Basic Ciphers

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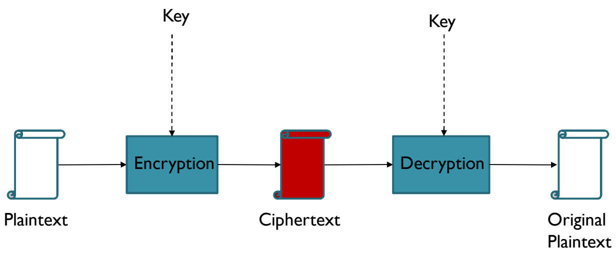
Basic Terminology in Cryptography – 1

- **Cryptography:** the study of mathematical techniques related to aspects of providing information security services.
- **Cryptanalysis:** the study of mathematical techniques for attempting to defeat information security services.
- **Cryptology:** the study of cryptography and cryptanalysis.

Basic Terminology in Cryptography – 2

- Encryption (encipherment): the process of transforming information (plaintext) using an algorithm (cipher) to make it unreadable to anyone except those possessing special knowledge
- Decryption (decipherment): the process of making the encrypted information readable again
- Key: the special knowledge shared between communicating parties
- Plaintext: the data to be concealed.
- Ciphertext: the result of encryption on the plaintext

Encryption & Decryption



Breaking Ciphers - 1

- There are different methods of breaking a cipher, depending on:
  - the type of information available to the attacker
  - the interaction with the cipher machine
  - the computational power available to the attacker

Breaking Ciphers - 2

- Ciphertext-only attack: The cryptanalyst knows only the ciphertext. Sometimes the language of the plaintext is also known.
  - The goal is to find the plaintext and the key.
  - Any encryption scheme vulnerable to this type of attack is considered to be completely insecure.
- Known-plaintext attack: The cryptanalyst knows one or several pairs of ciphertext and the corresponding plaintext.
  - The goal is to find the key used to encrypt these messages or a way to decrypt any new messages that use that key.

Breaking Ciphers - 3

- Chosen-plaintext attack : The cryptanalyst can choose a number of messages and obtain the ciphertexts for them
  - The goal is to deduce the key used in the other encrypted messages or decrypt any new messages using that key.
- Chosen-ciphertext attack: Similar to the chosen-plaintext attack, but the cryptanalyst can choose a number of ciphertexts and obtain the plaintexts.

Today's Ciphers

- Shift Cipher
- Transposition Cipher
- Mono-alphabetical Substitution Cipher
- Polyalphabetic Substitution Ciphers
- Rotor Machine
- Enigma

Shift Cipher

- A substitution cipher
- The Key Space:
  - [1 .. 25]
- Encryption given a key K:
  - each letter in the plaintext P is replaced with the K'th letter following corresponding number (shift right)
- Decryption given K:
  - shift left
- History: K = 3, Caesar's cipher

Shift Cipher: An Example

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
0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25

P = CRYPTOGRAPHYISFUN

K = 11

C = NCJAVZRCLASJTDQFY

C → 2 2+11 mod 26 = 13 → N

R → 17 17+11 mod 26 = 2 → C

…

N → 13 13+11 mod 26 = 24 → Y

Shift Cipher: Cryptanalysis

- Can an attacker find K?
  - YES: exhaustive search,
  - key space is small (<= 26 possible keys)
  - the attacker can search all the key space in very short time
- Once K is found, very easy to decrypt

Transposition Cipher

- Write the plaintext horizontally in fixed number columns and read vertically to encypt.
  - The ancient Spartans used a form of transposition cipher
- Example:
  - P = 'meet me near the clock tower at twelve midnight tonite'

```
m e e t m
e n e a r
t h e c l
o c k t o
w e r a t
t w e l v
e m i d n
i g h t t
o n i t e
```

- C ='metowteioenhcewmgneeekreihitactaldttmrlotvnte'

Transposition Cipher: Cryptanalysis

- Can an attacker decrypt a transposed text?
  - Do exhaustive search on number of columns
  - Since the key space is small, the attacker can search all the key space in very short time
- Once the number of columns is guessed, very easy to decrypt

