Bricklayer Attack: A Side-Channel Analysis on the ChaCha Quarter Round

Alexandre Adomnicai [1,3] Jacques J.A. Fournier [2] Laurent Masson [1]

[1] Trusted Objects

[2] CEA-Leti

[3] EMSE

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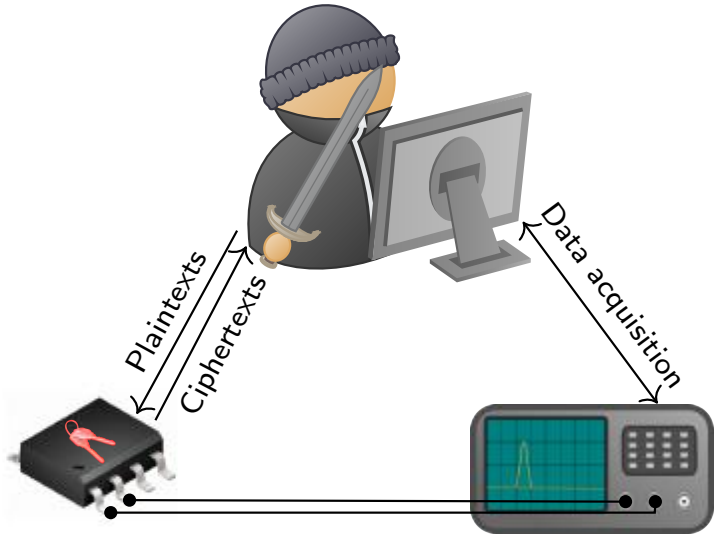
Side-Channel Attacks

- Cryptographic primitives are designed to be finally executed on a **physical system**.
- **The physical characteristics** of the computing platform produce **side effects** depending on the processed data
  - Power consumption
  - Electromagnetic emanations
  - Time execution
  - Sound ...



TRUSTED OBJECTS

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- **The physical characteristics** of the computing platform produce **side effects** depending on the processed data
  - Power consumption
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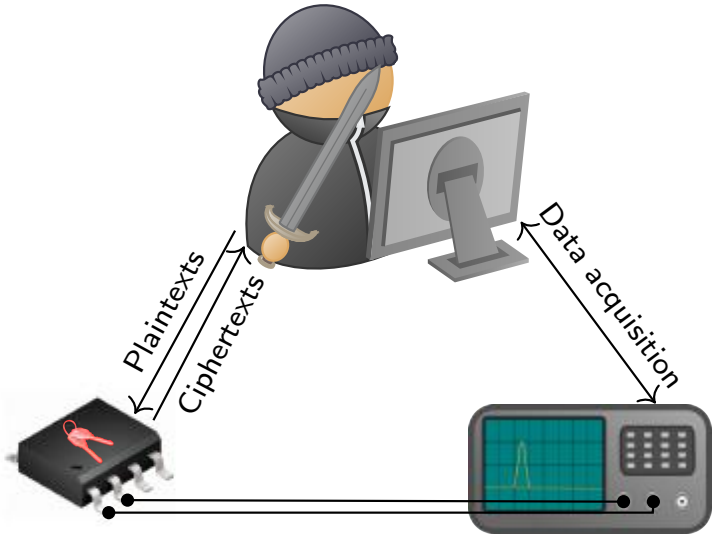
  - Sound ...
- One can **measure** these side effects to get information on the processed values during **sensitive operations**
- Using an appropriate **leakage model**, one can recover the **secrets** involved in calculations



TRUSTED OBJECTS

Selection Functions

- Differential Power/Electromagnetic analyses target an **intermediate state** y which depends on a **known input** x and a **secret** k.

- This value is defined by a **selection function** $\varphi(x, k) = y$.

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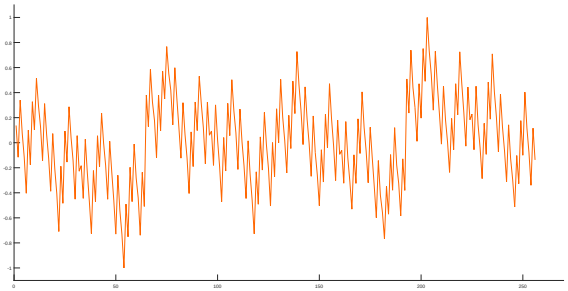
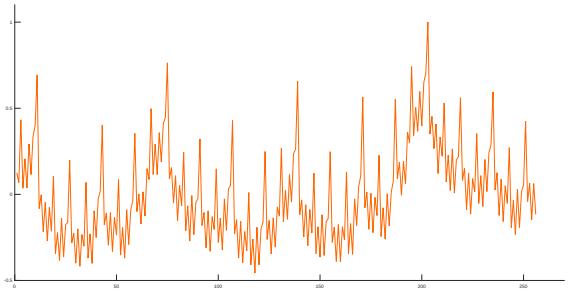
- This value is defined by a **selection function** $\varphi(x, k) = y$.
- **High non-linearity** is a valuable property as it ensures a good **distinguishability** between correct and incorrect key guesses.



$\varphi(x, k) = x \oplus k$



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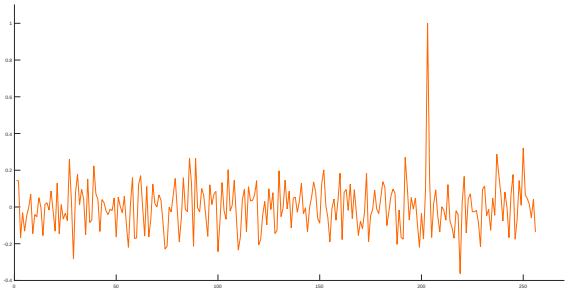

$\varphi(x, k) = \mathrm{AES}_{\mathrm{Sbox}}(x \oplus k)$

Simulation of **Correlation Power Analyses** (CPA) in the Hamming Weight model

TRUSTED OBJECTS

The ChaCha Family of Stream Ciphers

- **ChaCha** is a family of stream ciphers introduced by Daniel J. Bernstein in 2008.
- ChaCha is based on **Salsa20** (eSTREAM portfolio) while **improving diffusion without performance hit**.

