$$
$$\text{output } m.$$

Thus, $\mathcal{E}_{\text{EG}} = (G, E, D)$, and is defined over $(\mathcal{M}, \mathbb{G} \times \mathcal{C})$.

Note that the description of the group $\mathbb{G}$ and generator $g \in \mathbb{G}$ is considered to be a system parameter, rather than part of the public key.

The ElGamal system (a modern view)

- G: finite cyclic group of order n
- (E_s, D_s) : symmetric auth. encryption defined over (K,M,C)
- $H: G^2 \longrightarrow K$ a hash function

E(pk=(g,u), m) :

$b \leftarrow Z_n$, $v \leftarrow g^b$, $w \leftarrow u^b$

$k \leftarrow H(v, w)$, $c \leftarrow E_s(k, m)$

output (v, c)

D(sk=a, (v,c)) :

$w \leftarrow v^a$

$k \leftarrow H(v, w)$, $m \leftarrow D_s(k, c)$

output m

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Secrecy vs Integrity

	Private-Key Setting	**Public-Key Setting**
Secrecy	Private-key encryption	Public-key encryption
Integrity	Message authentication codes	Digital signature schemes

Digital signatures

- Functionally, a digital signature is similar to a MAC.
- In a MAC, both the signing and verification algorithms use the same secret key.
- In a signature scheme, the signing algorithm uses one key, sk, while the verification algorithm uses another, pk.

Digital signatures

- Functionally, a digital signature is similar to a MAC.
- In a MAC, both the signing and verification algorithms use the same secret key.
- In a signature scheme, the signing algorithm uses one key, sk, while the verification algorithm uses another, pk.

Definition 13.1. *A signature scheme $\mathcal{S} = (G, S, V)$ is a triple of efficient algorithms, G, S and V, where G is called a* ***key generation algorithm****, S is called a* ***signing algorithm****, and V is called a* ***verification algorithm****. Algorithm S is used to generate signatures and algorithm V is used to verify signatures.*

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Digital signatures

- G *is a probabilistic algorithm that takes no input. It outputs a pair* (pk, sk)*, where* sk *is called a secret* ***signing key*** *and* pk *is called a public* ***verification key****.*
- S *is a probabilistic algorithm that is invoked as* $\sigma \xleftarrow{R} E(sk, m)$*, where* sk *is a secret key (as output by* G*) and* m *is a message. The algorithm outputs a* ***signature*** σ*.*
- V *is a deterministic algorithm invoked as* $V(pk, m, \sigma)$*. It outputs either* accept *or* reject.
- *We require that a signature generated by* S *is always accepted by* V*. That is, for all* (pk, sk) *output by* G *and all messages* m*, we have*

$$\Pr[V(pk,\ m,\ S(sk,\ m)\ ) = \text{accept}] = 1.$$

As usual, we say that messages lie in a finite ***message space*** $\mathcal{M}$*, and signatures lie in some finite* ***signature space*** Σ*. We say that* $\mathcal{S} = (G, S, V)$ *is defined over* $(\mathcal{M}, \Sigma)$*.*

Secure signatures

The definition of a secure signature scheme is similar to the definition of secure MAC. We give the adversary the power to mount a **chosen message attack**, namely the attacker can request the signature on any message of his choice. Even with such power, the adversary should not be able to create an **existential forgery**, namely the attacker cannot output a valid message-signature pair (m, σ) for some new message m. Here "new" means a message that the adversary did not previously request a signature for.

More precisely, we define secure signatures using an attack game between a challenger and an adversary $\mathcal{A}$. The game is described below and in Fig. 13.1.

Attack Game (Signature security)

Attack Game 13.1 (Signature security). For a given signature scheme $\mathcal{S} = (G, S, V)$, defined over $(\mathcal{M}, \Sigma)$, and a given adversary $\mathcal{A}$, the attack game runs as follows:

- The challenger runs $(pk, sk) \xleftarrow{R} G()$ and sends pk to $\mathcal{A}$.
- $\mathcal{A}$ queries the challenger several times. For $i = 1, 2, \ldots,$ the ith *signing query* is a message $m_i \in \mathcal{M}$. Given m_i, the challenger computes $\sigma_i \xleftarrow{R} S(sk, m_i)$, and then gives σ_i to $\mathcal{A}$.
- Eventually $\mathcal{A}$ outputs a candidate forgery pair $(m, \sigma) \in \mathcal{M} \times \Sigma$.

Attack Game (Signature security)

We say that the adversary wins the game if the following two conditions hold:

- $V(pk, m, \sigma) = \mathsf{accept}$, and
- m is new, namely $m \notin \{m_1, m_2, \ldots\}$.

We define $\mathcal{A}$'s advantage with respect to $\mathcal{S}$, denoted $\mathsf{SIGadv}[\mathcal{A}, \mathcal{S}]$, as the probability that $\mathcal{A}$ wins the game. Finally, we say that $\mathcal{A}$ is a **Q-query adversary** if $\mathcal{A}$ issues at most Q signing queries.

