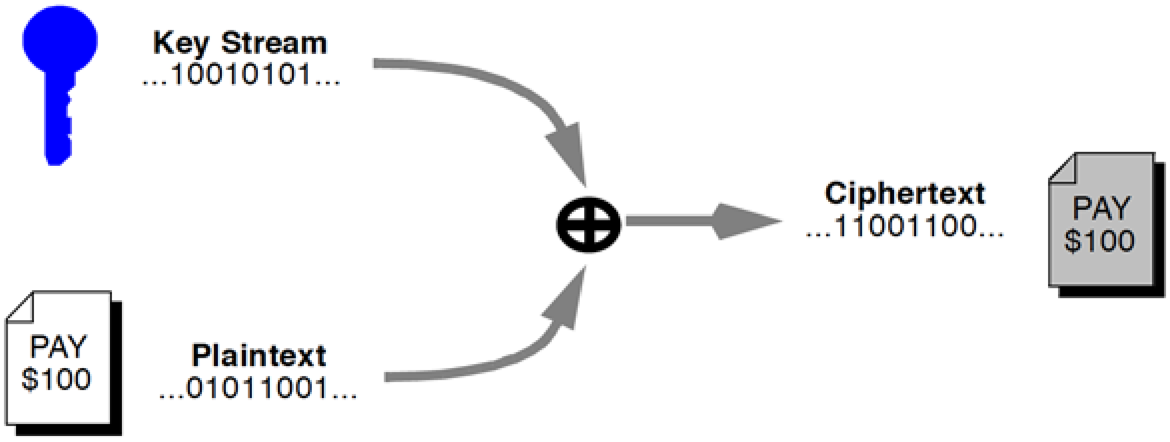
Stream Ciphers



Outline

- Intro to stream ciphers
- Random number generators (RNGs)
- One-Time Pad (OTP)
- Linear feedback shift registers (LFSRs)
- Trivium: a modern stream cipher