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- ChaCha is based on **Salsa20** (eSTREAM portfolio) while **improving diffusion without performance hit**.
- ChaCha20 has been **widely adopted** in practice
  - **Android phones** (ChaCha20-Poly1305 AEAD used in TLS with Chrome)
  - **Apple HomeKit for IoT devices** (ChaCha20-Poly1305 AEAD with HKDF-SHA-512 derived keys)
  - **Linux kernel 4.8+** (`/dev/urandom` based on ChaCha20)
  - **OpenBSD** (ChaCha20 now replaces RC4 for pseudo-random number generator)
  - Numerous security protocols (**TLS**, **SSH**, **IPsec**, ...)

TRUSTED OBJECTS

How to Dance the ChaCha

- Operate like an iterative **512-bit** block cipher using **CTR mode**

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- The internal state consists in a 4×4 **matrix of 32-bit elements**

‘expa’	‘nd 3’	‘2-by’	‘te k’
k_0	k_1	k_2	k_3
k_4	k_5	k_6	k_7
$\texttt{nonce}_0$	$\texttt{nonce}_1$	$\texttt{nonce}_2$	$\texttt{nonce}_3$

Initial State

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Initial State

```
a ⊞= b;   d ⊕= a;   d ⋘= 16;
c ⊞= d;   b ⊕= c;   b ⋘= 12;
a ⊞= b;   d ⊕= a;   d ⋘= 8;
c ⊞= d;   b ⊕= c;   b ⋘= 7;
```

QR(a,b,c,d) pseudo code

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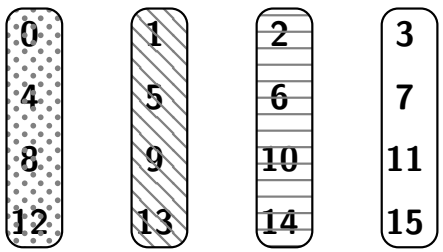
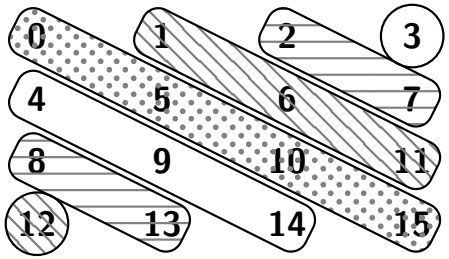


(a) Even round



(b) Odd round

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- After the last round, the keystream is obtained **by adding** the current state with the initial one

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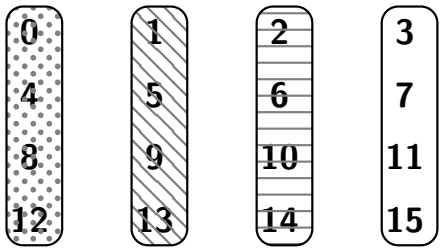

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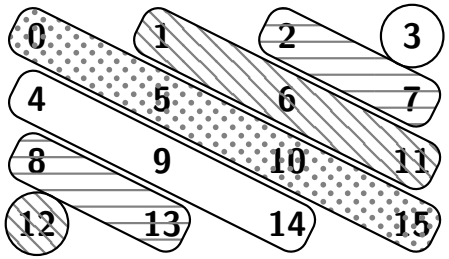

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Attack published at DATE 2017

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`quarter_round(‘expa’, `k_0`, `k_4`, `$\texttt{nonce}_0$`)`

1: $a \leftarrow$ ‘expa’ $\boxplus\ k_0$
2: $d \leftarrow a \oplus \texttt{nonce}_0$ ▷ k_0 recovery
3: $d \leftarrow d \lll 16$
4: $c \leftarrow d \boxplus k_4$ ▷ k_0 & k_4 recovery
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Practical experiments

- All practical experiments were done on an **ARM Cortex-M3** clocked at 24MHz using
  - Langer HF-U 5 near-field probe (30 MHz - 3 GHz)
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Device Under Test

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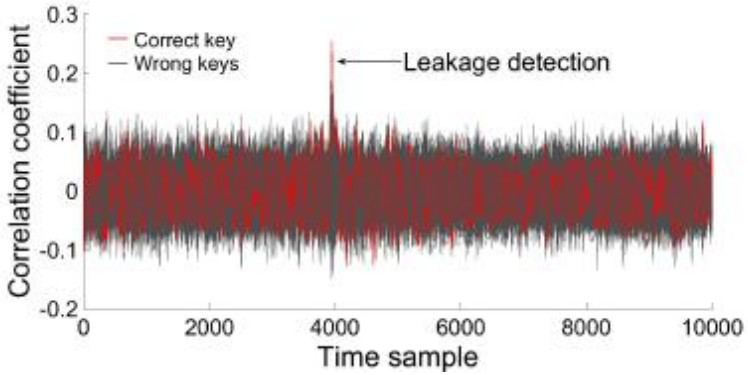
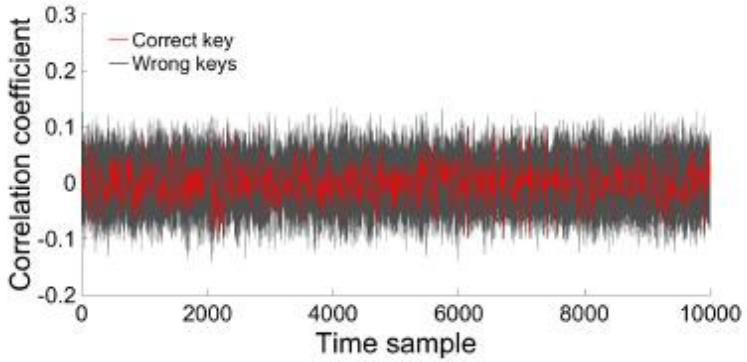
- Application of both attacks on two different ChaCha20 implementations
  - OpenSSL (1.0.1f) compiled using the GNU ARM C compiler (5.06)
  - Homemade ARM assembly

