CSE 565 Computer Security
Fall 2018

Lecture 2: Symmetric Encryption I

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Cryptographic Tools

- Cryptographic tools are essential in designing secure solutions and their understanding is crucial to correct usage
- We'll look at these types of cryptographic tools
  - symmetric encryption
  - hash functions and message authentication codes
  - public-key encryption
  - digital signatures and certificates
  - pseudo-random number generators
- The most basic problem of cryptography
  - ensure security of communication over insecure media

Goals of Cryptography

- **Security goals**
  - **confidentiality**
  - **data integrity**
- **Basic encryption terminology**
  - **plaintext**
  - **ciphertext**
  - **cryptographic key**
  - **encryption**
  - **decryption**
  - **cryptanalysis**

Symmetric Encryption

- **Symmetric (or secret-key) encryption means that the same key is used both for encryption and decryption**
- **The key must remain secret at both ends**
- **Such algorithms are:**
  - **normally very fast**
  - **can be used as primitives in more complex cryptographic protocols**
  - **the key often has a short lifetime**

Symmetric Encryption Formally

- **More formally, a computationally secure symmetric key encryption scheme is defined as:**
  - **a private-key encryption scheme consists of polynomial-time algorithms** (Gen, Enc, Dec) **such that**
    1. Gen**: on input the security parameter** n**, outputs key** k
    2. Enc**: on input a key** k **and a message** $m \in \{0,1\}^*$**, outputs ciphertext** c
    3. Dec**: on input a key** k **and ciphertext** c**, outputs plaintext** m
  - **we write** $k \leftarrow \mathsf{Gen}(1^n)$**,** $c \leftarrow \mathsf{Enc}_k(m)$**, and** $m := \mathsf{Dec}_k(c)$
    - **this notation means that** Gen **and** Enc **are probabilistic and** Dec **is deterministic**

Symmetric Encryption

- The above definition allows us to encrypt messages of any length
- In practice, there are Two types of symmetric key algorithms:
  - block ciphers
    - the key has a fixed size
    - prior to encryption, the message is partitioned into blocks
    - each block is encrypted and decrypted separately
  - stream ciphers
    - the message is processed as a stream
    - pseudo-random generator is used to produce a long key stream from a short key

Attacks Against Symmetric Encryption

- Encryption and decryption algorithms are assumed to be known to the adversary
- Types of attacks
  - ciphertext only attack: adversary knows a number of ciphertexts
  - known plaintext attack: adversary knows some pairs of ciphertexts and corresponding plaintexts
  - chosen plaintext attack: adversary knows ciphertexts for messages of its choice
  - chosen ciphertext attack: adversary knows plaintexts for ciphertexts of its choice
- We want a general-purpose algorithm to sustain all types of attacks

Security Against Chosen-Plaintext Attacks

- **In chosen-plaintext attack (CPA), adversary $\mathcal{A}$ is allowed to ask for encryptions of messages of its choice**
  - **it is active and adaptive**
- **$\mathcal{A}$ is given black-box access to encryption oracle and can query it on different messages**
  - **notation $\mathcal{A}^{\mathcal{O}(\cdot)}$ means $\mathcal{A}$ has oracle access to algorithm $\mathcal{O}$**
- **$\mathcal{A}$ is asked to distinguish between encryptions of messages of its choice**

CPA Security

- **CPA indistinguishability experiment** $\mathsf{PrivK}^{\mathsf{cpa}}_{\mathcal{A},\mathcal{E}}(n)$
  1. **random key** k **is generated by** $\mathsf{Gen}(1^n)$
  2. $\mathcal{A}$ **is given** 1^n **and ability to query** $\mathsf{Enc}_k(\cdot)$**, and chooses two messages** m_0, m_1 **of the same length**
  3. **random bit** $b \leftarrow \{0,1\}$ **is chosen, challenge ciphertext** $c \leftarrow \mathsf{Enc}_k(m_b)$ **is computed and given to** $\mathcal{A}$
  4. $\mathcal{A}$ **can use** $\mathsf{Enc}_k(\cdot)$ **and eventually outputs bit** b'
  5. **experiment outputs 1 if** $b' = b$ **(**$\mathcal{A}$ **wins) and 0 otherwise**

- $\mathcal{E} = (\mathsf{Gen}, \mathsf{Enc}, \mathsf{Dec})$ **has indistinguishable encryptions under the chosen-plaintext attack (CPA-secure) if for all PPT** $\mathcal{A}$

$$\Pr[\mathsf{PrivK}^{\mathsf{cpa}}_{\mathcal{A},\mathcal{E}}(n) = 1] \leq \frac{1}{2} + \mathsf{negl}(n)$$

