University of Houston

Foundations of Security

COSC 6347

Midterm Review

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1 Introduction to Security

1.1 Objectives

	Term	Definition
CIA	Confidentiality	not available to unauthorized entities
	Integrity	cannot be altered by unauthorized entities
	Availability	available to authorized entities
	Non-repudiation Accountability	actions can be provably traced back to an entity
	Privacy	individuals have control over information related to them

1.2 Challenges

Weakest link – principle that the defender needs to find and fix all vulnerabilities, but attacker needs to find only a single vulnerability

Security is a process, not a product – attackers continuously looking for new vulnerabilities, so systems must be regularly updated and continuously monitored.

Tension between security and
- usability
- functionality
- efficiency
- time-to-market
- development cost

Value of security often only perceived when there is a security failure

Can be measured by

- checking compliance
- pentesting

2 Introduction to Cryptography

2.1 Attacker Modeling Principles

Security is defined with respect to an attacker model – what the attacker
- can do
- knows
- wants to achieve

Generally better to overestimate the attacker's capabilities, knowledge, and determination.

Safe to assume attacker knows

- algorithms
- system design
- implementation
- configuaration

but the attacker cannot know *truly* random values.

2.2 Security by Obscurity

Security by obscurity – providing security by keeping the design or implementation of a system secret

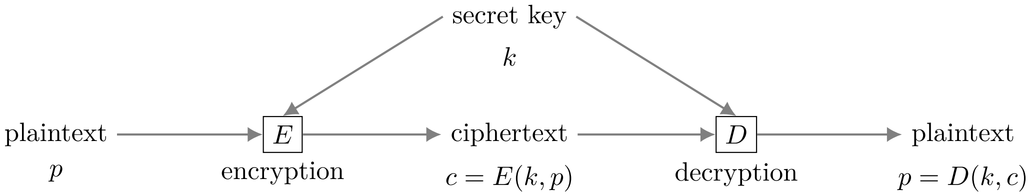
Generally rejected by security experts, researchers, standard bodies, i.e., everyone.

Obscurity can slow down, but not stop, an attack:
- if we thought of something, attacker might also
- attacker might try attack for many possible design/implementation choices

Can create false sense of security.

2.3 Symmetric-Key Ciphers

Sender and receiver share a secret key k



Types of attacks:

Acronym	Attack	Description
COA	ciphertext only	only the algorithms used and the ciphertext are known
KPA	known plaintext	one or more plaintext-cipher pairs is known
CCA	chosen ciphertext	one or more *chosen* plaintext-cipher pairs is known
CPA	chosen plaintext	can obtain the ciphertext for any plaintext
CTA	chosen text	both chosen ciphertext and chosen plaintext
	brute-force	every possible key is tried
	cryptanalytic	relies on the nature of the algorithm/characteristics of the plaintext

2.4 Kerckhoffs's Principle

Kerckhoffs's Principle – a cryptographic system should be secure, even if all of its details, except for the key, are publicly known. Rejection of security by obscurity

3 Stream Ciphers

3.1 Perfect Security

Perfect security – attacker gains no information about the plaintext from observing the ciphertext, formally,

$$\mathbb{P}(P = p) = \mathbb{P}(P = p \mid E(K, P) = c)$$

i.e., that the plaintext and ciphertext are independent

One-time pad – perfect security in which a single-use encryption key at least as long as the plaintext is chosen randomly and used to encrypt only a single message

3.2 Semantic Security

Semantic security – attacker advantage for any efficiently computable guess is negligible over random guessing

Many-time pad: reusing the one-time key for multiple plaintext. Attacker can recover $p_1 \oplus p_2$:

$$\begin{aligned} c_1 \oplus c_2 &= (p_1 \oplus k) \oplus (p_2 \oplus k) \\ &= (p_1 \oplus p_2) \oplus (k \oplus k) \\ &= p_1 \oplus p_2 \end{aligned}$$

and if attacker knows p_1, can recover p_2:

$$\begin{aligned} p_1 \oplus (c_1 \oplus c_2) &= p_1 \oplus (p_1 \oplus p_2) \\ &= (p_1 \oplus p_1) \oplus p_2 \\ &= p_2 \end{aligned}$$

3.3 General Model of Stream Ciphers

Make one-time pad practical by securely extending the key.

