Chapter 2

Types of modern encryption

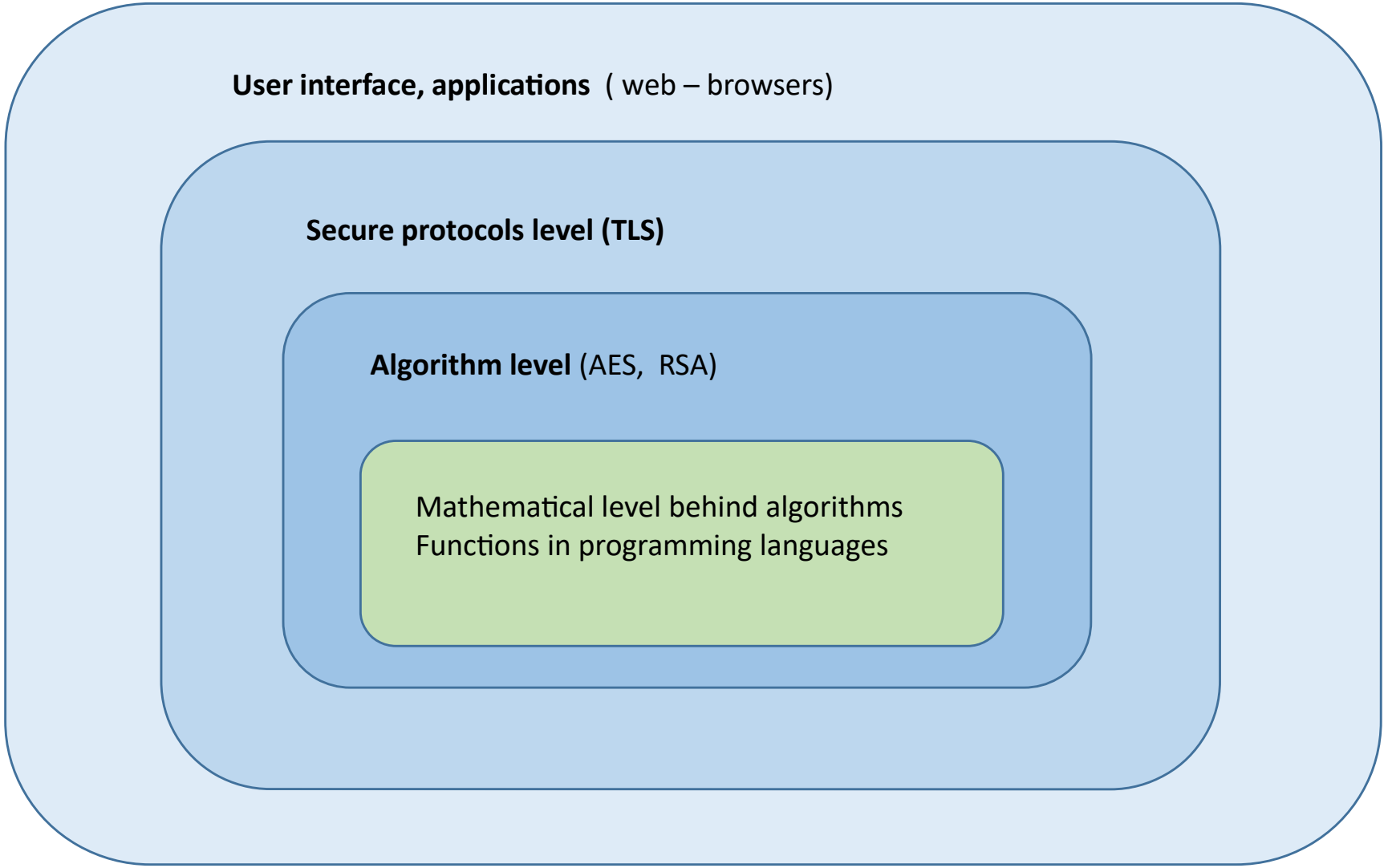
Secure connections viewed from different levels

- User interface, applications
- Secure protocols level
- Algorithm level
- Level of mathematical structures

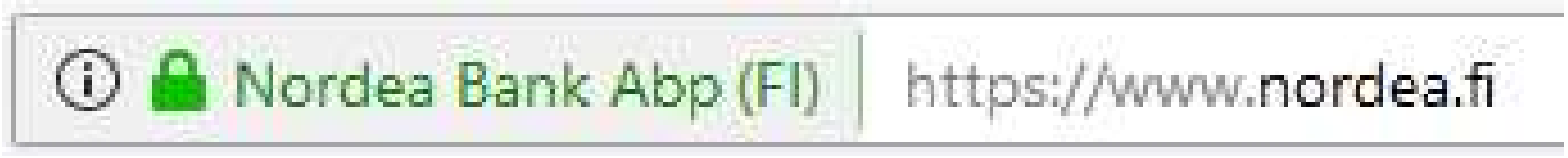
Block ciphers

Stream ciphers

Encryption at different levels



User level (browsers)



Users know that the connection is secure from the lock of URL row of the browser. If the lock is green, the connection is secure and encrypted and the server is authenticated. Red lock means possible security problems.

The encryption software which provides the secure connection is usually TLS.

Secure protocols level

In Mozilla Firefox browser clicking the lock reveals following information:

Tekniset tiedot
Yhteys salattu (TLS_ECDHE_RSA_WITH_AES_256_GCM_SHA384, 256-bittinen avain, TLS 1.2)

TLS ver 1.2 is a hybrid encryption software, which uses several algorithms for different functions. More than 95% of secure connections over Internet use TLS.

The basic functions of a hybrid encryption software are:

1. Authentication
2. Key exchange (agreeing of symmetric key)
3. Encryption of transmitted data
4. Digital signatures

Algorithmic level

Below list of algorithms is from Nordea Bank's TLS - connection

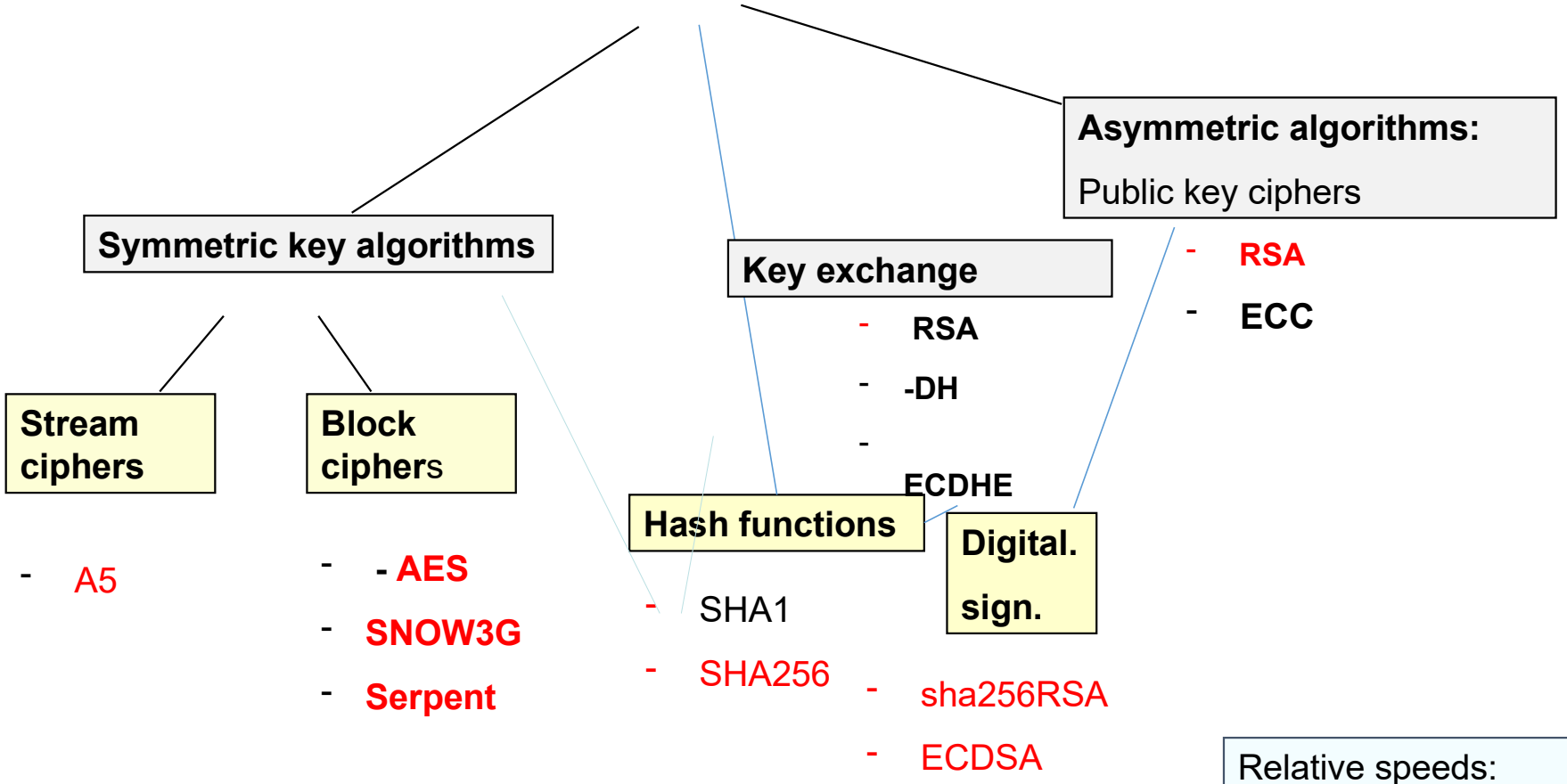
Function	Algorithm name
Server authentication	**RSA**
Key exchange	**ECDHE**
Encryption of transmitted data	**AES256 GCM-moodi**
Digital signature	**sha384RSA**

4. Mathematical level

The algorithms of TLS and other modern software require lots of mathematics

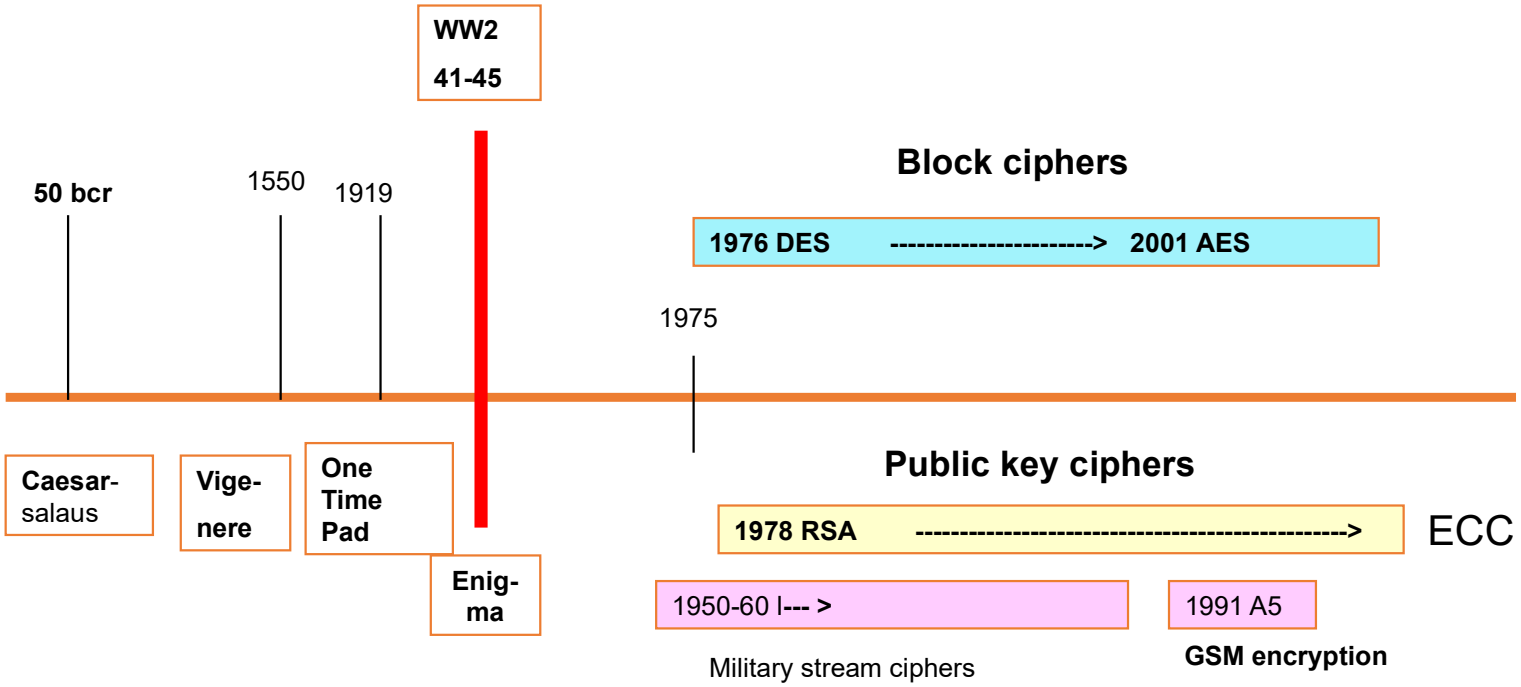
1. Fermat's and Euler's theorems, Extended Euclid's algorithm	
2. Random number generation	**pseurodandomness**
3. Prime generation, tests	**Fermat and Rabin- Miller tests**
4. Modular arithmetics	**number sets Z_n**
5. Fast exponentiation mod n	**Powermod - algorithm**
6. Inverses mod n	**Euclid's extended algorithm**
7. Cyclic group Z_p^*	**group theory**
8. Elliptic curves	**group theory**

Algorithm types



Relative speeds:	
Hash	3
Stream cipher	2
Block cipher	1
Asymmetric	0.02

Time line of encryption methods



Algorithms have long lifetime. RSA has been standard for 45 years in public key cryptography. Block cipher standard has changes only once during 45 years. Reasons for conservatism: 1. Changing algorithms costs money. 2. The security of algorithms are based on mathematical proofs, they have been tested for decennies.

Symmetric encryption algorithms

Classification

1. Block ciphers

-used both in wired and mobile communication
-Diffusion and confusion principles
-Permutation-substitution networks
-Modes of operation
-AES : block cipher standard

2. Syncronic stream ciphers

- no longer widely used
- GSM (G2)– encryption A5

Block ciphers

- Central part of secure connections. Block ciphers encrypt transmitted data reliably and effectively
- Provides fast symmetric encryption in which message is encrypted in blocks (size usually 128 bits)
- The present block cipher standard is AES (since 2001). It is used both in secure wired connections and in mobile networks

History of block ciphers

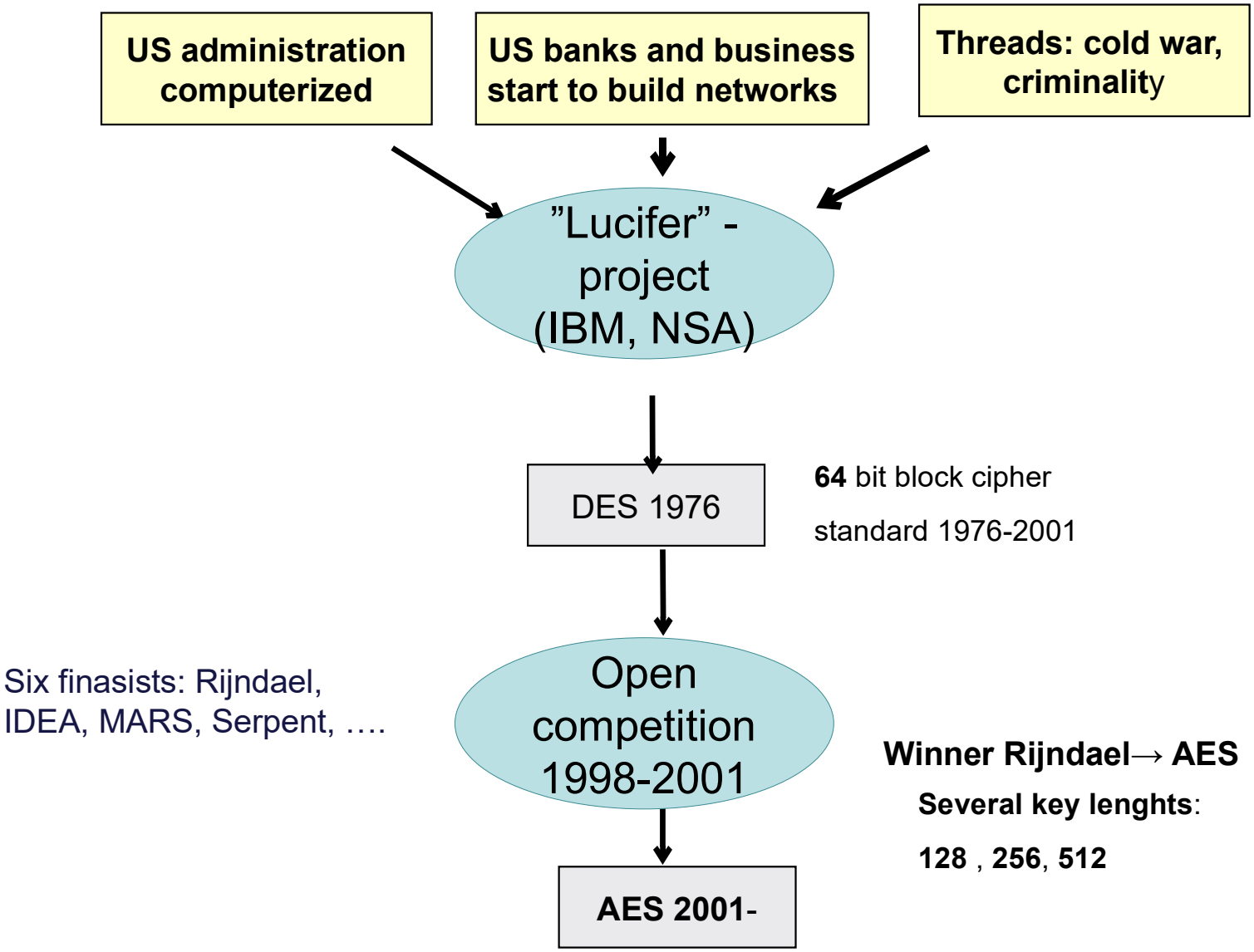
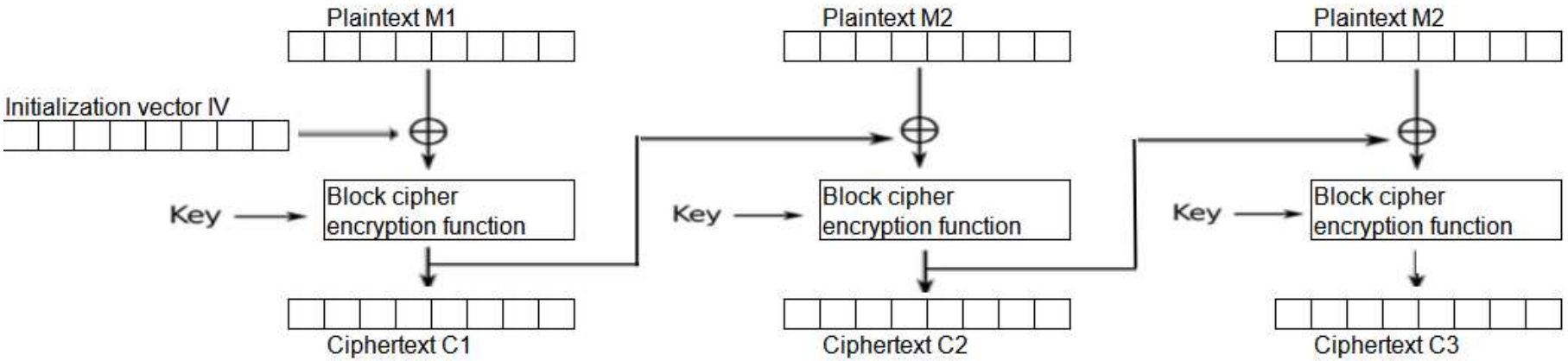


Diagram shows how block cipher works in CBC mode
(CBC = cipher block chaining)



Principle:

Message m is divided into 128 bit blocks m1, m2, m3, …

Key k has 128 bits in AES128. Cipher consists of blocks c1, c2, c3, ...

In CBC mode each output block is taken as 3rd input in calculation of next cipher block.

$$c_n = AES(m_n, k, c_{n-1})$$

Requirements for block ciphers

- Block cipher should have both software and hardware (chip) implementations (AES has both)
- Algorithm should be reliable and fast
- It can be applied to both data transfer and files
- Algorithm should be public and transparent (Kerckhoff principle)

- Key length should be at minimum 128 bits

Shannon's diffusion and confusion

The operation of block ciphers is based on two principles of Claude Shannon: diffusion and confusion

Diffusion: (dependence of cipher and message)
Changing one bit of message block should change in average half of the output bits. The output bits should equally depend on all input bits.

Confusion: (dependence of cipher and key)
Every bit of cipher should depend on all parts of the key. The change of one bit of the key, should change the output completely, not just part of it.

The ciphertext should be random and fulfill the properties of pseudorandom bit sequence (explained later)

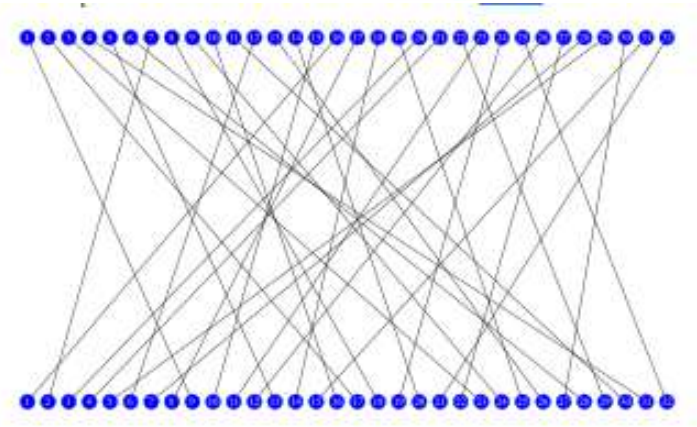
Permutation – Substitution networks

The principles of diffusion and confusion are usually implemented usign a permutation - substitution network.

Substitution = replacing certain bit patterns with image patterns, traditionally using substitution tables called SBOX:es. Below a table of Sbox nr 6 of DES block cipher. In example bit sequence 011011 is mapped to 1001

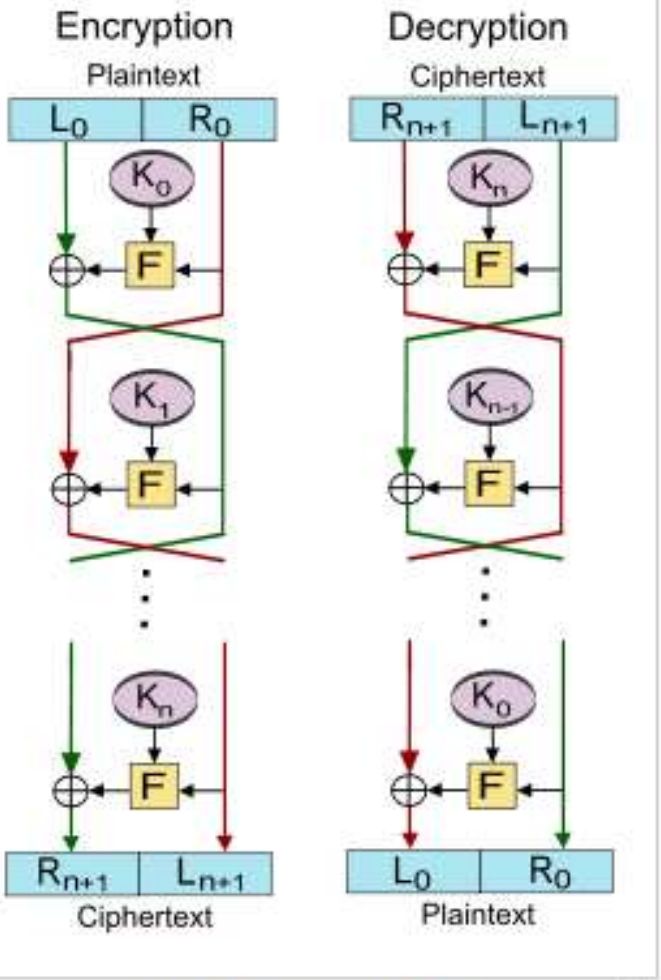
S_5		Middle 4 bits of input															
		0000	**0001**	**0010**	**0011**	**0100**	**0101**	**0110**	**0111**	**1000**	**1001**	**1010**	**1011**	**1100**	**1101**	**1110**	**1111**
Outer bits	**00**	0010	1100	0100	0001	0111	1010	1011	0110	1000	0101	0011	1111	1101	0000	1110	1001
	01	1110	1011	0010	1100	0100	0111	1101	0001	0101	0000	1111	1010	0011	1001	1000	0110
	10	0100	0010	0001	1011	1010	1101	0111	1000	1111	1001	1100	0101	0110	0011	0000	1110
	11	1011	1000	1100	0111	0001	1110	0010	1101	0110	1111	0000	1001	1010	0100	0101	0011

Permutation = reordering bits of a block using permutation tables. Figure shows how 64 bits are rearranged in P-box of DES block cipher.



Rounds: Permutation- Substitution loop runs several times, (f.e in DES algorithm 16 times) in order to remove all regularities in the cipher bit sequence.

Feistel network



Many block ciphers, such as DES and Blowfish utilize structures known as *Feistel ciphers*

IBM engineer Feistel created PS network in 1960's using permutations and SBOX:s (substitution tables).
Feistel network appeared originally in DES block cipher, it was later reused in Blowfish cipher and later in **Kasumi , which was recently a standard block cipher in 3G and 4G**
Today Kasumi is replaced by AES and SNOW3G

Feistel algorithm has 16 rounds. Each round uses different subkey K_i derived from the master key K

Each round starts with initial permutation and ends with final permutation (called P-BOX:s)

Between permutations there are eight S BOXes, which obscure the connection between the key and the ciphertext implementing Shannon's confusion principle

AES encryption standard

In late 1990's NIST organized a competition to choose a new block cipher standard. There were 6 finalist, from which the Rijndael algorithm was chosen as the new standard in 2001.
The winner got a new name *Advanced Encryption Standard* AES.

Advantages of AES

* It has many versions AES128, AES196, AES256, AES512. With flexible key lengths it answer the challenges of increasing computing power

* The security is based on provable, transparent mathematics

* It is generally thought that AES will be used as the standard block cipher for a long time in the forseeable future.

In this chapter we use in whole 12 slides to explain how AES works, not only because AES is the standard block cipher, but also because there is a connection to Finland: A Finnish cryptographer Kaisa Nyberg, emerita professor of Aalto University, has contributed to AES algorithm with a method of using theory of **Galois' Field GF(2^8)** in several key parts of AES.

The Stack problems related to AES mathematics are not compulsory, but they give bonus points to increase the grade.

AES handles blocks as tables of 16 bytes

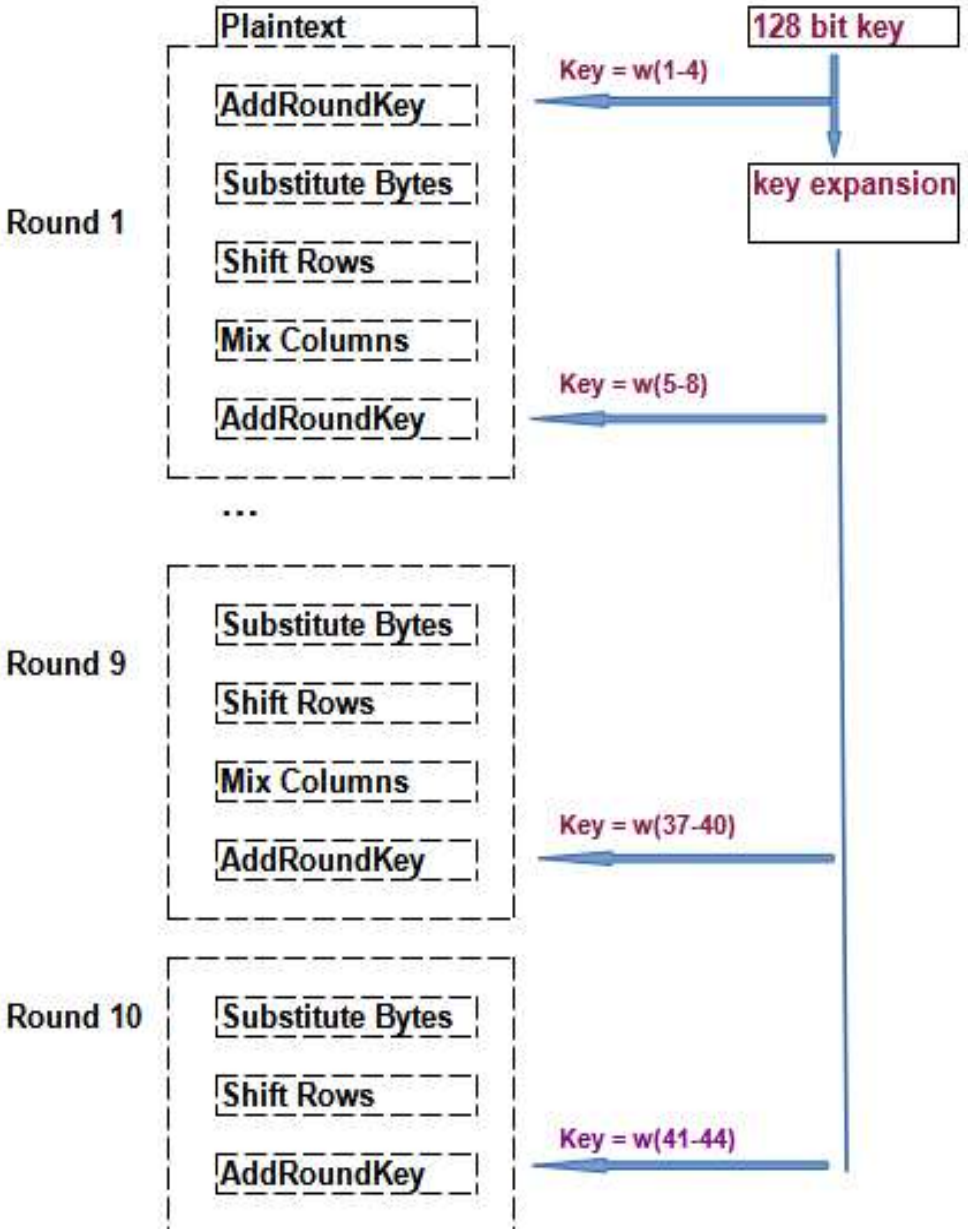
AES block size is 128 bits. Blocks are arranged to tables of 16 bytes (1 byte = 8 bits), as in the example below.

$$\begin{bmatrix} 12 & 3F & 95 & 8C \\ 35 & 62 & 87 & D3 \\ FA & 33 & 42 & 7E \\ 85 & 32 & 45 & 99 \end{bmatrix}$$

The elements of the table, which is also called ”AES state” are bytes, which are 8 bit binary numbers. Bytes are usually presented as hexadecimal number form.

For example byte 8C is in binary form 10001100 , because according to the table below 8 = 1000 and C = 1100.

hexadecimal	0	1	2	3	4	5	6	7	8	9	A	B	C	D	E	F
decimal	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
binary	0000	0001	0010	0011	0100	0101	0110	0111	1000	1001	1010	1011	1100	1101	1110	1111



AES128 uses a 128 bit key

AES128 algorithm has 10 rounds all of which use different ”**round keys**” derived from the master key.

Each round has many phases, which implement diffusion and confusion of bits.

Phases of rounds are:
-Substitute bytes (Sbox)
-Shift rows
-Mix columns
-Add round key

The finest part, Sboxes uses Theory of Galois Fields. The algorithm in Sboxes was invented in 1991 by a Finnish cryptographer Kaisa Nyberg.

Evariste Galois (1811-1832) was a great French mathematician who died at the age of 21

At first the key K is expanded to 10 Round Keys

Round Key generation

AES128 algorithm has 10 rounds. Each round has an own round key, which is derived from the 128 bit master key K.

Round Key Generation is a process, which can be described briefly as follows:

The 128 bit (=16 bytes) master **key K is expanded to 44 words w_1, w_2, ….,w_{44}.** (1 word = 4 bytes = 32 bits) usign a special algorithm. Details of the expansion can be found in internet if needed.

Round1 uses 8 words of the expanded key: w_1,...w_4 in the beginning and w_5, …,w_8 in the end of the round.

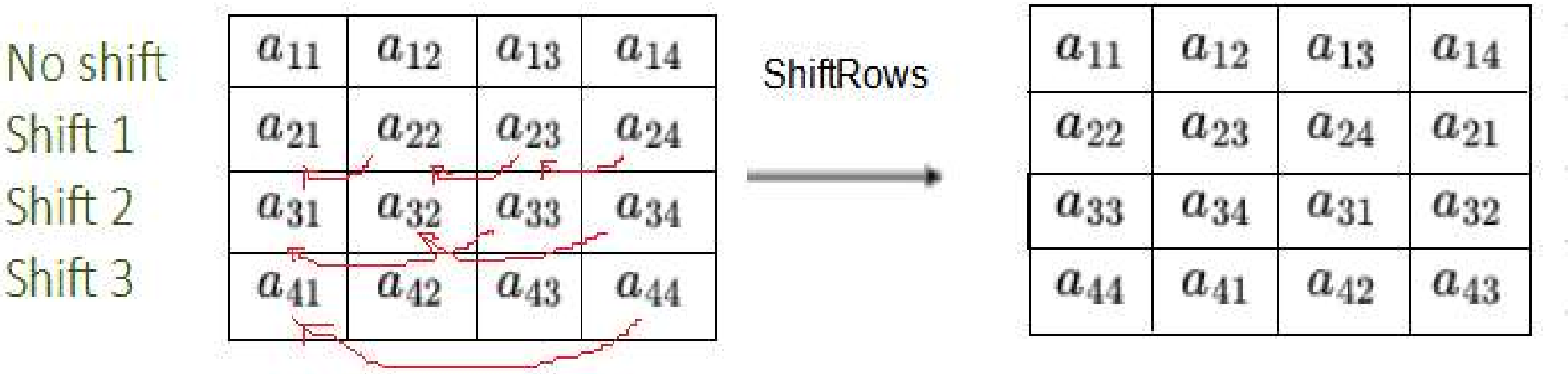
All the other rounds use 4 words each (see the picture in the previous slide)

Steps of AES rounds

Notice: Every step must be reversible. Inverted steps are needed in decryption of the cipher.

ShiftRows step

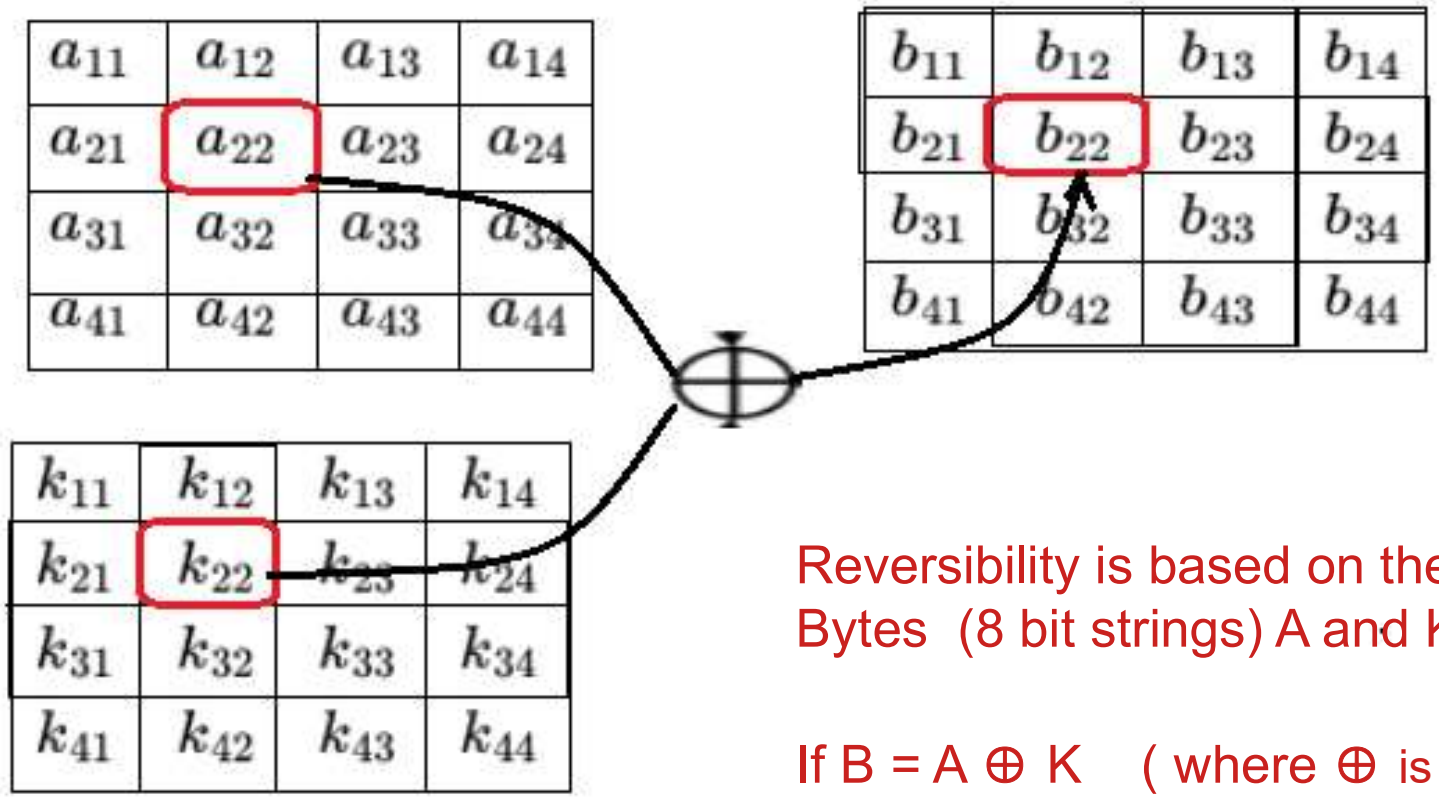
Bytes in each row of the state are shifted cyclically to the left.
The amount of shift differs incrementally for each row.



