0x1A Great Papers in Computer Security

Vitaly Shmatikov

http://www.cs.utexas.edu/~shmat/courses/cs380s/

Stream Ciphers

- One-time pad:

  Ciphertext(Key,Message)=Message⊕Key

  - Key must be a random bit sequence as long as message
- Idea: replace "random" with "pseudo-random"
  - Use a pseudo-random number generator (PRNG)
  - PRNG takes a short, truly random secret seed and expands it into a long "random-looking" sequence
    - E.g., 128-bit seed into a 10^6-bit pseudo-random sequence

No efficient algorithm can tell this sequence from truly random

- Ciphertext(Key,Msg)=IV, Msg⊕PRNG(IV,Key)
  - Message processed bit by bit (unlike block cipher)

Stream Cipher Terminology

- The seed of pseudo-random generator typically consists of initialization vector (IV) and key
  - The key is a secret known only to the sender and the recipient, not sent with the ciphertext
  - IV is usually sent with the ciphertext
- The pseudo-random bit stream produced by PRNG(IV,key) is referred to as keystream
- Encrypt message by XORing with keystream
  - ciphertext = message $\oplus$ keystream

Properties of Stream Ciphers

- Usually very fast (faster than block ciphers)
  - Used where speed is important: WiFi, DVD, RFID, VoIP
- Unlike one-time pad, stream ciphers do <u>not</u> provide perfect secrecy
  - Only as secure as the underlying PRNG
  - If used properly, can be as secure as block ciphers
- PRNG must be <u>cryptographically secure</u>

Weaknesses of Stream Ciphers

- No integrity
  - Associativity & commutativity: $(X \oplus Y) \oplus Z = (X \oplus Z) \oplus Y$
  - $(M_1 \oplus PRNG(seed)) \oplus M_2 = (M_1 \oplus M_2) \oplus PRNG(seed)$
- Known-plaintext attack is very dangerous if keystream is ever repeated
  - Self-cancellation property of XOR: $X \oplus X = 0$
  - $(M_1 \oplus PRNG(seed)) \oplus (M_2 \oplus PRNG(seed)) = M_1 \oplus M_2$
  - If attacker knows M_1, then easily recovers M_2
    - Most plaintexts contain enough redundancy that knowledge of M_1 or M_2 is not necessary to recover both from $M_1 \oplus M_2$

How Random is “Random?”

Cryptographically Secure PRNG

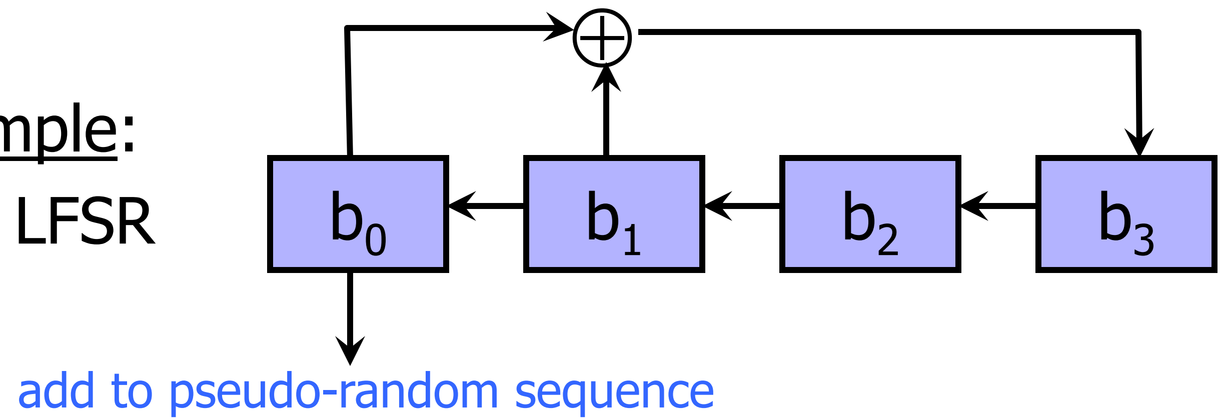
- Next-bit test: given N bits of the pseudo-random sequence, predict $(N+1)^{st}$ bit
  - Probability of correct prediction should be very close to 1/2 for any efficient adversarial algorithm

    (means what?)
- PRNG state compromise
  - Even if attacker learns complete or partial state of the PRNG, he should not be able to reproduce the previously generated sequence
    - … or future sequence, if there'll be future random seed(s)
- Common PRNGs are <u>not</u> cryptographically secure

LFSR: Linear Feedback Shift Register

<u>Example</u>:

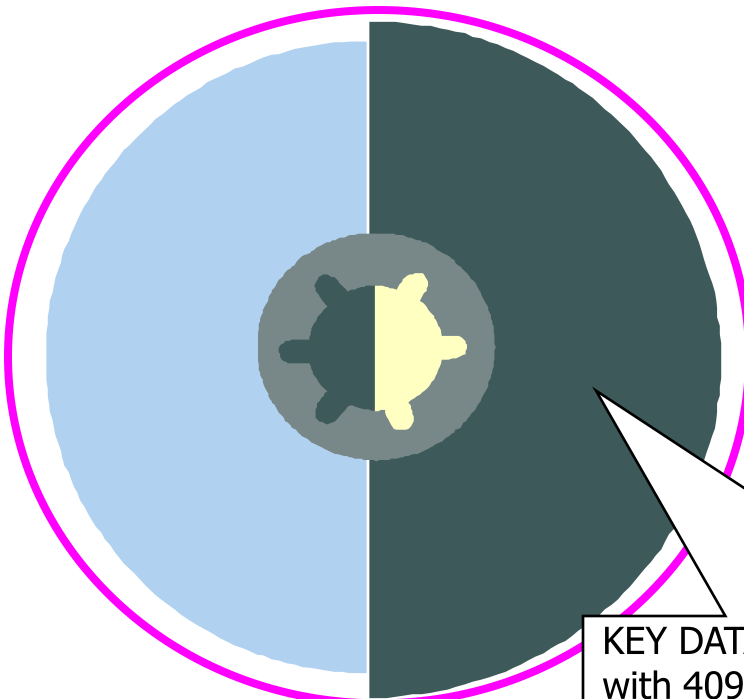
4-bit LFSR

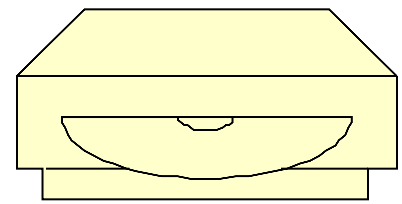


- Key is used as the seed
  - For example, if the seed is 1001, the generated sequence is 1001101011110001001…
- Repeats after 15 bits (2^4-1)

Content Scrambling System (CSS)

- DVD encryption scheme from Matsushita and Toshiba





Each player has its own PLAYER KEY (409 player manufacturers, each has its player key)

KEY DATA BLOCK contains disk key encrypted with 409 different player keys:

- $\text{Encrypt}_{\text{DiskKey}}(\text{DiskKey})$
- $\text{Encrypt}_{\text{PlayerKey1}}(\text{DiskKey})$ … $\text{Encrypt}_{\text{PlayerKey409}}(\text{DiskKey})$

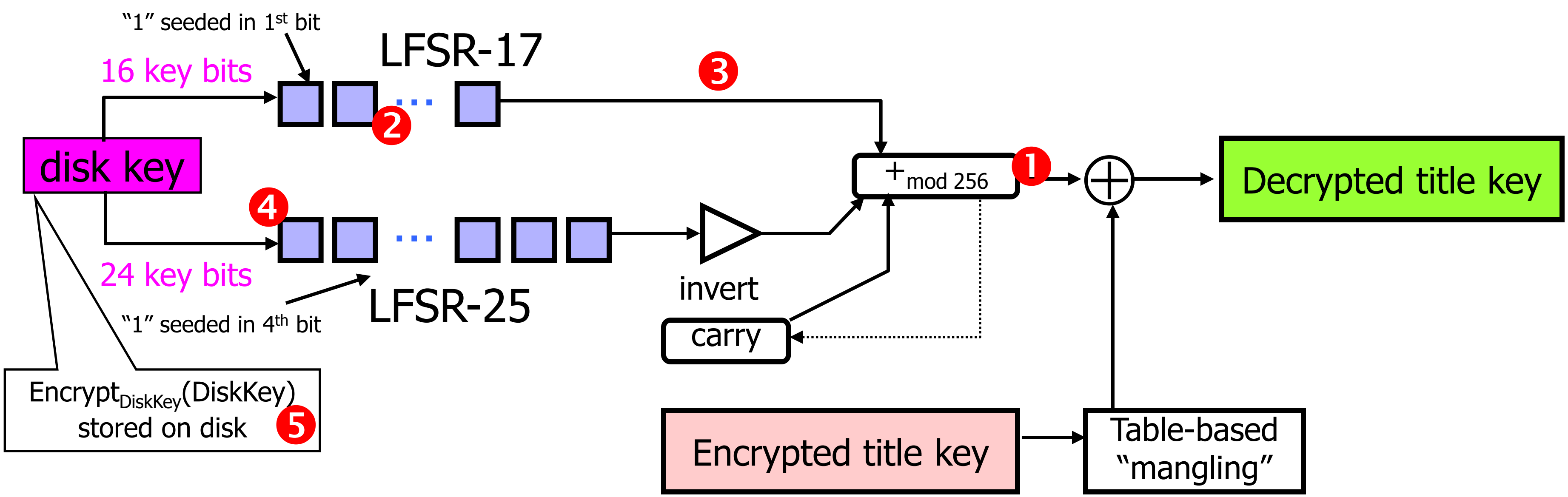
Each DVD is encrypted with a disk-specific 40-bit DISK KEY

This helps attacker verify his guess of disk key

What happens if even a single player key is compromised?

Attack on CSS Decryption Scheme

[Frank Stevenson]



❶ Given known 40-bit plaintext, repeat the following 5 times (once for each plaintext byte): guess the byte output by the sum of the two LFSRs; use known ciphertext to verify – this takes $O(2^8)$

❷ For each guessed output byte, guess 16 bits contained in LFSR-17 – this takes $O(2^{16})$

❸ Clock out 24 bits out of LFSR-17, use subtraction to determine the corresponding output bits of LFSR-25 – this reveals all of LFSR-25 except the highest bit

❹ "Roll back" 24 bits, try both possibilities – this takes $O(2)$

❺ Clock out 16 more bits out of both LFSRs, verify the key

This attack takes $O(2^{25})$

DeCSS

- In CSS, disk key is encrypted under hundreds of different player keys… including Xing, a software DVD player
- Reverse engineering the object code of Xing revealed its decryption key
  - Recall that every CSS disk contains the master disk key encrypted under Xing's key
  - One bad player $\Rightarrow$ entire system is broken!
- Easy-to-use DeCSS software

DeCSS Aftermath

- DVD CCA sued Jon Lech Johansen ("DVD Jon"), one of DeCSS authors - eventually dropped
- Publishing DeCSS code violates copyright
  - Underground distribution as haikus and T-shirts
  - "Court to address DeCSS T-Shirt: When can a T-shirt become a trade secret? When it tells you how to copy a DVD." - From Wired News

RC4

- Designed by Ron Rivest for RSA in 1987
- Simple, fast, widely used
  - SSL/TLS for Web security, WEP for wireless

```
Byte array S[256] contains a permutation of numbers from 0 to 255
i = j := 0
loop
    i := (i+1) mod 256
    j := (j+S[i]) mod 256
    swap(S[i],S[j])
    output (S[i]+S[j]) mod 256
end loop
```

RC4 Initialization

```
Divide key K into L bytes
for i = 0 to 255 do
    S[i] := i
j := 0
for i = 0 to 255 do
        j := (j+S[i]+K[i mod L]) mod 256
        swap(S[i],S[j])
```

Key can be any length up to 2048 bits

Generate initial permutation from key K

- To use RC4, usually prepend initialization vector (IV) to the key
  - IV can be random or a counter
- RC4 is not random enough… First byte of generated sequence depends only on 3 cells of state array S - this can be used to extract the key!
  - To use RC4 securely, RSA suggests discarding first 256 bytes

Fluhrer-Mantin-Shamir attack

N. Borisov, I. Goldberg, D. Wagner

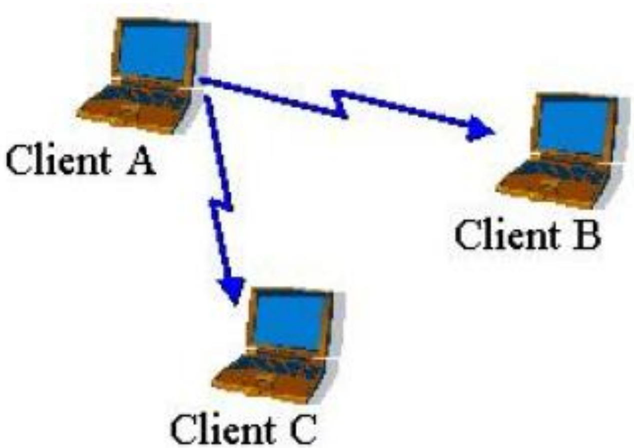
Intercepting Mobile Communications: The Insecurity of 802.11

(MOBICOM 2001)

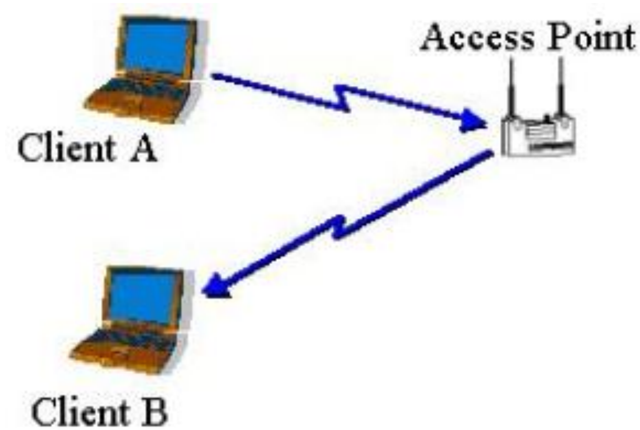


802.11b Overview

- Standard for wireless networks (IEEE 1999)
- Two modes: infrastructure and ad hoc



IBSS (ad hoc) mode



BSS (infrastructure) mode

Access Point SSID

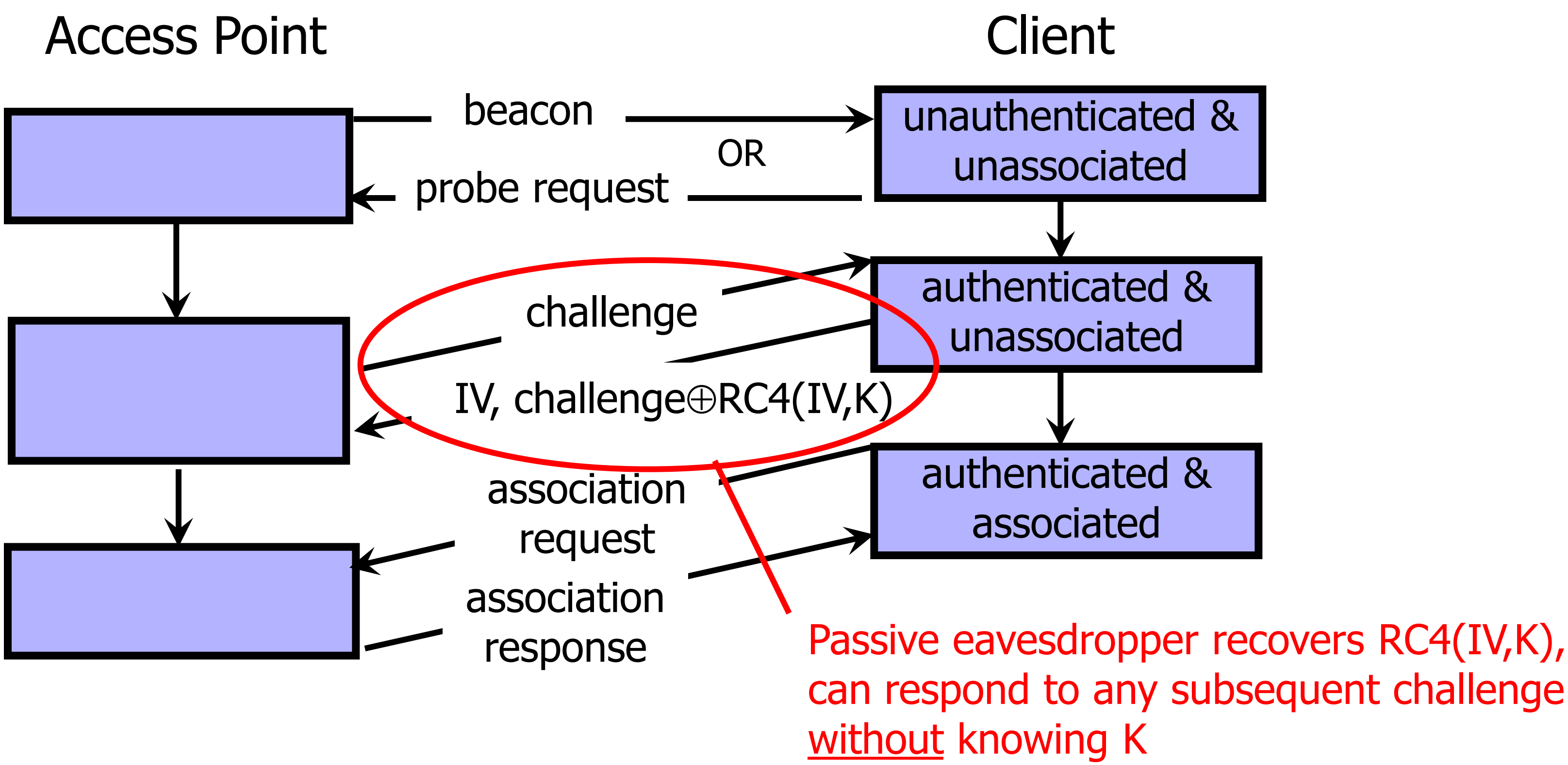
- Service Set Identifier (SSID) is the “name” of the access point
  - By default, access point broadcasts its SSID in plaintext “beacon frames” every few seconds
- Default SSIDs are easily guessable
  - Manufacturer’s defaults: “linksys”, “tsunami”, etc.
  - This gives away the fact that access point is active
- Access point settings can be changed to prevent it from announcing its presence in beacon frames and from using an easily guessable SSID
  - But then every user must know SSID in advance

WEP: Wired Equivalent Privacy

- Special-purpose protocol for 802.11b
  - Intended to make wireless as secure as wired network
- Goals: confidentiality, integrity, authentication
- Assumes that a secret key is shared between access point and client
- Uses RC4 stream cipher seeded with 24-bit initialization vector and 40-bit key
  - Terrible design choice for wireless environment

Shared-Key Authentication

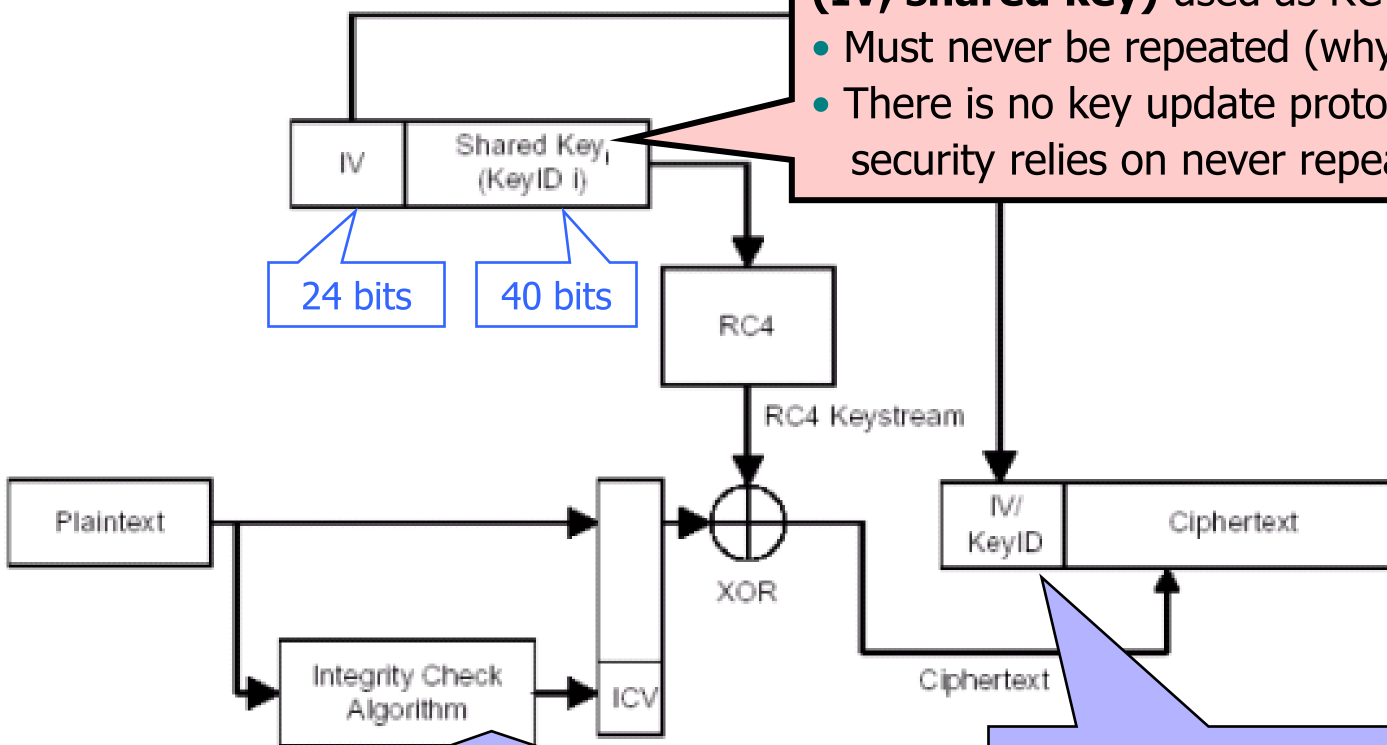
Prior to communicating data, access point may require client to authenticate



How WEP Works

(IV, shared key) used as RC4 seed

- Must never be repeated (why?)
- There is no key update protocol, so security relies on never repeating IV



IV sent in the clear

Worse: changing IV with each packet is optional!

CRC-32 checksum is linear in ⊕:

if attacker flips some plaintext bits, he knows which bits of CRC to flip to produce the same checksum

no integrity!

RC4 Is a Bad Choice for Wireless

- Stream ciphers require synchronization of key streams on both ends of connection
  - This is not suitable when packet losses are common
- WEP solution: a separate seed for each packet
  - Can decrypt a packet even if a previous packet was lost
- But number of possible seeds is not large enough!
  - RC4 seed = 24-bit initialization vector + fixed key
  - Assuming 1500-byte packets at 11 Mbps, 2^{24} possible IVs will be exhausted in about 5 hours
- Seed reuse is deadly for stream ciphers

Recovering Keystream

- Get access point to encrypt a known plaintext
  - Send spam, access point will encrypt and forward it
  - Get victim to send an email with known content
- If attacker knows plaintext, it is easy to recover keystream from ciphertext
  - $C \oplus M = (M \oplus RC4(IV,key)) \oplus M = RC4(IV,key)$
  - Not a problem if this keystream is <u>not</u> re-used
- Even if attacker doesn't know plaintext, can exploit regularities (plaintexts are not random)
  - For example, IP packet structure is very regular

Keystream Will Be Re-Used

- In WEP, repeated IV means repeated keystream
- Busy network will repeat IVs often
  - Many cards reset IV to 0 when re-booted, then increment by 1 $\Rightarrow$ expect re-use of low-value IVs
  - If IVs are chosen randomly, expect repetition in $O(2^{12})$ due to birthday paradox
- Recover keystream for each IV, store in a table
  - $(\text{KnownM} \oplus \text{RC4(IV,key)}) \oplus \text{KnownM} = \text{RC4(IV,key)}$
- Wait for IV to repeat, decrypt and enjoy plaintext
  - $(M' \oplus \text{RC4(IV,key)}) \oplus \text{RC4(IV,key)} = M'$

It Gets Worse

- Misuse of RC4 in WEP is a design flaw with no fix
  - Longer keys do not help!
    - The problem is re-use of IVs, their size is fixed (24 bits)
  - Attacks are passive and very difficult to detect
- Perfect target for the Fluhrer et al. attack on RC4
  - Attack requires known IVs of a special form
  - WEP sends IVs in plaintext
  - Generating IVs as counters or random numbers will produce enough "special" IVs in a matter of hours
- This results in key recovery (not just keystream)
  - Can decrypt even ciphertexts whose IV is unique

Fixing the Problem

- Extensible Authentication Protocol (EAP)
  - Developers can choose their own authentication method
    - Passwords (Cisco EAP-LEAP), public-key certificates (Microsoft EAP-TLS), passwords OR certificates (PEAP), etc.
- 802.11i standard fixes 802.11b problems
  - Patch (TKIP): still RC4, but encrypts IVs and establishes new shared keys for every 10 KBytes transmitted
    - No keystream re-use, prevents exploitation of RC4 weaknesses
    - Use same network card, only upgrade firmware
  - Long-term: AES in CCMP mode, 128-bit keys, 48-bit IVs
    - Block cipher (in special mode) instead of stream cipher
    - Requires new network card hardware

Hacking MIFARE Chips

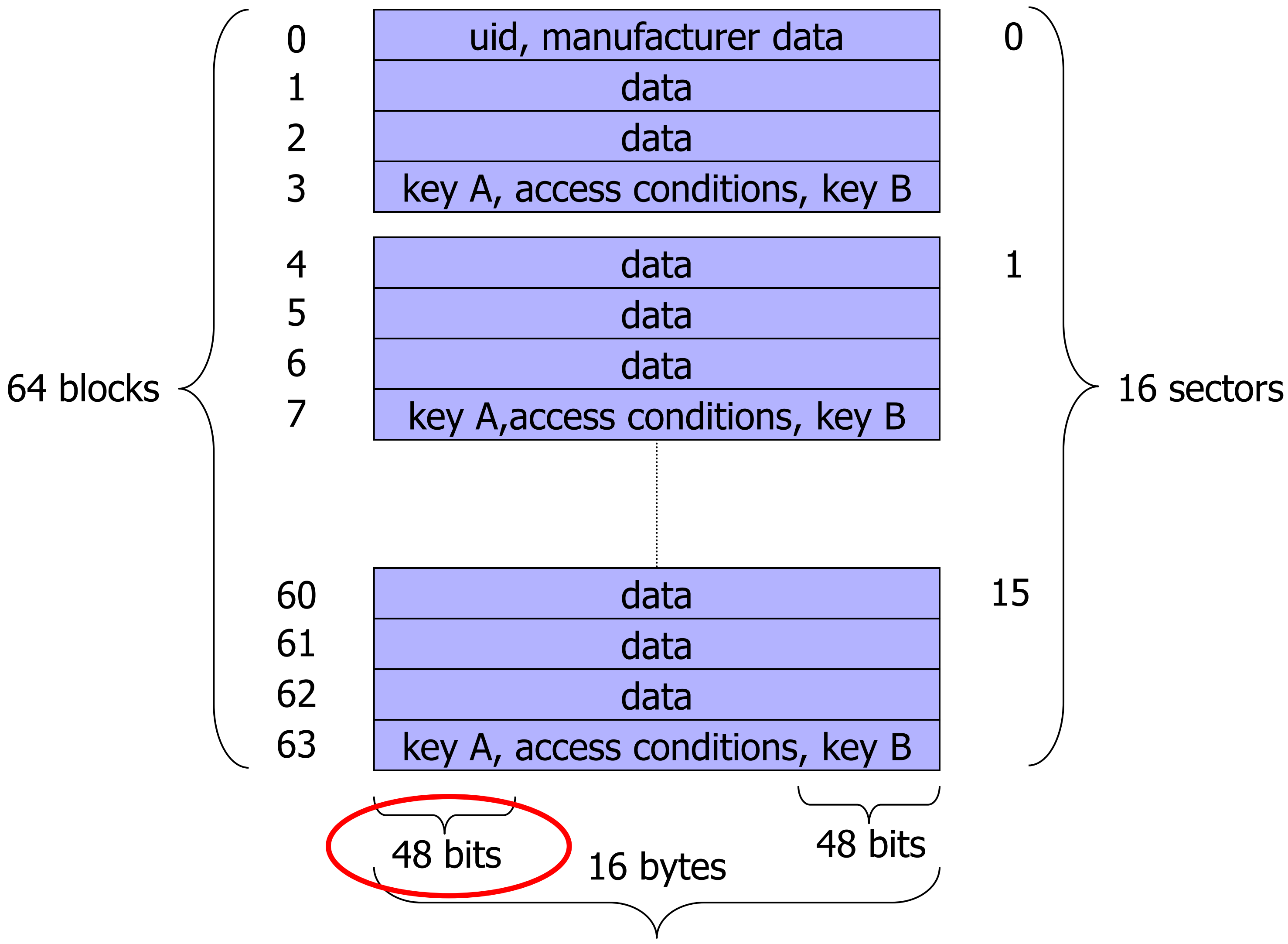
- Multi-year project on evaluating security of MIFARE cards at Radboud University in Holland
  - http://www.ru.nl/ds/research/rfid/
- MIFARE = case study in how not to design cryptographic authentication systems
- The following slides are from Peter Van Rossum

MIFARE Chips

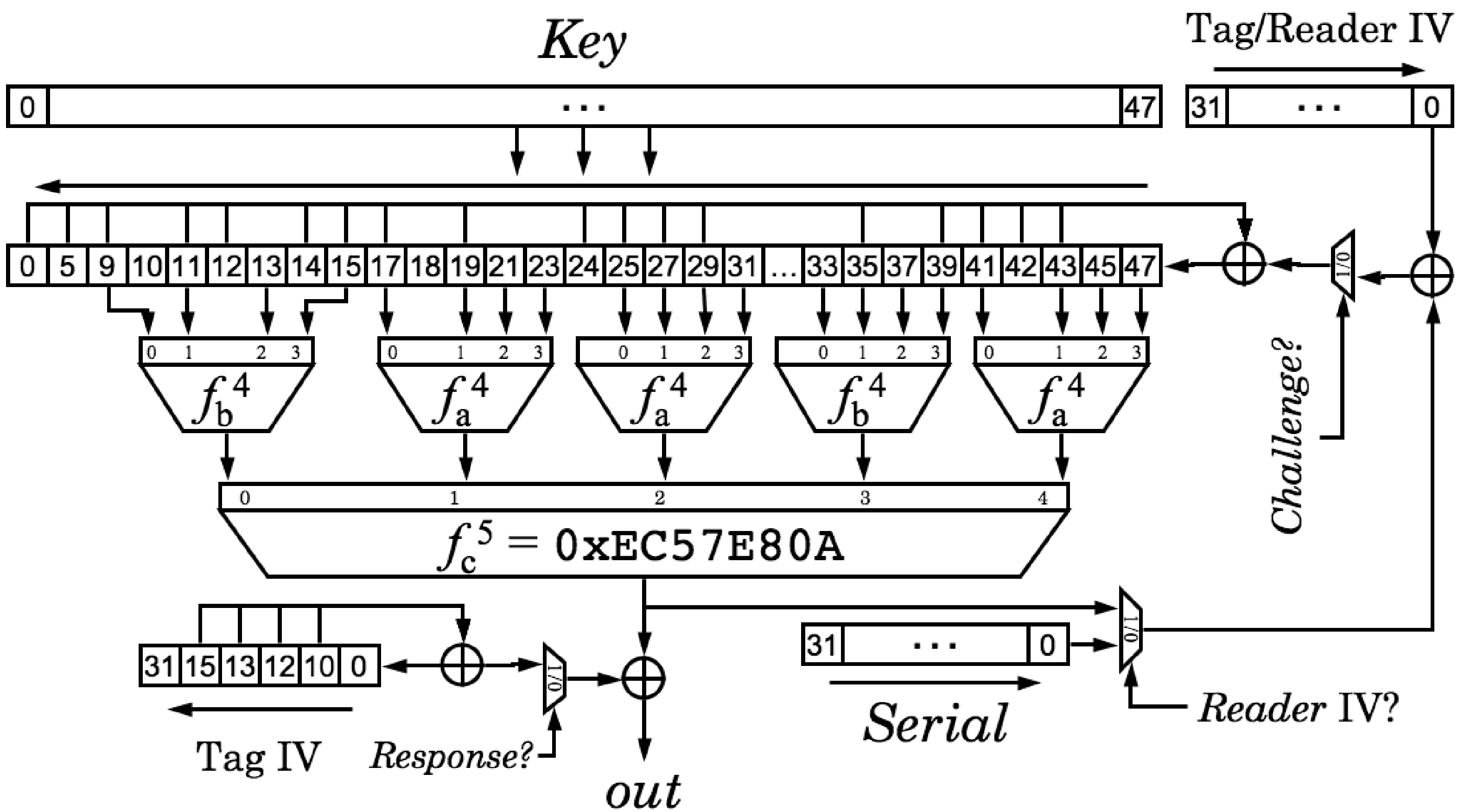
- Series of chips used in contactless smart cards
  - Developed by NXP Semiconductors in the Netherlands
- Very common in transport payment cards

- MIFARE Classic: 80% of the market
  - Over 1 billion sold, over 200 million in use

Memory Structure of the Card



Crypto1 Cipher

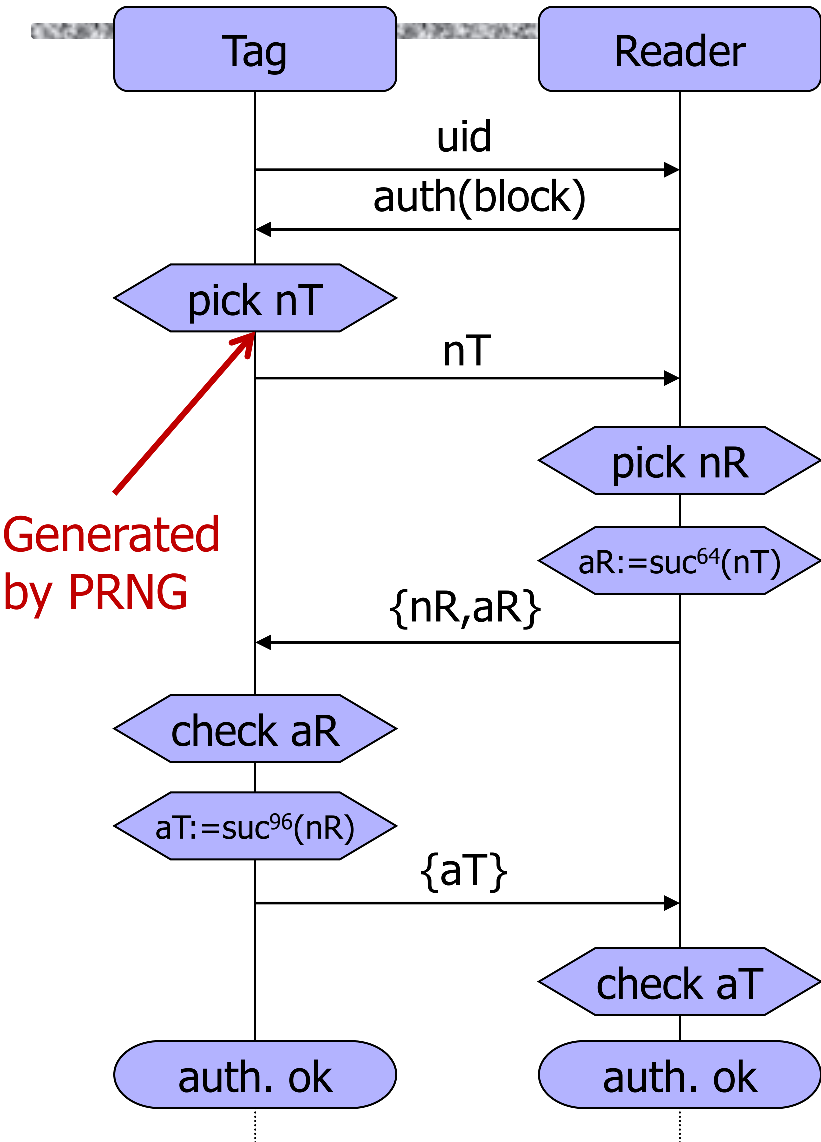


f_a^4 = 0x9E98 = (a+b)(c+1)(a+d)+(b+1)c+a

f_b^4 = 0xB48E = (a+c)(a+b+d)+(a+b)cd+b

Tag IV ⊕ Serial is loaded first, then Reader IV ⊕ NFSR

Challenge-Response in CRYPTO1



LFSR stream:

Initial state of the LFSR is the key

$a_i := k_i$ $\quad i \in [0,47]$

Shift nT + uid into the LFSR

$a_{i+48} := L(a_i,\ldots,a_{i+47}) + nT_i + uid_i$ $\quad i \in [0,31]$

Shift nR into the LFSR

$a_{i+48} := L(a_i,\ldots,a_{i+47}) + nR_{i-32}$ $\quad i \in [32,63]$

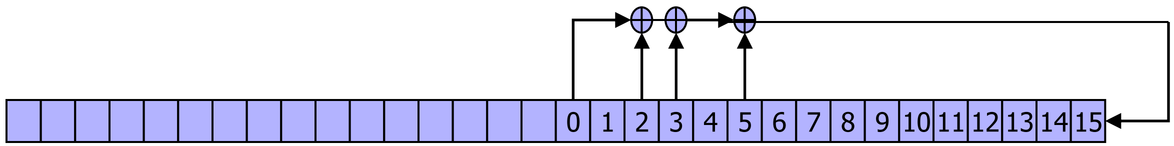
After authentication, LFSR keeps shifting

$a_{i+48} := L(a_i,\ldots,a_{i+47})$ $\quad i \in [64, \infty)$

Keystream:

$b_i := f(a_{i+9},a_{i+11},\ldots,a_{i+47})$ $\quad i \in [32, \infty)$

PRNG in CRYPTO1



- 32-bit nonces
- Linear feedback shift register
- 16-bit internal state
- Period $2^{16} - 1 = 65535$

Feedback:

$L_{16}(x_0,x_1,\ldots,x_{15}) := x_0+x_2+x_3+x_5$

Successor:

$suc(x_0,x_1,\ldots,x_{31}) := (x_1,x_2,\ldots,x_{30},L_{16}(x_{16},x_{17},\ldots,x_{31}))$

Replay Attack

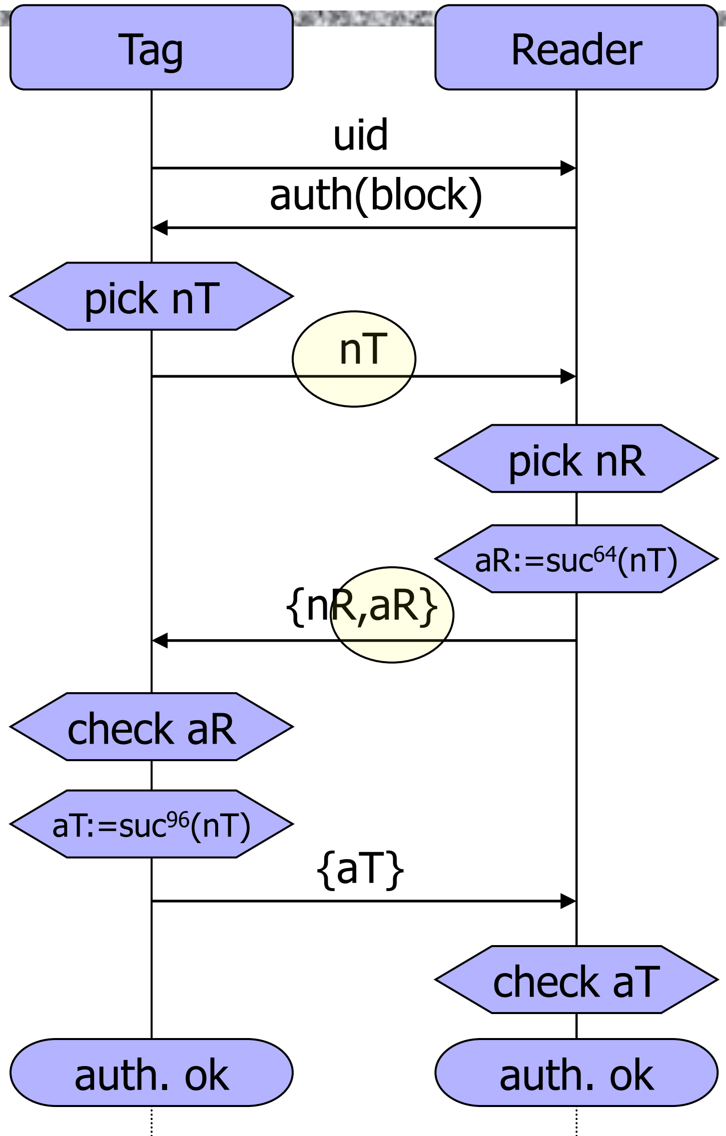
[Gans, Hoepman, Garcia]

- Good challenge-response authentication requires some form of "freshness" in each session
  - For example, timestamp or strong (pseudo)randomness
- MIFARE Classic: no clock + weak randomness
  - "Random" challenges repeat a few times per hour
- Eavesdrop and record communication session
- When challenge repeats, send known plaintext, extract keystream, use it to decrypt recorded communication that used the same challenge

Extracting the Key (Reader Only)

1. Acquire keystream
   - Observe authentication → keystream
   - 1 to 3 authentication sessions – takes microseconds
2. Invert the filter function
   - Keystream → internal state of LFSR
   - Approx. 2^{26} operations – take seconds
3. Roll back (“unshift”) the LFSR
   - Problem: bad PRNG design
   - Internal state of LFSR at any time → seed (key)
     – Cryptographically secure PRNG should not allow rollback and recovery of the seed even if state is compromised

Acquiring Keystream



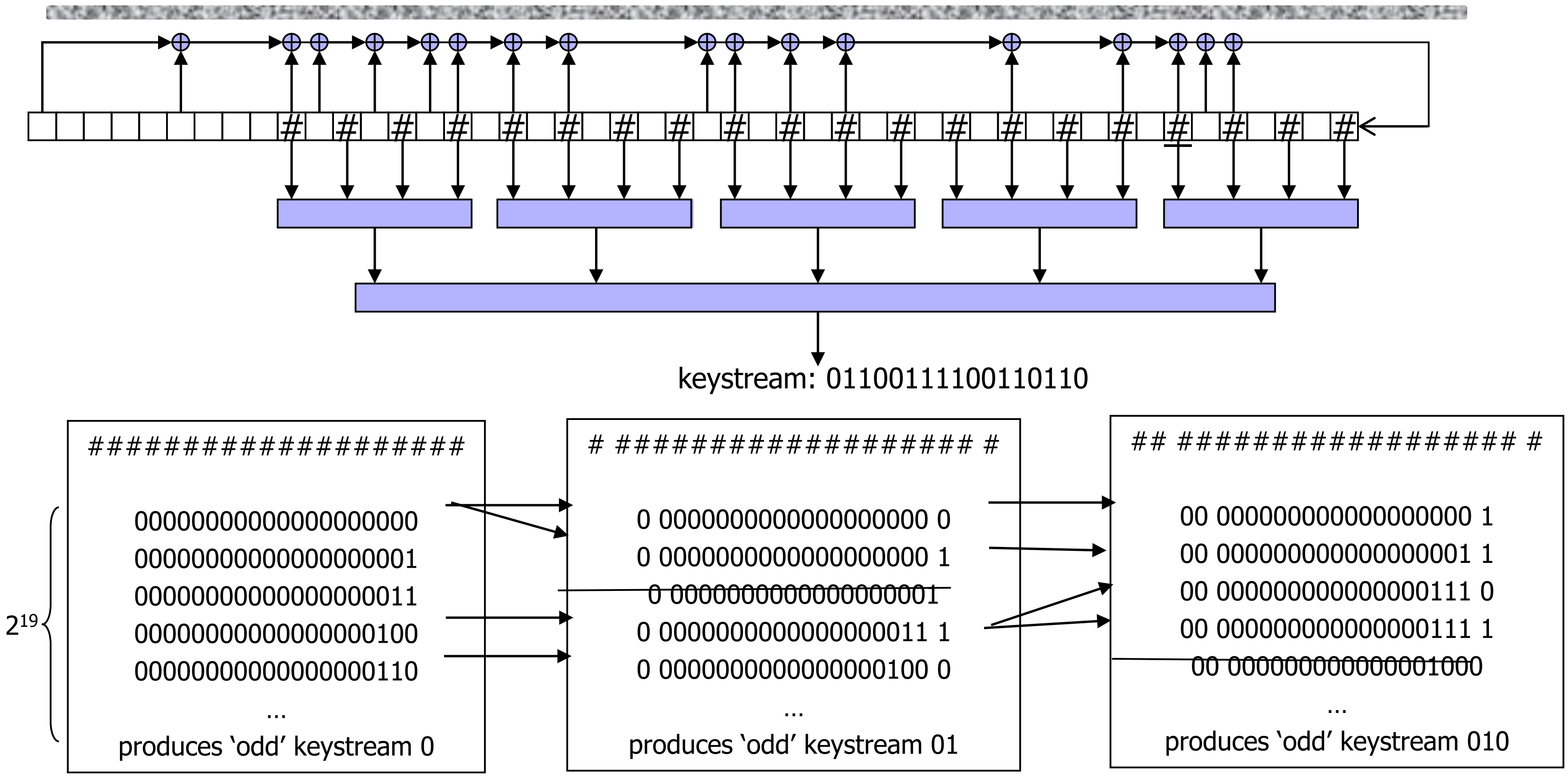
Intercepted communication:

- nT, {aR}, {aT} visible to attacker
- {aR} = suc^{64}(nT), {aT} = suc^{96}(nT)
- 64 keystream bits

Access to reader only:

- nT under attacker control
- {aR} = suc^{64}(nT) visible to attacker
- 32 keystream bits

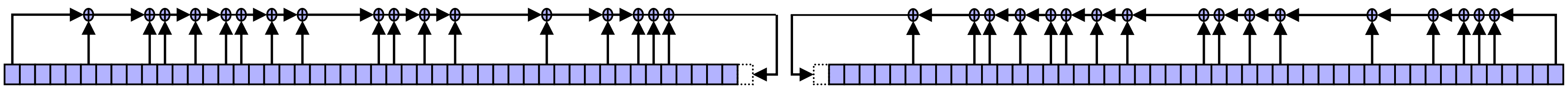
Inverting the Filter Function



Filter function only depends only on 20 odd bits of input → easily inverted

- Compute 'odd' bits of LFSR using table and deduce 'even' bits (linear relation) OR
- Compute 'odd' and 'even' bits of LFSR using tables separately and combine tables

Rolling Back the LFSR



Feedback:

$L(x_0,x_1,\ldots,x_{47}) := x_0+x_5+x_9+x_{10}+x_{12}+x_{14}$
$+x_{15}+x_{17}+x_{19}+x_{24}+x_{25}+x_{27}+x_{29}+x_{35}+x_{39}$
$+x_{41}+x_{43}$

LFSR stream:

Initial state of the LFSR is the key
$a_i := k_i \qquad i \in [0,47]$
Shift nT + uid into the LFSR
$a_{i+48} := L(a_i,\ldots,a_{i+47}) + nT_i + uid_i \quad i \in [0,31]$
Shift nR into the LFSR
$a_{i+48} := L(a_i,\ldots,a_{i+47}) + nR_{i-32} \qquad i \in [32,63]$
After authentication, LFSR keeps shifting
$a_{i+48} := L(a_i,\ldots,a_{i+47}) \qquad i \in [64, \infty)$

Keystream:

$b_i := f(a_{i+9},a_{i+11},\ldots,a_{i+47}) \qquad i \in \mathbb{N}$

Inverting feedback:

$R(x_1,\ldots,x_{47},x_{48}) := x_5+x_9+x_{10}+x_{12}+x_{14}$
$+x_{15}+x_{17}+x_{19}+x_{24}+x_{25}+x_{27}+x_{29}+x_{35}+x_{39}$
$+x_{41}+x_{43}+x_{48}$
$R(x_1,\ldots,x_{47},L(x_0,x_1,\ldots,x_{47})) = x_0$

Inverting LFSR stream:

Unshift LFSR until end of authentication
$a_i = R(a_{i+1},\ldots,a_{i+48}) \qquad i \in [64, \infty)$
Unshift nR from the LFSR
$a_i = R(a_{i+1},\ldots,a_{i+48}) + nR_{i-32} \qquad i \in [32,63]$
$= R(a_{i+1},\ldots,a_{i+48}) + \{nR\}_{i-32} + b_i$
$= R(a_{i+1},\ldots,a_{i+48}) + \{nR\}_{i-32} + f(a_{i+9},\ldots,a_{i+47})$
Unshift nT + uid from the LFSR
$a_i = R(a_{i+1},\ldots,a_{i+48}) + nT_i + uid_i \quad i \in [0,31]$
Key is the initial state of the LFSR
$k_i = a_i \qquad i \in [0,47]$

Summary: Weaknesses of CRYPTO1

- Stream cipher with 48-bit internal state
  - Enables brute-force attack
- Weak 16-bit random number generator
  - Enables chosen-plaintext attack and replay attack
- Authentication protocol leaks keystream
- Weak "one-way" filter function is easy to invert + simple LFSR structure
  - Enables "rolling back" the internal state to recover key
  - 64-bit keystream → recover unique key
  - 32-bit keystream → 216 candidate keys

Extracting the Key (Card Only)

- Parity bit of plaintext is encrypted with the same bit of the keystream as the next bit of plaintext
  - "One-time" pad is used twice
- If parity bit is wrong, encrypted error message is sent before authentication
  - Opens the door to card-only guessing attacks (chosen-plaintext, chosen-ciphertext) – why?
  - Wireless-only attack
- Recover secret key from the card in seconds
  - Result: full cloning