COMP 5074 Cryptography and Data Protection (2024)

Lecture 4: Stream ciphers

Dr. Yee Wei Law ⟨yeewei.law@unisa.edu.au⟩

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IETF Internet Engineering Task Force . . . 2
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NESSIE New European Schemes for Signatures, Integrity and Encryption . . . 1
PPT probabilistic polynomial-time . . . 3
TLS Transport-Layer Security . . . 2

1 Introduction

Provable security is a reductionist approach to proving the security properties of computational security schemes.

Leveraging provable security, cryptographers produced a useful array of cryptographic primitives.

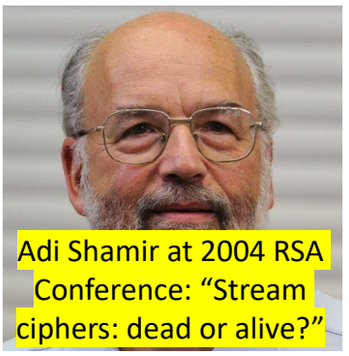
Let us be absolutely clear right from the outset: a symmetric-key encryption scheme can be constructed using 1️⃣ a stream cipher, or 2️⃣ a block cipher coupled with a mode of operation.

The term "stream cipher" is not defined in NIST's Computer Security Research Center Glossary. In fact, there is no NIST Special Publication or FIPS that covers stream ciphers.

Stream ciphers have had a bumpy road:

- The New European Schemes for Signatures, Integrity and Encryption (NESSIE) project that took place from 1999 till 2003 did not provide any recommendation for stream ciphers, partly because most stream ciphers in use were secret or proprietary designs [PBO+03, Sec. 3.3.5], and partly because of the uncertainties with the security of the candidate stream ciphers submitted to the project for study.

- It was around the time of the NESSIE project that multiple vulnerabilities of the once-standard stream cipher RC4 were discovered.
  - » In fact, there is an Internet Engineering Task Force (IETF) RFC, namely RFC 7465 [Pop15], that specifically prohibits the use of the troubled RC4 cipher suite in Transport-Layer Security (TLS).
  - » One of the most recent attacks is AlFardan et al.'s [ABP+13], which managed to recover the first 200 bytes of a plaintext stream after 2^{28} to 2^{32} (about 268 million to 4 billion) encryptions of the same plaintext; watch video.


Adi Shamir at 2004 RSA Conference: "Stream ciphers: dead or alive?"

- On the heels of the NESSIE project, the ECRYPT Stream Cipher (eSTREAM) project, which ran from 2004 till 2008, proposed 4 algorithms for software implementation and 3 algorithms for hardware implementation.
- Among the eSTREAM portfolio [RB08] are Salsa20 and Grain:
  - » **Salsa20** [RB08, pp. 84-97]: Created by D.J. Bernstein, this cipher has been succeeded by ChaCha20. Although not standardised by NIST, ChaCha20 is standardised in RFC 8439 [NL18], and implemented in OpenSSL, BoringSSL and Tink.
  - » **Grain** [RB08, pp. 179-190]: This started as two variants: 80-bit and 128-bit. The latter evolved into Grain-128AEAD [HJM+21], a finalist (but not a winner) in the NIST Lightweight Cryptography standardisation process.

Fortunately, a stream cipher can be constructed from a block cipher, and this is one of the reasons why there has been much more development in block ciphers than stream ciphers.

Nevertheless, stream ciphers are desirable 1️⃣ where exceptionally high throughput is required in software and 2️⃣ where exceptionally low resource consumption is required in hardware [RB08].

2 Definition and classification

Definition 1: Stream cipher [KL21, Sec. 3.6.1]

A stream cipher is a pair of deterministic algorithms (Init, f) where

- Init takes as input 1️⃣ a secret key serving as a seed s and 2️⃣ an optional initialisation vector (IV), and outputs some initial state σ_0.
- The next-state function f takes as input the current state σ_i and outputs a keystream bit z_i along with the updated state σ_{i+1}.

⚠ An IV is practically mandated for security, for example by the eSTREAM project [RB08, p. 2].

ℹ In practice, f outputs a byte or a larger number of random bits, but a bit is the smallest granularity.

Clearly, a stream cipher is stateful, and is sometimes referred to as a *state-based symmetric-key encryption scheme* [Gol04, Construction 5.3.1.2].

Inspired by the one-time pad, a stream cipher generates a pseudorandom *keystream* from a fixed-length secret key, with the intent that the keystream appears random to a probabilistic polynomial-time (PPT) adversary.

Stream ciphers can be classified as:

Synchronous/synchronised [MvV96, Definition 6.2]: Keystream is generated independently of the plaintext and ciphertext.

Asynchronous/unsynchronised/self-synchronising [MvV96, Def. 6.5]: Keystream is generated as a function of the key and a fixed number of previous ciphertext bits.

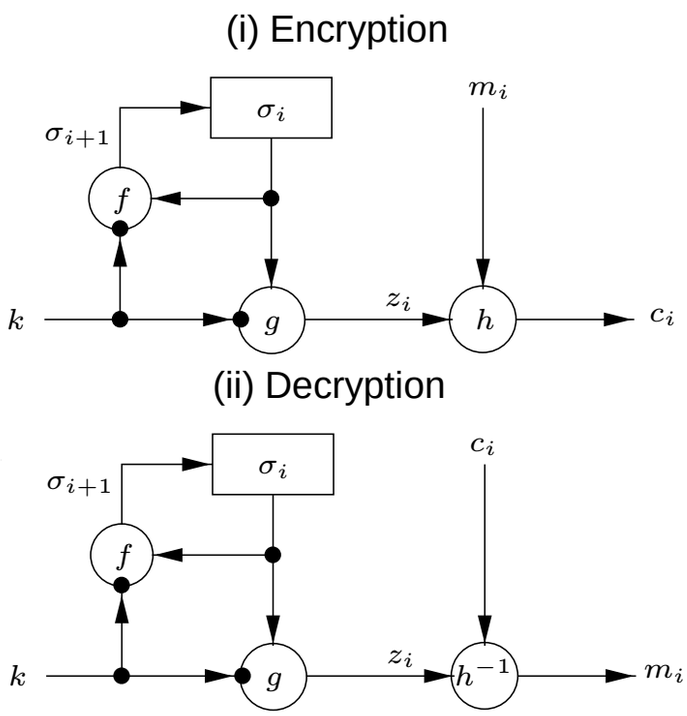


Figure 1: General model of a synchronous stream cipher [MvV96, Figure 6.1].

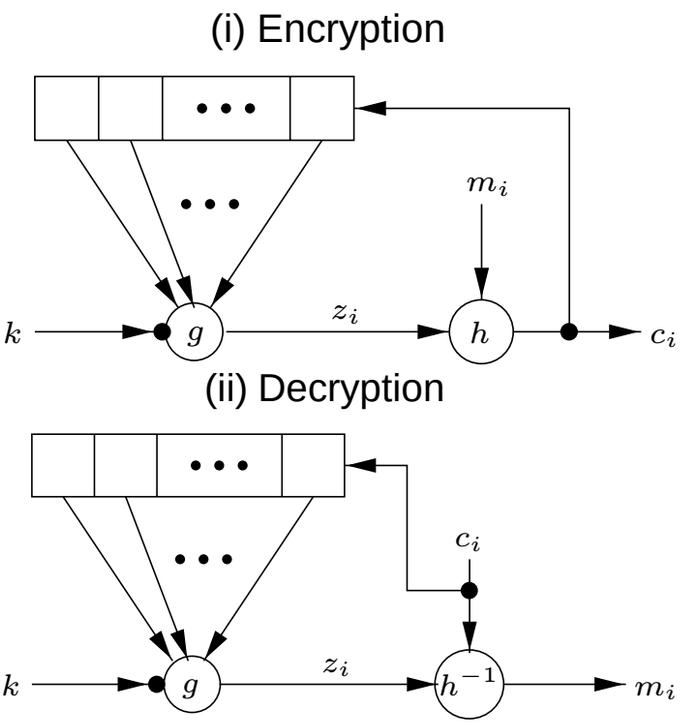


Figure 2: General model of an asynchronous stream cipher [MvV96, Figure 6.3].

As per Figure 1, the encryption process can be described by:

$$\sigma_{i+1} = f(\sigma_i, k), \tag{1a}$$
$$z_i = g(\sigma_i, k), \tag{1b}$$
$$c_i = h(z_i, m_i), \tag{1c}$$

where σ_0 is the secret initial state and maybe determined from the key k; g is a function that produces the keystream z_i; h is the output function that combines the keystream and plaintext m_i to produce ciphertext c_i.

A synchronous stream cipher can be constructed from a block cipher in the *output feedback* (OFB) mode or *counter* (CTR) mode; see knowledge base entry.

As per Figure 2, the encryption function can be described by:

$$\sigma_i = (c_{i-t}, c_{i-t+1}, \ldots, c_{i-1}), \tag{2a}$$
$$z_i = g(\sigma_i, k), \tag{2b}$$
$$c_i = h(z_i, m_i), \tag{2c}$$

where $\sigma_0 = (c_{-t}, c_{-t+1}, \ldots, c_{-1})$ is the non-secret initial state; k is the key; g is a function that produces the keystream z_i; h is the output function that combines the keystream and plaintext m_i to produce ciphertext c_i.

An asynchronous stream cipher can be constructed from a block cipher in the 1-bit *cipher feedback* (CFB) mode; see knowledge base entry.

An example of a synchronous stream cipher is:

Definition 2: Binary additive stream cipher [MvV96, Definition 6.4], [Sma16, Sec. 10.2]

A synchronous stream cipher in which the keystream, plaintext, and ciphertext digits are binary digits, and the output function h is the XOR function.

As shown in Figure 3, the binary additive stream cipher consists a *keystream generator* or *running key generator* implemented by the functions f and g in Eq. (1).

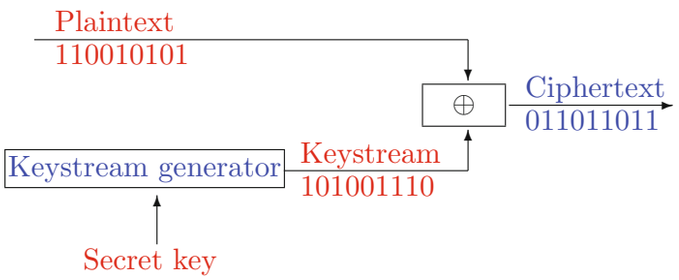


Figure 3: A binary additive stream cipher [Sma16, Figure 10.2]. IV omitted but usually present. Blue annotation indicates publicly available information. Red annotation indicates information available to legitimate parties.

The linear feedback shift register (LFSR) is a staple in keystream generator designs and the subject of the next section.

3 Linear feedback shift register

The LFSR has been a staple in keystream generator designs, because

1. it can readily be analysed using algebraic techniques,
2. it can produce bit streams that pass common statistical tests,
3. it is well-suited to efficient hardware implementation, and
4. it is well-studied.

See [RB08, p. 20] and [MvV96, Sec. 6.2.1].

An LFSR is a shift register whose input bit is a linear function of its previous state [Jet19]; watch

- Intro to Linear Feedback Shift Registers and Sequence Generators by David Tarnoff,
- Designing (Noncryptographic) Binary Sequence Generators with Shift Registers by David Tarnoff,
- Linear-feedback shift registers (LFSRs) as part of the LinkedIn Learning course “Symmetric Cryptography Essential Training”.

Each LFSR is associated with a primitive polynomial in a Galois field.

However, the linearity of the LFSR makes it susceptible to algebraic attacks [RB08].

For example, the stream cipher Toyocrypt was broken by an attack that can solve an overdefined system of multivariate equations for the initial state bits [CM03]; recovery of the initial state bits leads to recover of the key.

Thus, an LFSR is typically either used together with nonlinear structures, or replaced by nonlinear structures such as a *nonlinear feedback shift register* (NFSR); see Example 1.

Example 1

One of the ten finalists in NIST's lightweight AEAD standardisation process that started in 2017 is Grain-128AEAD.

Grain-128AEADv2 is the second version of the Grain-128AEAD and consists of binary additive stream cipher, as shown in Figure 4.

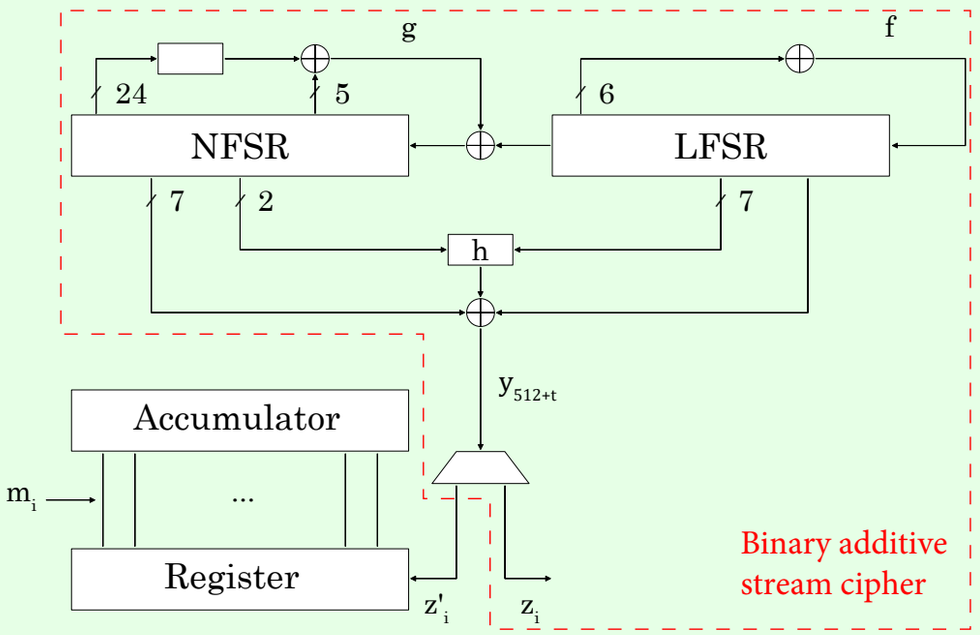


Figure 4: Building blocks of Grain-128AEADv2 [HJM+21, Figure 1]. ⚠ Functions f, g and h here are different from those in Eq. (1).

In Figure 4, the 128-bit LFSR is associated with the primitive polynomial:

$$f(x) = 1 + x^{32} + x^{47} + x^{58} + x^{90} + x^{121} + x^{128}.$$

The next-state function for the LFSR is

$$s_{127}^{t+1} = s_0^t + s_7^t + s_{38}^t + s_{70}^t + s_{81}^t + s_{96}^t,$$

where $s_0^t, \ldots, s_{127}^t$ denote the current 128 bits of the LFSR. The Boolean function (not output function) is

$$h(x) = x_0x_1 + x_2x_3 + x_4x_5 + x_6x_7 + x_0x_4x_8, \tag{3}$$

where $x_1 = s_8^t$, $x_2 = s_{13}^t$, $x_3 = s_{20}^t$, $x_5 = s_{42}^t$, $x_6 = s_{60}^t$, $x_7 = s_{79}^t$, $x_8 = s_{94}^t$.

Quiz 1

In Example 1, can you tell from [HJM+21, p. 7] what x_0 and x_4 in Eq. (3) are mapped to?

Advantages of stream ciphers:

- 👍 Compared to block ciphers, easier to achieve higher throughput and resource efficiency for the same security parameter.
- 👍 No error propagation: when a single ciphertext bit gets corrupted during transit (either naturally or due to attacks), only one bit of the decrypted plaintext is affected.

Disadvantages of stream ciphers:

- 👎 Reuse of keystream segment allows an adversary to discover the XOR of two plaintexts, since $(m_1 \oplus k) \oplus (m_2 \oplus k) = m_1 \oplus m_2$, where m_1 and m_2 are the compromised plaintexts.

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