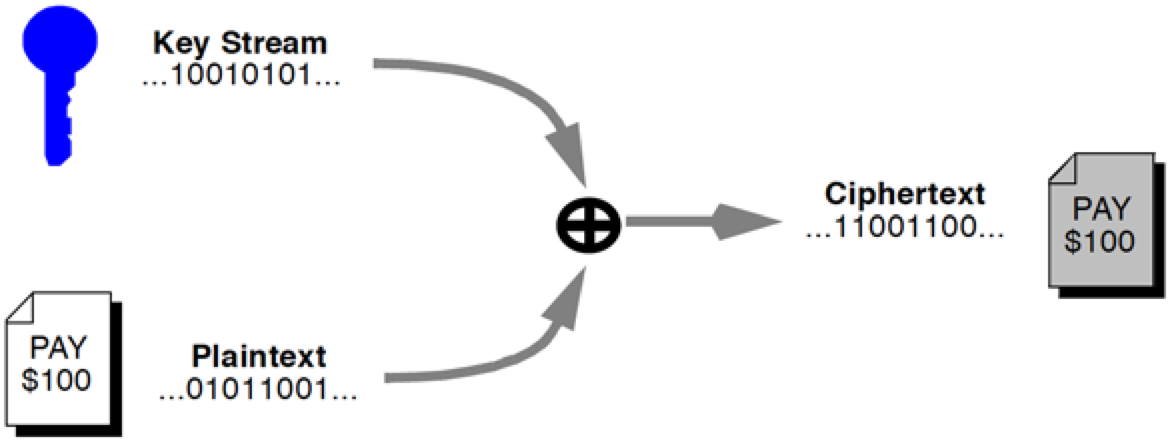
Stream Ciphers

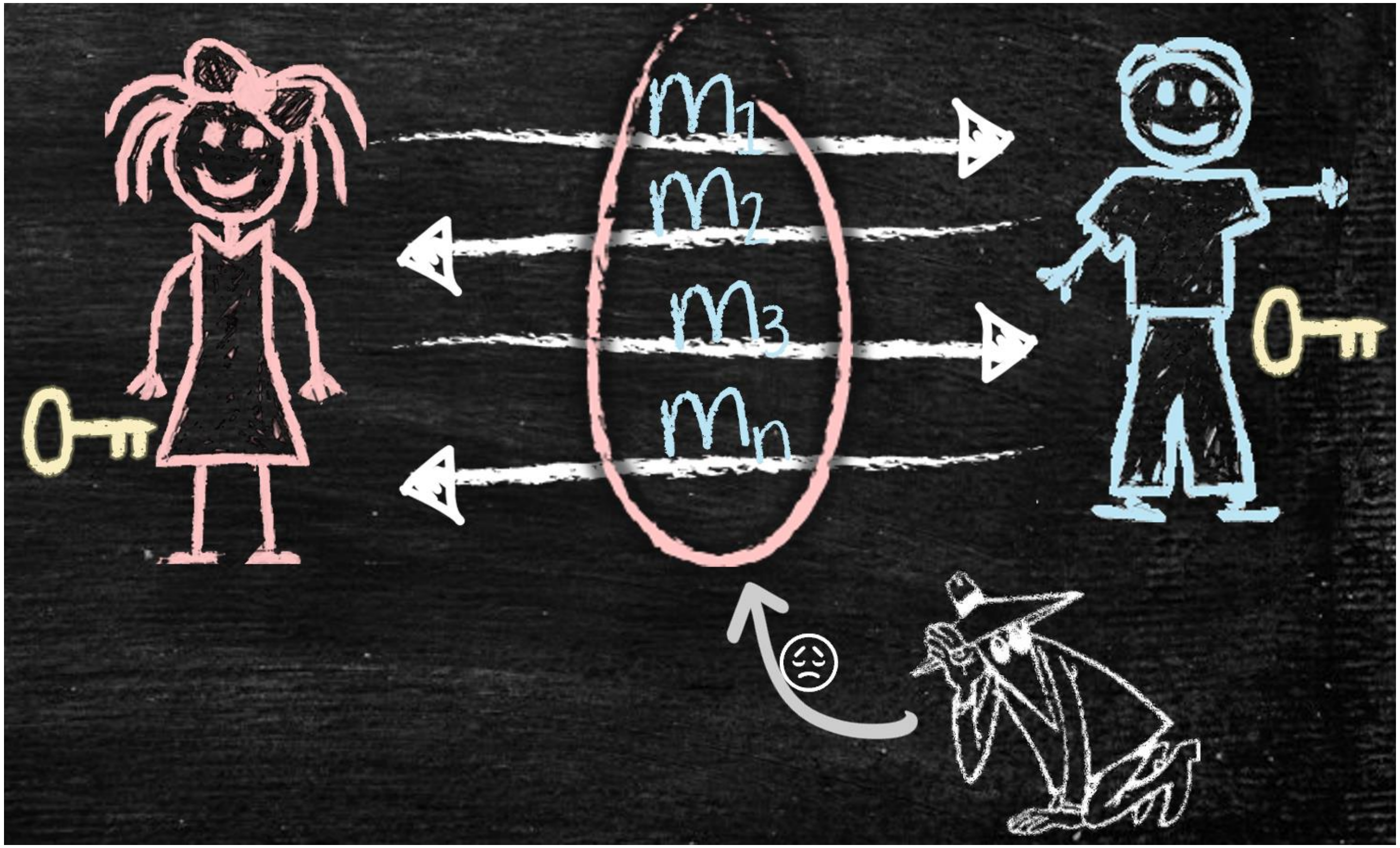


Outline

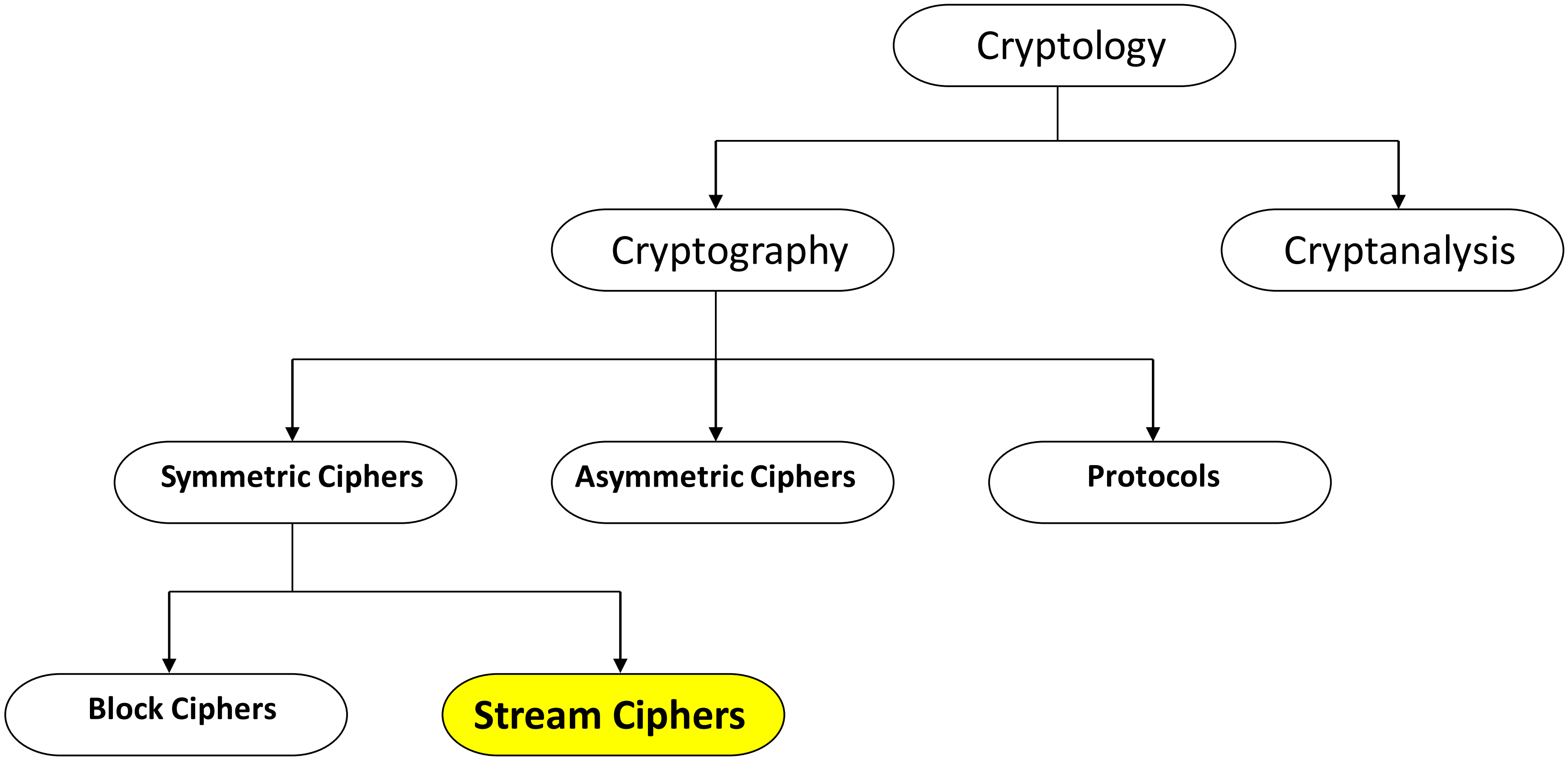
- One-Time Pad (OTP)
- Stream Ciphers
- Random Number Generators (RNGs)
- Linear Feedback Shift Registers (LFSRs)
- Popular Stream Ciphers:
  - A5/1 Cipher
  - RC4 Cipher