Device Under Test



(a) C compiled



(b) ARM Assembly

TRUSTED OBJECTS

Assembly VS C compiled

-O0 Compilation

```
LDR     r1,[sp,#0x10]
LDR     r0,[sp,#0x00]
ADD     r0,r0,r1
STR     r0,[sp,#0x00]
LDR     r1,[sp,#0x00]
LDR     r0,[sp,#0x30]
EORS    r0,r0,r1
LSLS    r1,r0,#16
LDR     r2,[sp,#0x00]
LDR     r0,[sp,#0x30]
EORS    r0,r0,r2
ORR     r0,r1,r0,LSR #16
STR     r0,[sp,#0x30]
LDR     r1,[sp,#0x30]
LDR     r0,[sp,#0x20]
ADD     r0,r0,r1
STR     r0,[sp,#0x20]
LDR     r1,[sp,#0x20]
LDR     r0,[sp,#0x10]
EORS    r0,r0,r1
LSLS    r1,r0,#12
LDR     r2,[sp,#0x20]
LDR     r0,[sp,#0x10]
EORS    r0,r0,r2
ORR     r0,r1,r0,LSR #20
STR     r0,[sp,#0x10]

        ...
```

-O3 Compilation

```
LDR     r1,[sp,#0x10]
LDR     r0,[sp,#0x00]
ADD     r0,r0,r1
STR     r0,[sp,#0x00]
LDR     r1,[sp,#0x00]
LDR     r0,[sp,#0x30]
EORS    r0,r0,r1
ROR     r0,r0,#16
STR     r0,[sp,#0x30]
LDR     r1,[sp,#0x30]
LDR     r0,[sp,#0x20]
ADD     r0,r0,r1
STR     r0,[sp,#0x20]
LDR     r1,[sp,#0x20]
LDR     r0,[sp,#0x10]
EORS    r0,r0,r1
ROR     r0,r0,#20
STR     r0,[sp,#0x10]

        ...
```

ARM Assembly

```
LDR     r1, [r0]
LDR     r2, [r0, #16]
LDR     r3, [r0, #32]
LDR     r4, [r0, #48]
ADD     r1, r1, r2
EOR     r4, r4, r1
ROR     r4, r4, #16
ADD     r3, r3, r4
EOR     r2, r2, r3
ROR     r2, r2, #20
ADD     r1, r1, r2
STR     r1, [r0]
EOR     r4, r4, r1
ROR     r4, r4, #24
STR     r4, [r0, #48]
ADD     r3, r3, r4
STR     r3, [r0, #32]
EOR     r2, r2, r3
ROR     r2, r2, #25
STR     r2, [r0, #16]
```

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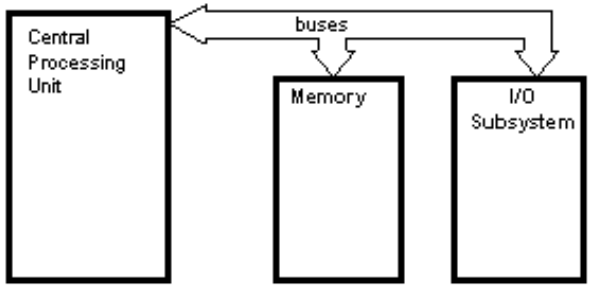
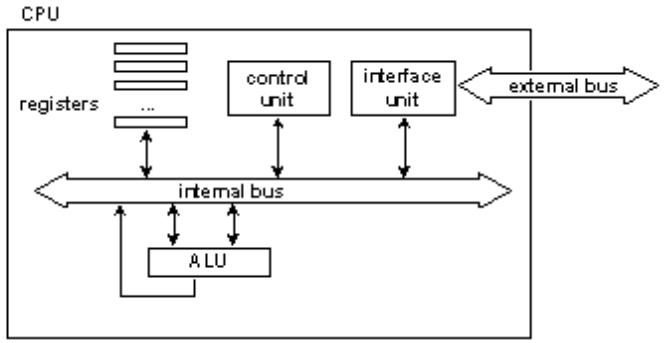
Information Leakage & Implementation Aspects

- **Load/store** architectures divide instructions into 2 categories
  - **Memory accesses**
  - **Arithmetic Logic Unit** (ALU) operations





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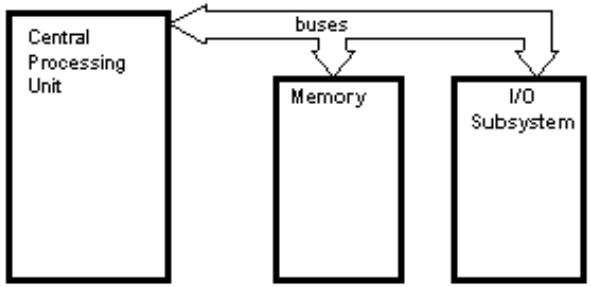

