Classical Encryption Techniques

CSS322: Security and Cryptography

Sirindhorn International Institute of Technology
Thammasat University

Prepared by Steven Gordon on 13 November 2013

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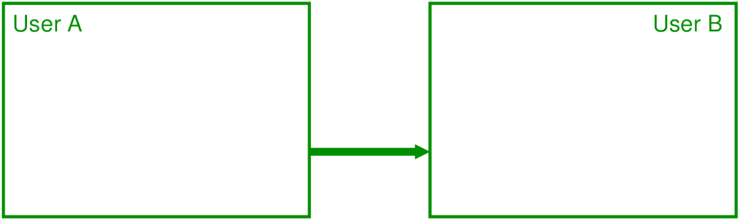
Contents

Encryption for Confidentiality

- Aim: assure confidential information not made available to unauthorised individuals (data confidentiality)
- How: encrypt the original data; anyone can see the encrypted data, but only authorised individuals can decrypt to see the original data
- Used for both sending data across network and storing data on a computer system

Model of Encryption for Confidentiality



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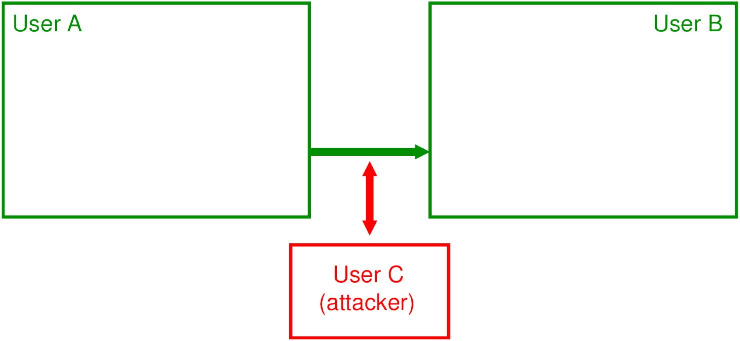

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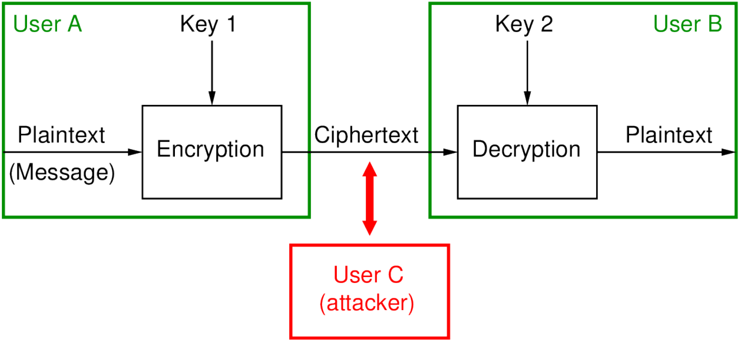

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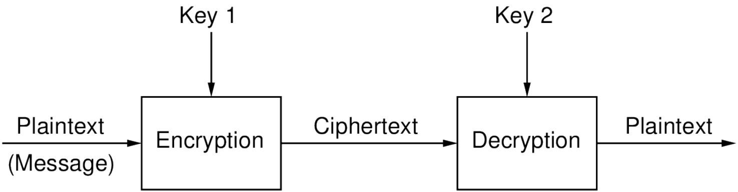


Terminology

Plaintext	original message
Ciphertext	encrypted or coded message
Encryption	convert from plaintext to ciphertext (enciphering)
Decryption	restore the plaintext from ciphertext (deciphering)
Key	information used in cipher known only to sender/receiver
Cipher	a particular algorithm (cryptographic system)
Cryptography	study of algorithms used for encryption
Cryptanalysis	study of techniques for decryption without knowledge of plaintext
Cryptology	areas of cryptography and cryptanalysis

Requirements and Assumptions

Requirements for secure use of symmetric encryption:

1. Strong encryption algorithm: Given the algorithm and ciphertext, an attacker cannot obtain key or plaintext
2. Sender/receiver know secret key (and keep it secret)

Assumptions:

- Cipher is known
- Secure channel to distribute keys

Characterising Cryptographic Systems

Operations used for encryption:

Substitution replace one element in plaintext with another

Transposition re-arrange elements

Product systems multiple stages of substitutions and transpositions

Number of keys used:

Symmetric sender/receiver use same key (single-key, secret-key, shared-key, conventional)