Pseudorandom Number Generator

pseudorandom number generator (PRNG) – takes fixed-length seed and generates a sequence of bits using a deterministic algorithm

Requirements:

- performance – generates key as long as plaintext, so must be computationally efficient
- security – generated sequence must be indistinguishable from true randomness
  - cryptanalytic attack
    - uniform distribution – 0s and 1s occur with approximately same frequency
    - independence – no subsequence can be inferred from another, disjoint subsequence
  - brute-force attack
    - n bit key has 2^n possible values – attacker can try all
    - key must be sufficiently long – in 2014, NIST recommends 112-bits
    - as computers become faster, key length must be increased

How Stream Cipher Works

stream cipher – takes fixed-length seed and uses a PRNG to produce sequence of bits as long as the plaintext then encrypts with XOR

Use PRNG to generate the sequence up to the length of the plaintext, then to

encrypt — XOR plaintext with key
decrypt — XOR ciphertext with key

3.4 Key-Reuse Problem

If attacker learns $p_1 \oplus p_2$, $p_2 \oplus p_3$, $p_1 \oplus p_3$, ..., they can recover other plaintexts. Solutions:

- one continuous sequence that allows seeking to any position in the key
- nonce – number used once
  - xor key with nonce for each plaintext to produce different key

3.5 RC4

Old WiFi and Web Security standard

RC4 Advantages

- variable key length (from 8 to 2048 bits)
- very simple, uses byte-oriented operations:
  - only 8 to 16 machine operations required per output byte

Applications

- Wifi: WEP and WPA
  - broken in 2001, deprecated in 2004
- Web Security (HTTPS): SSL and TLS
  - broken in 2013, deprecated in 2015

RC4 has been retired.

3.6 Salsa20/ChaCha20

State of the Art Stream Cipher Salsa20 (and more secure, more efficient variant ChaCha20)

Key length is 128 or 256 bits.

Advantages

- fast software implementation (simple 32-bit operations)
- can seek to any position in output sequence
- 64-bit nonce part of algorithm to prevent key-reuse

currently, no attacks better than brute-force attack known.

Algorithm

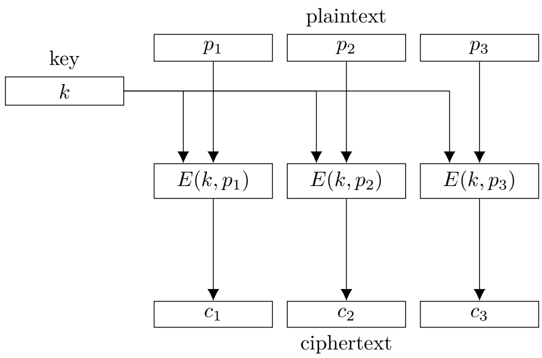
- Output in blocks of 16×32 bits
- internal state: 16×32 bits
  - initialized using key, nonce, and seek position
- State updated with XOR, 32-bit addition mod 2^{32}, and rotating 32 bit values
- Performs 20 rounds of XOR-add-rotate, each of which updates all values in state
- State added to original state to obtain output

4 Block Ciphers

Unlike stream ciphers, block ciphers have different encryption and decryption operations. A block cipher encrypts plaintext in fixed-length blocks

4.1 Design Considerations

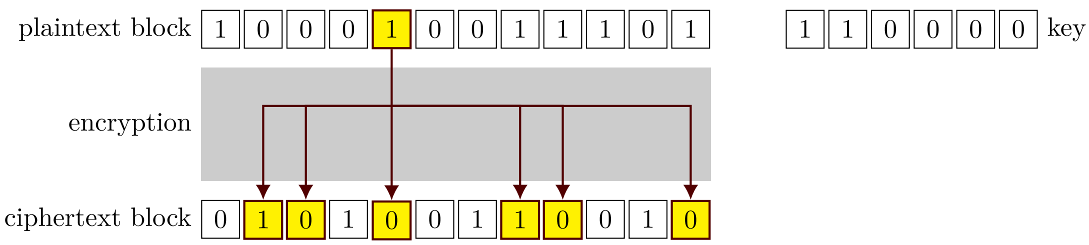
- Key Size
  - number of possible k-bit keys is 2^k
  - k must be sufficiently large to prevent brute-force attacks
- Block Size
  - too short $\rightarrow$ does not hide patterns in plaintext
    - e.g. $n = 8$ bits is 1 character
    - same as substitution cipher
  - too long – impractical, wasteful
- encryption must be invertible
  - different input blocks must be transformed into different output blocks
  - can be viewed as a permutation on all n-bit blocks
  - $(2^n)!$ possible permutations



