CS3053 Computer Security
Historical Ciphers

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Acknowledgment

These lecture notes are based on the *Chapter 7 on Historical Ciphers* of the textbook **Cryptography Made Simple**, by Nigel P Smart, Springer, 2016.

Introduction

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- The reverse process is called decryption (d) or decipherment and denoted as $m = d_k(c)$.
- It is important to note that encryption and decryption algorithms (e and d) are public and we assume that ciphertext (c) can also be easily (that is, publicly) accessed.

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- Algorithms with this property are called *symmetric cryptosystems* or *secret key cryptosystems*.

Ciphers for Human Readable Languages

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  - the peculiar statistical characteristics of the language.

- For example, the English language
- with 26 character alphabet (`A` to `Z`) and
- laguage-specific statistical characteristics
  - higher usage of characters `e`, `t`, `a`, `o`, `i` and
  - higher appearance of bigrams such as `th`, `he`, `an`, `in` or trigrams such as `the`, `ing`, `and`, `her`, `ere`.

Shift Cipher

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- When the key value is **3**, it is commonly called the *Caesar cipher*.

Shift Cipher as a Stream Cipher

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- We can consider this method of encryption as a *stream cipher* where a stream of plaintext characters (m_i) and a stream of keys (k_i) are input to a function $(m_i + k_i \mod 25)$ that output a stream of ciphertext characters (c_i).

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- In this shift cipher, the keystream has a repeating sequence of just one key value k.

Breaking the Shift Cipher

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- This is called an *exhaustive key search* attack.
- For this attack to be successful, the attacker must be able to *recognize* the correct plaintext when the key used originally for encryption is tried.

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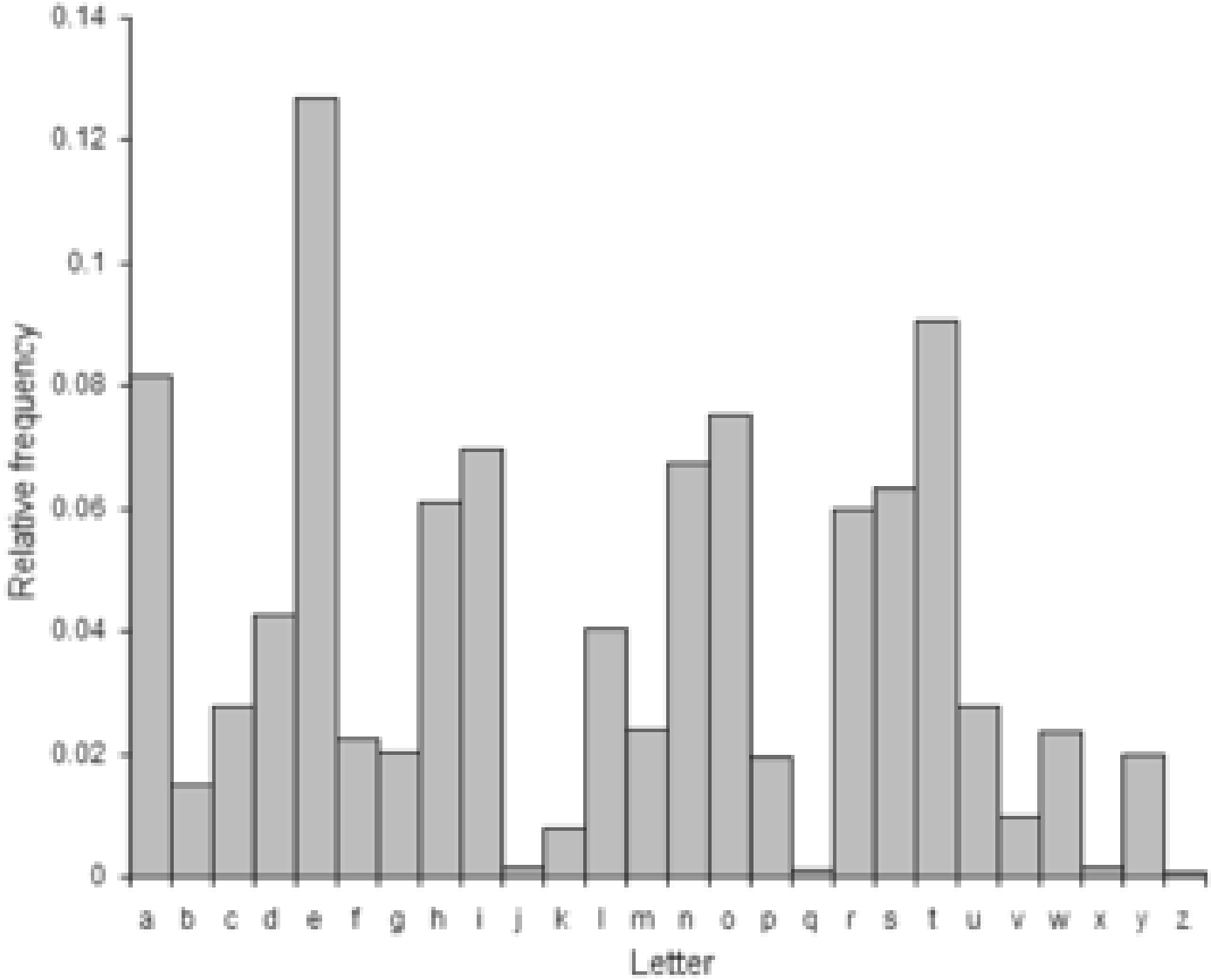
- This method will compute the frequency values for the characters in the ciphertext and match that with the character frequency table of the specific language (for example, English language).
- We can take the characters with the highest frequencies in the ciphertext and replace them with corresponding plaintext characters according to the standard character frequency table.