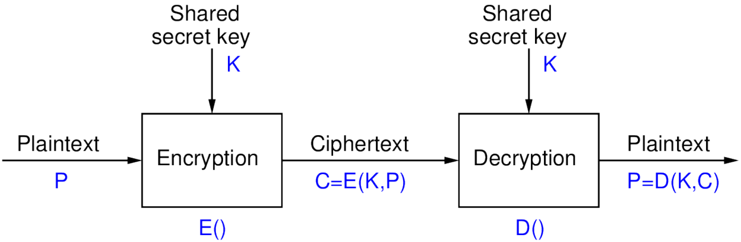
Public-key sender/receiver use different keys (asymmetric)

Processing of plaintext:

Block cipher process one block of elements at a time

Stream cipher process input elements continuously

Symmetric Key Encryption for Confidentiality



Requirements

- Strong encryption algorithm: given algorithm, ciphertext and known pairs of (plaintext, ciphertext), attacker should be unable to find plaintext or key
- Shared secret keys: sender and receiver both have shared a secret key; no-one else knows the key

Attacks

Goal of the Attacker

- Discover the plaintext (good)
- Discover the key (better)

Assumed Attacker Knowledge

- Ciphertext
- Algorithm
- Other pairs of (plaintext, ciphertext) using same key

Attack Methods

Brute-force attack Try every possible key on ciphertext

Cryptanalysis Exploit characteristics of algorithm to deduce plaintext or key

Assumption: attacker can recognise correct plaintext

Attacks on Block Ciphers

Brute Force Attack

- Approach: try all keys in key space
- Metric: number of operations (time)
- k bit key requires 2^k operations
- Depends on key length and computer speed

Cryptanalysis

- Approach: Find weaknesses in algorithms
- Methods: Linear cryptanalysis, differential cryptanalysis, meet-in-the-middle attack, side-channel attacks . . .
- Metrics:
  - Number of operations
  - Amount of memory
  - Number of known plaintexts/ciphertexts

Brute-Force Attacks

Key length	Key space	Worst case time at speed: 10^9/sec	10^{12}/sec	10^{15}/sec
32	2^{32}	4 sec	4 ms	4 us
56	2^{56}	833 days	20 hrs	72 sec
64	2^{64}	584 yrs	213 days	5 sec
128	2^{128}	10^{22} yrs	10^{19} yrs	10^{16} yrs
192	2^{192}	10^{41} yrs	10^{38} yrs	10^{35} yrs
256	2^{256}	10^{60} yrs	10^{57} yrs	10^{54} yrs
26!	2^{88}	10^{10} yrs	10^{7} yrs	10^{4} yrs

Age of Earth: 4×10^9 years
Age of Universe: 1.3×10^{10} years

Cryptanalysis: What is known to attacker . . .

Ciphertext Only encryption algorithm, ciphertext

Known Plaintext encryption algorithm, ciphertext;
: one or more plaintext–ciphertext pairs formed with the secret key

Chosen Plaintext encryption algorithm, ciphertext;
: Plaintext message chosen by attacker, together with its corresponding ciphertext generated with the secret key

Chosen Ciphertext encryption algorithm, ciphertext;
: Ciphertext chosen by attacker, together with its corresponding decrypted plaintext generated with the secret key

Chosen Text encryption algorithm, ciphertext;
: Plaintext message chosen by attacker, together with its corresponding ciphertext generated with the secret key
: Ciphertext chosen by attacker, together with its corresponding decrypted plaintext generated with the secret key

Measures of Security

Unconditionally Secure

- Ciphertext does not contained enough information to derive plaintext or key
- One-time pad is only unconditionally secure cipher (but not very practical)

Computationally Secure

- If either:
  - Cost of breaking cipher exceeds value of encrypted information
  - Time required to break cipher exceeds useful lifetime of encrypted information
- Hard to estimate value/lifetime of some information
- Hard to estimate how much effort needed to break cipher

Contents

Classical Substitution Ciphers

- Letters of plaintext are replaced by others letters or by numbers of symbols
- If plaintext viewed as sequence of bits, replace plaintext bit patterns with ciphertext bit patterns

Caesar Cipher

- Earliest known cipher, used by Julius Caesar (Roman general 2000 years ago)
- Replace each letter by the letter three positions along in alphabet

```
Plain : a b c d e f g h i j k l m n o p q r s t u v w x y z
Cipher: D E F G H I J K L M N O P Q R S T U V W X Y Z A B C
```

Generalised Caesar Cipher

- Allow shift by k positions
- Assume each letter assigned number ($a = 0$, $b = 1$, ...)