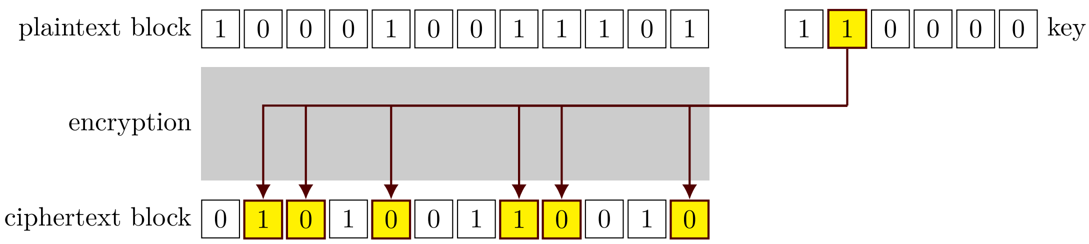
4.2 Secure Block Cipher

An n-bit block cipher is secure (for a computationally bounded attacker) if it is indistinguishable from a random permutation of n-bit blocks.

diffusion – each plaintext bit should affect the value of many ciphertext bits



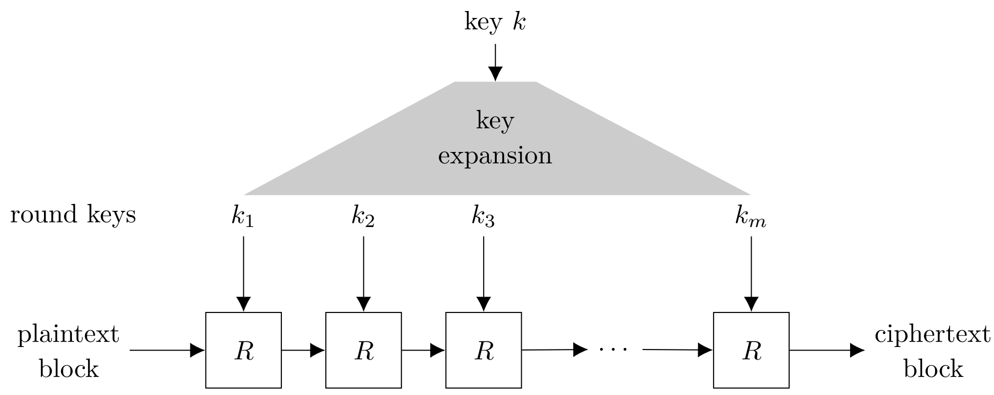
confusion – each bit of the ciphertext should depend on many bits of the key



4.3 Iterated Block Ciphers

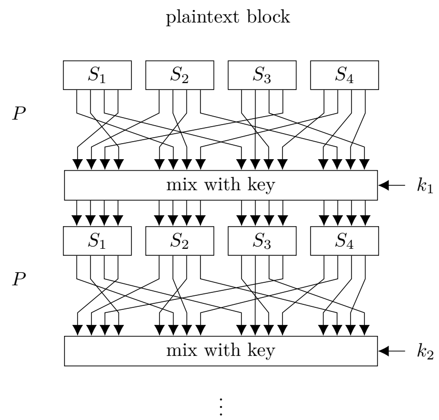
Hard to design a single invertible function that satisfies diffusion and confusion. Use a round function

- R – round function
  - relatively weak transformation that introduces diffusion and confusion
  - by iterating, builds strong block cipher



