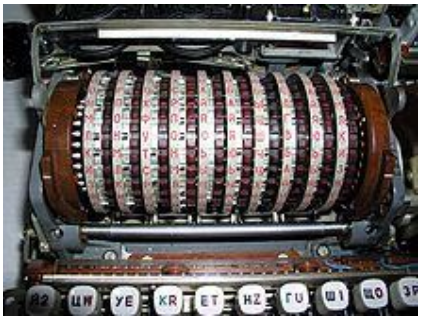
(8)

Cryptanalysis



Close-up of the rotors in a Fialka cipher machine

Definition:

Cryptanalysis (from the Greek *kryptós*, "hidden", and *analýein*, "to loosen" or "to untie") : is the study of methods for obtaining the meaning of encrypted information, without access to the secret information, or knowing the plaintext without knowing the key used in encryption process.

Typically, this involves knowing how the system works and finding a secret key.

In non-technical language, this is the practice of **codebreaking** or **cracking the code**.

"**Cryptanalysis**" is also used to refer to any attempt to circumvent the security of other types of cryptographic algorithms and protocols in general, and not just encryption.

Even though the goal has been the same, the methods and techniques of cryptanalysis have changed drastically through the history of cryptography, adapting to increasing cryptographic complexity, ranging from:

- the pen-and-paper methods of the past,
- through machines like Bombes and Colossus computers in World War II,
- to the computer-based schemes of the present.

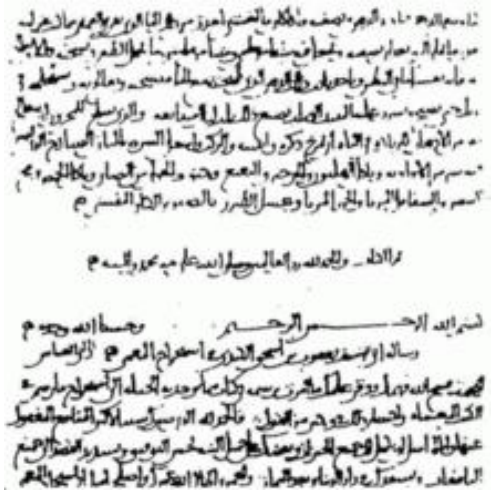
In the mid-1970s, a new class of cryptography was introduced: asymmetric cryptography. Methods for breaking these cryptosystems are typically radically different from before, and usually involve solving carefully-constructed problems in pure mathematics, the best-known being integer factorization.

Contents

History of cryptanalysis

Cryptanalysis has coevolved together with cryptography, and the contest can be traced through the history of cryptography—new ciphers being designed to replace old broken designs, and new cryptanalytic techniques invented to crack the improved schemes. In practice, they are viewed as two sides of the same coin: in order to create secure cryptography, you have to design against possible cryptanalysis.

Classical cryptanalysis



First page of Al-Kindi's 9th century Manuscript on Deciphering Cryptographic Messages

The first known recorded explanation of cryptanalysis was given by 9th-century Arabian polymath, Al-Kindi (also known as "Alkindus" in Europe), in *A Manuscript on Deciphering Cryptographic Messages*. This treatise includes a description of the method of f**requency analysis**.

Frequency analysis is the basic tool for breaking most classical ciphers.

In natural languages, certain letters of the alphabet appear more frequently than others; in English, "E" is likely to be the most common letter in any sample of plaintext.

Similarly, the digraph "TH" is the most likely pair of letters in English, and so on. Frequency analysis relies on a cipher failing to hide these statistics. For example, in a simple substitution cipher (where each letter is simply replaced with another), the most frequent letter in the ciphertext would be a likely candidate for "E". Frequency analysis of such a cipher is therefore relatively easy, **provided that the ciphertext is long enough to give a reasonably representative count of the letters of the alphabet that it contains**.

In Europe during the 15th and 16th centuries, the idea of a polyalphabetic substitution cipher was developed, by the French diplomat Blaise de Vigenère (1523–96). For some three centuries, the Vigenère cipher, which uses a repeating key to select different encryption alphabets in rotation, was considered to be completely secure .