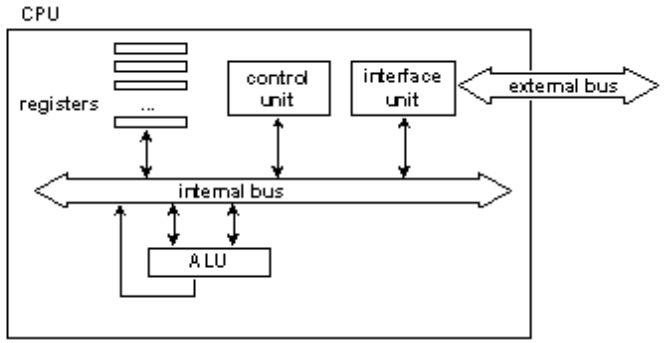

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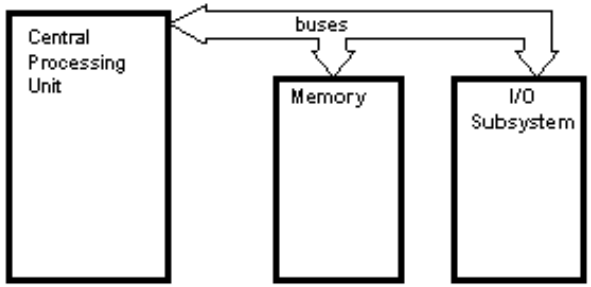

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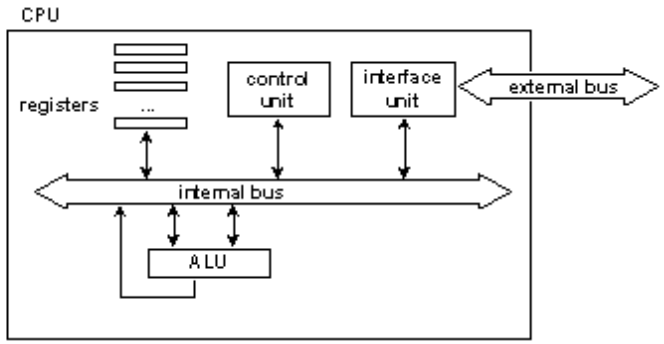

- When a CPU performs ALU operations
  - The operand registers' content are transferred to the ALU
  - The ALU performs the calculation and places the result in the output register

Is it easier to exploit leakages in relation to memory instructions?

TRUSTED OBJECTS

Focusing on Memory Instructions

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where $\tilde{k}_i = k_i \boxplus \mathtt{constant}_i$

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- φ_1 implies a side-channel attack on **2 key words at once** (*i.e.* $|\mathcal{K}| = 2^{64}$) $\Rightarrow$ undoable in practice!

Divide & Conquer

- It has been proved there is still a correlation when predicting a **subpart** of the word [4]

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- Targeting n bits of $y = \varphi_1(\texttt{nonce}_i, k_i \parallel k_{i+4})$ does not lead to a complexity equal to 2^{2n}

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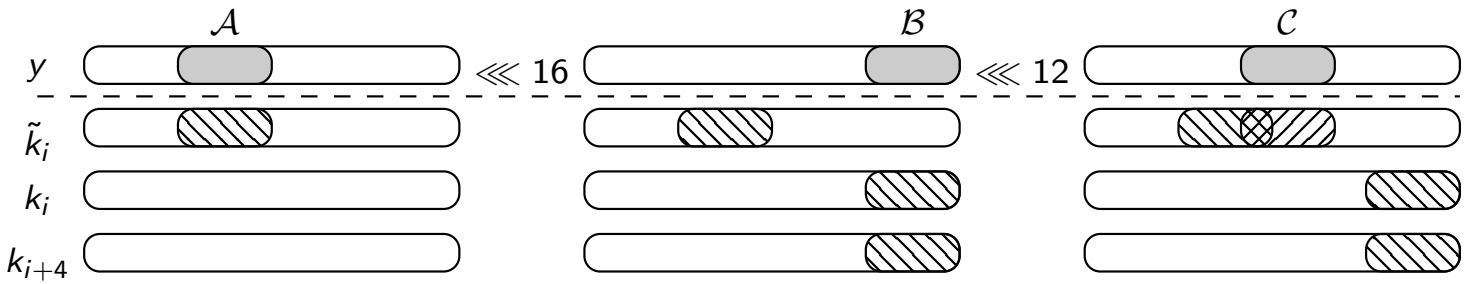
Divide & Conquer

- It has been proved there is still a correlation when predicting a **subpart** of the word [4]
- Targeting n bits of $y = \varphi_1(\texttt{nonce}_i, k_i \parallel k_{i+4})$ does not lead to a complexity equal to 2^{2n}
- The key search space depends on the **windows' size** n

$$|\mathcal{K}| = \begin{cases} 2^{4n}, & \text{if } n \leq 4 \\ 2^{3n+4}, & \text{if } 4 \leq n \leq 12 \\ 2^{2n+16}, & \text{if } 13 \leq n \leq 16 \\ 2^{n+32}, & \text{otherwise} \end{cases}$$



D&C approach on the ChaCha QR, $n = 8$

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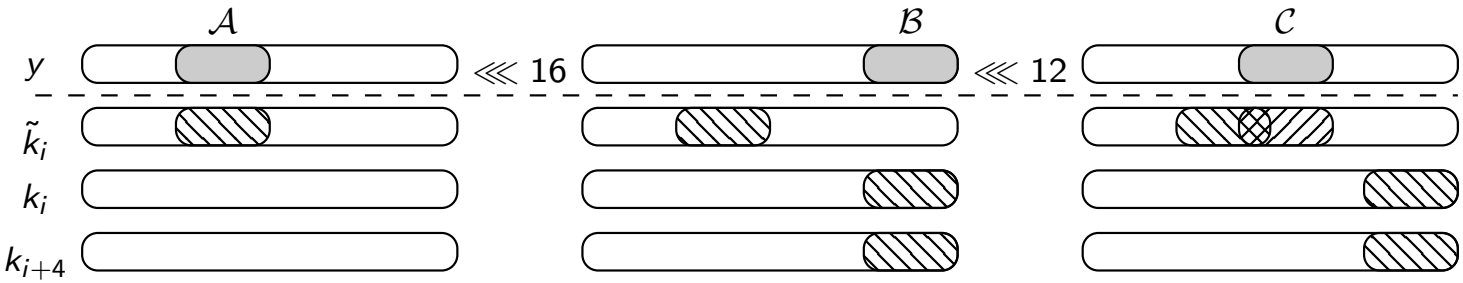

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TRUSTED OBJECTS

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- We performed software simulations using the **Hamming Weight model** (without any additional noise) and random nonces

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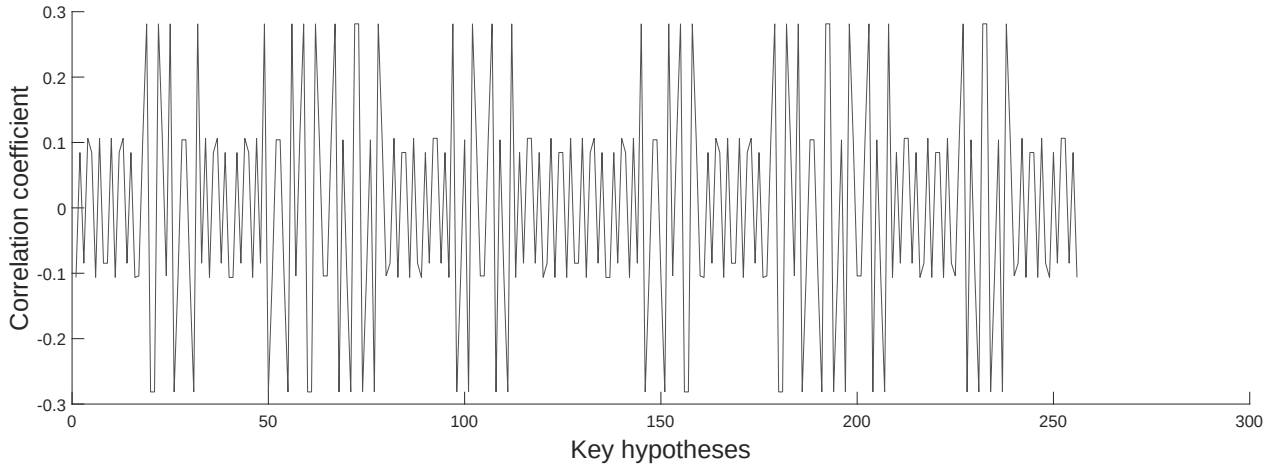
Proposition

An attack on $\varphi_{2,n}$ returns up to $n \cdot 2^{n+2}$ collisions.



Attack simulation on $\varphi_{2,2}$

TRUSTED OBJECTS

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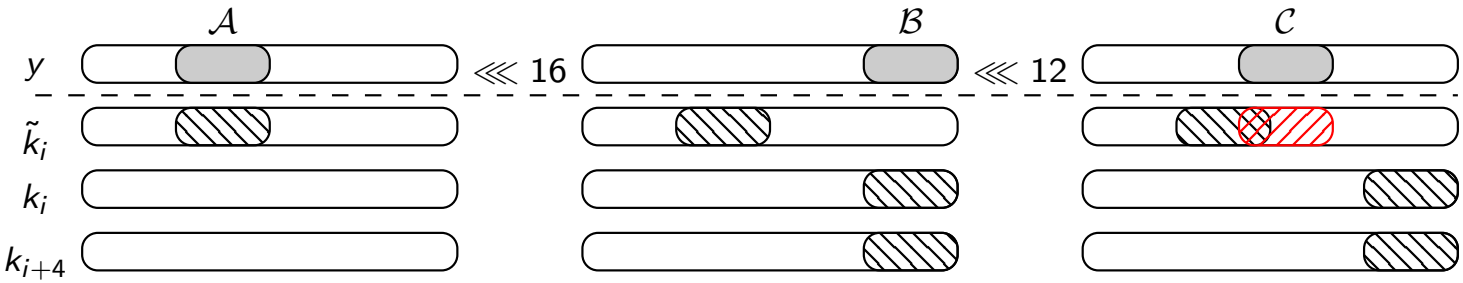
- On top of collisions, $\varphi_{2,n}$ is a victim of **carry propagations**

$$\varphi_{2,n}\left(\mathtt{nonce}_i, \tilde{k}_i^{\mathcal{A}} \parallel k_i^{\mathcal{B}} \parallel k_{i+4}^{\mathcal{B}} \parallel \tilde{k}_i^{\mathcal{C}}\right) = \mathtt{nonce}_i^{\mathcal{A}} \oplus \tilde{k}_i^{\mathcal{A}} \boxplus_n k_{i+4}^{\mathcal{B}} \oplus k_i^{\mathcal{B}} \boxplus_n \tilde{k}_i^{\mathcal{C}}$$



D&C approach on the ChaCha QR, $n = 8$

Focusing on the QR

- On top of collisions, $\varphi_{2,n}$ is a victim of **carry propagations**
- The attack should be run twice: **with** and **without** taking the carry into consideration

