Stream Cipher (流密码)

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Outline

1. Stream Ciphers and Pseudo-random Generators
   - Stream Ciphers
   - Instantiate PRGs with stream ciphers
2. Encrypt with stream ciphers
3. Linear-Feedback Shift Registers
4. Adding Nonlinearity
5. Two Tips on stream cipher usages

Stream ciphers (流密码)

What is a stream cipher? What is it used for?

- A deterministic algorithm that extends a short random seed to a stream of "random-looking" bits.
- Used as a cryptographic primitive, to instantiate PRGs, encrypt messages, ...
- Pro: good efficiency, **CON**: has no rigorous security proof

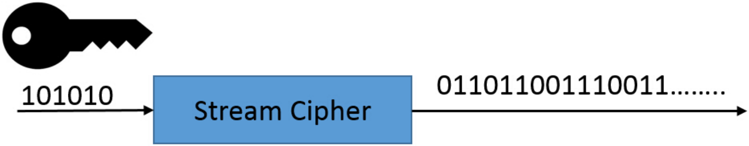


图 1: A stream cipher

Formal definition of stream ciphers

A **stream cipher** is a pair of deterministic algorithms:

- **Init**: $st_0 := Init(s, [IV])$.
- **GetBits**: $(y_i, st_i) := GetBits(st_{i-1})$ for $i = 1, 2, \ldots$

where

1. $st_0, st_1, \ldots$ are state information;
2. *Init* is an initialization algorithm that takes as input a seed s and an optional initialization vector IV, and outputs an initial state st_0;
3. *GetBits* algorithm takes as input a state st_{i-1} and outputs a bit y_i and a new state st_i.
4. the bit stream output $y_1, y_2, \ldots$ is often called the keystream (since it is generally XORed with the plaintext to generate the ciphertext).
5. In practice, y_i is often a block of bits instead of one bit.

Given a steam cipher and any desired expansion factor l, we can implement a PRG using the following algorithm:

Algorithm 1 Instantiate PRGs with stream ciphers

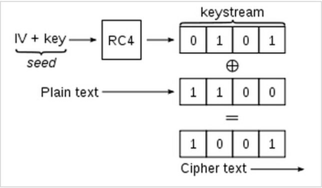
Input: Seed s and optional initialization vector IV

Output: $y_1, \ldots, y_l$

1: $st_0 := Init(s, IV)$
2: **for** $i = 1$ to l do;
3: $(y_i, st_i) := GetBits(st_{i-1})$
4: **return** $y_1, \ldots, y_l$

Encryption using stream ciphers

- Encryption is done via **XORing the plaintext and the keystream**.
- Pros: highly efficient, simple implementation in hardware, easy to handle messages of arbitrary length,...
- Cons:
  - cannot use the same key or keystream to encrypt different plaintexts, otherwise correlations in plaintexts can be easily spotted in corresponding ciphertexts.
  - vulnerable to bit-flipping attacks, thus message integrity validation is often needed (will talk about this soon).

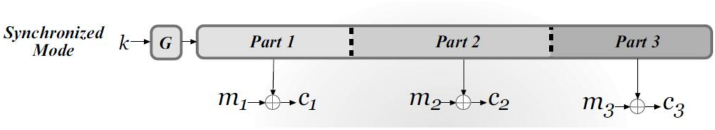


Basic WEP encryption: RC4 keystream XORed with plaintext

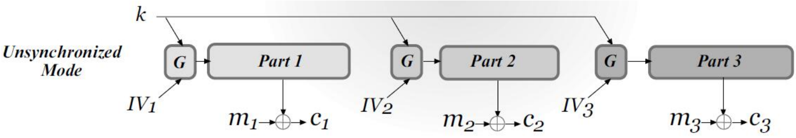
图 2: An example: WEP for WIFI network uses a stream cipher called RC4 to encrypt messages (Pic from wiki)

In practice, we have two "modes of operation" （工作模式） for encrypting with stream ciphers:

- **Synchronized mode**



- **Unsynchronized mode**



An (degree-n) **linear-feedback shift register** (LFSR) can be defined by:

- An array of n 1-bit registers: $s_{n-1}, \ldots, s_0$;
- n feedback coefficients: $c_{n-1}, \ldots, c_0$,

such that
its (current) state is the set of bits contained in all registers;
and the next state after time t is determined as:

$$\begin{aligned} \text{Shift: } s_i^{(t+1)} &:= s_{i+1}^{(t)}, & i = 0, \ldots, n-2 \\ \text{Linear-feedback: } s_{n-1}^{(t+1)} &:= \oplus_{i=0}^{n-1} c_i s_i^{(t)}; \end{aligned}$$

its output is the bit sequence $s_0^{(0)}, s_0^{(1)}, \ldots$.

