Defining Encryption

Lecture 2
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Simulation & Indistinguishability
Roadmap
Roadmap

First, Symmetric Key Encryption
Roadmap

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Defining the problem

We’ll do it elaborately, so that it will be easy to see different levels of security
Roadmap

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Defining the problem

We’ll do it elaborately, so that it will be easy to see different levels of security

Solving the problem

In theory and in practice
Roadmap

First, Symmetric Key Encryption

Defining the problem

We’ll do it elaborately, so that it will be easy to see different levels of security

Solving the problem

In theory and in practice

Today: defining symmetric-key encryption
Building the Model
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Alice, Bob and Eve. Alice and Bob share a key (a bit string)
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Alice wants Bob to learn a message, “without Eve learning it”
Building the Model

Alice, Bob and Eve. Alice and Bob share a key (a bit string)

Alice wants Bob to learn a message, “without Eve learning it”

Alice can send out a bit string on the channel. Bob and Eve both get it
Encryption: Syntax

Eve's Program

Alice's Program

Bob's Program
Encryption: Syntax

Three algorithms

**Key Generation:** What Alice and Bob do a priori, for creating the shared secret key

**Encryption:** What Alice does with the message and the key to obtain a "ciphertext"

**Decryption:** What Bob does with the ciphertext and the key to get the message out of it
Encryption: Syntax

Three algorithms

**Key Generation**: What Alice and Bob do a priori, for creating the shared secret key

**Encryption**: What Alice does with the message and the key to obtain a “ciphertext”

**Decryption**: What Bob does with the ciphertext and the key to get the message out of it

All of these are (probabilistic) computations
Modeling Computation
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In our model (standard model) parties are programs (computations, say Turing Machines)
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No side-information (timing, electric signals, ...) unless explicitly modeled
Modeling Computation

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- Can be probabilistic.
Modeling Computation

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Can be probabilistic

Ideal coin flips: If $n$ coins flipped, each outcome has probability $2^{-n}$
Modeling Computation

In our model (standard model) parties are programs (computations, say Turing Machines)

Effect of computation limited to be in a blackbox manner (only through input/output functionality)

- No side-information (timing, electric signals, ...) unless explicitly modeled
- Can be probabilistic
- Sometimes stateful

Ideal coin flips: If n coins flipped, each outcome has probability $2^{-n}$
The Environment
The Environment

Where does the message come from?
Where does the message come from?

Eve might already have partial information about the message, or might receive such information later.
The Environment

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- Includes the operating systems and other programs run by the participants, as well as other parties, if in a network.
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The environment

- Includes the operating systems and other programs run by the participants, as well as other parties, if in a network.
- Abstract entity from which the input comes and to which the output goes. Arbitrarily influenced by Eve.
Defining Security
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Eve shouldn't be able to produce any "bad effects" in any environment
Defining Security

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Or increase the probability of "bad effects"
Defining Security

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- Effects in the environment: modeled as a bit in the environment (called the output bit).
Defining Security

- Eve shouldn’t be able to produce any “bad effects” in any environment
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- Effects in the environment: modeled as a bit in the environment (called the output bit)
- What is bad?
Defining Security

Eve shouldn’t be able to produce any “bad effects” in any environment

Or increase the probability of “bad effects”

Effects in the environment: modeled as a bit in the environment (called the output bit)

What is bad?

Anything that Eve couldn’t have caused if an “ideal channel” was used
Defining Security

The REAL/IDEAL Paradigm
Eve shouldn't produce any more effects than she could have in the ideal world.
Defining Security

The REAL/IDEAL Paradigm

Eve shouldn’t produce any more effects than she could have in the ideal world.

IDEAL world: Message sent over a (physically) secure channel. No encryption in this world.
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**IDEAL world**: Message sent over a (physically) secure channel. No encryption in this world.

**REAL world**: Using encryption
The REAL/IDEAL Paradigm

Eve shouldn’t produce any more effects than she could have in the ideal world.

**IDEAL world**: Message sent over a (physically) secure channel. No encryption in this world.

**REAL world**: Using encryption

Encryption is **secure if** whatever Eve can do in the REAL world (using some strategy), she can do in the IDEAL world too (using an appropriate strategy).
Defining Security
The REAL/IDEAL Paradigm
Defining Security
The REAL/IDEAL Paradigm

The REAL/IDEAL Paradigm
Defining Security
A scheme is secure (and correct) if:

- \text{Key/Enc}
- \text{Key/Dec}

The REAL/IDEAL Paradigm

Defining Security
A scheme is secure (and correct) if:

\[ \forall \text{Key/Enc} \]

The REAL/IDEAL Paradigm

Defining Security
Defining Security

The REAL/IDEAL Paradigm

A scheme is secure (and correct) if:

∀ \exists s.t.

Key/Enc

Env

Send

Recv

IDEAL

REAL

Defining Security

The REAL/IDEAL Paradigm

A scheme is secure (and correct) if:

∀ \exists s.t.