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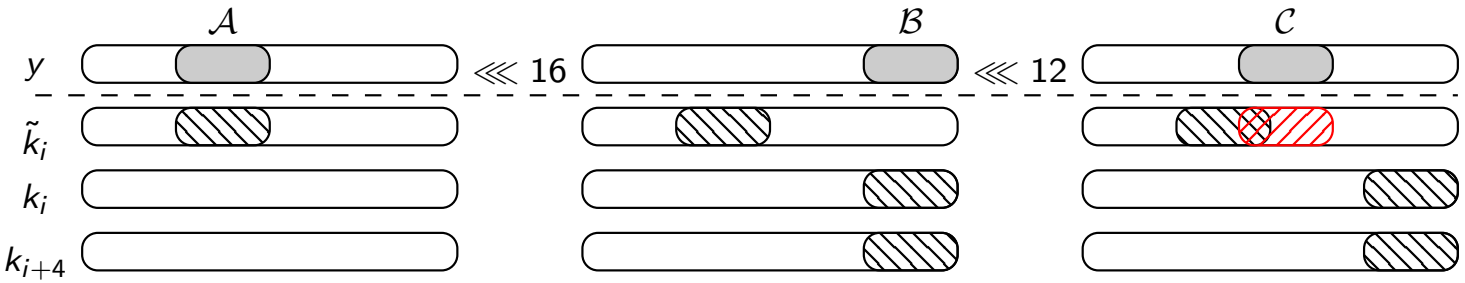

D&C approach on the ChaCha QR, $n = 8$

Benefits of the Inverse Quarter Round

```
a ⊞= b;   d ⊕= a;   d ⋘= 16;
c ⊞= d;   b ⊕= c;   b ⋘= 12;
a ⊞= b;   d ⊕= a;   d ⋘= 8;
c ⊞= d;   b ⊕= c;   b ⋘= 7;
```

QR(a,b,c,d) pseudo code

```
b ⋙= 7;   b ⊕= c;   c ⊟= d;
d ⋙= 8;   d ⊕= a;   a ⊟= b;
b ⋙= 12;  b ⊕= c;   c ⊟= d;
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$$\varphi_3\left(b \parallel c \parallel \tilde{d}_i, k_b \parallel k_c\right) = \left(b \boxminus k_b \ggg 7\right) \oplus \left(c \boxminus k_c \ggg 12\right) \oplus \left(c \boxminus k_c \boxminus \tilde{d}_i\right)$$

where $\tilde{d}_i = d_i \boxminus \mathtt{nonce}_i$

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- *a* **does not impact** the update of *b*

- The probability *p* of a **carry propagation** can be estimated

$$p = \mathbb{P}\left(k_b^{[0,x[} > b^{[0,x[}\right) = \frac{2^x - \left(b^{[0,x[} + 1\right)}{2^x}$$

TRUSTED OBJECTS

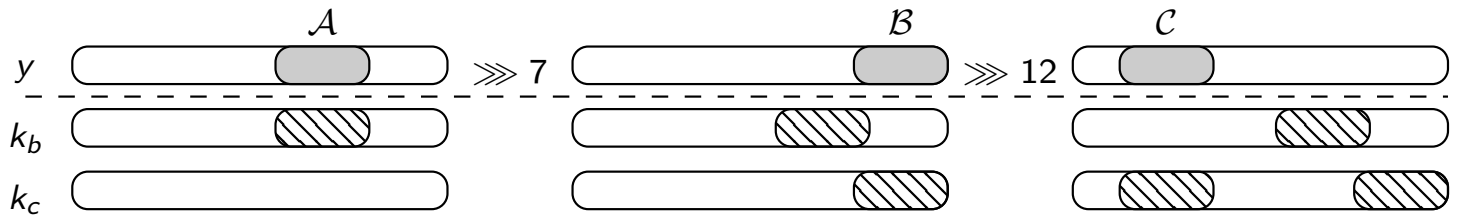
Benefits of the Inverse Quarter Round

- Discarding rotations results in

$$\varphi_{4,n}\left(b \parallel c \parallel \tilde{d}_i, k_b^{\mathcal{A}} \parallel k_c^{\mathcal{B}} \parallel k_c^{\mathcal{C}}\right) = \left(b^{\mathcal{A}} \boxplus_n k_b^{\mathcal{A}}\right) \oplus \left(c^{\mathcal{B}} \boxplus_n k_c^{\mathcal{B}}\right) \oplus \left(c^{\mathcal{C}} \boxplus_n k_c^{\mathcal{C}} \boxplus_n \tilde{d}_i^{\mathcal{C}}\right)$$

- **Smaller** key search space than $\varphi_{2,n}$

$$|\mathcal{K}| = \begin{cases} 2^{3n}, & \text{if } n \leq 12 \\ 2^{2n+12}, & \text{if } 12 \leq n \leq 20 \\ 2^{n+32}, & \text{otherwise} \end{cases}$$



D&C approach on the ChaCha IQR, $n = 8$

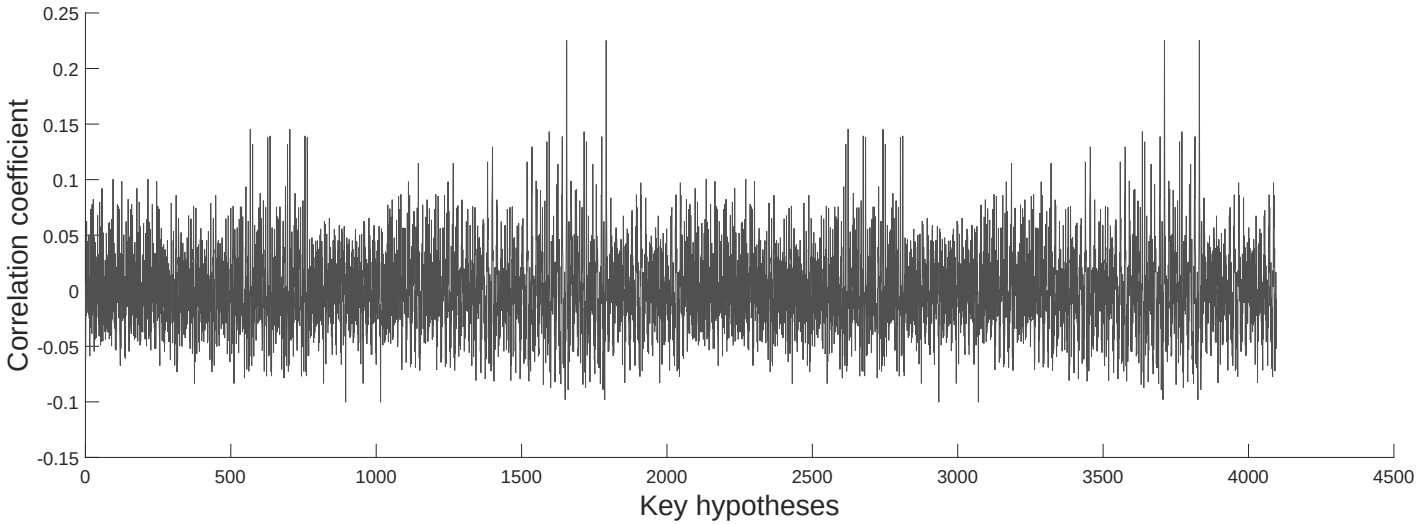
TRUSTED OBJECTS

Benefits of the Inverse Quarter Round

- Carries were taken into account if $p \geq \frac{3}{4}$
- Much **less collisions** than $\varphi_{2,n}$

Proposition

An attack on $\varphi_{4,n}$ returns 4 collisions.



Attack simulation on $\varphi_{4,4}$

TRUSTED OBJECTS

Bricklayer Attack

- **Sequential** approach
- Taking advantage of **windows previously recovered** instead of executing attacks in parallel

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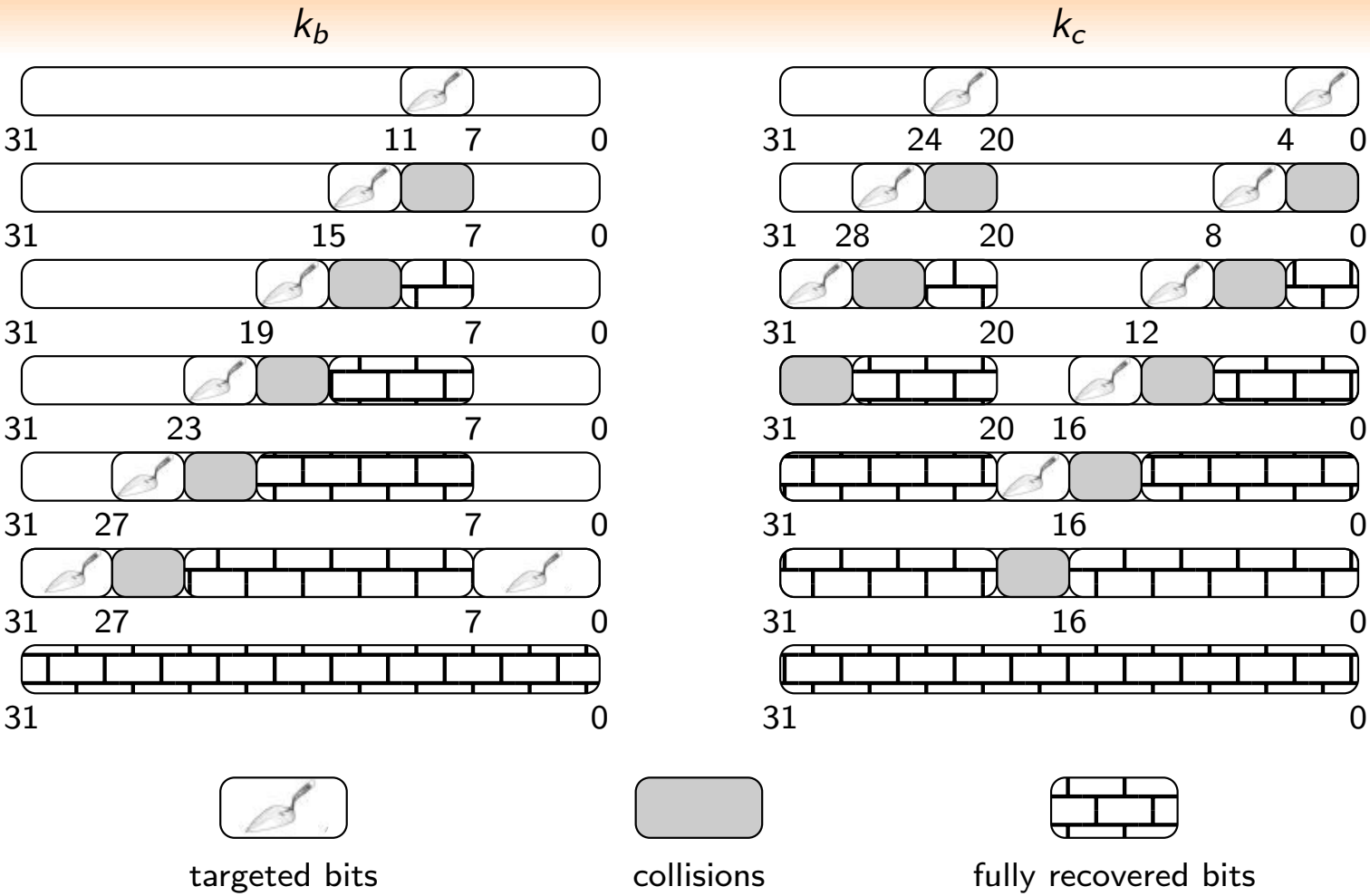
TRUSTED OBJECTS

Bricklayer Attack

- **Sequential** approach
- Taking advantage of **windows previously recovered** instead of executing attacks in parallel
- The **carry estimation is only necessary during the first attack** $\Rightarrow$ especially interesting for $\varphi_{2,n}$
- Collision bits' positions are changed at each attack $\Rightarrow$ some collisions cancelled
- In the case of $\varphi_{4,n}$, collisions only depends on MSBs $\Rightarrow$ **the bricklayer approach allows the correct collision to stand out**

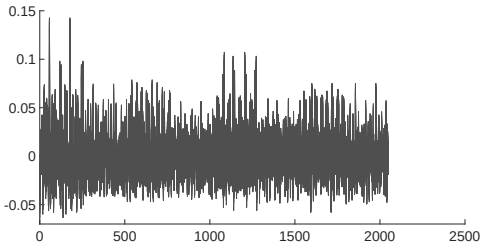
TRUSTED OBJECTS

Bricklayer Attack Overview

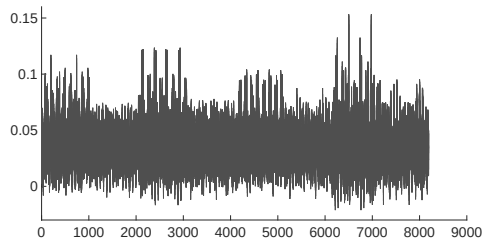


Bricklayer attack example on IQR

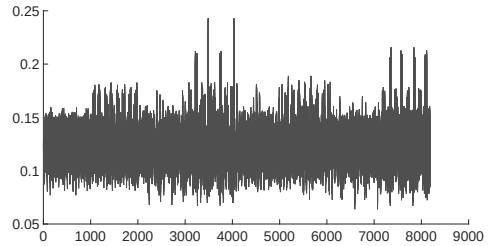
Practical Experiments



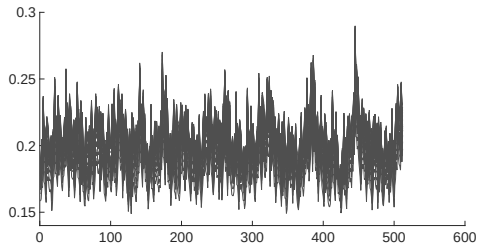
$\kappa = k_7^{23\ldots20} \parallel k_7^{3\ldots0} \parallel k_2^{10\ldots7}$



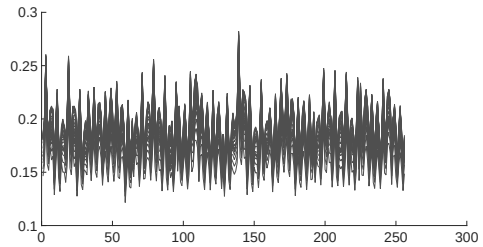
$\kappa = k_7^{27\ldots24} \parallel k_7^{7\ldots4} \parallel k_2^{14\ldots11}$



$\kappa = k_7^{31\ldots28} \parallel k_7^{11\ldots8} \parallel k_2^{18\ldots15}$



$\kappa = k_7^{15\ldots12} \parallel k_2^{22\ldots19}$



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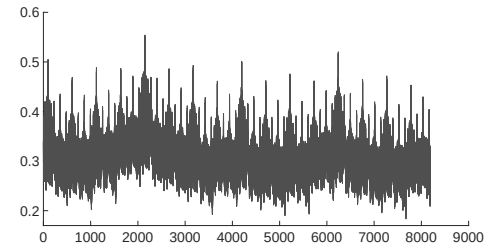

$\kappa = k_2^{31\ldots27} \parallel k_2^{6\ldots0}$

Figure: Bricklayer attack against k_2 and k_7

Application on Existing Protocols

- φ_1 requires the knowledge of **nonces**
- φ_3 requires the knowledge of **plaintexts + ciphertexts + nonces**

TRUSTED OBJECTS

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- XChaCha construction
  -
  - Implemented in **Libsodium** ($\geq$ `1.0.12`)
  - Extend the nonce size to pick it **at random**
  - The nonce is public and must be **sent with the cryptogram**

TRUSTED OBJECTS

Masking ARX Designs

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- Two approaches
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  - Perform additions on the **masked values**

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- Two approaches
  - **Switch** from one masking scheme to the other
  - Perform additions on the **masked values**
- **Boolean-to-arithmetic** conversions are cheap while **arithmetic-to-boolean** are very heavy
- **Secure adders** usually rely on arithmetic to boolean conversions $\Rightarrow$ same complexity

	Time	Penalty factor
ChaCha20 unmasked	4 380	1
ChaCha20 with Karroumi *et al.* SecAdd [3]	121 618	28
ChaCha20 with Coron *et al.* SecAdd [1]	93 993	22

Running time in clock cycles to encrypt a 512-bit block using ChaCha20 on an ARM Cortex-M3

TRUSTED OBJECTS

Conclusion & Perspectives

Conlusions

- ARX designs remain vulnerable to **power/electromagnetic** side-channel
- Our practical setup was able to exploit **memory accesses only**
- Introduced the **Bricklayer attack** with simulated & practical measurements
- Harder to attack the QR than its **reverse function**

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Open Questions

- How could we exploit **ALU operations**? Is **decapping** necessary?
- Can we use these properties to mask a **subset of instructions**?
- Is it possible to implement ChaCha20 in a secure way with **reasonable performances**?

TRUSTED OBJECTS

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Thank you for your attention!

Questions?

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