Example: A degree-4 LFSR

Figure 3 shows a degree-4 LFSR with feedback coefficients equaling 0,1,0,1:

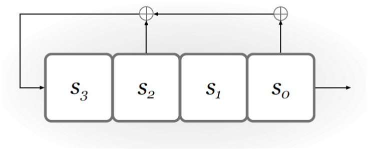


图 3: A degree-4 LFSR with feedback coefficients 0,1,0,1

Given the initial state $(0,0,1,1)$, then next states would be $(1,0,0,1)$, $(1,1,0,0)$, $(1,1,1,0)$, $(1,1,1,1)$, $(0,1,1,1)$, $(0,0,1,1)$, $(1,0,0,1)$, ...
Its output would be: 1, 1, 0, 0, 1, 1, 1, 1, ...

A few security analyses (1)

- **Q**: Can the degree-4 LFSR output an unlimited-length stream of "random bits"?
  A: No, the stream always repeats itself after outputting at most 2^4 bits.

A few security analysis (2)

- **Q**: What about a degree-n LFSR?
  A: Start to generate repeated bits after outputting at most 2^n bits.

A few security analysis (3)

- **Q**: When n is large, say $n = 128$, is the degree-n LFSR secure for cryptographic usage?
  A: No, even if we know how to make it a maximal-length LFSR of degree n, i.e. the LFSR that cycles through all 2^n states before generating repeated bits.

Reconstruction attacks on LFSR

- In general, LFSR is not suitable for cryptographic usages.
- Due to its internal linearity, the LFSR is vulnerable to reconstruction attacks: an adversary can reconstruct the entire states of a degree-n LFSR, after observing $2n$ output bits.

A reconstruction attack example

Example: an adversary observes a degree-4 LFSR with the 8 consecutive output bits: $1, 1, 0, 0, 1, 1, 1, 1$.

To reconstruct the LFSR, the adversary needs to know $(s_3^{(0)}, s_2^{(0)}, s_1^{(0)}, s_0^{(0)})$ and (c_3, c_2, c_1, c_0).

- The adversary knows $(s_3^{(0)}, s_2^{(0)}, s_1^{(0)}, s_0^{(0)}) = (0, 0, 1, 1)$.
- The adversary can compute (c_3, c_2, c_1, c_0) by solving 4 linear equations with 4 unknowns:

$$1 = c_3 \cdot 0 \oplus c_2 \cdot 0 \oplus c_1 \cdot 1 \oplus c_0 \cdot 1 \tag{1}$$

$$1 = c_3 \cdot 1 \oplus c_2 \cdot 0 \oplus c_1 \cdot 0 \oplus c_0 \cdot 1 \tag{2}$$

$$1 = c_3 \cdot 1 \oplus c_2 \cdot 1 \oplus c_1 \cdot 0 \oplus c_0 \cdot 0 \tag{3}$$

$$1 = c_3 \cdot 1 \oplus c_2 \cdot 1 \oplus c_1 \cdot 1 \oplus c_0 \cdot 0 \tag{4}$$

Solving (1-4), we know:

$$(c_3, c_2, c_1, c_0) = (0, 1, 0, 1).$$

Adding nonlinearity

- To thwart reconstruction attacks, nonlinearity can be introduced in the **GetBits** function.
- In particular, nonlinearity can be added into 1) the state updating procedure, or 2) bit-generating procedure, or 3) both.
- Examples include RC4, Trivium, and so on.

A **stream cipher** is a pair of deterministic algorithms:

- **Init**: $st_0 := Init(s, [IV])$.
- **GetBits**: $(y_i, st_i) := GetBits(st_{i-1})$ for $i = 1, 2, \ldots$

图 4: The **GenBits** algorithm of the stream cipher is responsible for 1) updating states and 2) generating bit outputs from the current state.

