- Agenda: explore **implementation attacks** via
  1. an "in theory", i.e., concept-oriented perspective,
     - 1.1 explanation,
     - 1.2 justification,
     - 1.3 formalisation.

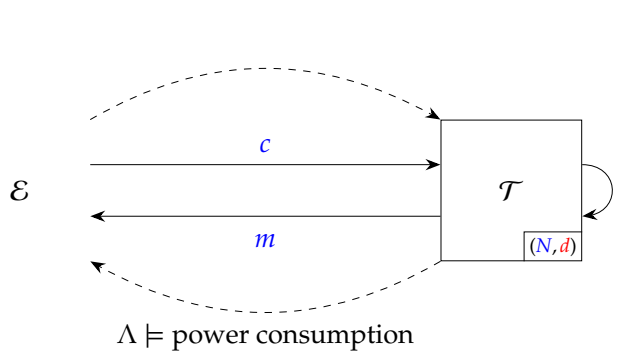
     and
  2. an "in practice", i.e., example-oriented perspective,
     - 2.1 attacks,
     - 2.2 countermeasures.
- Caveat!

  ~ 2 hours ⇒ introductory, and (very) selective (versus definitive) coverage.

Part 2.1: in practice (1)

Attacks: $\mathcal{T} \simeq$ RSA, Λ = power consumption

- Scenario:
  - given the following interaction between an **attacker** $\mathcal{E}$ and a **target** $\mathcal{T}$



$$m = \text{RSA.Dec}((N, d), c) = c^d \pmod{N}$$

```
1  algorithm RSA.Dec((N, d), c) begin
2      Pre-compute Π = (N, ρ, ω) from N
3      ĉ ← MontMul(Π, c, ρ² mod N)
4      r̂ ← MontMul(Π, c, ρ² mod N)
5      for i = |d| − 2 downto 0 do
6          r̂ ← MontSqr(Π, r̂)
7          if d_i = 1 then
8              r̂ ← MontMul(Π, r̂, ĉ)
9          end
10     end
11     return MontMul(Π, r̂, 1)
12 end
```

  - and noting that
    - there are no countermeasures implemented,
    - a dedicated Montgomery squaring implementation, i.e.,

$$\text{MontSqr}(\Pi, \hat{r}) = \hat{r} \times \hat{r} \times \rho^{-1} \pmod{N},$$

      is used, such that although

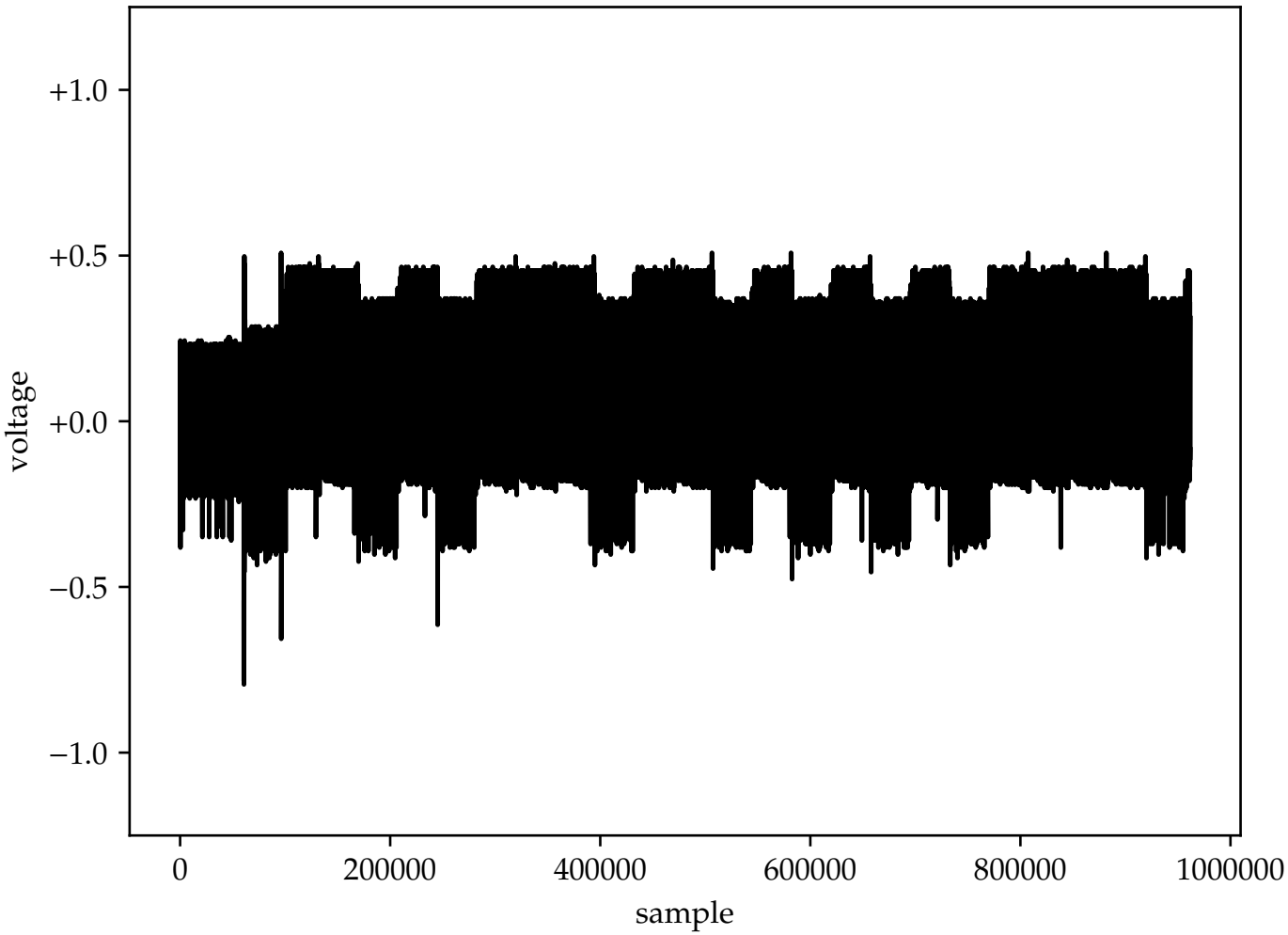
$$\text{MontSqr}(\Pi, \hat{r}) = \text{MontMul}(\Pi, \hat{r}, \hat{r}),$$

      the former is more efficient than the latter,
    - the Montgomery squaring and Montgomery multiplication implementations are FIOS-based [10],
  - how can $\mathcal{E}$ mount a successful attack, i.e., recover d ?

Part 2.1: in practice (2)

Attacks: $\mathcal{T} \simeq$ RSA, $\Lambda =$ power consumption

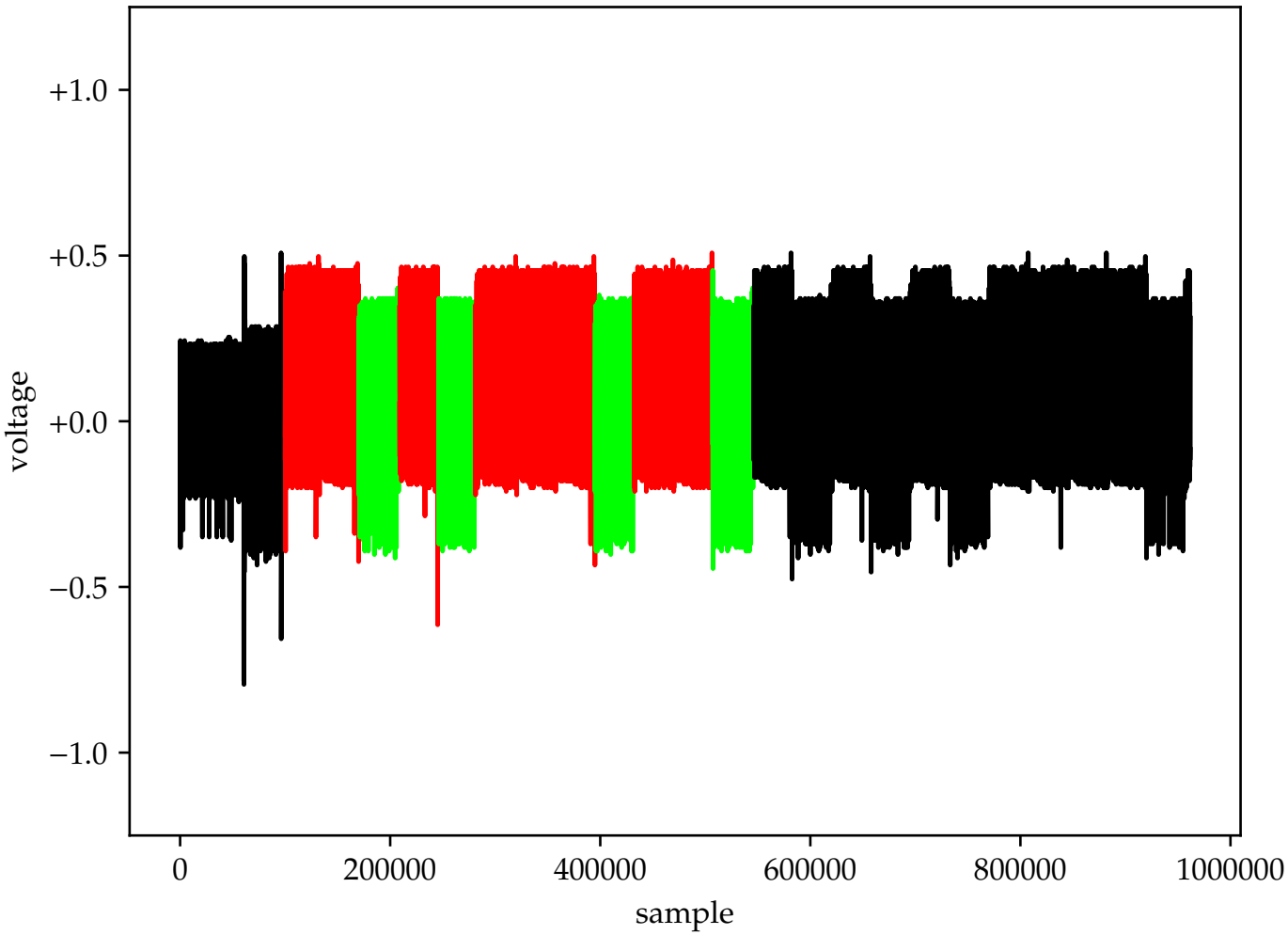
- Example: ARM Cortex-M3, $|N| = 1024$.



Part 2.1: in practice (2)

Attacks: $\mathcal{T} \simeq$ RSA, $\Lambda =$ power consumption

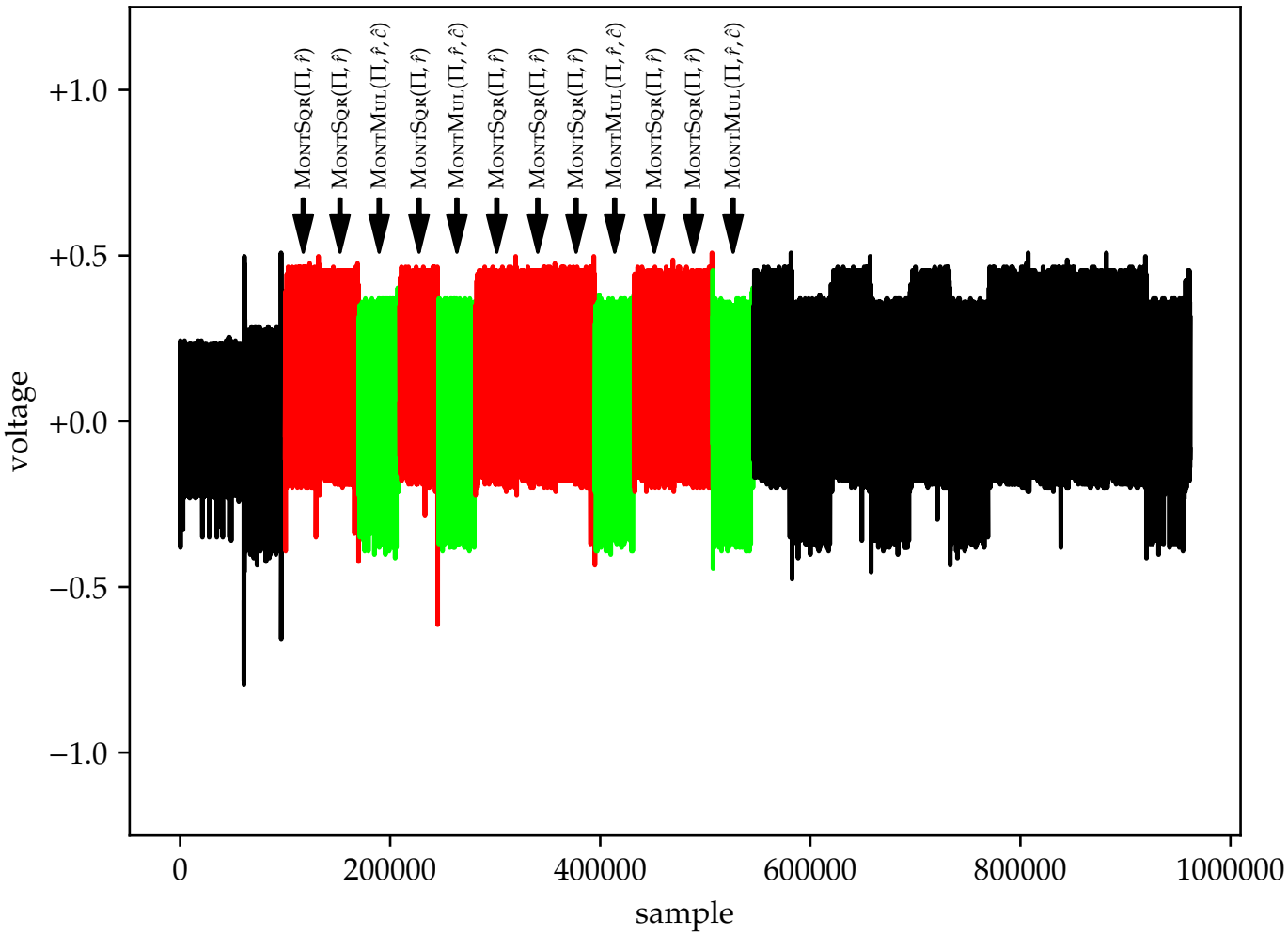
- Attack [11]:



Part 2.1: in practice (2)

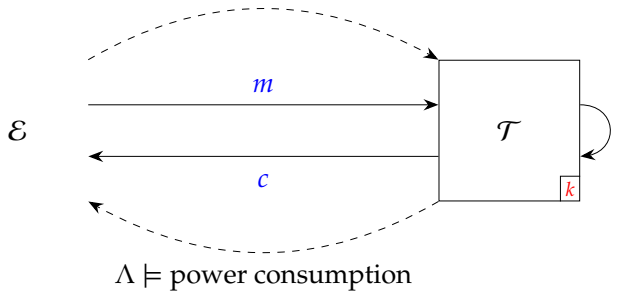
Attacks: $\mathcal{T} \simeq$ RSA, $\Lambda =$ power consumption

- Attack [11]:



Part 2.1: in practice (3)
Attacks: $\mathcal{T} \simeq$ AES, Λ = power consumption

- Scenario:
  - given the following interaction between an **attacker** $\mathcal{E}$ and a **target** $\mathcal{T}$



c = AES-128.Enc(k, m)

```
1  algorithm AES-128.Enc(k, m) begin
2      s ← m
3      s ← AddRoundKey(s, k = rk^(0))
4      for r = 1 upto 9 step +1 do
5          k ← EvolveRoundKey(k, rc^(r))
6          s ← SubBytes(s)
7          s ← ShiftRows(s)
8          s ← MixColumns(s)
9          s ← AddRoundKey(s, k = rk^(r))
10     end
11     k ← EvolveRoundKey(k, rc^(10))
12     s ← SubBytes(s)
13     s ← ShiftRows(s)
14     s ← AddRoundKey(s, k = rk^(10))
15     c ← s
16     return c
17 end
```

  - and noting that
    - there are no countermeasures implemented,
    - in the first round, the implementation computes

$$\text{S-box}(m_t \oplus k_t)$$

      for $0 \leq t < 16$: we can target this operation, and so recover each t-th byte independently,
    - power consumption can be modelled by Hamming weight, i.e.,

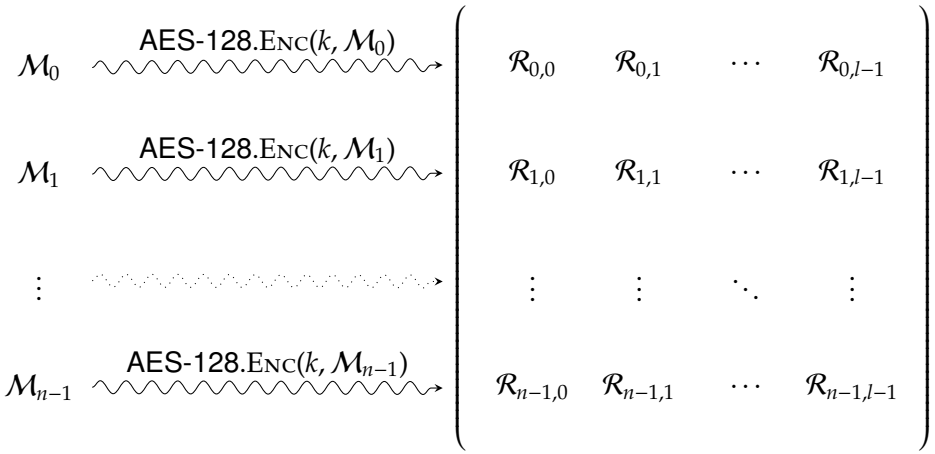
$$\text{HW}(\text{S-box}(m_t \oplus k_t))$$

      models the power consumption of the target operation (or result of it),
  - how can $\mathcal{E}$ mount a successful attack, i.e., recover k ?

Part 2.1: in practice (4)

Attacks: $\mathcal{T} \simeq$ AES, $\Lambda =$ power consumption

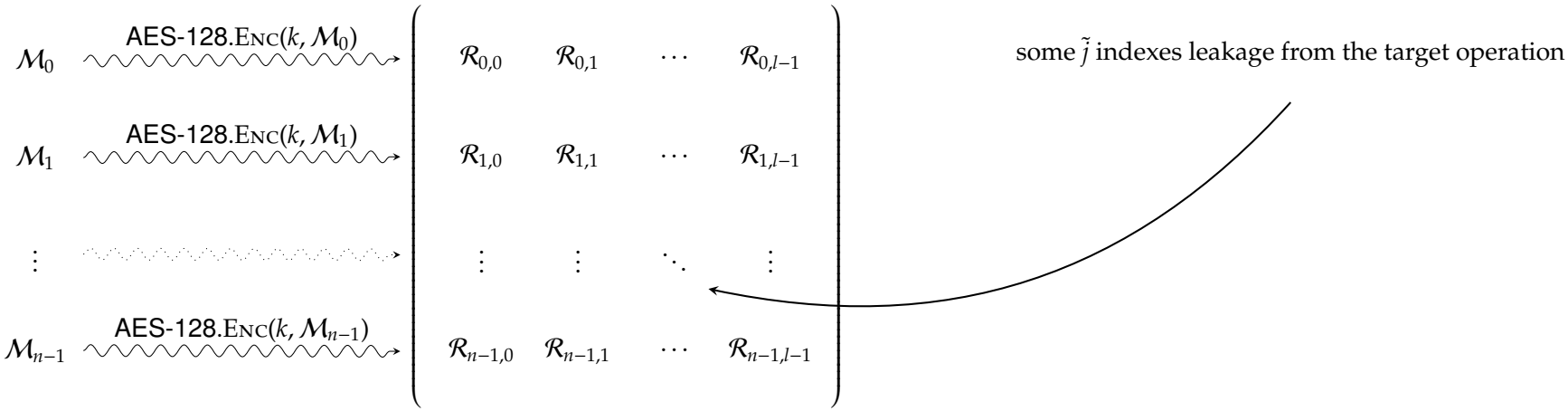
- Attack [7]:



Part 2.1: in practice (4)

Attacks: $\mathcal{T} \simeq$ AES, $\Lambda =$ power consumption

- Attack [7]:



Part 2.1: in practice (4)

Attacks: $\mathcal{T} \simeq$ AES, $\Lambda =$ power consumption

- Attack [7]:

$$
\begin{array}{ll}
\mathcal{M}_0 & \xrightarrow{\text{AES-128.Enc}(k, \mathcal{M}_0)} \\
\mathcal{M}_1 & \xrightarrow{\text{AES-128.Enc}(k, \mathcal{M}_1)} \\
\vdots & \\
\mathcal{M}_{n-1} & \xrightarrow{\text{AES-128.Enc}(k, \mathcal{M}_{n-1})}
\end{array}
\begin{pmatrix}
\mathcal{R}_{0,0} & \mathcal{R}_{0,1} & \cdots & \mathcal{R}_{0,l-1} \\
\mathcal{R}_{1,0} & \mathcal{R}_{1,1} & \cdots & \mathcal{R}_{1,l-1} \\
\vdots & \vdots & \ddots & \vdots \\
\mathcal{R}_{n-1,0} & \mathcal{R}_{n-1,1} & \cdots & \mathcal{R}_{n-1,l-1}
\end{pmatrix}
$$

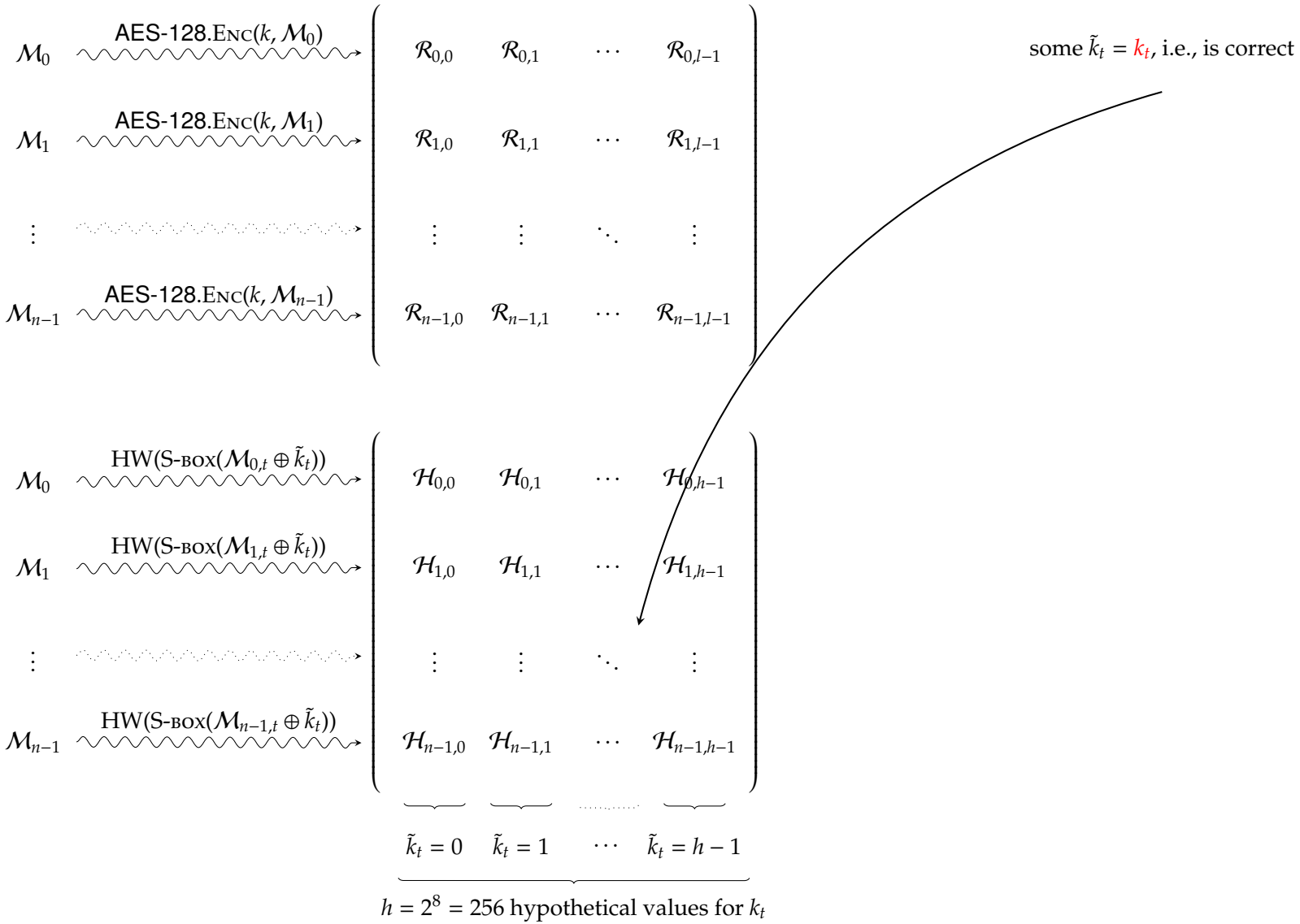
$$
\begin{array}{ll}
\mathcal{M}_0 & \xrightarrow{\text{HW}(\text{S-box}(\mathcal{M}_{0,t} \oplus \tilde{k}_t))} \\
\mathcal{M}_1 & \xrightarrow{\text{HW}(\text{S-box}(\mathcal{M}_{1,t} \oplus \tilde{k}_t))} \\
\vdots & \\
\mathcal{M}_{n-1} & \xrightarrow{\text{HW}(\text{S-box}(\mathcal{M}_{n-1,t} \oplus \tilde{k}_t))}
\end{array}
\underbrace{\begin{pmatrix}
\mathcal{H}_{0,0} & \mathcal{H}_{0,1} & \cdots & \mathcal{H}_{0,h-1} \\
\mathcal{H}_{1,0} & \mathcal{H}_{1,1} & \cdots & \mathcal{H}_{1,h-1} \\
\vdots & \vdots & \ddots & \vdots \\
\mathcal{H}_{n-1,0} & \mathcal{H}_{n-1,1} & \cdots & \mathcal{H}_{n-1,h-1}
\end{pmatrix}}_{\begin{array}{cccc} \tilde{k}_t = 0 & \tilde{k}_t = 1 & \cdots & \tilde{k}_t = h-1 \end{array}}
$$

$h = 2^8 = 256$ hypothetical values for k_t

Part 2.1: in practice (4)

Attacks: $\mathcal{T} \simeq$ AES, $\Lambda =$ power consumption

- Attack [7]:



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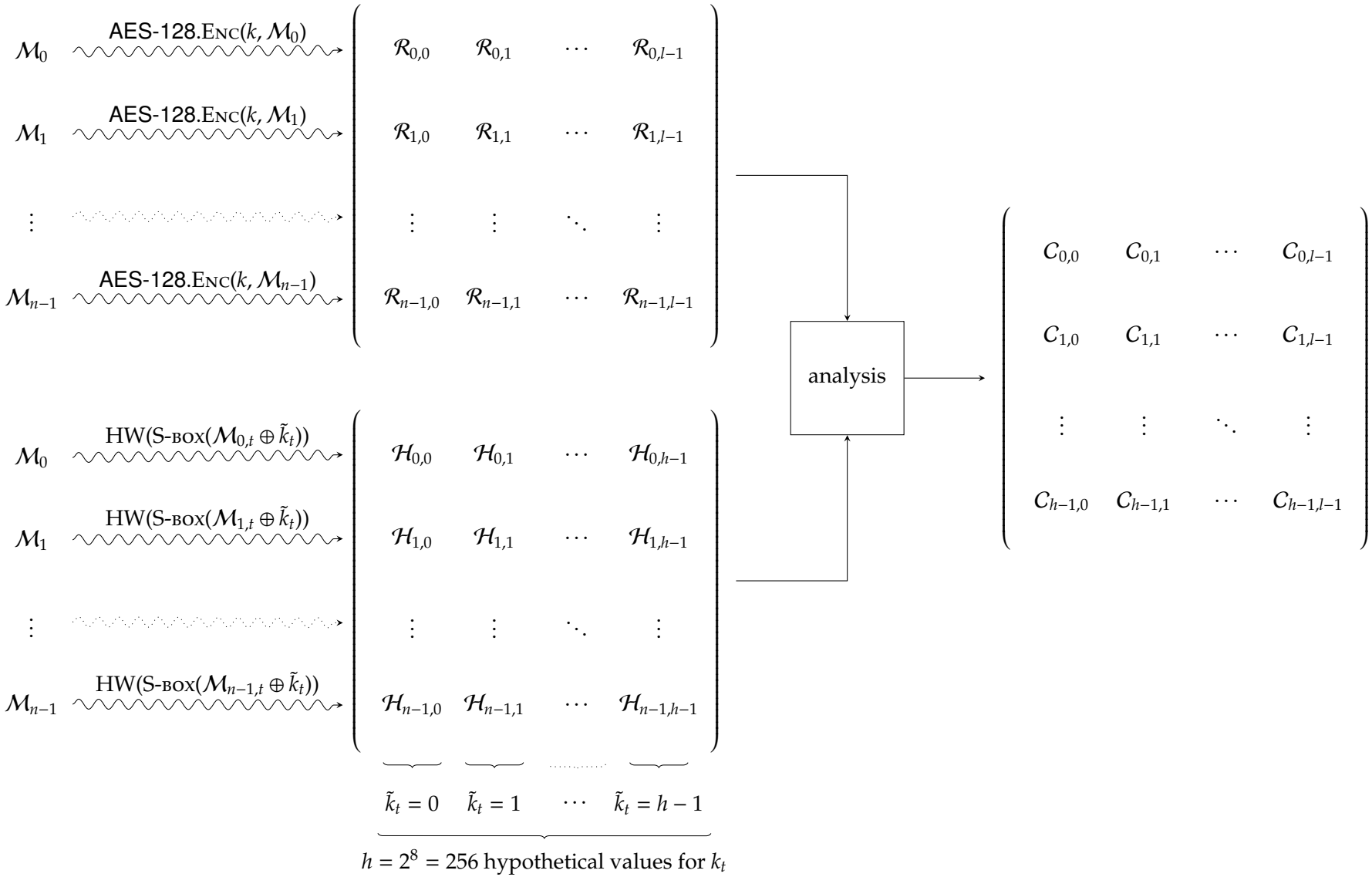

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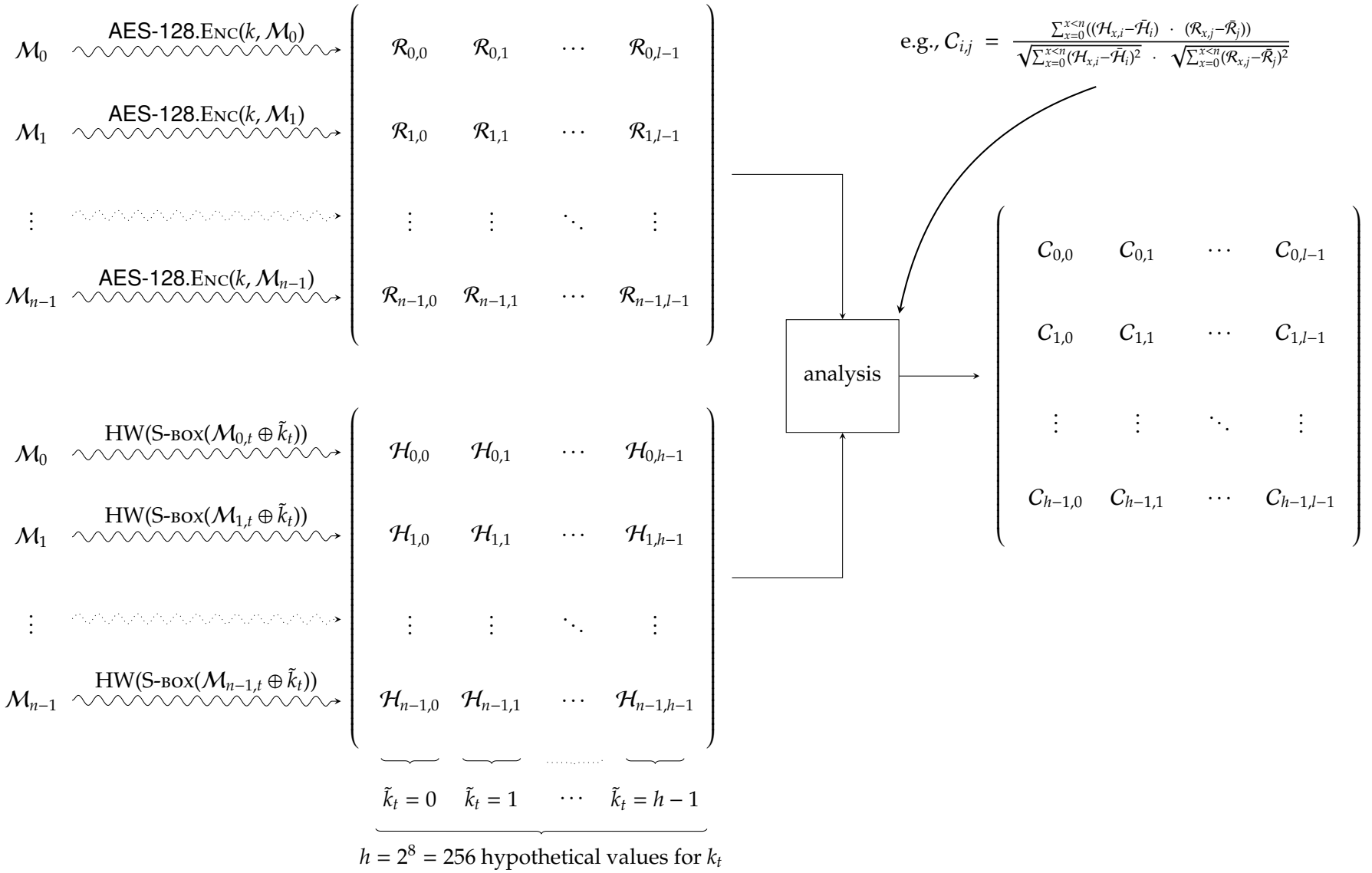

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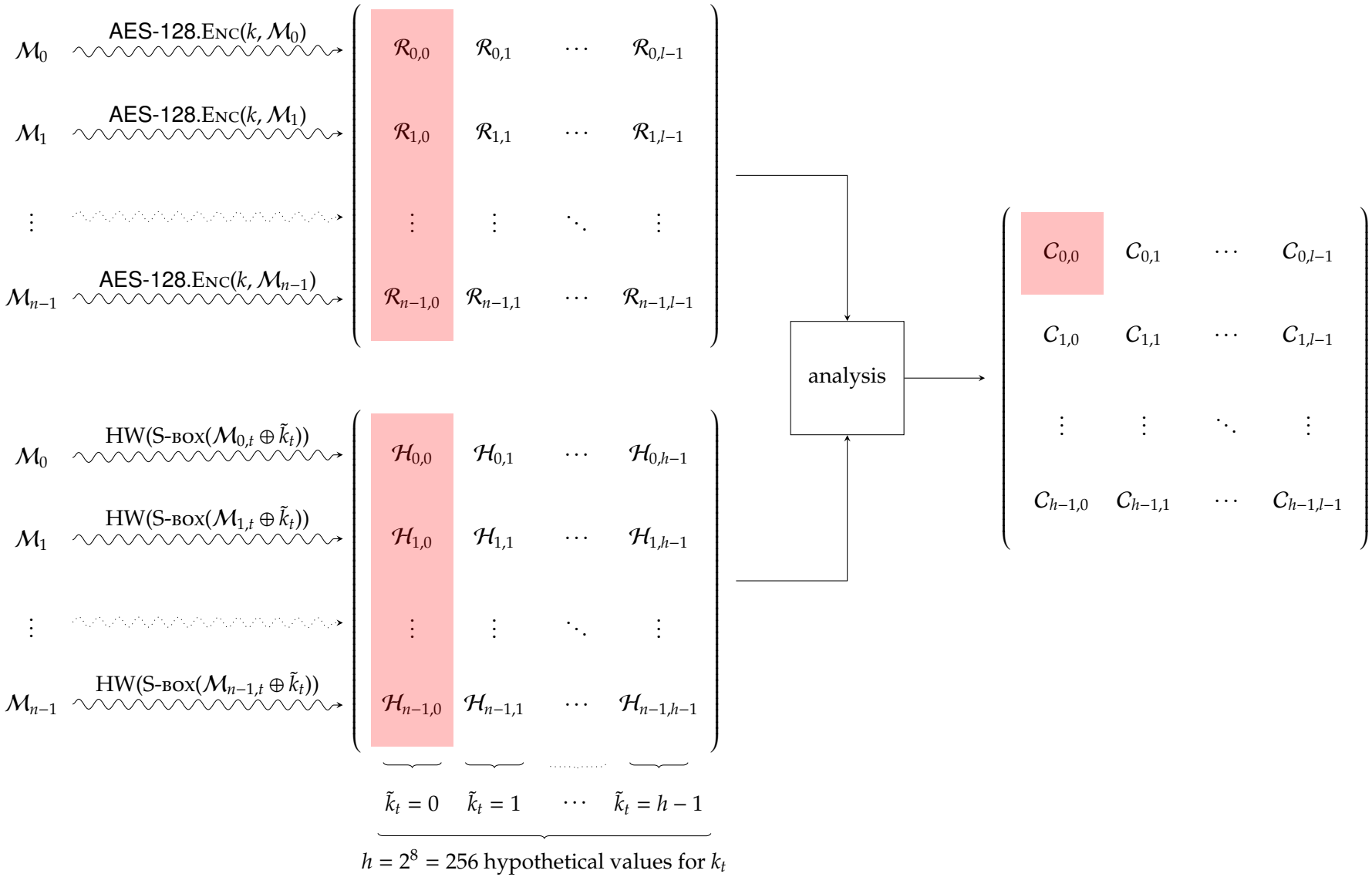

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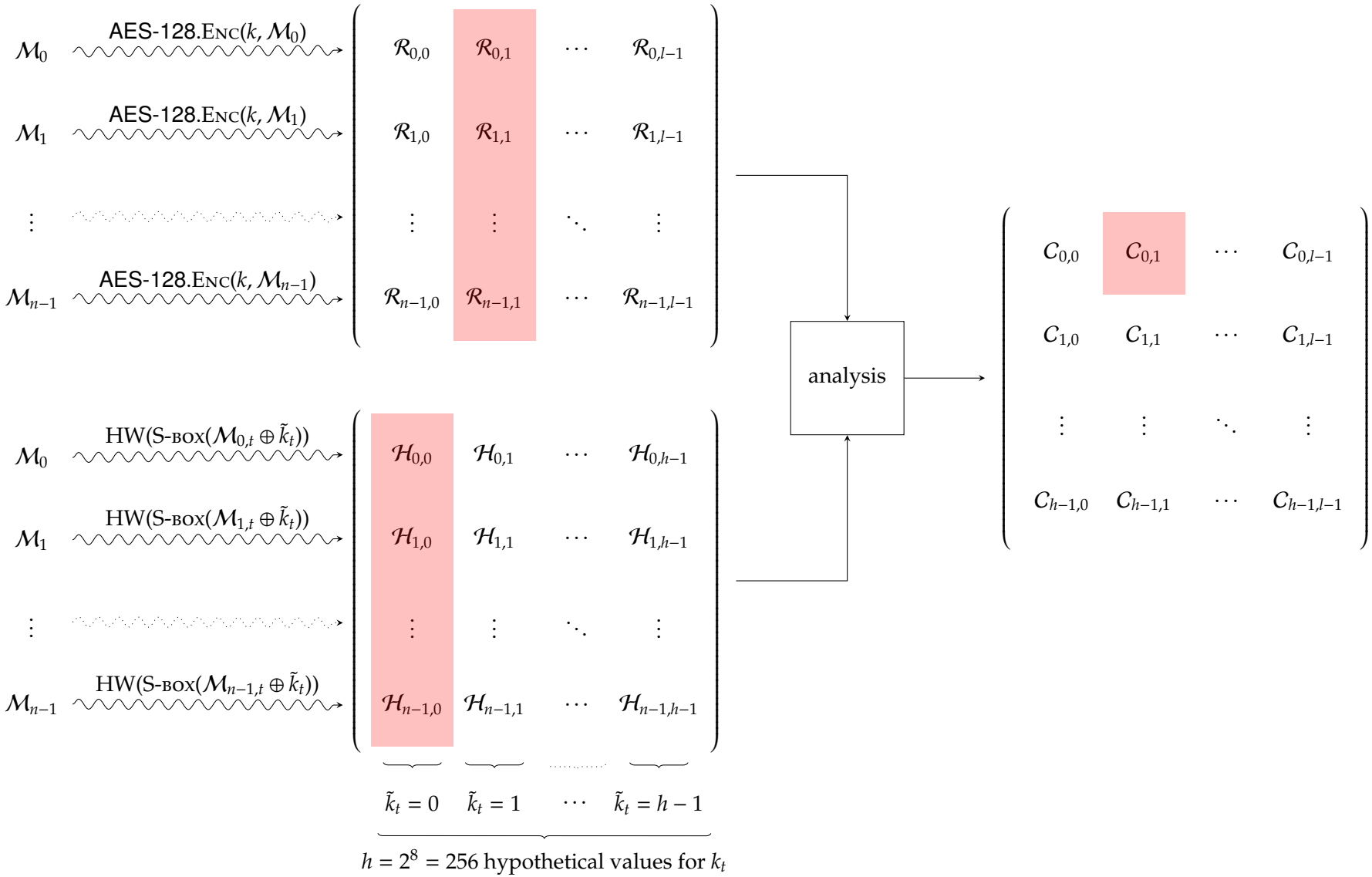

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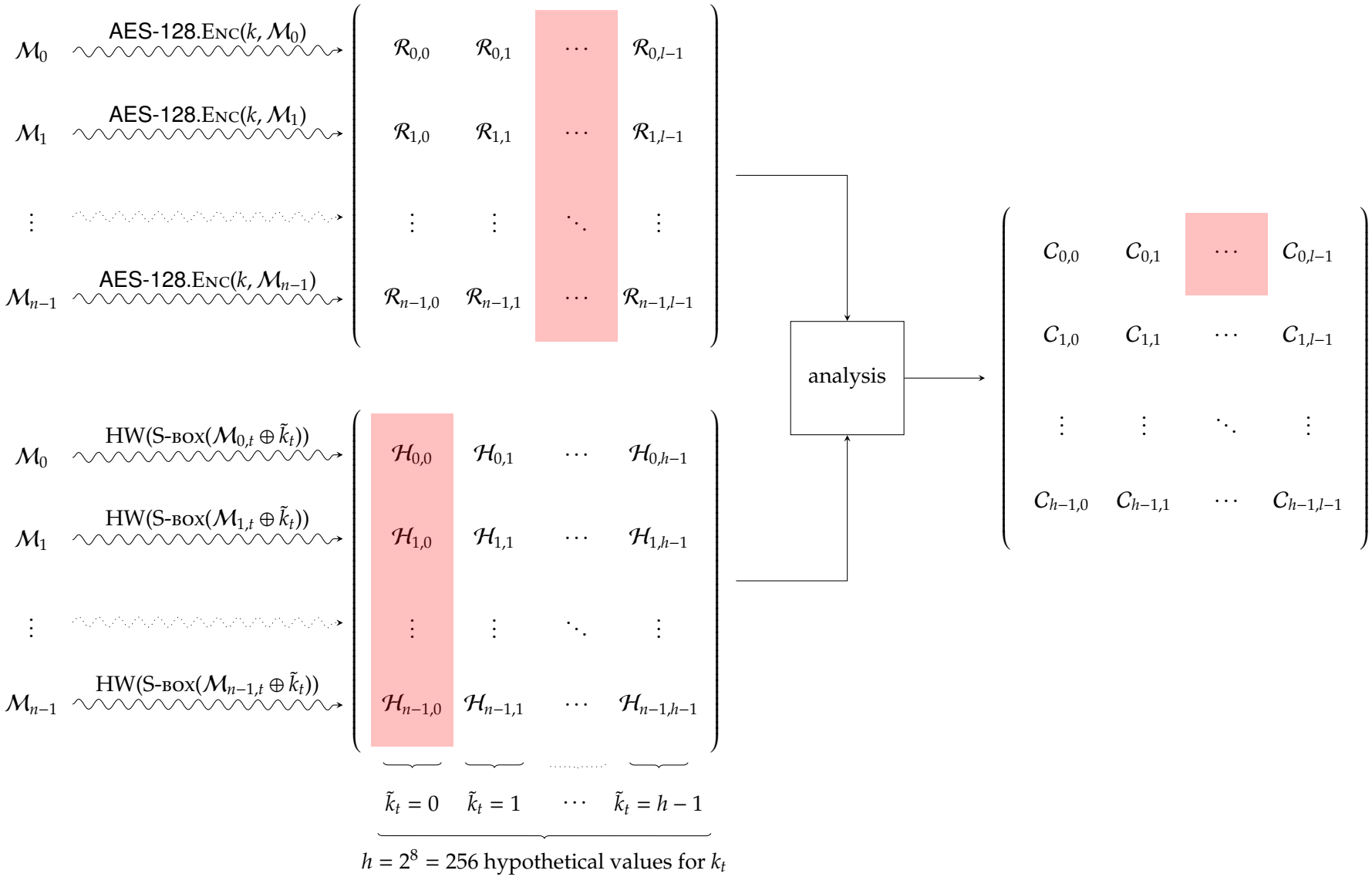

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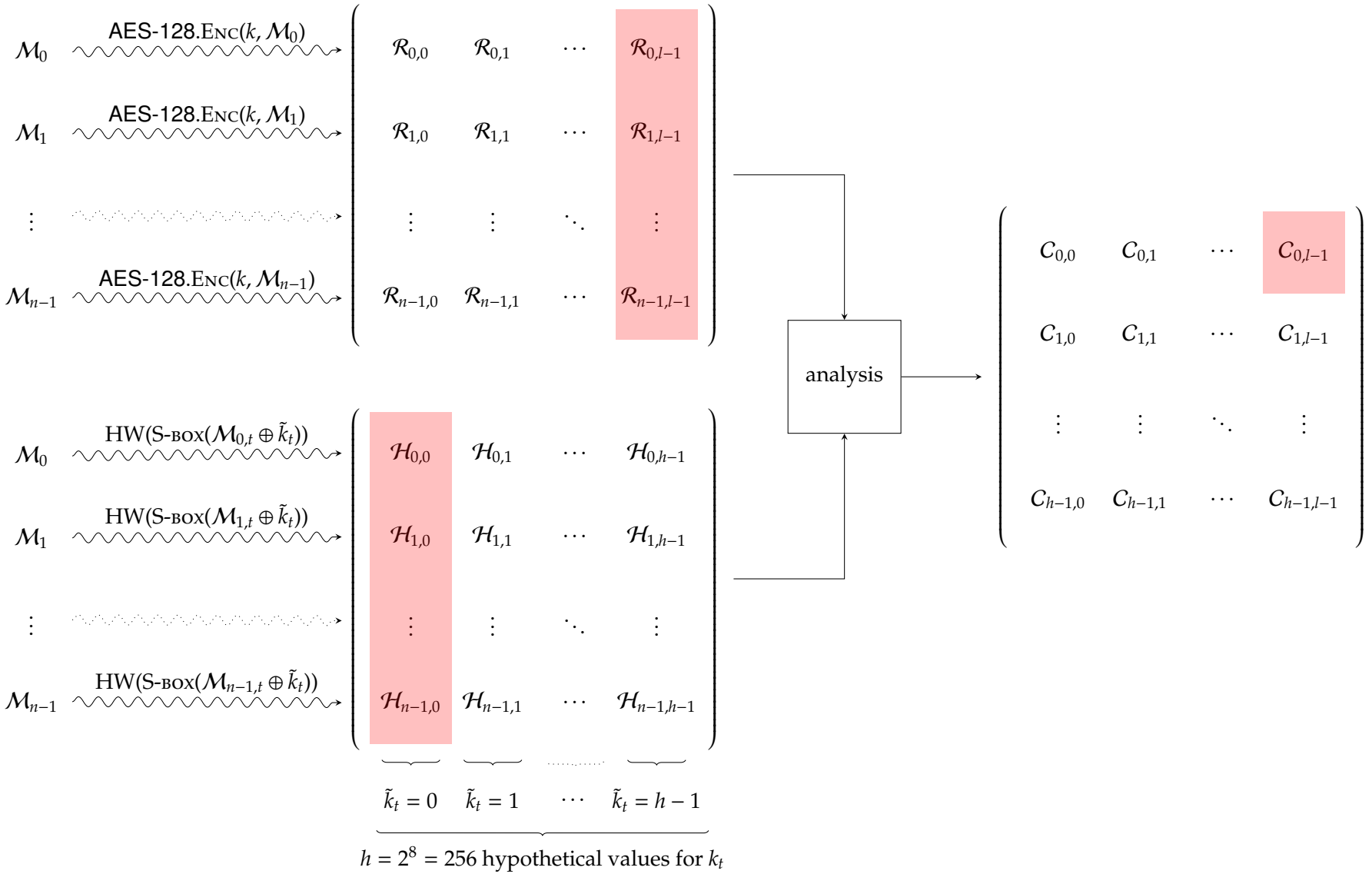

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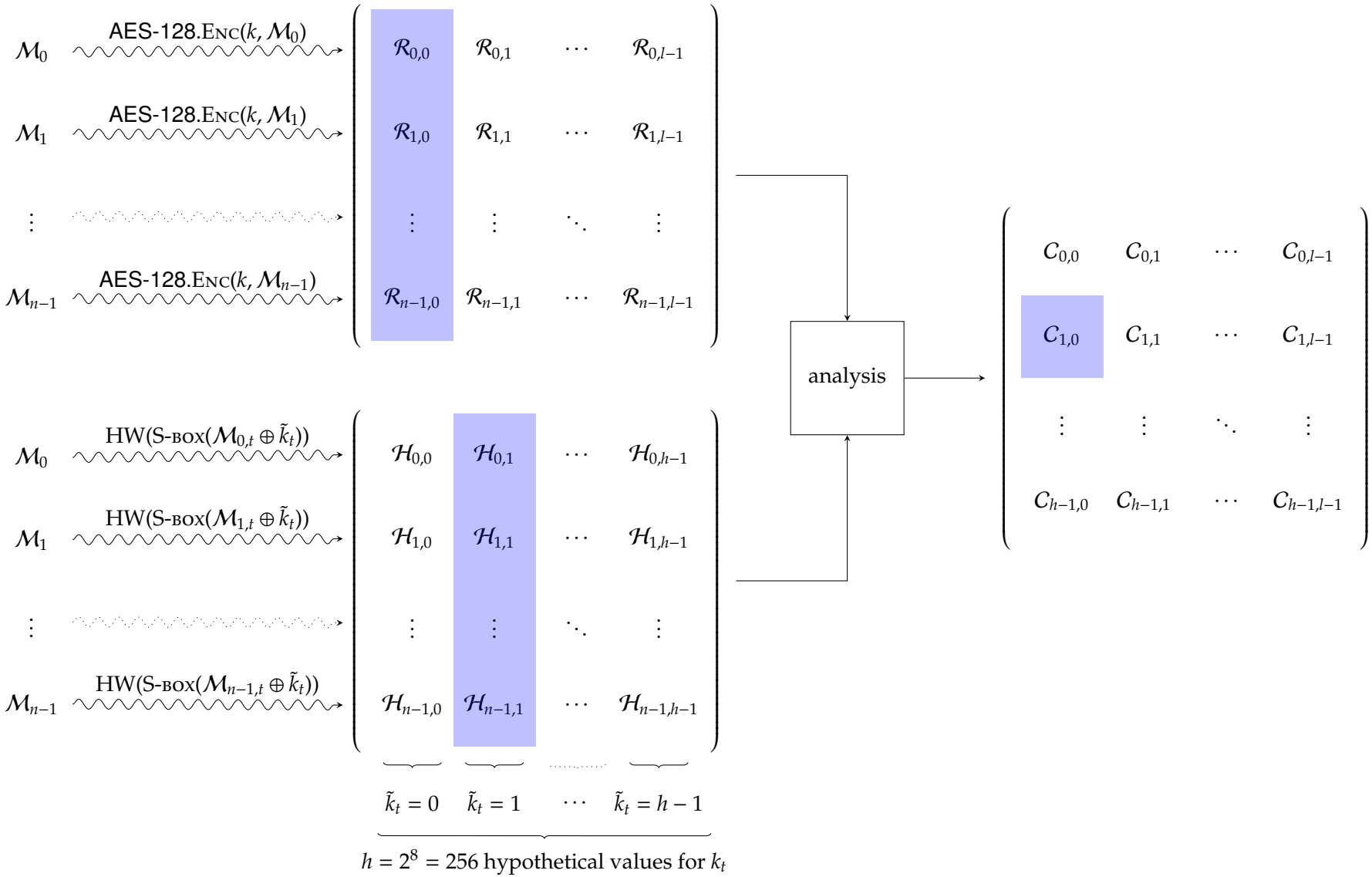

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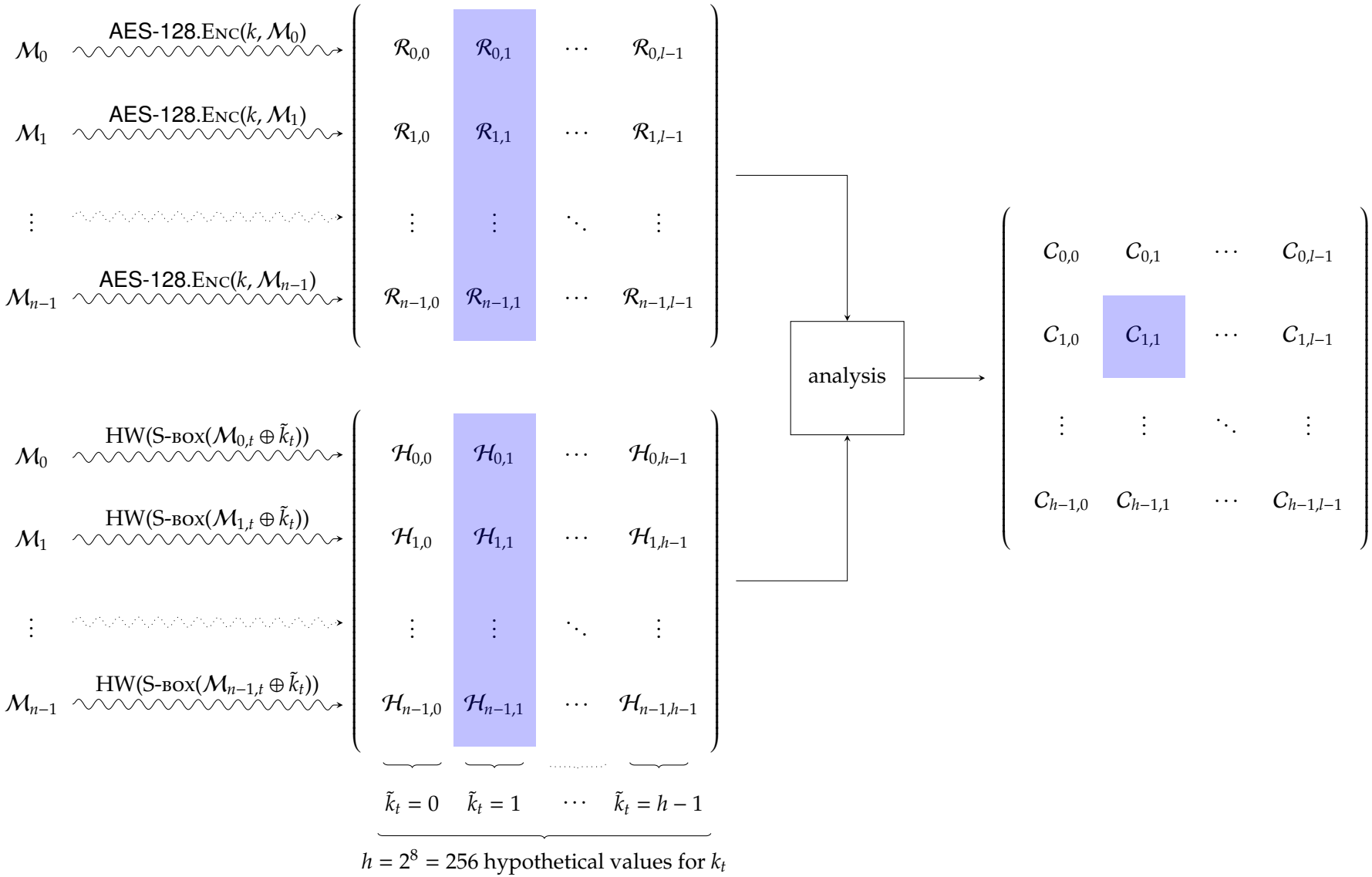

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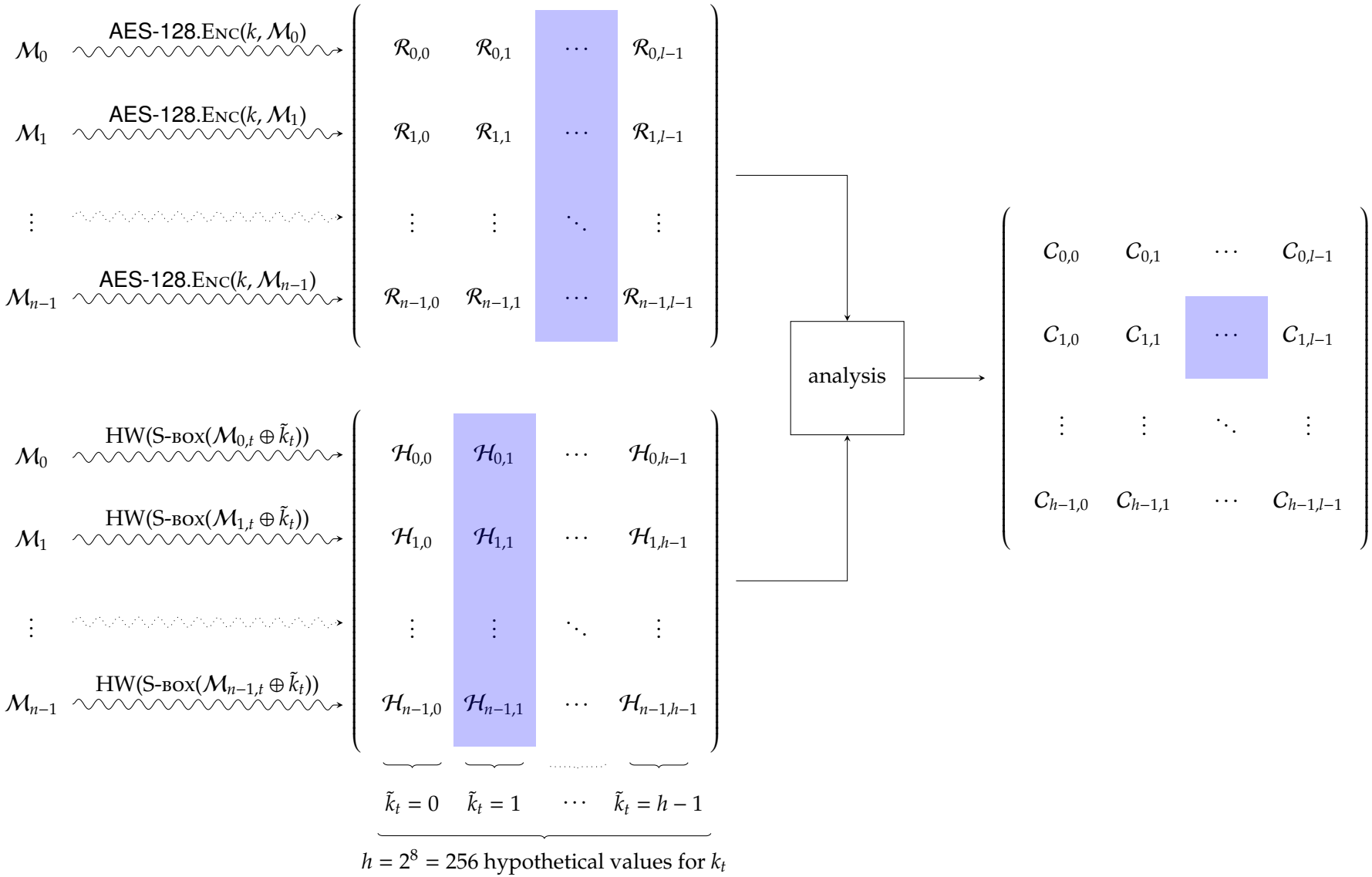

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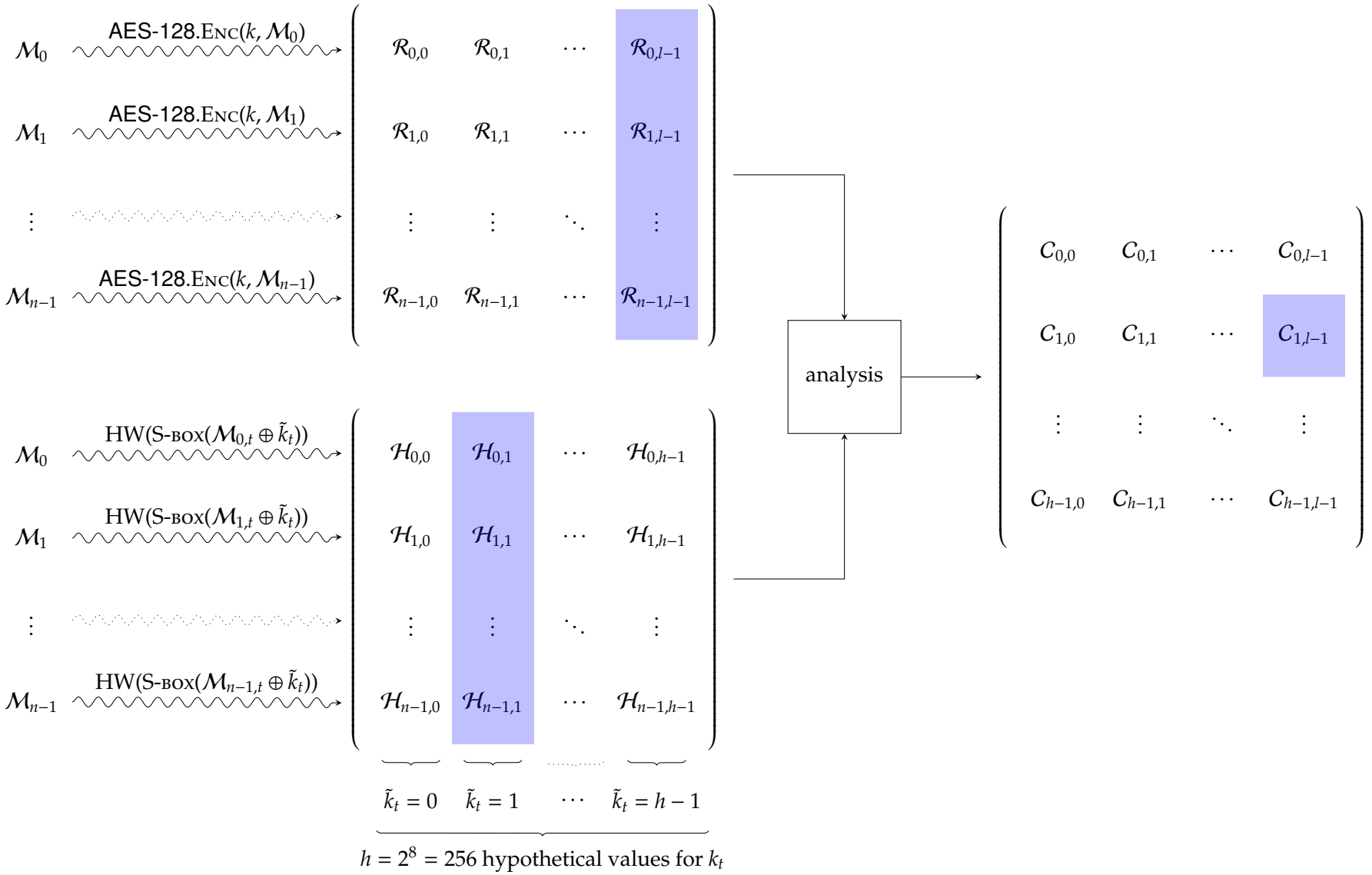

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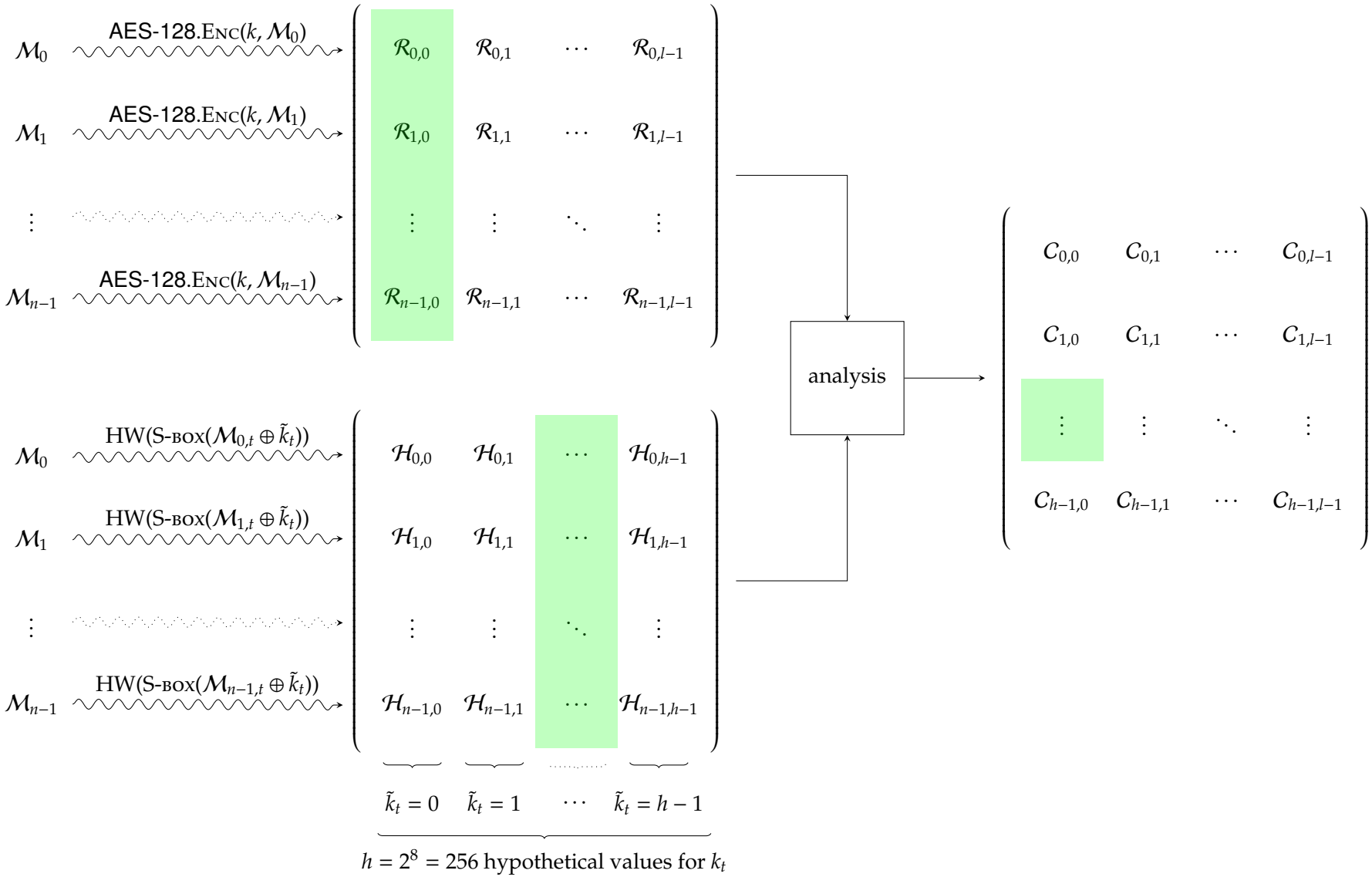

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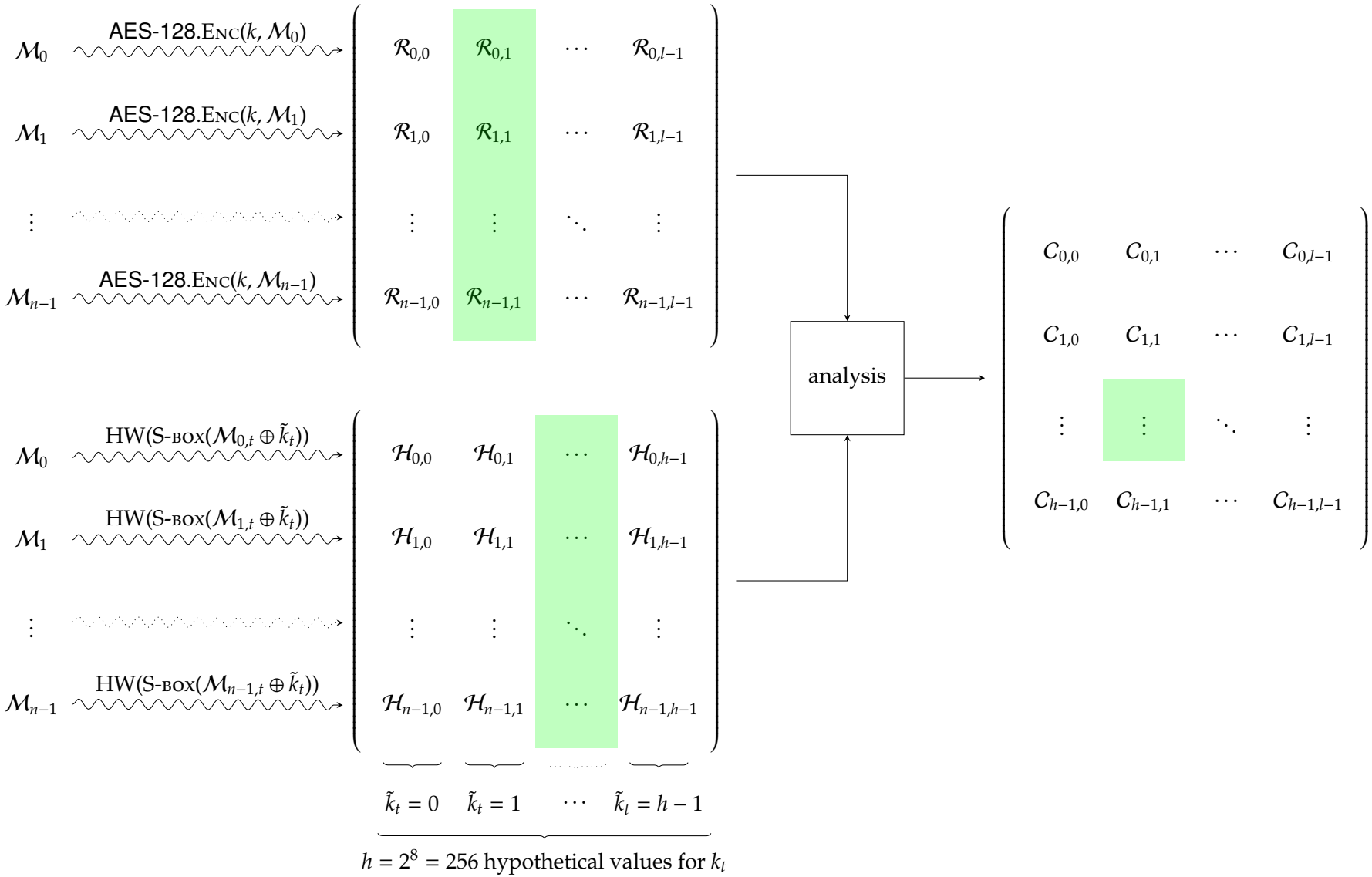

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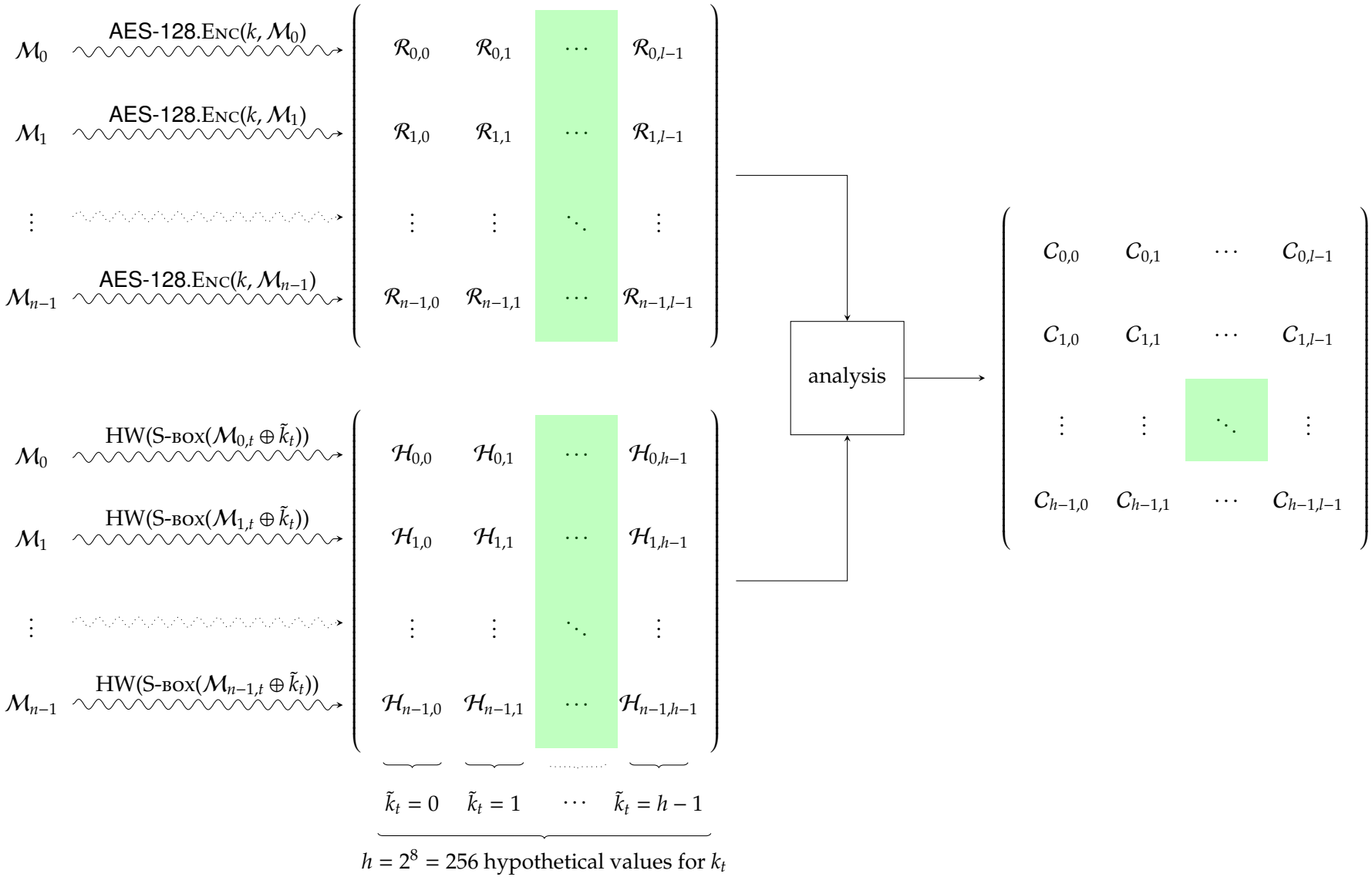

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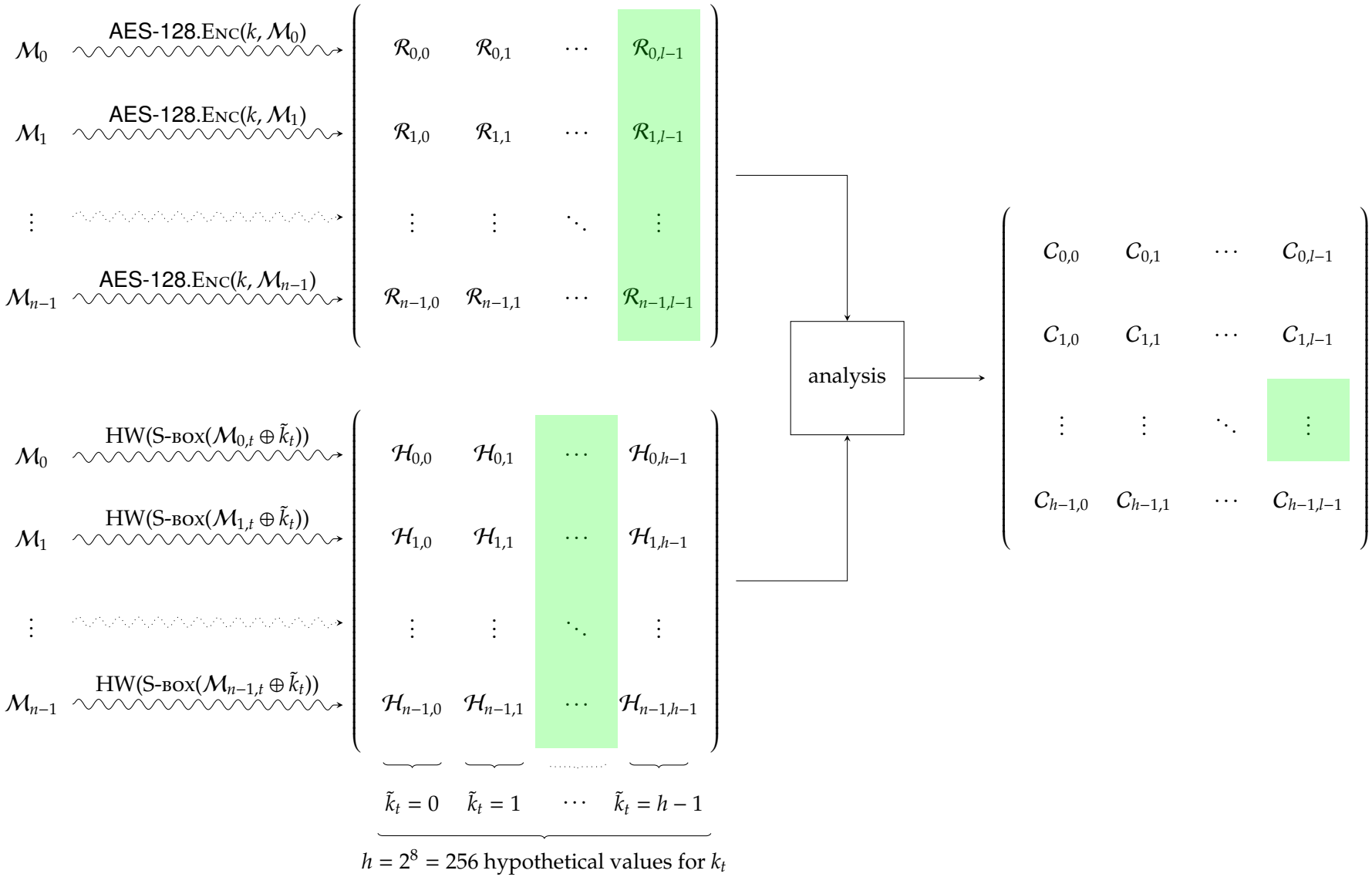

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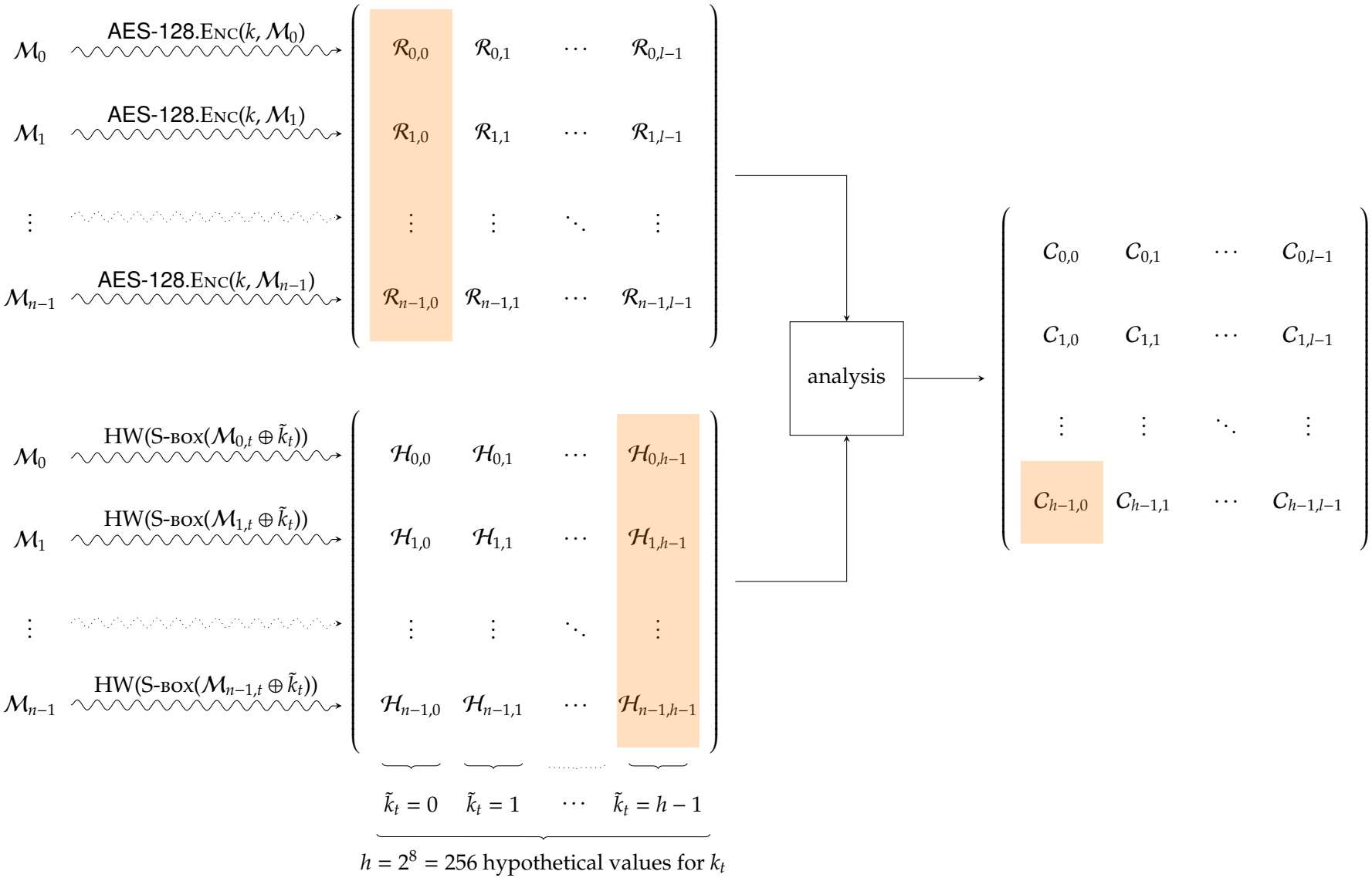

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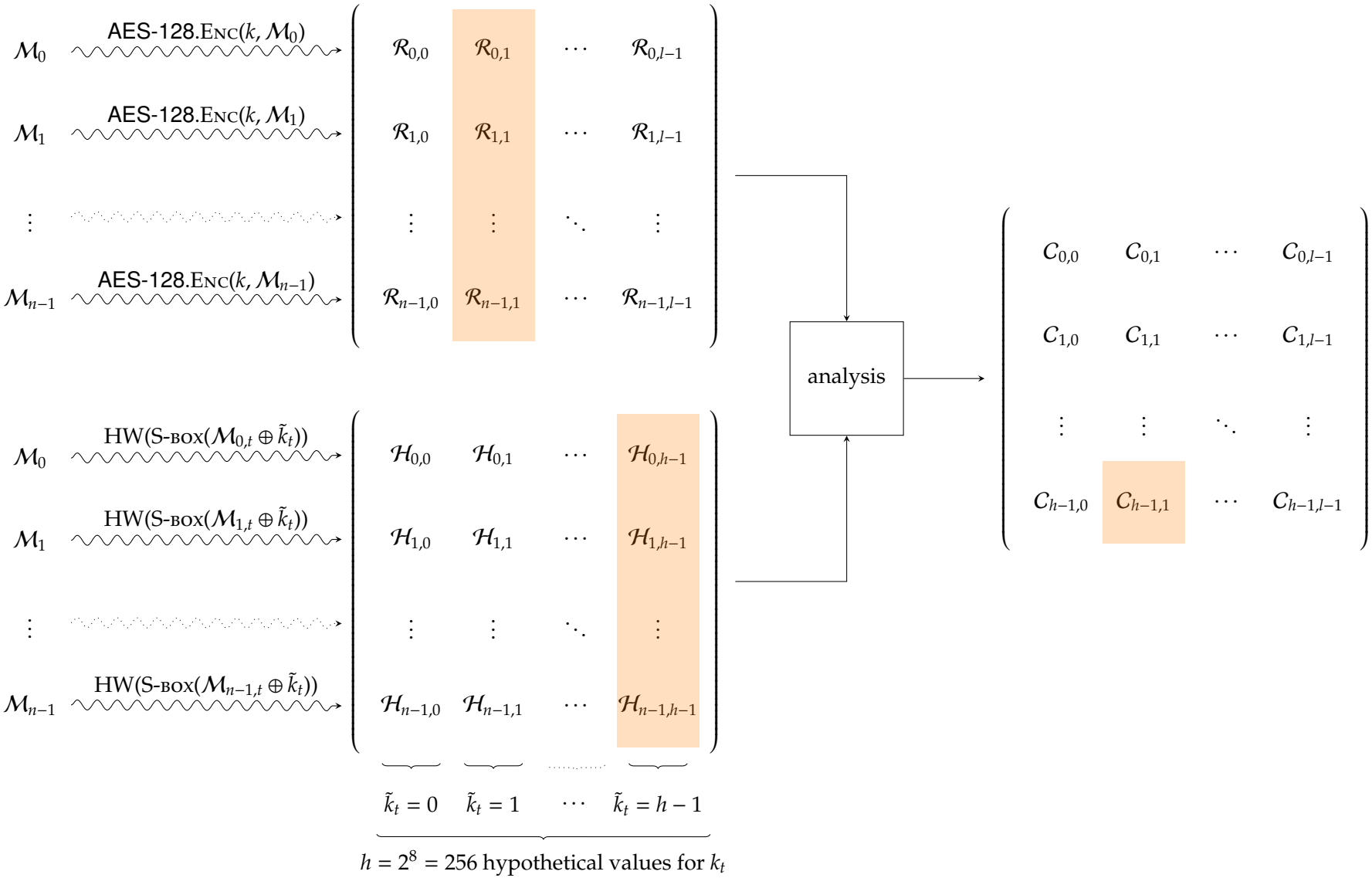

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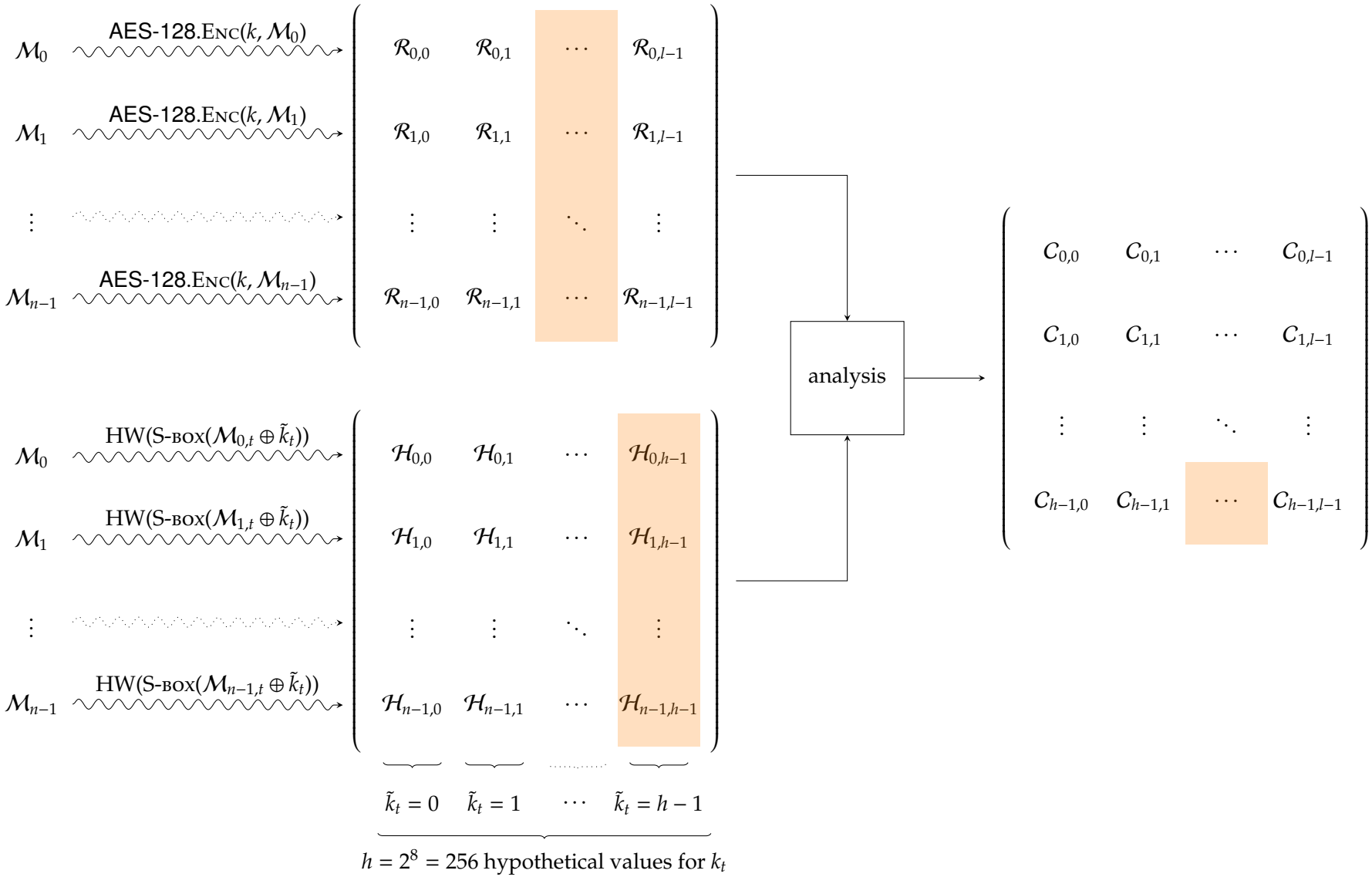

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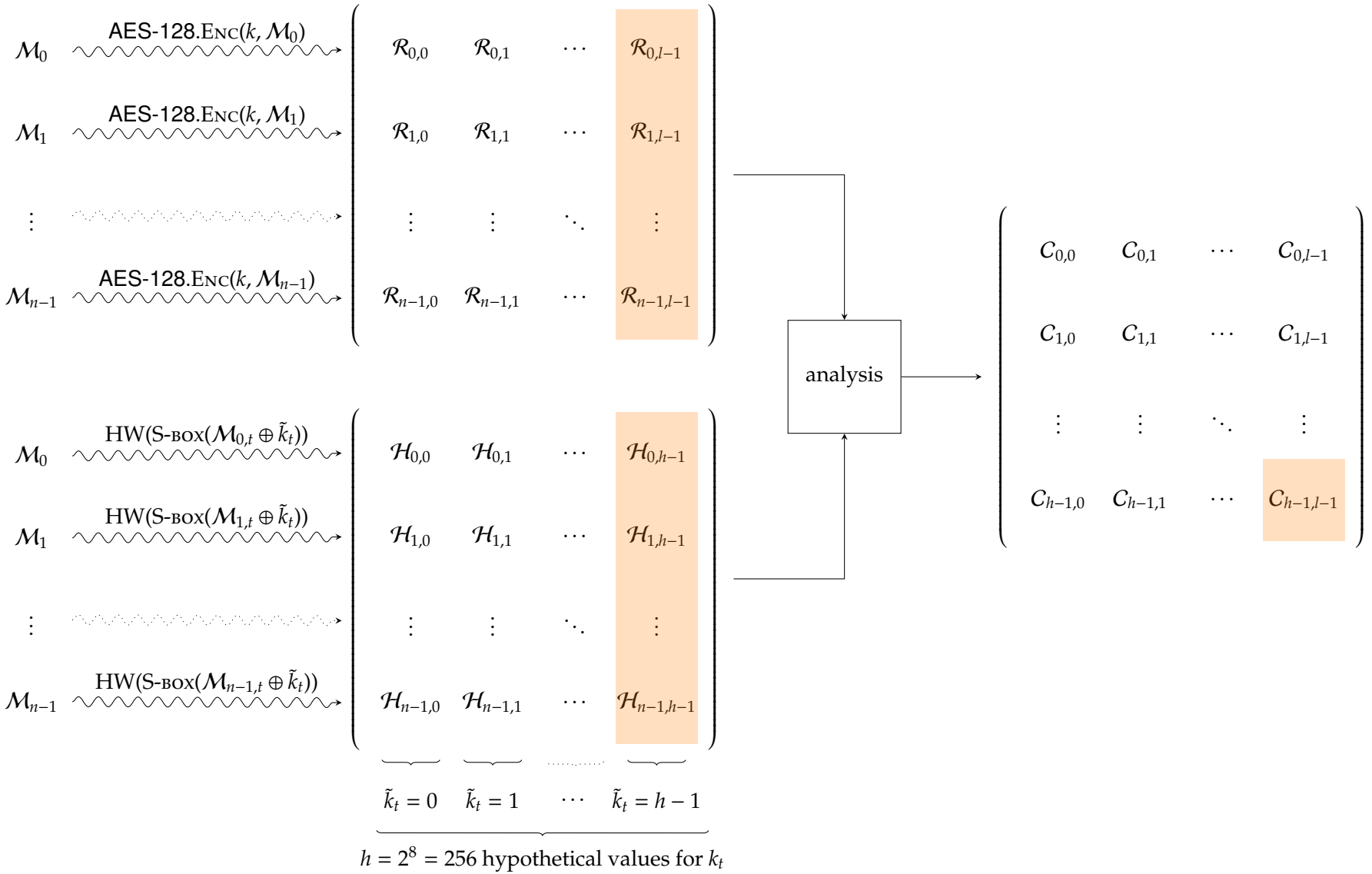

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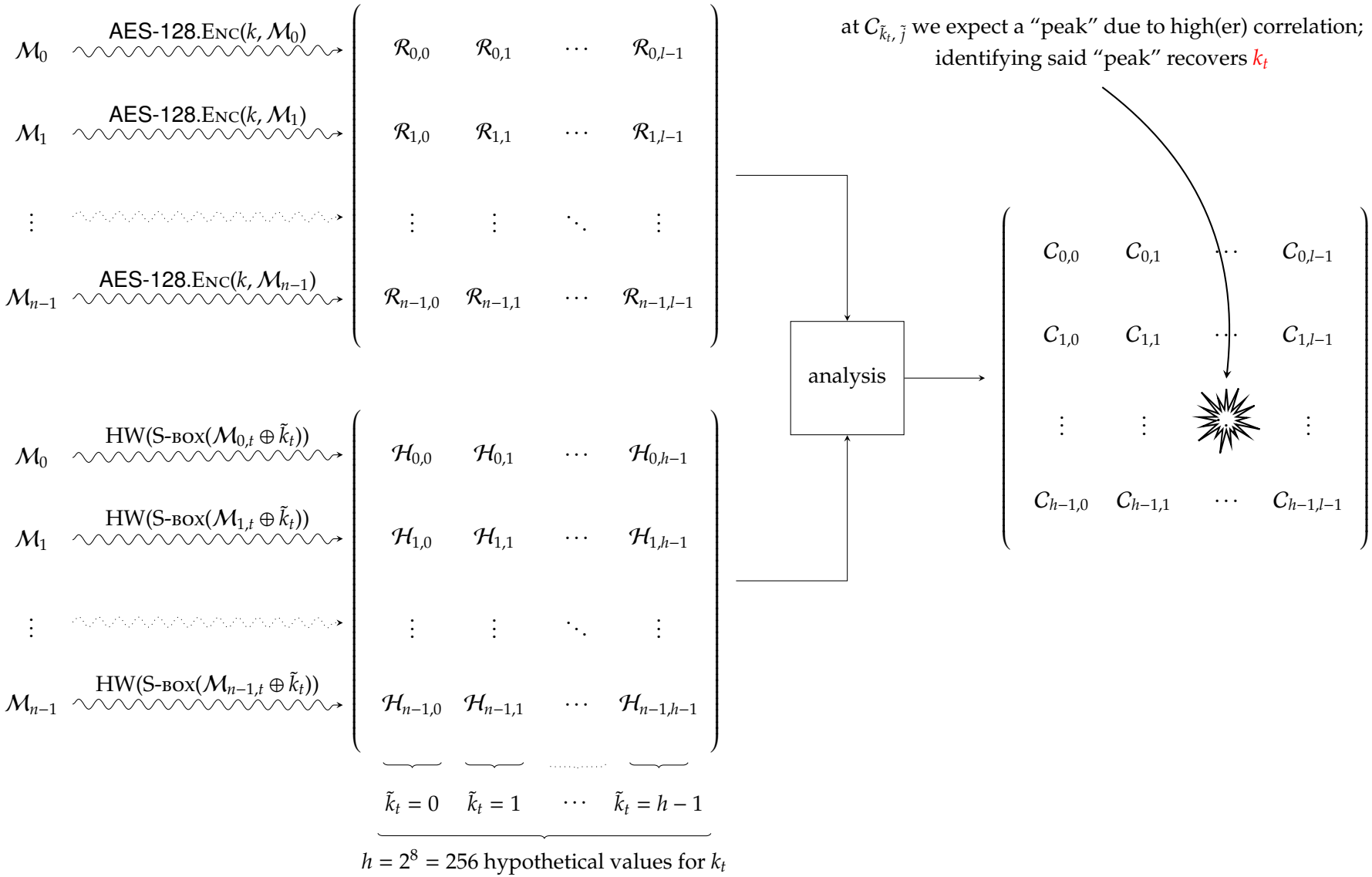
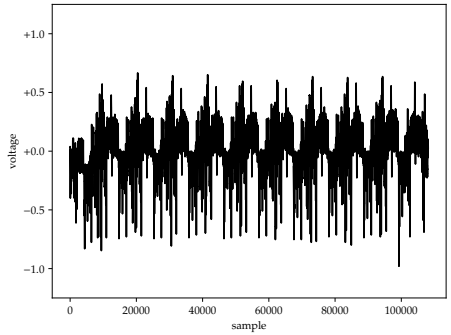


Part 2.1: in practice (5)

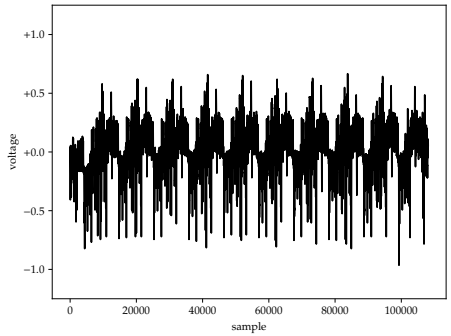
Attacks: $\mathcal{T} \simeq$ AES, $\Lambda =$ power consumption

- Example: ARM Cortex-M3, $n = 1000$, $l = 108124$.

$$\left.\begin{array}{rcl} k & = & \langle 2B_{(16)}, 7E_{(16)}, \ldots, 3C_{(16)} \rangle \\ \mathcal{M}_0 & = & \langle 1C_{(16)}, E5_{(16)}, \ldots, 4B_{(16)} \rangle \end{array}\right\} \rightsquigarrow \text{AES-128.Enc}(k, \mathcal{M}_0) \quad \mathcal{R}_0 =$$

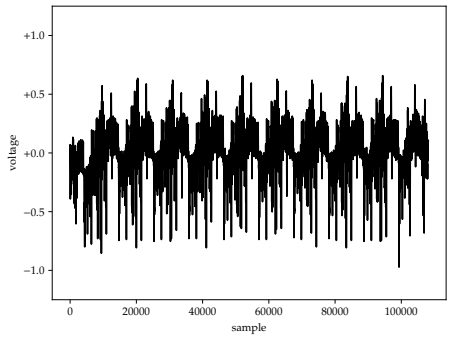


$$\left.\begin{array}{rcl} k & = & \langle 2B_{(16)}, 7E_{(16)}, \ldots, 3C_{(16)} \rangle \\ \mathcal{M}_1 & = & \langle 41_{(16)}, 62_{(16)}, \ldots, DF_{(16)} \rangle \end{array}\right\} \rightsquigarrow \text{AES-128.Enc}(k, \mathcal{M}_1) \quad \mathcal{R}_1 =$$

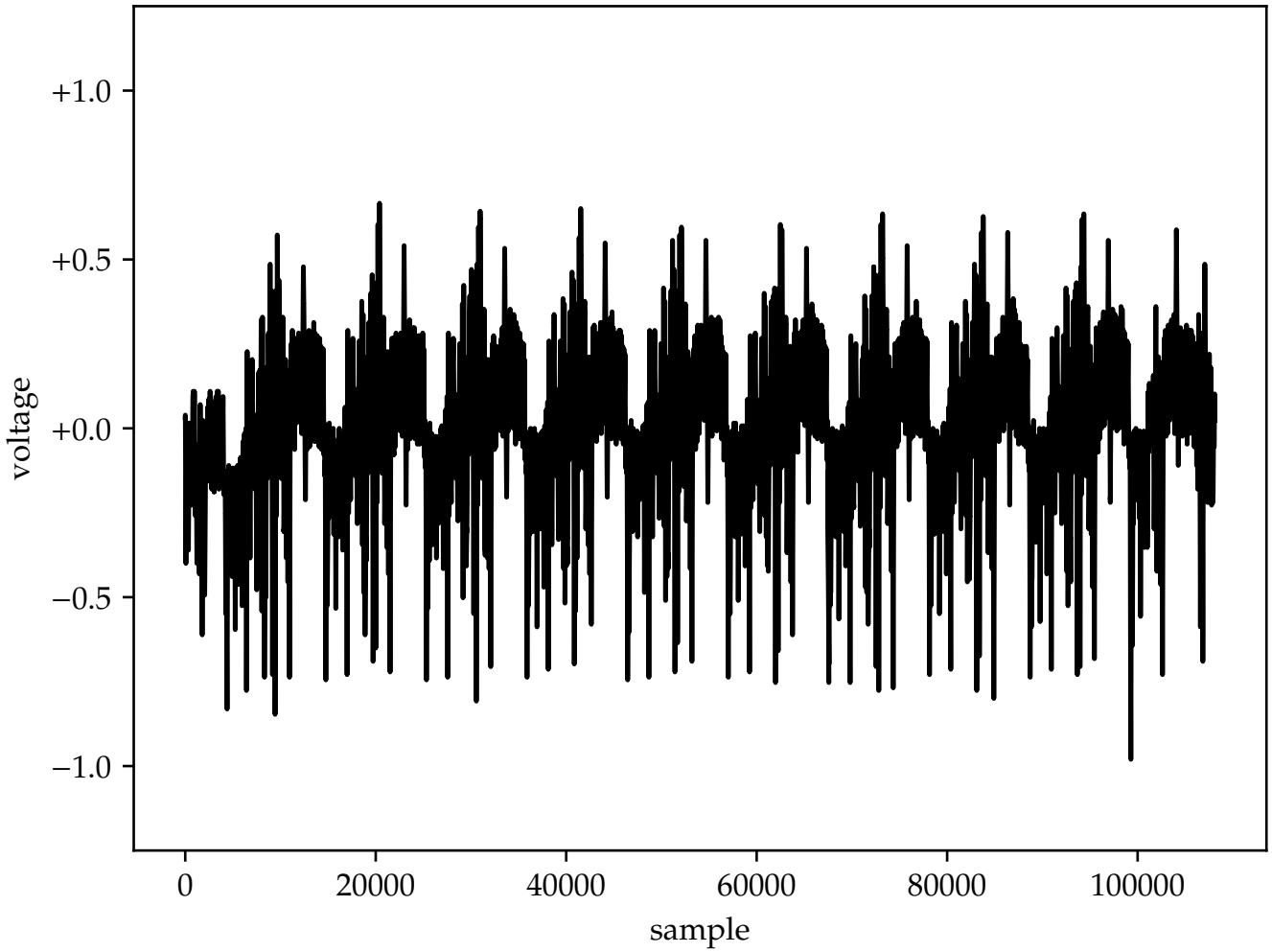


$$\vdots$$

$$\left.\begin{array}{rcl} k & = & \langle 2B_{(16)}, 7E_{(16)}, \ldots, 3C_{(16)} \rangle \\ \mathcal{M}_{n-1} & = & \langle E1_{(16)}, CF_{(16)}, \ldots, BE_{(16)} \rangle \end{array}\right\} \rightsquigarrow \text{AES-128.Enc}(k, \mathcal{M}_{n-1}) \quad \mathcal{R}_{n-1} =$$



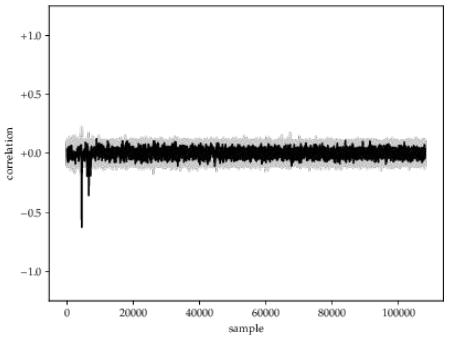
- Example: ARM Cortex-M3, $n = 1000$, $l = 108124$.



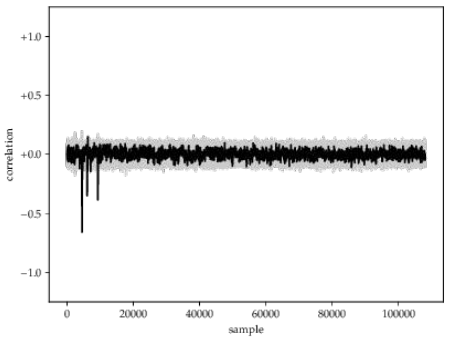
Part 2.1: in practice (5)

Attacks: $\mathcal{T} \simeq$ AES, $\Lambda =$ power consumption

- Example: ARM Cortex-M3, $n = 1000$, $l = 108124$.

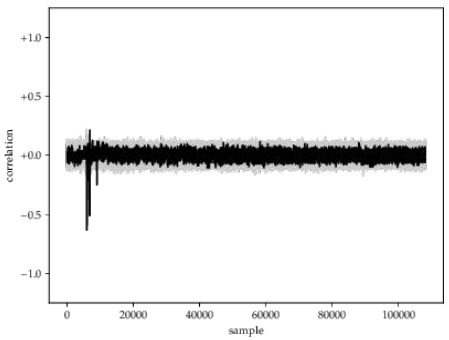
$t = 0$, $C =$ 

$\rightsquigarrow \tilde{k}_0 = k_0 = 2B_{(16)}$

$t = 1$, $C =$ 

$\rightsquigarrow \tilde{k}_1 = k_1 = 7E_{(16)}$

$\vdots$

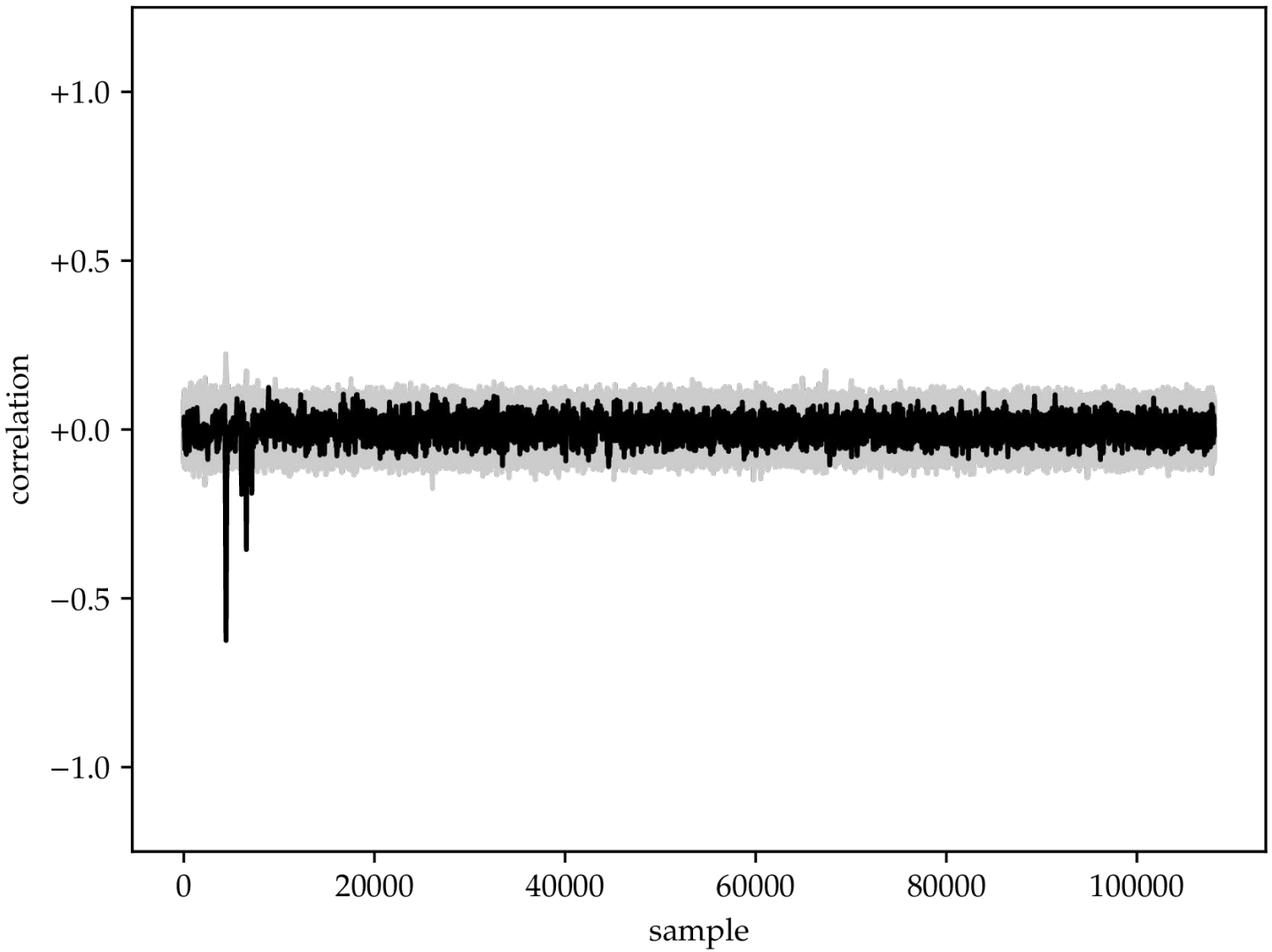
$t = 15$, $C =$ 

$\rightsquigarrow \tilde{k}_{15} = k_{15} = 3C_{(16)}$

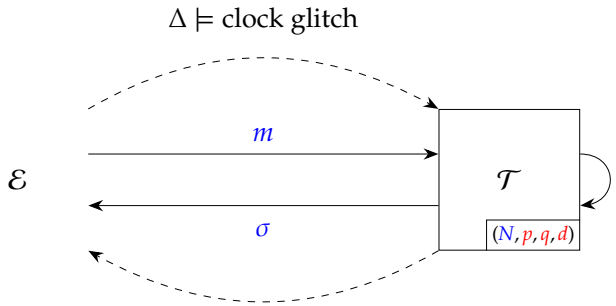
Part 2.1: in practice (5)

Attacks: $\mathcal{T} \simeq$ AES, $\Lambda =$ power consumption

- Example: ARM Cortex-M3, $n = 1000$, $l = 108124$.



- Scenario:
  - given the following interaction between an **attacker** $\mathcal{E}$ and a **target** $\mathcal{T}$



$\sigma = \text{RSA.Sig}((N, p, q, d), m)$
$= m^d \pmod N$

```
1 algorithm RSA.Sig((N, p, q, d), m) begin
2     σ_p ← m^(d mod p−1) (mod p)
3     σ_q ← m^(d mod q−1) (mod q)
4     σ ← crt(σ_p, σ_q)
5     return σ
6 end
```

  - and noting that
    - there are no countermeasures implemented,
    - to improve efficiency, a CRT-based [13] implementation is used,
    - based on pre-computation of

$$\begin{aligned} t_0 &= q^{p-1} \pmod N \\ t_1 &= p^{q-1} \pmod N \end{aligned}$$

      the Gauss-based recombination is such that

$$\sigma = \text{crt}(\sigma_p, \sigma_q) = \sigma_p \times t_0 + \sigma_q \times t_1 \pmod N,$$

    - the fault induced randomises computation of σ_p, i.e., the first "small" exponentiation,
  - how can $\mathcal{E}$ mount a successful attack, i.e., recover d ?

- Attack [6, Section 2.2]:
  - generate

$$\begin{array}{lll} \bar{\sigma} = \bar{\sigma}_p \times t_0 + \sigma_q \times t_1 \pmod{N} & \Leftarrow & \text{fault injected} \\ \sigma = \sigma_p \times t_0 + \sigma_q \times t_1 \pmod{N} & \Leftarrow & \text{no fault injected} \end{array}$$

    such that $\bar{\sigma} \neq \sigma$ due to the fault induced in the former,
  - observe that the CRT pre-computation means

$$t_0 \equiv 0 \pmod{q},$$

    i.e., t_0 is divisible by q, and so, likewise,

$$(\sigma_p - \bar{\sigma}_p) \times t_0 \equiv 0 \pmod{q},$$

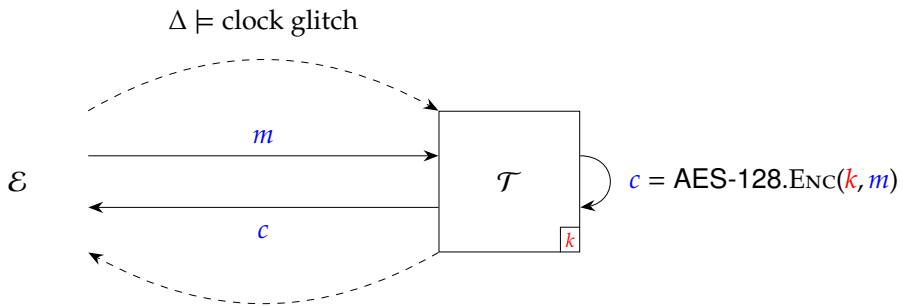
  - compute

$$\begin{array}{rcl} \gcd(\sigma - \bar{\sigma}, N) & = & \gcd((\sigma_p \times t_0 + \sigma_q \times t_1) - (\bar{\sigma}_p \times t_0 + \sigma_q \times t_1), N) \\ & = & \gcd((\sigma_p \times t_0) - (\bar{\sigma}_p \times t_0), N) \\ & = & \gcd((\sigma_p - \bar{\sigma}_p) \times t_0, N) \\ & = & q \end{array}$$

    i.e., factor N, then compute d.

Part 2.1: in practice (8)
Attacks: $\mathcal{T} \simeq$ AES, Δ = clock glitch

- Scenario:
  - given the following interaction between an **attacker** $\mathcal{E}$ and a **target** $\mathcal{T}$



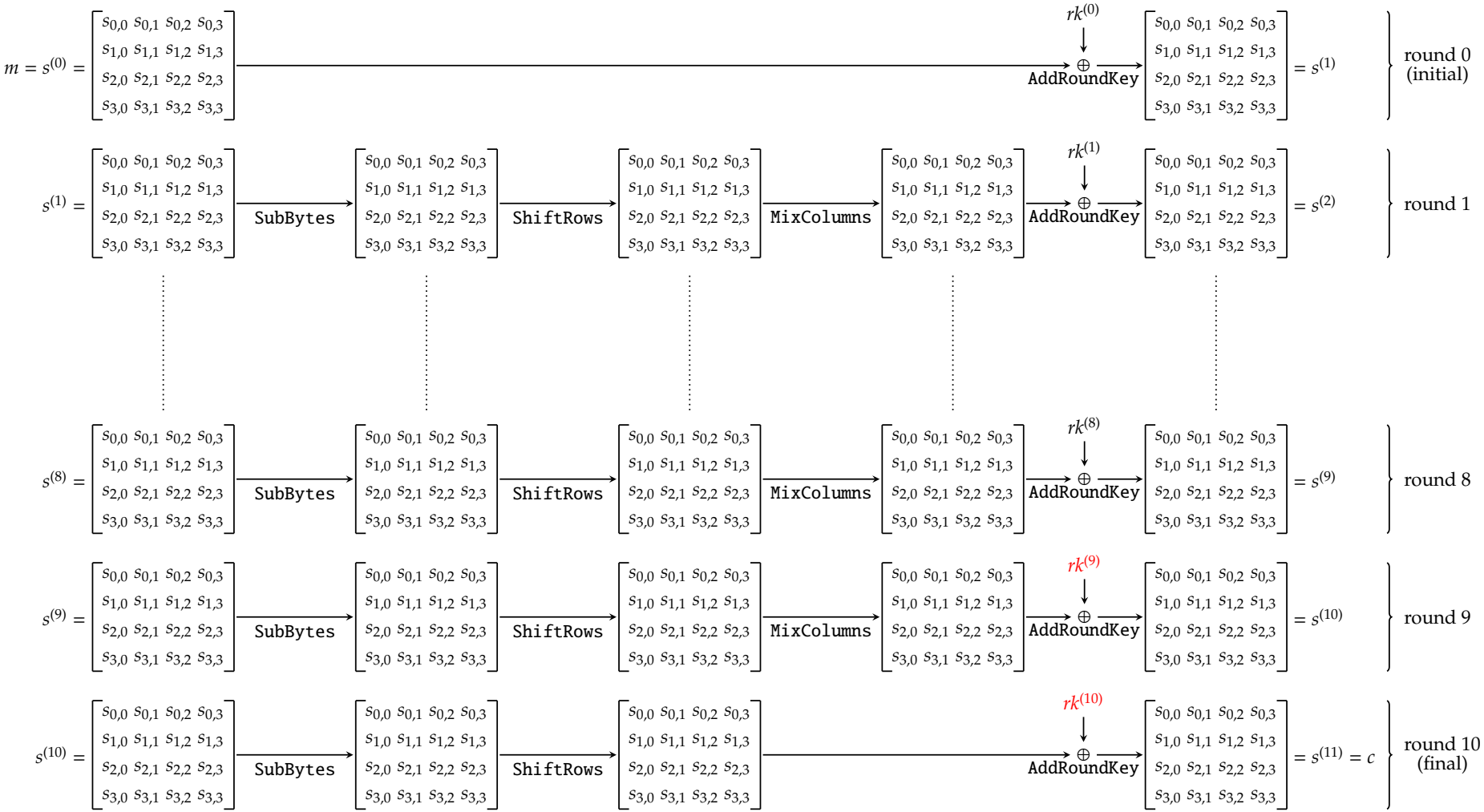

```
1  algorithm AES-128.Enc(k, m) begin
2      s ← m
3      s ← AddRoundKey(s, k = rk^(0))
4      for r = 1 upto 9 step +1 do
5          k ← EvolveRoundKey(k, rc^(r))
6          s ← SubBytes(s)
7          s ← ShiftRows(s)
8          s ← MixColumns(s)
9          s ← AddRoundKey(s, k = rk^(r))
10     end
11     k ← EvolveRoundKey(k, rc^(10))
12     s ← SubBytes(s)
13     s ← ShiftRows(s)
14     s ← AddRoundKey(s, k = rk^(10))
15     c ← s
16     return c
17 end
```

  - and noting that
    - there are no countermeasures implemented,
    - the fault injected randomises $s_{i,j}^{(8)}$, i.e., a chosen element of the state matrix used as input to the 8-th round,
  - how can $\mathcal{E}$ mount a successful attack, i.e., recover k ?

Part 2.1: in practice (9)

Attacks: $\mathcal{T} \simeq$ AES, Δ = clock glitch

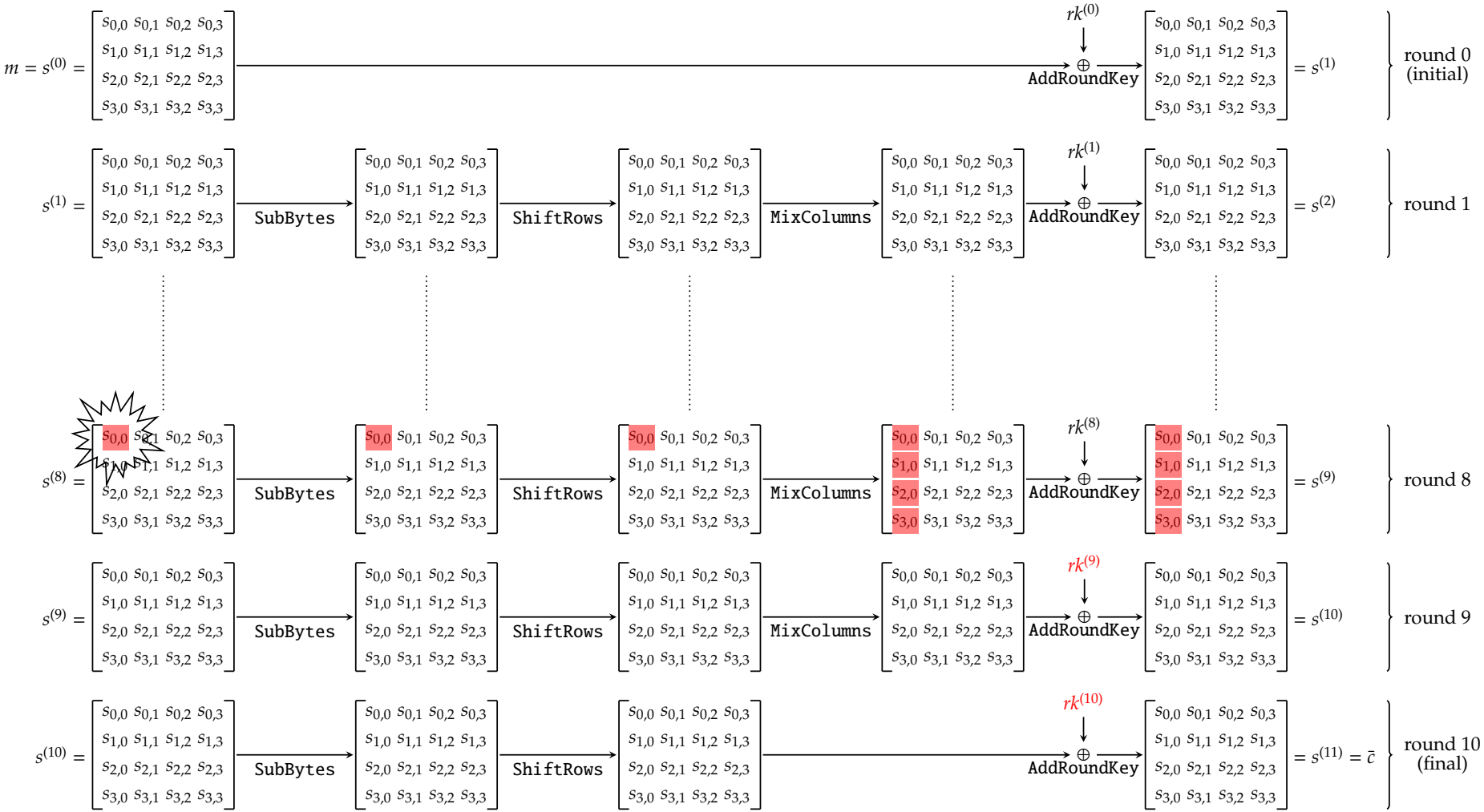
- Attack [14]:



Part 2.1: in practice (9)

Attacks: $\mathcal{T} \simeq$ AES, Δ = clock glitch

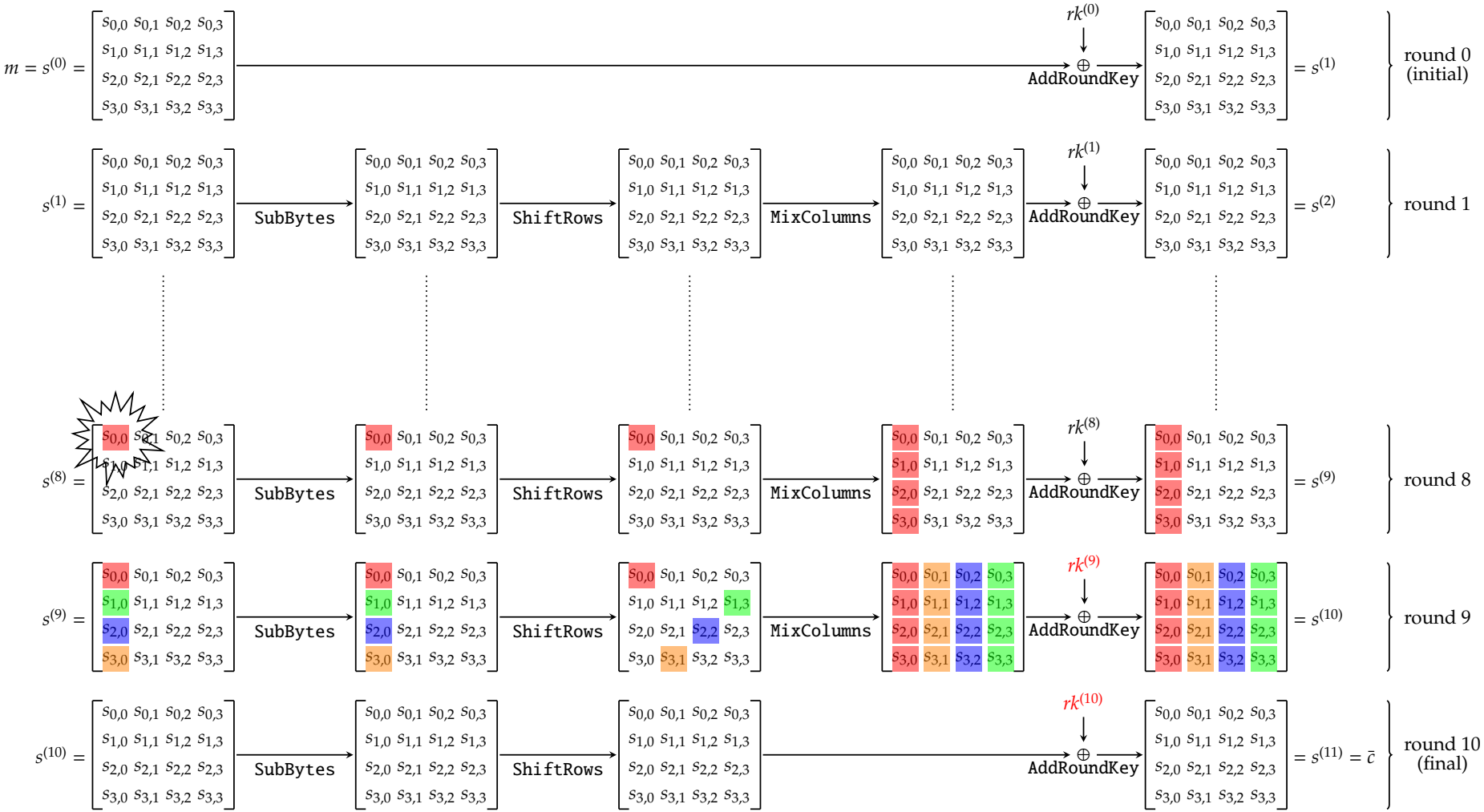
- Attack [14]:



Part 2.1: in practice (9)

Attacks: $\mathcal{T} \simeq$ AES, Δ = clock glitch

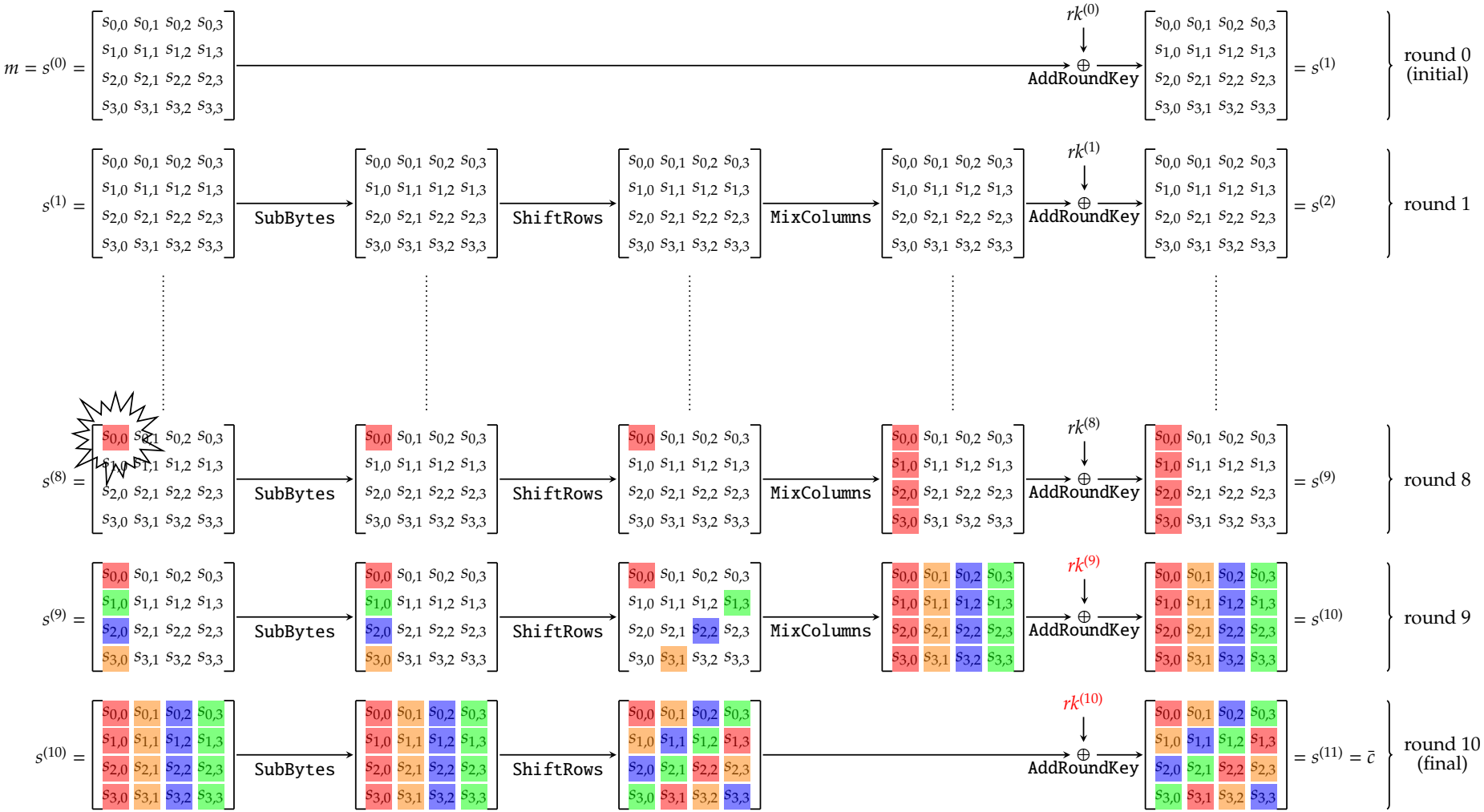
- Attack [14]:



Part 2.1: in practice (9)

Attacks: $\mathcal{T} \simeq$ AES, Δ = clock glitch

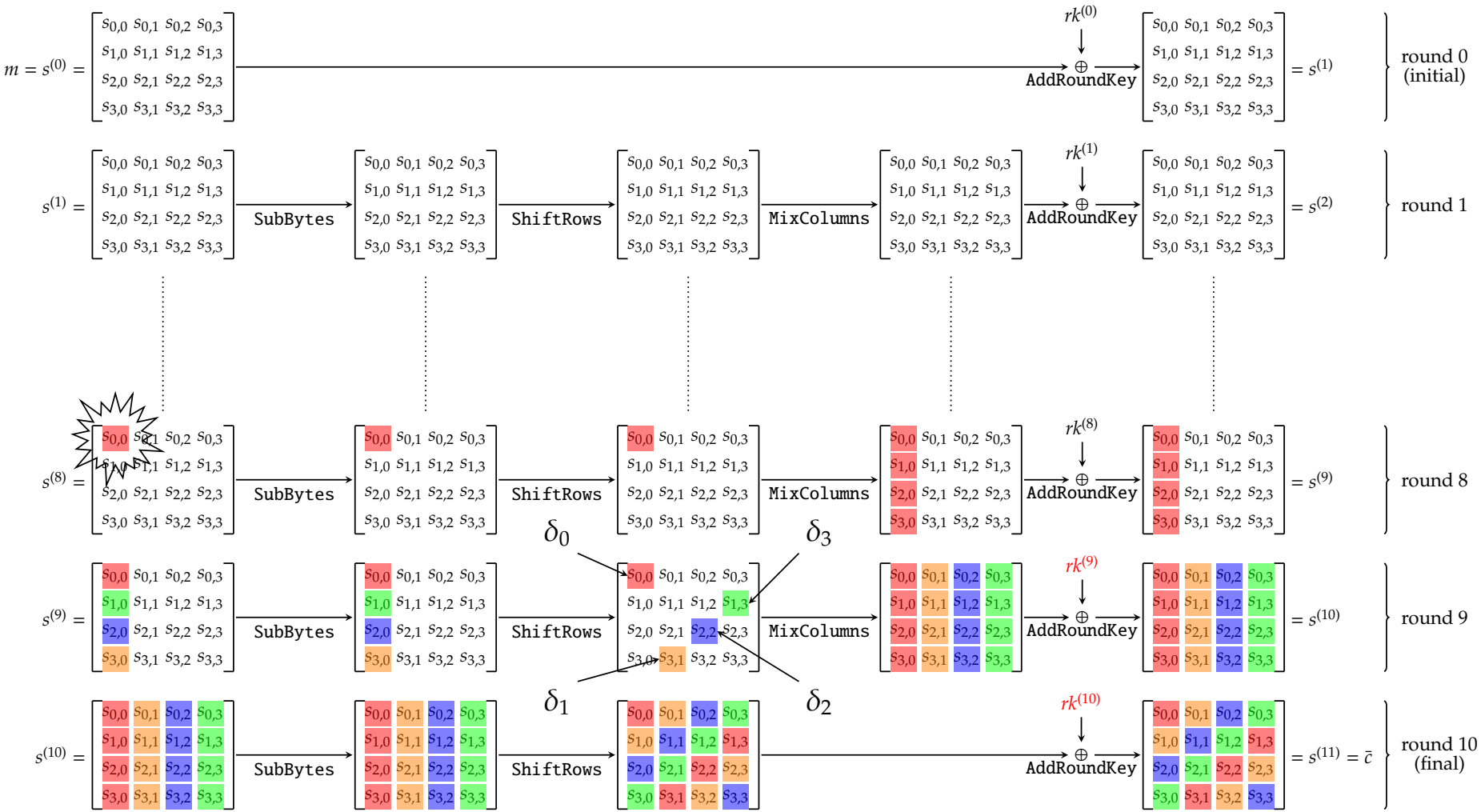
- Attack [14]:



Part 2.1: in practice (9)

Attacks: $\mathcal{T} \simeq$ AES, Δ = clock glitch

- Attack [14]:



- Attack [14]:
  - Step #1:
    - consider a fault injected into the input of the 8-th round, such that

$$\begin{aligned} \bar{c} &= \text{AES-128.}\textsc{Enc}(k, m) \quad \Leftarrow \quad \text{fault injected} \\ c &= \text{AES-128.}\textsc{Enc}(k, m) \quad \Leftarrow \quad \text{no fault injected} \end{aligned}$$

    and focus on the state after `ShiftRows` in the 9-th round,
    - formulate a set of constraints, e.g.,

$$\begin{aligned} \texttt{02} \otimes_{\mathbb{F}_{2^8}} \delta_0 &= \textsc{S-box}^{-1}(c_{0,0} \oplus_{\mathbb{F}_{2^8}} rk_{0,0}^{(10)}) \oplus_{\mathbb{F}_{2^8}} \textsc{S-box}^{-1}(\bar{c}_{0,0} \oplus_{\mathbb{F}_{2^8}} rk_{0,0}^{(10)}) \\ \texttt{01} \otimes_{\mathbb{F}_{2^8}} \delta_0 &= \textsc{S-box}^{-1}(c_{1,3} \oplus_{\mathbb{F}_{2^8}} rk_{1,3}^{(10)}) \oplus_{\mathbb{F}_{2^8}} \textsc{S-box}^{-1}(\bar{c}_{1,3} \oplus_{\mathbb{F}_{2^8}} rk_{1,3}^{(10)}) \\ \texttt{01} \otimes_{\mathbb{F}_{2^8}} \delta_0 &= \textsc{S-box}^{-1}(c_{2,2} \oplus_{\mathbb{F}_{2^8}} rk_{2,2}^{(10)}) \oplus_{\mathbb{F}_{2^8}} \textsc{S-box}^{-1}(\bar{c}_{2,2} \oplus_{\mathbb{F}_{2^8}} rk_{2,2}^{(10)}) \\ \texttt{03} \otimes_{\mathbb{F}_{2^8}} \delta_0 &= \textsc{S-box}^{-1}(c_{3,1} \oplus_{\mathbb{F}_{2^8}} rk_{3,1}^{(10)}) \oplus_{\mathbb{F}_{2^8}} \textsc{S-box}^{-1}(\bar{c}_{3,1} \oplus_{\mathbb{F}_{2^8}} rk_{3,1}^{(10)}) \end{aligned}$$

    - noting that each group involves 32 bits of $rk^{(10)}$, these constraints yield a set of *initial* hypotheses for $rk^{(10)}$.

- Attack [14]:
  - Step #1:
    - consider a fault injected into the input of the 8-th round, such that

$$\begin{array}{rcl} \bar{c} = \text{AES-128.}\textsc{Enc}(k, m) & \Leftarrow & \text{fault injected} \\ c = \text{AES-128.}\textsc{Enc}(k, m) & \Leftarrow & \text{no fault injected} \end{array}$$

      and focus on the state after `ShiftRows` in the 9-th round,
    - formulate a set of constraints, e.g.,

$$\begin{array}{rcl} \texttt{03} \otimes_{\mathbb{F}_{2^8}} \delta_1 & = & \text{S-box}^{-1}(c_{0,1} \oplus_{\mathbb{F}_{2^8}} rk_{0,1}^{(10)}) \oplus_{\mathbb{F}_{2^8}} \text{S-box}^{-1}(\bar{c}_{0,1} \oplus_{\mathbb{F}_{2^8}} rk_{0,1}^{(10)}) \\ \texttt{02} \otimes_{\mathbb{F}_{2^8}} \delta_1 & = & \text{S-box}^{-1}(c_{1,0} \oplus_{\mathbb{F}_{2^8}} rk_{1,0}^{(10)}) \oplus_{\mathbb{F}_{2^8}} \text{S-box}^{-1}(\bar{c}_{1,0} \oplus_{\mathbb{F}_{2^8}} rk_{1,0}^{(10)}) \\ \texttt{01} \otimes_{\mathbb{F}_{2^8}} \delta_1 & = & \text{S-box}^{-1}(c_{2,3} \oplus_{\mathbb{F}_{2^8}} rk_{2,3}^{(10)}) \oplus_{\mathbb{F}_{2^8}} \text{S-box}^{-1}(\bar{c}_{2,3} \oplus_{\mathbb{F}_{2^8}} rk_{2,3}^{(10)}) \\ \texttt{01} \otimes_{\mathbb{F}_{2^8}} \delta_1 & = & \text{S-box}^{-1}(c_{3,2} \oplus_{\mathbb{F}_{2^8}} rk_{3,2}^{(10)}) \oplus_{\mathbb{F}_{2^8}} \text{S-box}^{-1}(\bar{c}_{3,2} \oplus_{\mathbb{F}_{2^8}} rk_{3,2}^{(10)}) \end{array}$$

    - noting that each group involves 32 bits of $rk^{(10)}$, these constraints yield a set of *initial* hypotheses for $rk^{(10)}$.

- Attack [14]:
  - Step #1:
    - consider a fault injected into the input of the 8-th round, such that

$$\begin{array}{rcl} \bar{c} = \text{AES-128.}\textsc{Enc}(k, m) & \Leftarrow & \text{fault injected} \\ c = \text{AES-128.}\textsc{Enc}(k, m) & \Leftarrow & \text{no fault injected} \end{array}$$

      and focus on the state after `ShiftRows` in the 9-th round,
    - formulate a set of constraints, e.g.,

$$\begin{array}{rcl}
\texttt{01} \otimes_{\mathbb{F}_{2^8}} \delta_2 & = & \textsc{S-box}^{-1}(c_{0,2} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{0,2}) \oplus_{\mathbb{F}_{2^8}} \textsc{S-box}^{-1}(\bar{c}_{0,2} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{0,2}) \\
\texttt{03} \otimes_{\mathbb{F}_{2^8}} \delta_2 & = & \textsc{S-box}^{-1}(c_{1,1} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{1,1}) \oplus_{\mathbb{F}_{2^8}} \textsc{S-box}^{-1}(\bar{c}_{1,1} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{1,1}) \\
\texttt{02} \otimes_{\mathbb{F}_{2^8}} \delta_2 & = & \textsc{S-box}^{-1}(c_{2,0} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{2,0}) \oplus_{\mathbb{F}_{2^8}} \textsc{S-box}^{-1}(\bar{c}_{2,0} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{2,0}) \\
\texttt{01} \otimes_{\mathbb{F}_{2^8}} \delta_2 & = & \textsc{S-box}^{-1}(c_{3,3} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{3,3}) \oplus_{\mathbb{F}_{2^8}} \textsc{S-box}^{-1}(\bar{c}_{3,3} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{3,3})
\end{array}$$

    - noting that each group involves 32 bits of $rk^{(10)}$, these constraints yield a set of *initial* hypotheses for $rk^{(10)}$.

- Attack [14]:
  - Step #1:
    - consider a fault injected into the input of the 8-th round, such that

$$\begin{array}{rcl} \bar{c} = \text{AES-128.}\textsc{Enc}(k, m) & \Leftarrow & \text{fault injected} \\ c = \text{AES-128.}\textsc{Enc}(k, m) & \Leftarrow & \text{no fault injected} \end{array}$$

      and focus on the state after `ShiftRows` in the 9-th round,
    - formulate a set of constraints, e.g.,

$$\begin{array}{rcl} \texttt{01} \otimes_{\mathbb{F}_{2^8}} \delta_3 & = & \textsc{S-box}^{-1}(c_{0,3} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{0,3}) \oplus_{\mathbb{F}_{2^8}} \textsc{S-box}^{-1}(\bar{c}_{0,3} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{0,3}) \\ \texttt{01} \otimes_{\mathbb{F}_{2^8}} \delta_3 & = & \textsc{S-box}^{-1}(c_{1,2} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{1,2}) \oplus_{\mathbb{F}_{2^8}} \textsc{S-box}^{-1}(\bar{c}_{1,2} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{1,2}) \\ \texttt{03} \otimes_{\mathbb{F}_{2^8}} \delta_3 & = & \textsc{S-box}^{-1}(c_{2,1} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{2,1}) \oplus_{\mathbb{F}_{2^8}} \textsc{S-box}^{-1}(\bar{c}_{2,1} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{2,1}) \\ \texttt{02} \otimes_{\mathbb{F}_{2^8}} \delta_3 & = & \textsc{S-box}^{-1}(c_{3,0} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{3,0}) \oplus_{\mathbb{F}_{2^8}} \textsc{S-box}^{-1}(\bar{c}_{3,0} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{3,0}) \end{array}$$

    - noting that each group involves 32 bits of $rk^{(10)}$, these constraints yield a set of *initial* hypotheses for $rk^{(10)}$.

- Attack [14]:
  - Step #1:
    - consider a fault injected into the input of the 8-th round, such that

$$\begin{aligned} \bar{c} &= \text{AES-128.}\textsc{Enc}(k, m) \quad \Leftarrow \quad \text{fault injected} \\ c &= \text{AES-128.}\textsc{Enc}(k, m) \quad \Leftarrow \quad \text{no fault injected} \end{aligned}$$

      and focus on the state after `ShiftRows` in the 9-th round,
    - formulate a set of constraints, e.g.,

$$\begin{aligned} \texttt{01} \otimes_{\mathbb{F}_{2^8}} \delta_3 &= \textsc{S-box}^{-1}(c_{0,3} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{0,3}) \oplus_{\mathbb{F}_{2^8}} \textsc{S-box}^{-1}(\bar{c}_{0,3} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{0,3}) \\ \texttt{01} \otimes_{\mathbb{F}_{2^8}} \delta_3 &= \textsc{S-box}^{-1}(c_{1,2} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{1,2}) \oplus_{\mathbb{F}_{2^8}} \textsc{S-box}^{-1}(\bar{c}_{1,2} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{1,2}) \\ \texttt{03} \otimes_{\mathbb{F}_{2^8}} \delta_3 &= \textsc{S-box}^{-1}(c_{2,1} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{2,1}) \oplus_{\mathbb{F}_{2^8}} \textsc{S-box}^{-1}(\bar{c}_{2,1} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{2,1}) \\ \texttt{02} \otimes_{\mathbb{F}_{2^8}} \delta_3 &= \textsc{S-box}^{-1}(c_{3,0} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{3,0}) \oplus_{\mathbb{F}_{2^8}} \textsc{S-box}^{-1}(\bar{c}_{3,0} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{3,0}) \end{aligned}$$

    - noting that each group involves 32 bits of $rk^{(10)}$, these constraints yield a set of *initial* hypotheses for $rk^{(10)}$.
  - Step #2: *either*
    1. repeat step #1: successive faults, and so constraints, act to reduce the set of *initial* hypotheses,
    2. perform brute-force search of $\sim 2^{32}$ *initial* hypotheses,
    3. perform brute-force search of $\sim 2^{8}$ *filtered* hypotheses, produced by considering the relationship between $rk^{(9)}$ and $rk^{(10)}$ that stems from the key schedule.

- Problem: data-dependent computation within

$$\texttt{xtime}(x) = \mathbf{x} \otimes_{\mathbb{F}_{2^8}} x$$

  is observable via Λ.

- Idea: **hiding**, e.g., via
  1. original (i.e., no countermeasure):

$$\texttt{xtime}(x) \quad \mapsto \quad \left\{ \right.$$

```
1 uint8_t aes_gf28_mulx( uint8_t x ) {
2   if( ( x & 0x80 ) == 0x80 ) {
3     return 0x1B ^ ( x << 1 );
4   }
5   else {
6     return        ( x << 1 );
7   }
8 }
```

- Problem: data-dependent computation within

$$\texttt{xtime}(x) = \mathbf{x} \otimes_{\mathbb{F}_{2^8}} x$$

  is observable via Λ.

- Idea: **hiding**, e.g., via
  1. original (i.e., no countermeasure):

$$\texttt{xtime}(x) \quad \mapsto$$

```
1  uint8_t aes_gf28_mulx( uint8_t x ) {
2    uint8_t c;
3
4    c = x >> 7;
5    x = x << 1;
6
7    if( c ) {
8      x = x ^ 0x1B;
9    }
10
11   return x;
12 }
```

- Problem: data-dependent computation within

$$\texttt{xtime}(x) = \mathbf{x} \otimes_{\mathbb{F}_{2^8}} x$$

  is observable via Λ.

- Idea: **hiding**, e.g., via
  1. balanced (via dummy XOR):

$$\texttt{xtime}(x) \quad \mapsto$$

```
1  uint8_t aes_gf28_mulx( uint8_t x ) {
2    uint8_t c;
3
4    c = x >> 7;
5    x = x << 1;
6
7    if( c ) {
8      x = x ^ 0x1B;
9    }
10   else {
11     x = x ^ 0x00;
12   }
13
14   return x;
15 }
```

  although this assumes no, e.g., compiler-based strength reduction.

- Problem: data-dependent computation within

$$\texttt{xtime}(x) = \mathbf{x} \otimes_{\mathbb{F}_{2^8}} x$$

  is observable via Λ.

- Idea: **hiding**, e.g., via
  2. straight-line (via multiplexer):

$\texttt{xtime}(x) \quad \mapsto$

```
1  uint8_t aes_gf28_mulx( uint8_t x ) {
2    uint8_t c, t_0, t_1;
3
4    c = x >> 7;
5    x = x << 1;
6
7    t_0 = x ^ 0x00;
8    t_1 = x ^ 0x1B;
9
10   x = ( -c & ( t_0 ^ t_1 ) ) ^ t_0;
11
12   return x;
13 }
```

- Problem: data-dependent computation within

$$\texttt{xtime}(x) = \mathbf{x} \otimes_{\mathbb{F}_{2^8}} x$$

  is observable via Λ.

- Idea: **hiding**, e.g., via
  3. straight-line (via multiplexer):

$$\texttt{xtime}(x) \quad \mapsto \quad \left\{ \right.$$

```
1  uint8_t aes_gf28_mulx( uint8_t x ) {
2    uint8_t c;
3
4      c = x >> 7;
5      x = x << 1;
6
7      x = x ^ ( c * 0x1B );
8
9    return x;
10 }
```

although this assumes data-oblivious, i.e., constant-latency, multiplication.

- Problem: data-dependent computation within

$$\texttt{xtime}(x) = \mathbf{x} \otimes_{\mathbb{F}_{2^8}} x$$

  is observable via Λ.

- Idea: **hiding**, e.g., via

4. straight-line (via look-up):

$\texttt{xtime}(x) \quad \mapsto$

```
uint8_t aes_gf28_mulx( uint8_t x ) {
  uint8_t c, T[ 2 ];

  c = x >> 7;
  x = x << 1;

  T[ 0 ] = x ^ 0x00;
  T[ 1 ] = x ^ 0x1B;

  x = T[ c ];

  return x;
}
```

although this assumes data-oblivious, i.e., constant-latency, memory access.

- Problem: data-dependent computation within

$$\texttt{SubBytes}(s^{(r)})$$

  is observable via Λ.

- Idea: **hiding**, e.g., via
  1. original (i.e., no countermeasure):

$$\texttt{SubBytes}(s^{(r)}) \mapsto$$

```
1 void aes_enc_rnd_sub( uint8_t* s ) {
2   for( int i = 0; i < 16; i++ ) {
3     s[ i ] = aes_enc_sbox( s[ i ] );
4   }
5 }
```

- Problem: data-dependent computation within

$$\texttt{SubBytes}(s^{(r)})$$

  is observable via Λ.

- Idea: **hiding**, e.g., via
  2. temporal padding $\Rightarrow$ random delay:

$\texttt{SubBytes}(s^{(r)}) \mapsto$

```
1 void aes_enc_rnd_sub( uint8_t* s ) {
2   delay( prng() );
3
4   for( int i = 0; i < 16; i++ ) {
5     s[ i ] = aes_enc_sbox( s[ i ] );
6   }
7 }
```

- Problem: data-dependent computation within

$$\texttt{SubBytes}(s^{(r)})$$

  is observable via Λ.

- Idea: **hiding**, e.g., via
  3. temporal reordering $\Rightarrow$ random start index:

$\texttt{SubBytes}(s^{(r)}) \mapsto$

```
1 void aes_enc_rnd_sub( uint8_t* s ) {
2   int r = prng();
3
4   for( int i = 0; i < 16; i++ ) {
5     int j = ( i + r ) % 16;
6
7     s[ j ] = aes_enc_sbox( s[ j ] );
8   }
9 }
```

- Problem: data-dependent computation within

$$\texttt{SubBytes}(s^{(r)})$$

  is observable via Λ.

- Idea: **hiding**, e.g., via
  4. temporal reordering $\Rightarrow$ random permutation $\Rightarrow$ lower-quality, lower-overhead:

$$\texttt{SubBytes}(s^{(r)}) \quad \mapsto \quad \left\{ \right.$$

```
1 void aes_enc_rnd_sub( uint8_t* s ) {
2   int r = prng();
3
4   for( int i = 0; i < 16; i++ ) {
5     int j = ( i ^ r ) % 16;
6
7     s[ j ] = aes_enc_sbox( s[ j ] );
8   }
9 }
```

- Problem: data-dependent computation within

$$\texttt{SubBytes}(s^{(r)})$$

  is observable via Λ.

- Idea: **hiding**, e.g., via
  5. temporal reordering $\Rightarrow$ random permutation $\Rightarrow$ higher-quality, higher-overhead:

$$\texttt{SubBytes}(s^{(r)}) \quad \mapsto \quad \left\{ \right.$$

```
 1 void aes_enc_rnd_sub( uint8_t* s ) {
 2   int T[ 16 ];
 3
 4   for( int i = 15; i >= 0; i-- ) {
 5     T[ i ] = i;
 6   }
 7
 8   for( int i = 15; i >= 1; i-- ) {
 9     int j = prng() % ( i + 1 );
10
11     uint8_t t      = T[ j ];
12             T[ j ] = T[ i ];
13             T[ i ] = t     ;
14   }
15
16   for( int i = 0; i < 16; i++ ) {
17     int j = T[ i ];
18
19     s[ j ] = aes_enc_sbox( s[ j ] );
20   }
21 }
```

- Problem: data-dependent computation within

$$\text{AES-128.}\textsc{Enc}(k, m)$$

  is observable via Λ.

- Idea: (e.g., Boolean) **masking**.
  - use a randomised, redundant representation

$$x \quad \mapsto \quad \hat{x} = \langle \hat{x}[0], \hat{x}[1], \ldots, \hat{x}[d] \rangle,$$

    i.e., as $d + 1$ statistically independent shares, such that

$$x = \bigoplus_{i=0}^{i \leq d} \hat{x}[i],$$

  - computation of some functionality

$$r = f(x)$$

    can be described as three high-level steps:

    1. x is masked to yield $\hat{x}$,
    2. an alternative but compatible functionality $\hat{r} = \hat{f}(\hat{x})$ is executed, then
    3. $\hat{r}$ is unmasked to yield r.

- Problem: data-dependent computation within

$$\text{AES-128.}\textsc{Enc}(k, m)$$

  is observable via Λ.

- Idea [8, Section 3.1] (or see [2, Chapter 9]):
  - Step #1:
    1. generate random input (μ_0, μ_1, μ_2, μ_3, and μ_4) and output (ν_4) masks,
    2. pre-compute output masks

$$\begin{bmatrix} \nu_0 \\ \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} = \texttt{MixColumn}\left(\begin{bmatrix} \mu_0 \\ \mu_1 \\ \mu_2 \\ \mu_3 \end{bmatrix}\right),$$

    3. pre-compute a masked S-box, i.e., $\text{S-}\textsc{box}_{\mu_4}(x \oplus \mu_4) = \text{S-}\textsc{box}(x) \oplus \nu_4$.

Part 2.2: in practice (4)

Countermeasures: $\mathcal{T} \simeq$ AES, Λ = power consumption

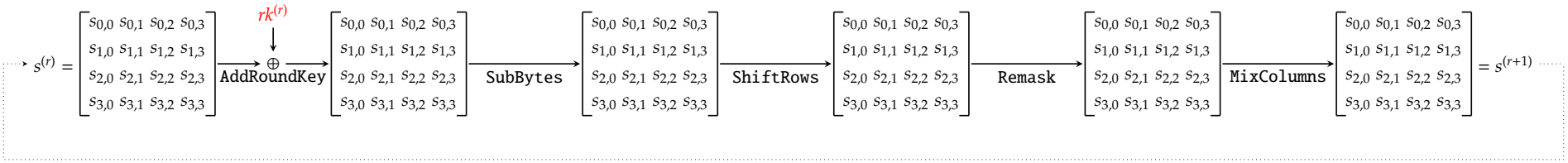
- Problem: data-dependent computation within

$$\text{AES-128.}\textsc{Enc}(k, m)$$

  is observable via Λ.

- Idea [8, Section 3.1] (or see [2, Chapter 9]):

  - Step #2: construct a masked round implementation



Part 2.2: in practice (4)

Countermeasures: $\mathcal{T} \simeq$ AES, Λ = power consumption

- Problem: data-dependent computation within

$$\text{AES-128.}\textsc{Enc}(k, m)$$

is observable via Λ.

- Idea [8, Section 3.1] (or see [2, Chapter 9]):

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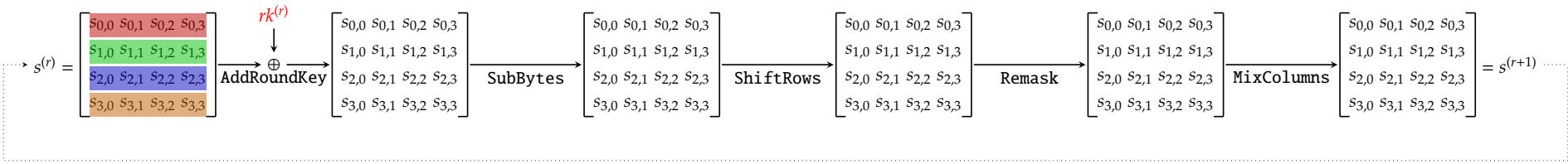


such that $s_{i,j}^{(r)}$ is masked with v_i.

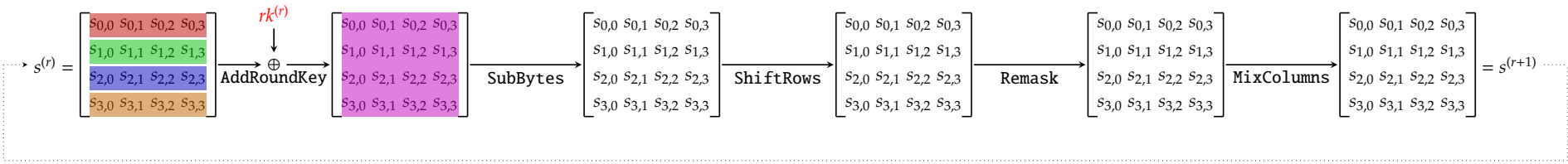
- Problem: data-dependent computation within

$$\text{AES-128.}\textsc{Enc}(k, m)$$

is observable via Λ.

- Idea [8, Section 3.1] (or see [2, Chapter 9]):

- Step #2: construct a masked round implementation



such that $s_{i,j}^{(r)}$ is masked with μ_4 due to alteration of key schedule (and thus $rk^{(r)}$).

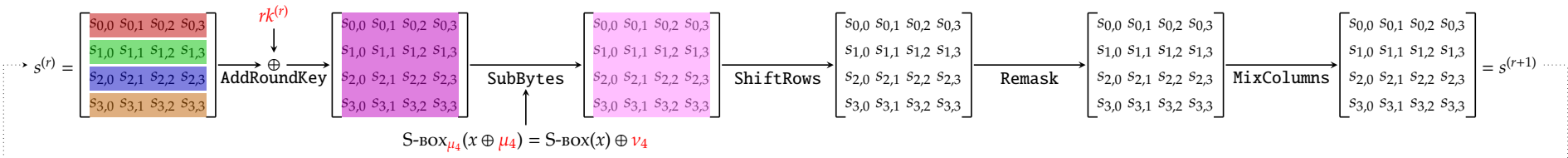
- Problem: data-dependent computation within

$$\text{AES-128.}\textsc{Enc}(k, m)$$

is observable via Λ.

- Idea [8, Section 3.1] (or see [2, Chapter 9]):

- Step #2: construct a masked round implementation



such that $s_{i,j}^{(r)}$ is masked with ν_4 due to alteration of S-box (i.e., use of S-box$_{\mu_4}$).

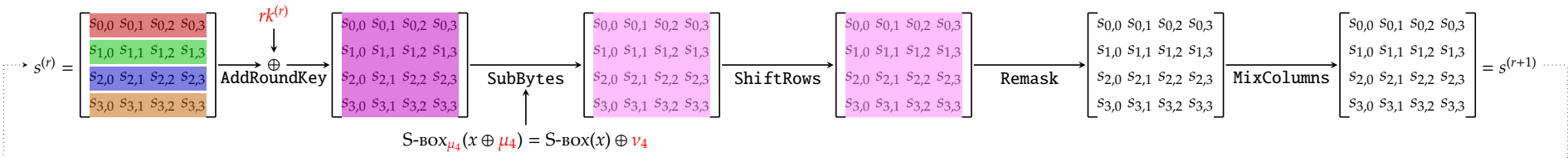
- Problem: data-dependent computation within

$$\text{AES-128.}\textsc{Enc}(k, m)$$

is observable via Λ.

- Idea [8, Section 3.1] (or see [2, Chapter 9]):

- Step #2: construct a masked round implementation



such that $s_{i,j}^{(r)}$ is (still) masked with ν_4.

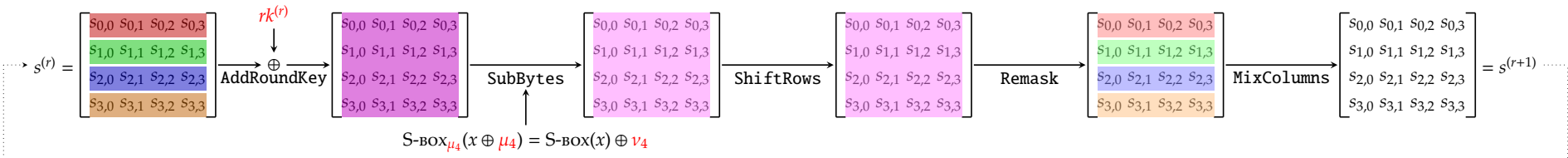
- Problem: data-dependent computation within

$$\text{AES-128.}\textsc{Enc}(k, m)$$

is observable via Λ.

- Idea [8, Section 3.1] (or see [2, Chapter 9]):

- Step #2: construct a masked round implementation



such that $s_{i,j}^{(r)}$ is masked with μ_i due to addition of `Remask`.

Part 2.2: in practice (4)

Countermeasures: $\mathcal{T} \simeq$ AES, Λ = power consumption

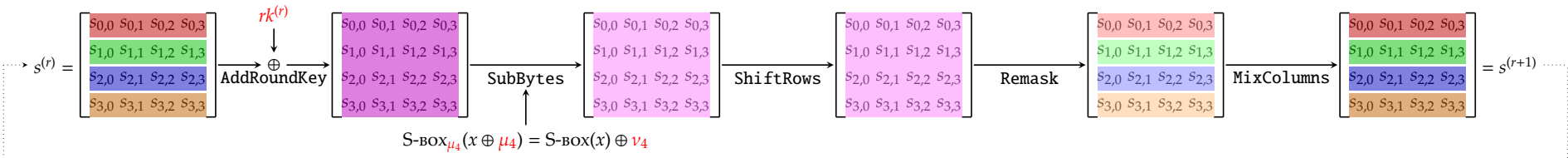
- Problem: data-dependent computation within

$$\text{AES-128.}\textsc{Enc}(k, m)$$

is observable via Λ.

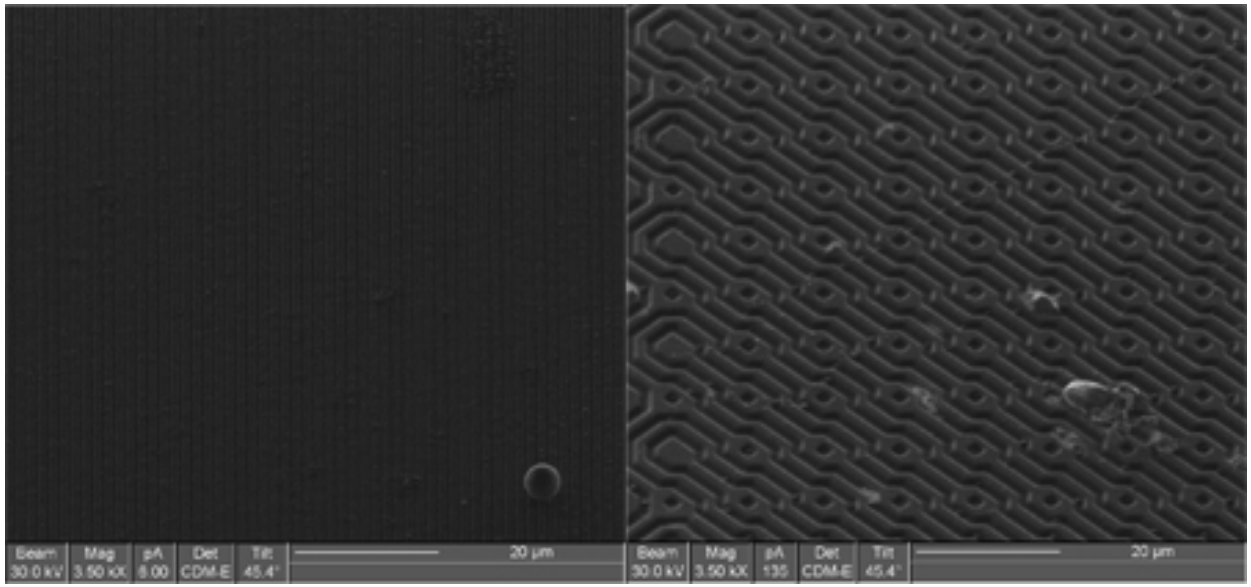
- Idea [8, Section 3.1] (or see [2, Chapter 9]):

- Step #2: construct a masked round implementation



such that $s_{i,j}^{(r)}$ is masked with ν_i due to alteration of `MixColumns`: this makes iteration possible.

- Problem: Δ can be used to influence, e.g., corrupt $s^{(r)}$.
- Idea: prevent physical access to device via a **mesh** (or **shield**).



i.e., a top-layer of metal which can be classed as

1. passive (or analogue), or
2. active (or digital).

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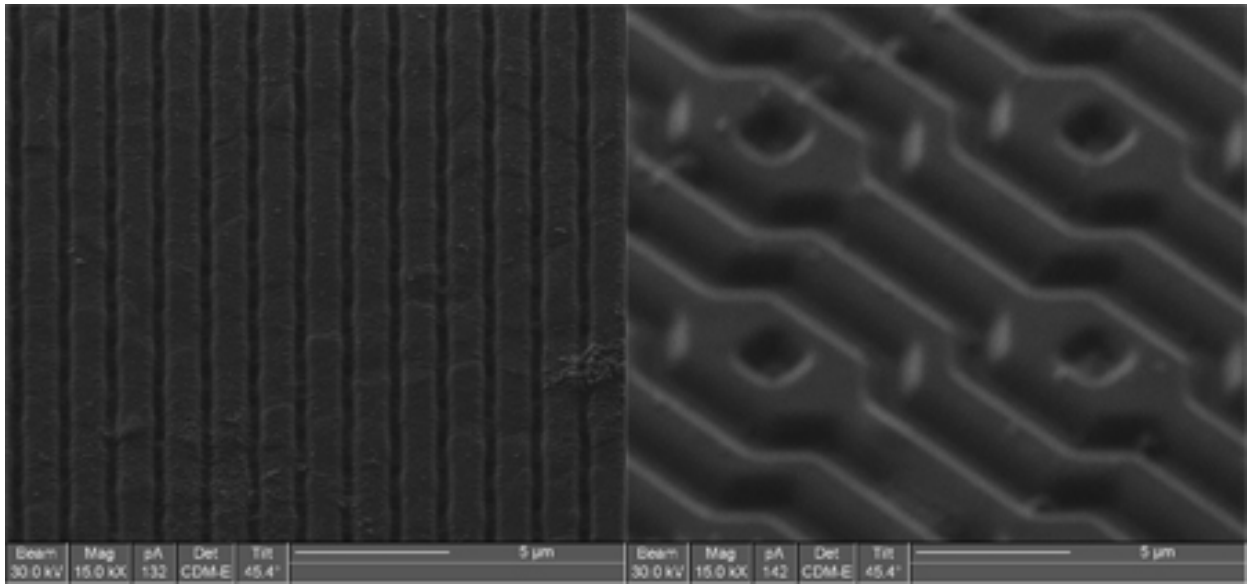
- Problem: Δ can be used to influence, e.g., corrupt $s^{(r)}$.
- Idea: prevent physical access to device via a **mesh** (or **shield**).



i.e., a top-layer of metal which can be classed as

1. passive (or analogue), or
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http://www.flylogic.net/blog/?p=86

- Problem: Δ can be used to influence, e.g., corrupt $s^{(r)}$.
- Idea [5]:
  - for $x \in \mathbb{F}_{2^8}$, let

$$\check{x} = \text{PAR}(x) = \bigoplus_{i=0}^{i<8} x_i$$

    denote the (even) **parity bit** for x,
  - let

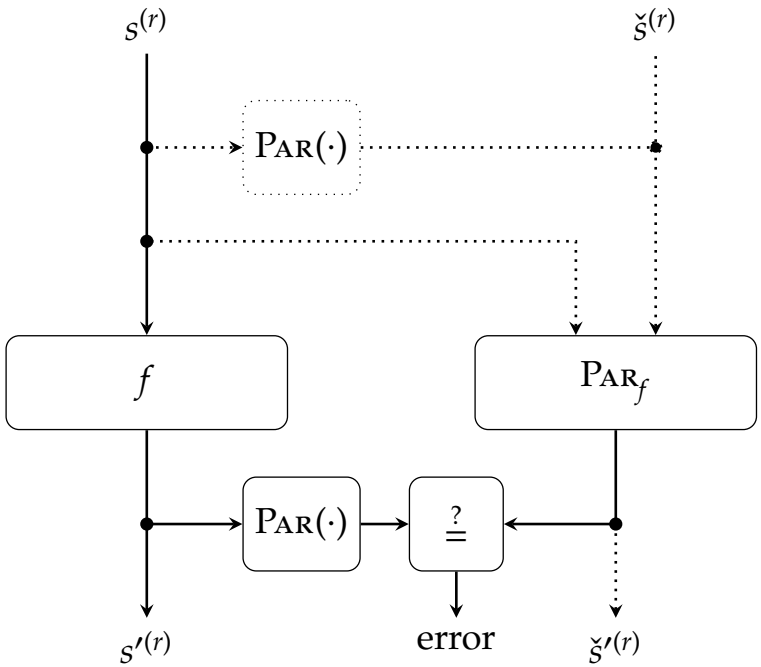
$$\check{s}^{(r)} = \begin{bmatrix} \check{s}^{(r)}_{0,0} & \check{s}^{(r)}_{0,1} & \check{s}^{(r)}_{0,2} & \check{s}^{(r)}_{0,3} \\ \check{s}^{(r)}_{1,0} & \check{s}^{(r)}_{1,1} & \check{s}^{(r)}_{1,2} & \check{s}^{(r)}_{1,3} \\ \check{s}^{(r)}_{2,0} & \check{s}^{(r)}_{2,1} & \check{s}^{(r)}_{2,2} & \check{s}^{(r)}_{2,3} \\ \check{s}^{(r)}_{3,0} & \check{s}^{(r)}_{3,1} & \check{s}^{(r)}_{3,2} & \check{s}^{(r)}_{3,3} \end{bmatrix}$$

    be the **parity matrix** associated with $s^{(r)}$, such that

$$\check{s}^{(r)}_{i,j} = \text{PAR}\left(s^{(r)}_{i,j} \right)$$

    and similarly for each round key $rk^{(r)}$.

- Problem: Δ can be used to influence, e.g., corrupt $s^{(r)}$.
- Idea [5]:
  - we can predict and check parity matrix per



at say a

1. round function,
2. round, or
3. encryption/decryption

granularity: we just need a PAR_f for each f ...

- Problem: Δ can be used to influence, e.g., corrupt $s^{(r)}$.
- Idea [5]:
  - for $x, y \in \mathbb{F}_{2^8}$, note that we have

$$\begin{aligned}
\textsc{Par}(x \oplus_{\mathbb{F}_{2^8}} y) &= \textsc{Par}(x) \oplus \textsc{Par}(y) \\
\textsc{Par}(\texttt{01} \otimes_{\mathbb{F}_{2^8}} x) &= \textsc{Par}(x) \\
\textsc{Par}(\texttt{02} \otimes_{\mathbb{F}_{2^8}} x) &= \textsc{MSB}(x) \oplus \textsc{Par}(x) \\
\textsc{Par}(\texttt{03} \otimes_{\mathbb{F}_{2^8}} x) &= \textsc{MSB}(x)
\end{aligned}$$

- Problem: Δ can be used to influence, e.g., corrupt $s^{(r)}$.
- Idea [5]:
  - putting everything together, we construct and use

$$\begin{aligned}
\text{PAR}_{\text{KEY-ADDITION}} &: \text{compute } \check{s}_{i,j}^{(r)} \oplus \check{rk}_{i,j}^{(r)} \\
\text{PAR}_{\text{SHIFT-ROWS}} &: \text{rotate each row of } \check{s}_{i,j}^{(r)} \\
\text{PAR}_{\text{SUB-BYTES}} &: \text{compute PAR}\left(\text{S-BOX}(s_{i,j}^{(r)})\right) \\
\text{PAR}_{\text{MIX-COLUMNS}} &: \text{apply PAR}_{\text{MIX-COLUMN}} \text{ to each column of } \check{s}_{i,j}^{(r)}
\end{aligned}$$

  where

$$\begin{bmatrix} \check{s}'^{(r)}_{0,j} \\ \check{s}'^{(r)}_{1,j} \\ \check{s}'^{(r)}_{2,j} \\ \check{s}'^{(r)}_{3,j} \end{bmatrix} = \text{PAR}_{\text{MIX-COLUMN}}\left(\begin{bmatrix} \check{s}^{(r)}_{0,j} \\ \check{s}^{(r)}_{1,j} \\ \check{s}^{(r)}_{2,j} \\ \check{s}^{(r)}_{3,j} \end{bmatrix}\right) = \begin{bmatrix} \left(\text{MSB}\left(s^{(r)}_{0,j}\right) \oplus \check{s}^{(r)}_{0,j}\right) \oplus \text{MSB}\left(s^{(r)}_{1,j}\right) \oplus \check{s}^{(r)}_{2,j} \oplus \check{s}^{(r)}_{3,j} \\ \check{s}^{(r)}_{0,j} \oplus \left(\text{MSB}\left(s^{(r)}_{1,j}\right) \oplus \check{s}^{(r)}_{1,j}\right) \oplus \text{MSB}\left(s^{(r)}_{2,j}\right) \oplus \check{s}^{(r)}_{3,j} \\ \check{s}^{(r)}_{0,j} \oplus \check{s}^{(r)}_{1,j} \oplus \left(\text{MSB}\left(s^{(r)}_{2,j}\right) \oplus \check{s}^{(r)}_{2,j}\right) \oplus \text{MSB}\left(s^{(r)}_{3,j}\right) \\ \text{MSB}\left(s^{(r)}_{0,j}\right) \oplus \check{s}^{(r)}_{1,j} \oplus \check{s}^{(r)}_{2,j} \oplus \left(\text{MSB}\left(s^{(r)}_{3,j}\right) \oplus \check{s}^{(r)}_{3,j}\right) \end{bmatrix}$$

Conclusions

- Take away points:
  - For $\mathcal{E}$, this is fun!
    - can ignore the rules (cf. do whatever possible, versus what is modelled),
    - less and less "low hanging fruit", but still lots of opportunity,
    - more and more applicability at scale,
    - ...
  - For $\mathcal{T}$, this can be *really* difficult!
    - implications go beyond technical, into, e.g., reputational,
    - many general principles apply, but often specific details matter,
    - need to consider multiple layers of abstraction,
    - satisfactory trade-offs (e.g., efficiency versus security) are challenging,
    - raise problematic questions re. development practice, supply-chain, etc.
    - ...

Additional Reading

- S. Mangard, E. Oswald, and T. Popp. *Power Analysis Attacks: Revealing the Secrets of Smart Cards*. Springer, 2007.
- P.C. Kocher et al. "Introduction to differential power analysis". In: *Journal of Cryptographic Engineering (JCEN)* 1.1 (2011), pp. 5–27.
- M. Joye and M. Tunstall, eds. *Fault Analysis in Cryptography*. Information Security and Cryptography. Springer, 2012.
- H. Bar-El et al. "The Sorcerer's Apprentice Guide to Fault Attacks". In: *Proceedings of the IEEE* 94.2 (2006), pp. 370–382.
- A. Barenghi et al. "Fault Injection Attacks on Cryptographic Devices: Theory, Practice, and Countermeasures". In: *Proceedings of the IEEE* 100.11 (2012), pp. 3056–3076.
- D. Karaklajić, J.-M. Schmidt, and I. Verbauwhede. "Hardware Designer's Guide to Fault Attacks". In: *IEEE Transactions on Very Large Scale Integration (VLSI) Systems* 21.12 (2013), pp. 2295–2306.
- B. Yuce, P. Schaumont, and M. Witteman. "Fault Attacks on Secure Embedded Software: Threats, Design, and Evaluation". In: *Journal of Hardware and Systems Security* 2.2 (2018), pp. 111–130.

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[2] S. Mangard, E. Oswald, and T. Popp. *Power Analysis Attacks: Revealing the Secrets of Smart Cards*. Springer, 2007 (see pp. 59–66, 74).

[3] H. Bar-El et al. "The Sorcerer's Apprentice Guide to Fault Attacks". In: *Proceedings of the IEEE* 94.2 (2006), pp. 370–382 (see p. 74).

[4] A. Barenghi et al. "Fault Injection Attacks on Cryptographic Devices: Theory, Practice, and Countermeasures". In: *Proceedings of the IEEE* 100.11 (2012), pp. 3056–3076 (see p. 74).

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[9] D. Karaklajić, J.-M. Schmidt, and I. Verbauwhede. "Hardware Designer's Guide to Fault Attacks". In: *IEEE Transactions on Very Large Scale Integration (VLSI) Systems* 21.12 (2013), pp. 2295–2306 (see p. 74).

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[11] P.C. Kocher, J. Jaffe, and B. Jun. "Differential Power Analysis". In: *Advances in Cryptology (CRYPTO)*. LNCS 1666. Springer-Verlag, 1999, pp. 388–397 (see pp. 4, 5).

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