Symmetric Key Cryptography

- A cryptographic technique where both parties in the communication share the same key



Stream Ciphers in the Field of Cryptology



One-Time Pad (OTP)

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One-Time Pad (OTP)

- OTP cryptosystem by Gilbert Vernam in 1918, another name: ***Vernam Cipher***
- Key has these 3 properties:
  - a truly random sequence of 0's and 1's
  - the same length as the message
  - use one time only
- Let the plaintext, ciphertext and key consist of individual bits

$x_i, y_i, k_i \in \{0,1\}$

Encryption: $e_{k_i}(x_i) = x_i \oplus k_i$

Decryption: $d_{k_i}(y_i) = y_i \oplus k_i$

- OTP is **unconditionally** secure **=** cannot be broken even with *infinite* computational resources

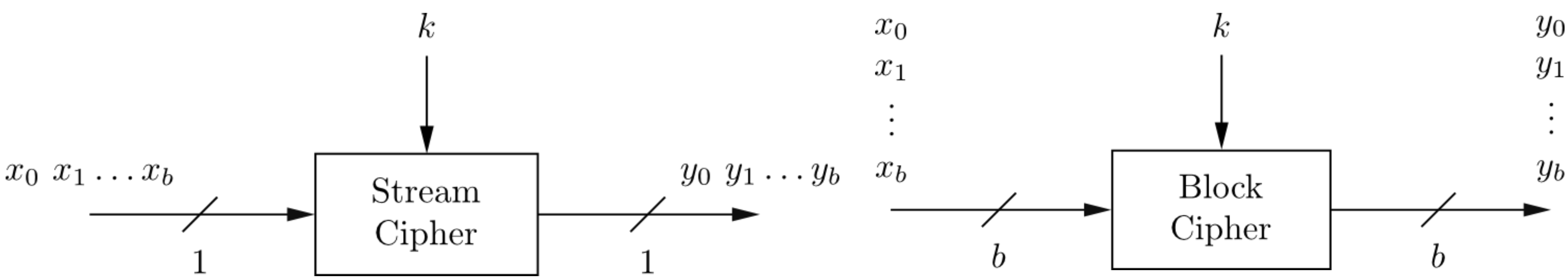
OTP is Secure but Impractical

- OTP is **impractical** because of **difficulty of key distribution and management**
  - Key must be as long as the plain-text! (Imagine you have to encrypt a 1GB message)

- **Solution :**
  - ✓ Stream Ciphers
  - ✓ Key-stream is generated in pseudo-random fashion form a relatively short secret key

Stream Ciphers

Stream Cipher vs. Block Cipher



- **Stream Ciphers**
  - Encrypt bits individually
  - Usually small and fast → common in embedded devices (e.g., A5/1 for GSM phones)
- **Block Ciphers:**
  - Always encrypt a full block (several bits)
  - Are common for Internet applications

Stream Ciphers

- Type of symmetric key crypto
- Use a fixed length key to produce a **pseudo-random stream of bits**
  - Same key gets you the same keystream
- XOR those bits with PT to encrypt
- XOR those same bits with CT to decrypt
- Tries to approximate a one-time-pad

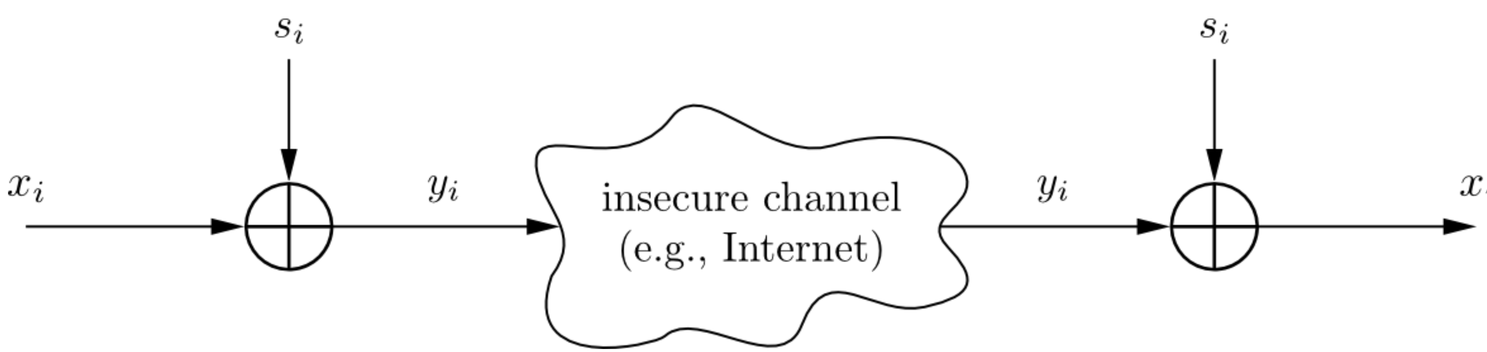
Real-Word Stream Ciphers

- RC4
  - Used in WEP for wireless network security
  - One option in TLS/HTTPS for encrypting web traffic
  - Not recommended for use anymore

- A5/1
  - Use for encrypting GSM phone data and conversations
  - NSA is known to be routinely breaking it

