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

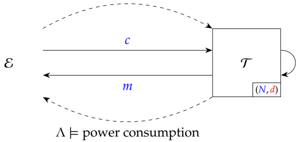
     and
  2. an "in practice", i.e., example-oriented perspective,
     2.1 attacks,
     2.2 countermeasures.
- Caveat!

$$\sim 2 \text{ hours} \quad \Rightarrow \quad \text{introductory, and (very) selective (versus definitive) coverage.}$$

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** $\mathcal{T}$



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

```
algorithm RSA.Dec((N, d), c) begin
  Pre-compute Π = (N, ρ, ω) from N
  ĉ ← MontMul(Π, c, ρ^2 mod N)
  r̂ ← MontMul(Π, c, ρ^2 mod N)
  for i = |d| − 2 downto 0 do
    r̂ ← MontSqr(Π, r̂)
    if d_i = 1 then
      r̂ ← MontMul(Π, r̂, ĉ)
    end
  end
  return MontMul(Π, r̂, 1)
end
```

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

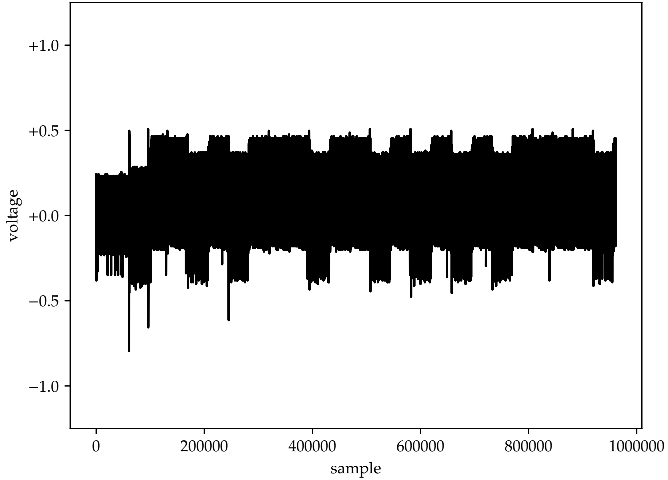
$$\text{MontSqr}(\Pi, \hat{r}) = \hat{r} \times \hat{r} \times \rho^{-1} \pmod N,$$

      is used, such that although

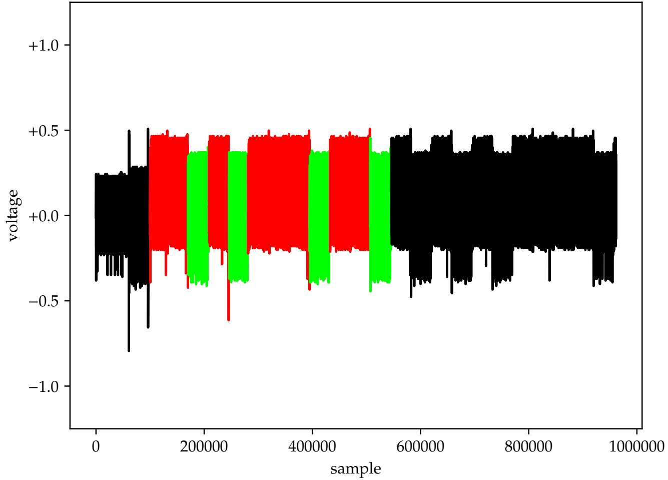
$$\text{MontSqr}(\Pi, \hat{r}) = \text{MontMul}(\Pi, \hat{r}, \hat{r}),$$

      the former is more efficient than the latter,
    - the Montgomery squaring and Montgomery multiplication implementations are FIOS-based [12],
  - how can $\mathcal{E}$ mount a successful attack, i.e., recover d ?

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



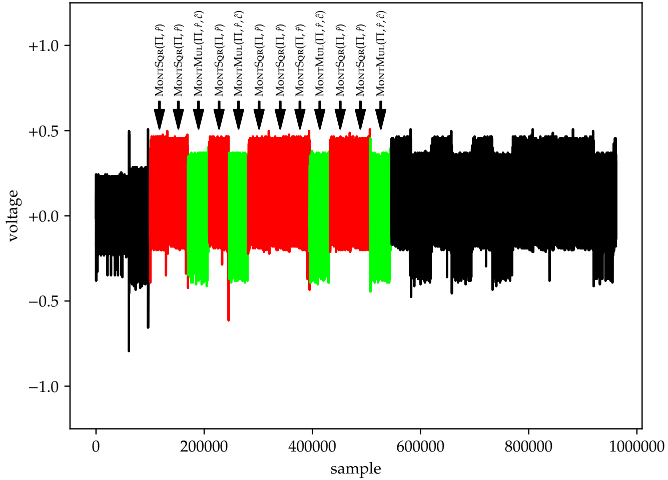
- Attack [14]:


+1.0
+0.5
+0.0
−0.5
−1.0
voltage
0
200000
400000
600000
800000
1000000
sample

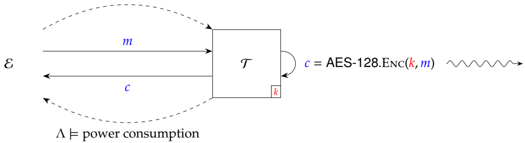
Part 2.1: in practice (2)

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

- Attack [14]:



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




```
algorithm AES-128.Enc(k, m) begin
  s ← m
  s ← AddRoundKey(s, k = rk^(0))
  for r = 1 upto 9 step +1 do
    k ← EvolveRoundKey(k, rc^(r))
    s ← SubBytes(s)
    s ← ShiftRows(s)
    s ← MixColumns(s)
    s ← AddRoundKey(s, k = rk^(r))
  end
  k ← EvolveRoundKey(k, rc^(10))
  s ← SubBytes(s)
  s ← ShiftRows(s)
  s ← AddRoundKey(s, k = rk^(10))
  c ← s
  return c
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, Λ = power consumption

- **Attack** [7]:

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

Part 2.1: in practice (4)

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

- Attack [7]:

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

some $\tilde{j}$ indexes leakage from the target operation

- **Attack [7]:**

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

$$\begin{array}{rc} \mathcal{M}_0 \xrightarrow{\text{HW}(\text{S-}\textsc{box}(\mathcal{M}_{0,t} \oplus \tilde{k}_t))} & \multirow{4}{*}{$\begin{pmatrix} \mathcal{H}_{0,0} & \mathcal{H}_{0,1} & \cdots & \mathcal{H}_{0,h-1} \\ \mathcal{H}_{1,0} & \mathcal{H}_{1,1} & \cdots & \mathcal{H}_{1,h-1} \\ \vdots & \vdots & \ddots & \vdots \\ \mathcal{H}_{n-1,0} & \mathcal{H}_{n-1,1} & \cdots & \mathcal{H}_{n-1,h-1} \end{pmatrix}$} \\ \mathcal{M}_1 \xrightarrow{\text{HW}(\text{S-}\textsc{box}(\mathcal{M}_{1,t} \oplus \tilde{k}_t))} & \\ \vdots & \\ \mathcal{M}_{n-1} \xrightarrow{\text{HW}(\text{S-}\textsc{box}(\mathcal{M}_{n-1,t} \oplus \tilde{k}_t))} & \\ & \underbrace{\begin{array}{cccc} \underbrace{\qquad}_{\tilde{k}_t = 0} & \underbrace{\qquad}_{\tilde{k}_t = 1} & \cdots & \underbrace{\qquad}_{\tilde{k}_t = h-1} \end{array}}_{h = 2^8 = 256 \text{ hypothetical values for } k_t} \end{array}$$

- Attack [7]:

some $\tilde{k}_t = k_t$, i.e., is correct

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

$$
\begin{array}{lc}
\mathcal{M}_0 & \xrightarrow{\text{HW}(\text{S-box}(\mathcal{M}_{0,t} \oplus \tilde{k}_t))} \\
\mathcal{M}_1 & \xrightarrow{\text{HW}(\text{S-box}(\mathcal{M}_{1,t} \oplus \tilde{k}_t))} \\
\vdots & \\
\mathcal{M}_{n-1} & \xrightarrow{\text{HW}(\text{S-box}(\mathcal{M}_{n-1,t} \oplus \tilde{k}_t))}
\end{array}
\underbrace{
\left(
\begin{array}{cccc}
\mathcal{H}_{0,0} & \mathcal{H}_{0,1} & \cdots & \mathcal{H}_{0,h-1} \\
\mathcal{H}_{1,0} & \mathcal{H}_{1,1} & \cdots & \mathcal{H}_{1,h-1} \\
\vdots & \vdots & \ddots & \vdots \\
\mathcal{H}_{n-1,0} & \mathcal{H}_{n-1,1} & \cdots & \mathcal{H}_{n-1,h-1} \\
\hline
\tilde{k}_t = 0 & \tilde{k}_t = 1 & \cdots & \tilde{k}_t = h-1
\end{array}
\right)
}_{h = 2^8 = 256 \text{ hypothetical values for } k_t}
$$

- Attack [7]:

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

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

$$h = 2^8 = 256 \text{ hypothetical values for } k_t$$

$$\boxed{\text{analysis}} \longrightarrow \left(\begin{array}{cccc} \mathcal{C}_{0,0} & \mathcal{C}_{0,1} & \cdots & \mathcal{C}_{0,l-1} \\ \mathcal{C}_{1,0} & \mathcal{C}_{1,1} & \cdots & \mathcal{C}_{1,l-1} \\ \vdots & \vdots & \ddots & \vdots \\ \mathcal{C}_{h-1,0} & \mathcal{C}_{h-1,1} & \cdots & \mathcal{C}_{h-1,l-1} \end{array} \right)$$

- Attack [7]:

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

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

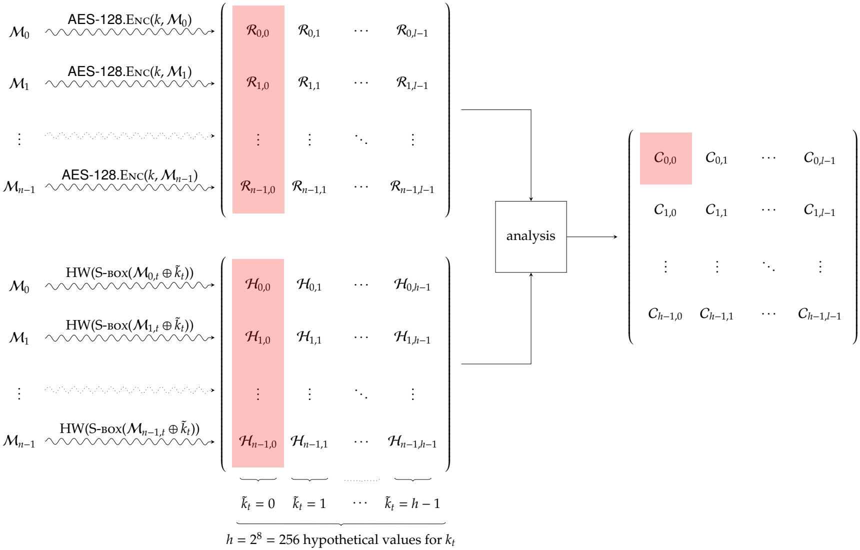
$$
\underbrace{\tilde{k}_t = 0 \quad \tilde{k}_t = 1 \quad \cdots \quad \tilde{k}_t = h-1}_{h \,=\, 2^8 \,=\, 256 \text{ hypothetical values for } k_t}
$$

analysis

$$
\left(\begin{array}{cccc}
C_{0,0} & C_{0,1} & \cdots & C_{0,l-1} \\
C_{1,0} & C_{1,1} & \cdots & C_{1,l-1} \\
\vdots & \vdots & \ddots & \vdots \\
C_{h-1,0} & C_{h-1,1} & \cdots & C_{h-1,l-1}
\end{array}\right)
$$

e.g., $C_{i,j} = \dfrac{\sum_{x=0}^{x<n}((\mathcal{H}_{x,i} - \bar{\mathcal{H}}_i) \cdot (\mathcal{R}_{x,j} - \bar{\mathcal{R}}_j))}{\sqrt{\sum_{x=0}^{x<n}(\mathcal{H}_{x,i} - \bar{\mathcal{H}}_i)^2} \cdot \sqrt{\sum_{x=0}^{x<n}(\mathcal{R}_{x,j} - \bar{\mathcal{R}}_j)^2}}$

- Attack [7]:



$\mathcal{M}_0$ AES-128.Enc$(k, \mathcal{M}_0)$
$\mathcal{M}_1$ AES-128.Enc$(k, \mathcal{M}_1)$
$\mathcal{M}_{n-1}$ AES-128.Enc$(k, \mathcal{M}_{n-1})$