Single Letter Frequency for English Language



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- However, as the 6 most frequently occurring characters account for approximately 44.4% of the characters in a block of text, the correct key value can be found easily.
- When you get just few ciphertext characters replaced with the correct plaintext characters, the original text becomes somewhat apparent even without a full decryption.

Statistical Distance in Shift Cipher Attacks 1/3

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- Another way to find the correct key is to compute the *statistical distance* between the standard character frequency distribution (say, X) and the character frequency distribution computed from the ciphertext (say, Y).

Statistical Distance in Shift Cipher Attacks 2/3

As we can consider distribution Y to be representing 26 possible arrangements of the alphabet based on the possible values of k, we in fact have a set of distributions $Y_k : k = 0 \ldots 25$.

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- Thereafter, we can calculate a set of statistical distance values as

$$\Delta[X, Y_k] = \frac{1}{2} \sum_{u \in V} \left| \underset{X \leftarrow D_{standard}}{Pr} [X = u] - \underset{Y \leftarrow D_k}{Pr} [Y = u] \right|$$

- X: random variable distributed according to standard character frequency
- Y_k: random variables distributed according to particular k shift
- V: the set of values which can occur for X or Y with non-zero probability

Statistical Distance in Shift Cipher Attacks 3/3

From the 26 values of $\Delta(XY_k)$, we can find the smallest such value and take the corresponding k value as the secret key.

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- As the number of possible keys is equal to the number of permutations, an English language cipher could now have a key space of $26! \approx 4.03 \cdot 10^{26} \approx 2^{88}$.
- While this massive key space appears to make a substitution cipher unbreakable, these ciphers can still be attacked using statistical techniques based on language characteristics.

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- A solution to this problem is to move from the *mono-alphabetic substitution ciphers* that uses a single substitution alphabet to *poly-alphabetic substitution ciphers* that use multiple substitution ciphers.
- For example, we can use one substitution alphabet for all the characters in odd-numbered positions in a block of text and a different cipher for characters in even-numbered positions.

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- The number of alphabets used in a poly-alphabetic substitution cipher can be increased to make it harder for attackers to break a cipher.
- For example, use of 5 alphabets would result in a total key space of $(26!)^5 \approx 2^{441}$. This massive key space is obtained at a relatively modest cost of having to remember a key of length $26 \cdot 5 = 130$ characters.