Encryption and Decryption with Stream Ciphers

Plaintext x_i, ciphertext y_i and key stream s_i consist of individual bits

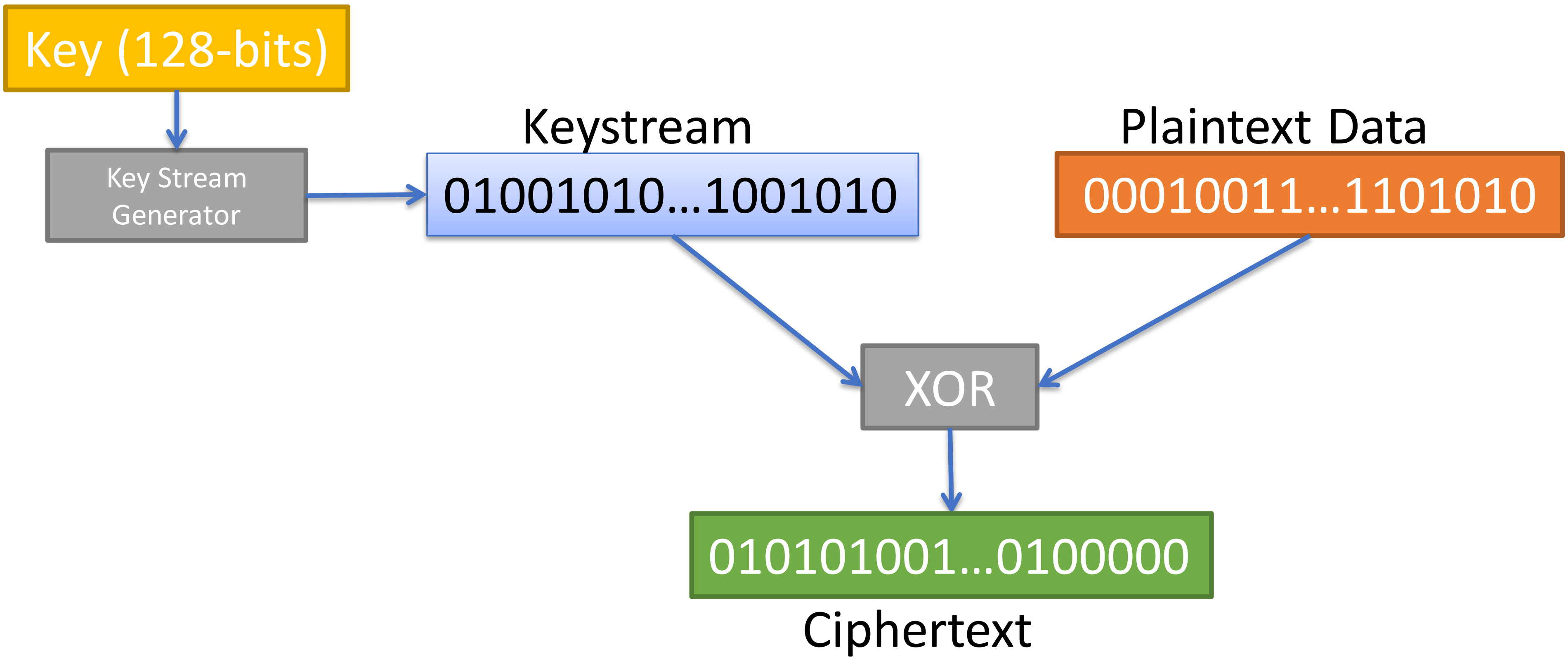


- Encryption and decryption are simple additions modulo 2 (aka XOR)
- Encryption and decryption are the same functions

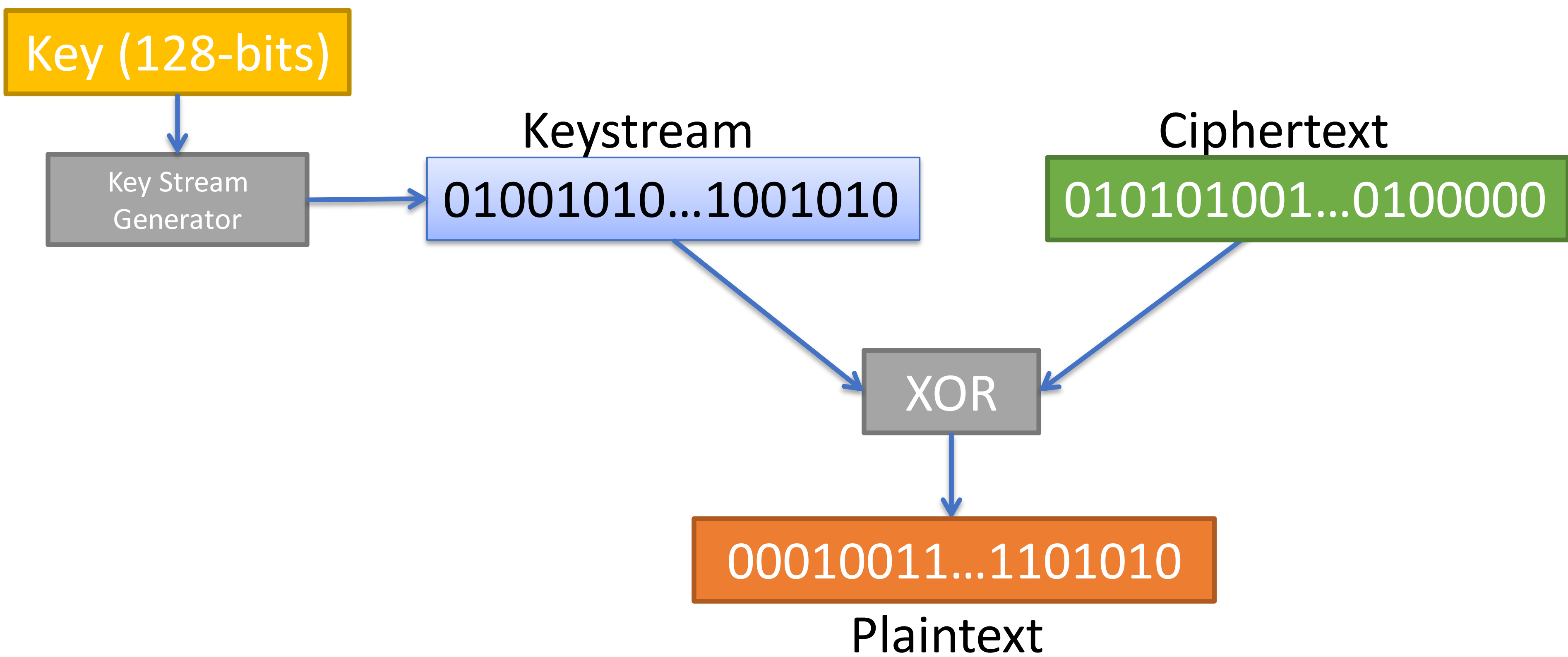
- **Encryption:** $y_i = e_{si}(x_i) = x_i + s_i \bmod 2$ $\quad x_i, y_i, s_i \in \{0,1\}$
- **Decryption:** $x_i = e_{si}(y_i) = y_i + s_i \bmod 2$

x_i XOR	s_i	y_i
0	0	0
0	1	1
1	0	1
1	1	0

Stream Cipher Encryption Example



Stream Cipher Decryption Example



Why Does XOR Work Here?

- A few properties of XOR:

$$A \oplus A = 0$$
$$A \oplus 0 = A$$
$$(A \oplus B) \oplus C = A \oplus (B \oplus C)$$

- Using XOR for encryption:

$$PT \oplus KEY = CT$$
$$CT \oplus KEY = PT$$
$$(PT \oplus KEY) \oplus KEY = PT$$
$$PT \oplus (KEY \oplus KEY) = PT$$
$$PT \oplus (0) = PT$$
$$PT = PT$$