Key/Dec

Env
A scheme is secure (and correct) if:

∀ ∈ \exists \text{s.t.} ∀ Key/Enc ∀ Key/Dec

The REAL/IDEAL Paradigm

Defining Security
Defining Security

The REAL/IDEAL Paradigm

A scheme is secure (and correct) if:

∀ output of is distributed identically in REAL and IDEAL
Ready to go...
REAL/IDEAL (a.k.a simulation-based) security forms the basic template for a large variety of security definitions.
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We will see three definitions of symmetric-key encryption.
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Security of “one-time encryption”
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- Security of “one-time encryption”
- Security of (multi-message) encryption
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- Security of “one-time encryption”
- Security of (muti-message) encryption
- Security against “active attacks”
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Will also see alternate (but essentially equivalent) security definitions.
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Will also see alternate (but essentially equivalent) security definitions.
Onetime Encryption
Onetime Encryption
The Syntax

Shared-key (Private-key) Encryption

Key Generation: Randomized

K ← ℋ, uniformly randomly drawn from the key-space
(or according to a key-distribution)

Encryption: Deterministic

Enc: ℳ × ℋ → ℂ

Decryption: Deterministic

Dec: ℂ × ℋ → ℳ
Onetime Encryption
Perfect Secrecy
Onetime Encryption

Perfect Secrecy

\[ \forall m, m' \in \mathcal{M}, \{\text{Enc}(m,K)\}_K^{\leftarrow \text{KeyGen}} = \{\text{Enc}(m',K)\}_K^{\leftarrow \text{KeyGen}} \]
Onetime Encryption

Perfect Secrecy

Perfect secrecy: \( \forall m, m' \in \mathcal{M} \)

\[ \{\text{Enc}(m,K)\}_{K \leftarrow \text{KeyGen}} = \{\text{Enc}(m',K)\}_{K \leftarrow \text{KeyGen}} \]

Distribution of the ciphertext
Onetime Encryption

Perfect Secrecy

**Perfect secrecy:** $\forall m, m' \in \mathcal{M}$

$\{\text{Enc}(m, K)\}_{K \leftarrow \text{KeyGen}} = \{\text{Enc}(m', K)\}_{K \leftarrow \text{KeyGen}}$

*Distribution of the ciphertext*

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<th>2</th>
<th>3</th>
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</thead>
<tbody>
<tr>
<td>a</td>
<td>x</td>
<td>y</td>
<td>y</td>
<td>z</td>
</tr>
<tr>
<td>b</td>
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Onetime Encryption

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Distribution of the ciphertext is defined by the randomness in the key
Onetime Encryption

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Onetime Encryption

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Assuming \( K \) uniformly drawn from \( \mathcal{K} \)

\[
\begin{align*}
\text{Pr}[ \text{Enc}(a, K) = x ] &= \frac{1}{4}, \\
\text{Pr}[ \text{Enc}(a, K) = y ] &= \frac{1}{2}, \\
\text{Pr}[ \text{Enc}(a, K) = z ] &= \frac{1}{4}
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**Onetime Encryption**

**Perfect Secrecy**

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<table>
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Same for \( \text{Enc}(b,K) \).
Onetime Encryption

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In addition, require **correctness**

\( \forall m, K, \ Dec( \text{Enc}(m,K), K) = m \)

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\text{Same for Enc(b,K).}
\end{align*}
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Perfect Secrecy

Onetime Encryption

Perfect Secrecy: \[ \forall m, m' \in M \]

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Distribution of the ciphertext is defined by the randomness in the key

In addition, require correctness

\[ \forall m, K, \quad \text{Dec}(\text{Enc}(m,K), K) = m \]

E.g. One-time pad: \( M = K = C = \{0,1\}^n \) and \( \text{Enc}(m,K) = m \oplus K, \text{Dec}(c,K) = c \oplus K \)

Assuming \( K \) uniformly drawn from \( K \)

\[
\begin{array}{cccc}
M & 0 & 1 & 2 & 3 \\
\hline
a & x & y & y & z \\
b & y & x & z & y \\
\end{array}
\]

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**Onetime Encryption**

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\( \forall m, K, \text{ Dec}(\text{Enc}(m,K), K) = m \)

E.g. **One-time pad:** \( \mathcal{M} = \mathcal{K} = \mathcal{C} = \{0,1\}^n \) and
\[ \text{Enc}(m,K) = m \oplus K, \text{ Dec}(c,K) = c \oplus K \]

More generally \( \mathcal{M} = \mathcal{K} = \mathcal{C} = \mathcal{G} \) (a finite group) and
\[ \text{Enc}(m,K) = m + K, \text{ Dec}(c,K) = c - K \]

Assuming \( K \) uniformly drawn from \( \mathcal{K} \)

- \( \Pr[\text{Enc}(a,K) = x] = \frac{1}{4} \),
- \( \Pr[\text{Enc}(a,K) = y] = \frac{1}{2} \),
- \( \Pr[\text{Enc}(a,K) = z] = \frac{1}{4} \)

Same for \( \text{Enc}(b,K) \).
Onetime Encryption
SIM-Onetime Security

SIM-Onetime secure if:
\(\forall \exists \text{s.t.}\)

