Foundation of Cryptography (0368-4162-01), Lecture 8

Encryption Schemes

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Section 1

Definitions

Correctness

Definition 1 (encryption scheme)

A trippet of PPT's $(\mathrm{G}, \mathrm{E}, \mathrm{D})$ such that

1. $\mathrm{G}(1^n)$ outputs a key $(e, d) \in \{0,1\}^* \times \{0,1\}^*$
2. $\mathrm{E}(e, m)$ outputs a string in $c \in \{0,1\}^*$
3. $\mathrm{D}(d, c)$ outputs $m \in \{0,1\}^*$

Correctness: $\mathrm{D}(d, \mathrm{E}(e, m)) = m$, for any $(e, d) \in \mathrm{Supp}(\mathrm{G}(1^n))$ and $m \in \{0,1\}^*$

- e – encryption key, d – decryption key
- m – plaintext, $c = \mathrm{E}(e, m)$ – ciphertext
- $E_e(m) \equiv E(e, m)$ and $D_d(c) \equiv D(d, c)$,
- public/private key

Security

- What would we like to achieve?
- Attempt: for any $m \in \{0,1\}^*$:

$$(m, E_{G(1^n)_1}(m)) \equiv (m, U_{\ell(|m|)})$$

  - Shannon – only for m with $|m| \leq |G(1^n)_1|$
  - Other concerns, e.g., multiple encryptions, active adversary

Semantic Security

1. Ciphertext reveal “no information" about the plaintext
2. Formulate via the simulation paradigm
3. Cannot hide the message length

Semantic security – private-key model

Definition 2 (Semantic Security – private-key model)

An encryption scheme $(\mathsf{G}, \mathsf{E}, \mathsf{D})$ is semantically secure in the private-key model, if for any PPT A, $\exists$ PPT A' s.t. $\forall$ poly-bounded dist. ensemble $\mathcal{M} = \{\mathcal{M}_n\}_{n\in\mathbb{N}}$ and poly-bounded functions $h, f\colon \{0,1\}^* \mapsto \{0,1\}^*$

$$\left|\Pr_{m\leftarrow\mathcal{M}_n, e\leftarrow G(1^n)_1}[\mathsf{A}(1^n, 1^{|m|}, h(1^n, m), E_e(m)) = f(1^n, m)] - \Pr_{m\leftarrow\mathcal{M}_n}[\mathsf{A}'(1^n, 1^{|m|}, h(1^n, m)) = f(1^n, m)]\right| = \operatorname{neg}(n)$$

- poly-bounded? for simplicity we assume polynomial length
- 1^n and $1^{|m|}$ can be omitted
- Non-uniform definition
- Reflection to $\mathcal{ZK}$
- public-key variant – A gets e

Indistinguishablity of encryptions

- The encryption of two strings is indistinguishable
- Less intuitive than semantic security, but easier to work with

Indistinguishablity of encryptions – private-key model

Definition 3 (Indistinguishablity of encryptions – private-key model)

An encryption scheme $(\mathrm{G}, \mathrm{E}, \mathrm{D})$ has indistinguishable encryptions in the private-key model, if for any $p, \ell \in \text{poly}$, $\{x_n, y_n \in \{0,1\}^{\ell(n)}\}_{n\in\mathbb{N}}$, $\{z_n \in \{0,1\}^{p(n)}\}_{n\in\mathbb{N}}$ and poly-time B,

$$\left|\Pr_{e\leftarrow G(1^n)_1}[\mathrm{B}(z_n, E_e(x_n)) = 1] - \Pr_{e\leftarrow G(1^n)_1}[\mathrm{B}(z_n, E_e(y_n)) = 1]\right| = \operatorname{neg}(n)$$

- Non-uniform definition
- Public-key variant

Equivalence of definitions

Theorem 4

An encryption scheme (G, E, D) *is semantically secure iff is has indistinguishable encryptions.*

We prove the private key case

Indistinguishability $\Longrightarrow$ Semantic Security

Fix $\mathcal{M}$, A, f and h, be as in Definition 2. We construct A$'$ as

Algorithm 5 (A$'$)

Input: 1^n, $1^{|m|}$ and $h(m)$

1. $e \leftarrow G(1^n)_1$
2. $c = E_e(1^{|m|})$
3. Output $A(1^n, 1^{|m|}, h(m), c)$