XOR Example

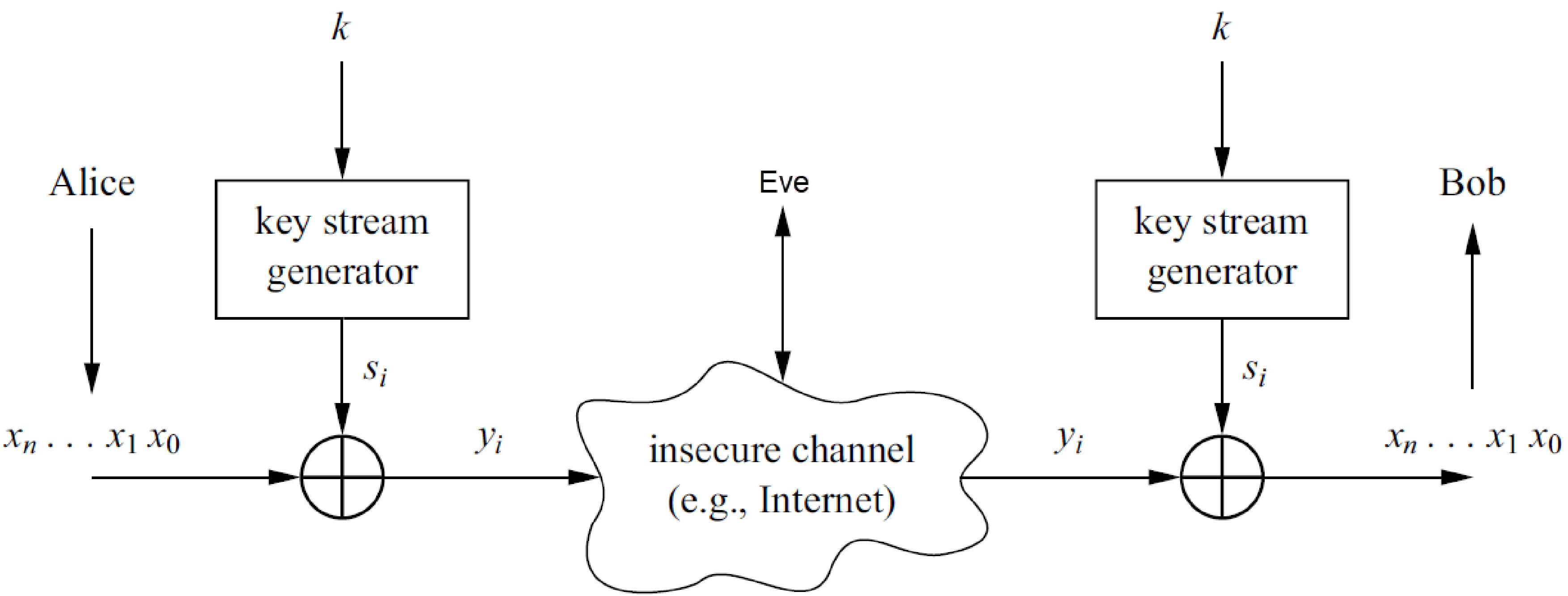
- Encrypt

Plaintext:	0110
Key:	1100
Ciphertext:	1010

- Decrypt

Ciphertext:	1010
Key:	1100
Plaintext:	0110

Key Stream Generator



- Security of stream cipher depends entirely on the key stream $\boldsymbol{s_i}$:
  - Should be **random** , i.e., Pr(s_i = 0) = Pr(s_i = 1) = 0.5
  - Must be **reproducible** by sender and receiver
- For perfectly random key stream s_i , each ciphertext output bit has a 50% chance to be 0 or 1
  → Good statistic property for the keystream

Stream Cipher: Throughput

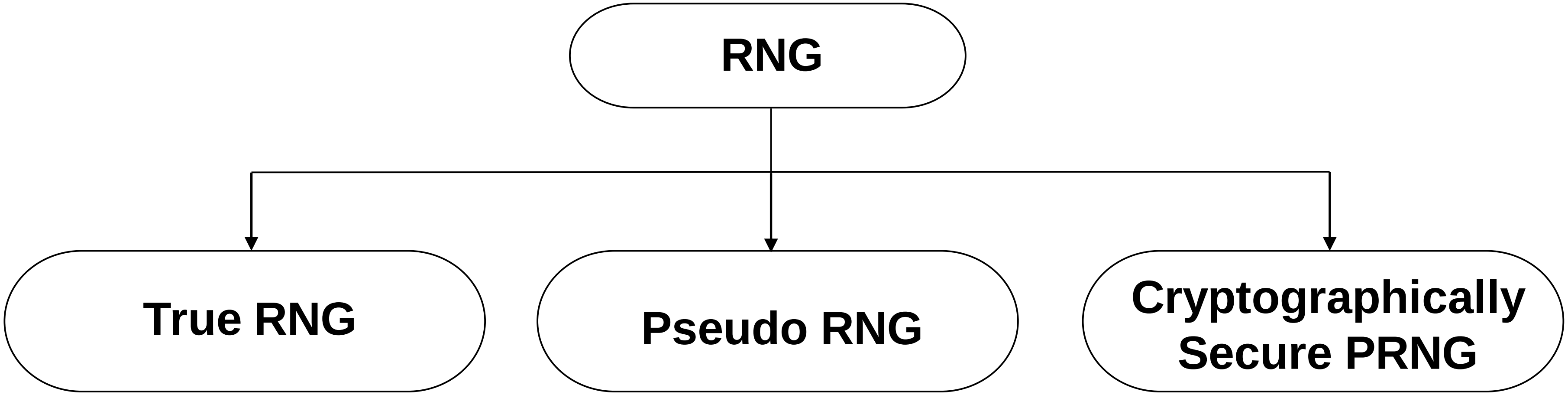
Performance comparison of symmetric ciphers (Pentium4):

Cipher	Key length	Mbit/s
DES	56	36.95
3DES	112	13.32
AES	128	51.19
RC4 (stream cipher)	(choosable)	211.34

Source: Zhao et al., Anatomy and Performance of SSL Processing, ISPASS 2005

Random number generators (RNGs)

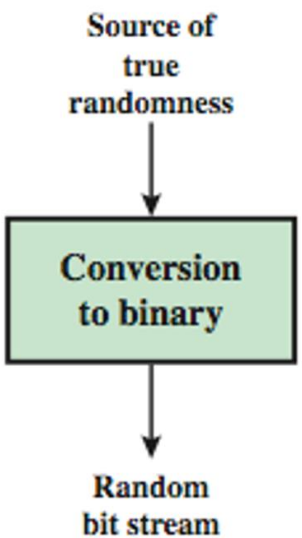
Random number generators (RNGs)



- Randomness is found everywhere in cryptography: **generation of secret keys**, **encryption ciphers**, **attacks on cryptosystems**
  - Without randomness, cryptography would be impossible because all operations would become predictable, and therefore insecure

- In all cases its critical that these random numbers be:
  - statistically random, uniform distribution, independent
  - unpredictability of future values from previous values

True Random Number Generators (TRNGs)



- Based on physical random processes: coin flipping, dice rolling, semiconductor noise, radioactive decay, mouse movement, clock jitter of digital circuits
- Output stream s_i should have good statistical properties:
  $Pr(s_i = 0) = Pr(s_i = 1) = 50\%$
- Output can neither be **predicted** nor be **reproduced**

Typically used for generation of keys, nonces (used only once values), one-time pads and for many other purposes

Generating Keys in Practice

- Secret keys are the crux of cryptographic security and should be randomly generated so that they are **unpredictable** and **secret**
- e.g., Use the OpenSSL toolkit to generate a random symmetric key by dumping pseudorandom bytes

```
openssl rand -hex 16
```

```
4d138b893c8b59c2363f5f3ddfc0ed55
```