\(\forall \text{IDEAL=REAL}\)
Onetime Encryption

SIM-Onetime Security

Class of environments which send only one message

SIM-Onetime secure if:
∀
∃
s.t.
∀
IDEAL=REAL
Onetime Encryption

SIM-Onetime Security

Class of environments which send only one message:

\[ \forall \exists \text{s.t.} \forall \]

\[ \text{Key/Enc} \rightarrow \text{Env} \rightarrow \text{Send} \rightarrow \text{Recv} \rightarrow \text{Key/Dec} \]

\[ \text{IDEAL} = \text{REAL} \]

SIM-Onetime secure if:

\[ \forall \exists \text{s.t.} \forall \]

\[ \text{IDEAL} = \text{REAL} \]

Equivalent to perfect secrecy + correctness
Perfect Secrecy + Correctness $\implies$ SIM-Onetime Security
Perfect Secrecy + Correctness $\Rightarrow$ SIM-Onetime Security

Consider this simulator: Runs adversary internally and lets it talk to the environment directly!
Perfect Secrecy + Correctness $\Rightarrow$ SIM-Onetime Security

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Consider this simulator: Runs adversary internally and lets it talk to the environment directly!
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Can show that IDEAL = REAL.
Consider this simulator: Runs adversary internally and lets it talk to the environment directly! Feeds it encryption of a dummy message.

Can show that IDEAL=REAL (Consider view of + for both)
Implicit Details
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Random coins used by the encryption scheme is kept private within the programs of the scheme (KeyGen, Enc, Dec)
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In particular no timing attacks
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- Message space is finite and known to Eve (and Eve’)
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- Message space is finite and known to Eve (and Eve’)
- Alternately, if message length is variable, it is given out to Eve’ in IDEAL as well
**Implicit Details**

- Random coins used by the encryption scheme is kept private within the programs of the scheme (KeyGen, Enc, Dec).

- If key is used for anything else (i.e., leaked to the environment) no more guarantees.

- In REAL, Eve+Env’s only inputs are ciphertext and Bob’s output.

- In particular no timing attacks.

- Message space is finite and known to Eve (and Eve’).

- Alternately, if message length is variable, it is given out to Eve’ in IDEAL as well.

- Also, Eve’ allowed to learn the fact that a message is sent.
Onetime Encryption

IND-Onetime Security
Onetime Encryption

IND-Onetime Security

IND-Onetime Experiment
Onetime Encryption

IND-Onetime Security

IND-Onetime Experiment
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IND-Onetime Security

IND-Onetime Experiment
Onetime Encryption
IND-Onetime Security

IND-Onetime Experiment

Experiment picks a random bit $b$. It also runs KeyGen to get a key $K$
Onetime Encryption

IND-Onetime Security

IND-Onetime Experiment

Experiment picks a random bit $b$. It also runs KeyGen to get a key $K$.
Onetime Encryption

IND-Onetime Security

- IND-Onetime Experiment
  - Experiment picks a random bit $b$. It also runs KeyGen to get a key $K$.
  - Adversary sends two messages $m_0$, $m_1$ to the experiment.
Onetime Encryption

IND-Onetime Security

- **IND-Onetime Experiment**

  - Experiment picks a random bit $b$. It also runs KeyGen to get a key $K$.

  - Adversary sends two messages $m_0$, $m_1$ to the experiment.

  - Experiment replies with $\text{Enc}(m_b, K)$. 

  - $b \leftarrow \{0, 1\}$
**Onetime Encryption**

**IND-Onetime Security**

**IND-Onetime Experiment**

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IND-Onetime Experiment

Experiment picks a random bit $b$. It also runs KeyGen to get a key $K$.

Adversary sends two messages $m_0, m_1$ to the experiment.

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Adversary returns a guess $b'$.
**Onetime Encryption**

**IND-Onetime Security**

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  - Experiment picks a random bit \( b \). It also runs KeyGen to get a key \( K \).
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\[ b \leftarrow \{0,1\} \]

\[ b' = b? \]
**Onetime Encryption**

**IND-Onetime Security**

- **IND-Onetime Experiment**
  - Experiment picks a random bit $b$. It also runs KeyGen to get a key $K$.
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  - Experiments outputs 1 iff $b' = b$.
### Onetime Encryption

**IND-Onetime Security**

- **IND-Onetime Experiment**
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  - **IND-Onetime secure if** for every adversary, $\Pr[b' = b] = 1/2$.
**Onetime Encryption**

**IND-Onetime Security**

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Equivalent to perfect secrecy.
Perspective on Definitions
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“Technical” vs. “Convincing”
Perspective on Definitions

“Technical” vs. “Convincing”

For simple scenarios technical definitions could be convincing
Perspective on Definitions

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e.g. Perfect Secrecy
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IND- definitions tend to be technical: more low-level details, but may not make the big picture clear. Could have “weaknesses”
Perspective on Definitions

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SIM- definitions give the big picture, but may not give details of what is involved in satisfying it. Could be “too strong”
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For simple scenarios technical definitions could be convincing

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SIM- definitions give the big picture, but may not give details of what is involved in satisfying it. Could be “too strong”

Best of both worlds when they are equivalent: use IND- definition while say, proving security of a construction; use SIM- definition when low-level details are not important