$\mathcal{R}_{0,0}$ $\mathcal{R}_{0,1}$ $\cdots$ $\mathcal{R}_{0,l-1}$
$\mathcal{R}_{1,0}$ $\mathcal{R}_{1,1}$ $\cdots$ $\mathcal{R}_{1,l-1}$
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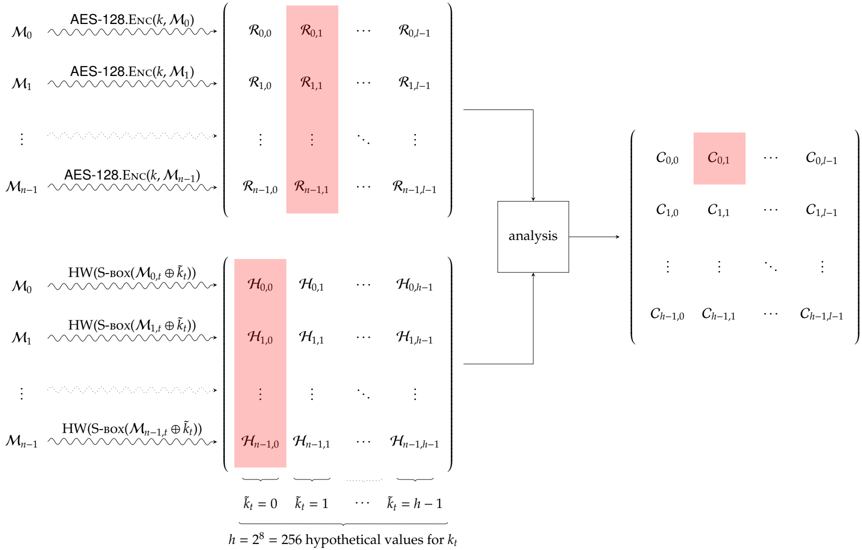
$\mathcal{H}_{0,0}$ $\mathcal{H}_{0,1}$ $\cdots$ $\mathcal{H}_{0,h-1}$
$\mathcal{H}_{1,0}$ $\mathcal{H}_{1,1}$ $\cdots$ $\mathcal{H}_{1,h-1}$
$\mathcal{H}_{n-1,0}$ $\mathcal{H}_{n-1,1}$ $\cdots$ $\mathcal{H}_{n-1,h-1}$
$\tilde{k}_t = 0$ $\tilde{k}_t = 1$ $\cdots$ $\tilde{k}_t = h-1$
$h = 2^8 = 256$ hypothetical values for k_t
analysis
$\mathcal{C}_{0,0}$ $\mathcal{C}_{0,1}$ $\cdots$ $\mathcal{C}_{0,l-1}$
$\mathcal{C}_{1,0}$ $\mathcal{C}_{1,1}$ $\cdots$ $\mathcal{C}_{1,l-1}$
$\mathcal{C}_{h-1,0}$ $\mathcal{C}_{h-1,1}$ $\cdots$ $\mathcal{C}_{h-1,l-1}$

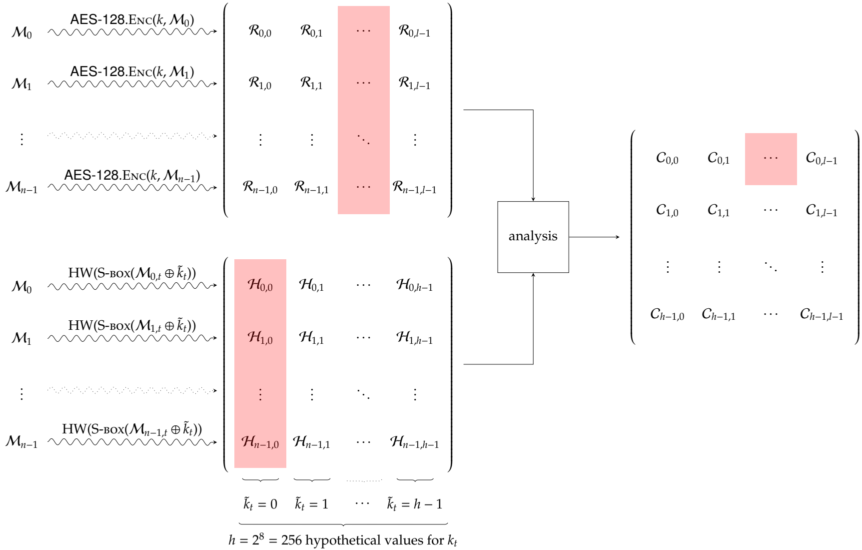
Part 2.1: in practice (4)

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

- Attack [7]:



- Attack [7]:



$\mathcal{M}_0$
AES-128.ENC$(k, \mathcal{M}_0)$
$\mathcal{M}_1$
AES-128.ENC$(k, \mathcal{M}_1)$
$\mathcal{M}_{n-1}$
AES-128.ENC$(k, \mathcal{M}_{n-1})$
$\mathcal{R}_{0,0}$ $\mathcal{R}_{0,1}$ $\cdots$ $\mathcal{R}_{0,l-1}$
$\mathcal{R}_{1,0}$ $\mathcal{R}_{1,1}$ $\cdots$ $\mathcal{R}_{1,l-1}$
$\mathcal{R}_{n-1,0}$ $\mathcal{R}_{n-1,1}$ $\cdots$ $\mathcal{R}_{n-1,l-1}$
$\mathcal{M}_0$
HW(S-BOX$(\mathcal{M}_{0,t} \oplus \tilde{k}_t)$)
$\mathcal{M}_1$
HW(S-BOX$(\mathcal{M}_{1,t} \oplus \tilde{k}_t)$)
$\mathcal{M}_{n-1}$
HW(S-BOX$(\mathcal{M}_{n-1,t} \oplus \tilde{k}_t)$)
$\mathcal{H}_{0,0}$ $\mathcal{H}_{0,1}$ $\cdots$ $\mathcal{H}_{0,h-1}$
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$\tilde{k}_t = 0$ $\tilde{k}_t = 1$ $\cdots$ $\tilde{k}_t = h-1$
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analysis
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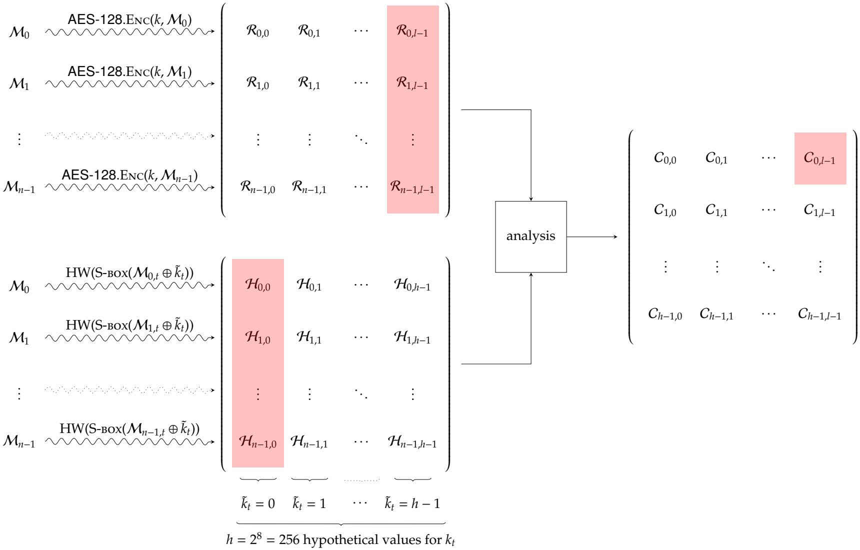
- Attack [7]:


$\mathcal{M}_0$
AES-128.ENC(k, $\mathcal{M}_0$)
$\mathcal{M}_1$
AES-128.ENC(k, $\mathcal{M}_1$)
$\mathcal{M}_{n-1}$
AES-128.ENC(k, $\mathcal{M}_{n-1}$)
$\mathcal{R}_{0,0}$ $\mathcal{R}_{0,1}$ $\cdots$ $\mathcal{R}_{0,l-1}$
$\mathcal{R}_{1,0}$ $\mathcal{R}_{1,1}$ $\cdots$ $\mathcal{R}_{1,l-1}$
$\mathcal{R}_{n-1,0}$ $\mathcal{R}_{n-1,1}$ $\cdots$ $\mathcal{R}_{n-1,l-1}$
HW(S-BOX($\mathcal{M}_{0,t} \oplus \tilde{k}_t$))
HW(S-BOX($\mathcal{M}_{1,t} \oplus \tilde{k}_t$))
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$\mathcal{H}_{0,0}$ $\mathcal{H}_{0,1}$ $\cdots$ $\mathcal{H}_{0,h-1}$
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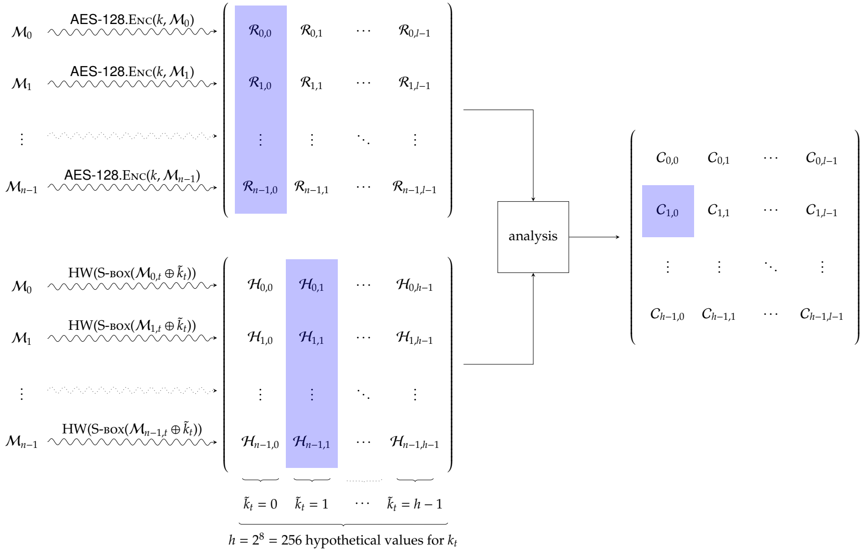
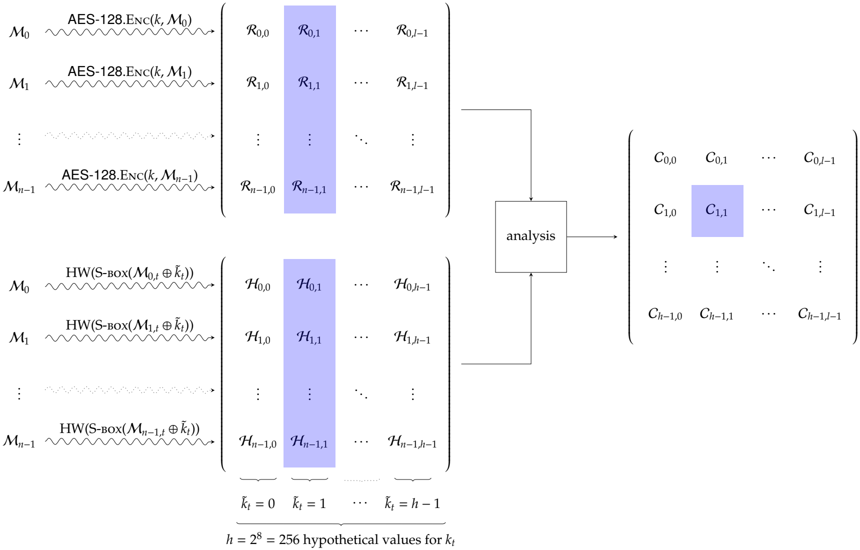
$\tilde{k}_t = 0$ $\tilde{k}_t = 1$ $\cdots$ $\tilde{k}_t = h-1$
$h = 2^8 = 256$ hypothetical values for k_t
analysis
$\mathcal{C}_{0,0}$ $\mathcal{C}_{0,1}$ $\cdots$ $\mathcal{C}_{0,l-1}$
$\mathcal{C}_{1,0}$ $\mathcal{C}_{1,1}$ $\cdots$ $\mathcal{C}_{1,l-1}$
$\mathcal{C}_{h-1,0}$ $\mathcal{C}_{h-1,1}$ $\cdots$ $\mathcal{C}_{h-1,l-1}$

Part 2.1: in practice (4)
Attacks: $\mathcal{T} \simeq$ AES, Λ = power consumption

- Attack [7]:



- Attack [7]:


$\mathcal{M}_0$ AES-128.Enc(k, $\mathcal{M}_0$)
$\mathcal{M}_1$ AES-128.Enc(k, $\mathcal{M}_1$)
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$\mathcal{H}_{0,0}$ $\mathcal{H}_{0,1}$ $\mathcal{H}_{0,h-1}$
$\mathcal{H}_{1,0}$ $\mathcal{H}_{1,1}$ $\mathcal{H}_{1,h-1}$
$\mathcal{H}_{n-1,0}$ $\mathcal{H}_{n-1,1}$ $\mathcal{H}_{n-1,h-1}$
$\tilde{k}_t = 0$ $\tilde{k}_t = 1$ $\tilde{k}_t = h-1$
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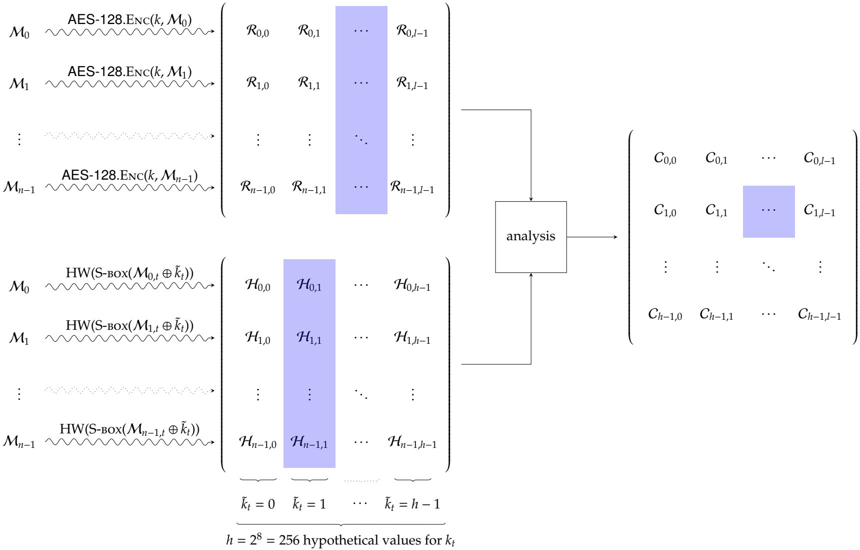
analysis
$\mathcal{C}_{0,0}$ $\mathcal{C}_{0,1}$ $\mathcal{C}_{0,l-1}$
$\mathcal{C}_{1,0}$ $\mathcal{C}_{1,1}$ $\mathcal{C}_{1,l-1}$
$\mathcal{C}_{h-1,0}$ $\mathcal{C}_{h-1,1}$ $\mathcal{C}_{h-1,l-1}$

Part 2.1: in practice (4)

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

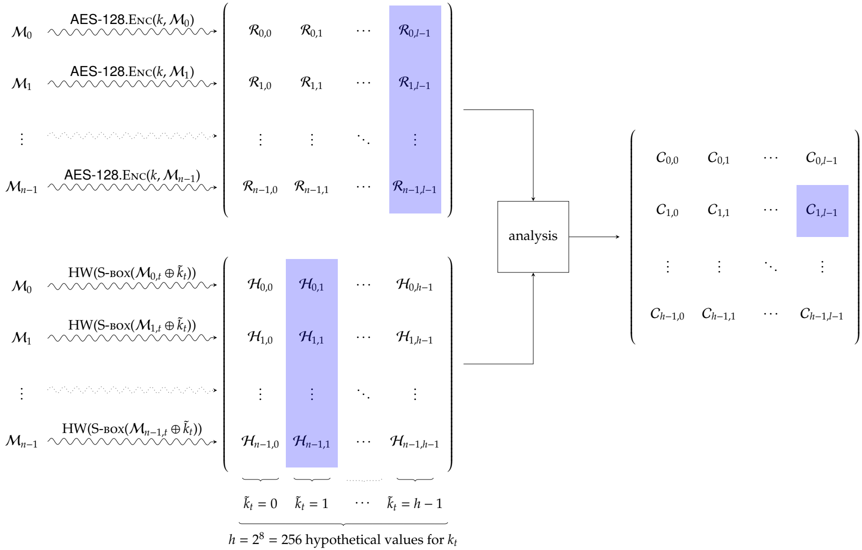
- Attack [7]:



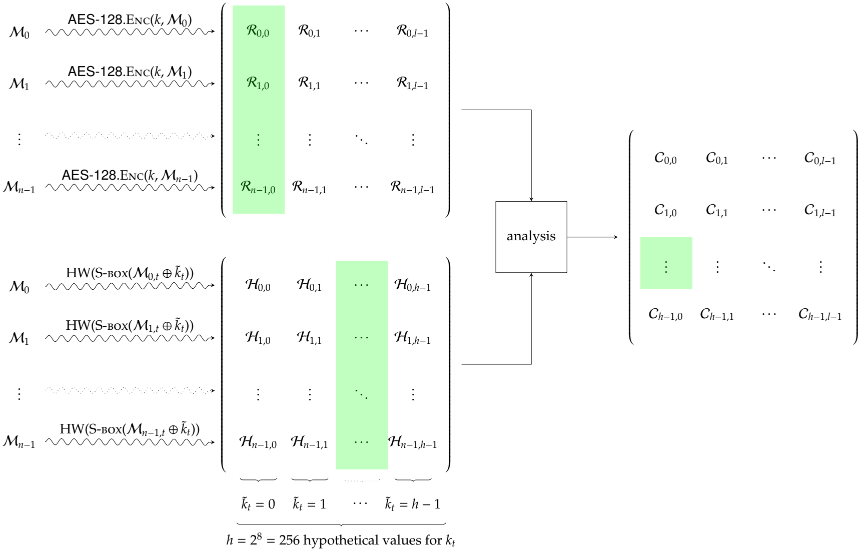
Part 2.1: in practice (4)

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

- Attack [7]:



- **Attack [7]:**



$\mathcal{M}_0$ AES-128.Enc(k, $\mathcal{M}_0$)
$\mathcal{M}_1$ AES-128.Enc(k, $\mathcal{M}_1$)
$\mathcal{M}_{n-1}$ AES-128.Enc(k, $\mathcal{M}_{n-1}$)
$\mathcal{R}_{0,0}$ $\mathcal{R}_{0,1}$ $\cdots$ $\mathcal{R}_{0,l-1}$
$\mathcal{R}_{1,0}$ $\mathcal{R}_{1,1}$ $\cdots$ $\mathcal{R}_{1,l-1}$
$\mathcal{R}_{n-1,0}$ $\mathcal{R}_{n-1,1}$ $\cdots$ $\mathcal{R}_{n-1,l-1}$
$\mathcal{M}_0$ HW(S-box($\mathcal{M}_{0,t} \oplus \tilde{k}_t$))
$\mathcal{M}_1$ HW(S-box($\mathcal{M}_{1,t} \oplus \tilde{k}_t$))
$\mathcal{M}_{n-1}$ HW(S-box($\mathcal{M}_{n-1,t} \oplus \tilde{k}_t$))
$\mathcal{H}_{0,0}$ $\mathcal{H}_{0,1}$ $\cdots$ $\mathcal{H}_{0,h-1}$
$\mathcal{H}_{1,0}$ $\mathcal{H}_{1,1}$ $\cdots$ $\mathcal{H}_{1,h-1}$
$\mathcal{H}_{n-1,0}$ $\mathcal{H}_{n-1,1}$ $\cdots$ $\mathcal{H}_{n-1,h-1}$
$\tilde{k}_t = 0$ $\tilde{k}_t = 1$ $\cdots$ $\tilde{k}_t = h-1$
$h = 2^8 = 256$ hypothetical values for k_t
analysis
$\mathcal{C}_{0,0}$ $\mathcal{C}_{0,1}$ $\cdots$ $\mathcal{C}_{0,l-1}$
$\mathcal{C}_{1,0}$ $\mathcal{C}_{1,1}$ $\cdots$ $\mathcal{C}_{1,l-1}$
$\mathcal{C}_{h-1,0}$ $\mathcal{C}_{h-1,1}$ $\cdots$ $\mathcal{C}_{h-1,l-1}$

Part 2.1: in practice (4)

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

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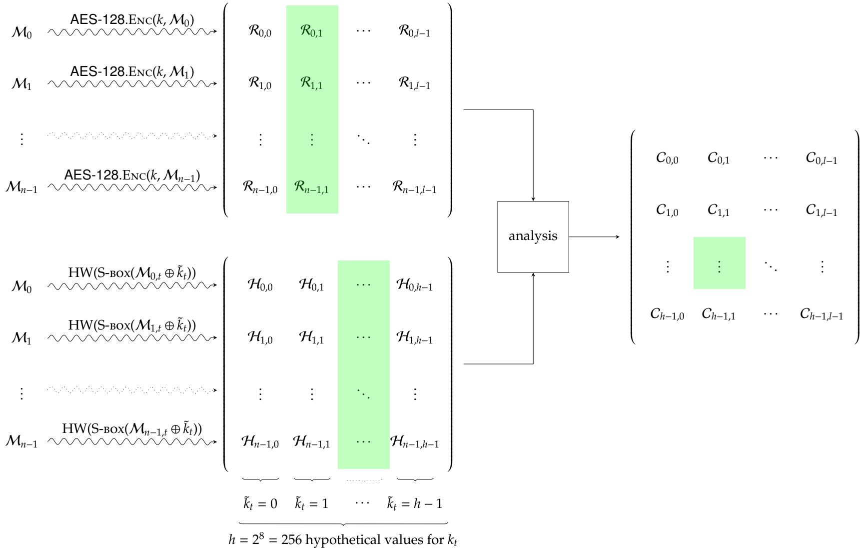
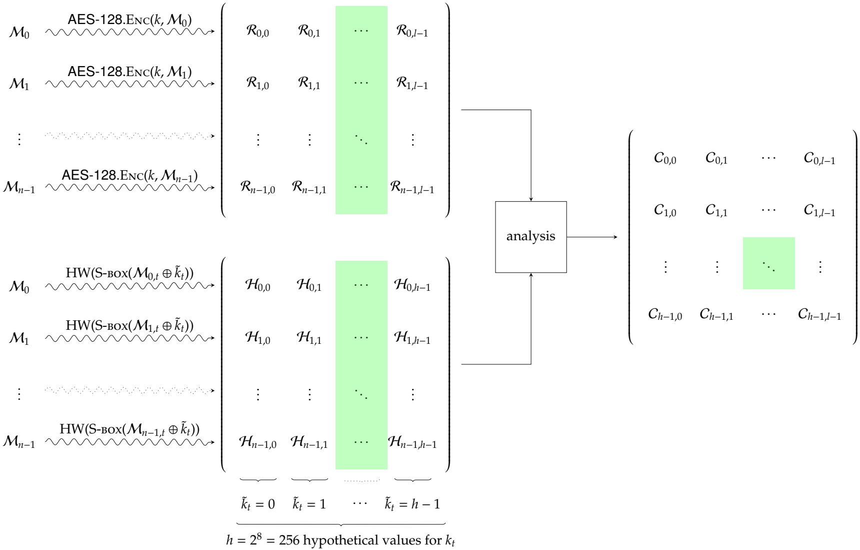


- **Attack [7]:**


$\mathcal{M}_0$
AES-128.Enc$(k, \mathcal{M}_0)$
$\mathcal{M}_1$
AES-128.Enc$(k, \mathcal{M}_1)$
$\mathcal{M}_{n-1}$
AES-128.Enc$(k, \mathcal{M}_{n-1})$
$\mathcal{R}_{0,0}$ $\mathcal{R}_{0,1}$ $\cdots$ $\mathcal{R}_{0,l-1}$
$\mathcal{R}_{1,0}$ $\mathcal{R}_{1,1}$ $\cdots$ $\mathcal{R}_{1,l-1}$
$\mathcal{R}_{n-1,0}$ $\mathcal{R}_{n-1,1}$ $\cdots$ $\mathcal{R}_{n-1,l-1}$
$\mathcal{M}_0$
HW(S-box$(\mathcal{M}_{0,t} \oplus \tilde{k}_t)$)
$\mathcal{M}_1$
HW(S-box$(\mathcal{M}_{1,t} \oplus \tilde{k}_t)$)
$\mathcal{M}_{n-1}$
HW(S-box$(\mathcal{M}_{n-1,t} \oplus \tilde{k}_t)$)
$\mathcal{H}_{0,0}$ $\mathcal{H}_{0,1}$ $\cdots$ $\mathcal{H}_{0,h-1}$
$\mathcal{H}_{1,0}$ $\mathcal{H}_{1,1}$ $\cdots$ $\mathcal{H}_{1,h-1}$
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$\tilde{k}_t = 0$ $\tilde{k}_t = 1$ $\cdots$ $\tilde{k}_t = h-1$
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$\mathcal{C}_{0,0}$ $\mathcal{C}_{0,1}$ $\cdots$ $\mathcal{C}_{0,l-1}$
$\mathcal{C}_{1,0}$ $\mathcal{C}_{1,1}$ $\cdots$ $\mathcal{C}_{1,l-1}$
$\mathcal{C}_{h-1,0}$ $\mathcal{C}_{h-1,1}$ $\cdots$ $\mathcal{C}_{h-1,l-1}$

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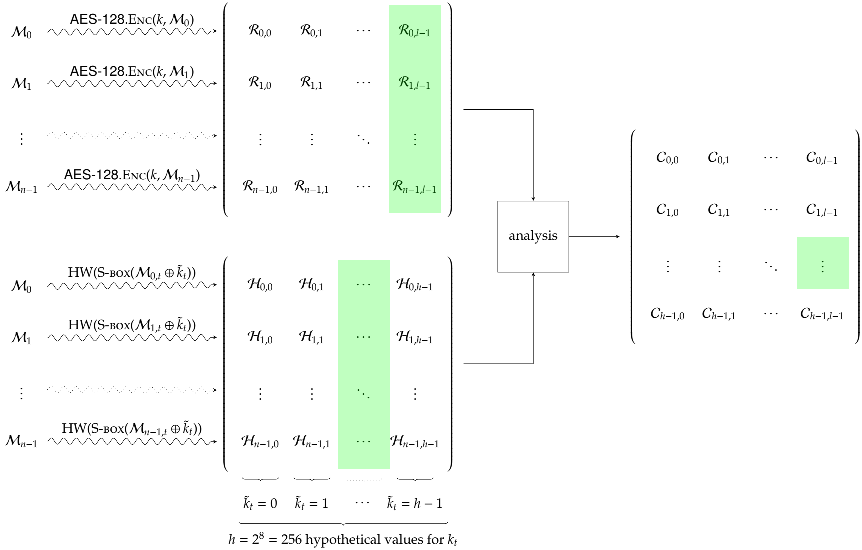

$\mathcal{M}_0$ AES-128.ENC(k, $\mathcal{M}_0$)
$\mathcal{M}_1$ AES-128.ENC(k, $\mathcal{M}_1$)
$\mathcal{M}_{n-1}$ AES-128.ENC(k, $\mathcal{M}_{n-1}$)
$\mathcal{R}_{0,0}$ $\mathcal{R}_{0,1}$ $\cdots$ $\mathcal{R}_{0,l-1}$
$\mathcal{R}_{1,0}$ $\mathcal{R}_{1,1}$ $\cdots$ $\mathcal{R}_{1,l-1}$
$\mathcal{R}_{n-1,0}$ $\mathcal{R}_{n-1,1}$ $\cdots$ $\mathcal{R}_{n-1,l-1}$
$\mathcal{M}_0$ HW(S-BOX($\mathcal{M}_{0,t} \oplus \tilde{k}_t$))
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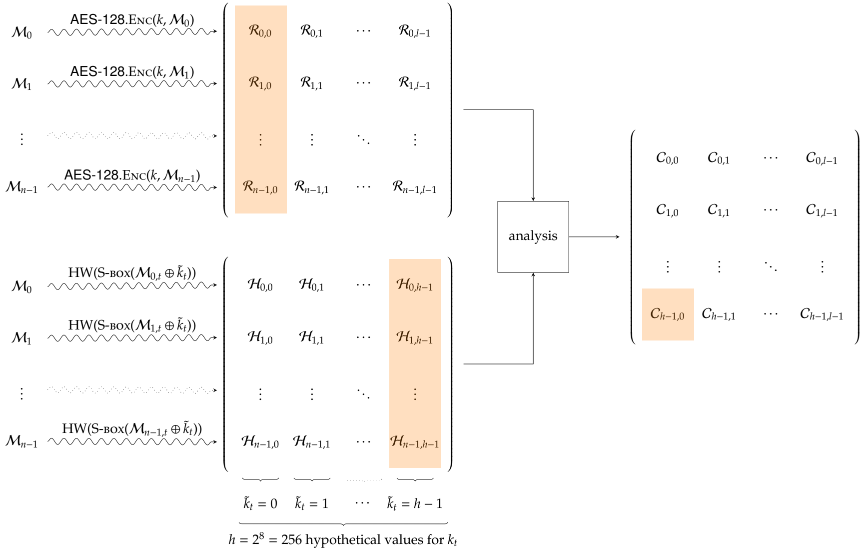
$\mathcal{M}_{n-1}$ HW(S-BOX($\mathcal{M}_{n-1,t} \oplus \tilde{k}_t$))
$\mathcal{H}_{0,0}$ $\mathcal{H}_{0,1}$ $\cdots$ $\mathcal{H}_{0,h-1}$
$\mathcal{H}_{1,0}$ $\mathcal{H}_{1,1}$ $\cdots$ $\mathcal{H}_{1,h-1}$
$\mathcal{H}_{n-1,0}$ $\mathcal{H}_{n-1,1}$ $\cdots$ $\mathcal{H}_{n-1,h-1}$
$\tilde{k}_t = 0$ $\tilde{k}_t = 1$ $\cdots$ $\tilde{k}_t = h-1$
$h = 2^8 = 256$ hypothetical values for k_t
analysis
$\mathcal{C}_{0,0}$ $\mathcal{C}_{0,1}$ $\cdots$ $\mathcal{C}_{0,l-1}$
$\mathcal{C}_{1,0}$ $\mathcal{C}_{1,1}$ $\cdots$ $\mathcal{C}_{1,l-1}$
$\mathcal{C}_{h-1,0}$ $\mathcal{C}_{h-1,1}$ $\cdots$ $\mathcal{C}_{h-1,l-1}$

- **Attack [7]:**



$\mathcal{M}_0$
AES-128.ENC(k, $\mathcal{M}_0$)
$\mathcal{M}_1$
AES-128.ENC(k, $\mathcal{M}_1$)
$\mathcal{M}_{n-1}$
AES-128.ENC(k, $\mathcal{M}_{n-1}$)
$\mathcal{R}_{0,0}$ $\mathcal{R}_{0,1}$ $\cdots$ $\mathcal{R}_{0,l-1}$
$\mathcal{R}_{1,0}$ $\mathcal{R}_{1,1}$ $\cdots$ $\mathcal{R}_{1,l-1}$
$\mathcal{R}_{n-1,0}$ $\mathcal{R}_{n-1,1}$ $\cdots$ $\mathcal{R}_{n-1,l-1}$
$\mathcal{M}_0$
HW(S-BOX($\mathcal{M}_{0,t} \oplus \tilde{k}_t$))
$\mathcal{M}_1$
HW(S-BOX($\mathcal{M}_{1,t} \oplus \tilde{k}_t$))
$\mathcal{M}_{n-1}$
HW(S-BOX($\mathcal{M}_{n-1,t} \oplus \tilde{k}_t$))
$\mathcal{H}_{0,0}$ $\mathcal{H}_{0,1}$ $\cdots$ $\mathcal{H}_{0,h-1}$
$\mathcal{H}_{1,0}$ $\mathcal{H}_{1,1}$ $\cdots$ $\mathcal{H}_{1,h-1}$
$\mathcal{H}_{n-1,0}$ $\mathcal{H}_{n-1,1}$ $\cdots$ $\mathcal{H}_{n-1,h-1}$
$\tilde{k}_t = 0$ $\tilde{k}_t = 1$ $\cdots$ $\tilde{k}_t = h-1$
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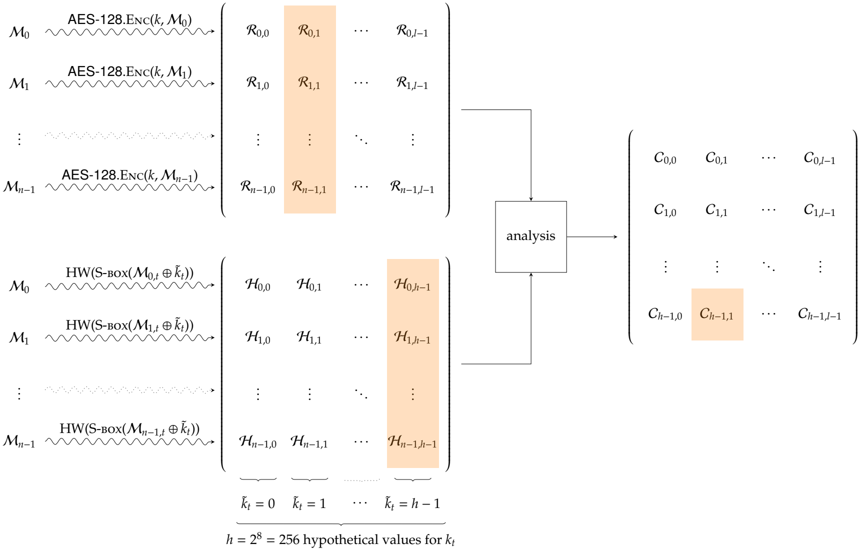
$\mathcal{C}_{1,0}$ $\mathcal{C}_{1,1}$ $\cdots$ $\mathcal{C}_{1,l-1}$
$\mathcal{C}_{h-1,0}$ $\mathcal{C}_{h-1,1}$ $\cdots$ $\mathcal{C}_{h-1,l-1}$

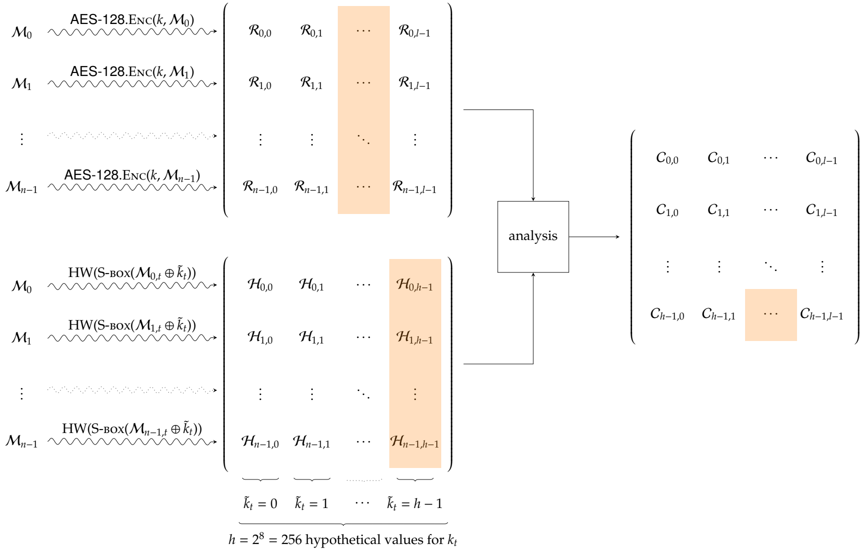
Part 2.1: in practice (4)

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

- **Attack [7]:**



- Attack [7]:


$\mathcal{M}_0$
AES-128.ENC(k, $\mathcal{M}_0$)
$\mathcal{M}_1$
AES-128.ENC(k, $\mathcal{M}_1$)
$\mathcal{M}_{n-1}$
AES-128.ENC(k, $\mathcal{M}_{n-1}$)
$\mathcal{R}_{0,0}$ $\mathcal{R}_{0,1}$ $\cdots$ $\mathcal{R}_{0,l-1}$
$\mathcal{R}_{1,0}$ $\mathcal{R}_{1,1}$ $\cdots$ $\mathcal{R}_{1,l-1}$
$\mathcal{R}_{n-1,0}$ $\mathcal{R}_{n-1,1}$ $\cdots$ $\mathcal{R}_{n-1,l-1}$
$\mathcal{M}_0$
HW(S-BOX($\mathcal{M}_{0,t} \oplus \tilde{k}_t$))
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$\mathcal{M}_{n-1}$
HW(S-BOX($\mathcal{M}_{n-1,t} \oplus \tilde{k}_t$))
$\mathcal{H}_{0,0}$ $\mathcal{H}_{0,1}$ $\cdots$ $\mathcal{H}_{0,h-1}$
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$\mathcal{H}_{n-1,0}$ $\mathcal{H}_{n-1,1}$ $\cdots$ $\mathcal{H}_{n-1,h-1}$
$\tilde{k}_t = 0$ $\tilde{k}_t = 1$ $\cdots$ $\tilde{k}_t = h-1$
$h = 2^8 = 256$ hypothetical values for k_t
analysis
$C_{0,0}$ $C_{0,1}$ $\cdots$ $C_{0,l-1}$
$C_{1,0}$ $C_{1,1}$ $\cdots$ $C_{1,l-1}$
$C_{h-1,0}$ $C_{h-1,1}$ $\cdots$ $C_{h-1,l-1}$

Part 2.1: in practice (4)

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

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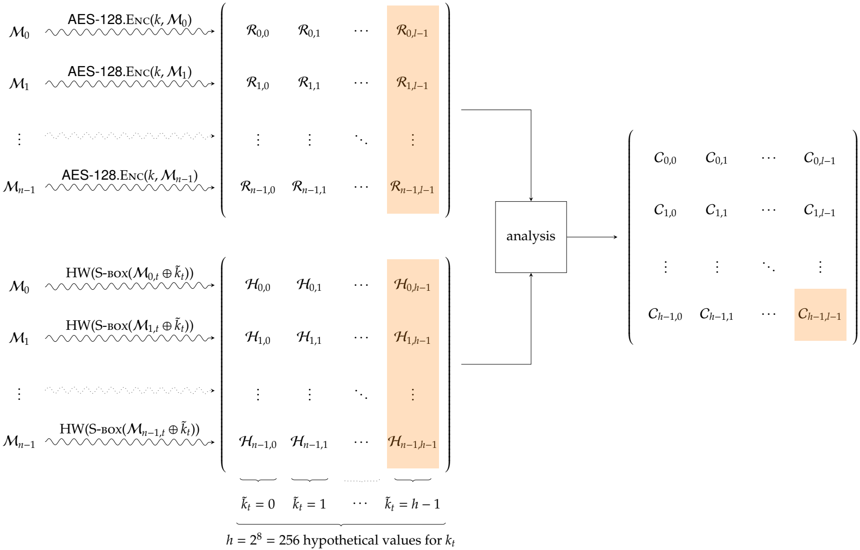
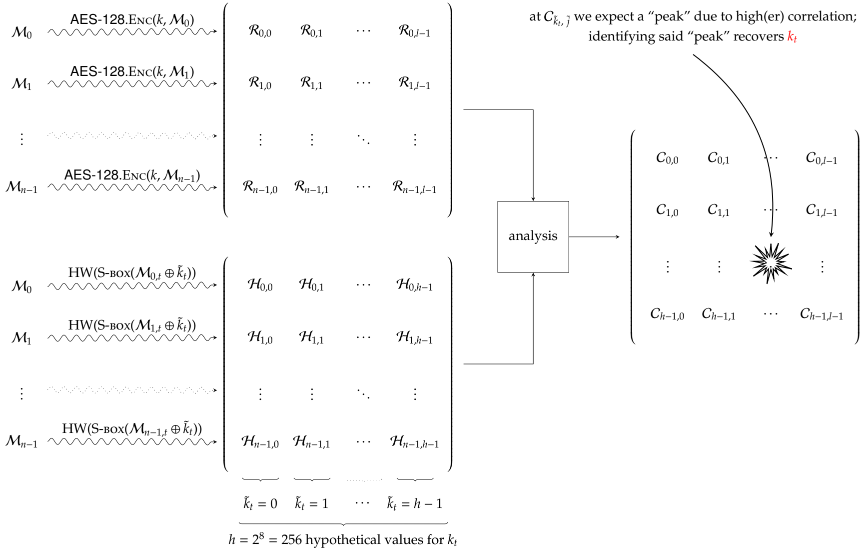


Part 2.1: in practice (4)

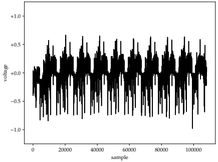
Attacks: $\mathcal{T} \simeq$ AES, Λ = power consumption

- Attack [7]:

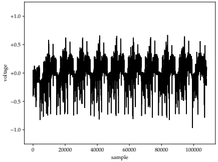


- **Example**: ARM Cortex-M3, $n = 1000$, $l = 108124$.

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

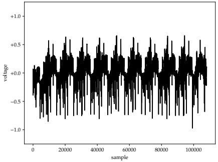


$$\left.\begin{array}{lcl} k & = & \langle 2B_{(16)}, 7E_{(16)}, \ldots, 3C_{(16)} \rangle \\ \mathcal{M}_1 & = & \langle 41_{(16)}, 62_{(16)}, \ldots, DF_{(16)} \rangle \end{array}\right\} \xrightarrow{\text{AES-128.}\textsc{Enc}(k, \mathcal{M}_1)} \mathcal{R}_1 =$$

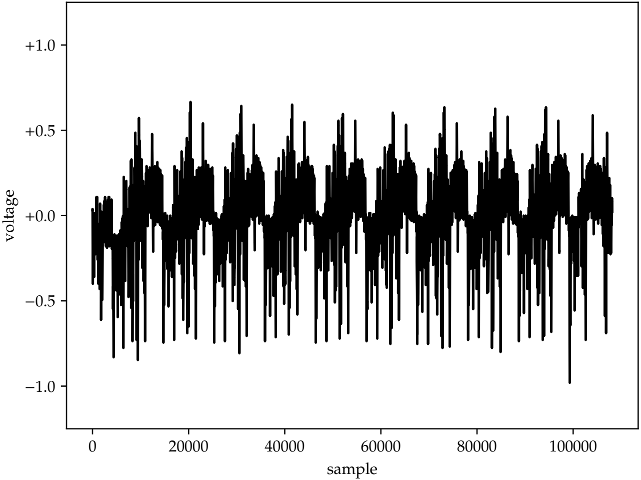


$$\vdots$$

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

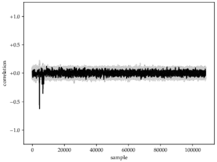


- Example: ARM Cortex-M3, $n = 1000$, $l = 108124$.



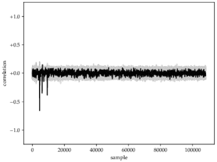
- Example: ARM Cortex-M3, $n = 1000$, $l = 108124$.

$t = 0,\ C =$



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

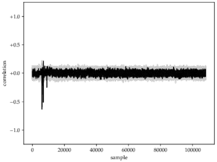
$t = 1,\ C =$



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

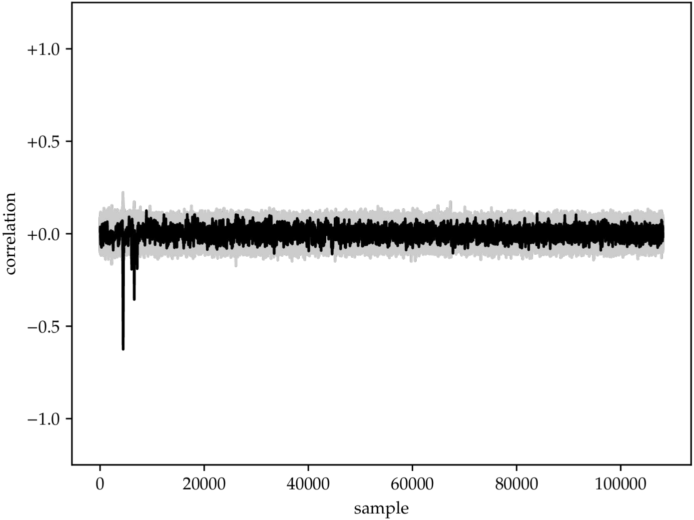
$\vdots$

$t = 15,\ C =$

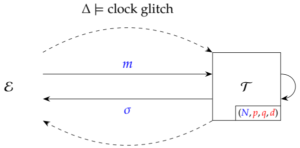


$\rightsquigarrow$ $\tilde{k}_{15} = k_{15} = 3C_{(16)}$

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



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



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

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

- and noting that
  - there are no countermeasures implemented,
  - to improve efficiency, a CRT-based [16] implementation is used,
  - based on pre-computation of

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

    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

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

    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,

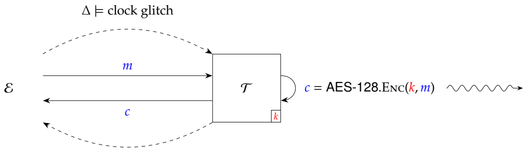
$$(\sigma_p - \bar{\sigma}_p) \times t_0 \equiv 0 \pmod{q},$$

  - 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.

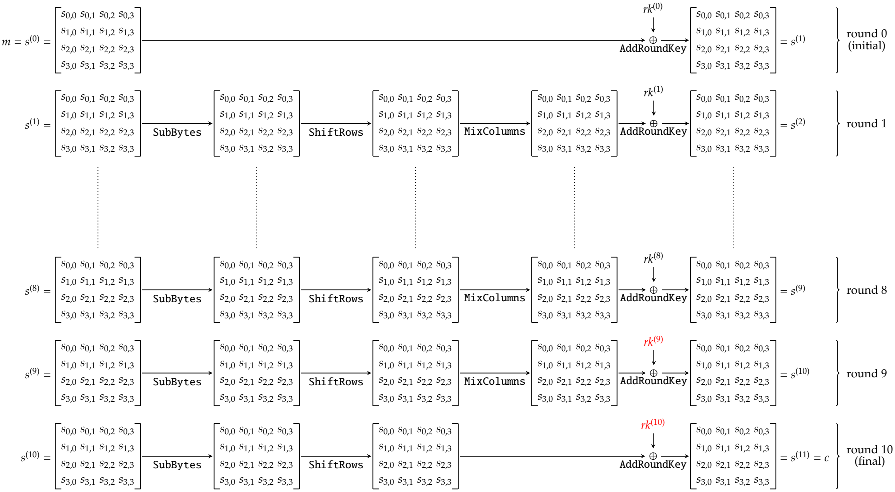
- Scenario:
  - given the following interaction between an **attacker** $\mathcal{E}$ and a **target** $\mathcal{T}$




