CM3110 Security

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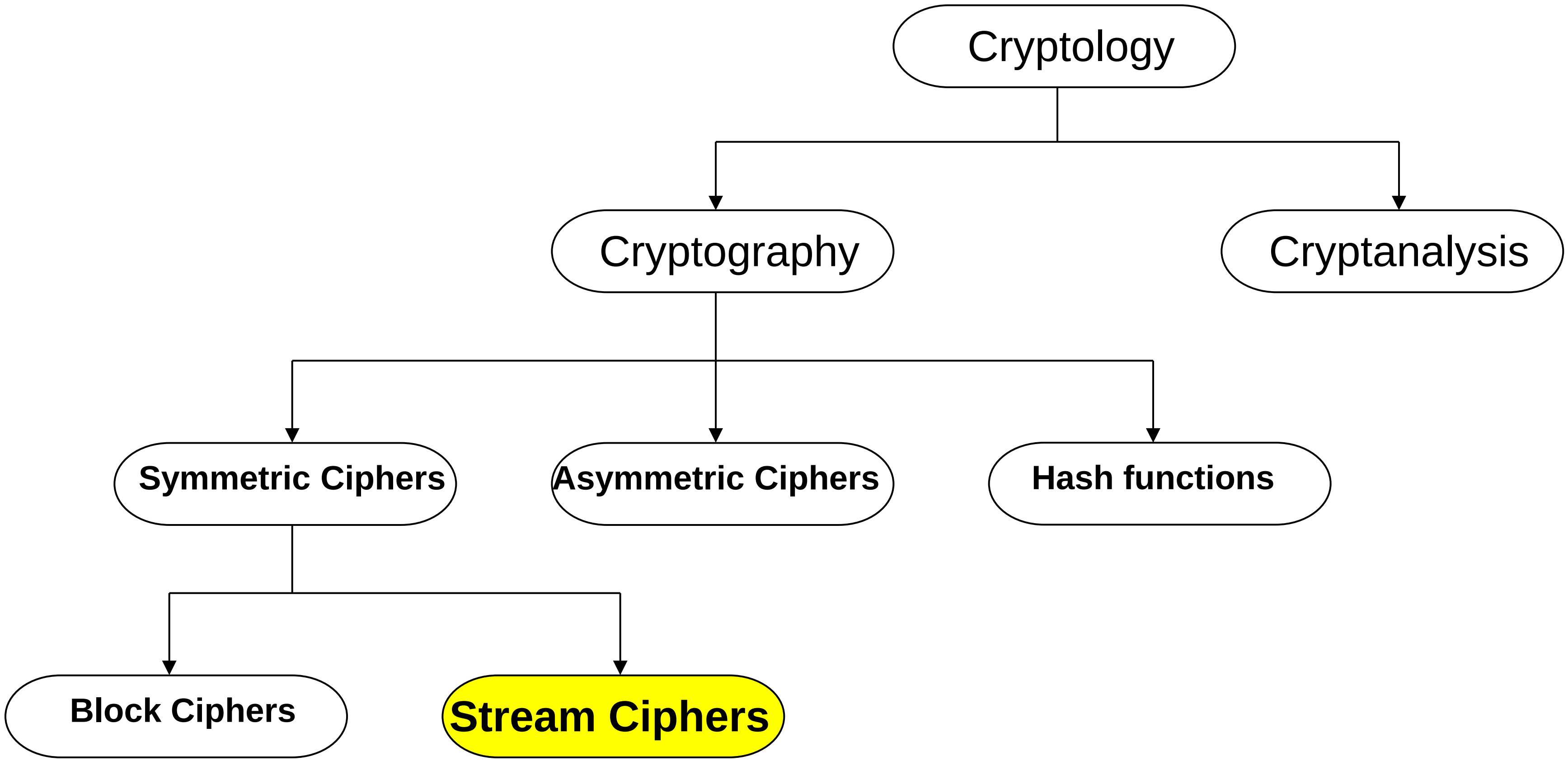
Symmetric Cryptography

- Terminology and basic scenario
- Intro to Cryptanalysis
  - Substitution Cipher
  - Brute-force attack and Frequency analysis
- Modular Arithmetic
  - Caesar's Cipher
  - Affine Cipher
- **Modern Symmetric ciphers**
  - **Stream Ciphers**
  - Block Ciphers (AES)
  - Modes of operation (ECB, CBC, CTR)

Stream Ciphers

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

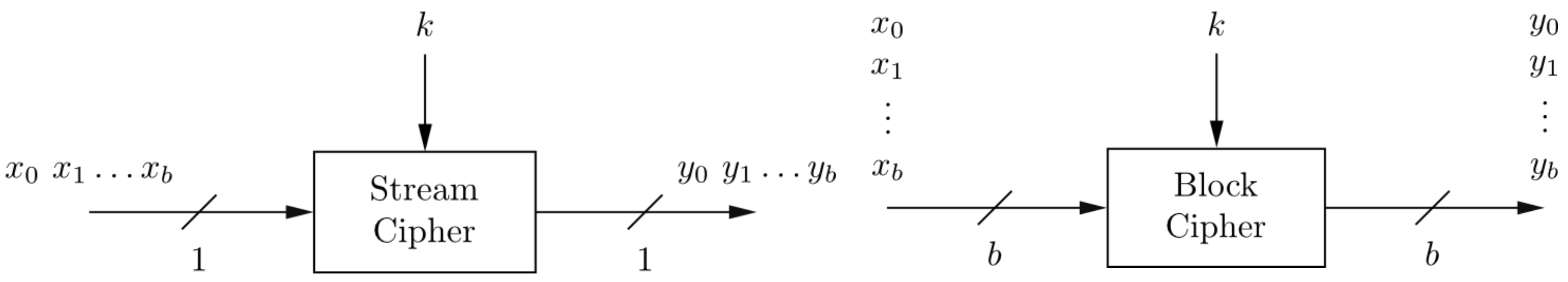
Stream Ciphers: Big picture



Stream Ciphers were invented in 1917 by Gilbert Vernam

Chapter 2 of Understanding Cryptography by Christof Paar and Jan Pelzl

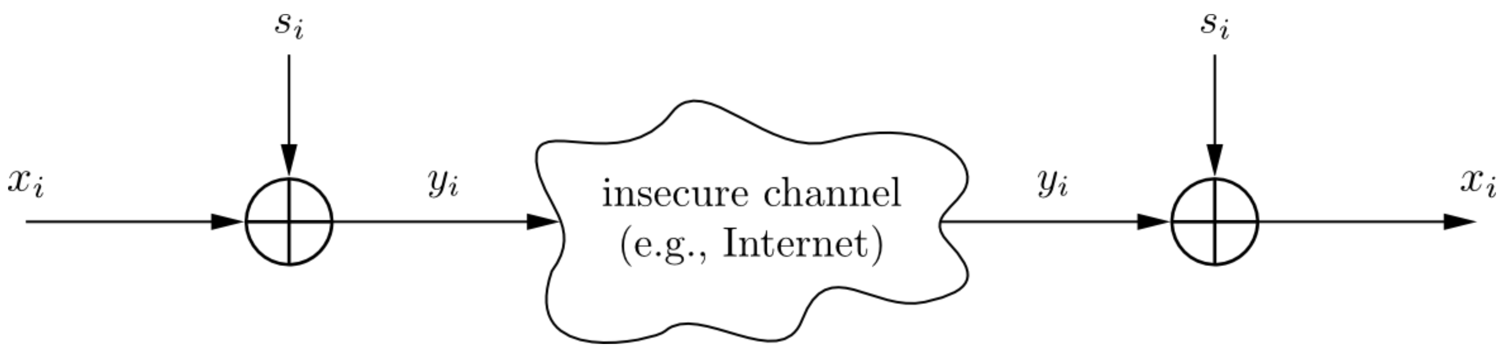
Stream Cipher vs. Block Cipher



- **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, usually 128) in one go
  - Are common for Internet applications

Encryption and Decryption with Stream Ciphers

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

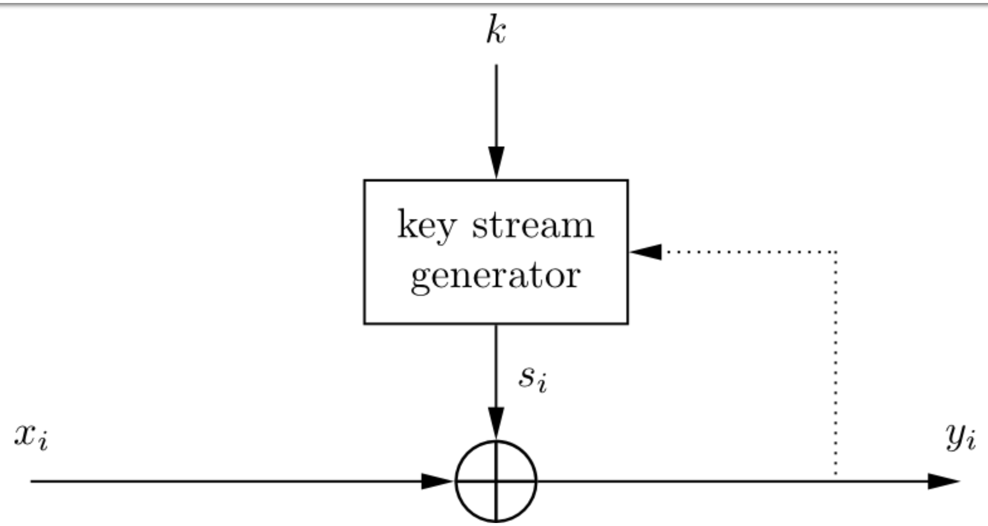


- Encryption and decryption are simple additions modulo 2 (aka XOR)
- Encryption and decryption are the same functions

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

- Let's encrypt and decrypt something to see whether this works…

Synchronous vs. Asynchronous Stream Cipher



- 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
- **Synchronous Stream Cipher**
  - Key stream depends only on the key (and possibly an initialization vector IV)
- **Asynchronous Stream Cipher**
  - Key stream depends also on the ciphertext (dotted feedback enabled)

Why is Modulo 2 Addition a Good Encryption Function?

- Modulo 2 addition is equivalent to XOR operation
- For perfectly random key stream s_i, each ciphertext output bit has a 50% chance to be 0 or 1
  → Good statistical property for ciphertext
- Inverting XOR is simple, since it is the same XOR operation

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

Stream Cipher: Throughput

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

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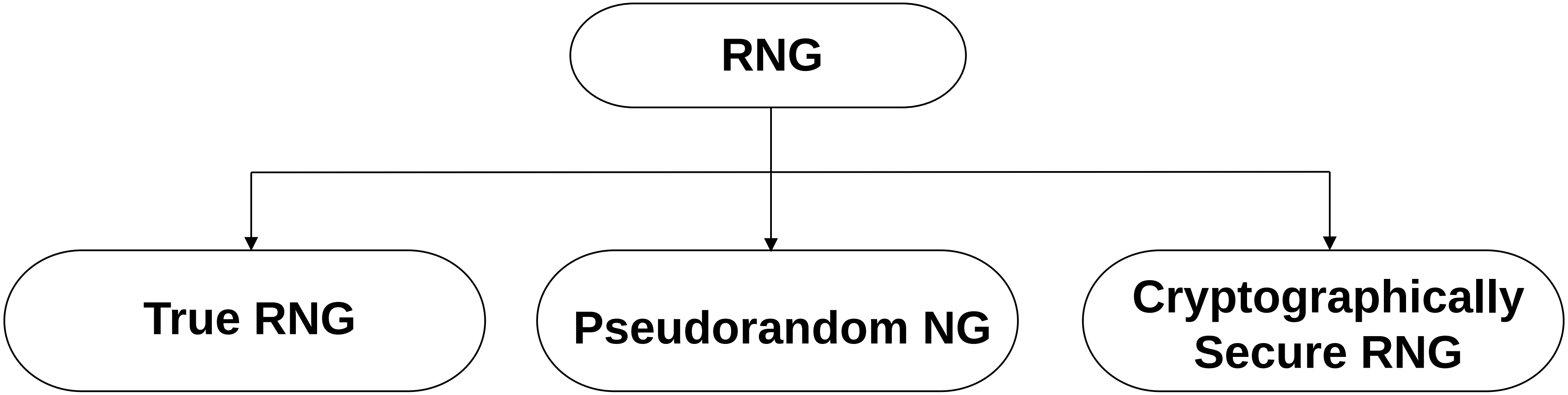
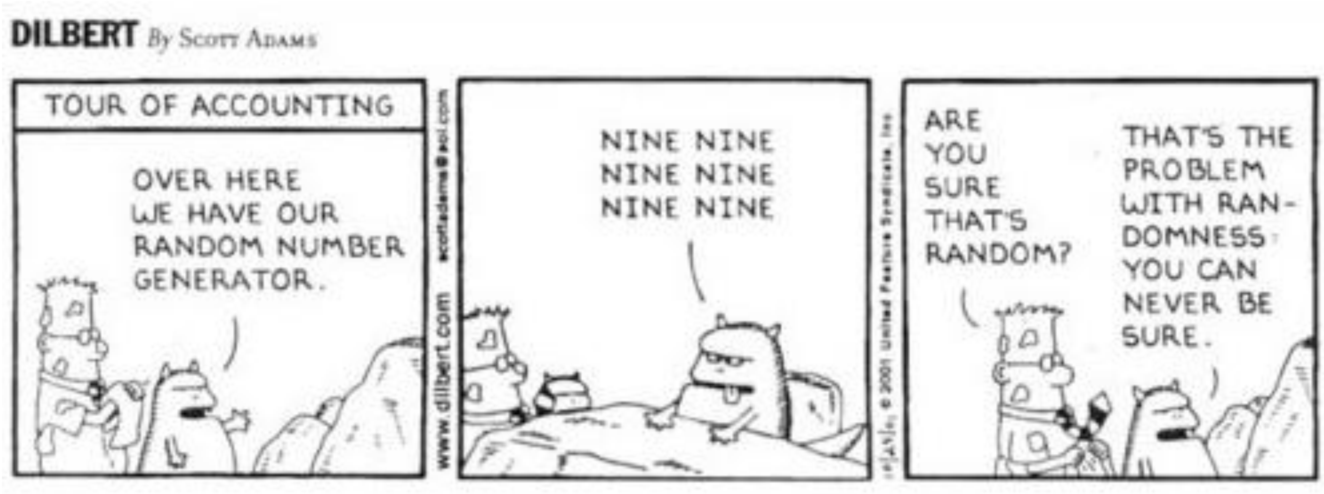
Random number generators (RNGs)



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: $Pr(s_i = 0) = Pr(s_i = 1) = 50\%$ (often achieved by post-processing)
- Output can neither be predicted nor reproduced

Typically used for generation of keys, nonces (used only-once values)



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**

$$S_0 = seed$$

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

Assume

- unknown A, B *and* S_0 as key
- Size of A, B and S_i to be 100 bits
- 300 bit of output are known, i.e. S_1, S_2 and S_3

Solving

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

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

...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, s_{i+1}, ..., s_{i+n-1}, the subsequent output bits s_{i+n}, s_{i+n+1}, ... cannot be predicted (in polynomial time).

- Needed in cryptography, in particular for stream ciphers

- Remark: There are almost no other applications that need unpredictability, whereas many, many (technical) systems need PRNGs.

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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:
- 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 bit k_i is only used once!

One-Time Pad (OTP)

Unconditionally secure cryptosystem:

$$y_0 = x_0 \oplus k_0$$
$$y_1 = x_1 \oplus k_1$$
$$\vdots$$

Every equation is a linear equation with two unknowns

$\Rightarrow$ For every y_i, $x_i = 0$ and $x_i = 1$ are equiprobable!

$\Rightarrow$ This is true iff $k_0, k_1, \ldots$ are independent, and each is 0 w.prob 50% and 1 w. prob 50%, i.e., all k_i have to be generated truly randomly

$\Rightarrow$ It can be shown that this system 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.)

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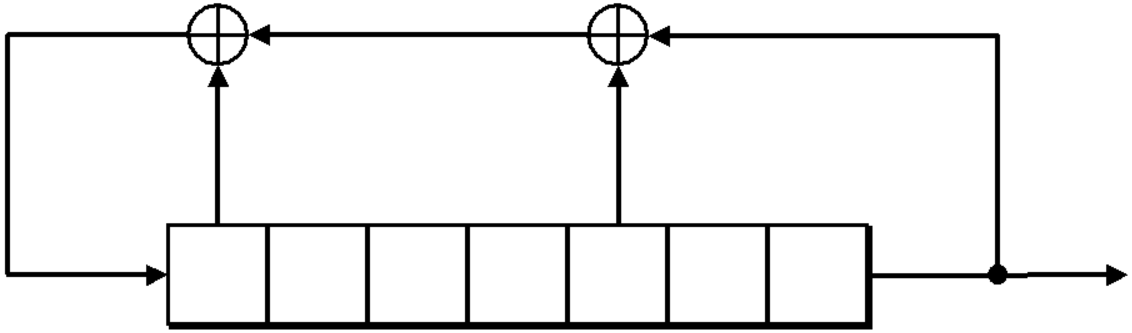
- One-Time Pad (OTP)
- **Linear feedback shift registers (LFSRs)**
- Trivium: a modern stream cipher

Linear Feedback Shift Register

- Try to emulate the OTP
  - Design a random number generator
  - XOR output with plaintext stream
- LFSRs
  - Choose length of register
  - Choose number/location of "taps"



http://www.emc.com/emc-plus/rsa-labs/images/lfsr.gif

LFSR

- Using a single LFSR is bad
  - The LFSR structure can be determined given enough output
- Principle of the Shrinking generator
  - Use 2 LFSRs, A and B
  - If A=1, then output B
  - If A=0, output nothing

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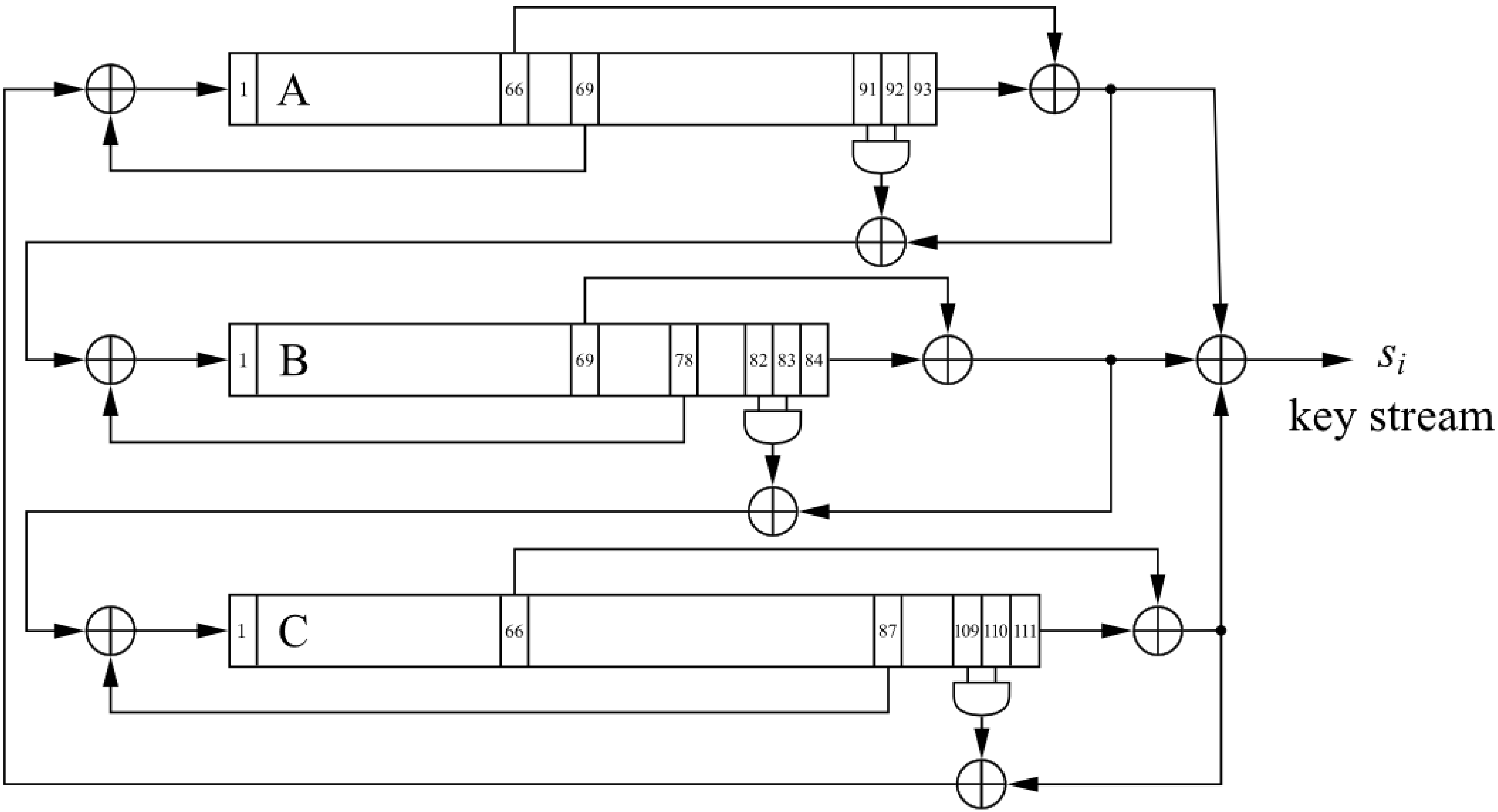
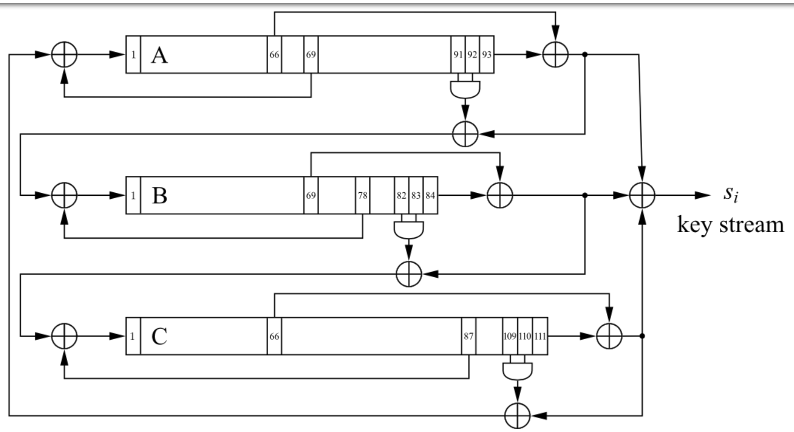
A Modern Stream Cipher - Trivium



Chapter 2 of *Understanding Cryptography* by Christof Paar and Jan Pelzl

Trivium



Small in Hardware:

- Total register count: 288
- Non-linearity: 3 AND-Gates
- 7 XOR-Gates (4 with three inputs)

Initialization:

- Load 80-bit IV into A (nonce)
- 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

Stream Ciphers: Lessons Learned

- Stream ciphers are less popular than block ciphers in most domains such as Internet security. There are exceptions, for instance, the popular stream cipher RC4.
- 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.
- 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.