Claim 6

A$'$ is a good simulator for A (according to Definition 2)

Proving Claim 6

For $n \in \mathbb{N}$, let

$$\delta(n) := \Big|\Pr_{m \leftarrow \mathcal{M}_n, e \leftarrow G(1^n)_1}[\mathsf{A}(1^n, 1^{|m|}, h(1^n, m), E_e(m)) = f(1^n, m)] - \Pr_{m \leftarrow \mathcal{M}_n}[\mathsf{A}'(1^n, 1^{|m|}, h(1^n, m)) = f(1^n, m)]\Big|$$

Claim 7

For every $n \in \mathbb{N}$, exists $x_n \in \mathrm{Supp}(\mathcal{M}_n)$ with

$$\delta(n) \leq \Big|\Pr_{e \leftarrow G(1^n)_1}[\mathsf{A}(1^n, 1^{|x_n|}, h(1^n, x_n), E_e(x_n)) = f(1^n, x_n)] - \Pr[\mathsf{A}'(1^n, 1^{|x_n|}, h(1^n, x_n)) = f(1^n, x_n)]\Big|$$

Proof: Write the lhs and rhs terms in the definition of $\delta(n)$ as sums over the different choices of $m \in \mathrm{Supp}(\mathcal{M}_n)$, pair the two terms of each $m \in \mathrm{Supp}(\mathcal{M}_n)$ into a term a_m, and use $\left|\sum_{m \in \mathrm{Supp}(\mathcal{M}_n)} \mathcal{M}_n(m) \cdot a_m\right| \leq \max_{m \in \mathrm{Supp}(\mathcal{M}_n)} |a_m|$

Assume $\exists$ an infinite $\mathcal{I} \subseteq \mathbb{N}$ and $p \in$ poly s.t. $\delta(n) > 1/p(n)$ for every $n \in \mathcal{I}$.
The following algorithm contradicts the indistinguishability of (G, E, D) with respect to $\{(x_n, y_n = 1^{|x_n|})\}_{n\in\mathbb{N}}$ and $\{z_n = (1^n, 1^{|x_n|}, h(1^n, x_n), f(1^n, x_n))\}_{n\in\mathbb{N}}$.

Algorithm 8 (B)

Input: $z_n = (1^n, 1^{|x_n|}, h(1^n, x_n), f(1^n, x_n))$, c
Output 1 iff $\mathsf{A}(1^n, 1^{|x_n|}, h(x_n), c) = f(1^n, x_n)$

Semantic Security $\Longrightarrow$ Indistinguishability

Assume $\exists$ PPT B, $\{x_n, y_n \in \{0,1\}^{\ell(n)}\}_{n\in\mathbb{N}}$ and a $\{z_n\}_{n\in\mathbb{N}}$, such that (wlg) for infinitely many n's:

$$\Pr_{e\leftarrow G(1^n)_1}[\mathrm{B}(z_n, E_e(x_n)) = 1] - \Pr_{e\leftarrow G(1^n)_1}[\mathrm{B}(z_n, E_e(y_n)) = 1] \geq \frac{1}{p(n)} \tag{1}$$

- Let $\mathcal{M}_n$ be x_n wp $\frac{1}{2}$ and y_n otherwise.
- Let $f(1^n, x_n) = 1$, $f(1^n, y_n) = 0$ and $h(1^n, \cdot) = z_n$.
- Define $\mathrm{A}(1^n, 1^{\ell(n)}, z_n, c)$ to return $\mathrm{B}(z_n, c)$.

$$\Pr_{m\leftarrow\mathcal{M}_n, e\leftarrow G(1^n)_1}[\mathrm{A}(1^n, 1^{|m|}, h(1^n, m), E_e(m)) = f(1^n, m)] \geq \frac{1}{2} + \frac{1}{p(n)} \tag{2}$$

where for *any* A′

$$\Pr_{m\leftarrow\mathcal{M}_n, e\leftarrow G(1^n)_1}[\mathrm{A}'(1^n, 1^{|m|}, h(1^n, m), E_e(m)) = f(1^n, m)] \leq \frac{1}{2} \tag{3}$$