Block Ciphers

- The algorithm maps an n-bit plaintext block to an n-bit ciphertext block
- Most modern block ciphers are product ciphers
  - we sequentially apply more than one operation to the message
- Often a sequence of permutations and substitutions is used
- A common design for an algorithm is to proceed in iterations
  - one iteration is called a round
  - each round consists of similar operations
  - ith round key k_i is derived from the secret key k using a fixed, public algorithm

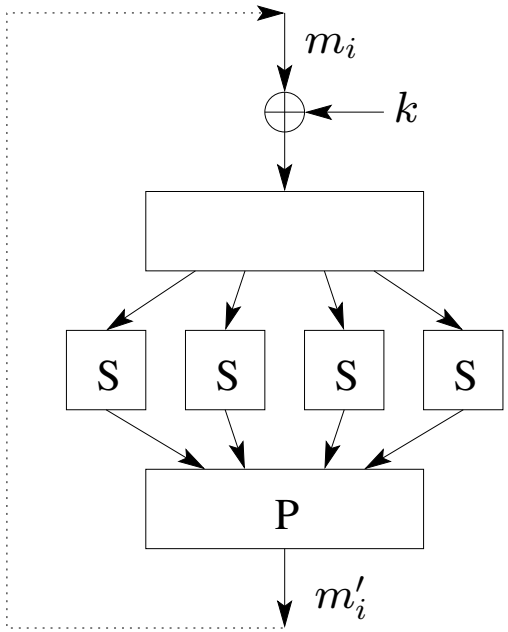
Design Principles of Block Ciphers

- **Confusion-diffusion paradigm**
  - **split a block into small chunks**
  - **define a permutation on each chunk separately (confusion)**
  - **mix outputs from different chunks by rearranging bits (diffusion)**
  - **repeat to strengthen the result**

Design Principles of Block Ciphers

- **Substitution-permutation networks**
  - **since a permutation on a block can be specified as a lookup table, this is called substitution**
  - **instead of having substitutions defined by the key, such functions are fixed and applied to messages and keys**
  - **mixing algorithm is called mixing permutation**

Design Principles of Block Ciphers



- **For this type of algorithm to be reversible, each operation needs to be invertible**

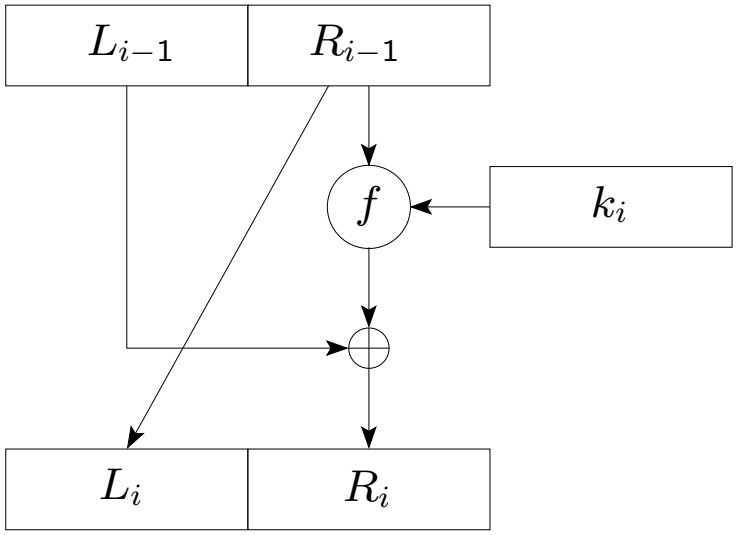
Design Principles of Block Ciphers

- Let's denote one iteration or round by function g
- The initial state s_0 is the message m itself
- In round i:
  - g's input is round key k_i and state s_{i-1}
  - g's output is state s_i
- The ciphertext c is the final state s_{Nr}, where Nr is the number of rounds
- Decryption algorithm applies g^{-1} iteratively
  - the order of round keys is reversed
  - set $s_{Nr} = c$, compute $s_{i-1} = g^{-1}(k_i, s_i)$

Design Principles of Block Ciphers

- **Another way to realize confusion-diffusion paradigm is through Feistel network**
  - **in Feistel network each state is divided into halves of the same length: L_i and R_i**
  - **in one round:**
    - $L_i = R_{i-1}$
    - $R_i = L_{i-1} \oplus f(k_i, R_{i-1})$