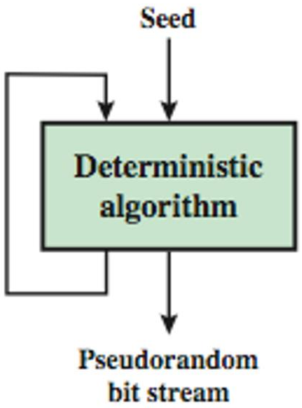
- Generating asymmetric keys (e.g., web site's public key and its associated private key may be valid for years). It requires constructing a private key and its respective public key, ensuring that both satisfy all the necessary criteria

```
openssl genrsa 2048 -out example.key
```

```
-----BEGIN RSA PRIVATE KEY-----
MIIEowIBAAKCAQEA6OQ6RBPoQNdWw1n9xjZ6d0uMUz2lcNEIvdXKKpp+u+ScLeWa/iQ9gLX0NmHb5+6BWnkqb1exJ/ccZWWIISrDqtbwfMITtRlxyvSEm6hME1rgXVdYGsxbEX1wMUfDHMt3fWpAOHwtBBMZfT
6QH/3Ki5zw4GFMrrqrfc6/HHYl9nmXMsbdD2eTQxT9KX5qKgXF3pLRn79xlJ+vzoAITEyBJasltKEZnY/aKZS5PvXsMndtKsrNHo/RMDKVHj+YrZ8du3W+rIayMmUXgj5XwIr3Vcj626lPr53RVrUZuw2RvjtF
YcgvLp6/kR5wY/GVAtzJLUBQWGYanqV8U3sjFKZ7hwIDAQABAoIBAQCC7awEEd0EdwuED9en04DOCF7/fSzBXAM6FjLt+KU/JKrY8rhMIDujXKfK2wEyRtfZ8Tx2FCq4eSgxqP77BnuyU9wnh0RlD8T1gLn8eI
UsbG6uiygxCKo6Dvc//UQnsAuhKlaoascz/zjZPI7yLU/tZXHV812U7cTzmYO/kHyPL4GYQUV1t6ByQHefV5jOpaG0mL+/LM9BXC46PGt93kFWRNnIqEAc+nfOK4uk2phXQiZTfljoe+u8TGw1SDEsdj16h7VY
Olt+VihZ0PWwpZIUO2t9mgIR7UdsirRdA022BUrCjLllnmegZOH8fd2xen4e+a5ev5CONn0X4H99DaYhAoGBAP4/JyNEHvgh5ukL3klBD9prAPQDEpfRVIFDvFvuXF6Oyr6wtRARr9TB1YzaOTzA2t5R/YGWsx
/8suF77tSvgUbFGenzvnC/m/oPIECc+36JyCCGaFyDymjokQQi4AaclsmzC4GVmnDGu1l4Z49nCwbCUj/WbGyS6wel4Ah7sdkjAoGBAOp/X9FszuLSdtrkPRoAdNjl65s+Qk3BUwWykrfUWeuVaohUFxxho8ne
V+kMc43UUIF3k+2D/jyUsHmB4OHdjCLU3C3huSNmRHDpbDEWFgajnCIroywQSaEdcYlow/69kT674vofeuQoYQQtmpI+vWPbL8kFgWWwS+aOjNm+9+RNAoGAbpxLCqy4THtzWjAvpO8JVpz27THpBOOtQA+YAu
bQiNLWod9+5l7LgGRT49OM00GT9uT0xUwq4d+ucyrX3O/97iwR+hZw49x4n3G1NmcVgxeuWXggLx+nD70eWg5SKI43i8i5WMcdSbMsDuCzLVBHG8muvtcqlJHWbp1bulUWKsECgYAqNCB3naCifAR+IsPIcTqW
atL7jrn6KogZp2j2gtZoKu0QeinqprwGseiafe4yIXsXwgCyp6XTG2OjireBjxEQl8TE0TIz58z7kVcygmoWac3I7Jeib5AA2j6730ofB9kjNEeGgrHobEgBq399QKNvXFx+Tmpadd9DMHazHcaZpQKBgBAJsz
Z+LVDPV66p+fNW0m4NmaH4IRl97qyH+aINiI1ufqwcrAnHOe9y5mMbNCxGTZ8qUU4kR2XFtKwpN1yrpUJHAGrffu6befPbEnqJIKr+gDwvEBUlE4w96whZS/EVbhYX/w8gOP4j+ibTQewAnAuCiV64sdVbBPy0
AmJ5YJrP-----END RSA PRIVATE KEY-----
```

```
openssl rsa -in example.key -pubout
```

Pseudorandom Number Generator (PRNG)



- Many PRNGs exist such as **Linear Congruential Generator (LCG)**
  - Generate sequences from initial seed value
  - Output ***looks random*** (but is in fact the sequence is deterministically generated from some hidden internal state) + can be ***reproduced*** *(using the same A, B and S_0)*

- The key stream is computed in a recursive way:

$$S_0 = seed$$

$$S_{i+1} = AS_i + B \bmod m$$

Unknowns *A, B and S_o* can be initialized using the key

Example: *rand() function* in ANSI C:

$$s_0 = 12345$$

$$s_{i+1} = 1103515245 s_i + 12345 \bmod 2^{31}$$

Most PRNGs have bad cryptographic properties! and maybe broken by cryptanalysis

Cryptanalyzing LCG

Linear Congruential Generator (LCG):

$$S_0 = seed$$

$$S_{i+1} = AS_i + B \bmod m$$

- Can be **cracked** if 3 output are known, i.e. S_1, S_2 and S_3 by solving:

$$S_2 = AS_1 + B \bmod m$$

$$S_3 = AS_2 + B \bmod m$$

$$A \equiv (S_2 - S_3)/(S_1 - S_2) \bmod m$$

$$B \equiv S_2 - S_1(S_2 - S_3)/(S_1 - S_2) \bmod m$$

...directly reveals A and B. All S_i can be computed easily!

Bad cryptographic properties due to the linearity of most PRNGs

Cryptographically Secure PRNG (CSPRNG)

- Special PRNG with additional property:

Output must be **unpredictable** (even when using cryptanalysis *with full knowledge of the algorithm)*

More precisely: Given *n* consecutive bits of output s_i , the following output bits s_{n+1} cannot be predicted (in polynomial time) => resist attempts by an attacker to predict its next output

- Needed in cryptography, in particular for stream ciphers
- Example algorithms:
  - The Blum Blum Shub algorithm
  - Others https://en.wikipedia.org/wiki/Cryptographically_secure_pseudorandom_number_generator

Linear feedback shift registers (LFSRs)

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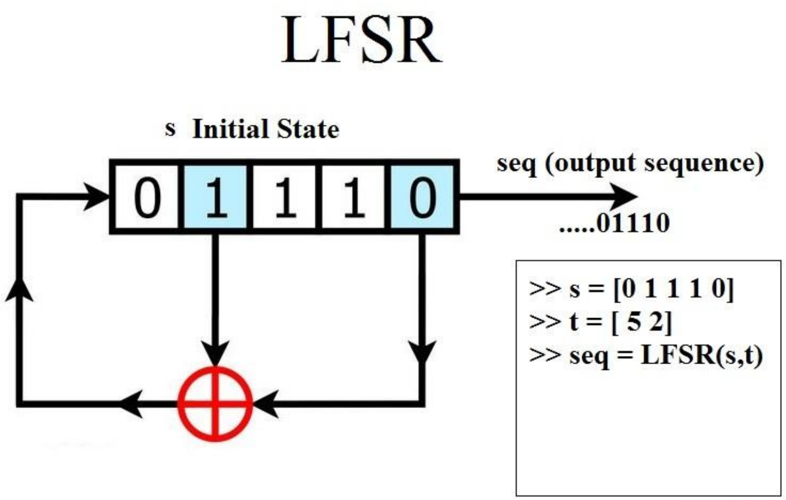
Linear Feedback Shift Registers (LFSRs)