It is obvious that this step can be reversed by changing the direction of shifts

AddRoundKey Step

Every round of AES has an own Round Key derived from the primary key.
In AddRoundKey Step each byte of the state is combined with a byte of the Round Key using XOR – addition (symbol ⊕)



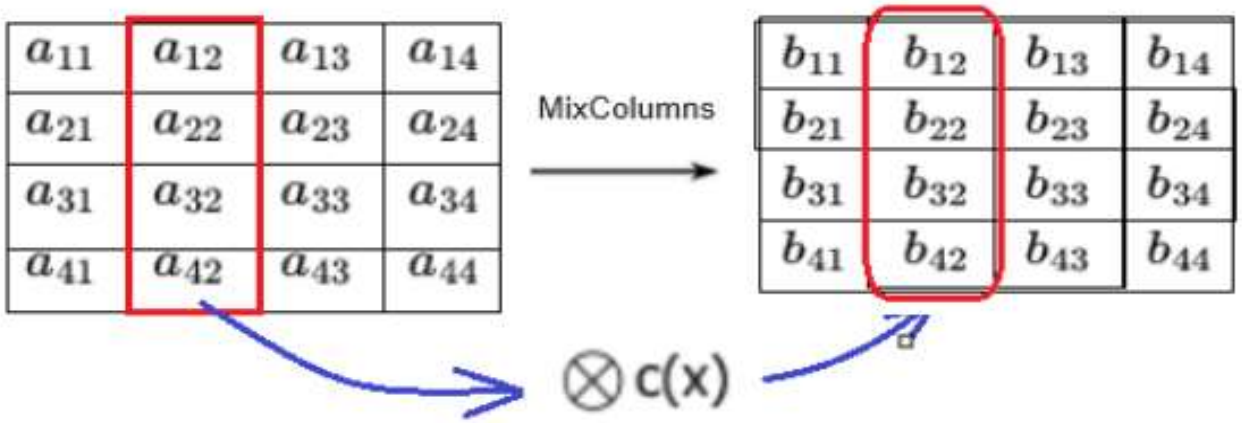
Reversibility is based on the fact that for any Bytes (8 bit strings) A and K it is true that

If B = A ⊕ K (where ⊕ is bitwise XOR), then A = B ⊕ K

Proof: A ⊕ K ⊕ K = A ⊕ (K ⊕ K) = A

MixColumns step

Each column of the state is multiplied with a fixed polynomial c(x) using Galois' Field multiplication rule, which is explained a couple of slides later.



For those who are interested, there is a detailed description in **Appendix1** of the way polynomial multiplication is used in MixColumns step. There is a bonus problem related to Appendix1.

Reversibility of MixColumns step:

In Galois' Field every polynomial has an inverse polynomial, which can be used to invert the operation, which is needed in AES decryption.

That is: if $b(x) = c(x)a(x)$, then $a(x) = c^{-1}(x)b(x)$

MixColumns and Substitute Bytes steps use the theory of Galois' Fields.
Next slides contain an explanation and calculated example of how multiplication of bytes can be defined using polynomials.

How bytes can be presented as polynomials in Galois' Field GF(2^8)

An 8 bit binary number $(b_1b_2b_3b_4b_5b_6b_7b_8)$, where each $b_i \in \{0,1\}$ are in Galois' theory presented as 7th degree polynomials $b_1 x^7 + b_2 x^6 + b_3 x^5 + b_4 x^4 + b_5 x^3 + b_6 x^2 + b_7 x + b_8$.

Example: Present bytes D4 and 69 as polynomials.
$D4_{16} = 1101\ 0100 = x^7 + x^6 + x^4 + x^2$
$69_{16} = 0110\ 1001 = x^6 + x^5 + x^3 + 1$

Galois' field multiplication rule: steps + calculated example

The "Galois' product" of two bytes a and b is calculated with following steps:
Step1: Calculate the product of polynomials using normal polynomial multiplication
Step2: Reduce the coefficients of the product to binaries using rule even→ 0, odd→ 1.
Step3: Divide the result of step2 with 8. degree polynomial called "Field Irreducible polynomial" which in AES is $x^8 + x^4 + x^3 + x + 1$. The final result is the polynomial remainder of the division, where coefficients are reduced to binaries as in step 2

In the next slides it is shown how product D4⊗69 can be calculated, first using polynomial presentations and then using bit operations.

Method 1. Calculation of D4⊗69 using polynomials

Step1) Using standard polynomial multiplication we get

$(x^7 + x^6 + x^4 + x^2)(x^6 + x^5 + x^3 + 1) = x^{13} + 2x^{12} + x^{11} + 2x^{10} + 2x^9 + x^8 + 3x^7 + x^6 + x^5 + x^4 + x^2$

Step2) Reduction of coefficients using rule: even → 0 , odd → 1 gives

$a*b = x^{13} + x^{11} + x^8 + x^7 + x^6 + x^5 + x^4 + x^2$

Steps 1 and 2 can be done with a single WolframAlpha. command : expand (x7 +x6 +x4 +x2)(x6 +x5 +x3 +1) mod 2 , which gives $x^{13} + x^{11} + x^8 + x^7 + x^6 + x^5 + x^4 + x^2$

Step3) **T**he result of step2 is divided with $x^8 + x^4 + x^3 + x + 1$ in order to calculate the polynomial remainder. Division can be done manually using the algorithm taught in school. More convenient way is to use calculators like WolframAlpha.

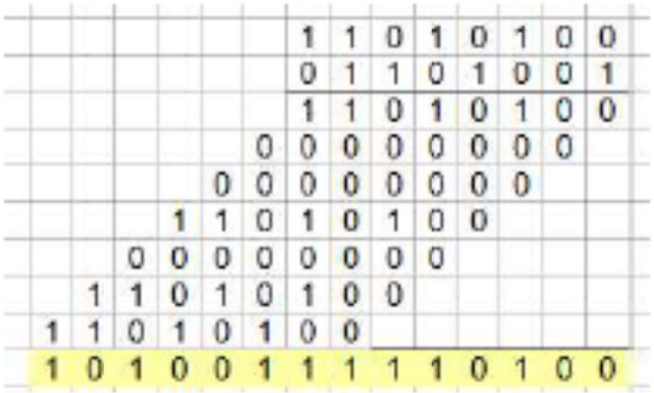
Wolfram Alpha command remainder $(x^{13} + x^{11} + x^8 + x^7 + x^6 + x^5 + x^4 + x^2)/(x^6 + x^5 + x^4 + x^3 + x)$ gives $-x^6 + x^5 + x^4 - x^3 + 2x^3 + x$. Reduction with even → 0 and odd → 1 gives polynomial $x^6 + x^5 + x^4 + x^3 + x$

The result $x^6 + x^5 + x^4 + x^3 + x$ corresponds byte 7A = 0111 1010. Thus D4⊗69 = 7A

One can guess, that the use of polynomial presentations is not very efficient way of calculating the product of bytes. There is a faster method explained in the next slide, which uses binary operations.

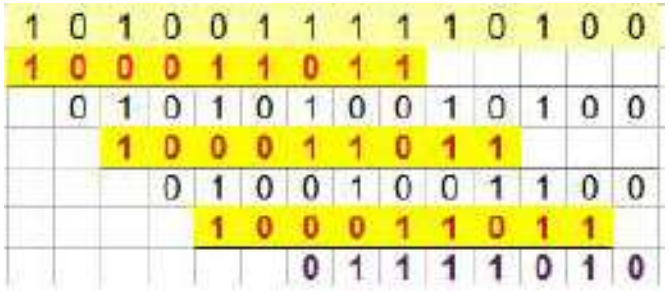
Method 2. Calculation of D4⊗69 using binary operations

Step1&2: Multiply bytes **$D4_{16}$ = 1101 0100 and 69_{16} = 0110 1001** using normal multiplication algorithm. When summing the columns use XOR addition.



The last line corresponds the result of steps 1 and 2 of polynomial method.

Step3. The divisor polynomial $x^8 + x^4 + x^3 + x + 1$, in binary form 100011011 corresponds modulus of modular arithmetics. One can add the modulus and its multiples to any number without changing it. In Galois' Field we can add the sequence 100011011 to eliminate 1's of the binary number starting from the left until the result is a 8-bit binary number.



In our example addition of 100011011 is needed three times to receive the answer 0111 10101 = 7A

AES Sbox which is based of Galois' Field multiplication can be presented in table form as follows

	Y															
	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
0	63	7C	77	7B	F2	6B	6F	C5	30	01	67	2B	FE	D7	AB	76
1	CA	82	C9	7D	FA	59	47	F0	AD	D4	A2	AF	9C	A4	72	C0
2	B7	FD	93	26	36	3F	F7	CC	34	A5	E5	F1	71	D8	31	15
3	04	C7	23	C3	18	96	05	9A	07	12	80	E2	EB	27	B2	75
4	09	83	2C	1A	1B	6E	5A	A0	52	3B	D6	B3	29	E3	2F	84
5	53	D1	00	ED	20	FC	B1	5B	6A	CB	BE	39	4A	4C	58	CF
6	D0	EF	AA	FB	43	4D	33	85	45	F9	02	7F	50	3C	9F	A8
7	51	A3	40	8F	92	9D	38	F5	BC	B6	DA	21	10	FF	F3	D2
8	CD	0C	13	EC	5F	97	44	17	C4	A7	7E	3D	64	5D	19	73
9	60	81	4F	DC	22	2A	90	88	46	EE	B8	14	DE	5E	0B	DB
a	E0	32	3A	0A	49	06	24	5C	C2	D3	AC	62	91	95	E4	79
b	E7	C8	37	6D	8D	D5	4E	A9	6C	56	F4	EA	65	7A	AE	08
c	BA	78	25	2E	1C	A6	B4	C6	E8	DD	74	1F	4B	BD	8B	8A
d	70	3E	B5	66	48	03	F6	0E	61	35	57	B9	86	C1	1D	9E
e	E1	F8	98	11	69	D9	8E	94	9B	1E	87	E9	CE	55	28	DF
f	8C	A1	89	0D	BF	E6	42	68	41	99	2D	0F	B0	54	BB	16

X

Figure 3.
AES S-box

A byte can be presented in hexadecimal form as XY, where 00 ≤XY≤ FF

In SubByte phase XY is replaced with a hex number found in the row X and in the column Y of the table.

Example: Image of 5D
Is 4C

Reversibility: The hexadecimal numbers in the substitution table are obtained by Galois' Field polynomial multiplication. Galois Field GF(2^8) forms a group with respect to multiplication, which means that the multiplier polynomial has an inverse. With the inverse polynomial it is possible to invert the substitution table. The inverse table is used in AES decryption.