Security Under Multiple Encryptions

Definition 9 (Indistinguishablity for multiple encryptions – private-key model)

An encryption scheme $(\mathrm{G}, \mathrm{E}, \mathrm{D})$ has indistinguishable encryptions for multiple messages in the private-key model, if for any $p, \ell, t \in \text{poly}$,
$\{x_{n,1}, \ldots x_{n,t(n)}, y_{n,1}, \ldots, y_{n,t(n)} \in \{0,1\}^{\ell(n)}\}_{n\in\mathbb{N}}$,
$\{z_n \in \{0,1\}^{p(n)}\}_{n\in\mathbb{N}}$ and polynomial-time B,

$$\Big|\Pr_{e\leftarrow G(1^n)_1}[\mathrm{B}(z_n, E_e(x_{n,1}), \ldots E_e(x_{n,t(n)})) = 1]$$
$$-\Pr_{e\leftarrow G(1^n)_1}[\mathrm{B}(z_n, E_e(y_{n,1}), \ldots E_e(y_{n,t(n)})) = 1\Big| = \text{neg}(n)$$

Extensions:

- Different length messages
- Semantic security version
- Public-key definition

Multiple Encryption in the Public-Key Model

Theorem 10

A public-key encryption scheme has indistinguishable encryptions for multiple messages, iff it has indistinguishable encryptions for a single message.

Proof: Assume (G, E, D) is public-key secure for a single message and not for multiple messages with respect to B, $\{x_{n,1}, \ldots x_{n,t(n)}, y_{n,1}, \ldots, y_{n,t(n)} \in \{0,1\}^{\ell(n)}\}_{n\in\mathbb{N}}$, $\{z_n \in \{0,1\}^{p(n)}\}_{n\in\mathbb{N}}$.
It follows that for some function $i(n) \in [t(n)]$

$$\big|\Pr[\mathrm{B}(1^n, e, E_e(x_{n,1}), \ldots, E_e(x_{n,i-1}), E_e(y_{n,i}) \ldots, E_e(y_{n,t(n)})) = 1]$$
$$-\Pr[\mathrm{B}(1^n, e, E_e(x_{n,1}), \ldots, E_e(x_{n,i}), E_e(y_{n,i+1}) \ldots, E_e(y_{n,t(n)})) = 1]\big|$$
$$> \mathrm{neg}(n)$$

where in both cases $e \leftarrow \mathrm{G}(1^n)_1$

Algorithm 11 (B′)

Input: 1^n, $z_n = (i(n), x_{n,1}, \ldots x_{n,t(n)}, y_{n,1}, \ldots, y_{n,t(n)})$, e ,c
Return $\mathrm{B}(c, E_e(x_{n,1}), \ldots, E_e(x_{n,i-1}), c, E_e(y_{n,i+1}) \ldots, E_e(y_{n,t(n)}))$

B′ is critically using the public key

Multiple Encryption in the Private-Key Model

Fact 12

Assuming (non uniform) OWFs exists, there exists an encryption scheme that has private-key indistinguishable encryptions for a single messages, but not *for multiple messages*

Proof: Let $g\colon \{0,1\}^n \mapsto \{0,1\}^{n+1}$ be a (non-uniform) PRG, and for $i \in \mathbb{N}$ let g^i be its "iterated extension" to output of length i (see Lecture 2, Construction 15).

Construction 13

- $\mathrm{G}(1^n)$ outputs $e \leftarrow \{0,1\}^n$,
- $\mathrm{E}_e(m)$ outputs $g^{|m|}(e) \oplus m$
- $\mathrm{D}_e(c)$ outputs $g^{|c|}(e) \oplus c$

Claim 14

(G, E, D) has private-key indistinguishable encryptions for a single message

Proof: Assume not, and let B, $\{x_n, y_n \in \{0,1\}^{\ell(n)}\}_{n\in\mathbb{N}}$ and $\{z_n \in \{0,1\}^{p(n)}\}_{n\in\mathbb{N}}$ be the triplet that realizes it. Namely,

$$\left|\Pr[\mathsf{B}(z_n, g^{\ell(n)}(U_n) \oplus x_n) = 1] - \Pr[\mathsf{B}(z_n, g^{\ell(n)}(U_n) \oplus y_n) = 1]\right| > \mathrm{neg}(n) \tag{4}$$

Hence, B yields a (non-uniform) distinguisher for g

Claim 15

(G, E, D) does not have a private-key indistinguishable encryptions for multiple messages

Proof: Take $x_{n,1} = x_{n,2}$, $y_{n,1} \neq y_{n,2}$ and let B be the algorithm that on input (c_1, c_2), outputs 1 iff $c_1 = c_2$.

