CSE 410/565 Computer Security
Spring 2022

Lecture 2: Symmetric Encryption I

Department of Computer Science and Engineering
University at Buffalo

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

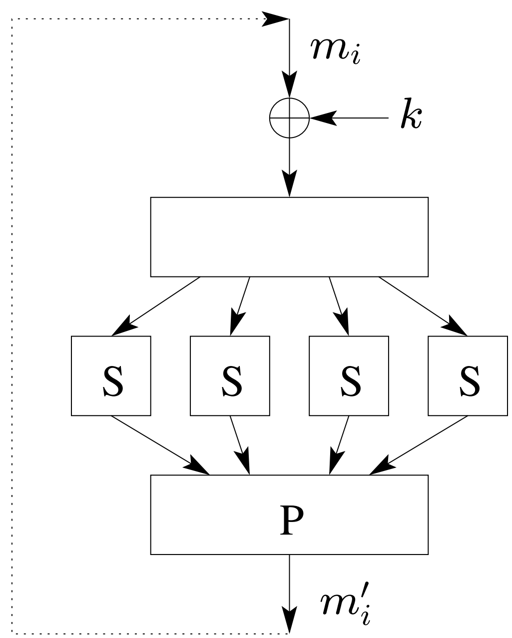
Design Principles of Block Ciphers

- 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

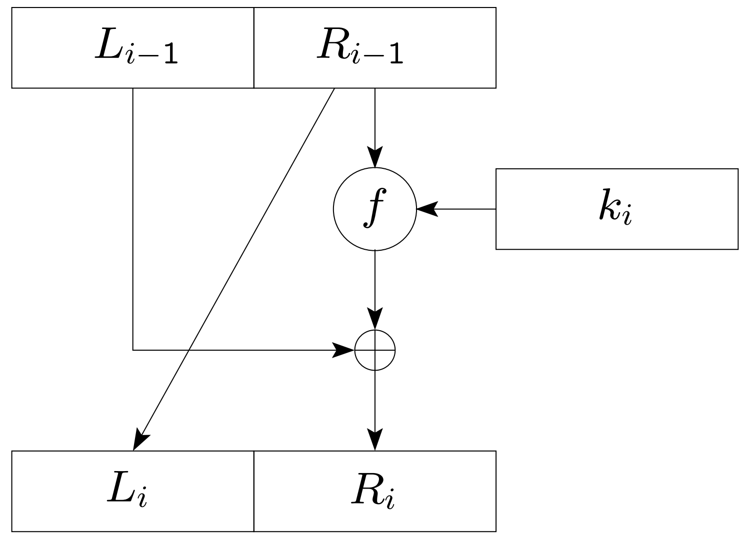
Design Principles of Block Ciphers

- 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

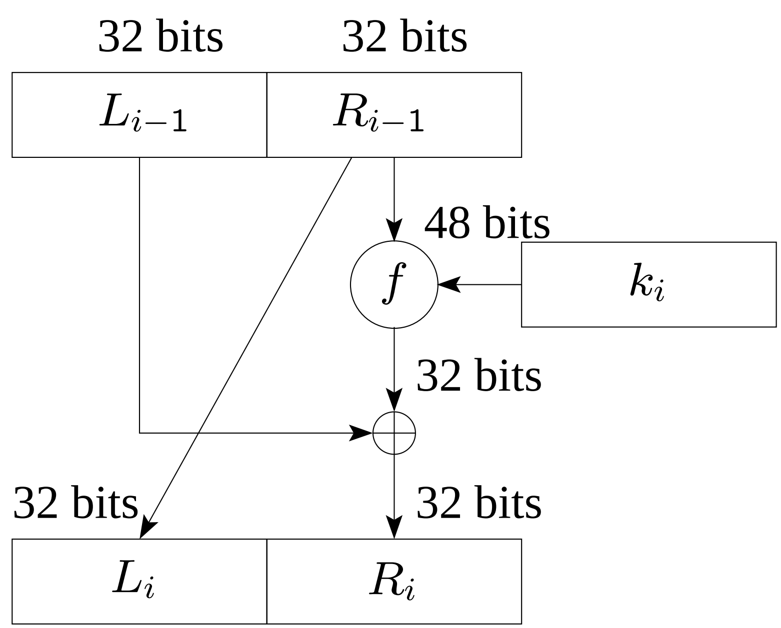
- Larger key size means greater security
  - for n-bit keys, brute force search takes $2^n/2$ time on average
- More rounds often provide better protection
  - the number of rounds must be large enough for proper mixing
- Larger block size offers increased security
  - security of a cipher also depends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