Intro to stream ciphers

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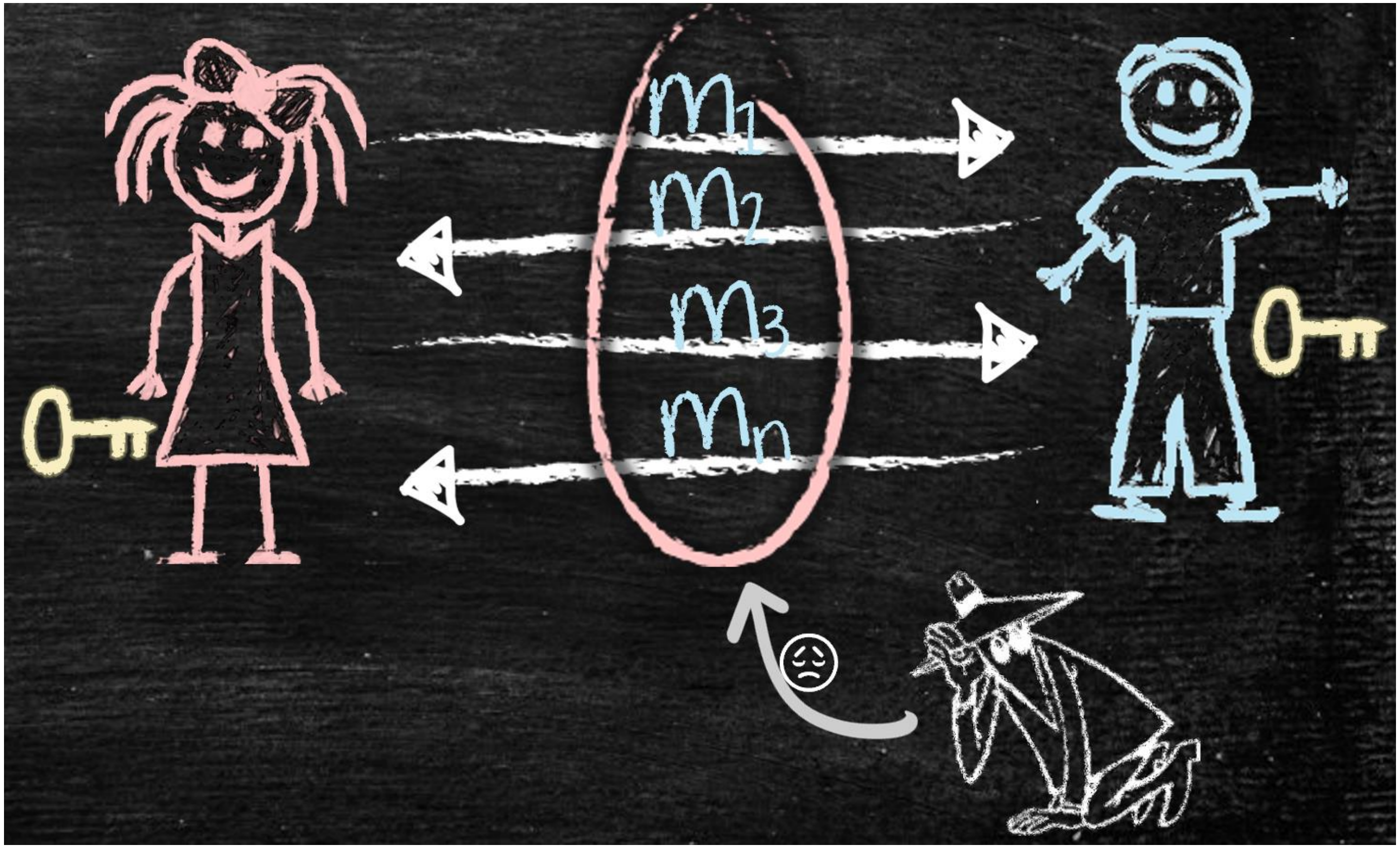
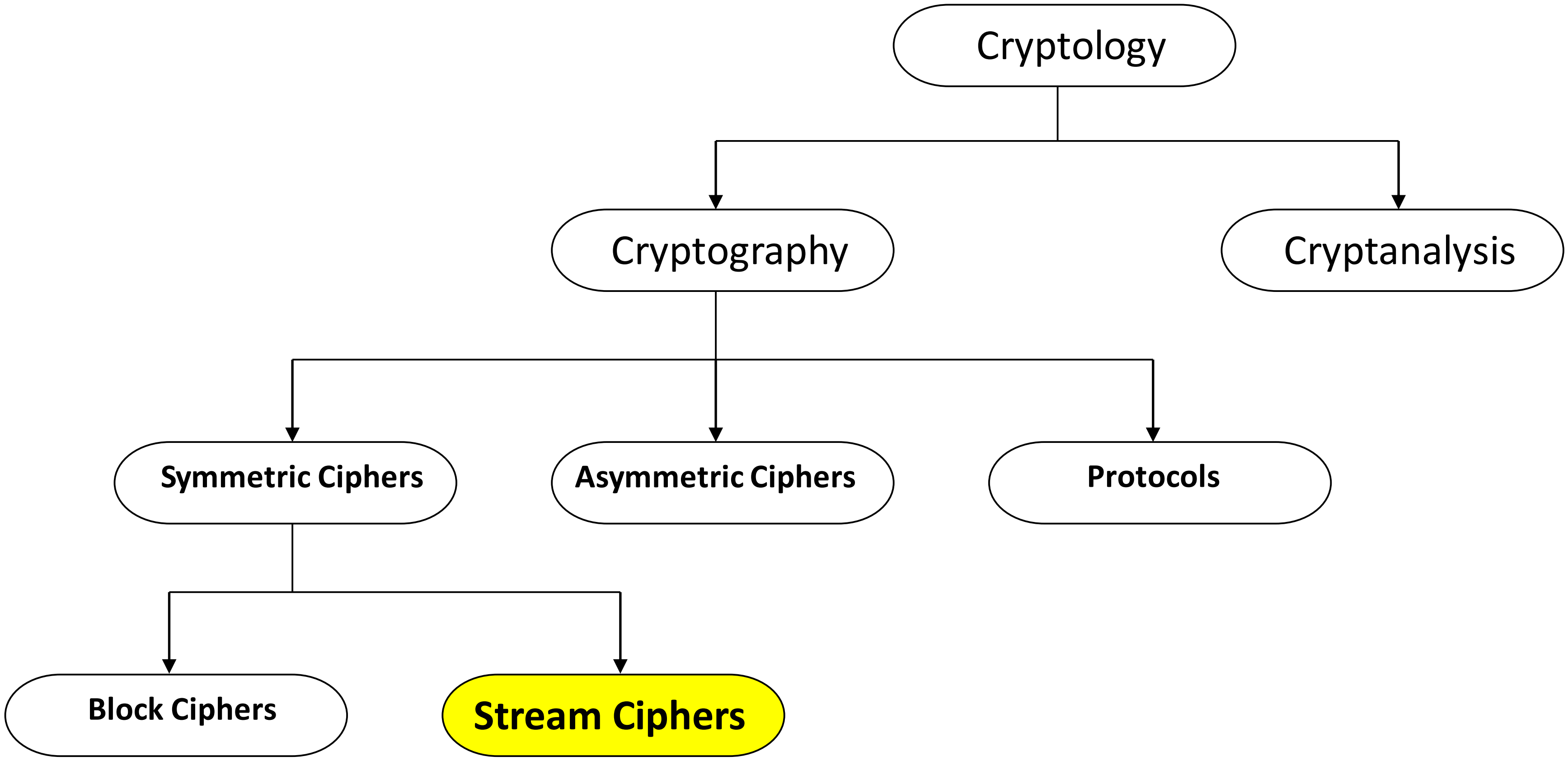
Symmetric Key Cryptography