Section 2

Constructions

Private key indistinguishable encryptions for multiple messages

Suffice to encrypt messages of some fixed length (here the length is n).

Let $\mathcal{F}$ be a (non-uniform) length preserving PRF

Construction 16

- $\mathrm{G}(1^n)$: output $e \leftarrow \mathcal{F}_n$,
- $\mathrm{E}_e(m)$: choose $r \leftarrow \{0,1\}^n$ and output $(r, e(r) \oplus m)$
- $\mathrm{D}_e(r, c)$: output $e(r) \oplus c$

Claim 17

$(\mathrm{G}, \mathrm{E}, \mathrm{D})$ has private-key indistinguishable encryptions for a multiple messages

Proof:

Public-key indistinguishable encryptions for multiple messages

Let (G, f, Inv) be a (non-uniform) TDP, and let b be an hardcore predicate for it.

Construction 18 (bit encryption)

- $\mathrm{G}(1^n)$: output $(e, d) \leftarrow \mathrm{G}(1^n)$
- $\mathrm{E}_e(m)$: choose $r \leftarrow \{0,1\}^n$ and output $(y = f_e(r), c = b(r) \oplus m)$
- $\mathrm{D}_d(y, c)$: output $b(\mathrm{Inv}_d(y)) \oplus c$

Claim 19

$(\mathrm{G}, \mathrm{E}, \mathrm{D})$ has public-key indistinguishable encryptions for a multiple messages

- We believe that public-key encryptions schemes are “more complex" than private-key ones

Section 3

Active Adversaries

Active Adversaries

- Chosen plaintext attack (CPA):
  The adversary can ask for encryption and choose the messages to distinguish accordingly
- Chosen ciphertext attack (CCA):
  The adversary can also ask for *decryptions* of certain messages

- In the public-key settings, the adversary is also given the public key
- We focus on indistinguishability, but each of the above definitions has an equivalent semantic security variant.

CPA Security

Let $(\mathsf{G}, \mathsf{E}, \mathsf{D})$ be an encryption scheme. For a pair of algorithms $\mathsf{A} = (\mathsf{A}_1, \mathsf{A}_2)$, $n \in \mathbb{N}$, $z \in \{0,1\}^*$ and $b \in \{0,1\}$, let:

Experiment 20 ($\mathsf{Exp}^{\mathsf{CPA}}_{\mathsf{A},n,z}(b)$)

1. $(e, d) \leftarrow G(1^n)$
2. $(m_0, m_1, s) \leftarrow \mathsf{A}_1^{E_e(\cdot)}(1^n, z)$
3. $c \leftarrow \mathsf{E}_e(m_b)$
4. Output $\mathsf{A}_2^{E_e(\cdot)}(1^n, s, c)$

Definition 21 (private key CPA)

$(\mathsf{G}, \mathsf{E}, \mathsf{D})$ has indistinguishable encryptions in the private-key model under CPA attack, if $\forall$ PPT $\mathsf{A}_1, \mathsf{A}_2$, and poly-bounded $\{z_n\}_{n \in \mathbb{N}}$:

$$|\Pr[\mathsf{Exp}^{\mathsf{CPA}}_{\mathsf{A},n,z_n}(0) = 1] - \Pr[\mathsf{Exp}^{\mathsf{CPA}}_{\mathsf{A},n,z_n}(1) = 1]| = \mathsf{neg}(n)$$

- public-key variant...
- The scheme from Construction 16 has indistinguishable encryptions in the private-key model under CPA attack (for short, private-key CPA secure)
- The scheme from Construction 18 has indistinguishable encryptions in the public-key model under CPA attack (for short, public-key CPA secure)
- In both cases, definitions are *not* equivalent

CCA Security

Experiment 22 ($\mathrm{Exp}^{\mathrm{CCA1}}_{\mathsf{A},n,z}(b)$)

