Hacking the NFC cards for fun and honor degrees

Ricardo J. Rodríguez

All wrongs reversed

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$whoami

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Not giving any new 0-day or vulnerability, just recalling the state-of-the-art

Outline

Outline

Near Field Communication: What is it? (I)

Near Field Communication (NFC)

- Standard to establish radio communication between devices
  - By touching or bringing them into close proximity
- Builds upon RFID
  - Radio-Frequency ID: identify and track (things/animals/people) using radio waves
  - Works at 13.56MHz band on ISO/IEC 18000-3 (no license needed)
- Distance needed: $\leq$ 10cm (theoretically $\leq$ 20)
- Rates: $106 - 424$ kbit/s
- Two main actors
  - Initiator: generates a RF field
  - Target
- Two working modes
  - Passive: initiator device provides a carrier field. Target is a transponder
  - Active: initiator + target generate their own fields

Near Field Communication: What is it? (II)

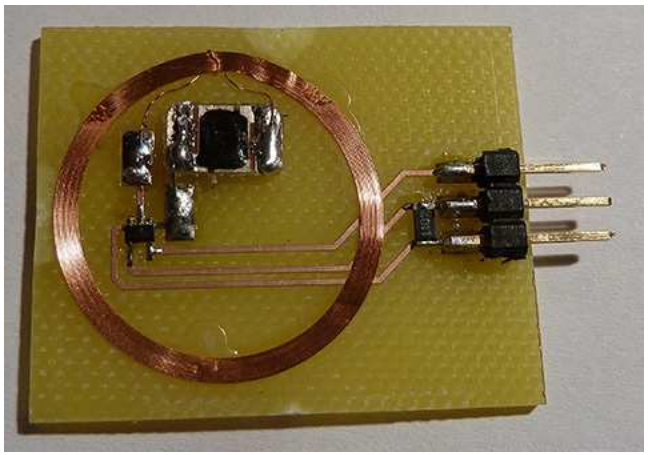
"Big" actors

NFC Forum

- Non-profit industry association
- Formed on March 18, 2004
- Founders: NXP Semiconductors (formerly Philips Semiconductors), Sony and Nokia
- Promotes implementation and standardisation of NFC
- 190 member companies (June 2013). Some located at Spain:
  - Applus
  - AT4 Wireless

Near Field Communication: What is it? (III)

Real actors (1)

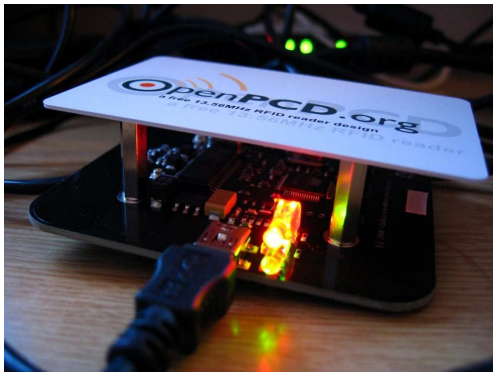


PICC

- Proximity Integrated Circuit Card
- Commonly named as *tag*
- Passive or active (depends on power supply)
  - Widely used (cheaper): passive ones
- It contains:
  - Internal capacitor
    - Stores the energy coming from the reader
  - Resistor

Near Field Communication: What is it? (III)

Real actors (2)

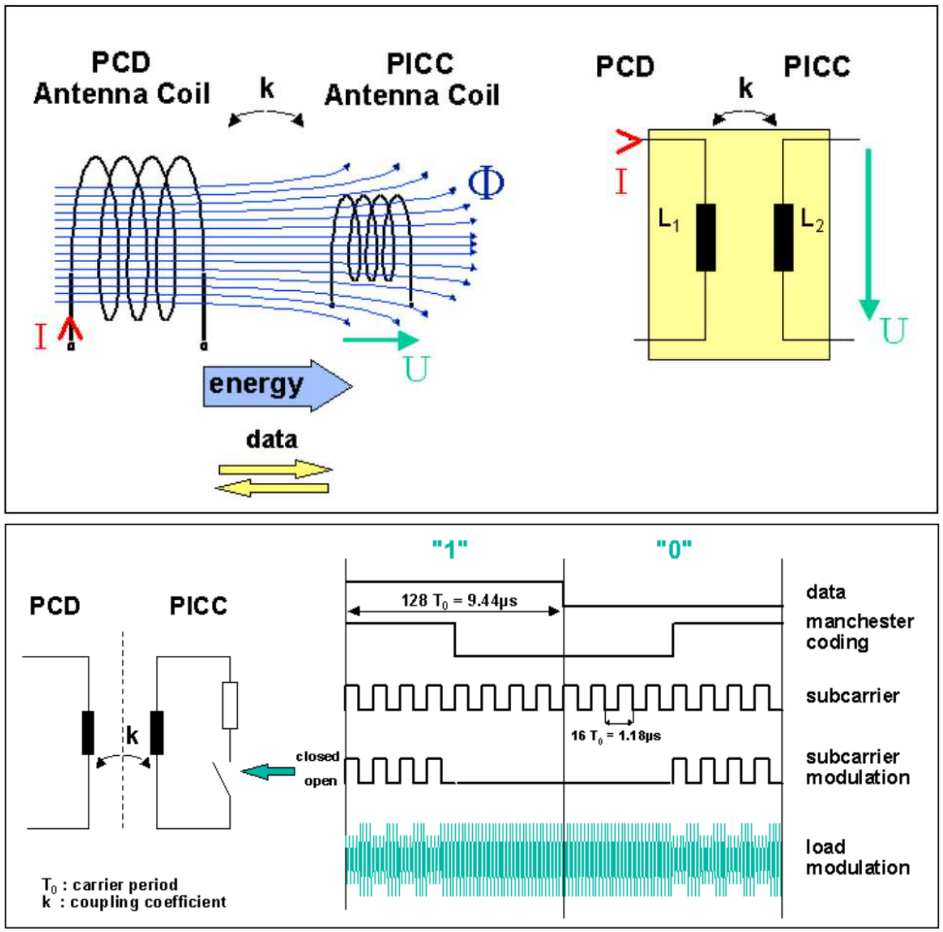


PCD

- Proximity Coupling Device
- Commonly named as *reader/writer*
- Active (forced)
- Contains the antenna
  - Communication at the 13.56MHz ($\pm$7kHz) frequency
  - Electronic field

Near Field Communication: What is it? (IV)

An interesting reading on this topic...



[Taken from 13.56 MHz RFID Proximity Antennas (`http://www.nxp.com/documents/application_note/AN78010.pdf`)]

Near Field Communication: Where is it used? (V)

Outline

MIFARE Classic (I): What is it?

MIFARE product family

- Introduced in 1995 by NXP
- "Advanced technology for RFID identification"
- Based on ISO/IEC 14443 Type A 13.56 MHz standard
- Several products:
  - Ultralight
  - Classic
  - DESFire
  - SmartMX

MIFARE Classic (I): What is it?