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- The Vigenère cipher of Bellaso is a variant on the poly-alphabetic cipher scheme where the ciphertext alphabets used were restricted to only cyclic shifts of the standard alphabet.
- In this scheme, a 5 alphabet Vigenère cipher would only have a total key space of $26^5 \approx 2^{23}$ but at a cost of just 5 numeric values as the key, which is far easier to remember.

Vigenère Cipher as a Stream Cipher

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- As expected from a poly-alphabetic substitution cipher, the same character in the plaintext is substituted by multiple different character in the ciphertext based on the positional value of the plaintext character in the input block of text.
- This results in a character frequency graph that is largely devoid of any significant peaks helping to identify characters with high frequency of appearance in the plaintext.

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- This often happens with commonly occurring bigrams and trigrams of the language.

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- As an aside, it is claimed that Charles Babbage, the British mathematician called the *father of the computer* has known about this technique earlier than Kasiski.

Playfair Cipher 1/2

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- Thereafter, the remaining cells are filled with the letters of the alphabet in their natural order with letters already in the secret word skipped.

Playfair Cipher 2/2

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- A special rule handles double letters by inserting a pre-agreed extra letter to breakup the pairings falling in the same row or column.

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- Therefore, to use frequency analysis of bigrams, a much larger amount of ciphertext needs to be captured by an attacker.

Playfair Cipher Example

The 5 x 5 grid with the secret keyword `CSE`

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

The encryption of plaintext `COMPUTER` would give the ciphertext `BKKRPUGX`

Rules

- If the two letters form a rectangle then take the letters on the horizontal opposite corner of the rectangle.
- If both letters are in the same column then take the letter below each one (going back to the top if at the bottom).
- If both letters are in the same row then take the letter to the right of each one (going back to the leftmost if at the rightmost position).

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- This results in a permutation group denoted as S_n where the permutation $\sigma \in S_n$ is the secret key (with block length n).
- For example, with

$$\sigma = \begin{pmatrix} 1\,2\,3\,4\,5 \\ 2\,4\,1\,3\,5 \end{pmatrix}$$

the plaintext word `HELLO` would be encrypted as ciphertext `LHLEO`.

Attacking Permutation Ciphers 1/2

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- Then to successfully attack the cipher, we need to find the block length.
- If the plaintext has repeating character sequences that are aligned to the same block position, then there would be similar repeating character sequences in the ciphertext also.
- This would help us to determine the block length (or possibly a multiple of the block length) by considering the distance between two repeating blocks.

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- If we have two such different repeating character sequences, then finding the two distance values and computing their greatest common divisor would help find the block length.
- Once the block length is known, an exhaustive search can be used to deduce the permutation.

Epilogue - Historical Figures

Giovan Battista Bellaso

Giovan Battista Bellaso, was an Italian cryptologist born in 1505.[from Wikipedia]

Blaise de Vigenère

Blaise de Vigenère (1523 - 1596), born in Central France, was a French diplomat, cryptographer, translator and alchemist.[from Wikipedia]

Charles Babbage

Charles Babbage (1791 -1871), born in London, was a mathematician, philosopher, inventor and mechanical engineer. Babbage originated the concept of a digital programmable computer and hence considered by some to be "father of the computer". Babbage is credited with inventing the first mechanical computer known as Babbage's Analytical Engine.[from Wikipedia]

Charles Wheatstone

Sir Charles Wheatstone (1802 - 1875), was an English scientist and inventor of many scientific breakthroughs of the Victorian era, including the English concertina, the stereoscope (a device for displaying three-dimensional images), and the Playfair cipher (an encryption technique). However, Wheatstone is best known for his contributions in the development of the Wheatstone bridge, originally invented by Samuel Hunter Christie, which is used to measure an unknown electrical resistance, and as a major figure in the development of telegraphy.[from Wikipedia]

Friedrich Wilhelm Kasiski

Friedrich Wilhelm Kasiski (1805 - 1881), born in Kingdom of Prussia (present day Poland) was a German infantry officer, cryptographer and archaeologist. He wrote the book "Secret writing and the Art of Deciphering" (in German) that focused on cryptanalysis of poly-alphabetic substitution ciphers.[from Wikipedia]