1. $(e, d) \leftarrow G(1^n)$
2. $(m_0, m_1, s) \leftarrow \mathsf{A}_1^{E_e(\cdot), D_d(\cdot)}(1^n, z)$
3. $c \leftarrow \mathsf{E}_e(m_b)$
4. Output $\mathsf{A}_2^{E_e(\cdot)}(1^n, s, c)$

Experiment 23 ($\mathrm{Exp}^{\mathrm{CCA2}}_{\mathsf{A},n,z_n}(b)$)

1. $(e, d) \leftarrow G(1^n)$
2. $(x_0, x_1, s) \leftarrow \mathsf{A}_1^{E_e(\cdot), D_d(\cdot)}(1^n, z)$
3. $c \leftarrow \mathsf{E}_e(x_b)$
4. Output $\mathsf{A}_2^{E_e(\cdot), D_d^{\neg c}(\cdot)}(1^n, s, c)$

Definition 24 (private key $\mathsf{CCA1}/\mathsf{CCA2}$)

$(\mathsf{G}, \mathsf{E}, \mathsf{D})$ has indistinguishable encryptions in the private-key model under $x \in \{\mathsf{CCA1}, \mathsf{CCA2}\}$ attack, if $\forall$ PPT $\mathsf{A}_1, \mathsf{A}_2$, and poly-bounded $\{z_n\}_{n\in\mathbb{N}}$:

$$|\Pr[\mathsf{Exp}^x_{\mathsf{A},n,z_n}(0) = 1] - \Pr[\mathsf{Exp}^x_{\mathsf{A},n,z_n}(1) = 1]| = \mathsf{neg}(n)$$

- The public key definition is analogous

Private-key CCA2

- Is the scheme from Construction 16 private-key CCA1 secure?
- CCA2 secure?

Let (G, E, D) be a private key CPA scheme, and let $(\mathrm{Gen}_M, \mathrm{Mac}, \mathrm{Vrfy})$ be an existential unforgeable strong MAC.

Construction 25

- $\mathrm{G}'(1^n)$: Output $(e \leftarrow \mathrm{G}_E(1^n), k \leftarrow \mathrm{Gen}_M(1^n))$.[a]
- $\mathrm{E}'_{e,k}(m)$: let $c = \mathrm{E}_e(m)$ and output $(c, t = \mathrm{Mac}_k(c))$
- $\mathrm{D}_{e,k}(c, t)$: if $\mathrm{Vrfy}_k(c, t) = 1$, output $\mathrm{D}_e(c)$. Otherwise, output $\perp$

[a] We assume for simplicity that the encryption and decryption keys are the same.

Theorem 26

Construction 25 is a private-key CCA2*-secure encryption scheme.*

Proof: ?

Public-key CCA1

Let (G, E, D) be a public-key CPA scheme and let (P, V) be a NIZK for $\mathcal{L} = \{(c_0, c_1, pk_0, pk_1) \colon \exists (m, z_0, z_1) \;\; s.t. \; c_0 = \mathsf{E}_{pk_0}(m, z_0) \wedge c_1 = \mathsf{E}_{pk_1}(m, z_1)\}$

Construction 27 (The Naor-Yung Paradigm)

- $\mathsf{G}'(1^n)$:
  1. For $i \in \{0,1\}$: set $(sk_i, pk_i) \leftarrow \mathsf{G}(1^n)$.
  2. Let $r \leftarrow \{0,1\}^{\ell(n)}$, and output $pk' = (pk_0, pk_1, r)$ and $sk' = (pk', sk_0, sk_1)$
- $\mathsf{E}'_{pk'}(m)$:
  1. For $i \in \{0,1\}$: $c_i = \mathsf{E}_{pk_i}(m, z_i)$, where z_i is a uniformly chosen string of the right length
  2. $\pi \leftarrow \mathsf{P}((c_0, c_1, pk_0, pk_1), (m, z_0, z_1), r)$
  3. Output (c_0, c_1, π).
- $\mathsf{D}'_{sk'}(c_0, c_1, \pi)$: If $\mathsf{V}((c_0, c_1, pk_0, pk_1), \pi, r) = 1$, return $\mathsf{D}_{sk_0}(c_0)$. Otherwise, return $\perp$

Omitted details:

- We assume for simplicity that the encryption key output by $\mathsf{G}(1^n)$ is of length at least n.
- ℓ is an arbitrary polynomial, and determines the maximum message length to encrypt using "security parameter" n.