```
algorithm AES-128.Enc(k, m) begin
  s ← m
  s ← AddRoundKey(s, k = rk^(0))
  for r = 1 upto 9 step +1 do
    k ← EvolveRoundKey(k, rc^(r))
    s ← SubBytes(s)
    s ← ShiftRows(s)
    s ← MixColumns(s)
    s ← AddRoundKey(s, k = rk^(r))
  end
  k ← EvolveRoundKey(k, rc^(10))
  s ← SubBytes(s)
  s ← ShiftRows(s)
  s ← AddRoundKey(s, k = rk^(10))
  c ← s
  return c
end
```

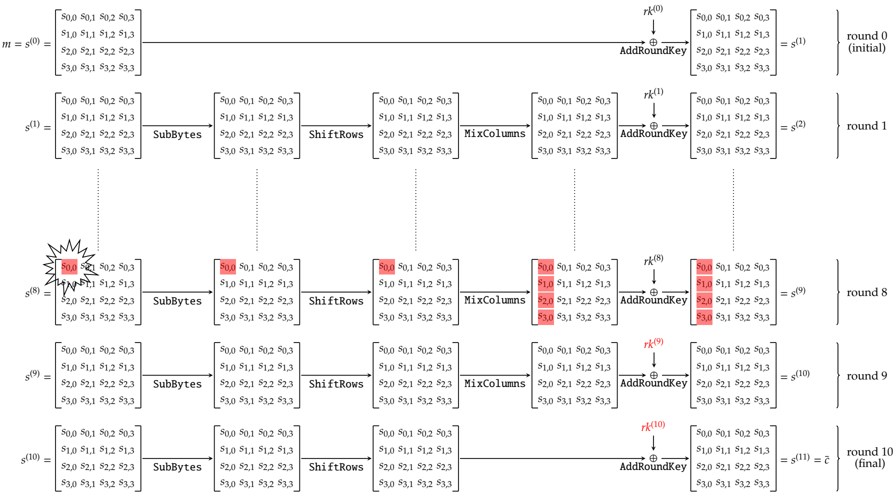
  - and noting that
    - there are no countermeasures implemented,
    - the fault induced randomises $s^{(8)}_{i,j}$, i.e., a chosen element of the state matrix used as input to the 8-th round,
  - how can $\mathcal{E}$ mount a successful attack, i.e., recover k ?

- Attack [17]:



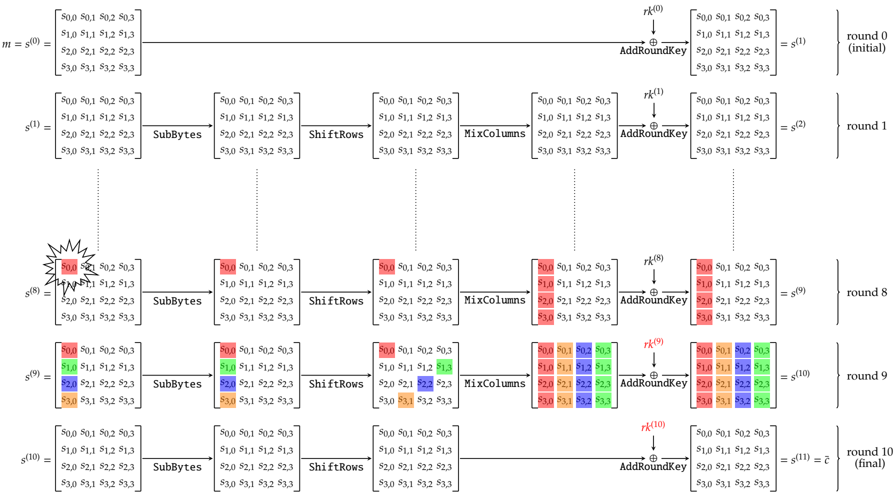
$m = s^{(0)} =$
$rk^{(0)}$
AddRoundKey
$= s^{(1)}$
round 0 (initial)
$s^{(1)} =$
SubBytes
ShiftRows
MixColumns
$rk^{(1)}$
AddRoundKey
$= s^{(2)}$
round 1
$s^{(8)} =$
$rk^{(8)}$
$= s^{(9)}$
round 8
$s^{(9)} =$
$rk^{(9)}$
$= s^{(10)}$
round 9
$s^{(10)} =$
$rk^{(10)}$
$= s^{(11)} = c$
round 10 (final)

- Attack [17]:



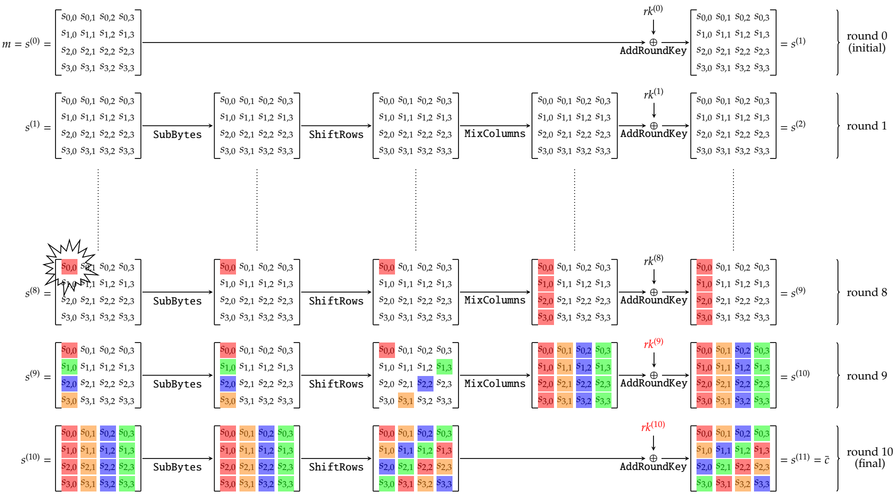
$m = s^{(0)} =$
$rk^{(0)}$
AddRoundKey
$= s^{(1)}$
round 0 (initial)
$s^{(1)} =$
SubBytes
ShiftRows
MixColumns
$rk^{(1)}$
AddRoundKey
$= s^{(2)}$
round 1
$s^{(8)} =$
$rk^{(8)}$
$= s^{(9)}$
round 8
$s^{(9)} =$
$rk^{(9)}$
$= s^{(10)}$
round 9
$s^{(10)} =$
$rk^{(10)}$
$= s^{(11)} = \bar{c}$
round 10 (final)

- Attack [17]:

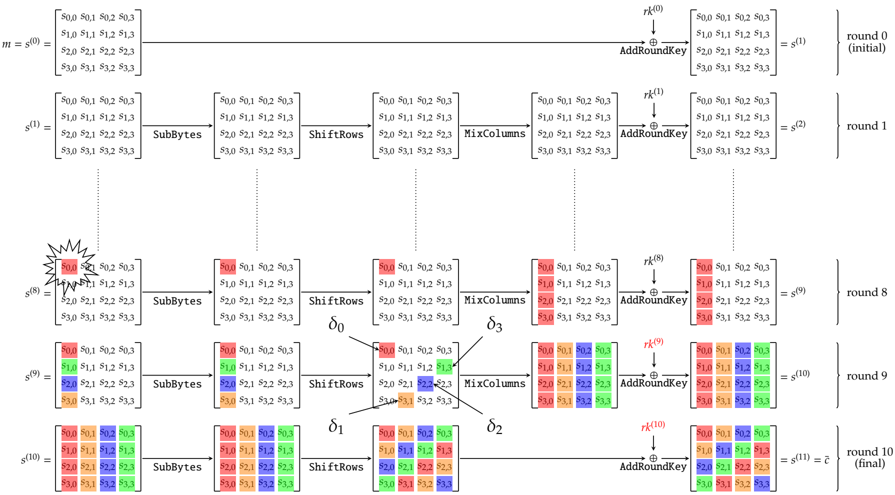


$m = s^{(0)} =$
$rk^{(0)}$
AddRoundKey
$= s^{(1)}$
round 0 (initial)
$s^{(1)} =$
SubBytes
ShiftRows
MixColumns
$rk^{(1)}$
AddRoundKey
$= s^{(2)}$
round 1
$s^{(8)} =$
$rk^{(8)}$
$= s^{(9)}$
round 8
$s^{(9)} =$
$rk^{(9)}$
$= s^{(10)}$
round 9
$s^{(10)} =$
$rk^{(10)}$
$= s^{(11)} = \bar{c}$
round 10 (final)

- Attack [17]:


$m = s^{(0)} =$
$rk^{(0)}$
AddRoundKey
$= s^{(1)}$
round 0 (initial)
$s^{(1)} =$
SubBytes
ShiftRows
MixColumns
$rk^{(1)}$
AddRoundKey
$= s^{(2)}$
round 1
$s^{(8)} =$
$rk^{(8)}$
$= s^{(9)}$
round 8
$s^{(9)} =$
$rk^{(9)}$
$= s^{(10)}$
round 9
$s^{(10)} =$
$rk^{(10)}$
$= s^{(11)} = \tilde{c}$
round 10 (final)

- Attack [17]:


$m = s^{(0)} =$
$rk^{(0)}$
AddRoundKey
$= s^{(1)}$
round 0 (initial)
$s^{(1)} =$
SubBytes
ShiftRows
MixColumns
$rk^{(1)}$
AddRoundKey
$= s^{(2)}$
round 1
$s^{(8)} =$
$rk^{(8)}$
$= s^{(9)}$
round 8
$s^{(9)} =$
δ_0
δ_1
δ_2
δ_3
$rk^{(9)}$
$= s^{(10)}$
round 9
$s^{(10)} =$
$rk^{(10)}$
$= s^{(11)} = \bar{c}$
round 10 (final)

- Attack [17]:
  - Step #1:
    - consider a fault induced in the input of the 8-th round, such that

$$\begin{array}{rcll} \tilde{c} &=& \text{AES-128.Enc}(k, m) & \Leftarrow \quad \text{fault induced} \\ c &=& \text{AES-128.Enc}(k, m) & \Leftarrow \quad \text{no fault induced} \end{array}$$

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

$$\begin{array}{rcl} \texttt{02} \otimes_{\mathbb{F}_{2^8}} \delta_0 &=& \text{S-BOX}^{-1}(c_{0,0} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{0,0}) \oplus_{\mathbb{F}_{2^8}} \text{S-BOX}^{-1}(\tilde{c}_{0,0} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{0,0}) \\ \texttt{01} \otimes_{\mathbb{F}_{2^8}} \delta_0 &=& \text{S-BOX}^{-1}(c_{1,3} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{1,3}) \oplus_{\mathbb{F}_{2^8}} \text{S-BOX}^{-1}(\tilde{c}_{1,3} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{1,3}) \\ \texttt{01} \otimes_{\mathbb{F}_{2^8}} \delta_0 &=& \text{S-BOX}^{-1}(c_{2,2} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{2,2}) \oplus_{\mathbb{F}_{2^8}} \text{S-BOX}^{-1}(\tilde{c}_{2,2} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{2,2}) \\ \texttt{03} \otimes_{\mathbb{F}_{2^8}} \delta_0 &=& \text{S-BOX}^{-1}(c_{3,1} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{3,1}) \oplus_{\mathbb{F}_{2^8}} \text{S-BOX}^{-1}(\tilde{c}_{3,1} \oplus_{\mathbb{F}_{2^8}} rk^{(10)}_{3,1}) \end{array}$$

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

- Attack [17]:
  - Step #1:
    - consider a fault induced in the input of the 8-th round, such that

$$\begin{array}{rcll} \tilde{c} &=& \text{AES-128.}\textsc{Enc}(k, m) & \Leftarrow \quad \text{fault induced} \\ c &=& \text{AES-128.}\textsc{Enc}(k, m) & \Leftarrow \quad \text{no fault induced} \end{array}$$

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

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

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

- Attack [17]:
  - Step #1:
    - consider a fault induced in the input of the 8-th round, such that

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

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

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

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

- Attack [17]:
  - Step #1:
    - consider a fault induced in the input of the 8-th round, such that

$$\begin{array}{rcll} \tilde{c} & = & \text{AES-128.ENC}(k, m) & \Leftarrow \quad \text{fault induced} \\ c & = & \text{AES-128.ENC}(k, m) & \Leftarrow \quad \text{no fault induced} \end{array}$$

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

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

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

- Attack [17]:
  - Step #1:
    - consider a fault induced in the input of the 8-th round, such that

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

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

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

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

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

```
uint8_t aes_gf28_mulx( uint8_t x ) {
  if( ( x & 0x80 ) == 0x80 ) {
    return 0x1B ^ ( x << 1 );
  }
  else {
    return        ( x << 1 );
  }
}
```

Part 2.2: in practice (1)

Countermeasures: $\mathcal{T} \simeq \text{AES}$, Λ = execution time

- 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):

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

```c
uint8_t aes_gf28_mulx( uint8_t x ) {
  uint8_t c;

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

  if( c ) {
    x = x ^ 0x1B;
  }

  return x;
}
```

Part 2.2: in practice (1)

Countermeasures: $\mathcal{T} \simeq$ AES, Λ = execution time

- 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):

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

```
uint8_t aes_gf28_mulx( uint8_t x ) {
  uint8_t c;

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

  if( c ) {
    x = x ^ 0x1B;
  }
  else {
    x = x ^ 0x00;
  }

  return x;
}
```

     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):

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

```
uint8_t aes_gf28_mulx( uint8_t x ) {
  uint8_t c, t_0, t_1;

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

  t_0 = x ^ 0x00;
  t_1 = x ^ 0x1B;

  x = ( -c & ( t_0 ^ t_1 ) ) ^ t_0;

  return x;
}
```

- 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):

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

```
uint8_t aes_gf28_mulx( uint8_t x ) {
  uint8_t c;

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

    x = x ^ ( c * 0x1B );

  return x;
}
```

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

Part 2.2: in practice (1)

Countermeasures: $\mathcal{T} \simeq$ AES, Λ = execution time

- Problem: data-dependent computation within

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

  is observable via Λ.
- Idea: **hiding**, e.g., via
  4. straight-line (via look-up):

$$\mathtt{xtime}(x) \mapsto$$

```
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):

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

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

- **Problem**: data-dependent computation within

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

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

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

```
void aes_enc_rnd_sub( uint8_t* s ) {
  delay( prng() );

  for( int i = 0; i < 16; i++ ) {
    s[ i ] = aes_enc_sbox( s[ i ] );
  }
}
```

- **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:

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

```
void aes_enc_rnd_sub( uint8_t* s ) {
  int r = prng();

  for( int i = 0; i < 16; i++ ) {
    int j = ( i + r ) % 16;

    s[ j ] = aes_enc_sbox( s[ j ] );
  }
}
```

Part 2.2: in practice (2)

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

- 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:

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

```
void aes_enc_rnd_sub( uint8_t* s ) {
  int r = prng();

  for( int i = 0; i < 16; i++ ) {
    int j = ( i ^ r ) % 16;

    s[ j ] = aes_enc_sbox( s[ j ] );
  }
}
```

- 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:

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

```
void aes_enc_rnd_sub( uint8_t* s ) {
  int T[ 16 ];

  for( int i = 15; i >= 0; i-- ) {
    T[ i ] = i;
  }

  for( int i = 15; i >= 1; i-- ) {
    int j = prng() % ( i + 1 );

    uint8_t t      = T[ j ];
            T[ j ] = T[ i ];
            T[ i ] = t     ;
  }

  for( int i = 0; i < 16; i++ ) {
    int j = T[ i ];

    s[ j ] = aes_enc_sbox( s[ j ] );
  }
}
```

- 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

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

    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** [10, 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

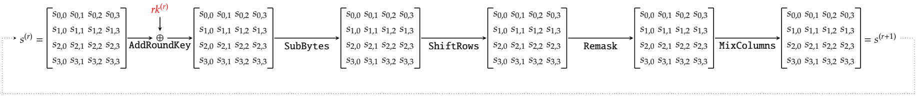
$$\begin{bmatrix} \nu_0 \\ \nu_1 \\ \nu_2 \\ \nu_3 \end{bmatrix} = \texttt{MixColumn}\left(\begin{bmatrix} \mu_0 \\ \mu_1 \\ \mu_2 \\ \mu_3 \end{bmatrix} \right),$$

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

- **Problem**: data-dependent computation within

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

is observable via Λ.
- **Idea** [10, 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** [10, Section 3.1] (or see [2, Chapter 9]):

  - **Step #2**: construct a masked round implementation

$$s^{(r)} = \begin{bmatrix} s_{0,0} & s_{0,1} & s_{0,2} & s_{0,3} \\ s_{1,0} & s_{1,1} & s_{1,2} & s_{1,3} \\ s_{2,0} & s_{2,1} & s_{2,2} & s_{2,3} \\ s_{3,0} & s_{3,1} & s_{3,2} & s_{3,3} \end{bmatrix} \xrightarrow[\texttt{AddRoundKey}]{\oplus\ rk^{(r)}} \begin{bmatrix} s_{0,0} & s_{0,1} & s_{0,2} & s_{0,3} \\ s_{1,0} & s_{1,1} & s_{1,2} & s_{1,3} \\ s_{2,0} & s_{2,1} & s_{2,2} & s_{2,3} \\ s_{3,0} & s_{3,1} & s_{3,2} & s_{3,3} \end{bmatrix} \xrightarrow{\texttt{SubBytes}} \begin{bmatrix} s_{0,0} & s_{0,1} & s_{0,2} & s_{0,3} \\ s_{1,0} & s_{1,1} & s_{1,2} & s_{1,3} \\ s_{2,0} & s_{2,1} & s_{2,2} & s_{2,3} \\ s_{3,0} & s_{3,1} & s_{3,2} & s_{3,3} \end{bmatrix} \xrightarrow{\texttt{ShiftRows}} \begin{bmatrix} s_{0,0} & s_{0,1} & s_{0,2} & s_{0,3} \\ s_{1,0} & s_{1,1} & s_{1,2} & s_{1,3} \\ s_{2,0} & s_{2,1} & s_{2,2} & s_{2,3} \\ s_{3,0} & s_{3,1} & s_{3,2} & s_{3,3} \end{bmatrix} \xrightarrow{\texttt{Remask}} \begin{bmatrix} s_{0,0} & s_{0,1} & s_{0,2} & s_{0,3} \\ s_{1,0} & s_{1,1} & s_{1,2} & s_{1,3} \\ s_{2,0} & s_{2,1} & s_{2,2} & s_{2,3} \\ s_{3,0} & s_{3,1} & s_{3,2} & s_{3,3} \end{bmatrix} \xrightarrow{\texttt{MixColumns}} \begin{bmatrix} s_{0,0} & s_{0,1} & s_{0,2} & s_{0,3} \\ s_{1,0} & s_{1,1} & s_{1,2} & s_{1,3} \\ s_{2,0} & s_{2,1} & s_{2,2} & s_{2,3} \\ s_{3,0} & s_{3,1} & s_{3,2} & s_{3,3} \end{bmatrix} = s^{(r+1)}$$

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

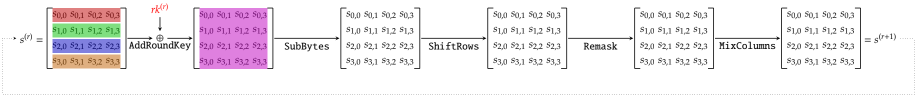
- **Problem**: data-dependent computation within

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

  is observable via Λ.

- **Idea** [10, Section 3.1] (or see [2, Chapter 9]):

  - **Step #2**: construct a masked round implementation



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

Part 2.2: in practice (4)

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

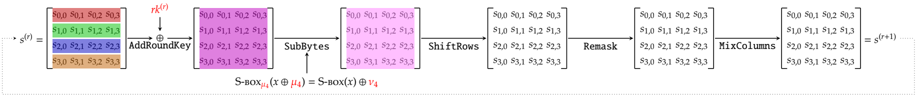
- **Problem**: data-dependent computation within

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

  is observable via Λ.

- **Idea** [10, Section 3.1] (or see [2, Chapter 9]):

  - **Step #2**: construct a masked round implementation



    such that $s^{(r)}_{i,j}$ is masked with ν_4 due to alteration of S-BOX (i.e., use of S-BOX_{μ_4}).

Part 2.2: in practice (4)

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

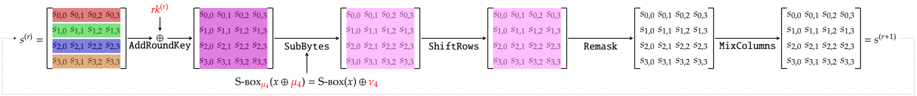
- Problem: data-dependent computation within

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

  is observable via Λ.

- Idea [10, Section 3.1] (or see [2, Chapter 9]):

  - Step #2: construct a masked round implementation



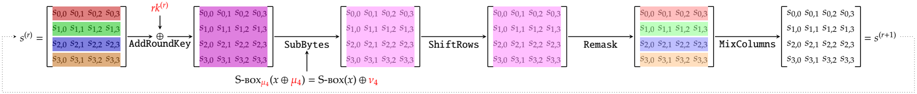
  such that $s^{(r)}_{i,j}$ is (still) masked with ν_4.

- Problem: data-dependent computation within

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

  is observable via Λ.
- Idea [10, Section 3.1] (or see [2, Chapter 9]):

  - Step #2: construct a masked round implementation



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

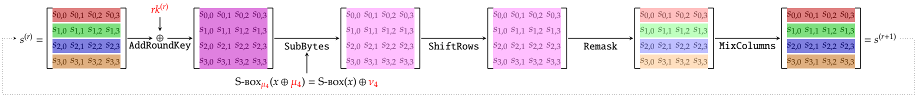
- **Problem**: data-dependent computation within

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

  is observable via Λ.

- **Idea** [10, 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**: data-dependent sequence of $m \leftarrow m^2 \pmod{N}$ and $m \leftarrow m \cdot c \pmod{N}$.
- **Solution**:
  - *blind*, i.e., randomise, the exponent [13, Section 10]:
    1. select random $m \in \mathbb{Z}$ and compute
    $$d' = d + m \cdot \Phi(N),$$
    2. compute
    $$\begin{array}{lcll} c^{d'} & \equiv & c^{d+m\cdot\Phi(N)} & \pmod{N} \\ & \equiv & c^{d} \cdot c^{m\cdot\Phi(N)} & \pmod{N} \\ & \equiv & c^{d} \cdot (c^{m})^{\Phi(N)} & \pmod{N} \\ & \equiv & c^{d} \cdot 1 & \pmod{N} \\ & \equiv & c^{d} & \pmod{N} \end{array}$$

    and/or
  - *blind*, i.e., randomise, the base [13, Section 10]:
    1. select random $m, m' \in \mathbb{Z}_N^*$ st.
    $$\frac{1}{m'} \equiv m^d \pmod{N},$$
    2. compute
    $$\begin{array}{lcll} m' \cdot ((m \cdot c)^{d}) & \equiv & m' \cdot m^{d} \cdot c^{d} & \pmod{N} \\ & \equiv & m' \cdot \frac{1}{m'} \cdot c^{d} & \pmod{N} \\ & \equiv & c^{d} & \pmod{N} \end{array}$$

- **Problem**: Δ can be used to influence, e.g., corrupt

  $$\sigma_p = m^{d \bmod p-1} \pmod{p}$$

  or

  $$\sigma_q = m^{d \bmod q-1} \pmod{q}$$

  i.e., "small" exponentiations during CRT.
- **Solution** [21]:
  1. select a random $r \in \mathbb{Z}$,
  2. compute the exponentiation step of the CRT as

     $$\begin{array}{rcll} \sigma_p & = & m^{d \bmod \Phi(p \cdot r)} & \pmod{p \cdot r} \\ \sigma_q & = & m^{d \bmod \Phi(q \cdot r)} & \pmod{q \cdot r} \end{array}$$

  3. if

     $$\sigma_p \not\equiv \sigma_q \pmod{r}$$

     then abort,
  4. otherwise apply the recombination step to

     $$\begin{array}{ll} \sigma_p & \pmod{p} \\ \sigma_q & \pmod{q} \end{array}$$

- 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.
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