Nevertheless, Charles Babbage (1791–1871) and later, independently, Friedrich Kasiski (1805–81) succeeded in breaking this cipher.

During World War I, inventors in several countries developed rotor cipher machines such as Arthur Scherbius' Enigma, in an attempt to minimize the repetition that had been exploited to break the Vigenère system.

{ In practice, "**Frequency Analysis**" relies as much on **linguistic** knowledge as it does on **statistics**, but as ciphers became more complex, mathematics became more important in cryptanalysis. This change was particularly evident before and during World War II, where efforts to crack Axis ciphers required new levels of mathematical sophistication. Moreover, automation was first applied to cryptanalysis in that era with the Polish Bomba device, the British Bombe development of it, the use of punched card equipment, and in the Colossus computers — the first electronic digital computers to be controlled by a program }.

Depth

Sending two or more messages with the same key is an insecure process. To a cryptanalyst the messages are then said to be *"in depth"*. This may be detected by the messages having the same ***indicator*** by which the sending operator informs the receiving operator about the key generator initial settings for the message.

In **a symmetrical cipher**, the same key that was applied to the plaintext to produce the ciphertext is applied to the ciphertext to recover the plaintext. A simple example of such a system is the Vernam cipher in which a long key is bit-for-bit combined with the plaintext or ciphertext using the "XOR" operator (symbolized by ⊕):

Plaintext ⊕ Key = *Ciphertext* at each bit position

and

Ciphertext ⊕ *Key* = *Plaintext* at each bit position

When the ciphertexts are in depth, combining them eliminates the common key, leaving just a combination of the two plaintexts:

Ciphertext1 ⊕ *Ciphertext2*= α = *Plaintext1* ⊕ *Plaintext2*
at each bit position

The individual plaintexts can then be worked out by trying ***"probable words"*** (or phrases) at various locations; when the corresponding section of **α** is XORed with a correct guess at the **probable word**, a stretch of the other plaintext is revealed, which can be recognized and (quite often) extended at each end, working back and forth between the plaintexts to recover much or all of them. When a recovered plaintext is then combined with its ciphertext, the key is revealed:

Plaintext ⊕ *Ciphertxt* = *Key*
at each bit position

Knowledge of keys from a cipher may allow cryptanalysts to work out the system used for constructing them.

One way to properly align multiple messages that use the same periodic key starting at different positions is by the kappa test.

Modern cryptanalysis

The Bombe replicated the action of several Enigma machines wired together. Each of the rapidly rotating drums, pictured above in a Bletchley Park museum mockup, simulated the action of an Enigma rotor.

Even though computation was used to great effect in cryptanalysis of the Enigma and other systems during World War II, it also made possible new methods of cryptography orders of magnitude more complex than ever before.

Taken as a whole, **modern cryptography** has become much more impervious to cryptanalysis than the **pen-and-paper systems** of the past, and now seems to have the upper hand against pure cryptanalysis.

The historian David Kahn notes:

{ **going on to mention increased opportunities for interception, bugging, side channel attacks, and quantum computers as replacements for the traditional means of cryptanalysis.** }

In **2010**, former **NSA** technical director Brian Snow said that both academic and government cryptographers are **"moving very slowly forward in a mature field."**

The effectiveness of cryptanalytic methods employed by **intelligence agencies** remains unknown, many serious attacks against both academic and practical cryptographic primitives have been published in the modern era of computer cryptography: (مهمة)

- The **Block Cipher** Madryga, proposed in 1984 but not widely used, was found to be susceptible to ciphertext-only attacks in 1998.
- FEAL-4, proposed as a replacement for the **DES** standard encryption algorithm but not widely used, was demolished by a spate of attacks from the academic community, many of which are entirely practical.
- The **A5/1, A5/2, CMEA**, and DECT systems used in mobile and wireless phone technology can all be broken in hours, minutes or even in real-time using widely-available computing equipment.
- **Brute-Force Key Space Search** has broken some real-world ciphers and applications, including **single-DES** (see EFF DES cracker), 40-bit "export-strength" cryptography, and the DVD Content Scrambling System.
- In 2001, **Wired Equivalent Privacy** (WEP), a protocol used to secure Wi-Fi wireless networks, was shown to be breakable in practice because of a weakness in the RC4 cipher and aspects of the WEP design that made related-key attacks practical. WEP was later replaced by Wi-Fi Protected Access.
- In 2008, researchers conducted a proof-of-concept break of SSL using weaknesses in the **MD5 hash function** and certificate issuer practices that made it possible to exploit collision attacks on hash functions. The certificate issuers involved changed their practices to prevent the attack from being repeated.