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- Introduced in 1995 by NXP
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- Based on ISO/IEC 14443 Type A 13.56 MHz standard
- Several products:
  - Ultralight
  - Classic
  - DESFire
  - SmartMX
- 50M reader and 5B card components sold
- $\sim$ 80% contactless ticketing credentials (according to ABI Research)

MIFARE Classic (II): Some of its common uses

Some systems using MIFARE Classic

- Access Controls
  - University of Zaragoza
  - Personal entrance Schiphol Airport (AMS)
  - Dutch military bases
  - Hotel room keys
  - Many office and official buildings
- Ticketing events
- Public transport systems
  - OV-Chipkaart (NL)
  - Oyster card (London, UK)
  - Smartrider (AU)
  - EMT (Málaga, Spain)
  - Wikipedia: `http://en.wikipedia.org/wiki/MIFARE`

MIFARE Classic (III): Internal Structure (1)

Logical Structure

- EEPROM memory
- Basic unit: 16B block
- A sector is a set of blocks
- Two size variants:
  - 1KB (16 sectors, 4 blocks each)
  - 4KB (40 sectors, first 32 sectors are 4-block, the rest 16-block)

MIFARE Classic (III): Internal Structure (1)

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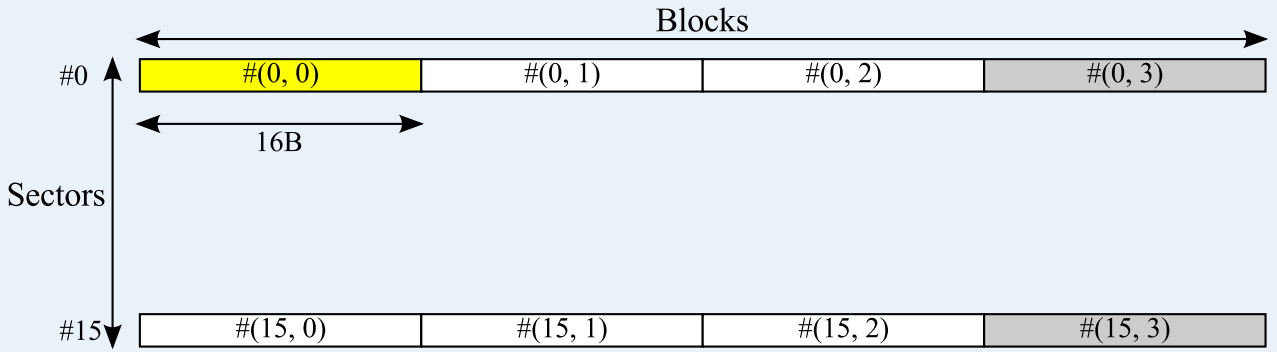
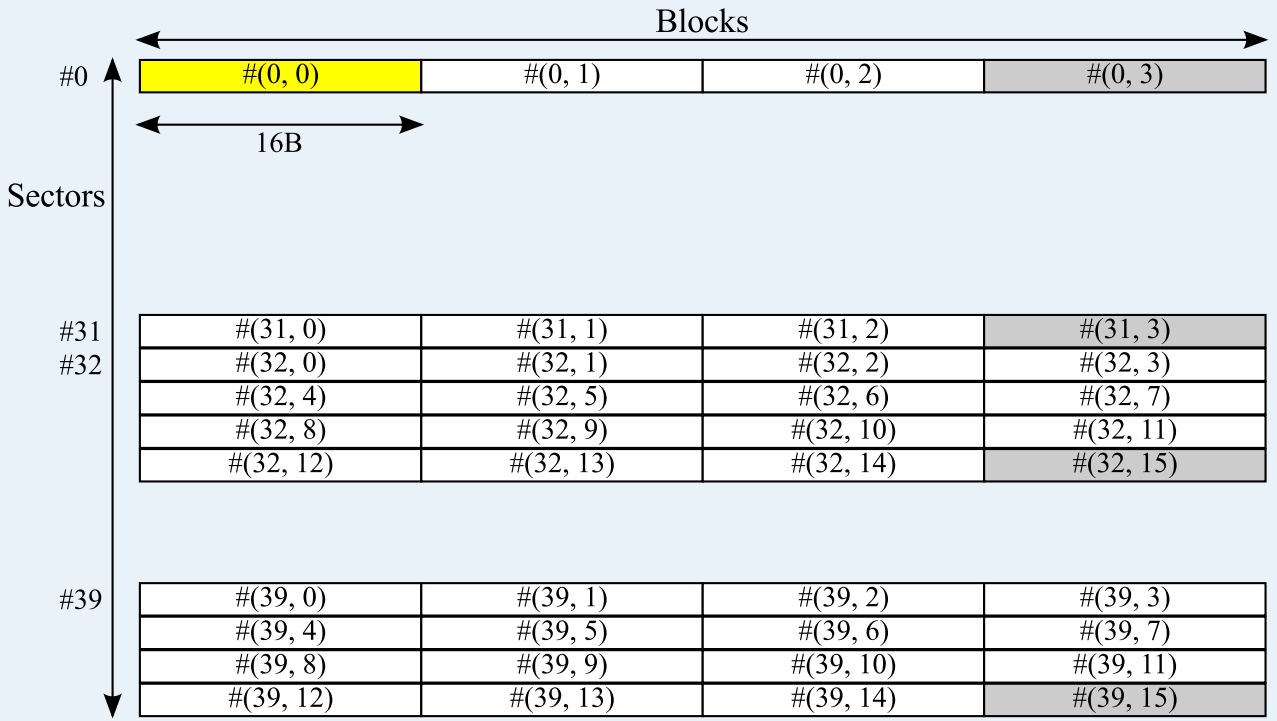
Let me show you this graphically...

MIFARE Classic (III): Internal Structure(2)





MIFARE Classic (III): Internal Structure (3)

Manufacturer block

- Sector 0, block 0 (yellow one in previous slide)
- Contains:
  - UID (4B)
  - BCC (bit count check, 1B): XOR-ing of UID bytes
  - Manufacturer data (11B)
- Set and locked by manufacturer → read only!

MIFARE Classic (III): Internal Structure (3)

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- Sector 0, block 0 (yellow one in previous slide)
- Contains:
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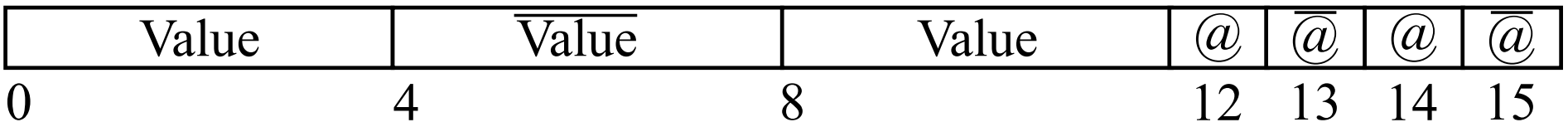
  - BCC (bit count check, 1B): XOR-ing of UID bytes
  - Manufacturer data (11B)
- Set and locked by manufacturer → read only!
  - Not the case for some Chinese cards ☺

MIFARE Classic (III): Internal Structure (4)

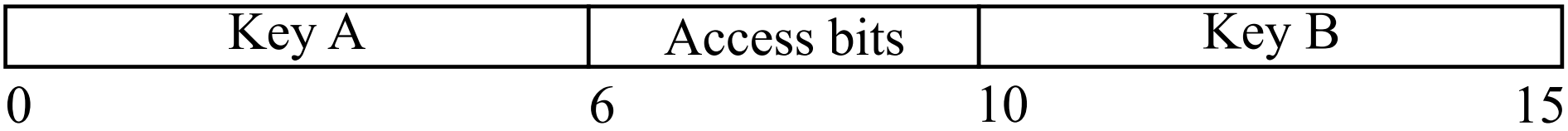
Storing data...