$$C = \mathrm{E}(k, p) = (p + k) \bmod 26$$

$$p = \mathrm{D}(k, C) = (C - k) \bmod 26$$

Breaking the Caesar Cipher

- Brute force attack
  - Try all 25 keys, e.g. $k = 1$, $k = 2$, ...
  - Plaintext should be recognised
- Recognising plaintext in brute force attacks
  - Need to know "structure" of plaintext
  - Language? Compression?
- How to improve against brute force?
  - Hide the encryption/decryption algorithm: Not practical
  - Compress, use different language: Limited options
  - Increase the number of keys

Mono-alphabetic (Substitution) Ciphers

- Mono-alphabetic: use a single alphabet for both plaintext and ciphertext
- Arbitrary substitution: one element maps to any other element
  - n element alphabet allows $n!$ permutations or keys
- Example:

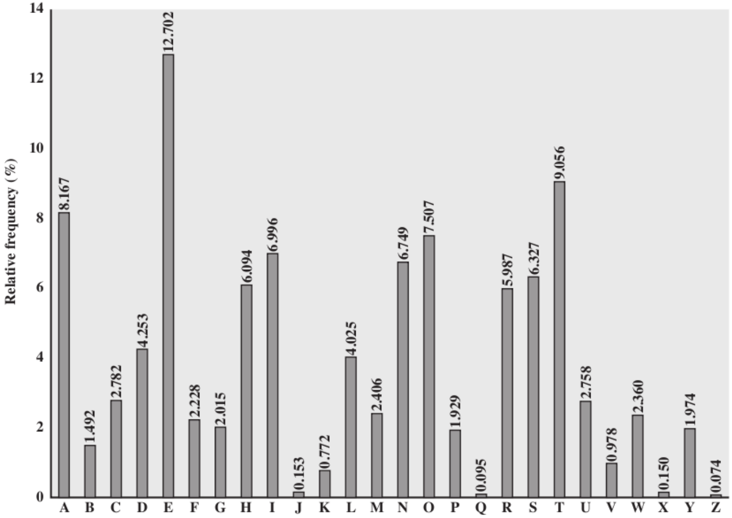
```
Plain :a b c d e ... w x y z
Cipher:D Z G L S ... B T F Q
```

- Try brute force ...
  - Caesar cipher: 26 keys
  - Mono-alphabetic (English alphabet): 26! keys ($> 4 \times 10^{26}$)

Attacks on Mono-alphabetic Ciphers

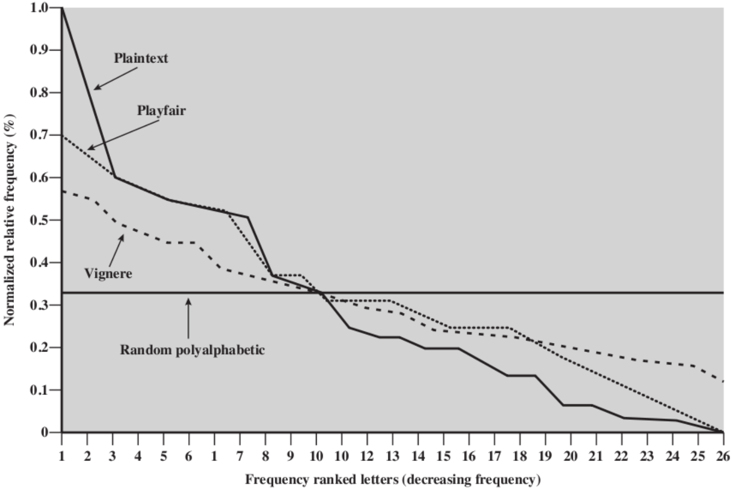
- Exploit the regularities of the language
  - Frequency of letters, digrams, trigrams
  - Expected words
- Fundamental problem with mono-alphabetic ciphers
  - Ciphertext reflects the frequency data of original plaintext
  - Solution 1: encrypt multiple letters of plaintext
  - Solution 2: use multiple cipher alphabets

Relative Frequency of Letters in English Text



Credit: Figure 2.5 in Stallings, *Cryptography and Network Security*, 5th Ed., Pearson 2011

Relative Frequency of Occurrence of Letters



Credit: Figure 2.6 in Stallings, *Cryptography and Network Security*, 5th Ed., Pearson 2011

Playfair Cipher

Initialisation

1. Create 5x5 matrix and write keyword (row by row)
2. Fill out remainder with alphabet, not repeating any letters
3. Special: Treat I and J as same letter

Encryption

1. Operate on pair of letters (digram) at a time
2. Special: if digram with same letters, separate by special letter (e.g. x)
3. Plaintext in same row: replace with letters to right
4. Plaintext in same column: replace with letters below
5. Else, replace by letter in same row as it and same column as other plaintext letter

Playfair Cipher Example

- Plaintext: `hello`
- Keyword: `thailand`
- Ciphertext: `LDAZEU`

Playfair Cipher - Is it Breakable?

