Practical Attacks Against White-Box Crypto Implementations

Séminaire de Cryptographie, Rennes 1

Philippe Teuwen
Quarkslab

2/12/2016

$ whoami

Philippe Teuwen alias @doegox

- @ Quarkslab
- ♥ free software, security, CTFs, ...
- 웹 http://wiki.yobi.be

Outline

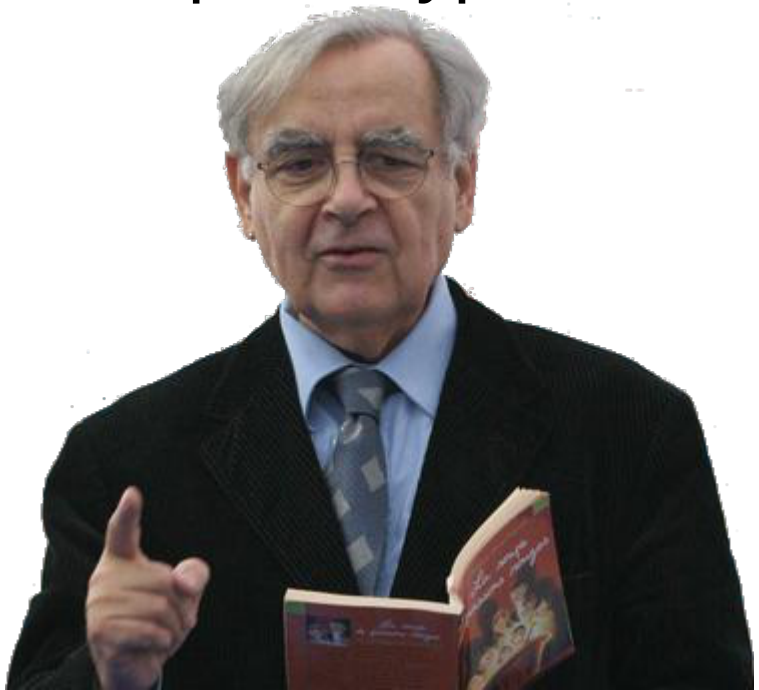
- Introduction to white-box cryptography
- Software execution traces
- Differential Computation Analysis
- Differential Fault Analysis

Mes excuses mais...

Credits:

Ecole de pensée française:

on dit “chiffrer”, pas “crypter”

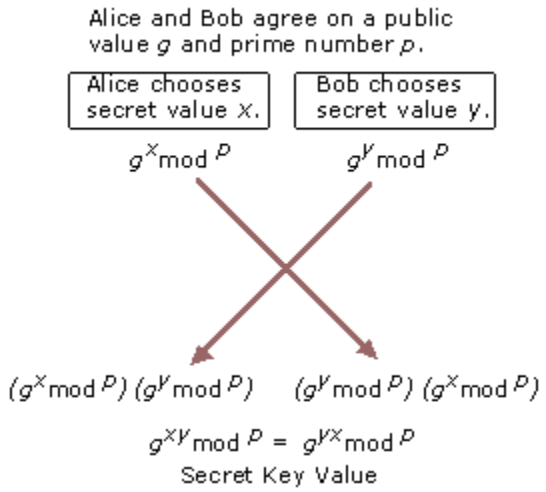


Ecole de pensée belge:

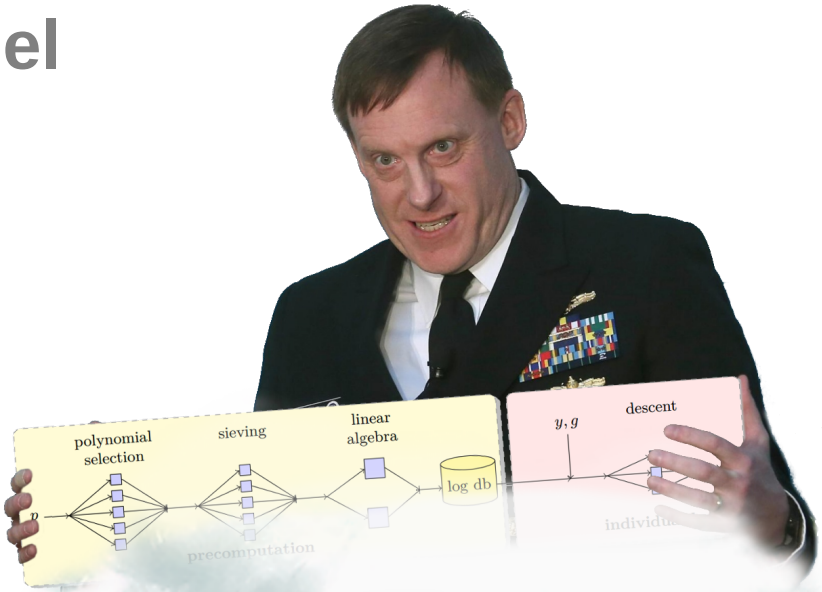
“décrypte le cipher”

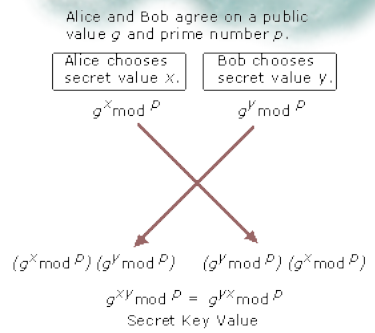
INTRODUCTION TO WHITE-BOX CRYPTOGRAPHY

Black box model



Black box model

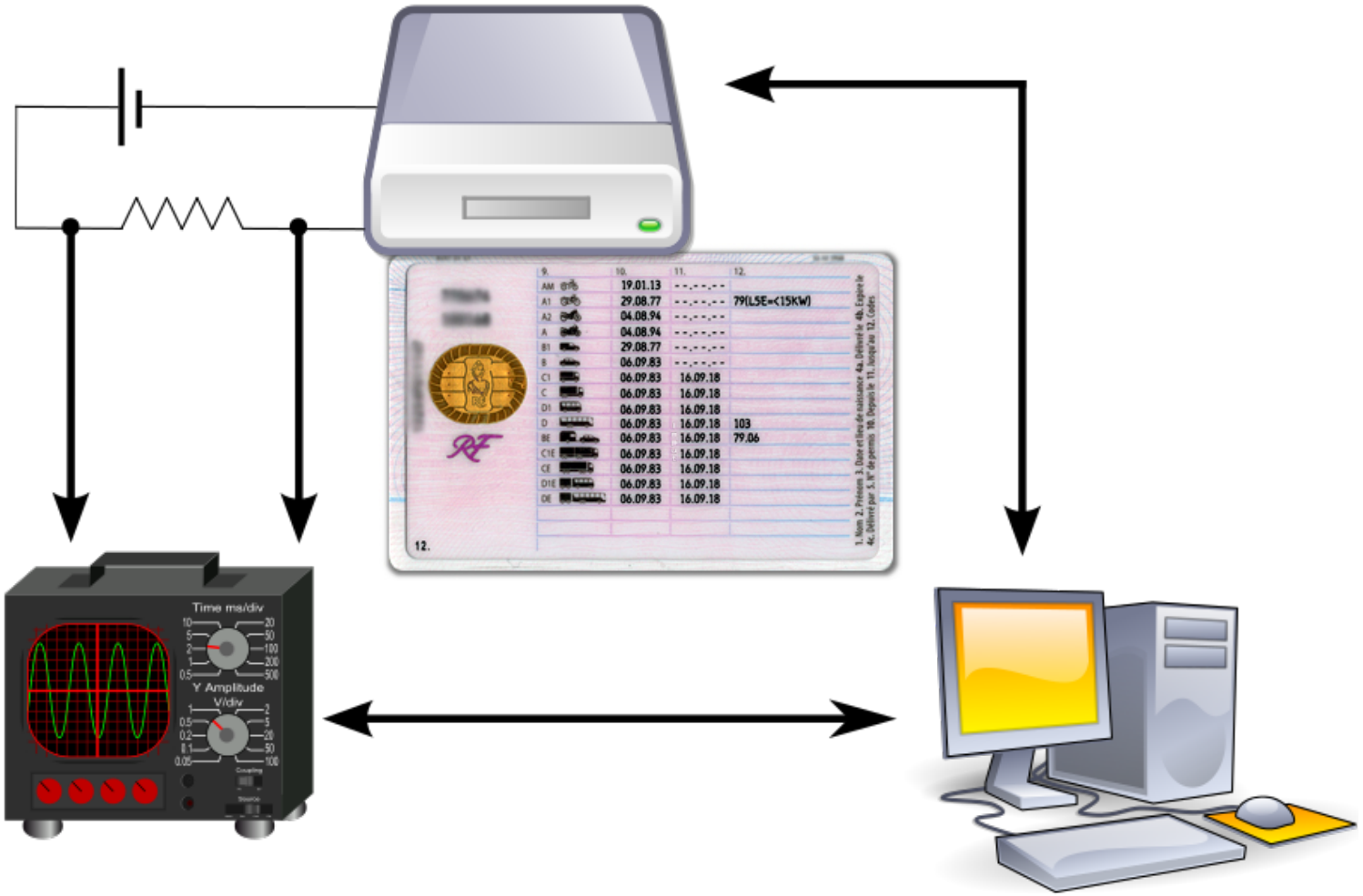




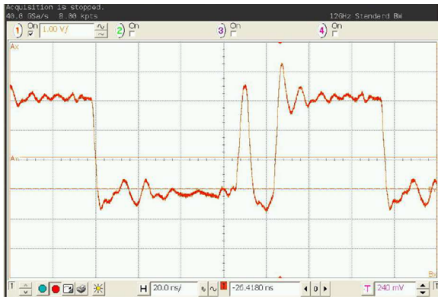
Black box model

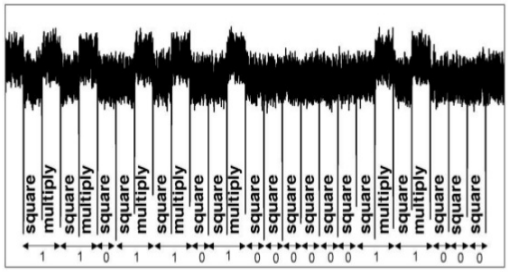
Grey box model

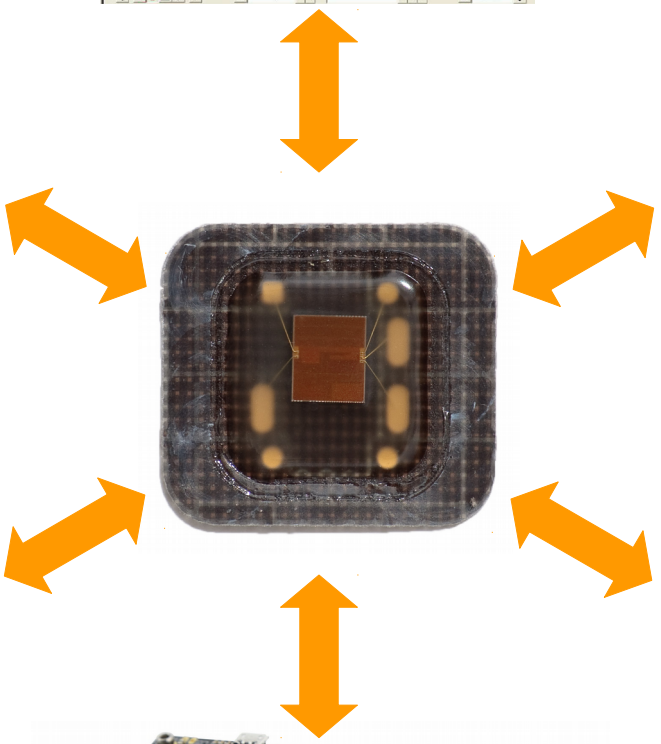
Grey box model

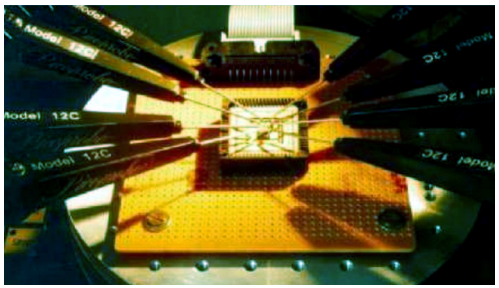


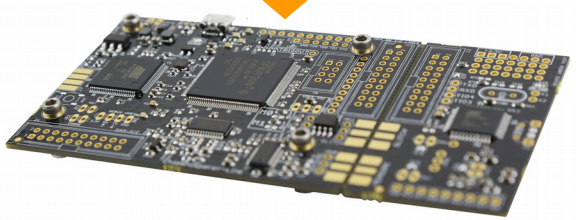
Grey box model





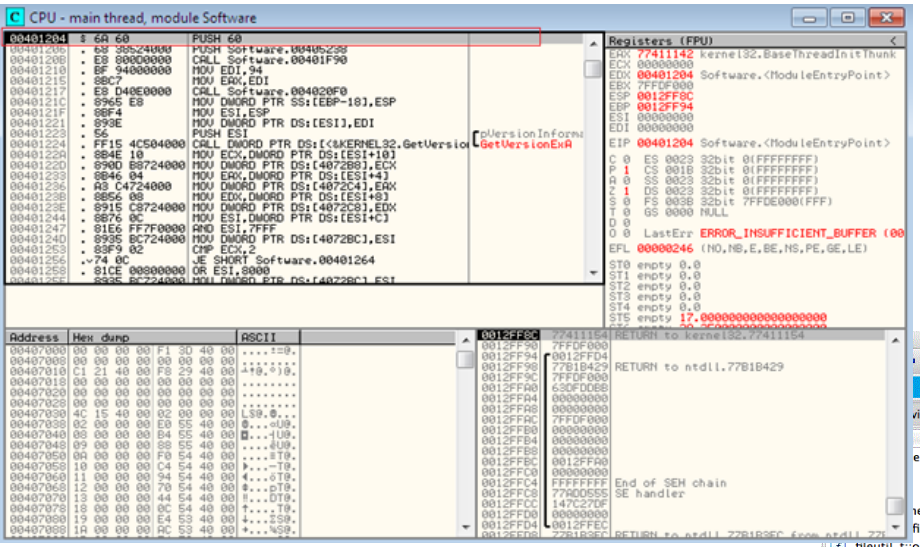


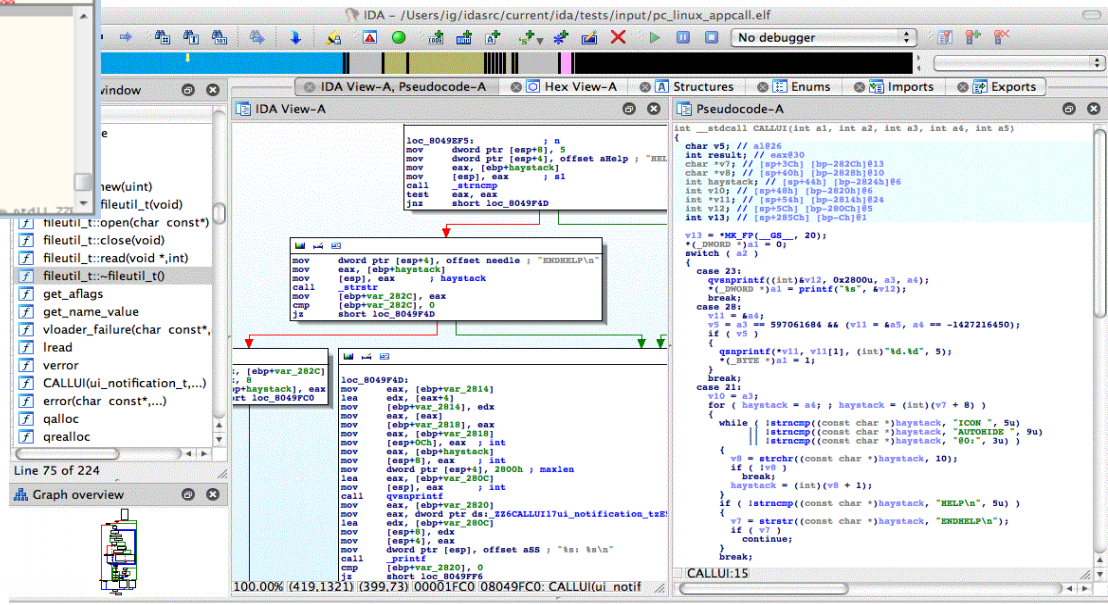




White box model

White box model





White box model

Sole line of defense:

Implementation

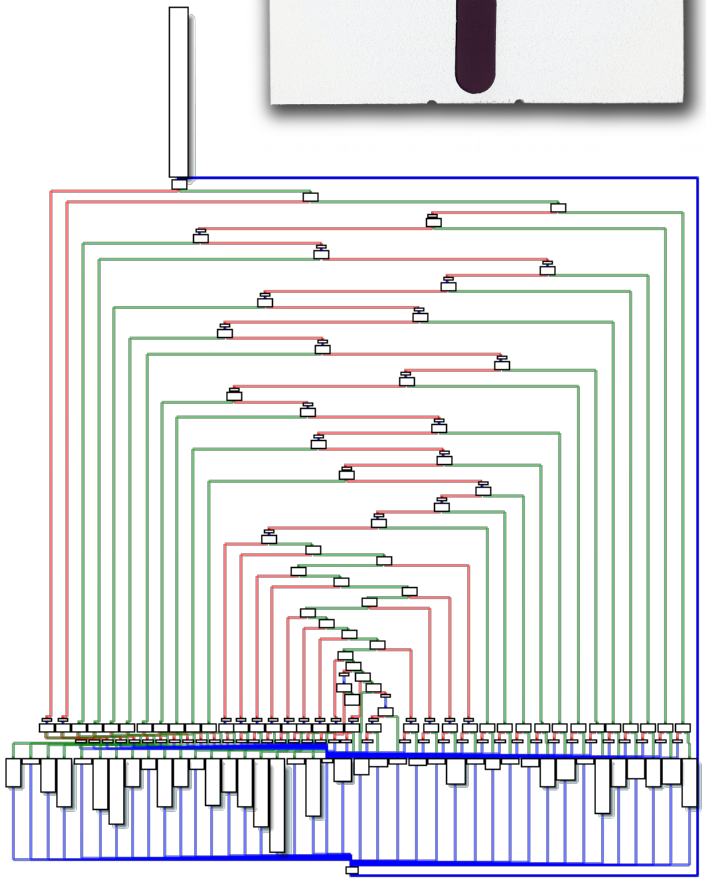
Usual countermeasures

Code obfuscation

Integrity checks

Anti-debug tricks

```
mov eax,0x0                    mov ebx,[eax+0x80a051e]        mov edx,0x0
mov ax,[0x80a0451]             mov eax,[ebx]                  mov dx,[eax+eax+0x80c0bba]
mov byte [eax+0x80e17bc],0x0   mov edx,0x0                    mov [ebx],edx
mov al,[eax+0x80e17bc]         mov dx,[eax+eax+0x80c0bba]     mov eax,[0x80a0556]
mov [0x80a0451],al             mov [ebx],edx                  mov ebx,[eax+0x80a051e]
mov eax,[0x80a0556]            mov eax,[0x80a0556]            mov eax,[ebx]
mov edx,[eax+0x80a058e]        mov ebx,[eax+0x80a051e]        mov edx,0x0
mov eax,[0x80a0451]            mov eax,[ebx]                  mov dx,[eax+eax+0x80c0bba]
mov eax,[eax+edx]              mov edx,0x0                    mov [ebx],edx
mov [0x80a044d],eax            mov dx,[eax+eax+0x80c0bba]     mov eax,[0x80a0556]
mov eax,[0x80a044d]            mov [ebx],edx                  mov ebx,[eax+0x80a051e]
mov eax,[eax+0x80a054e]        mov eax,[0x80a0556]            mov eax,[ebx]
mov dword [eax],0x139          mov ebx,[eax+0x80a051e]        mov edx,0x0
mov eax,[0x80a044d]            mov eax,[ebx]                  mov dx,[eax+eax+0x80c0bba]
```



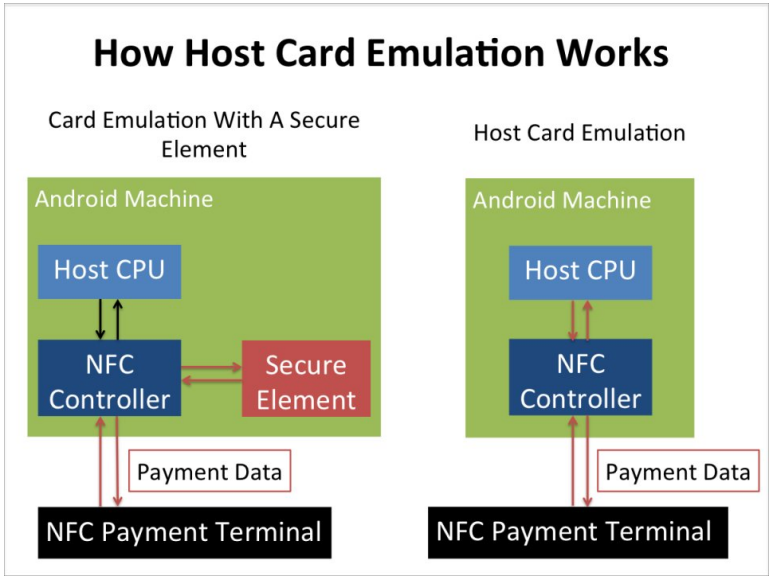
Illustrations: by @xoreaxeaxeax about M/o/Vfuscator and blog.quarkslab.com about OLLVM

Cryptography under White-box model

What if you need to do some crypto in such hostile environment?

- DRM schemes ↔ ~~criminals~~ users
- Mobile payment, HCE ↔ malwares

Source: “l'industrie du film”



Source: Business Insider

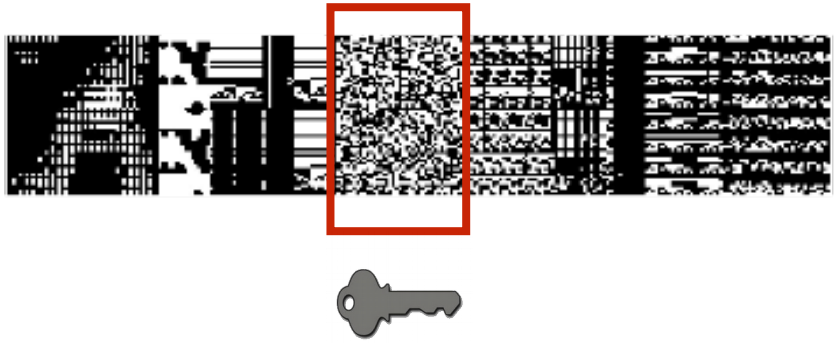
Cryptography under White-box model

What if you need to do some crypto in such hostile environment?

- DRM schemes ↔ ~~criminals~~ users
- Mobile payment, HCE ↔ malwares

Obfuscation techniques alone are mostly insufficient

- Obfuscation mainly about securing code but here:
  standard crypto algo in need for strong key protection
- E.g. entropy attack on RSA by Shamir and Van Someren (1999)



White-box cryptography

Chow et al. (2002)

- “Ideal” WB AES implementation:
  One big lookup table
  4.94×10^{27} TB
- Practical WB AES:
  Network of smaller tables
  752kB
  Encoding on intermediate values

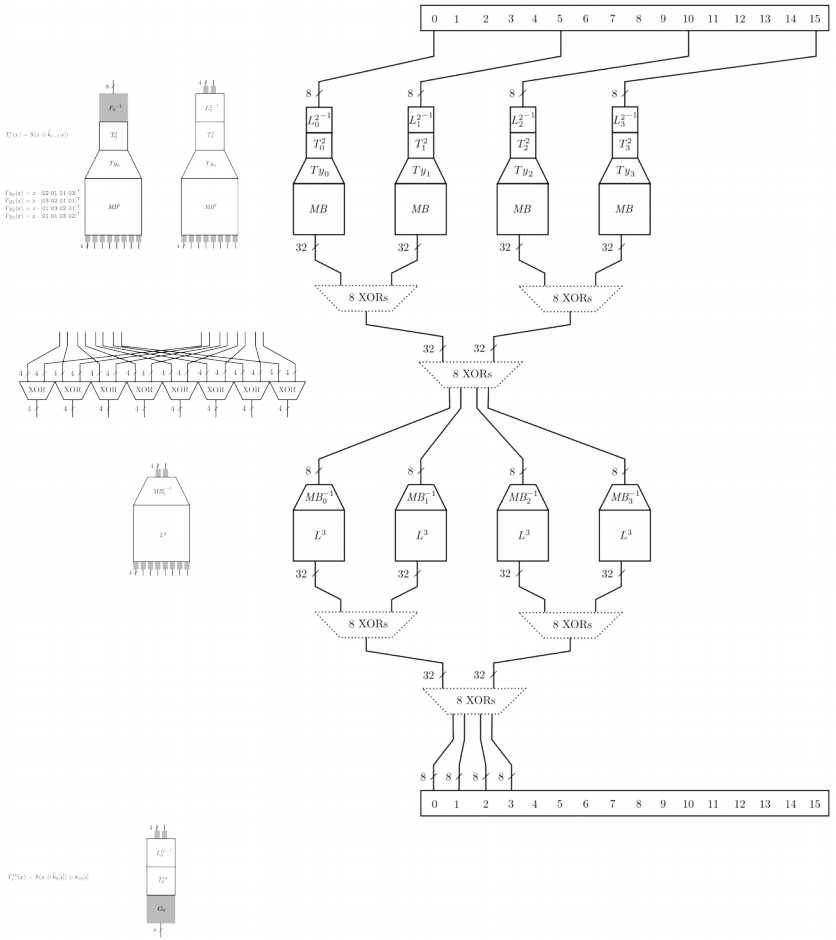


Illustration from “A Tutorial on White-box AES” by James A. Muir

White-box cryptography

History:

- Academic attacks → new designs → ...
- Today, all academic schemes have been broken

White-box cryptography

History:

- Academic attacks → new designs → ...
- Today, all academic schemes have been broken

Industry response:

- Keep white-box designs secret
- Bury white-box implementation under layers of code obfuscation, integrity checks, anti-debug tricks
- Some claim to be equivalent to a Secure Element

“Academic” attacks?

Require reversing of all the obfuscation layers
Require knowledge on the design
Then apply attack:

Definition 3. *The mapping* $\overline{AES}_{enc}^{(r,j)} : (\mathbf{F}_2^8)^4 \rightarrow (\mathbf{F}_2^8)^4$ *for* $1 \leq r \leq 9$ *and* $0 \leq j \leq 3$, *called an encoded AES subround with byte permutations, is defined by*

$$\overline{AES}_{enc}^{(r,j)} = (Q_0^{(r,j)}, Q_1^{(r,j)}, Q_2^{(r,j)}, Q_3^{(r,j)}) \circ \overline{AES}^{(r,j)} \circ (P_0^{(r,j)}, P_1^{(r,j)}, P_2^{(r,j)}, P_3^{(r,j)}) \ ,$$

where the mapping $\overline{AES}^{(r,j)}$ *is defined by*

$$\Pi_2^{(r,j)} \circ AES^{(r,\pi^{(r)}(j))} \circ \Pi_1^{(r,j)} = \mathtt{MC}^{(r,j)} \circ (S,S,S,S) \circ \oplus_{[\bar{k}_i^{(r,j)}]_{0\leq i\leq 3}} \ ,$$

$$\begin{array}{lll} \textit{with} & [\bar{k}_i^{(r,j)}]_{0\leq i\leq 3} = (\Pi_1^{(r,j)})^{-1}\left([k_i^{(r,\pi^{(r)}(j))}]_{0\leq i\leq 3}\right) \\ \textit{and} & \mathtt{MC}^{(r,j)} = \Pi_2^{(r,j)} \circ \mathtt{MC} \circ \Pi_1^{(r,j)} \ . \end{array}$$

As a result of the algorithm mentioned above, the white-box adversary has black-box access to the following structures of each round $R_r|_{r=1,\ldots,10}$:

$$\begin{cases} \mathtt{SR} \circ \bigoplus_{K'_{10}} \circ \{S_{10,i}\}|_{i=0,\ldots,15} \circ \bigoplus_{K_9} \circ \Lambda_9'^{-1} & \text{for } R_{10} \ , \\ \mathtt{MC} \circ \mathtt{SR} \circ \Lambda_r'' \circ \{S_{r,i}\}|_{i=0,\ldots,15} \circ \bigoplus_{K_{r-1}} \circ \Lambda_{r-1}'^{-1} & \text{for } R_r|_{2\leq r\leq 9} \ , \\ \mathtt{MC} \circ \mathtt{SR} \circ \Lambda_1'' \circ \{S_{1,i}\}|_{i=0,\ldots,15} \circ \bigoplus_{K_0} & \text{for } R_1 \ , \end{cases} \quad (5)$$

The second step then implements the function $\tau_{r,i}^k$ in which $\mu_r(n)$ describes the corresponding position of the bit in the output of the t-boxes, and PB is the DES p-box operation:

$$\tau_{r,i}^k(x)(L_r^i, R_r'^i) = \left(\underbrace{\alpha_{r,i}^k(x|_{8\gamma_r(i)}^4,\ x|_{8\gamma_r(i)+4},\ x|_{8\gamma_r(i)+5})}_{\textit{depends on } R_{r-1} \textit{ only}} \right) \Big\| \left(EP_i \left[PB \left(\underbrace{x|_{\gamma_r(0)}^4 \,\|\, x|_{\gamma_r(1)}^4 \,\|\, \ldots \,\|\, x|_{\gamma_r(11)}^4}_{\textit{depends on } R_{r-1} \textit{ only}} \right) \oplus \left(\underbrace{x|_{\mu_r(0)} \,\|\, \ldots \,\|\, x|_{\mu_r(32)}}_{\textit{depends on } L_{r-1} \textit{ only}} \right) \right] \right)$$

$$\tau_r^k(x) = \tau_{r,0}^k(x) \,\|\, \tau_{r,1}^k(x) \,\|\, \ldots \,\|\, \tau_{r,11}^k(x)$$

ψ_r and ϕ_r are different non-linear bijective encodings on 4-bit blocks, and δ_r

$$\delta_r(L, R') = \gamma_r(\mu_r((L|0^{24}), R'))$$

$$\begin{aligned} \mu_r(x_0x_1\ldots x_{47}, y_0\ldots y_{47}) &= y_0\ldots y_5 x_{\mu_r^{-1}(0)} x_{\mu_r^{-1}(1)} y_6\ldots y_{11} x_{\mu_r^{-1}(2)} x_{\mu_r^{-1}(3)} \cdots y_{42}\ldots y_{47} x_{\mu_r^{-1}(22)} x_{\mu_r^{-1}(23)} \cdots x_{\mu_r^{-1}(47)} \\ \gamma_r(z_0z_1\ldots z_{95}) &= z_{\gamma_r^{-1}(0)}\cdots z_{(\gamma_r^{-1}(0)+5)} z_6 z_7 \ldots z_{\gamma_r^{-1}(11)}\cdots z_{(\gamma_r^{-1}(11)+5)} z_{94} z_{95} \end{aligned}$$

The obfuscated t-box is

$$T_r'^k(x) = (\phi_r\, T_r^k\, \psi_{r-1}^{-1})(x).$$

Hence the transformed function is:

$$E^k(x) = \left[(\lambda^{-1}\delta_n^{-1}\psi_n^{-1}) \cdot \left(\psi_n\delta_n\tau_n^k\phi_n^{-1}\right) \cdot \left(\phi_n T_n^k \psi_{n-1}^{-1}\right) \cdot \ldots \cdot \left(\psi_1\delta_1\tau_1^k\phi_1^{-1}\right) \cdot \left(\phi_1 T_1^k \psi_0^{-1}\right) \cdot (\psi_0\delta_0\beta\lambda) \right](x)$$

with

$$\beta(L, R) = L \,\|\, EP(R)$$

By setting

$$\tau_r'^k = \begin{cases} \psi_0\ \delta_0\ \beta\ \lambda & r = 0 \\ \psi_r\ \delta_r\ \tau_r^k\ \phi_r^{-1} & r = 1, .., n \\ \lambda^{-1}\ \delta_n^{-1}\ \psi_n^{-1} & r = n+1 \end{cases}$$

the resulting encryption operation is

$$E^k(x) = \left[\tau_{n+1}'^k \cdot \left(\tau_n'^k \cdot T_n'^k\right) \cdot \ldots \cdot \left(\tau_1'^k \cdot T_1'^k\right) \cdot \tau_0'^k \right](x)$$

Excerpts:

- “Two Attacks on a White-Box AES”
- “Cryptanalysis of a Perturbated White-Box AES Implementation”
- “Attacking an obfuscated cipher by injecting faults”

“Academic” attacks?

= a lot of effort
then, anyway, for me:

Definition 3. *The mapping* $\overline{AES}_{enc}^{(r,j)} : (\mathbf{F}_2^8)^4 \to (\mathbf{F}_2^8)^4$ *for* $1 \leq r \leq 9$ *and* $0 \leq j \leq 3$, *called an encoded AES subround with byte permutations, is defined by*

$$\overline{AES}_{enc}^{(r,j)} = (Q_0^{(r,j)}, Q_1^{(r,j)}, Q_2^{(r,j)}, