Cryptography

Systems and Information Security
Informatics Engineering (3rd year, 2nd sem.)

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Cryptography

Preamble

Basic Concepts

Applied Cryptography

Information Security

CIA triad

- **Confidentiality:** Preserving authorised restrictions on information access and disclosure, including means for protecting personal privacy and proprietary information. A loss of confidentiality is the unauthorised disclosure of information.
- **Integrity:** Guarding against improper information modification or destruction, including ensuring information nonrepudiation and authenticity. A loss of integrity is the unauthorised modification or destruction of information.
- **Availability:** Ensuring timely and reliable access to and use of information. A loss of availability is the disruption of access to or use of information or an information system.

Cryptography & Information Security

- "*Cryptography is an important computer security tool that deals with techniques to store and transmit information in ways that prevent unauthorized access or interference*" [ISO]
- Cryptography serve as a crucial line of defence against various threats, including unauthorised access, data breaches, tampering, and eavesdropping.
- Cryptography is a **security mechanism**, used in combination with others to achieve the goals of information security.

Cryptography

Preamble

Basic Concepts

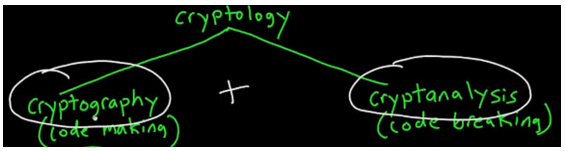
Applied Cryptography

Origins of the concept

- "Kryptós" + "Gráphein" (hidden writing)
- ...art of transmitting "secrets" (in an open channel)
- Used since ancient times, often associated with military and diplomatic activities.
- Today, the goals have expanded to encompass additional aspects of the communication process in hostile environments:
  - **Confidentiality**: secrecy of messages;
  - **Authenticity**: establish the origin of messages;
  - **Integrity**: transmitted message has not been tampered;
  - …
- Obs.: notice that the meanings of properties have been narrowed w.r.t. their use in the context of Information Security.

Cryptoanalysis

- In contrast, **cryptanalysis** aims to undermine the goals of cryptography.
- A cryptographic technique is deemed **broken** if its objectives have been successfully compromised through cryptanalysis.
- Cryptography and Cryptanalysis form an area sometimes called **Cryptology**.
- As a scientific discipline, cryptology touches on several different fields, such as probability, complexity theory, information theory, computer science, etc.



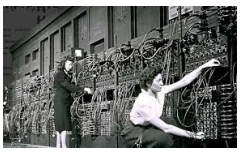
brief history

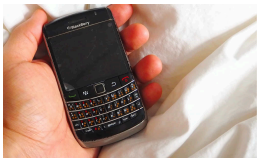
- The use of (proto) ciphers has been known since the 15th century BC.
- Armies of classical empires (e.g. Romans) regularly used cryptography

- The sophistication of the techniques has evolved over the centuries
- E.g. Enigma machine - WW2, Germany.
- Shortly after World War II, Claude Shannon (video) published two papers on Information Theory, which allowed for the formalisation of cipher security — considered the birth of Cryptography as a scientific field.

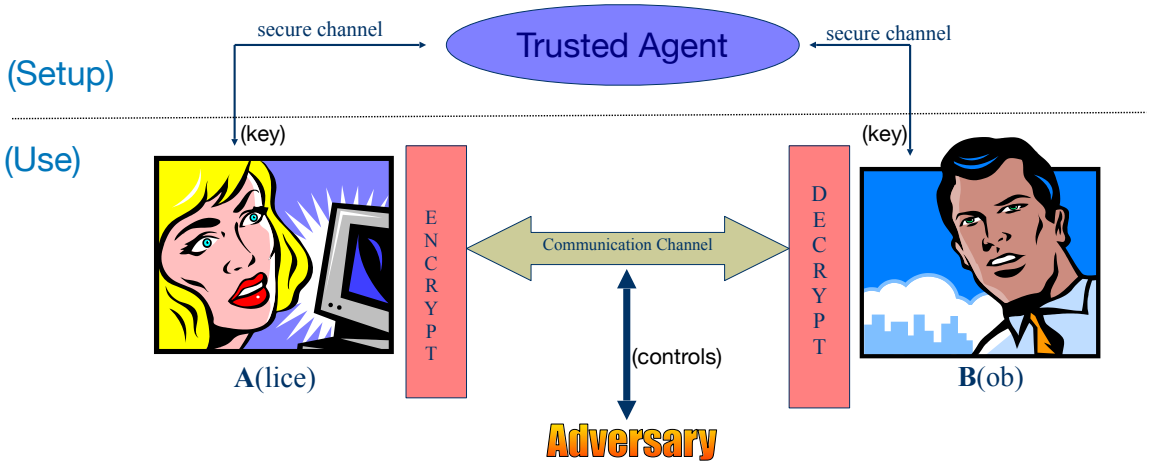
Modern Cryptography

- 1948/9 – Teoria da Informação (Claude Shannon).
- 1970/7 – Data Encryption Standard (DES).
- 1976 – Criptografia de Chave-Pública (Diffie & Hellmann)
- 2001 – Escolha do substituto do DES: Advanced Encryption Standard (AES).
- 2022/… – Criptografia Post-Quantum
- …



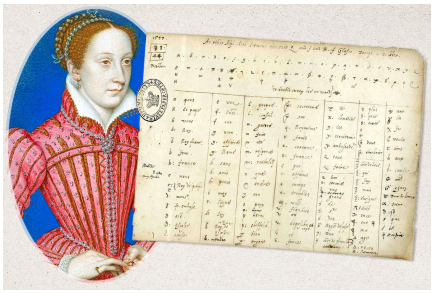

Model
(confidentiality)



Some more terminology

- **plaintext** (or **cleartext**): content of the message;
- **encryption**: operation that encodes the plaintext into an obscured message (**cyphertext**, or **cryptogram**);
- **decryption**: inverse operation of encryption
- **cryptographic system**: specification of the (possibly probabilistic) algorithms that perform some cryptographic technique (e.g. key-generation; encryption; decryption).
- **attack**: compromising the goals of a cryptographic technique (e.g. obtain the transmitted message without the corresponding key).
- **adversary** (intruder; enemy; …): hostile environment.

Security of Encryption



- Historically, security was largely attributed to the secrecy associated with the underlying technique
- ...which had disastrous consequences!
- The trend described was still present in the 20th century. However, as early as the 19th century, *Auguste Kerckhoff* established the following principle.:

  the security of a cipher must be assessed on the assumption that all the details of its construction is public knowledge

- Corollary: security can only be derived from a parameter that is explicitly secret - the **key**

Adversary

- Personalisation of the **hostile environment**
- …also known by the name of **enemy**; **spy**; **(E)ve**; **(M)allory**; …

Adversary success ⇒ ***Attack*** *on the cryptographic technique*

- **Cryptographic security** can defined as the absence of attacks:

A cryptographic technique is said to be **secure** if no adversary succeeds in attacking it.

- In practice, it's important to describe the adversary's capabilities:
  - The control he exercises over the channel (read only, read + write):
    - **Passive** - the adversary can only eavesdrop on the communication channel.;
    - **Active** - in addition, the adversary has the ability to manipulate the information circulating on the communication channel (modify / block / insert or repeat messages).
  - Computational power:
    - **computationally unbounded** - adversary is able to execute any algorithm instantaneously (with no memory limitation);
    - **computationally bounded** - adversary can only execute algorithms in some complexity class (Probabilistic Polynomial Time - PPT).
  - Additional information (e.g. previous communications);
  - etc.
- Depending on the type of adversary being considered, different notions of (cryptographic) security can be achieved
  - **Unconditional** (or **information-theoretically**) s**ecurity**— secure against a computationally unbounded adversary;
  - **Computational security** — secure against a computationally bounded adversary (PPT).

Classic Ciphers

Caesar Cipher

- Known to have been used by Julius Caesar during the Gallic campaign
- The encryption is a shift of the letters of the alphabet. .

Texto limpo:	A	B	C	D	E	F	···	T	U	V	X	W	Y	Z
Criptograma ($K = 6$):	G	H	I	J	K	L	···	Z	A	B	C	D	E	F

- To decipher, the shift is made in the opposite direction.
- The total number of possible keys is 26 (one of which is weak).
- Example: Encrypting the message `CartagoEstaNoPapo` with key K=6 results in `IGXZGMUKYZGTUVGVU`.

…attacking Caesar

- E.g. want to attack the ciphertext: FXLNTQCLOPNPDLC
- Small key-space suggests the following **strategy #1**:
  - decrypt with every possible key…
  - …and spot the one(s) that "make sense"

CRIPTOGRAMA:		FXLNTQCLOPNPDLC
+1	:	GYMOURDMPQOQEMD
+2	:	HZNPVSENQRPRFNE
....	:	.....
[MSG]+15	:	UMACIFRADECESAR (K=26-15=11)
....	:	.....
+24	:	DVJLROAJMNLNBJA
+25	:	EWKMSPBKNOMOCKB

- **Strategy #2**: frequency analysis allows for more efficient attacks…

  high frequency of 'L' suggests that it encrypts 'A' (that is, K = 'L'-'A' = 11)

Brute-force Attack

- Strategy #1 attack is known as **Brute-force Attack**

  the adversary searches the entire key space in the hope of finding the right key

- It assumes that:
  - there is enough redundancy in the original message,
  - or a plaintext/ciphertext pair is known.
- Often seen as an attack that can always be applied to a cryptosystem...
- …but its feasibility depends on the size of the key space.
- **Conclusion**: key sizes are a necessary (although not sufficient) criterion for the security of ciphers.

big numbers!

…what is as reasonable key size?

- If we consider keys to be arbitrary bitstrings, the size of the key space increases exponentially on the key size
- Example:

Key Size	**Time** ($1\mu sec/test$)	**Time** ($1\mu sec/10^6 tests$)
32 bit	35.8 min.	2.15 msec.
40 bit	6.4 days	550 msec
56 bit	1140 years	10 hours
64 bit	500000 years	107 days
128 bit	$5 * 10^{24}$ years	$5 * 10^{18}$ years

- Baseline: 2^{112} provides a reasonable security level!

Monoalphabetic Substitution Cipher

- Instead of the shift used in the Ceaser Cipher, encryption performs an arbitrary permutation of the alphabet (decryption uses the inverse permutation);
- E.g.:

A	B	C	.....	W	Y	Z
R	X	K	.....	B	I	F

- Much larger key-space ($26! \approx 17.5 * 10^{24}$)

…should we trust the security of this cipher?

…an attack

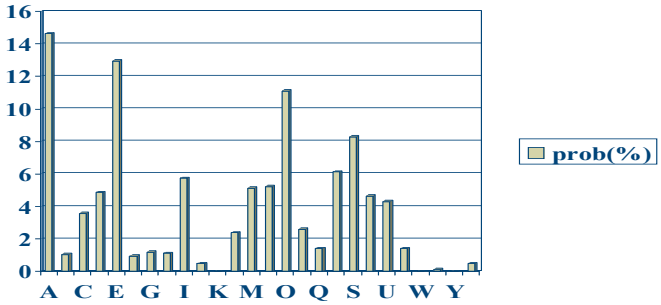
- Consider the following ciphertext:

```
FPGFBNBVPKFBDMSBEMDMGUCDKDGUGDMUSPMMDBEFLEFEQDCPPGIDEXDCBKPMDHKPMPFQBUGPSUGHKEGPF
QBMPXPKSESEBSURBHKBHBMEQBFUFSDSBGHKPPFCECPHDKQPDHDKQPFDBADVEDFDCDDCEZPKLDZEDGMPPM
NDKPMDGDVPEMPDNUPFQDVDMPCPZGEFUQBMCPUGMEOPFSEBHPFBMBFBDUNPCDPXSEQDSDBCBBUQBFBCPMU
KNEKDGUGDMHPKMBFDNPFMCPBKENPGBIMSUKDSBGJUPGPFQKPQEVPSBFSEOEDIUOBMPGKPMQDUKDFQPMPX
SPFQKESBMPMMPMQKDZEDGUGDHPKNUFQDQPKKEVPOBJUPPJUPVDEMUSPCPKKPMHBFCEOAPMJUPFDBMDIED
PPOPMBOADKDGHDKDBHKDQBSBGEFJUEPQDSDB
```

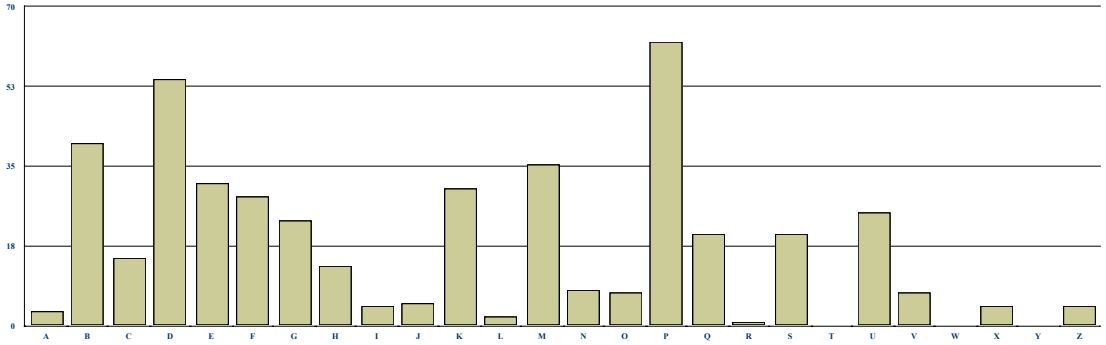
- …known to be a Portuguese text.

how should we proceed?

- Letter frequency of Portuguese:



- Histogram of letters in the ciphertext:



- Suggests matching “A”; “E”; “O” with “P”; “B”; “D”
- Pairs or triples of letters can also be considered, such as “os”; “es”; “que”; “nao”; …
- Several occurrences of the pairs “PM”, “PF”, “MP”, and “JUP” suggest the following partial decryption: {…; F:M; …}

```
ME-MO-O-E-MOAS-O-SAS-U-A-A-U-ASU-ESSAO-M--M--A-EE--A--A-O-ESA--ESEM-OU-E-U--
---EM-OSE-E-----O-U-O--O-OS--OMUM-A-O---EEM---E-A--EA-A--EMAO-A--AMA-AA---E-
-A--A-SEES-A-ESA-A-E-SEA-UEM-A-ASE-E---MU-OS-EU-S--EM--O-EMOSOMOAU-E-AE----
A-AO-OOU-OMO-ESU----A-U-AS-E-SOMA-EMS-EO---E-O-S-U-A-O-QUE-EM--E---E-OM----
A-U-OSE--ES-AU-AM-ESE--EM----OSESSES--A--A-U-A-E--UM-A-E----E-OQUEEQUE-A-SU-
E-E--ES-OM----ESQUEMAOSA--AEE-ESO--A-A--A-AO--A-O-O--MQU-E-A-AO
```

- …which, on closer inspection, does not seem to make much sense.… :-(

- We need to backtrack on some of our hypotheses…
- Reassigning the decryption of F into N…
- …we get something a lot more promising:

```
NE-NO-O-ERNOAS-O-SAS-U-ARA-U-ASU-ESSAO-N--N-TA-EE--A--A-ORESA-RESENTOU-E-U--R--
ENTOSE-ER----O-U-O-RO-OS-TONUN-A-O--REEN---E-ARTEA-ARTENAO-A--ANA-AA---ER-A--A-
SEES-ARESA-A-E-SEA-UENTA-ASE-E---NUTOS-EU-S--EN--O-ENOSONOAU-E-AE---TA-AO-
OOUTONO-ESUR--RA-U-AS-ERSONA-ENS-EOR--E-O-S-URA-O-QUE-ENTRET--E-ON----A-U-OSE-
RESTAURANTESE--ENTR--OSESSESTRA--A-U-A-ER-UNTATERR--E-OQUEEQUE-A-SU-E-ERRES-ON---
-ESQUENAOSA--AEE-ESO--ARA--ARAO-RATO-O--NQU-ETA-AO
```

- which rapidly leads to the whole plaintext

```
NEMNOGOVERNOASCOISASMUDARAMUMASUCESSAOINFINITADEEMBAIXADORESAPRESENTOUMECUMPRIMEN
TOSEXERCICIOCUJOPROPOSITONUNCACOMPREENDIDEPARTEAPARTENAOHAVIANADAADIZERFAZIAMSEES
GARESAMAVEISEAGUENTAVASEDEZMINUTOSDEUMSILENCIOPENOSONOAUGEDAEXCITACAODOOUTONODESU
RGIRAMUMASPERSONAGENSDEORIGEMOBSCURACOMQUEMENTRETIVECONCILIABULOSEMRESTAURANTESEX
CENTRICOSESSESTRAZIAMUMAPERGUNTATERRIVELOQUEEQUEVAISUCEDERRESPONDILHESQUENAOSABIA
EELESOLHARAMPARAOPRATOCOMINQUIETACAO
```

Vigenère Cipher

(polyalphabetic substitution)

- Attributed to *Blaise Vigenère* (16th century). Known as "*le chiffre indéchiffrable*".
- It interleaves multiple Caesar ciphers.
- Broken in the 19th century by *Charles Babbage* and *Friedrich Kasiski*.
- Description:
  - key is a password — each letter corresponds to a single Caesar cipher key (A=0; B=1; …);
  - Encryption: apply the Caesar cipher with each character of the key in sequence, starting over when no more key characters are available.
- Observations:
  - same letter is not always encrypted in the same way (add some hurdles to the frequency analysis)
  - … but if the plaintext is much larger than the key, patterns in the plaintext shall be reflected in the ciphertext.
  - The cryptanalysis techniques that have been developed exhibit already some degree of sophistication.

Transposition Cipher

- Encryption permutes character positions (instead of changing them…)
- E.g.
  - consider a permutation [2; 1; 3] (key)
  - to encrypt “AindaOutraCifra”, write it on a matrix…

2	1	3
A	I	N
D	A	O
U	T	R
A	C	I
F	R	A

  - …and read the columns (with header [1; 2; 3])
  - resulting ciphertext: “IATCRADUAFNORIA”
- Observation: frequency analysis is now useless!

Cipher Composition

- Having seen different simple ciphers…
- Is it sensible to construct more intricate ciphers, which are more secure, by combining multiple simpler ciphers?

- It depends!
  - it may happen that it doesn't add any value (e.g. combining two ciphers by substitution)
  - but there are combination patterns that can be advantageous (e.g. by interleaving substitutions with permutations — aka *SP-networks*).

One-Time Pad

(Vernam Cipher - 1917)

- Generalises Vigenère cipher with:
  1. key size is, at least, the plaintext size;
  2. key is fully random;
  3. key is only used in a single encryption.
- Normally described as operating on a binary alphabet: encryption/decryption is the *exclusive-or* (xor) with the corresponding key bit.

$$C_i = T_i \oplus K_i \qquad M_i = C_i \oplus K_i$$

- Shown to be secure (**information-theoretically secure**) by *Claude Shannon — "knowing the ciphertext does not reduce the uncertainty about the plaintext"*.
- Key generation and distribution make this cipher unfeasible in realistic scenarios.

Conclusion

- In cryptanalysis, all available information is used, including:
  - partial information about the transmitted message;
  - previous cipher's use (e.g. messages encrypted with the same key);
  - and possible weaknesses in the cipher's use (e.g. deficiencies in the choice of keys, etc.).
- Although unconditionally secure techniques exist, they often have such strict requirements that they become impractical.
- Most (all?) cryptographic techniques used today are based on **computational security**, which limits the adversary's computational capabilities.
- The size of a cipher's key should be determined based on the desired level of security (e.g. 2^{112}), while taking into account the amount of key size that is “consumed” by known cryptanalysis techniques.

Cryptography & Security

(Cryptographic) Security Properties

- We have mainly focused on ciphers — a cryptographic primitive whose goal is to ensure *confidentiality*.
- But cryptography is used today to provide guarantees for a wide range of security properties:
  - **confidentiality** — content of the message is only known to the legitimate parties;
  - **integrity** — the recipient would "reject" messages that have been tampered;
  - **autenticity** — ensures the "origin" of the message to the recipient;
  - **non-repudiation** — the “origin” of the message cannot deny it;
  - **anonymity** — no information available regarding the “origin” of the message;
  - **identification** — establish the “identity” of a party;
  - …

Cryptographic Services and Protocols

- Usually, one is interested in a combination of these properties (e.g. a secure channel between two parties aims to guarantee confidentiality, authenticity and integrity).
- On the other hand, some of these properties do not directly follow from a single cryptographic technique, but rather from a combination of techniques.
- Leading to what is known as **cryptographic protocols** — specifications for message exchanges that rely on cryptography to achieve a desired end.
- The security of those protocols relies not only on the security of the underlying cryptographic techniques, but also on subtle interactions between them.

Cryptography & Security

*The security of a system using cryptography **is not just** the security of the underlying cryptographic techniques.*

- We can distinguish (at least) the following levels when establishing the security of a system that uses cryptography:
  - cryptographic scheme;
  - protocol;
  - implementation (coding);
  - usage.

A breach at any of these levels jeopardises the security of the entire system!

Applied Cryptography

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Applied Cryptography

Symmetric Crypto

Asymmetric Crypto

Applications

Roadmap

- Ciphers
  - Stream ciphers
  - Block ciphers
- One-Way Functions
  - Cryptographic Hash Functions
  - Message Authentication Codes (MAC)
  - Key-Derivation Functions (KDF)
- Key-Management

Stream Ciphers

Recall OTP (one-time pad)

- Known to be (information-theoretically) secure

- Inherent issues:

  1. keys cannot be reused

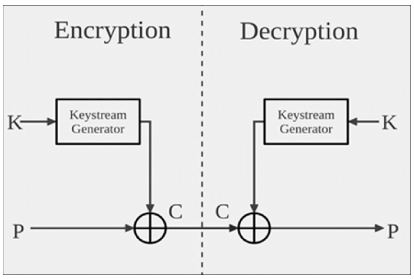
  2. truly random key with size greater than the plaintext

  3. does not promote diffusion — information on the structure of the message can be used to manipulate it (bit swapping).

- Difficulties associated with key-generation and key-distribution render the OTP mostly unusable in real-world applications.

Stream-Ciphers

- **Basic idea**: approximate OTP using a key stream generator which generates an arbitrary length keystream from a short, fixed-length key.

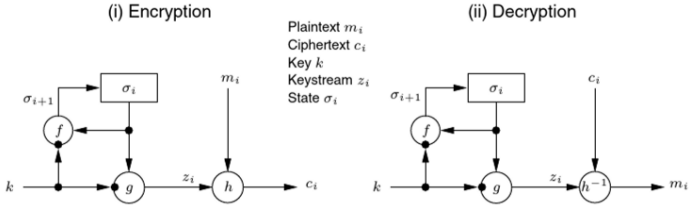


- The generation of the keystream must be reproducible (deterministic) — a finite state machine.
- Therefore, the sequence must necessarily be **cyclic**. The **period** is the length of the sequence before it repeats..

Criteria for the design of Stream Ciphers

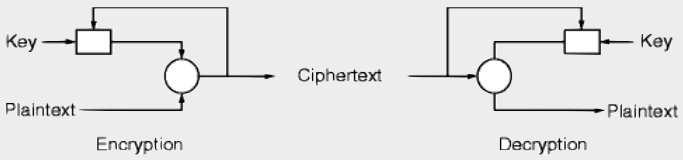
- Period should be as long as possible (always longer than the plaintext).
- Key sequence must be:
  - **pseudo-random**: statistic properties of the sequence are those of a truly-random sequence;
  - **unpredictable**: should be impossible to predict the “next bit”, after observing a given prefix of the sequence
- Other characteristics
  - synchronism:
    - **synchronous** — keystream is independent of the message;
    - **self-synchronising** — able to recover synchronism when bits of the ciphertext are lost .
  - error-propagation: the impact of transmission errors on decrypted messages
  - …

Synchronous Stream Ciphers



- Keystream is independent of the message;
- Loss or insertion of bits in the cryptogram results in loss of synchronisation.
- Transmission errors (bit swapping) only affect the corresponding position of the original message.
- The key might affect:
  - The next-state function *f* — **Output-Feedbak Mode**.
  - The output function *g* — **Counter Mode**.
  - Both...

Self-synchronising Stream Ciphers



- Next-bit is computed from the last n bits of the ciphertext (and key);
- A IV (initialisation vector) is used to initiate the process;
- In case of a transmission error, synchronisation is restored once the flipped bit is no longer used for the next bit computation.
- Possible problem: vulnerable to replay attacks.

Cryptographic-Secure Pseudo-Random Number Generation

- *Golomb*'s Randomness Postulates:
    1. The difference in the number of 1s and 0s must tend towards zero;
    2. The expected number of sub-sequences of repeated symbols (runs) with length *l* is given by $r(l)=r/2^l$;
    3. The auto-correlation must be a constant value for any deviation other than *0 (mod p)*.
- Cryptographic Security:

    The generated sequence must be indistinguishable from a random sequence for any Probabilistic Polynomial Time (PPT) adversary.

Key reuse and NONCEs

- The above description of sequential ciphers inherits a problem from OTP: **key reuse**
    - encrypting different messages with the same key shall lead to the same generated keystream.
- This problem is generally overcome by using NONCEs — abbreviation of **Number used only ONCE**.
    - A number that should never be repeated;
    - but not required to be kept secret (i.e. it can be sent along with the cryptogram).
- In practice, the Nonce is typically a sequence of randomly generated bytes used during encryption and sent along with the cryptogram.

Some Examples

- Stream ciphers are used in several well-known applications:
  - **A5** (**A5/2**), used in the GSM standard;
  - **E0**, used in the Bluetooth protocol;
  - **CSS** (Content Scramble System), used to protect DVD discs.

  (Note: All of the above examples are known to offer weak security guarantees.)
- **RC4** (ArcFour) — a cipher designed for efficient software implementation, which was once widely used but **is now considered broken**.
- **ChaCha20** — a modern (and secure) stream cipher.

Block Ciphers