Minimalism in Symmetric Cryptography

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Minimalism

Credit: Hans Peter Schaefer

Maybe less exciting?

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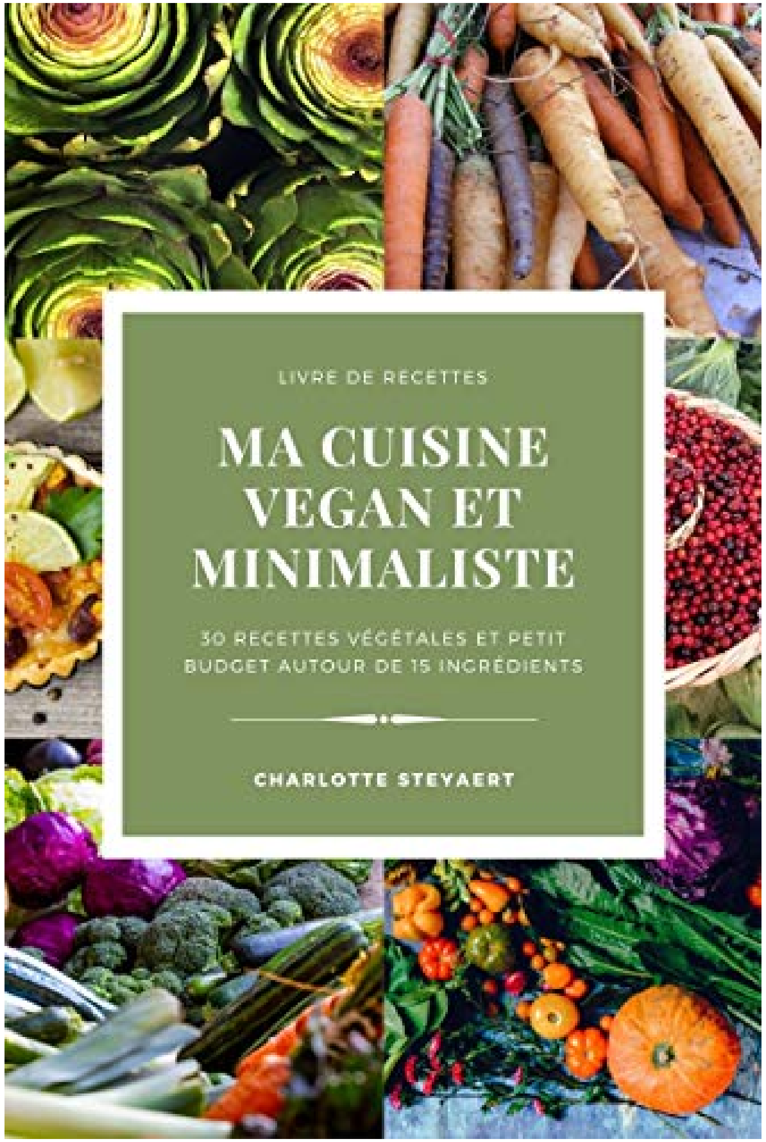

Why is minimalism interesting?

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Besides (niche) application needs, it helps us understand where security comes from.

Outline

1. Designing a practical PRP
2. How to make it lightweight?
3. Possible weaknesses coming from “minimal” Sboxes

Designing a Practical PRP

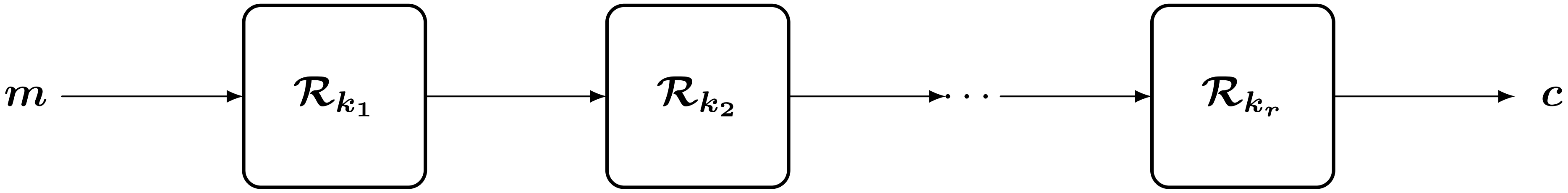
Practical PRP

$$E_k : \{0,1\}^n \longrightarrow \{0,1\}^n$$

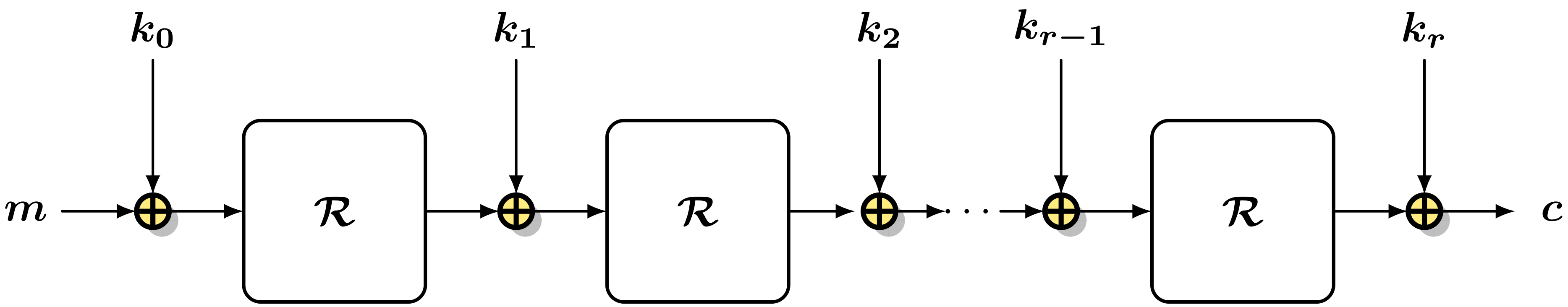
- indistinguishable from randomly chosen permutations of $\{0,1\}^n$ with $n \in \{64, 128\}$
- implementable

$\rightarrow$ Contradiction!

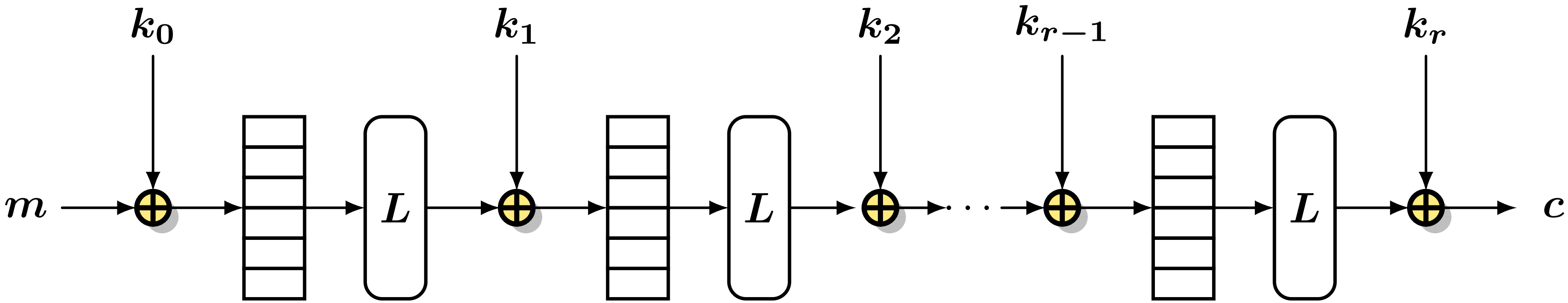
Iterated construction



Iterated construction



Iterated construction



AES [Daemen-Rijmen 98][FIPS PUB 197]

- blocksize: $\mathbf{128}$ bits
- $\mathbf{10}$ rounds for the $\mathbf{128}$-bit key version
- Sbox operates on $\mathbf{8}$ bits
- diffusion layer is linear over $\mathbf{F}_{\mathbf{2}^8}$
- nonlinear key schedule.

How to make it lightweight?

Lightweight block ciphers

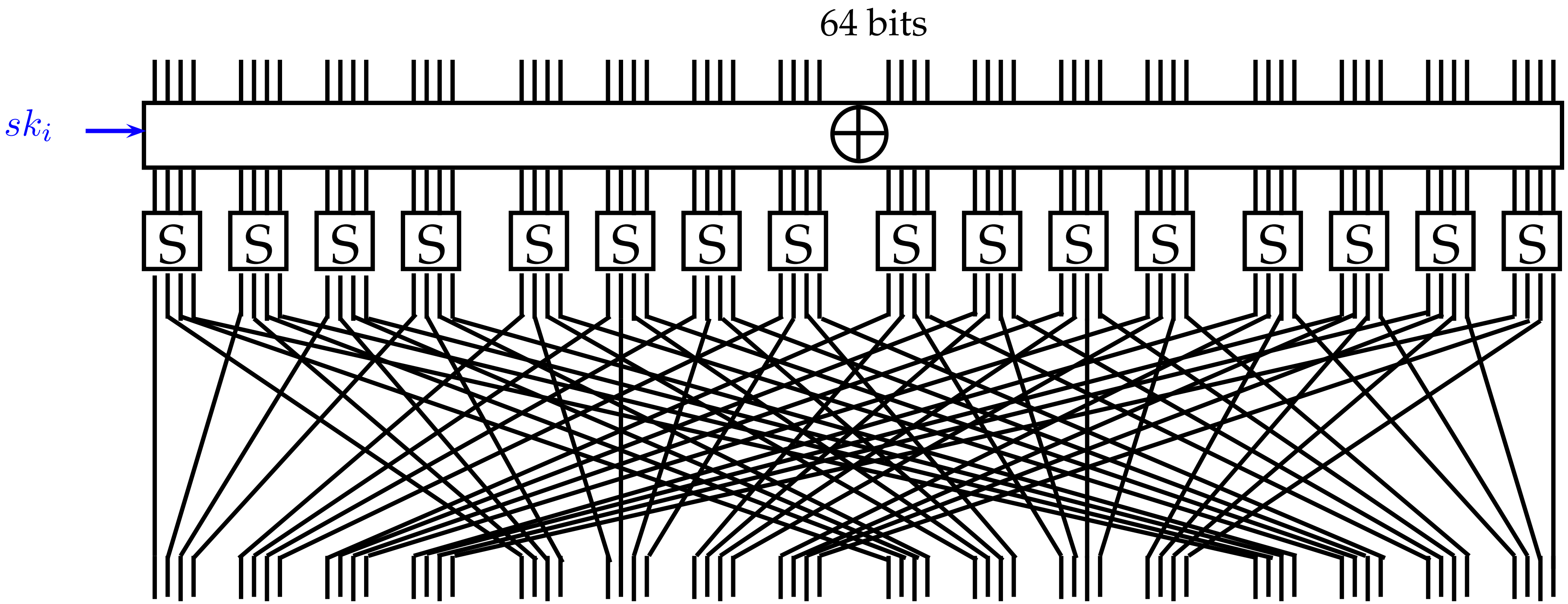
AES [Daemen-Rijmen 98][FIPS PUB 197]

- blocksize: 128 bits
- Sbox operates on 8 bits
- diffusion layer is linear over $\mathbf{F}_{2^8}$

To make it smaller in hardware:

- blocksize: 64 bits
- smaller Sbox, on 3 or 4 bits
- linear diffusion layer over a smaller alphabet
- simplified key-schedule

The usual design strategy: PRESENT [Bogdanov et al. 07]



31 rounds (+ a key addition)

Lightweight but secure...

Increase the number of rounds!

- PRESENT [Bogdanov et al. 07]. 31 rounds
- LED [Guo et al. 11]:
  LED-64: 32 rounds, LED-128: 48 rounds
- SPECK [Beaulieu et al. 13]:
  SPECK64/128: 27 rounds, SPECK128/256: 34 rounds
- SIMON [Beaulieu et al. 13]:
  SIMON64/128: 44 rounds, SIMON128/256: 72 rounds

Does lightweight mean "light + wait"? [Knežević et al. 12]

Lightweight Competitions

CAESAR for authenticated encryption (2014-2019) :

`https://competitions.cr.yp.to/caesar.html`

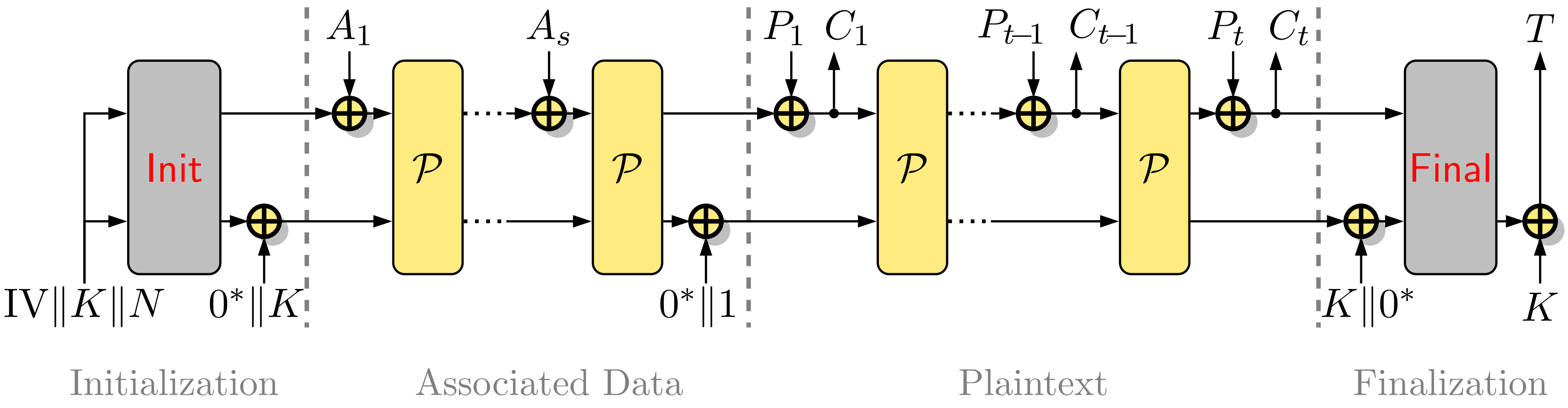
Use case 1: Lightweight applications (resource constrained environments)

1. Ascon [Dobraunig, Eichlseder, Mendel, Schläffer 14]
2. Acorn [Wu 14]

NIST Lightweight Cryptography standardization process (2019-2023)

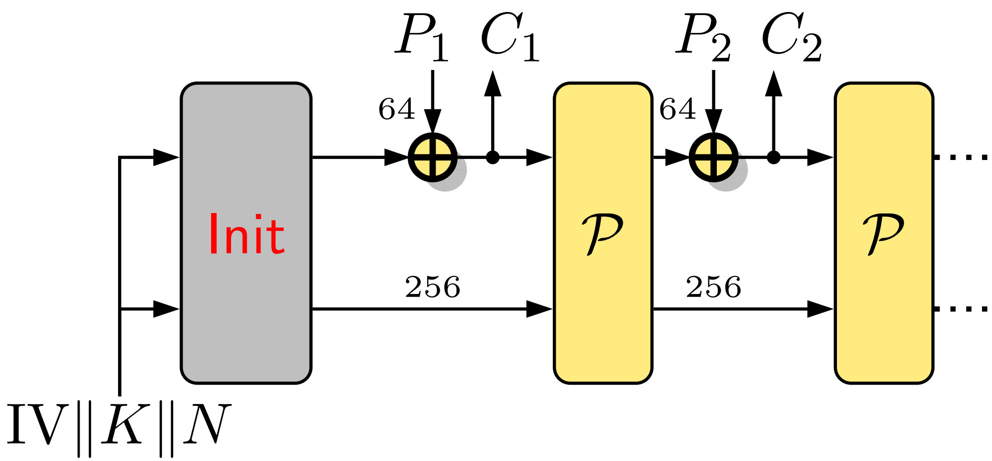
Ascon family (announced in Feb. 2023)

Duplex-Sponge mode for AEAD encryption [Bertoni et al. 12]



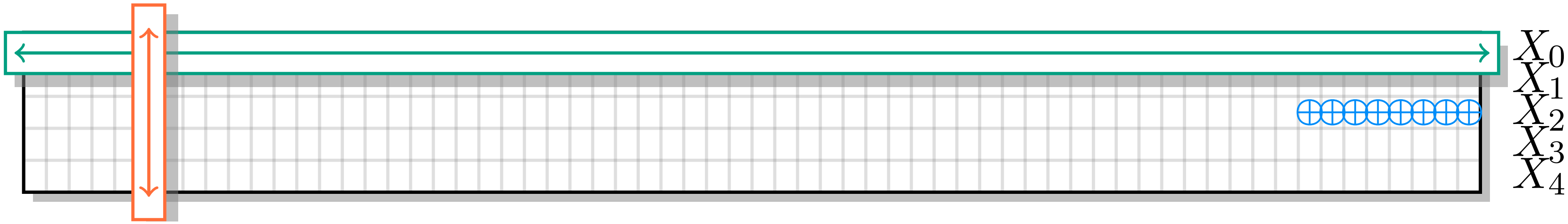
where $\mathcal{P}$ is a permutation of $\{0,1\}^n$.

Duplex-Sponge mode in Ascon



where $\mathcal{P}$ is a permutation on 320 bits of which 64 are known/controlled.

$\mathcal{P}$ in Ascon [Dobraunig, Eichlseder, Mendel, Schläffer 16]



Permutation operating on a 320-bit state:

- 8-bit constant addition;
- Nonlinear Sbox on 5 bits of degree 2 (on the 64 columns);
- 5 simple linear transformations on 64 bits

$$\Sigma_i(X_i) = X_i \oplus (X_i \ggg a_i) \oplus (X_i \ggg b_i)$$

$\rightarrow$ 6 rounds

Use low-cost Sboxes

Algebraic Normal Form of $f : \mathbf{F}_2^n \rightarrow \mathbf{F}_2$:

unique polynomial representation in $\mathbf{F}_2[x_1, \ldots, x_n]/(x_1^2 - x_1, \ldots, x_n^2 - x_n)$.

$$f(x_1, \ldots, x_n) = \bigoplus_{u \in \mathbb{F}_2^n} c_u x^u \text{ with } c_u \in \mathbb{F}_2$$

Evaluation of a monomial:

Evaluation of $x^{(0101)}$ at $x = (0011)$:

$$0^0 0^1 1^0 1^1 = 1011 = 0$$

$$x^u = 1 \text{ if and only if } u \preceq x$$

i.e., $u_i \leq x_i$ for all $1 \leq i \leq n$.

ANF and values:

$$f(a) = \bigoplus_{u \preceq a} c_u \text{ and } c_u = \bigoplus_{a \preceq u} f(a)$$

Cube-like attacks [Dinur-Shamir 09]

$$\begin{array}{rccc} f: & \mathbb{F}_2^{64} \times \mathbb{F}_2^{256} & \to & \mathbb{F}_2 \\ & (x, k) & \mapsto & f(x, k) \end{array}$$

$$f(x, k) = \bigoplus_{u \in \mathbb{F}_2^{64}} \underbrace{\left(\bigoplus_{u \in \mathbb{F}_2^{256}} \alpha_{u,v} \; k^v \right)}_{A_u(k)} x^u$$

Attack:

- Offline: determine the polynomial expression of $A_u(k)$ for a given u.
- Online: for the key used k^*, compute the value

$$A_u(k^*) = \bigoplus_{v \preceq u} f(v, k^*)$$

Cube-like attacks on Ascon [Rohit et al. 21][Baudrin-C.-Perrin 22]

$$S(x, a, b, c, d) = \begin{cases} (a \oplus 1)x & \oplus \quad ab \oplus ad \oplus a \oplus b \oplus c \\ x & \oplus \quad ab \oplus ac \oplus bc \oplus a \oplus b \oplus c \oplus d \\ & \quad\;\; cd \oplus a \oplus b \oplus d \oplus 1 \\ (c \oplus d \oplus 1)x & \oplus \quad a \oplus b \oplus c \oplus d \\ ax & \oplus \quad ad \oplus a \oplus c \oplus d \end{cases}$$

→ The degree in x after r rounds is 2^{r-1}, for $r \leq 6$.

After two rounds:

The coefficient of $x_0 x_i$ is

$$(a_0 \oplus 1)P \oplus Q \oplus (c_0 \oplus d_0 \oplus 1)R \oplus a_0 S.$$

For some well-chosen i, it equals $(a_0 \oplus 1)P$ or $(c_0 \oplus d_0 \oplus 1)R$.

Cube attack on Ascon [Baudrin-C.-Perrin 22]

After six rounds:

For all 64 outputs, the coefficient of some monomials of degree $\mathbf{2^5}$ containing x_0 can be written as

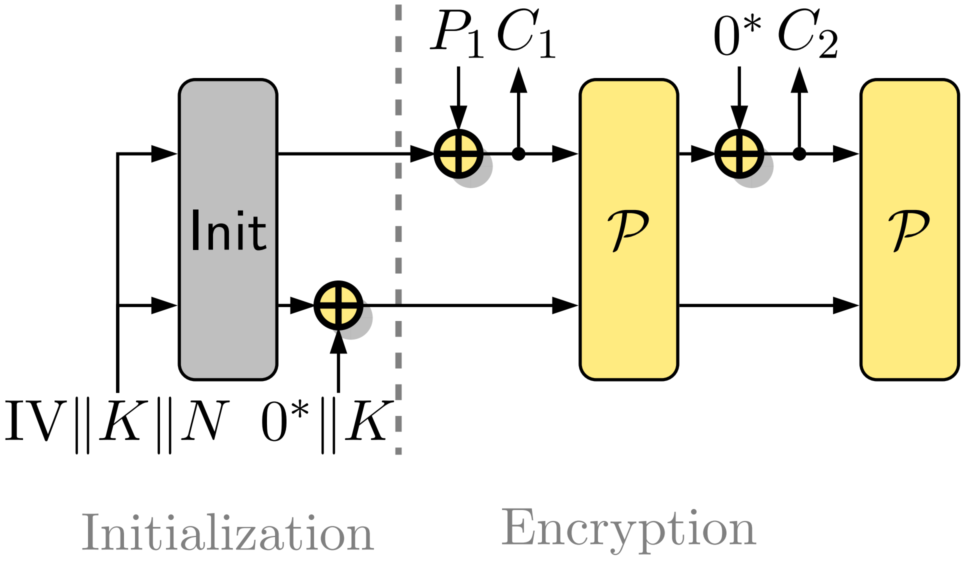
$$(a_0 \oplus 1)P \oplus (c_0 \oplus d_0 \oplus 1)R$$

$\rightarrow$ If these 64 coefficients do not all vanish, then

$$a_0 = 0 \text{ or } c_0 \oplus d_0 = 0$$

$+$ The converse also holds in practice.

Practical attack in the nonce-misused scenario [Baudrin-C.-Perrin 22]



Recover the full initial state from less than $\mathbf{2^{39.6}}$ ciphertexts obtained from the same $(\boldsymbol{K}, \boldsymbol{N})$ with time complexity $\mathbf{2^{40}}$.

Minimalism in cryptography is more fun than in cooking