Definition 13.2. *We say that a signature scheme $\mathcal{S}$ is secure if for all efficient adversaries $\mathcal{A}$, the quantity $\mathsf{SIGadv}[\mathcal{A}, \mathcal{S}]$ is negligible.*

In case the adversary wins Attack Game 13.1, the pair (m, σ) it outputs is called an **existential forgery**. Systems that satisfy Definition 13.2 are said to be **existentially unforgeable under a chosen message attack**.

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Signature attack game

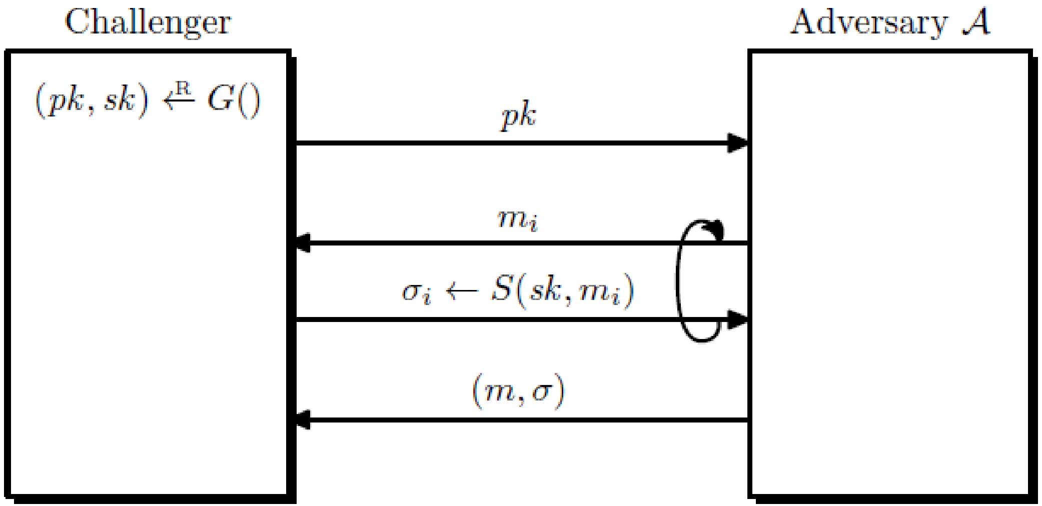

Figure 13.1: Signature attack game (Attack Game 13.1)

Applications of digital signatures

Software distribution:

- Suppose a software company releases a software update for its product.
- Customers download the software update file U Before installing U on their machine.
- Customers want to verify that U really is from the company.
- A MAC system is of no use in this setting because the company does not maintain a shared secret key with each of its customers.

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Applications of digital signatures

The signing process works as follows:

- The company generates a secret signing key sk along with some corresponding public key denoted pk and keeps the secret key sk to itself.
- To sign a software update file U, the company runs a signing algorithm S that takes (sk; U) as input and outputs a short signature σ.
- The company then ships the pair (U; σ) to all its customers.
- A customer given the update (U; σ) and the public key pk, checks validity of this message signature pair using a signature verification algorithm V that takes (pk;U; σ) as input.

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Applications of digital signatures

Authenticated email:

- Suppose Bob receives an email claiming to be from his friend Alice. Bob wants to verify that the email really is from Alice. A MAC system would do the job but requires that Alice and Bob have a shared secret key. What if they never met before and do not share a secret key?
- Digital signatures provide a simple solution.
- First, Alice generates a public/secret key pair (pk; sk). When sending an email m to Bob, Alice generates a signature σ on m derived using her secret key. She then sends (m; σ) to Bob.
- Bob receives (m; σ) and verifies that m is from Alice in two steps. First, Bob retrieves Alice's public key pk. Second, Bob runs the signature verification algorithm on the triple (pk; m; σ).

Applications of digital signatures

Certificates:

- We could assume that public keys are obtained from a read-only public directory. In practice, however, there is no public directory. Instead, Alice's public key pk is certified by some third party called a *certificate authority* or CA for short.

Applications of digital signatures

To generate a certified public key:

- Alice first generates a public/private key pair (pk; sk) and presents her public key pk to the CA. The CA then verifies that Alice is who she claims to be.
- The CA signs the message m using its own secret key sk_{CA} and sends the pair *Cert* := (m; σ_{CA}) back to Alice. This pair *Cert* is called a **certificate** or pk.
- Bob obtains Alice's certificate from Alice and verifies the CA's signature in the certificate. If the signature is valid, Bob has some confidence that pk is Alice's public key.

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Applications of digital signatures

Non-repudiation:

- An interesting property of the authenticated email system above is that Bob now has evidence that the message m is from Alice.
- He could show the pair (m; σ) to a judge who could also verify Alice's signature.
- This property provided by digital signatures is called **non-repudiation**.