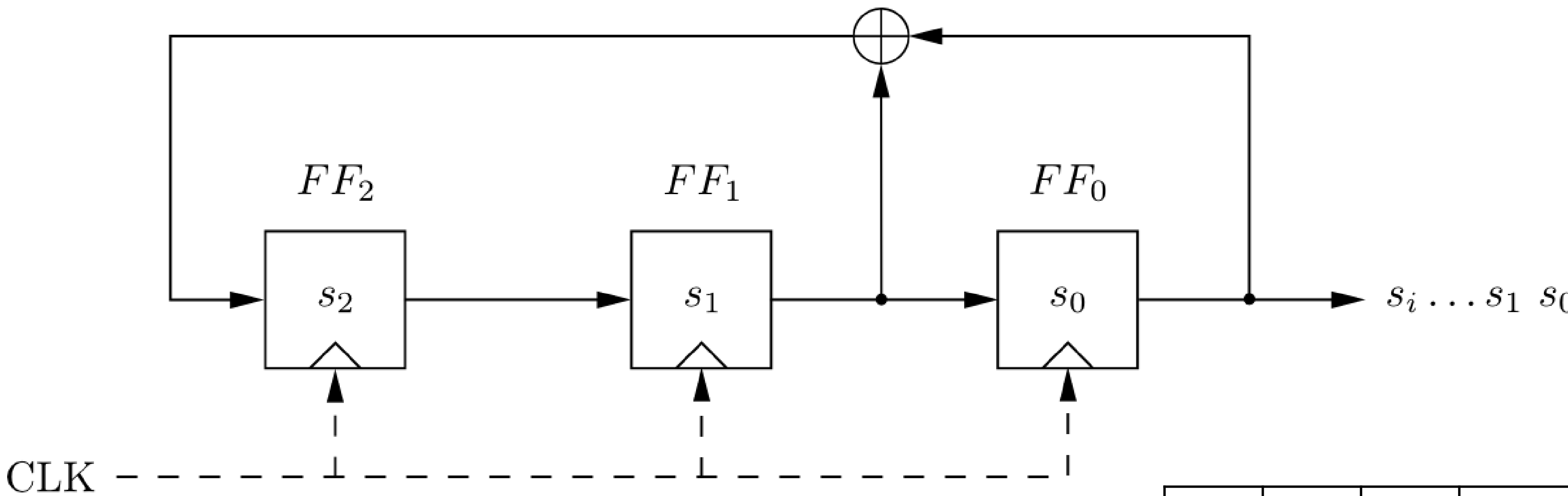
- Is a shift register whose input bit is a linear function (e.g., XOR) of its previous state:

  - shift all the bits one position to the right and

  - replace the vacated bit by *XOR* of certain bits of the new state

- Output sequence repeats periodically
- Feedback computes fresh input by XOR of certain state bits
- *Degree m* given by number of storage elements
- Maximum output length: 2^m-1

Linear Feedback Shift Registers (LFSRs): Example with m=3



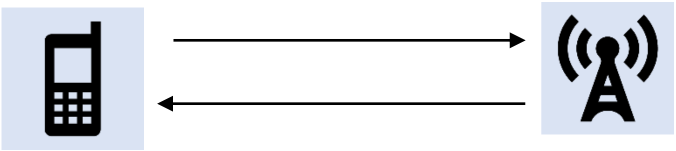
- LFSR output described by recursive equation:

$$s_{i+3} = s_{i+1} + s_i \bmod 2$$

- Maximum output length (of 2^3-1=7)
- Vulnerable to attacks => many stream ciphers use **combinations** of LFSRs

clk	*FF_2*	*FF_1*	*FF_0=s_i*
0	1	0	0
1	0	1	0
2	1	0	1
3	1	1	0
4	1	1	1
5	0	1	1
6	0	0	1
7	1	0	0
8	0	1	0

A5/1 Cipher



Widely used cryptosystem for GSM

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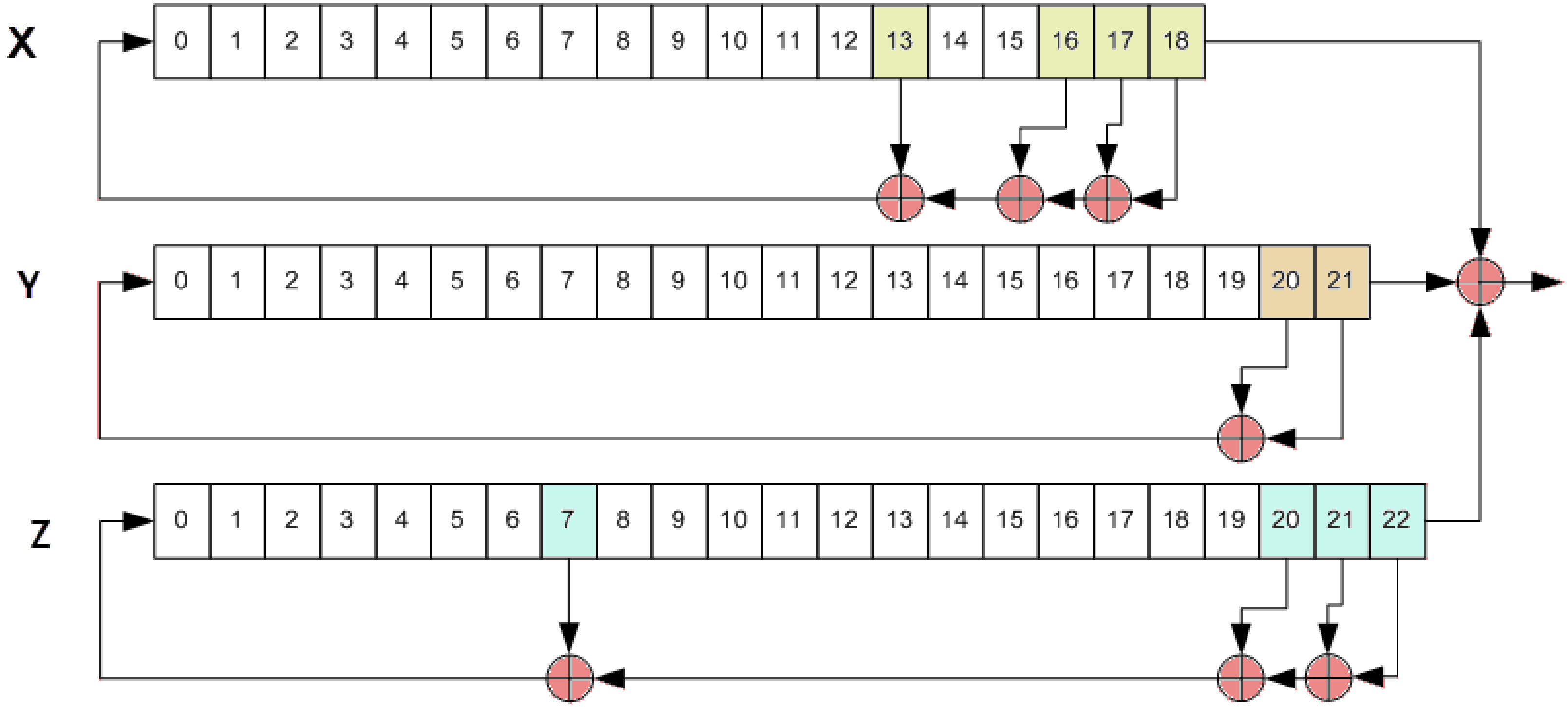
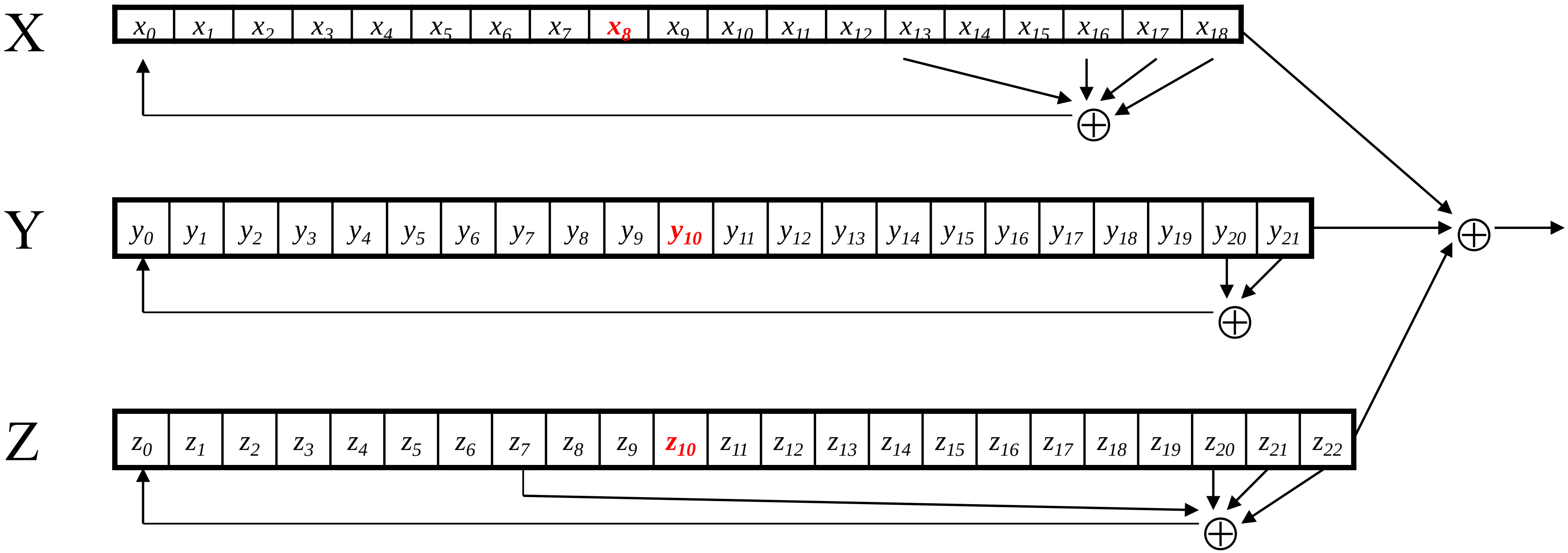
A5/1 Stream Cipher