Design Principles of Block Ciphers



- **Are there any advantages over the previous design?**
  - **operations no longer need to be reversible, as the inverse of the algorithm is not used!**
  - **reverse one round's computation as $R_{i-1} = L_i$ and $L_{i-1} = R_i \oplus f(k_i, R_{i-1})$**

Design Principles of Block Ciphers

- In both types of networks, the substitution and permutation algorithms must be carefully designed
  - choosing random substitution/permutation strategies leads to significantly weaker ciphers
  - each bit difference in S-box input creates at least 2-bit difference in its output
  - mixing permutation ensures that difference in one S-box propagates to at least 2 S-boxes in next round

Block Ciphers

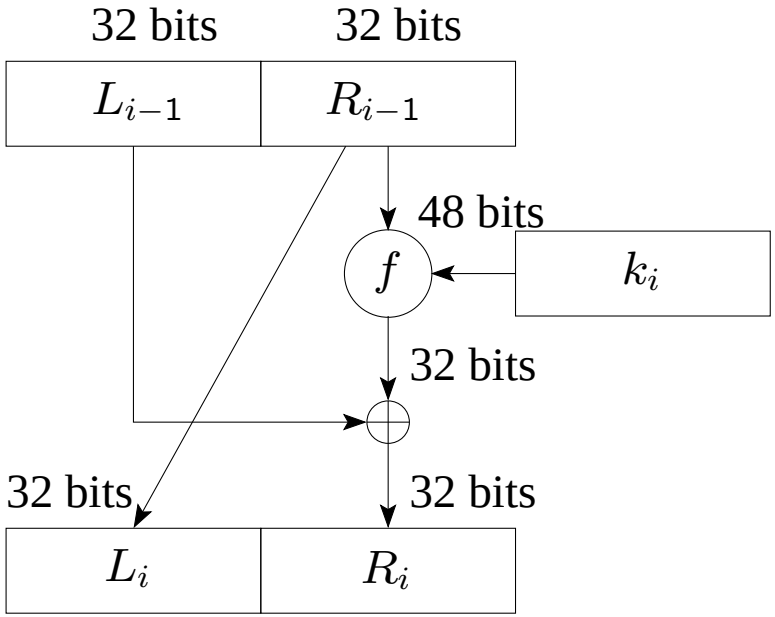
- **Larger key size means greater security**
  - **for n-bit keys, brute force search takes $2^n/2$ time on average**
- **More rounds often provide better protection**
  - **the number of rounds must be large enough for proper mixing**
- **Larger block size offers increased security**
  - **security of a cipher also depends on the block length**

Data Encryption Standard (DES)

- In 1973 National Institute of Standards and Technology (NIST) published a solicitation for cryptosystems
- DES was developed by IBM and adopted as a standard in 1977
- It was expected to be used as a standard for 10–15 years
- Was replaced only in 2001 with AES (Advanced Encryption Standard)
- DES characteristics:
  - key size is 56 bits
  - block size is 64 bits
  - number of rounds is 16

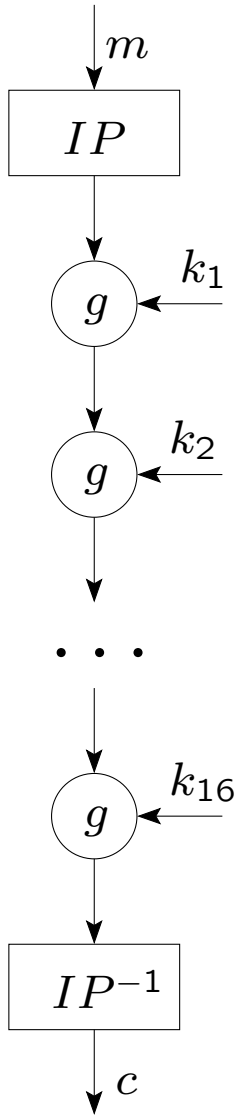
DES

- **DES uses Feistel network**
  - **Feistel network is used in many block ciphers such as DES, RC5, etc.**
  - **not used in AES**
  - **in DES, each L_i and R_i is 32 bits long; k_i is 48 bits long**