General Mono-alphabetical Substitution Cipher

- The key space: all permutations of $\Sigma = \{A, B, C, \ldots, Z\}$
- Encryption given a key π:
  - each letter X in the plaintext P is replaced with $\pi(X)$
- Decryption given a key π:
  - each letter Y in the ciphertext P is replaced with $\pi^{-1}(Y)$

Example:

```
    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
π=B A D C Z H W Y G O Q X S V T R N M S K J I P F E U
```

BECAUSE → AZDBJSZ

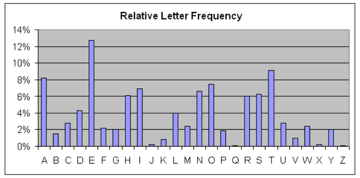
General Substitution Cipher: Cryptanalysis

- Exhaustive search is infeasible
  - for the letter A, there are 26 probabilities
  - for the letter B, there are 25 probabilities
  - for the letter C, there are 24 probabilities
  - … and so on
- Key space size is $26! \approx 4*10^{26}$

Cryptanalysis of Substitution Ciphers: Frequency Analysis

- Basic ideas:
  - Each language has certain features: frequency of letters, or of groups of two or more letters.
  - Substitution ciphers preserve the language features.
  - Substitution ciphers are vulnerable to frequency analysis attacks.
- History of frequency analysis:
  - Earliest known description of frequency analysis is in a book by the ninth-century scientist al-Kindi
  - Rediscovered or introduced from the Arabs in the Europe during the Renaissance

Frequency Features of English



- Vowels, which constitute 40 % of plaintext, are often separated by consonants.
- Letter A is often found in the beginning of a word or second from last.
- Letter I is often third from the end of a word.
- Letter Q is followed only by U
- Some words are more frequent, such as the, and, at, is, on, in

Cryptanalysis using Frequency Analysis

- The number of different ciphertext characters or combinations are counted to determine the frequency of usage.
- The cipher text is examined for patterns, repeated series, and common combinations.
- Replace ciphertext characters with possible plaintext equivalents using known language characteristics.
- Frequency analysis made substitution cipher insecure

Improve the Security of Substitution Cipher

- Using nulls
  - e.g., using numbers from 1 to 99 as the ciphertext alphabet, some numbers representing nothing are inserted randomly
- Deliberately misspell words
  - e.g., "Thys haz thi ifekkt off diztaughting thi ballans off frikwenseas"
- Homophonic substitution cipher
  - each letter is replaced by a variety of substitutes
- These make frequency analysis more difficult, but not impossible

Summary

- Shift ciphers are easy to break using brute force attacks, they have small key space.
- Substitution ciphers preserve language features and are vulnerable to frequency analysis attacks.

Polyalphabetic Substitution Ciphers

- Main weaknesses of monoalphabetic substitution ciphers
  - each letter in the ciphertext corresponds to only one letter in the plaintext letter
- Idea for a stronger cipher (1460's by Alberti)
  - use more than one cipher alphabet, and switch between them when encrypting different letters
  - Developed into a practical cipher by Vigenère (published in 1586)

The Vigenère Cipher

- **Definition:**
  - Given m, a positive integer, $P = C = (Z_{26})^n$, and $K = (k_1, k_2, \ldots, k_m)$ a key, we define:
- **Encryption:**
  - $E_k(p_1, p_2 \ldots p_m) = (p_1+k_1, p_2+k_2 \ldots p_m+k_m) \pmod{26}$
- **Decryption:**
  - $D_k(c_1, c_2 \ldots c_m) = (c_1-k_1, c_2-k_2 \ldots c_m-k_m) \pmod{26}$

Example:

Plaintext:	C R Y P T O G R A P H Y
Key:	L U C K L U C K L U C K
Ciphertext:	N L A Z E I I B L J J I

Security of Vigenère Cipher

- Vigenere masks the frequency with which a character appears in a language: one letter in the ciphertext corresponds to multiple letters in the plaintext. Makes the use of frequency analysis more difficult.
- Any message encrypted by a Vigenere cipher is a collection of as many shift ciphers as there are letters in the key.