- A5/1 uses 3 LFSRs (X, Y, Z)
  - X: 19 bits $(x_0, x_1, x_2, \ldots, x_{18})$
  - Y: 22 bits $(y_0, y_1, y_2, \ldots, y_{21})$
  - Z: 23 bits $(z_0, z_1, z_2, \ldots, z_{22})$
- XOR the outputs of all 3 LFSRs to generate key stream s_i

A5/1 Keystream

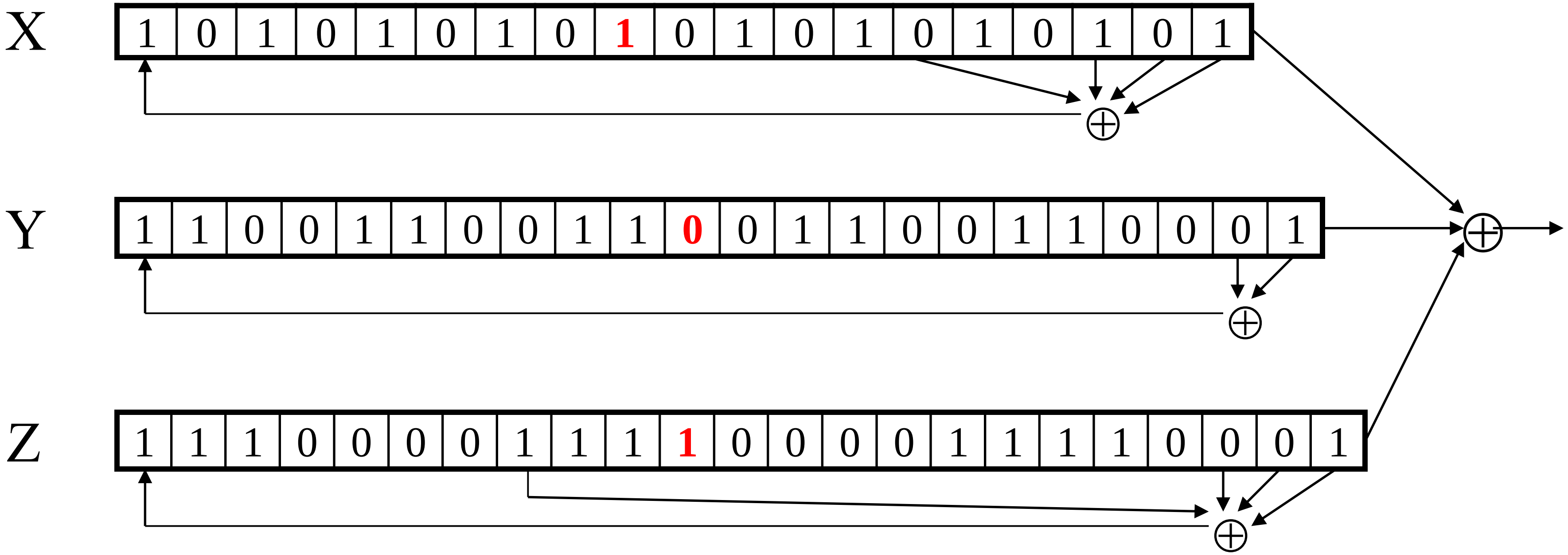


- Each variable here is a single bit
- Key is used as **initial fill** of registers
- Each register steps (or not) based on $\mathrm{maj}(x_8, y_{10}, z_{10})$
- Keystream bit is XOR of rightmost bits of registers

A5/1 Keystream

- At each step: $m = \mathrm{maj}(x_8, y_{10}, z_{10})$
  - Examples: $\mathrm{maj}(0,1,0) = 0$ and $\mathrm{maj}(1,1,0) = 1$
- If $x_8 = m$ then X *steps*
  - $t = x_{13} \oplus x_{16} \oplus x_{17} \oplus x_{18}$
  - $x_i = x_{i-1}$ for $i = 18,17,\ldots,1$ and $x_0 = t$
- If $y_{10} = m$ then Y *steps*
  - $t = y_{20} \oplus y_{21}$
  - $y_i = y_{i-1}$ for $i = 21,20,\ldots,1$ and $y_0 = t$
- If $z_{10} = m$ then Z *steps*
  - $t = z_7 \oplus z_{20} \oplus z_{21} \oplus z_{22}$
  - $z_i = z_{i-1}$ for $i = 22,21,\ldots,1$ and $z_0 = t$
- Keystream **bit** is $(x_{18} \oplus y_{21} \oplus z_{22})$