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

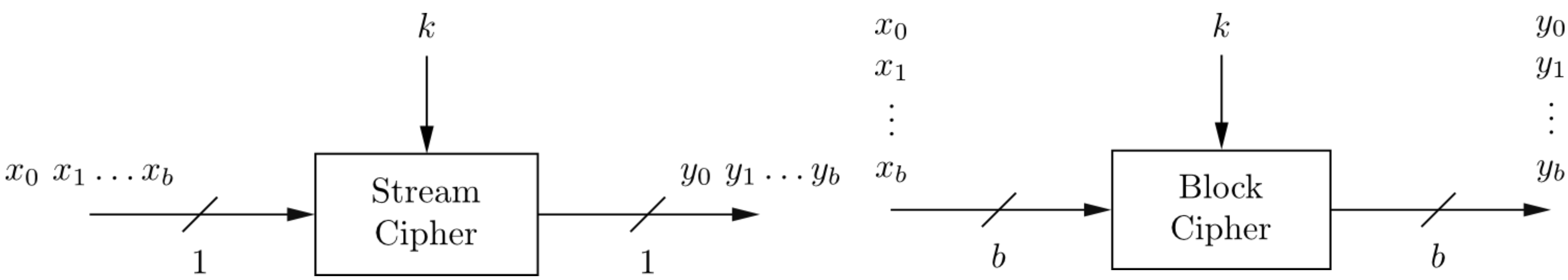


Stream Ciphers in the Field of Cryptology



Stream Ciphers were invented in 1917 by Gilbert Vernam

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 stream
- XOR those bits with your PT in order to encrypt
- XOR those same bits with your CT in order to decrypt
- Tries to approximate a one-time-pad