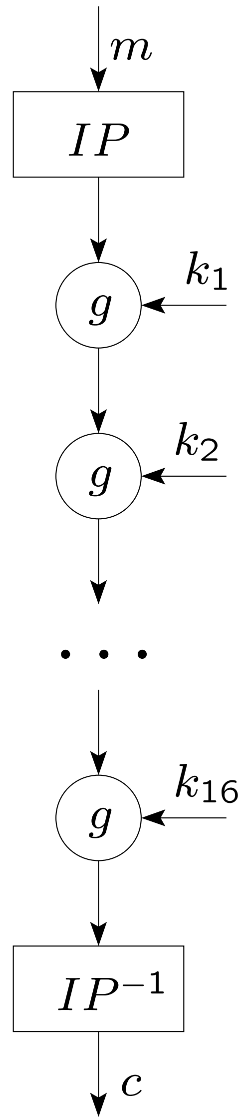
- DES uses Feistel network
  - Feistel network is used in many block ciphers such as DES, RC5, etc.
  - not used in AES
  - in DES, each L_i and R_i is 32 bits long; k_i is 48 bits long



DES

- DES has a fixed initial permutation IP prior to 16 rounds of encryption

- The inverse permutation IP^{-1} is applied at the end

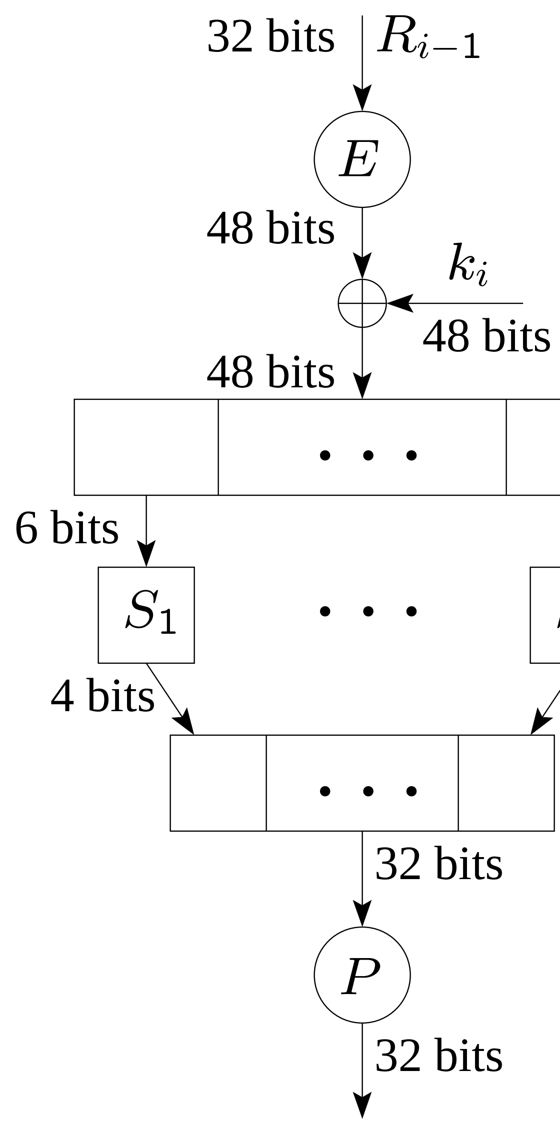


DES

- 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

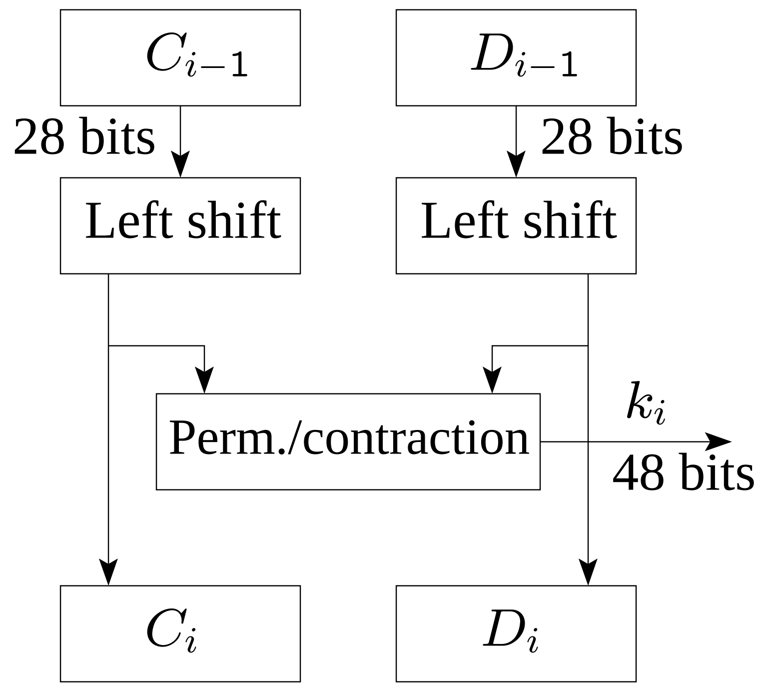
  - input to each S-box is 6 bits $b_1 b_2 b_3 b_4 b_5 b_6$
  - row = $b_1 b_6$, column = $b_2 b_3 b_4 b_5$
  - output is 4 bits

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