A5/1



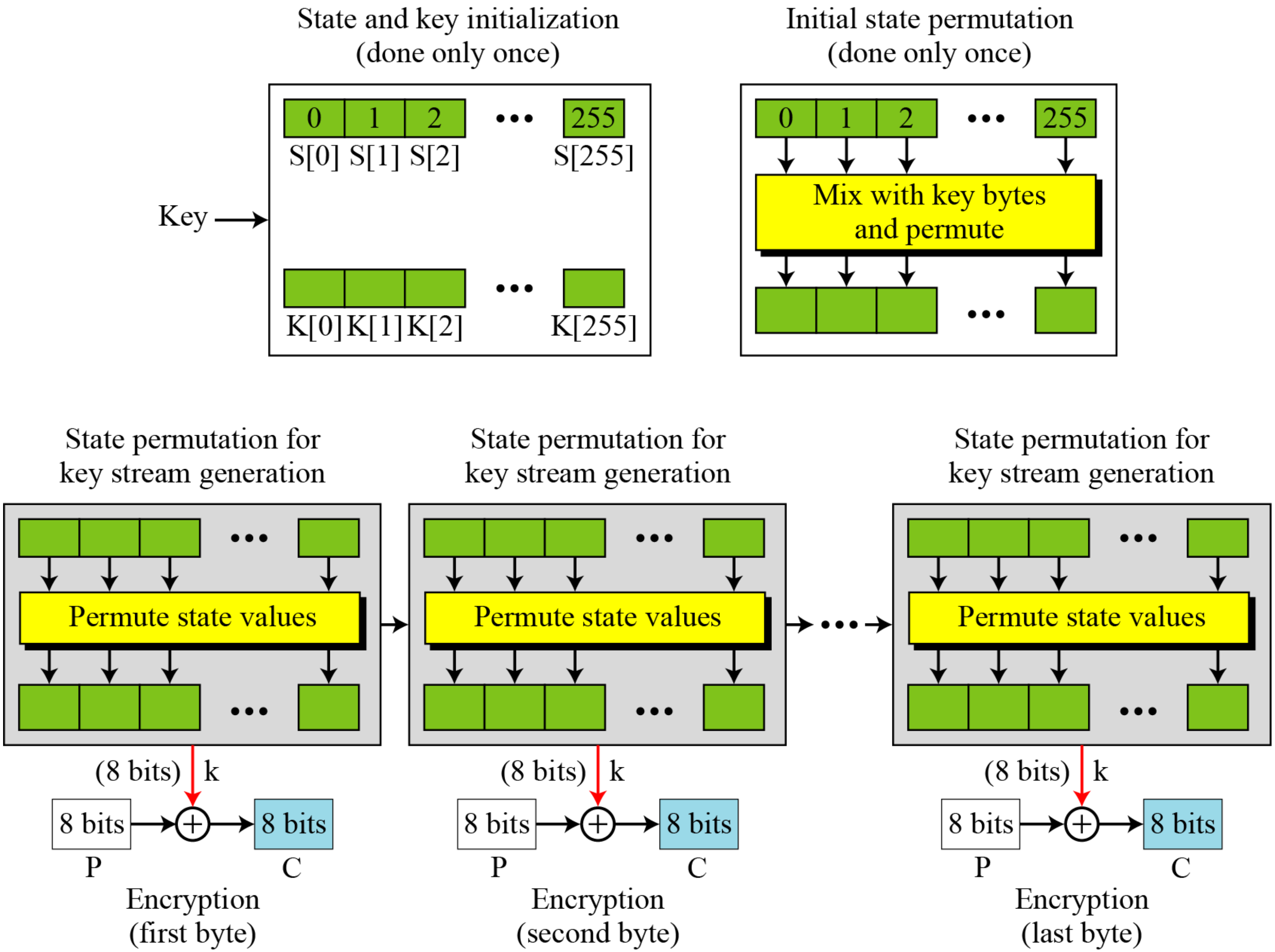
- In this example, $m = \mathrm{maj}(x_8, y_{10}, z_{10}) = \mathrm{maj}(\mathbf{1},\mathbf{0},\mathbf{1}) = \mathbf{1}$
- Register X steps, Y does not step, and Z steps
- Keystream bit is XOR of right bits of registers
- Here, keystream bit will be $0 \oplus 1 \oplus 0 = 1$

RC4 Cipher

RC4

- Rivest Cipher 4 (RC4) invented by Ron Rivest in 1987
- **Variable key size,** normally uses 64 bit or 128 bit key
- WiFi security and can be used for SSL
- Uses a self-modifying lookup table
  - First initialize it with **permutation** of values from 0 to 255 using the key
  - At each step, RC4 does the following
    - Swaps elements in current lookup table
    - Selects a keystream **byte** from table
- Each step of RC4 produces a **byte** (efficient in software)
- Each step of A5/1 produces only a bit (efficient in hardware)

Overall Operation of RC4

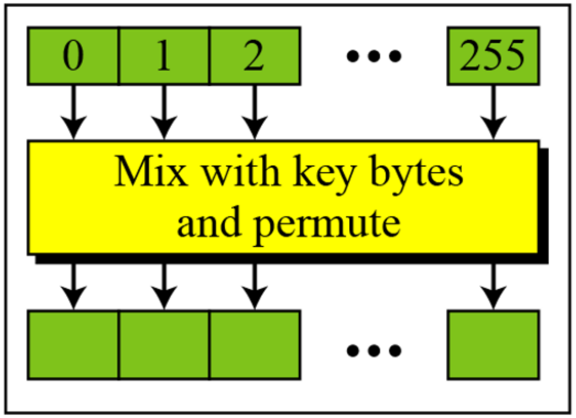


RC4 Initialization

Use the secret key to initialize and permutate a state vector **S**

- `S[] is permutation of 0,1,...,255`
- `key[] contains N bytes of key`

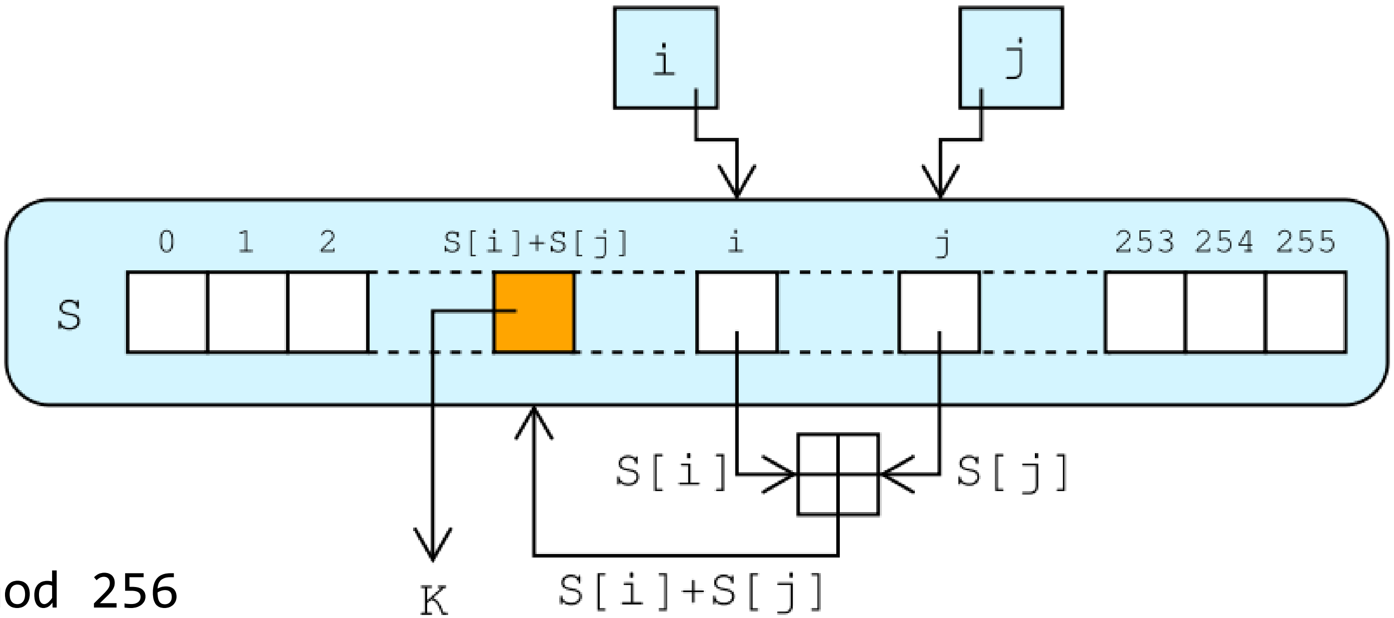
Permutation done once




```
for i = 0 to 255
      S[i] = i
      K[i] = key[i (mod N)]
next i
j = 0
for i = 0 to 255
      j = (j + S[i] + K[i]) mod 256
      swap(S[i], S[j])
next i
```

RC4 Keystream

- The output byte is selected by look up the values of S[i] and S[j], swap them, add them together modulo 256, and then look up the sum in S




```
i = (i + 1) mod 256
j = (j + S[i]) mod 256
swap(S[i], S[j])
t = (S[i] + S[j]) mod 256
keystream = S[t]
```

Summary

- The One-Time Pad is a provable secure symmetric cipher. However, it is highly impractical for most applications because the key length has to equal the message length and it must be used only once
- Stream ciphers produce a pseudo-random stream of bits that you XOR with PT to produce CT and vise-versa
- Stream ciphers require fewer resources and suitable for use in constrained environments such as cell phones (e.g., A5/1 cipher)
  - Linear feedback shift registers (LFSRs) efficient in hardware
- Stream ciphers are less popular than block ciphers in most domains such as Internet security.