4.4 Substitution-Permutation Ciphers

Common subtype of iterated block cipher, each round R consists of

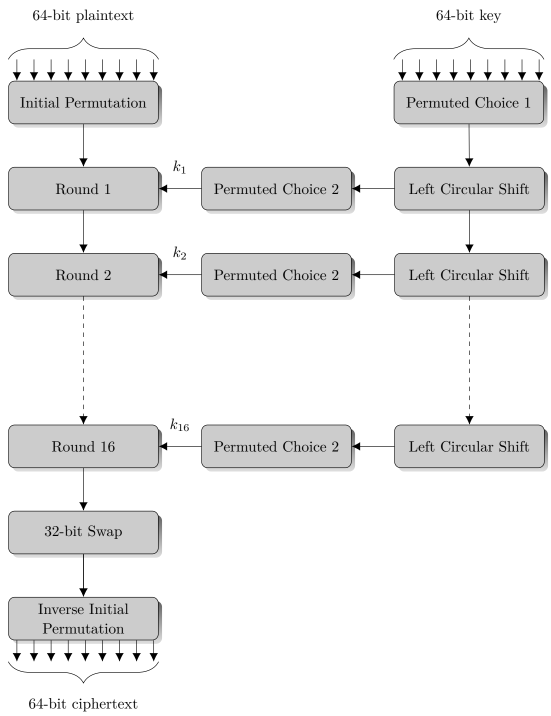


- Substitution S
  - substitutes small block with another small block
  - ideally, changing one input bit changes half of output bits
- Permutation P
  - permutation of all bits

4.5 DES

Data Encryption Standard (DES)

- block size – 64 bits
- key size – 56 bits
  - 56 bit random
  - 8 bit parity check
- iterated substitution cipher of 16 rounds
- initial permutation
  - no cryptographic significance
  - facilities loading blocks in and out of 8-bit hardware
- key permutation
  - discards parity bits
  - no cryptographic significance



4.6 Feistel Network

Consists of encryption and decrpytion round

- Encryption round
  - input – block from previous round (or plaintext)
  - divide input in half – L_i and R_i
  - derive round key k_i from secret key (different each round)
  - output

$$L_{i+1} = R_i$$
$$R_{i+1} = L_i \oplus F(k_i, R_i)$$

- Decryption round
  - we can invert encryption without inverting F

$$R_i = L_{i+1}$$
$$L_i = R_{i+1} \oplus F(k_i, L_{i+1}) = R_{i+1} \oplus F(k_i, R_i)$$

DES is vulnerable to brute-force attacks.

4.7 AES

Advanced Encryption Standard (AES)

- Substitution-permutation
  - but **not** a Feistel network
- each round must be invertible for decrpytion
- key expansion and schedule – generates different round key each round
- number of rounds n depends on key size k

k	n
128	10
192	12
256	14

4.8 AES Round

- input
  - 128-bit state from previous round (or plaintext) as 4×4 byte matrix
  - 128-but round key from key schedule
- output – 128-bit state
- each round consists of multiple steps
  - AddRoundKey – xor round key to state
  - 128-but round key from key schedule
  - substitution and permutation
    * SubBytes
    * ShiftRows
    * MixColumns

SubBytes

- Each byte is replaced using an 8-bit substitution box (S-box)
  - defined using mathematical operations: multiplicative inverse over a finite field + affine transformation
- designed to resist cryptanalysis
  - minimize correlation to linear functions
  - minimize difference propagation

ShiftRows

- Cyclically shifts 2nd, 3rd, and 4th rows left

row	shift
2nd	1
3rd	2
4th	3

- ensures the 4 bytes of each column are spread to 4 different columns → provides diffusion
  - without this step each input byte would only affect a single column

MixColumns

- Each column is multiplied by a fixed matrix
  - invertible linear transformation
- good mixing among bytes of each column → provides diffusion
  - in conjunction with ShiftRows, ensures each output bit depends on every input bit after a few rounds

4.9 AES Decryption

- each step is invertible
  - InvertMatrixColumns – multiply by matrix inverse
  - InvertShiftRows – shift rows cyclically to right
  - InvertSubBytes – invert affine transformation and multiplicative inverse
  - InvertAddRoundKey – xor round key to state

- Round keys are used in reverse order

4.10 AES Performance and Security

- Operations on bytes and 32-bit words
  - most operations can be precomputed
- Supported by hardware – AES instruction set for CPUs
- Best known attack takes 2^{126} steps, only 4x faster than brute-force attack

5 Block Cipher Modes of Operation

6 Public-Key Encryption

7 Hash Functions

8 Message Authentication

9 Digital Signatuers

10 Key Distribution

11 Public-Key Distribution