Thus, while the best modern ciphers may be far more resistant to cryptanalysis than the Enigma, cryptanalysis and the broader field of information security remain quite active.

Types of Cryptanalytic Attack

Cryptanalytic attacks vary in potency and how much of a threat they pose to real-world cryptosystems. A ***certificational weakness*** is a theoretical attack that is unlikely to be applicable in any real-world situation; the majority of results found in modern cryptanalytic research are of this type.

Essentially, **the practical importance of an attack is dependent on the answers to the following four questions** (مهمة):

1. What **knowledge** and capabilities does the attacker need?
2. How much **additional secret information** is deduced?
3. How much computation is required? (What is the **computational complexity**?)
4. Does the attack break the full cryptosystem, or only a weakened version?

Access needed for the attack

Cryptanalysis can be performed under a number of assumptions about how much access the attacker has to the system under attack.

As a basic starting point it is normally assumed that, for the purposes of analysis, the general algorithm is known;

this is **Kerckhoffs' principle** of "**the enemy knows the system**".

This is a reasonable assumption in practice

Other assumptions include:

- ***Ciphertext-Only***: the cryptanalyst has access only to a collection of ciphertexts or codetexts.
- ***Known-plaintext*:** the attacker has a set of ciphertexts to which he knows the corresponding plaintext.
- ***Chosen-plaintext*** (*chosen-ciphertext*): the attacker can obtain the ciphertexts (plaintexts) corresponding to an arbitrary set of plaintexts (ciphertexts) of his own choosing.

- ***Adaptive chosen-plaintext***: like a chosen-plaintext attack, except the attacker can choose subsequent plaintexts based on information learned from previous encryptions. Similarly *Adaptive chosen ciphertext attack*.
- ***Related-Key Attack***: Like a chosen-plaintext attack, except the attacker can obtain ciphertexts encrypted under two different keys. The keys are unknown, but the relationship between them is known; for example, two keys that differ in the one bit.

These types of attack clearly **differ in how plausible** they would be to mount in practice. Although **some are more likely than others**, cryptographers will often take a conservative approach to security and assume the worst-case when designing algorithms, reasoning that if a scheme is secure even against unrealistic threats, then it should also resist real-world cryptanalysis as well.

مهمة Important

{ **The assumptions are often more realistic than they might seem upon first glance. For a known-plaintext attack, the cryptanalyst might well know or be able to guess at a likely part of the plaintext, such as an encrypted letter beginning with "Dear Sir", or a computer session starting with "LOGIN:". A chosen-plaintext attack is less likely, but it is sometimes plausible: for example, you could convince someone to forward a message you have given them, but in encrypted form. Related-key attacks are mostly theoretical, although they can be realistic in certain situations, for example, when constructing cryptographic hash functions using a block cipher.** }

Usefulness of attack results

The results of cryptanalysis can also vary in usefulness. For example, cryptographer Lars Knudsen (1998) classified various types of attack on block ciphers according to the amount and quality of secret information that was discovered:

- ***Total break*** — the attacker deduces the secret key.
- ***Global deduction*** — the attacker discovers a functionally equivalent algorithm for encryption and decryption, but without learning the key.

- ***Instance (local) deduction*** — the attacker discovers additional plaintexts (or ciphertexts) not previously known.
- ***Information deduction*** — the attacker gains some Shannon information about plaintexts (or ciphertexts) not previously known.
- ***Distinguishing algorithm*** — the attacker can distinguish the cipher from a random permutation.

Similar considerations apply to attacks on other types of cryptographic algorithm.

Computational Resources Required

Attacks can also be characterised by the resources they require. Those resources include:

- **Time** — the number of *computation steps* (like encryptions) which must be performed.
- **Memory** — the amount of *storage* required to perform the attack.
- **Data** — the quantity of *plaintexts and ciphertexts* required.

It's sometimes difficult to predict these quantities precisely, especially when the attack isn't practical to actually implement for testing. But academic cryptanalysts tend to provide at least the estimated ***order of magnitude*** of their attacks' difficulty, saying, for example:

"SHA-1 collisions now 2^{52}"

Bruce Schneier notes that even computationally impractical attacks can be considered breaks:

{"**Breaking a cipher simply means finding a weakness in the cipher that can be exploited with a complexity less than brute force. Never mind that brute-force might require 2^{128} encryptions; an attack requiring 2^{110} encryptions would be considered a break...simply put, a break can just be a certificational weakness: evidence that the cipher does not perform as advertised**." }

Academic weakness versus practical weakness

In academic cryptography, a *weakness* or a *break* in a scheme is usually defined quite conservatively: it might require impractical amounts of time, memory, or known plaintexts. It also might require the attacker be able to do things many real-world attackers can't: for example, the attacker may need to choose particular plaintexts to be encrypted or even to ask for plaintexts to be encrypted using several keys related to the secret key.

Furthermore, it might only reveal a small amount of information, enough to prove the cryptosystem imperfect but too little to be useful to real-world attackers. Finally, an attack might only apply to a weakened version of cryptographic tools, like a reduced-round block cipher, as a step towards breaking of the full system.

Cryptanalysis of Asymmetric Cryptography

Asymmetric cryptography (or public key cryptography) is cryptography that relies on using two keys; one private, and one public. Such ciphers invariably rely on "hard" mathematical problems as the basis of their security, so **an obvious point of attack is to develop methods for solving the problem**. The security of two-key cryptography depends on mathematical questions in a way that single-key cryptography generally does not, and conversely links cryptanalysis to wider mathematical research in a new way.

Asymmetric schemes are designed around the (conjectured) difficulty of solving various mathematical problems. If an improved algorithm can be found to solve the problem, then the system is weakened.

For example, the security of the Diffie-Hellman key exchange scheme depends on the difficulty of calculating the **discrete logarithm**.

In 1983, Don Coppersmith found a faster way to find discrete logarithms (in certain groups), and thereby requiring cryptographers to use larger groups (or different types of groups).

RSA's security depends (in part) upon the difficulty of integer factorization — a breakthrough in factoring would impact the security of RSA.

In 1980, one could factor a difficult "50-digit number" at an expense of 10^{12} elementary computer operations.

By 1984 the state of the art in factoring algorithms had advanced to a point where a "**75-digit number could be factored in 10^{12} operations**".

Advances in computing technology also meant that the operations could be performed much faster, too.

Moore's law predicts that computer speeds will continue to increase. Factoring techniques may continue to do so as well, but will most likely depend on mathematical insight and creativity, neither of which has ever been successfully predictable.

"150-digit numbers of the kind once used in RSA have been factored".

The effort was greater than above, but was not unreasonable on fast modern computers.

By the start of the 21st century, "**150-digit numbers** " were no longer considered a large enough key size for RSA.

Numbers with several hundred digits were still considered too hard to factor in 2005, though methods will probably continue to improve over time, requiring key size to keep pace or other methods such as elliptic curve cryptography to be used.

Another distinguishing feature of asymmetric schemes is that, unlike attacks on symmetric cryptosystems, any cryptanalysis has the opportunity to make use of knowledge gained from the public key.

Quantum computing applications for cryptanalysis

Quantum computers, which are still in the early phases of research, have potential use in cryptanalysis. For example, Shor's Algorithm could factor large numbers in polynomial time, in effect breaking some commonly used forms of public-key encryption.

By using Grover's algorithm on a quantum computer, brute-force key search can be made quadratically faster. However, this could be countered by doubling the key length.