Vigenere Cipher: Cryptanalysis

- Find the length of the key.
  - Divide the message into that many shift cipher encryptions.
  - Use frequency analysis to solve the resulting shift ciphers.
- Vigenère cipher is vulnerable: once the key length is found, a cryptanalyst can apply frequency analysis.
- How to Find the Key Length?
  - For Vigenere, as the length of the keyword increases, the letter frequency shows less English-like characteristics and becomes more random.
  - Two methods to find the key length:
    - Kasisky test
    - Index of coincidence (Friedman)

Kasisky Test

- Two identical segments of plaintext will be encrypted to the same ciphertext, if the they occur in the text at the distance Δ, (Δ≡0 (mod m), m is the key length).
- Algorithm:
  - Search for pairs of identical segments of length at least 3
  - Record distances between the two segments: Δ1, Δ2, …
  - m divides gcd(Δ1, Δ2, …)

PT	T H E S U N A N D T H E M A N I N T H E M O O N
Key	K I N G K I N G K I N G K I N G K I N G K I N G
CT	D P R Y E V N T N **B U K W** I A O X **B U K W** W B T

Rotor Machines-1

- Basic idea: if the key in Vigenere cipher is very long, then the attacks won't work
- Implementation idea: multiple rounds of substitution
- A machine consists of multiple cylinders
  - each cylinder has 26 states, at each state it is a substitution cipher: the wiring between the contacts implements a fixed substitution of letters
  - each cylinder rotates to change states according to different schedule changing the substitution

Rotor Machines-2

- A m-cylinder rotor machine has 26^m different substitution ciphers
  - 26^3 = 17576
  - 26^4 = 456,976
  - 26^5 = 11,881,376

Enigma Machine

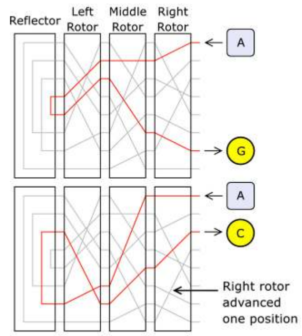
- Patented by Scherius in 1918
  - Came on the market in 1923, weighted 50 kg (about 110 lbs), later cut down to 12kg (about 26 lbs)
  - It cost about $30,000 in today's prices
  - 34 x 28 x 15 cm
- Widely used by the Germans from 1926 to the end of second world war
  - First successfully broken by Polish in the thirties by exploiting the repeating of the message key and knowledge of the machine design)
  - During the WW II, Enigma was broken by Alan Turing (1912 - 1954) in the UK intelligence. He was an english mathematician, logician and cryptographer, father of modern computer science.

Enigma

- Use 3 scramblers (rotors): 17576 substitutions
- 3 scramblers can be used in any order: 6 combinations
- Plug board: allowed 6 pairs of letters to be swapped before the scramblers process started and after it ended.
- Total number of keys ≈ 10^{16}
- Later versions use 5 rotors and 10 pairs of letters

Key Mapping

- A reflector enables to map a character twice with each rotor
- First rotor rotates after each key press
- Second rotor rotates after first had a complete revolution,
- and so on



Encrypting with Enigma

- Machine was designed under the assumption that the adversary may get access to the machine
- Daily key: The settings for the rotors and plug boards changed daily according to a codebook received by all operators
  - A day key has the form
    - Plugboard setting: A/L–P/R–T/D–B/W–K/F–O/Y
    - Scrambler arrangement: 2-3-1
    - Scrambler starting position: Q-C-W
- Message key: Each message was encrypted with a unique key defined by the position of the 3 rotors

How to Break the Enigma Machine?

- Recover 3 secrets
  - Internal connections for the 3 rotors
  - Daily keys
  - Message keys
- With 2 months of day keys and Enigma usage instructions, the Polish mathematician Rejewski succeeded to reconstruct the internal wiring

Lessons Learned From Breaking Enigma

- Keeping a machine (i.e., a cipher algorithm) secret does not help
  - The Kerckhoff's principle
  - Security through obscurity doesn't work
- Large number of keys are not sufficient
- Known plaintext attack was easy to mount
- Key management was the weakest link
- People were also the weakest link
- Even a strong cipher, when used incorrectly, can be broken

Kerckhoffs's Principle

- Auguste Kerckhoff (1835 – 1903) was a Dutch linguist and cryptographer who was professor of languages at the School of Higher Commercial Studies in Paris in the late 19th century.

- The security of a protocol should rely only on the secrecy of the keys, protocol designs should be made public (1883)
  - secrecy of a protocol does not work