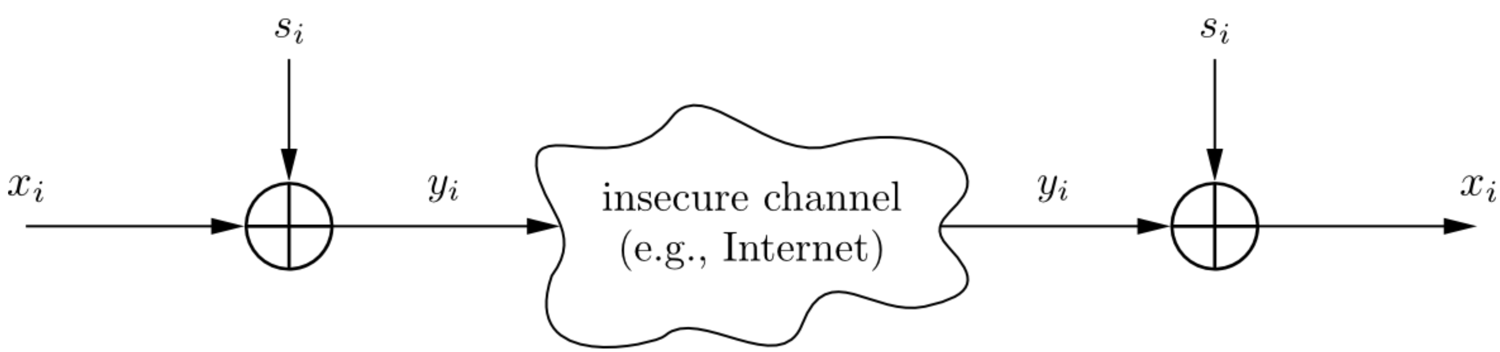
Real-Word Stream Ciphers

- 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

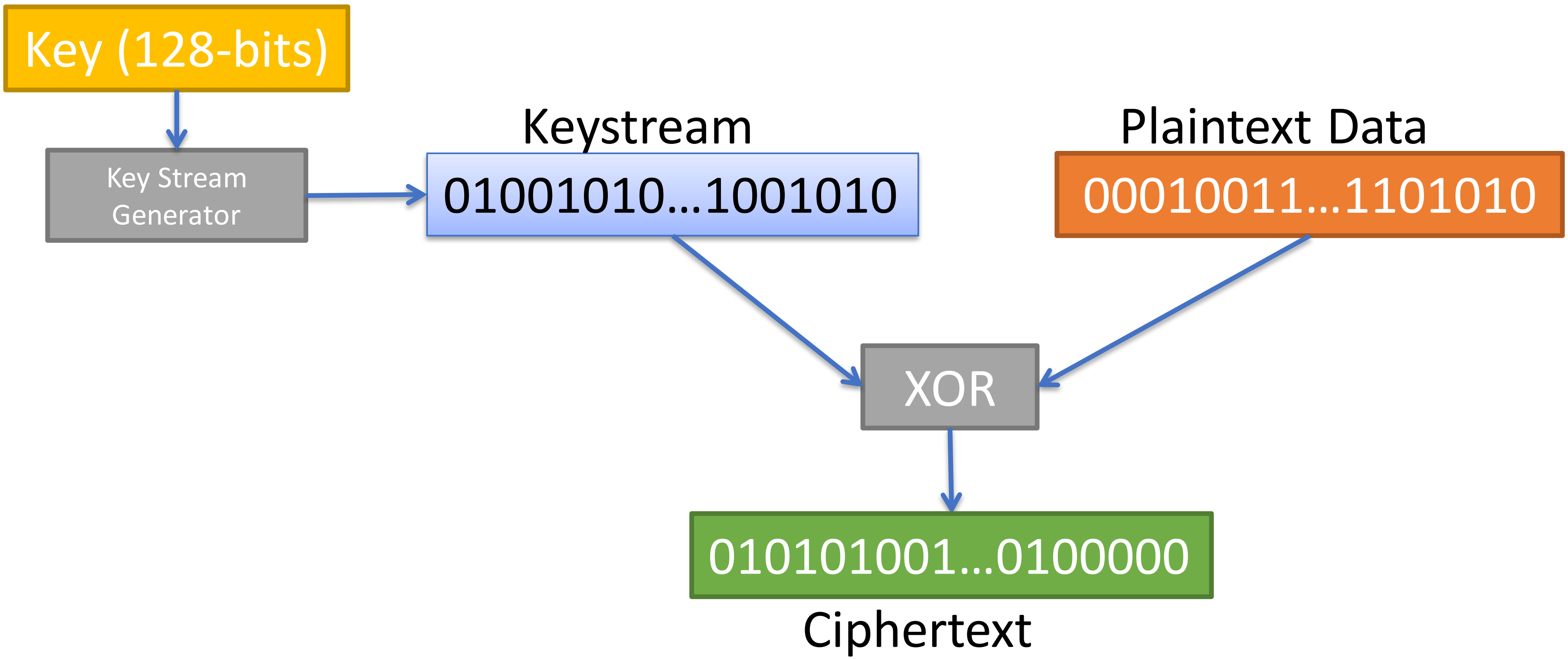


- Encryption and decryption are simple additions modulo 2 (aka XOR)
- Encryption and decryption are the same functions

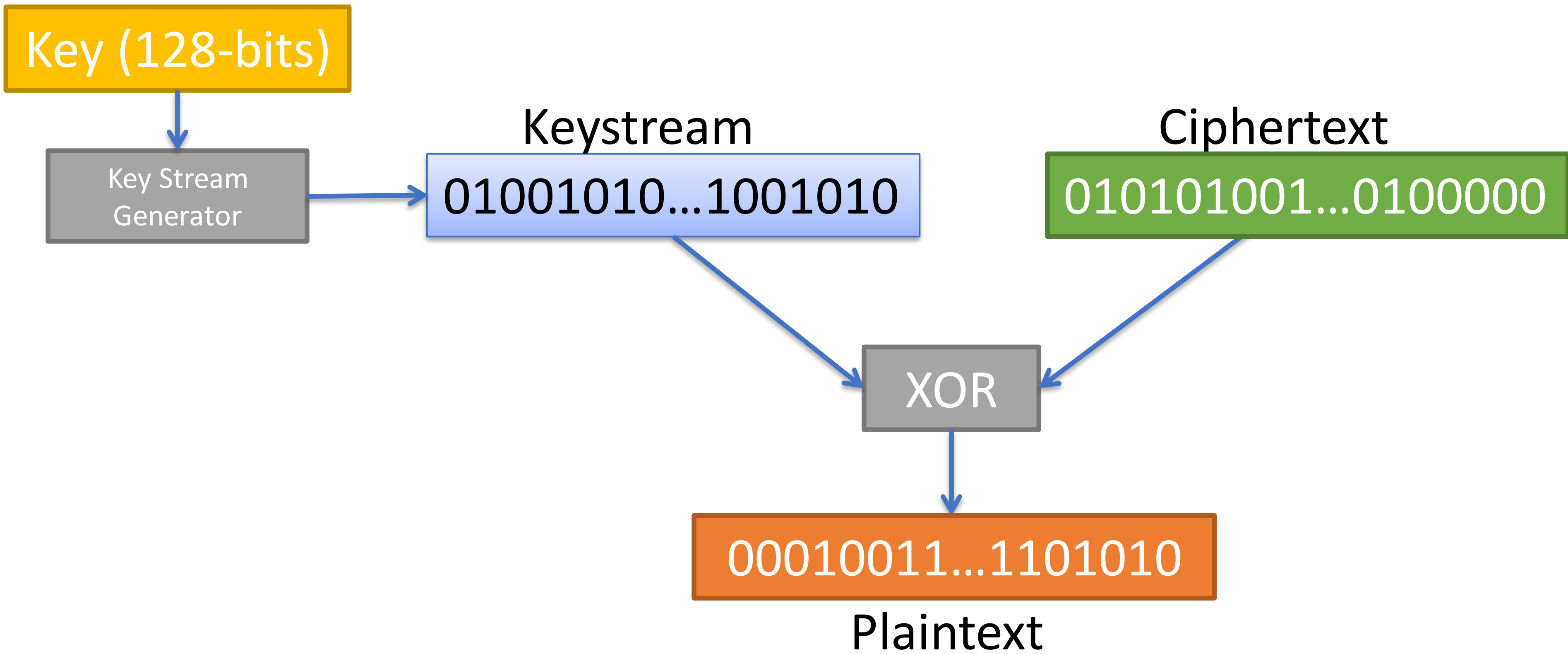
- **Encryption:** $y_i = e_{si}(x_i) = x_i + s_i \bmod 2$ $\quad x_i, y_i, s_i \in \{0,1\}$
- **Decryption:** $x_i = e_{si}(y_i) = y_i + s_i \bmod 2$