1. Stream Ciphers and Pseudo-random Generators
2. Encrypt with stream ciphers
3. Linear-Feedback Shift Registers
4. Adding Nonlinearity
   - RC4
   - Attacking RC4-based WEP
5. Two Tips on stream cipher usages

RC4 (Rivest Cipher 4 also known ARC4 or ARCFOUR meaning Alleged RC4) is a prominent stream cipher.

- designed by Ron Rivest in 1987.
- efficient for both hardware implementation and software implementation.
- widely used today. e.g. in Wired Equivalent Privacy (WEP) for WIFI networks, and in TLS/SSL protocols.
- Recent researches have shown serious cryptographic weakness (i.e. statistical biases) and it should NO LONGER be used.[4]

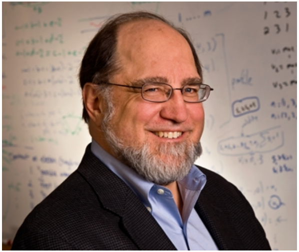


图 5: R. Rivest, co-inventor of the RSA algorithm, Turing award winner (2002), photo downloaded from https://www.soldierx.com/

The Init algorithm of RC4

- Init algorithm outputs a permuted array of $S = (1, 2, \ldots, 255)$.

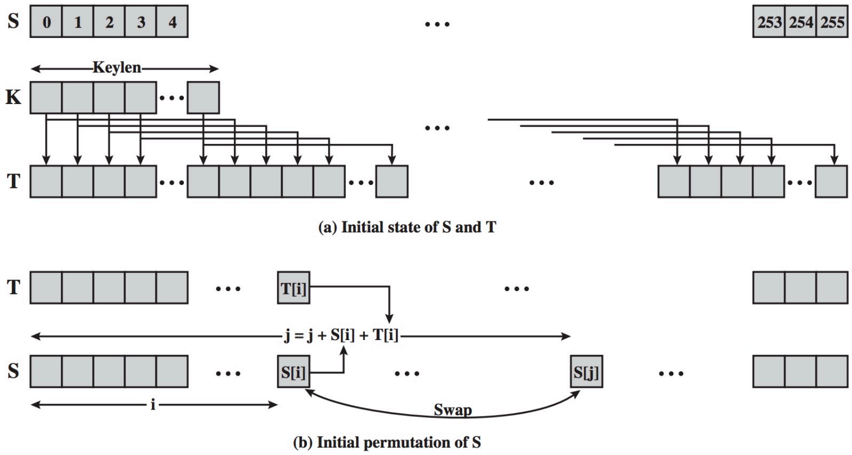


图 6: The Init algorithm of RC4 (pic from W. Stallings "Cryptography and Network Security")

The Init algorithm of RC4

Algorithm 2 Init algorithm for RC4 (All addition is done modulo 256)

Input: 16-byte key k

Output: Initial state (S, i, j)

for $i = 0$ to 255:

for $S[i] := i$

for $T[i] := k[i \bmod 16]$

$j := 0$

for $i = 0$ to 255:

for j:=j+S[i]+T[i]

for Swap S[i] and S[j]

$i := 0$, $j := 0$

return (S, i, j)

- At every clock tick, GetBits algorithm outputs an element of the permuted array of $S = (1, 2, \dots, 255)$, and re-permutes the array by swapping two elements in the array.

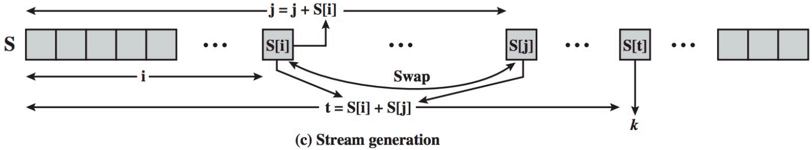


图 7: The GetBits algorithm of RC4 (pic from W. Stallings "Cryptography and Network Security")

The GetBits algorithm of RC4

Algorithm 3 GetBits algorithm for RC4 (All addition is done modulo 256)

Input: Current state (S, i, j)

Output: Output byte y; updated state (S, i, j)

$i := i + 1$

$j := j + S[i]$

Swap $S[i]$ and $S[j]$

$t := S[i] + S[j]$

$y := S[t]$

return $(S, i, j), y$

- **Wired Equivalent Privacy (WEP)** protocol for WIFI networks adopts RC4 for message confidentiality, and CRC-32 for correctness validation.
- Standard 64-bit WEP uses a 40-bit key (10 hexadecimal character $0-9, A-F$) and a 24-bit IV.
- Two WEP users firstly share the same key, and then use different IVs to encrypt different messages to avoid using same keystreams in encryptions.

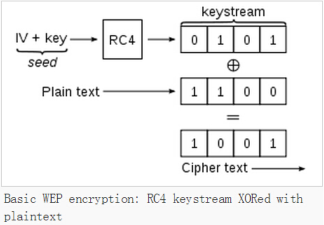


图 8: Pic from WEP on Wikipedia

The short IV flaw of WEP

- There are only 2^{24} possible IVs in total.
- All IVs would be exhausted by a busy access point (e.g. constantly sends 1500-byte packets at 11Mbps) after 5 hrs approximately ($2^{24} * 1500 * 8/(11 * 10^{60}) \approx$ 5 hrs).
- After that, repeated keystreams start to exist.
- Users have been advised to never use WEP (can be broken in minutes).
- Although **Wi-Fi Protected Access (WPA)** uses RC4 in a more secure way, users are now advised to abandon WPA too since RC4 has been shown to be insecure.

WEP, WPA, WPA2, WPA3

- For WIFI security, users are suggested to **WPA2 or WPA3** now.
- WPA2 and WPA3 use the block cipher AES to encrypt, and other security measures.

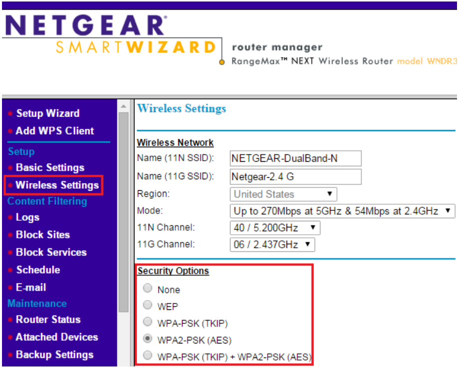


图 9: Security options in a router (pic from `http://kbnetgearrouter.net`)

Tip 1

- **Stop using unsafe stream ciphers.**

RC4	1987	7 W_{P5} [1]	8-2048 usually 40-256	2064	Shamir Initial-Bytes Key-Derivation OR KPA	2^{13} OR 2^{33}
Salsa20	Pre-2004	4.24 (W_{G4}) – 11.84 (W_{P4})	256	512	Probabilistic neutral bits method	2^{251} for 8 rounds (2007)
Scream	2002	4 – 5 (W_{soft})	128 + a 128-bit Nonce	64-bit round function	?	?
SEAL	1997	?	?	?	?	?
SNOW	Pre-2003	?	128 OR 256	?	?	?
SOBER-128	2003	?	up to 128	?	Message Forge	2^{-6}
SOSEMANUK	Pre-2004	?	128	?	?	?
Trivium	Pre-2004	4 (W_{x86}) – 8 (W_{LG})	80	288	Brute force attack (2006)	2^{135}
Turing	2000 – 2003	5.5 (W_{x86})	?	?	?	?
VEST	2005	42 (W_{ASIC}) – 64 (W_{FPGA})	Variable usually 80-256	256 – 800	N/A (2006)	N/A (2006)
WAKE	1993	?	?	8192	CPA & CCA	Vulnerable
Stream Cipher	Creation Date	Speed (cycles per byte)			Attack	
			Effective Key-Length	Internal State	Best Known	Computational Complexity

图 10: Comparison of streaming ciphers (Tbl from https://en.wikipedia.org/wiki/Stream_cipher)

Tip 1

- **Stop using unsafe stream ciphers**.
- a few recommended ones include:
  - Zuc 128/256 stream cipher ("**祖冲之流密码**") by **国家密码局** (2012~now).
  - Enocoro-80/128, Trivium-80 by ISO/IEC 29192 (2012~now).
  - Grain128-AEAD is the stream cipher in NIST's Lightweight Crypto Competition's finalist (still under review, 2021~now).[1]

[1] Read https://billatnapier.medium.com/after-aes-nist-is-defining-the-next-great-standard-for-encryption-light-we if interested.

Tip 2

- In private-key encryptions, for better security, **block ciphers are generally preferable to stream ciphers**