- Better than mono-alphabetic: relative frequency of digrams much less than of individual letters
- But relatively easy (digrams, trigrams, expected words)

Poly-alphabetic Ciphers

- Use different mono-alphabetic substitutions as proceed through plaintext
  - Set of mono-alphabetic ciphers
  - Key determines which mono-alphabetic cipher to use for each plaintext letter
- Examples:
  - Vigenère cipher
  - Vernam cipher (see textbook)
  - One time pad

Vigenère Cipher

- Set of 26 general Caesar ciphers
- Letter in key determines the Caesar cipher to use
  - Key must be as long as plaintext: repeat a keyword
- Example:

```
Plain:  internettechnologies
Key:    sirindhornsirindhorn
Cipher: AVKMEQLHKRUPEWYRNWVF
```

- Multiple ciphertext letters for each plaintext letter

Vigenère Cipher - Is it Breakable?

- Yes
- Monoalphabetic or Vigenère cipher? Letter frequency analysis
- Determine length of keyword
- For keyword length m, Vigenère is m mono-alphabetic substitutions
- Break the mono-alphabetic ciphers separately

Weakness is repeating, structured keyword

One Time Pad

- Similar to Vigenère, but use random key as long as plaintext
- Only known scheme that is unbreakable (unconditional security)
  - Ciphertext has no statistical relationship with plaintext
  - Given two potential plaintext messages, attacker cannot identify the correct message
- Two practical limitations:
  1. Difficult to provide large number of random keys
  2. Distributing unique long random keys is difficult
- Limited practical use

One Time Pad Example

Attacker knows the ciphertext:

```
ANKYODKYUREPFJBYOJDSPLREYIUNOFDOIUERFPLUYTS
```

Attacker tries all possible keys. Two examples:

```
key1:       pxlmvmsydofuyrvzwc tnlebnecvgdupahfzzlmnyih
plaintext1: mr mustard with the candlestick in the hall

key2:       pftgpmiydgaxgoufhklllmhsqdqogtewbqfgyovuhwt
plaintext2: miss scarlet with the knife in the library
```

There are many other legible plaintexts obtained with other keys. No way for attacker to know the correct plaintext

Contents

Rail Fence Transposition

- Plaintext letters written in diagonals over N rows (depth)
- Ciphertext obtained by reading row-by-row
- Easy to break: letter frequency analysis to determine depth
- Example:

```
plaintext: internettechnologiesandapplications
depth: 3
```

Rows/Columns Transposition

- Plaintext letters written in rows
- Ciphertext obtained by reading column-by-column, but re-arranged
- Key determines order of columns to read
- Easy to break using letter frequency (try different column orders)
- Example:

```
plaintext: securityandcryptography
key: 315624
```

Rows/Columns Transposition

Transposition ciphers can be made stronger by using multiple stages of transposition

```
plaintext:  attackpostponeduntiltwoamxyz
key: 4312567
ciphertext: TTNAAPTMTSUOAODWCOIXKNLYPETZ
```

Transpose again using same key:

```
output:     NSCYAUOPTTWLTMDNAOIEPAXTTOKZ
```

Original plaintext letters, by position:

01 02 03 04 05 06 07 08 09 10 11 12 13 14
15 16 17 18 19 20 21 22 23 24 25 26 27 28

After first transposition:

03 10 17 24 04 11 18 25 02 09 16 23 01 08
15 22 05 12 19 26 06 13 20 27 07 14 21 28

After second transposition:

17 09 05 27 24 16 12 07 10 02 22 20 03 25
15 13 04 23 19 14 11 01 26 21 18 08 06 28

Contents

Steganography

- Hide a real message in a fake, but meaningful, message
- Assumes recipient knows the method of hiding
- Examples:
  - Selected letters in a document are marked to form the hidden message
  - Invisible ink (letters only become visible when exposed to a chemical or heat)
  - Using selected bits in images or videos to carry the message
- Advantages
  - Does not *look like* you are hiding anything
- Disadvantages
  - Once attacker knows your method, everything is lost
  - Can be inefficient (need to send lot of information to carry small message)

Steganography Example

Dear George,
Greetings to all at Oxford. Many thanks for your letter and for the Summer examination package. All Entry Forms and Fee Forms should be ready for final despatch to the Syndicate by Friday 20th or at the very latest, I'm told, by the 21st. Admin has improved here, though there's room for improvement still; just give us all two or three more years and we'll really show you! Please don't let these wretched 16+ proposals destroy your basic O and A pattern. Certainly this sort of change, if implemented immediately, would bring chaos.
Sincerely yours.