Storing data into blocks

- Read/write block
  - You can store data as you want, no matter how
- Data block
  - Predefined format (look below!)
  - Don't worry: APIs will help you!
    - Only need a *value*, it puts all the values properly on its own...)
  - Contains:
    - Value (twice)
    - Value negated (once)
    - 1-byte address (twice)
    - 1-byte address negated (twice)



MIFARE Classic (III): Internal Structure (5)



Sector trailer

- Last one in each sector (grey ones in previous slide)
- Contains:
  - Key A
  - Access Bits
  - Key B
- Authentication per sector before any operation is allowed
- Access bits define how is the auth. required and what operations are allowed
- Having fun with access bits may provoke a useless tag!
- Keys are set to `FFFFFFFFFFFFh` at delivery

MIFARE Classic (III): Internal Structure (6)

Operations

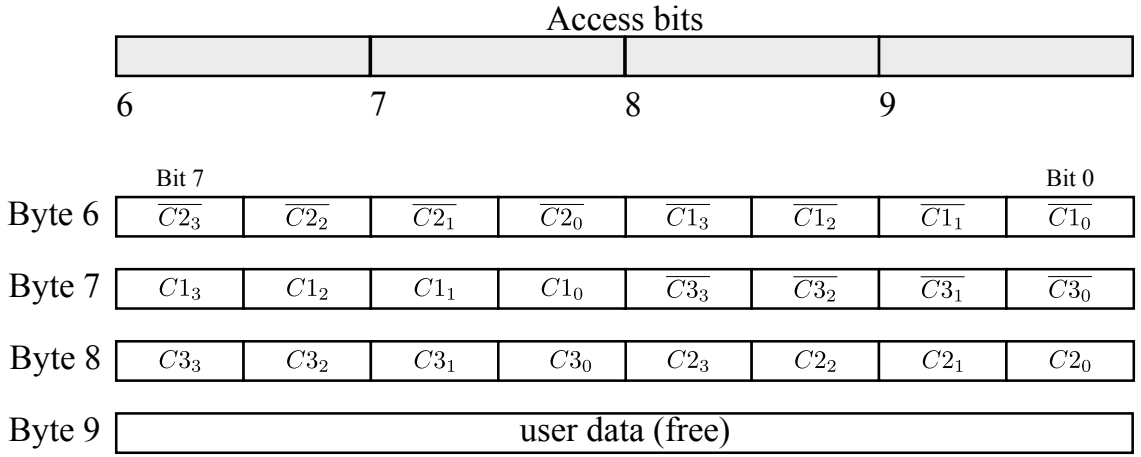
Operation	**Description**	**Valid for...**		
		R/W block	Value block	Sector trailer
Read	Reads a memory block	√	√	√
Write	Writes a memory block	√	√	√
Increment	Reads the value, increments it and stores		√	
Decrement	Reads the value, decrements it and stores		√	
Transfer	Transfers contents of internal register to a block		√	
Restore	Loads contents of a block to internal register		√	

MIFARE Classic (III): Internal Structure (7)

Access Conditions

Access Bits	Valid Commands	Block
$C1_0\,C2_0\,C3_0$	(all operations)	0
$C1_1\,C2_1\,C3_1$	(all operations)	1
$C1_2\,C2_2\,C3_2$	(all operations)	2
$C1_3\,C2_3\,C3_3$	Read, Write	3

- 3 bits defines the access conditions for every data block and sector trailer
- Stored non-negated and negated
- Commands are executed only after a successful authentication



MIFARE Classic (III): Internal Structure (8)

Access Conditions for sector trailer

Access Bits			**Access condition for...**					
			Key A		**Access bits**		**Key B**	
$C1$	$C2$	$C3$	read	write	read	write	read	write
0	0	0	-	key A	key A	-	key A	key A
0	0	1	-	key A	key A	key A	key A	key A
0	1	0	-	-	key A	-	key A	-
0	1	1	-	key B	key A (or B)	key B	-	key B
1	0	0	-	key B	key A (or B)	-	-	key B
1	0	1	-	-	key A (or B)	key B	-	-
1	1	0	-	-	key A (or B)	-	-	-
1	1	1	-	-	key A (or B)	-	-	-

(- means never)

MIFARE Classic (III): Internal Structure (9)

Access Conditions for data blocks

Access Bits			Access condition for...				Application
$C1$	$C2$	$C3$	Read	Write	Increment	Decrement, Transfer, Restore	
0	0	0	key A (or B)†	key A (or B)	key A (or B)	key A (or B)	Transport configuration
0	0	1	key A (or B)†	-	-	key A (or B)	Value block
0	1	0	key A (or B)†	-	-	-	R/W block
0	1	1	key B	key B	-	-	R/W block
1	0	0	key A (or B)	Key B	-	-	R/W block
1	0	1	key B	-	-	-	R/W block
1	1	0	key A (or B)	key B	key B	key A (or B)	Value block
1	1	1	-	-	-	-	R/W block

(- means never)

† if key B can be read in the sector trailer, then it cannot be used for authentication

MIFARE Classic: Communication Protocol (I)

Protocol steps

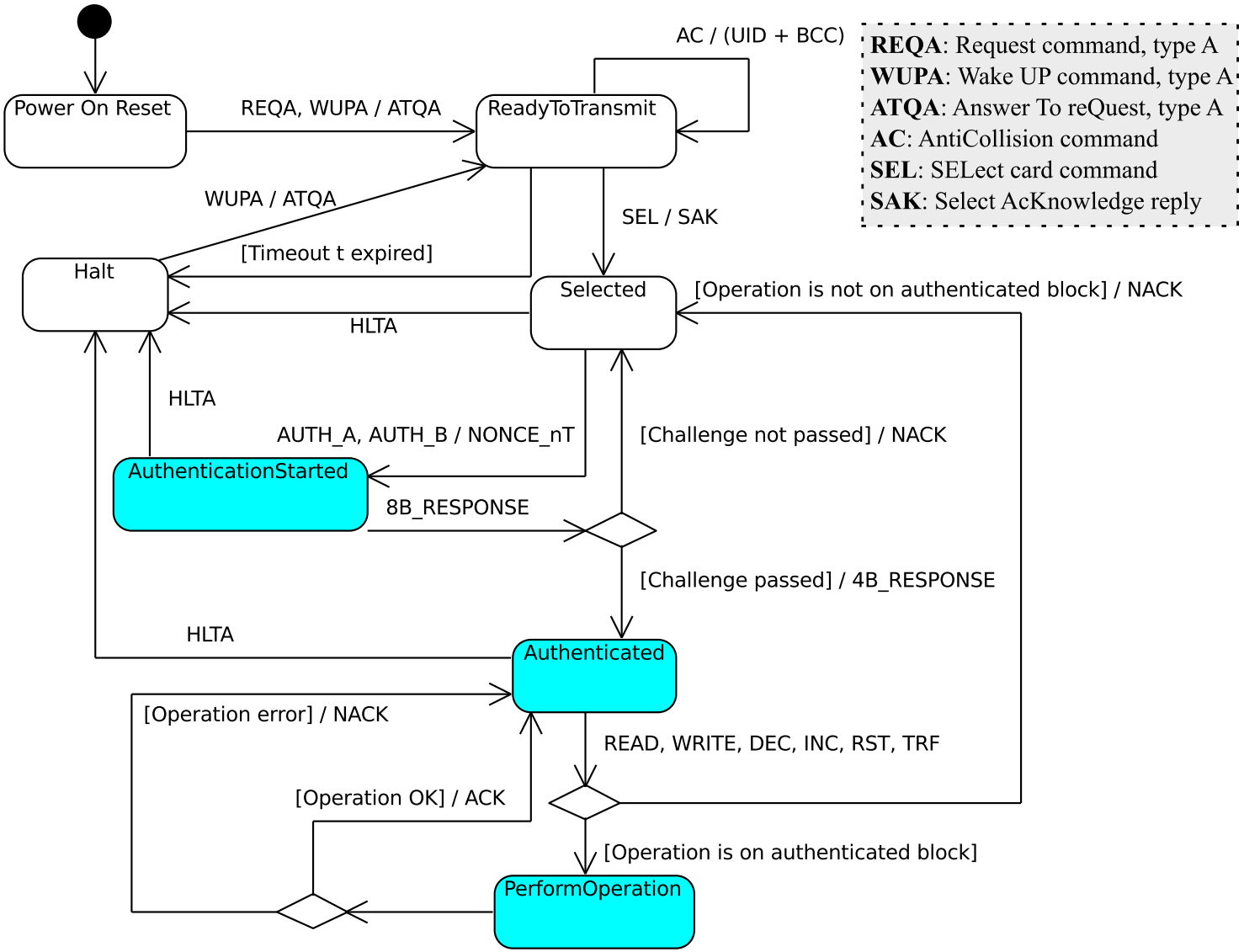
1. Get the tags in the reader's range
2. Select only one tag (anticollision loop)
3. Access a block, with key A or key B (starts authentication step)

Authentication step

- Challenge-response mutual authentication using nonces
  - Nonce: randomly generated information
  - Nonces generated from a LFSR (next slides)

MIFARE Classic: Communication Protocol (II)

UML-SM of a NFC tag



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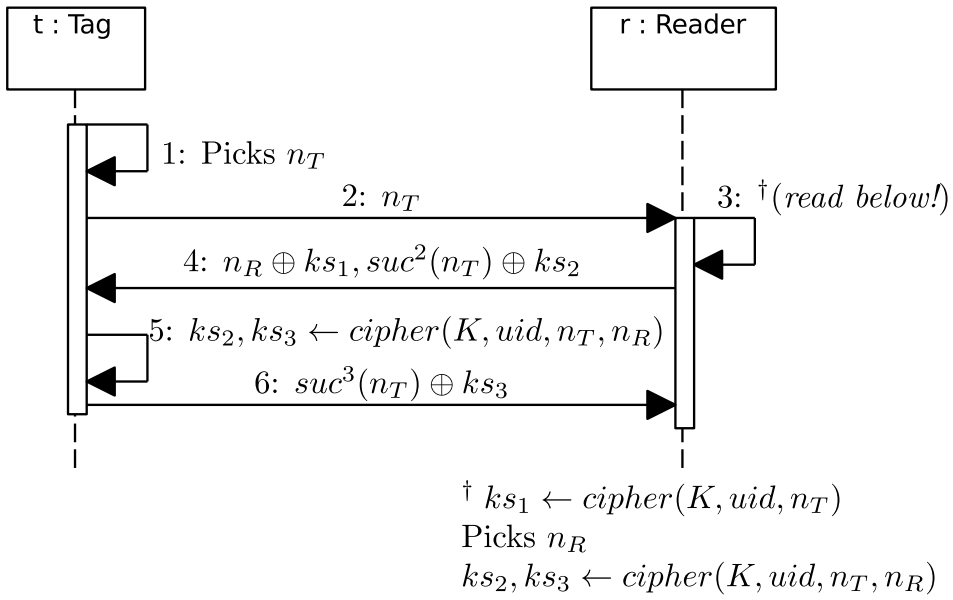
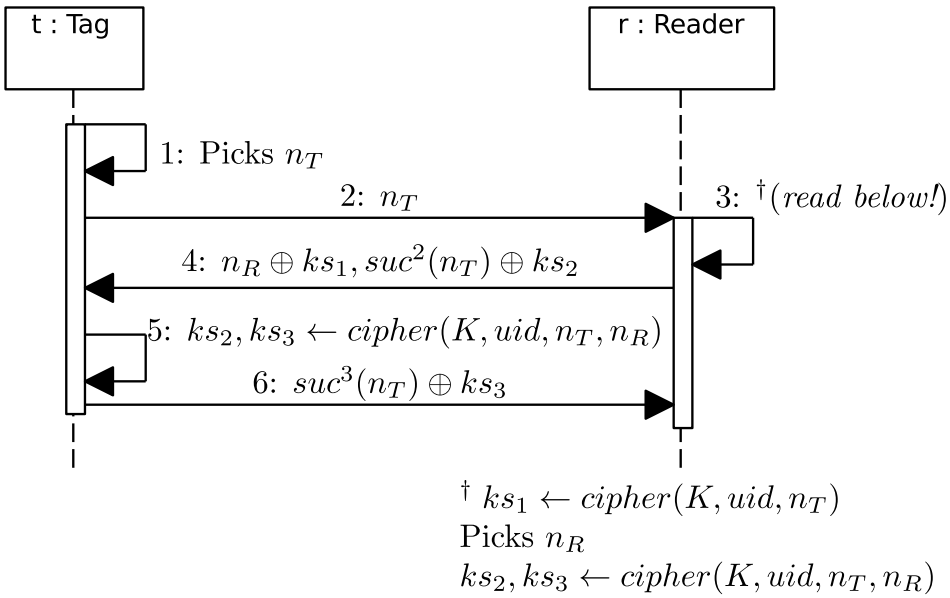


- Three-pass authentication
  1. Send nonce (n_T) as challenge
     - Generated by a 16-bit LFSR ($g(x) = x^{16} + x^{14} + x^{13} + x^{11} + 1$)
  2. Send response and other nonce n_R as challenge
  3. Send response
- Note: from n_T, communication is ciphered

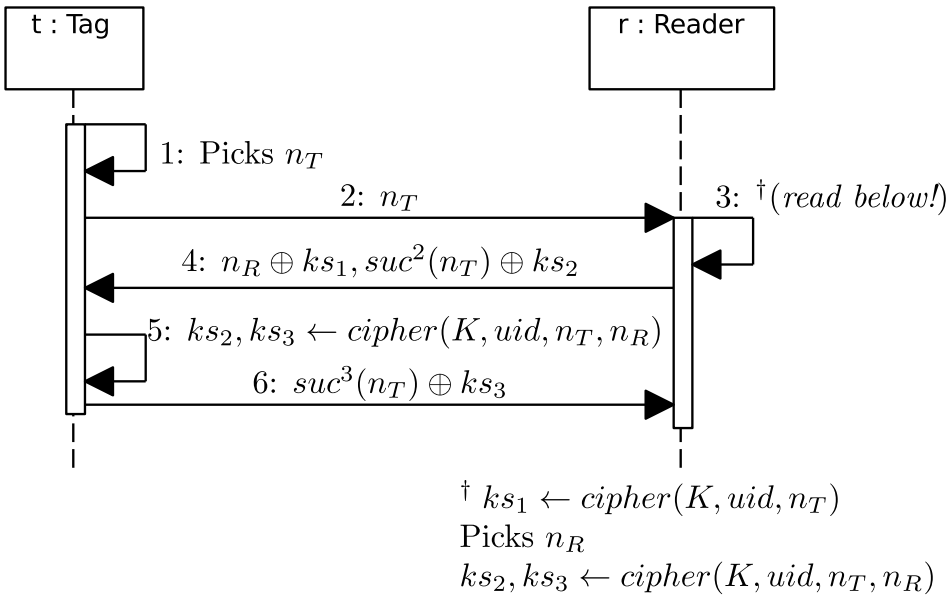
MIFARE Classic: Communication Protocol (IV)



Known plaintext [GKMRVSJ-ESORICS-08]

- Recall: n_T is in plaintext

MIFARE Classic: Communication Protocol (IV)



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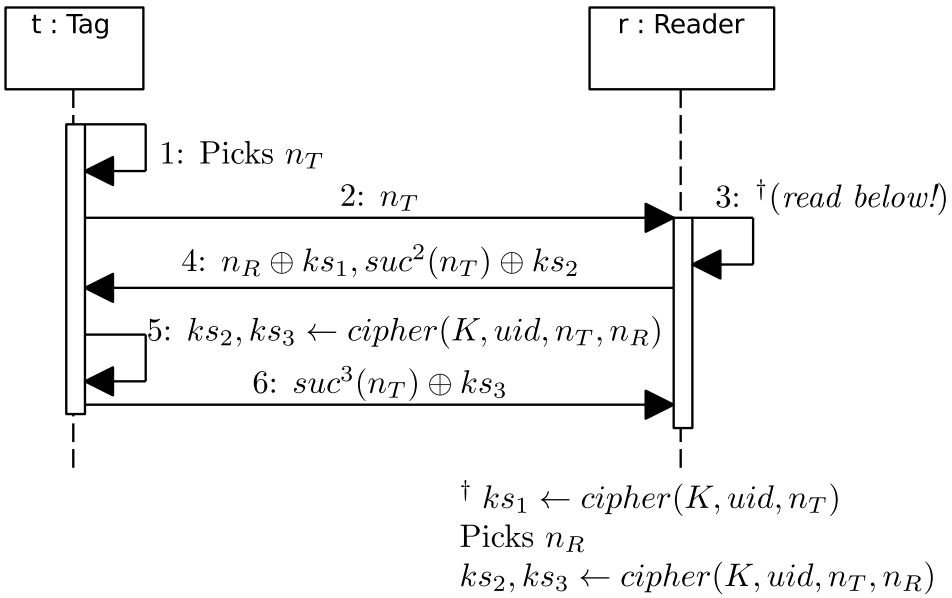
- Recall: n_T is in plaintext
- Given n_T, compute $suc^2(n_T) \rightarrow ks_2 = n_T \oplus suc^2(n_T)$

MIFARE Classic: Communication Protocol (IV)



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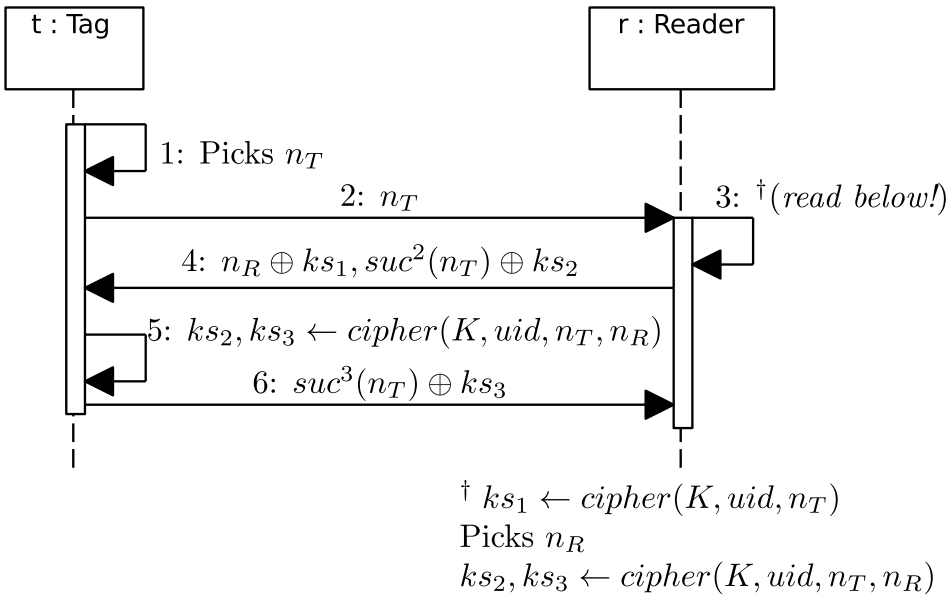

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- When tag does not send last response, some readers time out and send `HLT` command XORed ks_3
  - `HLT` command is known, then we recover ks_3
- Eavesdropping a successful authentication session
  - ks_2, ks_3 recovered from $suc^2(n_T) \oplus n_T, suc^3(n_T) \oplus n_T$

MIFARE Classic: CRYPTO1 (I)

- Proprietary stream cipher. Key length of 48 bits
- "Security by obscurity" principle
- Hardware on-chip: faster cryptographic operations!
- Reverted some years ago...:
  - K. Nohl and H. Plötz: "Mifare: Little Security, Despite Obscurity", in *Chaos Communication Congress*, 2007. Reverse engineering on silicon implementation
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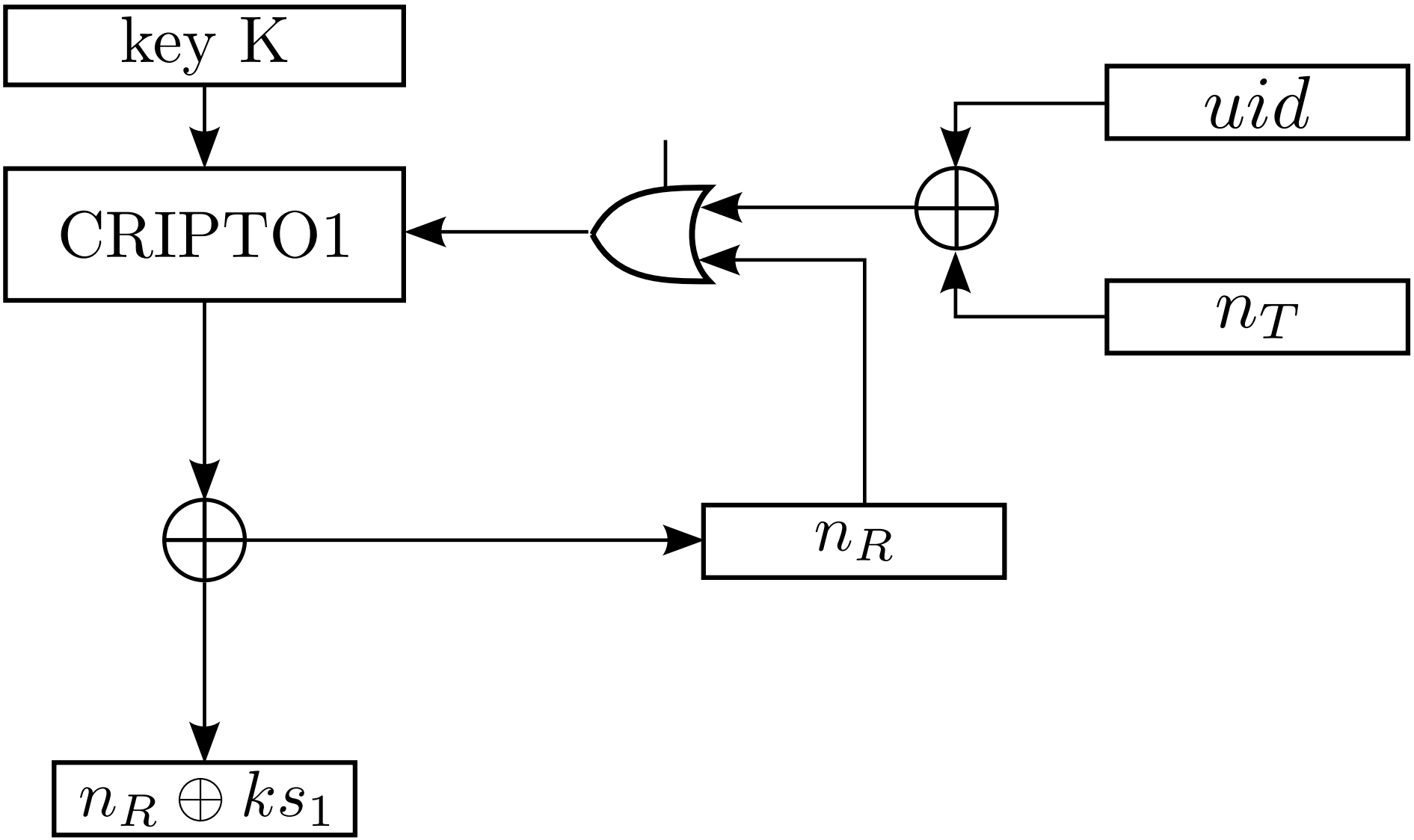
- Linear Feedback Shift Register (LFSR) + two-layer non-linear filter generator
  - At every clock tick, register is shifted one bit to the left
  - Leftmost bit: discarded
  - Feedback bit: computed with $g(x)$

$$g(x) = x^{48} + x^{43} + x^{39} + x^{38} + x^{36} + x^{34} + x^{33} + x^{31} + x^{29} + x^{24} + x^{23} + x^{21} + x^{19} + x^{13} + x^{9} + x^{7} + x^{6} + x^{5} + 1$$

MIFARE Classic: CRYPTO1 (II)

Initialisation diagram



MIFARE Classic: Known Weaknesses (I)

On the Pseudo-Random Number Generator

MOST CRITICAL weakness

Low entropy

- LFSR generating nonces: 16-bit length
- 0.6 seconds to generate ALL possible nonces ([NESP-USENIX-08])
- Generator resets to a known state every time the tag starts operating
  - Just a wait a fixed number of clock cycles...
  - Experimentally possible to get the same nonce every 30ms using Proxmark 3 reader

MIFARE Classic: Known Weaknesses (II)

On the Cryptographic Cipher

$$x_9, x_{11}, x_{13}, \ldots, x_{47}$$

Keystream generation

- Odd bits as inputs to the filter functions
- Divide-and-Conquer technique
  - Split even, odd bits in groups
  - Firstly focus on odd group:
    - After 2 shifts, new input is $x_{11}, x_{13}, \ldots, x_{47}$ and x_{49}
    - Used for generating two keystreams
    - Explore what bits generate the right keystreams
- Attack: Recover all sector keys without the needed of a genuine reader

MIFARE Classic: Known Weaknesses (III)

On the Cryptographic Cipher

$$x_9, x_{11}, x_{13}, \ldots, x_{47}$$

Leftmost bit not used in filter generator

- First 9 bits unused
- Attack: Rollback LFSR state bit a bit
  - Recover the initial state of LFSR

Statistical Bias [C-SECRYPT-09]

- With a $\pi = 0.75$, ks_1 is independent of the last three bits of n_R
- Attack: card-only attack
  - Recover one key, then apply nested authentication attack ([GKMRVSJ-ESORICS-08])
  - Does not require any pre-computation
  - Extremely fast, and requires a few hundred queries
  - More in the paper: `http://eprint.iacr.org/2009/137.pdf`

MIFARE Classic: Known Weaknesses (IV)

On the Communication Protocol

One-Time Padding (OTP)

- ISO-14443-A: every byte sent is followed by a parity bit
- MIFARE Classic computes parity bit over plaintext instead of ciphertext
- LFSR is not shifted after parity bit encryption

MIFARE Classic: Known Weaknesses (IV)

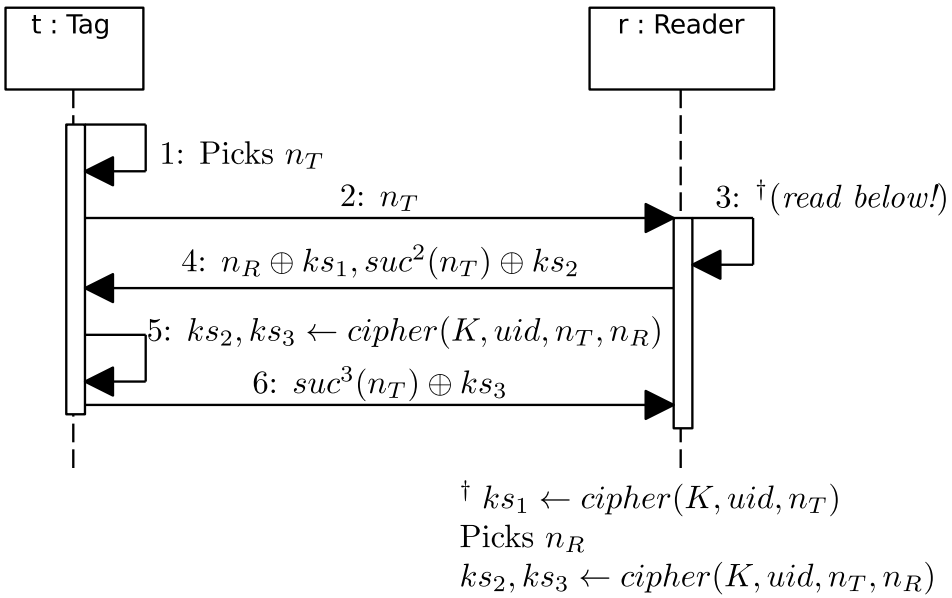
On the Communication Protocol

One-Time Padding (OTP)

- ISO-14443-A: every byte sent is followed by a parity bit
- MIFARE Classic computes parity bit over plaintext instead of ciphertext
- LFSR is not shifted after parity bit encryption
- Next plaintext and parity bit use the same keystream $\rightarrow$ OTP seems not to be OTP...
- More examples of violating OTP property:
  - Venona Project (U.S. counter-intelligence program during Cold War)
  - Point-to-Point Tunneling Protocol (PPTP)
  - IEEE 802.11 WEP

MIFARE Classic: Known Weaknesses (V)

On the Communication Protocol



Information Leak from Parity

- Second step in authentication, reader sends $n_R, suc^2(n_T)$
- PICC checks parity bits in n_R before checking $suc^2(n_T)$
  - When parity is incorrect, PICC does not answer
  - When $suc^2(n_T)$ is incorrect, it answers `NACK` (transmission error)
- `NACK` sent encrypted $\rightarrow$ ks_3 can be recovered

MIFARE Classic: Known Weaknesses (VI)

On the Deployment

Default Keys

- Some chip manufacturers leave default keys on chips
- This is obvious, as companies must make the effort to do system integration for clients. . . (sic!)
- RTFM: Chip manufacturer warns about CHANGING default keys
- Default keys are well-known and documented

FFFFFFFFFFFFh	000000000000h	1A982C7E459Ah
A0A1A2A3A4A5h	B0B1B2B3B4B5h	AABBCCDDEEFFh
D3F7D3F7D3F7h	4D3A99C351DDh	

Outline

Related Work (I)

On MIFARE Classic weaknesses analysis (1)

NP-CCC-07 K. Nohl and H. Plötz, "Mifare: Little Security, Despite Obscurity", in *Chaos Communication Congress*, 2007.

GKMRVSJ-ESORICS-08 García et al., "Dismantling MIFARE Classic", in *Procs. of the European Symposium on Research in Computer Security* (ESORICS), 2008.

KHG-CARDIS-08 G.d Koning Gans et al., "A Practical Attack on the MIFARE Classic", in *Procs. of the Smart Card Research and Advanced Applications Conference* (CARDIS), 2008.

NESP-USENIX-08 K. Nohl et al., "Reverse-Engineering a Cryptographic RFID Tag". In *USENIX Security Symposium*, 2008.

GRBS-SP-09 F.D. García et al., "Wirelessly Pickpocketing a Mifare Classic Card", in *Procs. of the 30th IEEE Symposium on Security and Privacy* (S&P), 2009.

Related Work (II)

On MIFARE Classic weaknesses analysis (2)

C-SECRYPT-09 N.T. Courtois, "The Dark Side of Security by Obscurity and Cloning MiFare Classic Rail and Building Passes Anywhere, Anytime". In *Procs. of the Int. Conf. on Security and Cryptography* (SECRYPT), 2009

GRBS-SP-09 F.D. García et al., "Wirelessly Pickpocketing a Mifare Classic Card", in *Procs. of the 30th IEEE Symposium on Security and Privacy* (S&P), 2009

Tan-MScThesis-09 W.H. Tan, "Practical Attacks on the MIFARE Classic", Imperial College London, 2009

On NFC Attacks

VK-NFC-11 R. Verdult and F. Kooman, "Practical Attacks on NFC Enabled Cell Phones". In *Procs. of the 3rd Int. Workshop on Near Field Communication*, 2011

Related Work (III)

On MIFARE Attacks

- Sogeti ESEC Pentest: "Playing with NFC for fun and coffee"
- BackTrack Linux: "RFID Cooking with Mifare Classic" (2012)
- C. Miller, "Exploring the NFC Attack Surface", in *BlackHat US*, 2012.
- ComputerWorld article: "Android NFC hack enables travelers to ride subways for free, researchers say" (2012)
- HackPlayers: "Cómo colarse en el metro de forma elegante" (2012)
- Security ArtWork: "Hacking RFID, rompiendo la seguridad de Mifare" (2010)

On NFC-related issues

- R. Lifchitz, Hacking the NFC credit cards for fun and debit (Hackito Ergo Sum 2012)
- J.M. Esparza, Give me your credit card, the NFC way (NcN'12)

Outline

A Case Study (I)

Once upon a time. . .

- Imagine a place using MIFARE Classic cards
- Used for multiple purposes:
  - Access to public transport services
  - Use of public facilities

A Case Study (I)

Once upon a time. . .

- Imagine a place using MIFARE Classic cards
- Used for multiple purposes:
  - Access to public transport services
  - Use of public facilities
- In the (near) future:
  - Taxi payments
  - Citizen rent info for discounts

A Case Study (II)

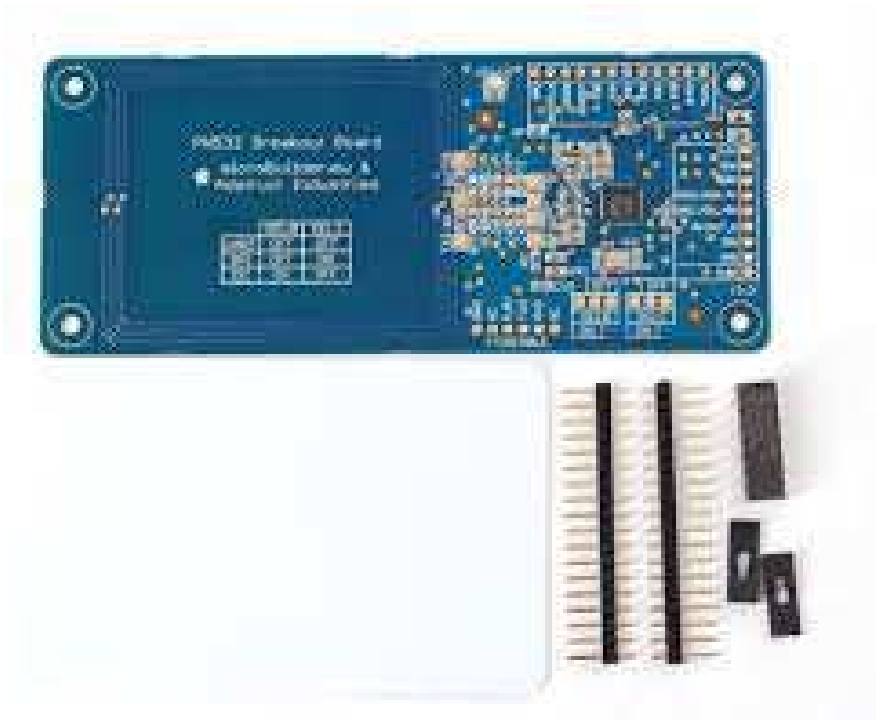
Problem Analysis

Specific goals

- Figure out the pair of keys (A, B)
- Make a dump of a real card
- Study the card content
- Check any integrity about unauthorised content alteration
- Make a clone card
- Do a mobile app for card-hacking

A Case Study (III)

Lab Environment



Hardware

- AdaFruit PN532 and USB-FTDI cable
- A computer
- A NFC-enabled phone*

Software

- C compiler
- NFC Library (`libnfc`)
- NFC tools (`nfc-tools`)
- Mifare Offline Cracker (`mfoc`)

Recall: Tell the story about phones

A Case Study (IV)

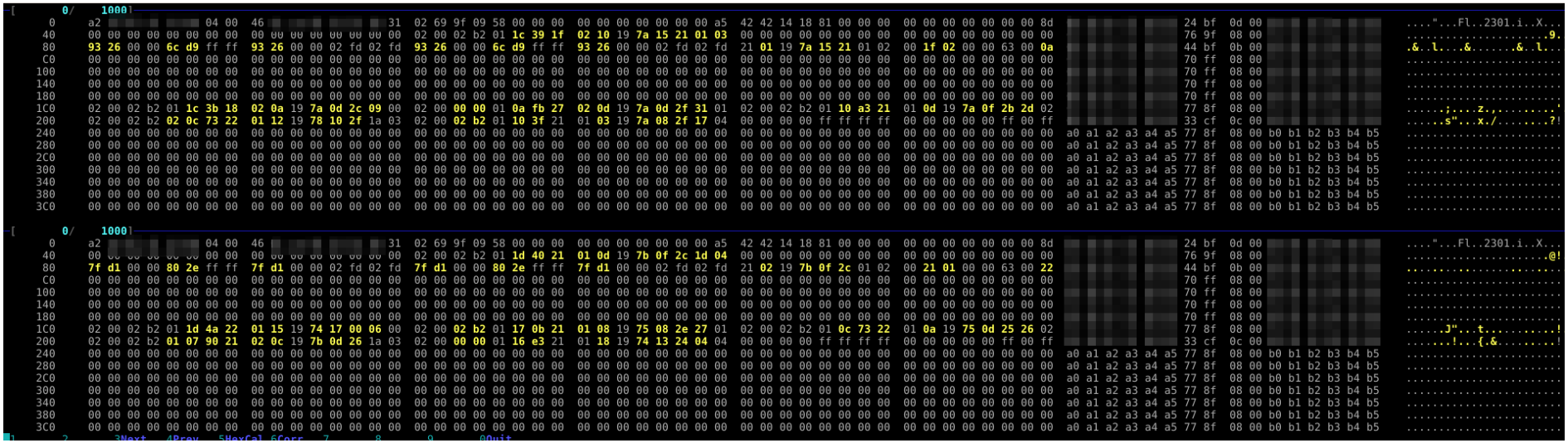
- Two different Classic version
  - MIFARE Classic 1K (T1)
  - MIFARE Classic 4K (T2)

```
death@mulita:~/Downloads/mfoc-0.10.2/src$ time sudo mfoc -O out -P 100
    ATQA (SENS_RES): 00  04
* UID size: single
* bit frame anticollision supported
      UID (NFCID1):
     SAK (SEL_RES): 08
* Not compliant with ISO/IEC 14443-4
* Not compliant with ISO/IEC 18092
Fingerprinting based on ATQA & SAK values:
* Mifare Classic 1K
* Mifare Plus (4-byte UID) 2K SL1
* SmartMX with Mifare 1K emulation
[Key: 000000000000] -> [................]
[Key: f          f] -> [................]
[Key: f          f] -> [................]
[Key: a          9] -> [xxxxxxxxxx......]
[Key: a          6] -> [xxxxxxxxxx......]
[Key: a          0] -> [xxxxxxxxxx......]
[Key: a          8] -> [xxxxxxxxxx......]
[Key: a          4] -> [xxxxxxxxxx......]
[Key: 7          b] -> [xxxxxxxxxxxx..xx]
[Key: 2          3] -> [xxxxxxxxxxxx..xx]
[Key: c          2] -> [xxxxxxxxxxxx..xx]
[Key: 3          0] -> [xxxxxxxxxxxx..xx]
[Key: 5          b] -> [xxxxxxxxxxxxxxxx]
[Key: 3          6] -> [xxxxxxxxxxxxxxxx]
[Key: 6          1] -> [xxxxxxxxxxxxxxxx]
[Key: 0          3] -> [xxxxxxxxxxxxxxxx]
[Key: 0          3] -> [xxxxxxxxxxxxxxxx]
[Key: 0          9] -> [xxxxxxxxxxxxxxxx]
[Key: a          5] -> [xxxxxxxxxxxxxxxx]
[Key: b          5] -> [xxxxxxxxxxxxxxxx]
[Key: 7          9] -> [xxxxxxxxxxxxxxxx]

Sector 00 -  FOUND KEY  [A]  Sector 00 -  FOUND KEY  [B]
```

```
Block 15, type A, key a          9 :00  00  00  0
Block 14, type A, key a          9 :00  00  00  0                                                  00  00
Block 13, type A, key a          9 :00  00  00  0                                                  00  00
Block 12, type A, key a          9 :00  00  00  0                                                  00  00
Block 11, type A, key a          9 :00  00  00  0                                                  3b  a2
Block 10, type A, key a          9 :00  00  00  0                                                  00  00
Block 09, type A, key a          9 :00  00  00  0                                                  02  fd
Block 08, type A, key a          9 :00  00  00  0                                                  02  fd
Block 07, type A, key a          9 :00  00  00  0                                                  3b  a2
Block 06, type A, key a          9 :00  00  00  0                                                  00  00
Block 05, type A, key a          9 :03  00  02  b                                                  35  04
Block 04, type A, key a          9 :00  00  00  0                                                  00  00
Block 03, type A, key a          9 :00  00  00  0                                                  3b  a2
Block 02, type A, key a          9 :54  5a  03  0                                                  00  2c
Block 01, type A, key a          9 :03  00  00  0                                                  00  dd
Block 00, type A, key a          9 :

real    0m35.551s
user    0m0.244s
sys     0m0.004s
```

A Case Study (V)

Understanding the card content...

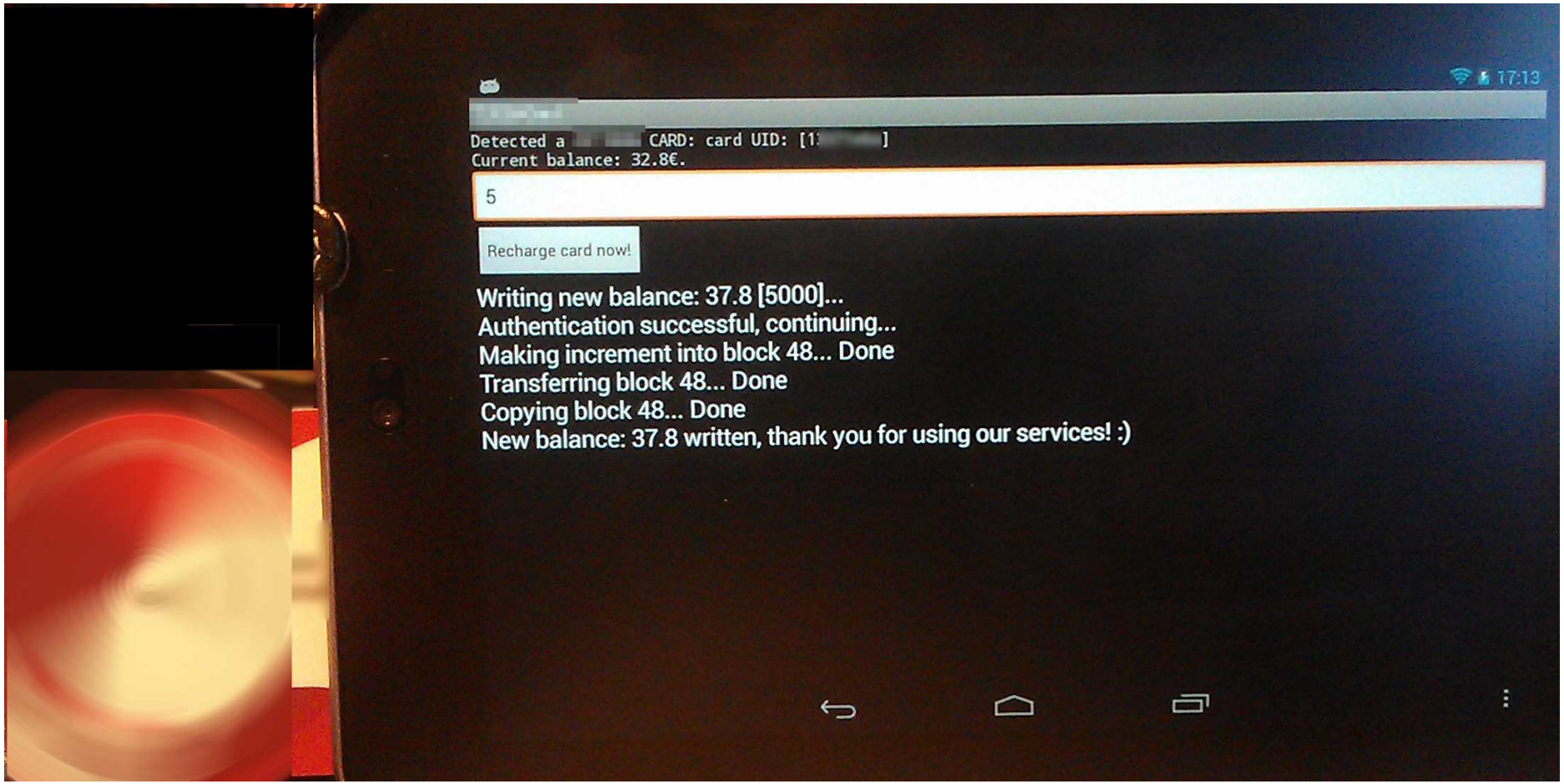


Summary of data

	T1	T2
Card ID	(0, 3)	(10, 3)
Last bus used	(1, 2)	(1, 2)
Current balance	(2, [1, 2])	(12, [1, 2])
Historic	(7, [1, 2, 3]), (8, [1, 2])	(7, [1, 2, 3]), (8, [1, 2])

A Case Study (VI)

Building a PoC in Android O.S. (1)



A Case Study (VII)

Building a PoC in Android O.S. (2)

It's demo time!

A Case Study (IIX)

Recalling the initial goals

Goal	Achieved?	Some remarks
Figure out the pair of keys (A, B)	$\surd$	Some keys are the default ones
Make a dump of a real card	$\surd$	Fast, and simple
Study the card content	$\surd$	Not a single bit encrypted
Check any integrity about unauthorised content alteration	$\surd$	no integrity
Make a clone card	$\surd^*$	A perfect clone (Chine cards rulez!)
Do a mobile app for card-hacking	$\surd$	Android fuc·ing rocks!

A Case Study (IIX)

Thinking (and acting?) badly... (1)

What else could be done...

- Identity spoofing
  - Possible penalties for spoofed people
  - Consume the real balance of someone else
- Use of all public services for free
- Black market?
  - Fake recharge point
  - Whether I sold a card illegitimately charged...
- Just put the app in Google Play, and have fun ☺

A Case Study (IX)

Thinking (and acting?) badly... (2): Replay attacks

A Case Study (IX)

Event timeline

Nov 2012 Nice chat with J.M. Esparza ⌣̈

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(today) As they don't care, me neither. Here I am! ☺

A Case Study (X)

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- It's good to collaborate with police... but you need to be patient
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- Security is not considered (as normally) in a Spanish company
  - Not at the beginning of a product design
  - Not even when someone spots out the problem
  - They quantify the risk of people exploiting the problem...
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Remember, not economic gain but free beer instead!

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Thinking to deploy MIFARE Classic as an access control system?

Don't.

Hacking the NFC cards for fun and honor degrees

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All wrongs reversed

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