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

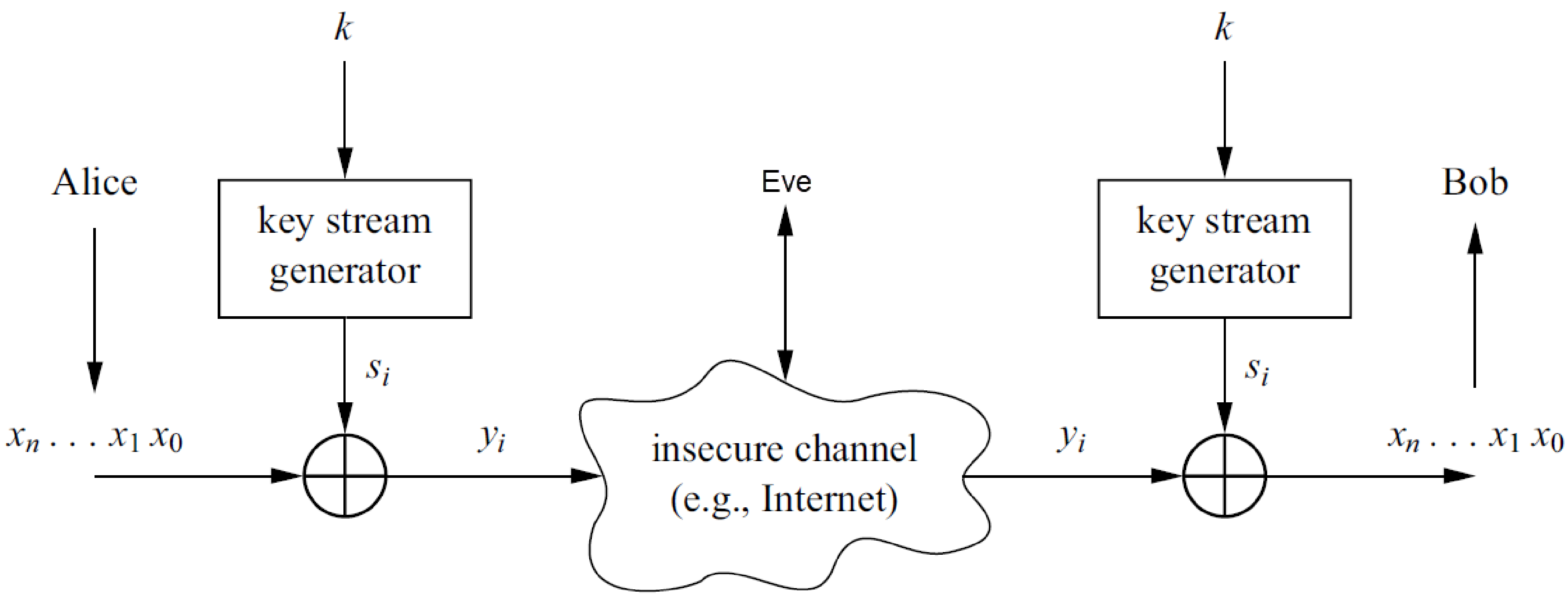
- Encrypt

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 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 ciphertext
- Inverting XOR is simple, since it is the same XOR operation

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)

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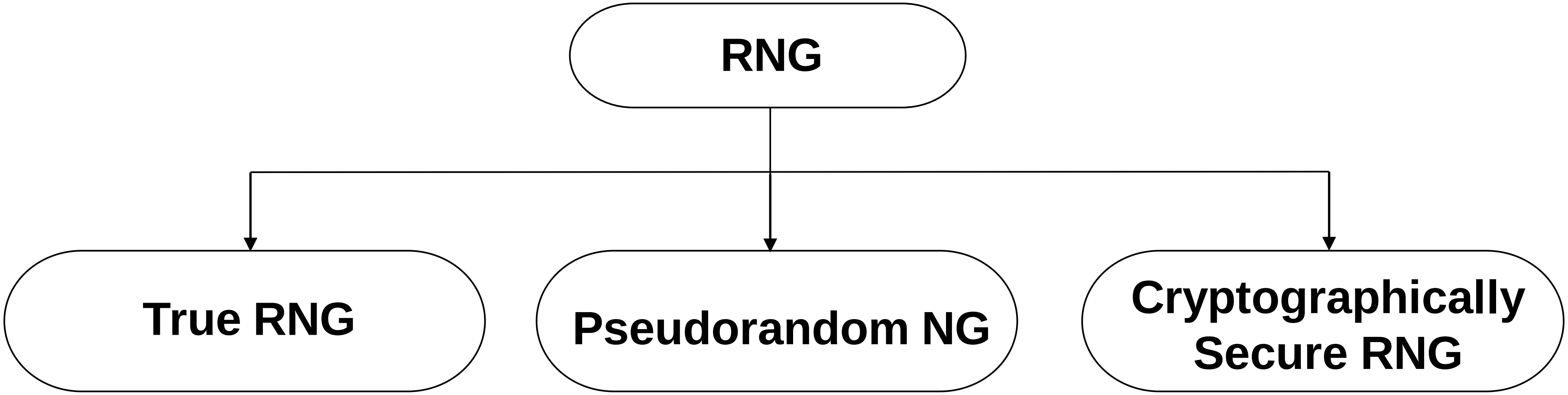
Random number generators (RNGs)



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) and for many other purposes

Pseudorandom Number Generator (PRNG)

- Generate sequences from initial seed value
- Typically, output stream has good statistical properties
- Output can be reproduced and can be predicted

Often computed in a recursive way:

$$s_0 = seed$$

$$s_{i+1} = f(s_i, s_{i-1}, \ldots, s_{i-t})$$

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!

Cryptanalyzing a Simple PRNG

Simple PRNG: **Linear Congruential Generator (LCG)**

$$S_0 = seed$$

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

Assume

- unknown *A, B and* S_0 as key
- Assumer that 3 output are known, i.e. S_1, S_2 and S_3

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 Pseudorandom Number Generator (CSPRNG)

- Special PRNG with additional property:
  - Output must be **unpredictable**

More precisely: Given *n* consecutive bits of output s_i , the following output bits s_{n+1} cannot be predicted (in polynomial time)

- Needed in cryptography, in particular for stream ciphers

One-Time Pad (OTP)

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One-Time Pad (OTP)

Unconditionally secure cryptosystem:

- A cryptosystem is unconditionally secure if it cannot be broken even with *infinite* computational resources

One-Time Pad

- A cryptosystem developed by Mauborgne that is based on Vernam's stream cipher. Has these properties:

  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 if and only if the key k_i is used once!

One-Time Pad (OTP)

Unconditionally secure cryptosystem:

$$y_0 = x_0 \oplus k_0$$

$$y_1 = x_1 \oplus k_1$$

Every equation is a linear equation with two unknowns

$\Longrightarrow$ for every y_i are $x_i = 0$ and $x_i = 1$ equiprobable!

$\Longrightarrow$ This is true if k_0, k_1, ... are independent, i.e., all k_i have to be generated truly random

$\Longrightarrow$ It can be shown that this systems can *provably* not be solved

Disadvantage: For almost all applications the OTP is **impractical** since the key must be as long as the message! (Imagine you have to encrypt a 1GByte email attachment)

Linear feedback shift registers (LFSRs)

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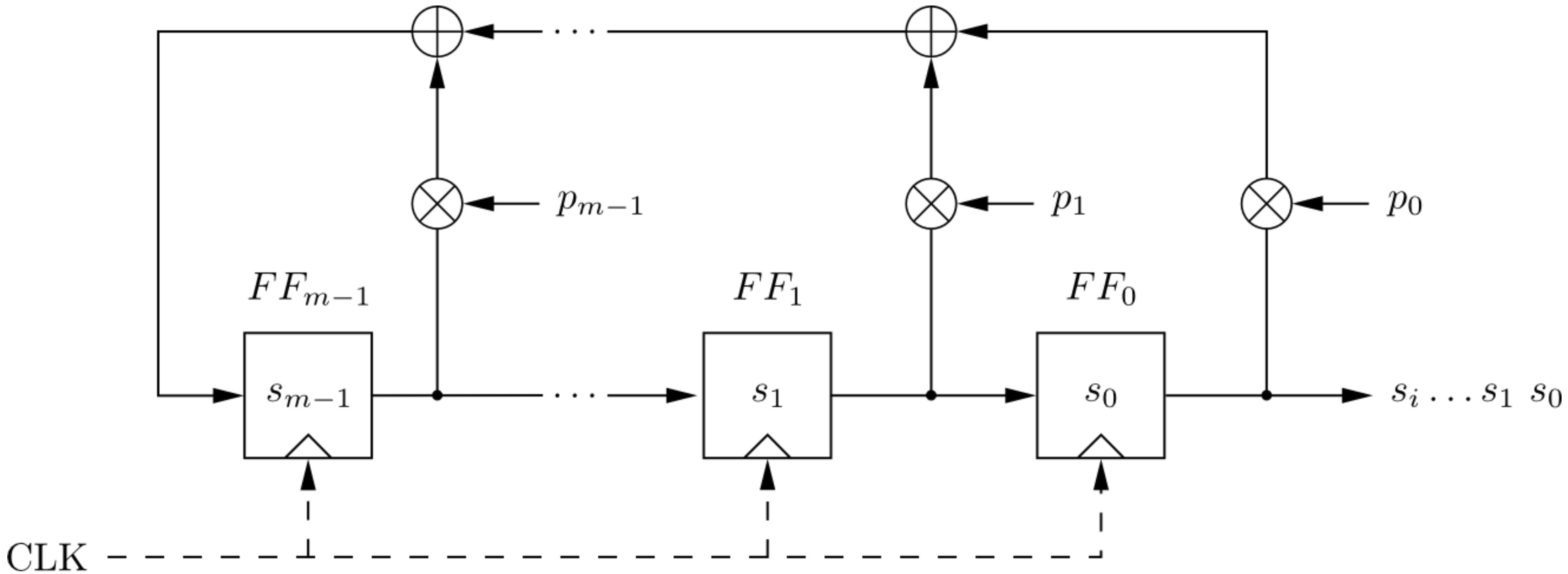
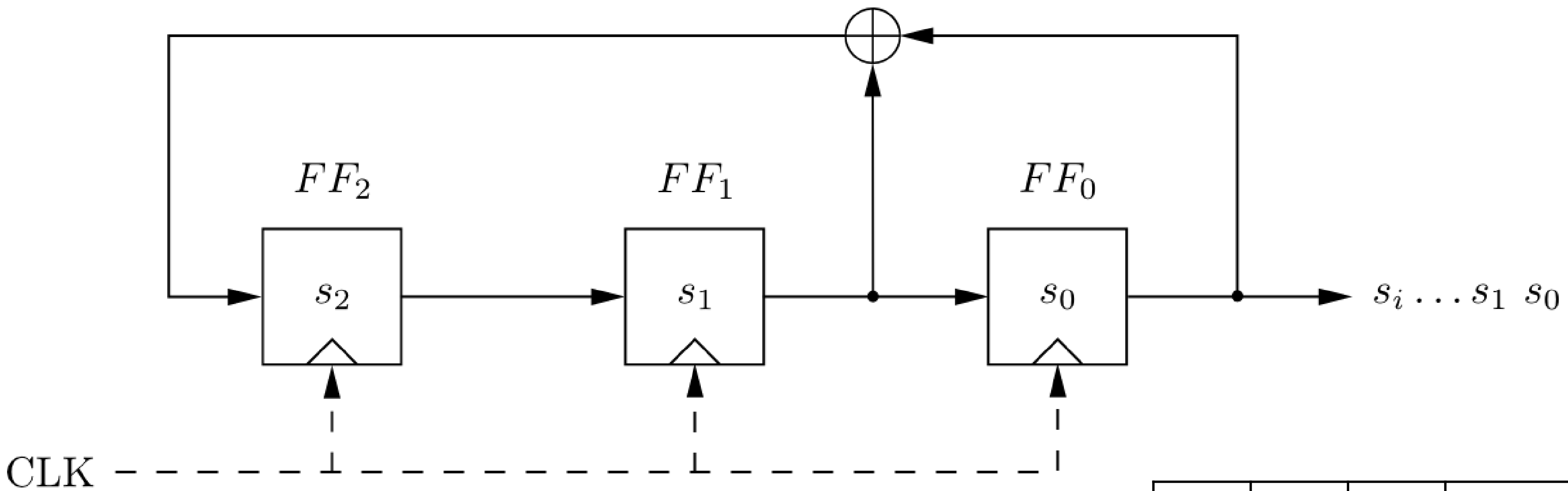
Linear Feedback Shift Registers (LFSRs)



- Concatenated *flip-flops (FF)*, i.e., a shift register together with a feedback path
- Feedback computes fresh input by XOR of certain state bits
- *Degree m* given by number of storage elements
- If p_i = 1, the feedback connection is present ("closed switch), otherwise there is not feedback from this flip-flop ("open switch")
- Output sequence repeats periodically
- Maximum output length: 2^m-1

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



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

- LFSR output described by recursive equation:

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

- Maximum output length (of 2^3-1=7) achieved only for certain feedback configurations, .e.g., the one shown here.

Security of LFSRs

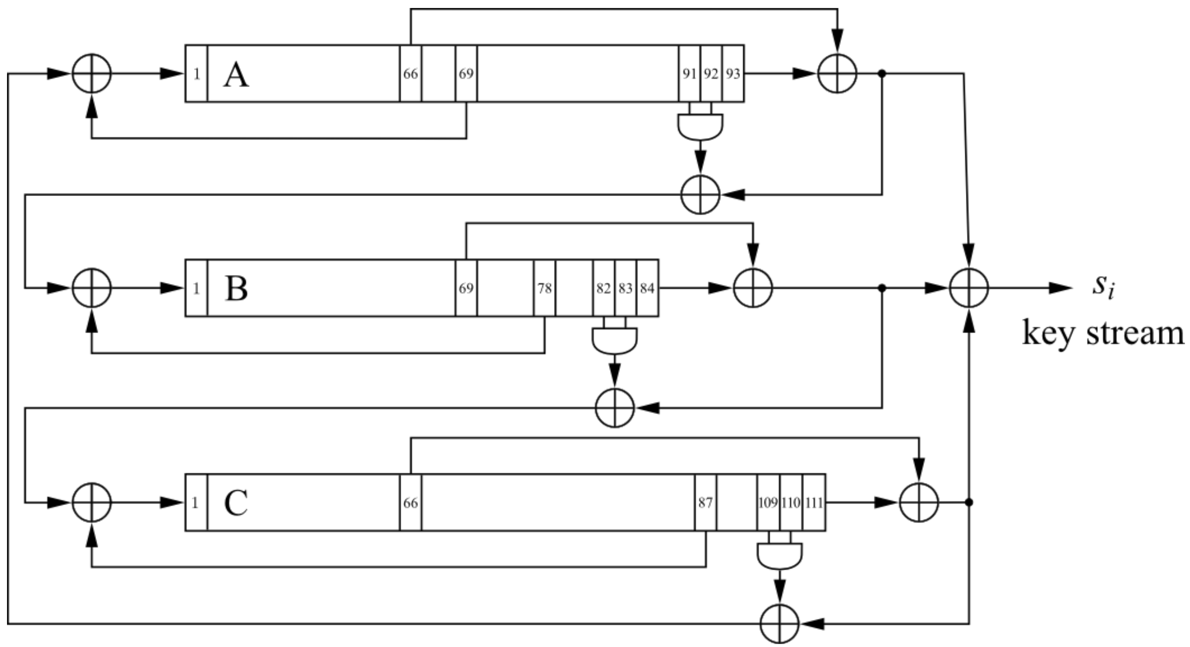
LFSRs typically described by polynomials:

$$P(x) = x^m + p_{l-1}x^{m-1} + \ldots + p_1 x + p_0$$

- Single LFSRs generate highly predictable output
- If 2*m* output bits of an LFSR of degree *m* are known, the feedback coefficients p_i of the LFSR can be found by solving a system of linear equations*
- Because of this many stream ciphers use **combinations** of LFSRs

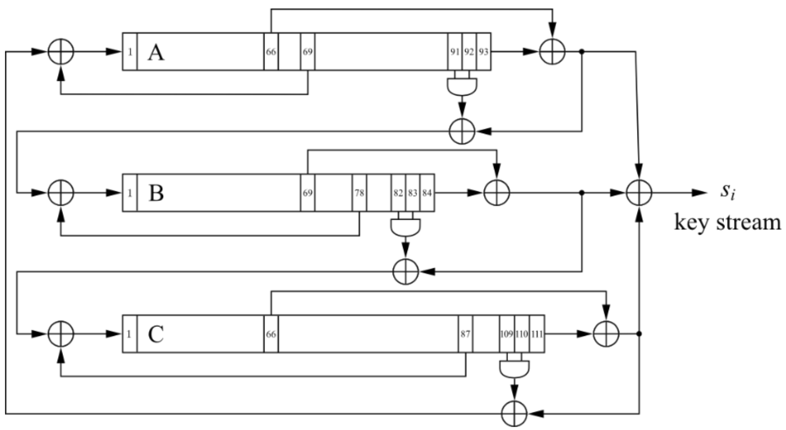
Trivium: a modern stream cipher

A Modern Stream Cipher - Trivium



- Three *nonlinear* LFSRs (NLFSR) of length 93, 84, 111
- XOR-Sum of all three NLFSR outputs generates key stream s_i
- Small in Hardware:
  - Total register count: 288
  - Non-linearity: 3 AND-Gates
  - 7 XOR-Gates (4 with three inputs)

Trivium



Initialization:

- Load 80-bit IV into A
- Load 80-bit key into B
- Set c_{109} , c_{110} , c_{111} =1, all other bits 0

Warm-Up:

- Clock cipher 4 x 288 = 1152 times without generating output

Encryption:

- XOR-Sum of all three NLFSR outputs generates key stream s_i

Design can be parallelized to produce up to 64 bits of output per clock cycle

Summary

- Stream ciphers produce a pseudo-random stream of bits that you XOR with your PT
  - Sender and receiver need to share the same key
- Stream ciphers sometimes require fewer resources, e.g., code size or chip area, for implementation than block ciphers, and they are attractive for use in constrained environments such as cell phones (e.g., RC4 and A5/1)
- The requirements for a *cryptographically secure pseudorandom number generator* are far more demanding than the requirements for pseudorandom number generators used in other applications such as testing or simulation
- 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
- Single LFSRs make poor stream ciphers despite their good statistical properties. However, careful combinations of several LFSR can yield strong ciphers