Is the scheme CCA1 secure? We need the NIZK to be "adaptive secure".

Theorem 28

Assuming that (P, V) *is adaptive secure, then Construction 27 is a public-key* CCA1 *secure encryption scheme.*

Proof: Given an attacker A' for the CCA1 security of $(\mathsf{G}', \mathsf{E}', \mathsf{D}')$, we use it to construct an attacker A on the CPA security of $(\mathsf{G}, \mathsf{E}, \mathsf{D})$.
Let $\mathsf{S} = (\mathsf{S}_1, \mathsf{S}_2)$ be the (adaptive) simulator for $(\mathsf{P}, \mathsf{V}, \mathcal{L})$

Algorithm 29 (A)

Input: $(1^n, pk)$

1. let $j \leftarrow \{0,1\}$, $pk_{1-j} = pk$, $(pk_j, sk_j) \leftarrow \mathrm{G}(1^n)$ and $(r, s) \leftarrow \mathrm{S}_1(1^n)$
2. Emulate $\mathrm{A}'(1^n, pk' = (pk_0, pk_1, r))$ as follows:
3. On query (c_0, c_1, π) of A' to D':
   If $\mathrm{V}((c_0, c_1, pk_0, pk_1), \pi, r) = 1$, answer $\mathrm{D}_{sk_j}(c_j)$.
   Otherwise, answer $\perp$.
4. Output the same pair (m_0, m_1) as A' does
5. On challenge c $(= \mathrm{E}_{pk}(m_b))$:
   - Set $c_{1-j} = c$, $a \leftarrow \{0,1\}$, $c_j = \mathrm{E}_{pk_j}(m_a)$, and $\pi \leftarrow \mathrm{S}_2((c_0, c_1, pk_0, pk_1), r, s)$
   - Send $c' = (c_0, c_1, \pi)$ to A'
6. Output the same value that A' does

Claim 30

Assume that A' breaks the CCA1 security of (G', E', D') with probability $\delta(n)$, then A breaks the CPA security of (G, E, D) with probability $(\delta(n) - \mathrm{neg}(n))/2$.

The adaptive soundness and adaptive zero-knowledge of (P, V), yields that

$$\Pr[A' \text{ “makes" } A(1^n) \text{ decrypt an invalid cipher}] = \mathrm{neg}(n) \quad (5)$$

Hence, only negligible information leaks about j.
Let $A'(1^n, a^*, b^*)$ be the output of $A'(1^n)$ in the emulation induced by A, where $a = a^*$ and $b = b^*$. It holds that

1. $A'(1^n, 0, 1) \equiv A'(1^n, 1, 0)$
2. The adaptive zero-knowledge of (P, V) yields that $|\Pr[A'(1^n, 1, 1) = 1] - \Pr[A'(1^n, 0, 0) = 1]| \geq \delta(n) - \mathrm{neg}(n)$

Let A(b) be the outputs of A when the challenge is b.

$$
\begin{aligned}
&|\Pr[\mathsf{A}(1) = 1] - \Pr[\mathsf{A}(0) = 1]| \\
&\quad = |\frac{1}{2}(\Pr[\mathsf{A}'(0,1) = 1] + \Pr[\mathsf{A}'(1,1) = 1]) \\
&\qquad - \frac{1}{2}(\Pr[\mathsf{A}'(0,0) = 1] + \Pr[\mathsf{A}'(1,0) = 1])| \\
&\quad \geq \frac{1}{2}|\Pr[\mathsf{A}'(1,1) = 1] - \Pr[\mathsf{A}'(0,0) = 1]| \\
&\qquad - \frac{1}{2}|\Pr[\mathsf{A}'(1,0) = 1] - \Pr[\mathsf{A}'(0,1) = 1]| \\
&\quad \geq (\delta(n) - \mathrm{neg}(n))/2
\end{aligned}
$$

Public-key CCA2

- Is Construction 27 CCA2 secure?
- **Problem:** Soundness might not hold with respect to the simulated CRS, after seeing a proof for an *invalid* statement
- **Solution:** use *simulation sound* NIZK