Summary of AES

- **AES** encryption algorithm consists of rounds: AES128 has 10 rounds, AES256 has 14 rounds.
- Each round include several steps which produce necessary confusion and diffusion.
- All steps are reversible. MixColumn and Substitute Bytes steps use Galois' Field polynomial multiplication. Galois' theory is well established and thoroughly transparent, which makes AES a provably secure algorithm.

Modes of operation

1) ECB : (Electronic Codebook mode)

Message blocks are encrypted independently => Identical message blocks have identical cipher blocks. This is why ECB mode is not secure and not used in block ciphers

2) CBC : Cipher Block Chaining mode (used in TLS until 2017)

Each cipher block functions as extra input of encryption of next block. The ciphers of first block affects all remaining blocks. This increases security.

The following line from 2017 describing algorithms of Nordea Bank's TLS connections

3) **GCM : Galois Counter Mode** (todays standard in TLS)

In 2023 Nordea Bank's TLS uses AES in GCM mode

About AES_CBC and AES_GCM modes

One can still find TLS servers using AES_CBC .

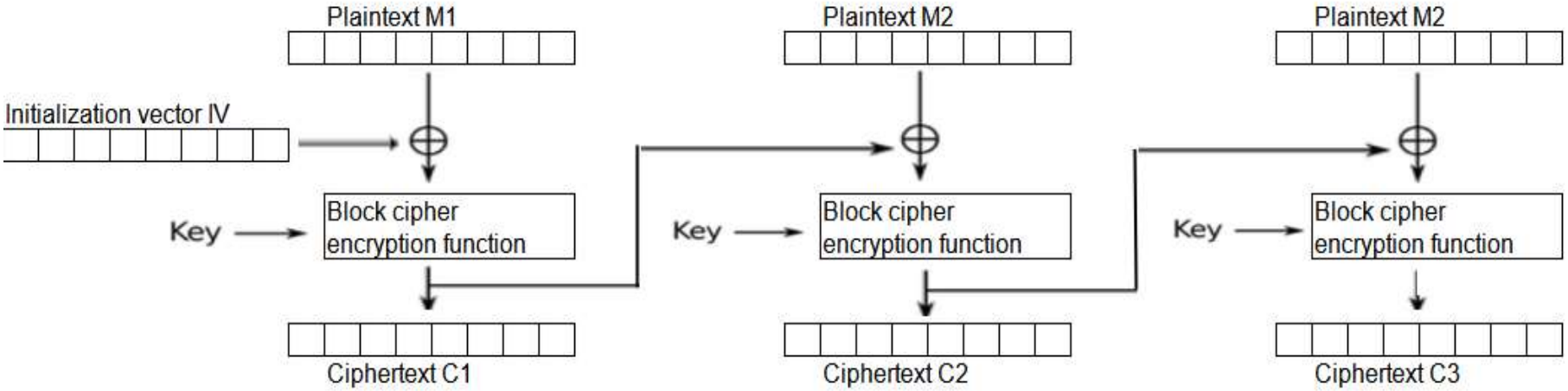


Diagram of CBC mode

Data is encrypted in 128 bit blocks. Input of each encryption are message, key, and the cipherblock of previous encryption (or IV). Every cipherblocks affects all next cipher blocks, which makes the encryption stronger against attacks and makes manipulations of some part of the cipher during transmission impossible..

GCM – mode (”Galois Counter Mode”)

has replaced CBC mode in net banks providing stronger protection of integrity and authentication of sender.

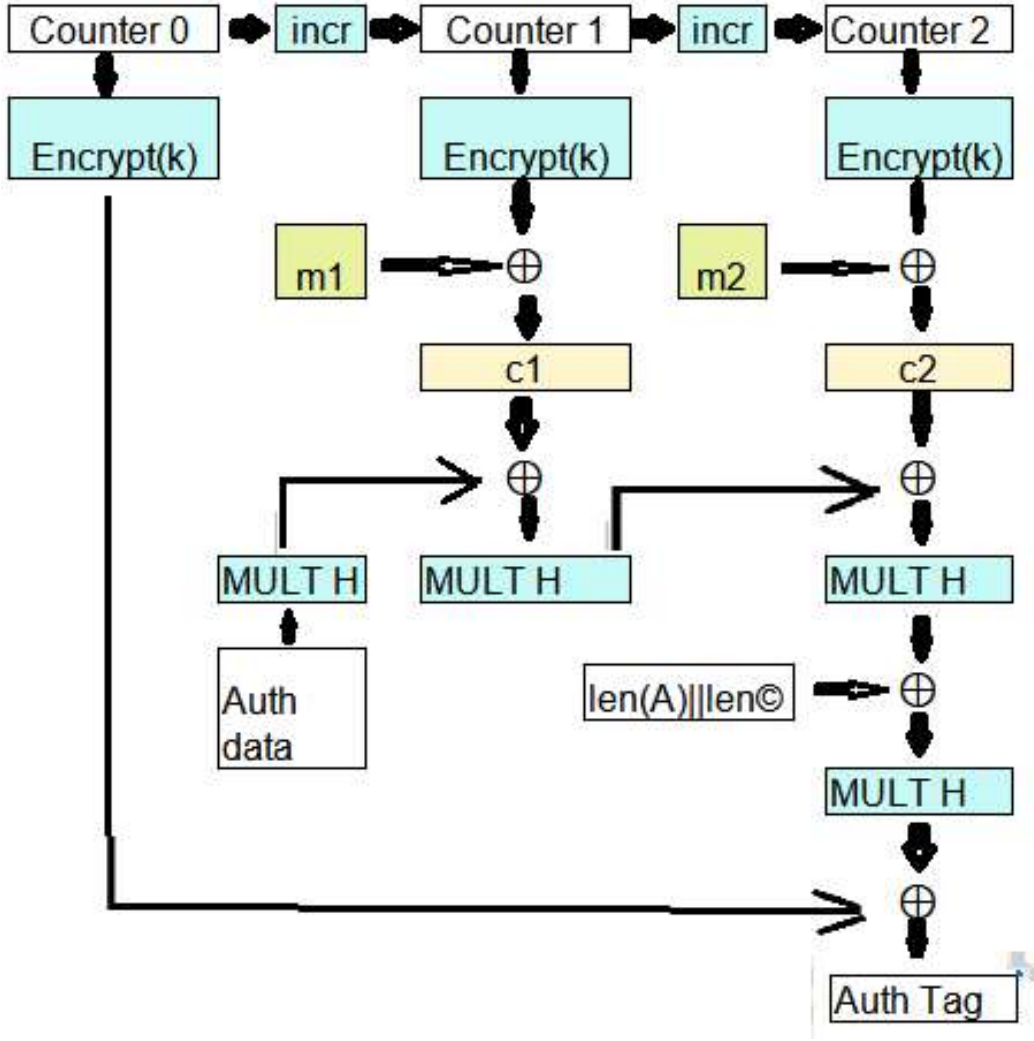
Tekniset tiedot

Yhteys salattu (TLS_ECDHE_ECDSA_WITH_AES_256_GCM_SHA384, 256-bittinen avain, TLS 1.2)

In GCM- mode the counter value (1,2,…) is encrypted with AES with key K. The output (128 bits) is XOR:ed with the first message block m1 to produce the first cipher block c1.

Authentication data (senders personal data + previous cipher blocks) is collected to a 384 bit hash value using Galois Field multiplication rule.

The goals of this mode are to make attacks impossible and secure the integrity and authenticity of the sender



Finnish governments instructions for block ciphers

National security classification	IV	III	II	I
Block ciphers allowed	AES 128 Serpent(128)	AES 196 Serpent(196)	AES 256 Serpent(256)	none *)

*) Top secret documents (class 1) should be kept only in paper form.

In practice the government uses AES encryption

Source: Cyper security center of Finland

Is AES post-quantum secure?

Quantum computers will be ”game changers” in cryptography.

According to today's knowledge AES128 will no longer be secure in post-quantum world, but AES256 and AES512 still provide adequate security. *)

*) There is a quantum algorithm called Grover’s algorithm, which can crack AES128 key in a short time using 128 qubit quantum computers (such computers don’t exist yet)

However Grover’s algorithm is not able to crack the AES256 key of 256 bit length. The security of AES256 remains at the level that corresponds AES128 in the present pre-quantum world.

Next topics:

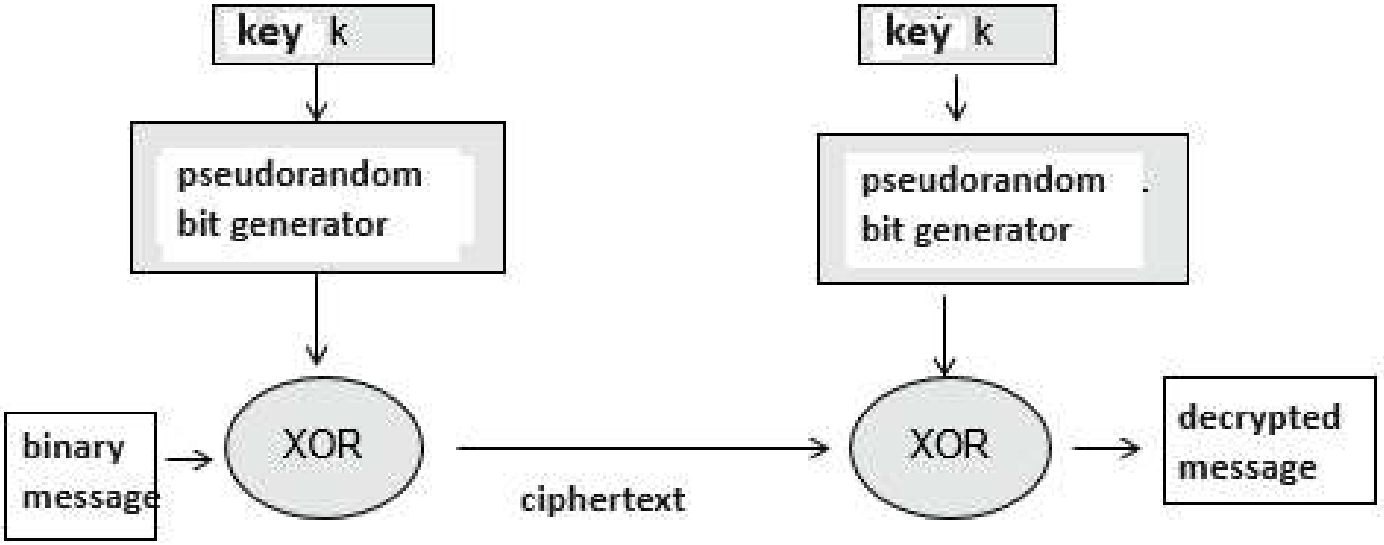
Synchronous stream ciphers

Pseudorandom number generation

LFSR registers

Mobile network encryption

Syncronous stream ciphers



The **encryption algorithm A5** of GSM phones is a syncronous stream cipher. It imitates the idea of Vernam's version of One Time Pad, in which key is an one time random bit sequence of same length as the message.

GSM phones have a micro circuit which produces a pseudorandom bit sequence, which is added with XOR to the binary message.

GSM call would be safer, if the key sequence would be truely random, which it is not.: Key sequence created by GSM phone looks random, but it is deterministic.

GSM calls are not secure, encyption of GSM calls can be broken. GSM network has been replaced by 3G, 4G and 5G networks, which are more secure.

Definition of pseudorandomness

PN- sequence (PN = ”pseudo noise”) or pseudorandom bit sequence is **a key -based, deterministic bit sequence**, which satisfies three properties defined by **Samuel W Colomb** in 1950’s..

PN sequence properties:

G1. Sequence must have 50% ones 50% zeros

G2. Relative frequencies of blocks repeating same bit (0 or 1)

0**1**0	**or**	1**0**1	single bit block
0**11**0		1**00**1	two identical bits block
0**111**0		1**000**1	three identical bits block
0**1111**0		1**0000**1	four identical bits block

have ratios **1/2 , 1/4 , 1/8 , 1/16**

G3. When a sequence is rotated and the rotated sequence is compared with the original, the number of incidences and disincidences should be approximately equal. This property is measured by so called autocorrelation coefficient, which should be close to zero for all rotations of sequence, which means that the sequence does not have internal periodicity.

Additional features required from cryptographic random number generators

4. All PRNG generators have a period. (They start to produce same numbers when period is full). **Period should be as large as possible**

5. Random number generation should be **very fast**

6. It should be impossible to calculate next or previous random numbers knowing one of the numbers.

”Cryptographically secure random number generation”

Secure communication needs **”cryptographically secure” pseudorandom number generators (CSPRNG)** for example in creating symmetric keys for AES.
(Most pseudorandom number generators are not cryptographically secure).

Some CSPRNG methods

1. **Enthropy source method**. Unpredictable data stream is collected mainly from computers operating system (key inputs, time stamps, interruptions, sensors, ….). This data is hashed to create random numbers.

2. ”**Streching entropy”.** Data obtained from 1st method is limited, if lots of random numbers are needed at once. One can extend the quantity of random numbers using for example AES in counter mode. Each output is a random number..

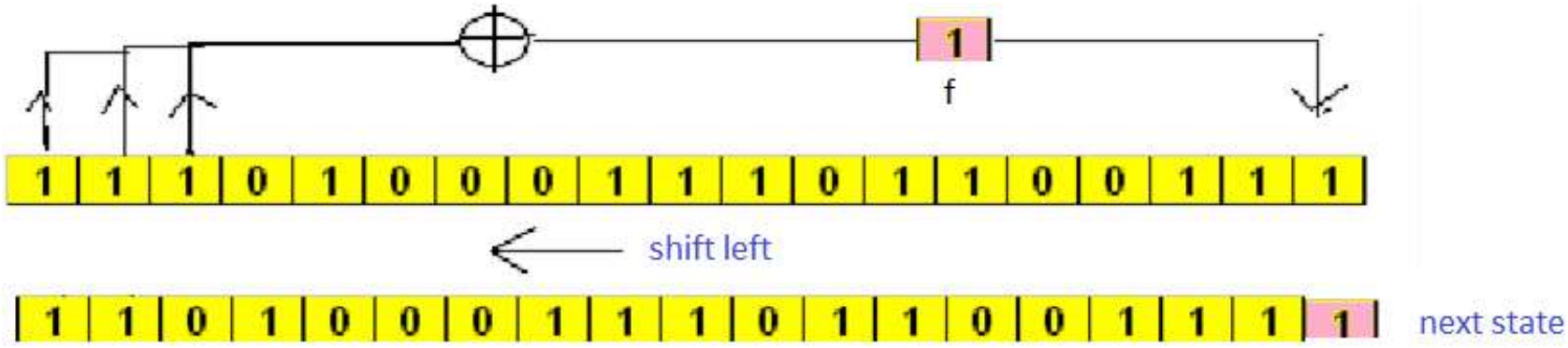
Random key generation is critical issue for safe communication. A non-safe random number generator has been deliberately used for eavedropping communication.
”The Guardian and The New York Times have reported in 2013 that the National Security Agency (NSA) inserted a backdoor into a pseudorandom number generator (PRNG) of NIST SP 800-90A which allows the NSA to readily decrypt material that was encrypted with the aid of Dual EC DRBG. Both papers report[30][31] that, as independent security experts long suspected,[32] the NSA has been introducing weaknesses into CSPRNG standard 800-90; this being confirmed for the first time by one of the top secret documents leaked to the Guardian by Edward Snowden.” (Wikipedia)

LFSR - linear feedback shift register

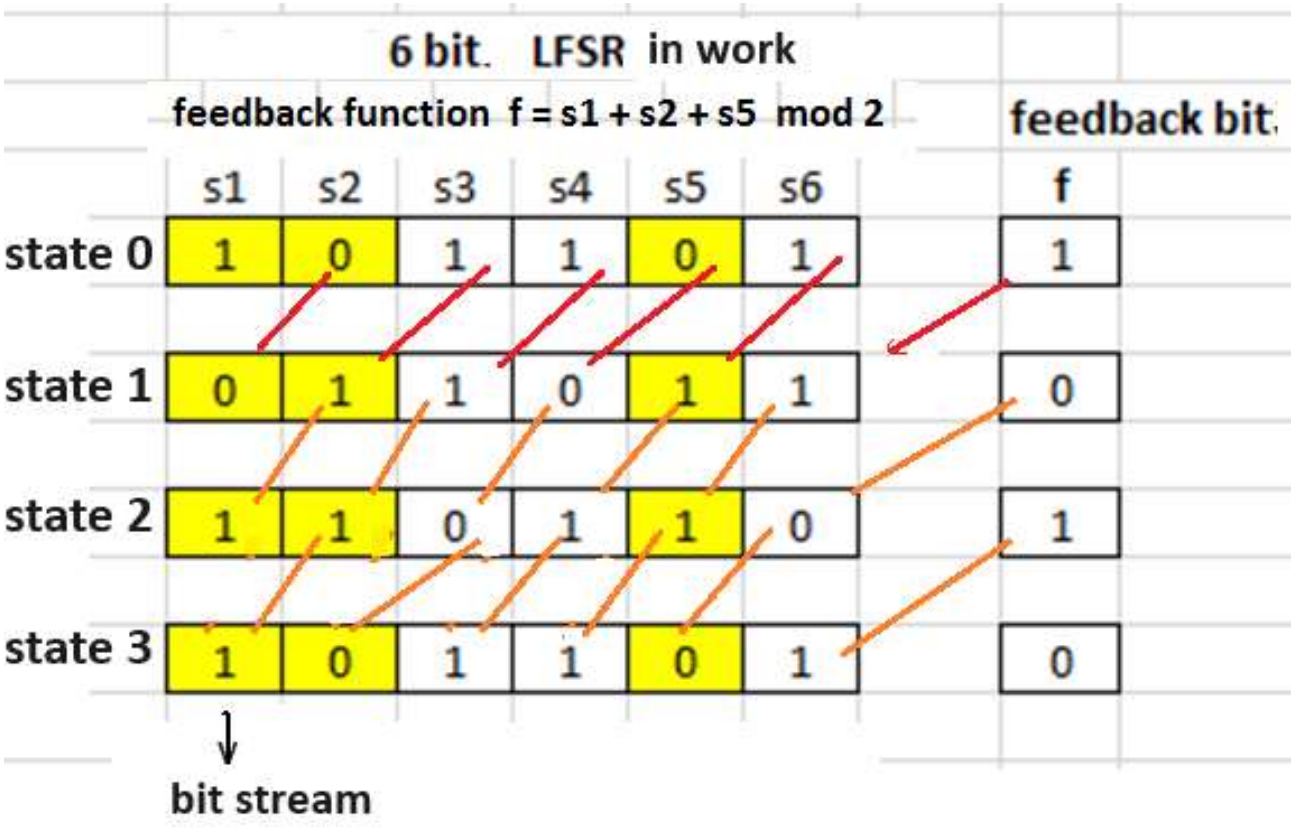
Is a microcircuit traditionally used in RAND function of pocket calculators and later in GSM phones

* LFSR is n bit register which can be used to produce random numbers. During every clock pulse the bits of the registers are shifted one step to the left. The new rightmost bit, called the feedback bit, is calculated using XOR addition from specific bit values just before the shift

In the picture feedback bit is calculated from first three bits. In the example feedback bit f = 1+ 1+1 mod 2 which is equal to 1.



Example of LFSR in operation

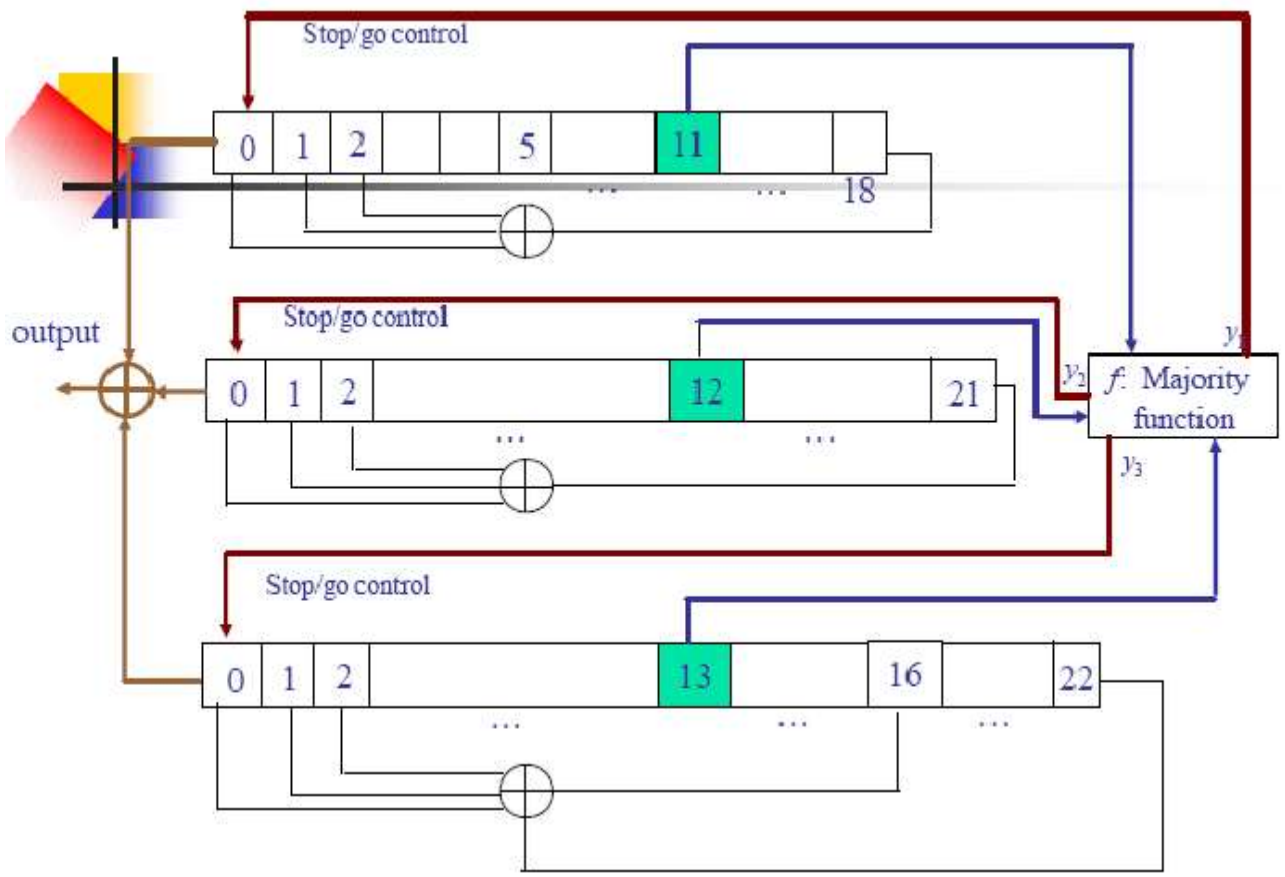


Feedback bit is calculated using formula
$f = s_1+s_2+s_5 \pmod 2$
before bits are shifted to left.

LFSR registers leftmost s1 bits form a sequence, which fulfills the three properties of definition of pseudorandomness.

LFSR registers were used earlier in GSM phones. Today some 3G, 4G and 5G networks use SNOW3G encryption, which also uses LFSR registers.

GSM phones A5 PRNG -generator



GSM – phone has 3 LFSR-registers of lengths 19, 22 and 23 bits

Initial state is the 64 bit symmetric key. 19 +22+23 = 64

At each clock pulse circuit generates one pseudo random bit, which is a XOR-sum of zero bits.

To increase security a majority function f is added to the circuit. It is calculated from bits marked green in the picture, which of the three registers are shifted during one clock pulse and which remain as they are.

Majority function: If all marked green bits have identical values, all registers move forwards. In other cases those two move, which have identical values .

A5 bit stream fulfills pseudorandomness postulates G1, G2, G3

```
0, 1, 1, 0, 0, 0, 0, 0, 0, 0, 0, 0, 1, 0, 0, 0, 0, 1,
1, 1, 1, 0, 0, 1, 1, 0, 0, 1, 0, 0, 0, 1, 1, 1, 0, 1,
1, 1, 0, 0, 0, 0, 1, 1, 0, 0, 1, 0, 0, 1, 0, 1, 0, 0,
1, 1, 1, 1, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1, 0, 1, 0, 1, 1,
1, 0, 0, 1, 0, 1, 0, 0, 1, 0, 0, 1, 0, 1, 0, 0, 1, 0,
1, 0, 1, 0, 1, 0, 0, 0, 1, 0, 1, 0, 1, 1, 1, 0, 0, 1,
1, 1, 0, 1, 1, 1, 0, 1, 1, 1, 0, 1, 1, 1, 1, 0, 0, 0,
0, 1, 0, 1, 1, 1, 0, 0, 1, 1, 1, 1, 0, 1, 1, 0, 0, 1,
1, 1, 0, 0, 1, 1, 1, 1, 1, 1, 1, 1, 1, 0, 1, 0, 1, 0,
1, 1, 0, 0, 0, 1, 1, 0, 0, 0, 1, 0, 0, 0, 1, 1, 1, 1,
0, 1, 0, 0, 0, 1, 0, 0, 1, 0, 1, 0, 1, 0, 0, 1, 1, 1,
1, 1, 1, 0, 0, 0, 1, 0, 1, 1, 0, 1, 0, 1, 0, 1, 0, 0,
1, 1, 0, 1, 0, 0, 0, 1, 0, 0, 1, 1, 1, 0, 1, 0, 0, 0,
1, 0, 1, 1, 1, 0, 0, 1, 0, 1, 1, 0, 1, 1, 1, 0, 0, 1,
1, 1, 0, 0, 1, 1, 1, 0, 1, 0, 0, 0, 1, 1, 1, 0, 0, 0,
```

GSM encryption: The key stream and digitalized voice are added using XOR to produce the encrypted signal

Operators server has a similar PRNG and same symmetric initial state
Operator decrypts signal.using XOR.
Signal is encrypted only in air, not in the cable.

GSM security

1. Key in A5 encryption is 64 bits, which is not secure.
2. Key sequence is periodic, effective period is $4/3*2^{23}$
3. GSM signal is encrypted only between the mast and the phone (not in cables)
4. GSM is not secure against professional hackers

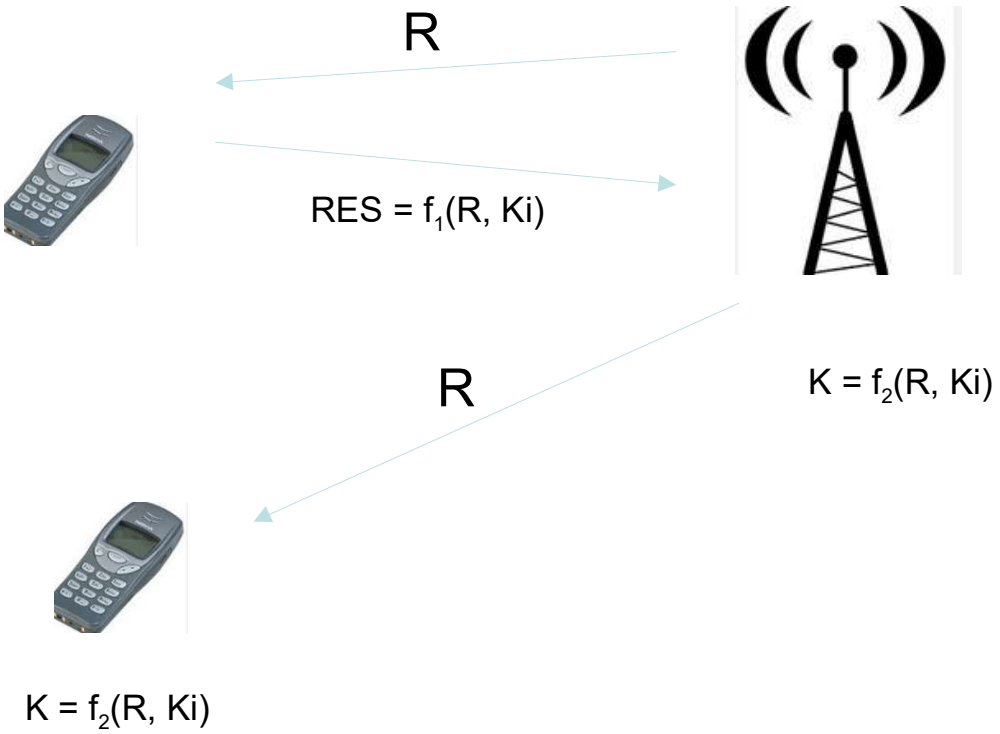
Authentication and key agreement in GSM

Authentication A3. Operator sends to the phone a random challenge number R.
Phone calculates and sends a response RES from R and SIM-key.

Operator calculates RES in the same way. If there is a match, the phone is authenticated.

Key agreement A8. Operator sends the phone a random R. The phone calculates a 64 bit key K from R and SIM-key.

The key K is the initial state for the three LFSR -registers



3G, 4G, 5G network encryption

3G and 4G use block ciphers: AES128 or SNOW3G

- key length = 128 bits
- two way authentication is used: both the phone and the mast authenticate themselves in the beginning of communication

5G encryption uses 256 bit versions of AES and SNOW3G

SNOW3G is a Swedish encryption algorithm created in Lund university.
It uses LFSR register technology