DES

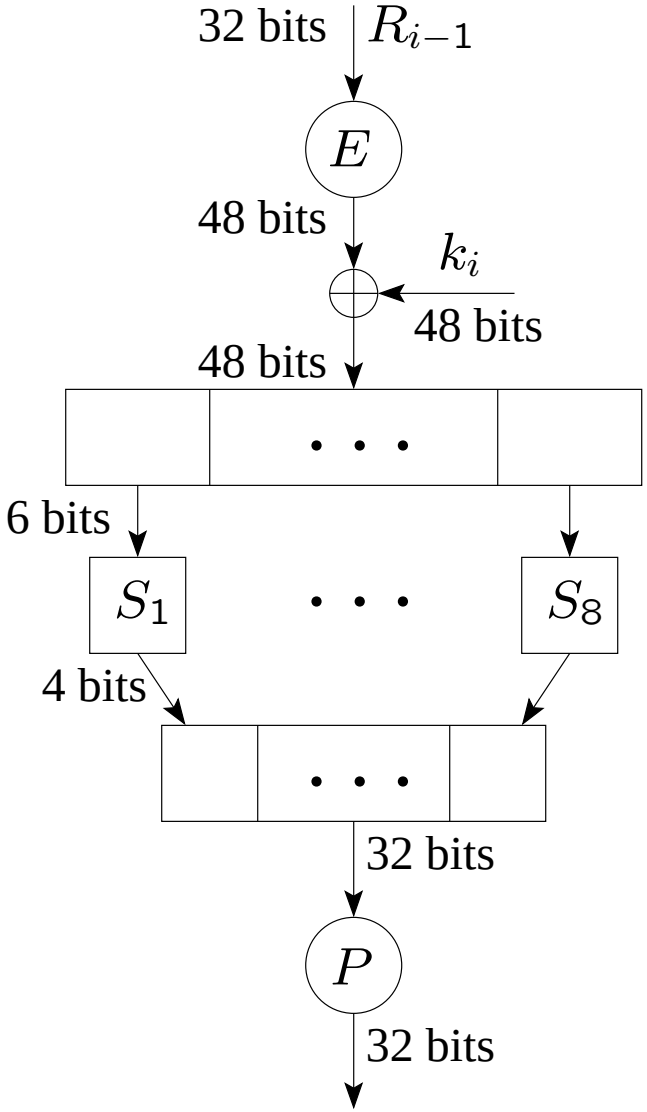
- **DES has a fixed initial permutation IP prior to 16 rounds of encryption**
- **The inverse permutation IP^{-1} is applied at the end**



DES

- **The f function $f(k_i, R_{i-1})$**
  1. **first expands R_{i-1} from 32 to 48 bits (k_i is 48 bits long)**
  2. **XORs expanded R_{i-1} with k_i**
  3. **applies substitution to the result using S-boxes**
  4. **and finally permutes the value**

DES f Function



DES

- **There are 8 S-boxes**
  - **S-boxes are the only non-linear elements in DES design**
  - **they are crucial for the security of the cipher**
- **Example:** S_1

14	**4**	**13**	**1**	**2**	**15**	**11**	**8**	**3**	**10**	**6**	**12**	**5**	**9**	**0**	**7**
0	**15**	**7**	**4**	**14**	**2**	**13**	**1**	**10**	**6**	**12**	**11**	**9**	**5**	**3**	**8**
4	**1**	**14**	**8**	**13**	**6**	**2**	**11**	**15**	**12**	**9**	**7**	**3**	**10**	**5**	**0**
15	**12**	**8**	**2**	**4**	**9**	**1**	**7**	**5**	**11**	**3**	**14**	**10**	**0**	**6**	**13**

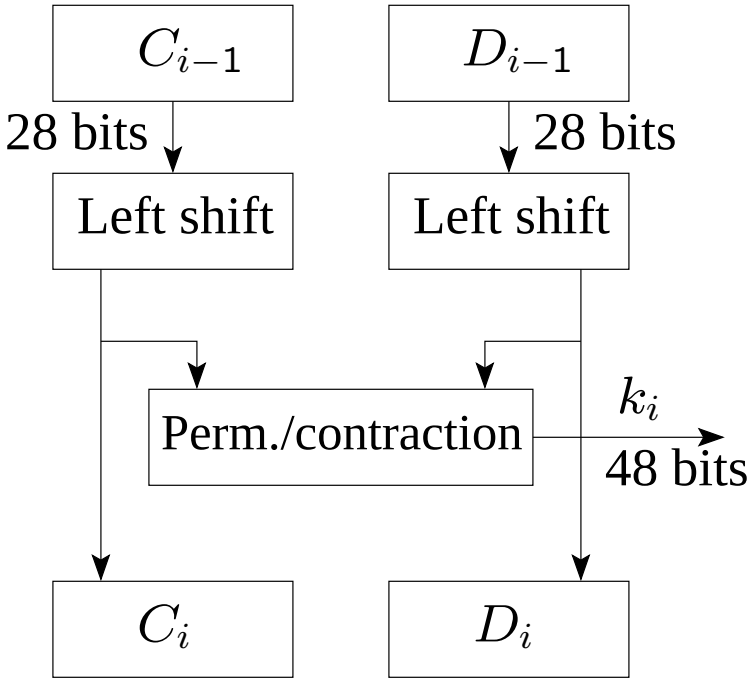
  - **input to each S-box is 6 bits** $b_1b_2b_3b_4b_5b_6$
  - **row =** b_1b_6**, column =** $b_2b_3b_4b_5$
  - **output is 4 bits**

DES

- **More about S-boxes..**
  - **a modified version of IBM's proposal was accepted as the standard**
  - **some of the design choices of S-boxes weren't public, which triggered criticism**
  - **in late 1980s – early 1990s differential cryptanalysis techniques were discovered**
  - **it was then revealed that DES S-boxes were designed to prevent such attacks**
  - **such cryptanalysis techniques were known almost 20 years before they were discovered by others**

DES Key Schedule

- **Key computation consists of:**
  - **circular shift**
  - **permutation**
  - **contraction**



DES

- **Why does decryption work?**
  - **round function g is invertible**
    - **compute $L_{i-1} = R_i \oplus f(k_i, L_i)$**
    - **compute $R_{i-1} = L_i$**
  - **in the beginning apply IP and at the end apply IP^{-1}**
  - **round keys $k_{16}, \ldots, k_1$ and the f function are computed as before**

DES Weak Keys

- The master key k is used to generate 16 round keys
- Some keys result in the same round key to be generated in more than one round
  - this reduces complexity of the cipher
- Solution: check for weak keys at key generation
- DES has 4 weak keys:
  - `0000000 0000000`
  - `0000000 FFFFFFF`
  - `FFFFFFF 0000000`
  - `FFFFFFF FFFFFFF`

Attacks on DES

- **Brute force attack: try all possible 2^{56} keys**
  - **time-consuming, but no storage requirements**
- **Differential cryptanalysis: traces the difference of two messages through each round of the algorithm**
  - **was discovered in early 90s**
  - **not effective against DES**
- **Linear cryptanalysis: tries to find linear approximations to describe DES transformations**
  - **was discovered in 1993**
  - **has no practical implication**

Brute Force Search Attacks on DES

- It was conjectured in 1970s that a cracker machine could be built for $20 million
- In 1990s RSA Laboratories called several DES challenges
  - Challenge II-2 was solved in 1998 by Electronic Frontier Foundation
    - a DES Cracker machine was built for less than $250,000 and found the key was in 56 hours
  - Challenge III was solved in 1999 by the DES Cracker in cooperation with a worldwide network of 100,000 computers
    - the key was found in 22 hours 15 minutes
    - `http://www.distributed.net/des`

Increasing Security of DES

- **DES uses a 56-bit key and this raised concerns**
- **One proposed solution is double DES**
  - **apply DES twice by using two different keys k_1 and k_2**
  - **encryption $c = E_{k_2}(E_{k_1}(m))$**
  - **decryption $m = D_{k_1}(D_{k_2}(c))$**
- **The resulting key is $2 \cdot 56 = 112$ bits, so it should be more secure, right?**
  - **an attack called meet-in-the-middle discovers keys k_1 and k_2 with 2^{56} computation and storage**
  - **better, but not substantially than regular DES**

Triple DES

- **Triple DES with two keys k_1 and k_2:**
  - **encryption** $c = E_{k_1}(D_{k_2}(E_{k_1}(m)))$
  - **decryption** $m = D_{k_1}(E_{k_2}(D_{k_1}(c)))$
  - **key space is** $2 \cdot 56 = 112$ **bits**
- **Triple DES with three keys k_1, k_2, and k_3:**
  - **encryption** $c = E_{k_3}(D_{k_2}(E_{k_1}(m)))$
  - **decryption** $m = D_{k_1}(E_{k_2}(D_{k_3}(c)))$
  - **key space is** $3 \cdot 56 = 168$ **bits**
- **There is no known practical attack against either version**
- **Can be made backward compatible by setting $k_1 = k_2$ or $k_3 = k_2$**

Summary of Attacks on DES

- **DES**
  - **best attack: brute force search**
  - 2^{55} **work on average**
  - **no other requirements**
- **Double DES**
  - **best attack: meet-in-the-middle**
  - **requires 2 plaintext-ciphertext pairs**
  - **requires 2^{56} space and about 2^{56} work**
- **Triple DES**
  - **best practical attack: brute force search**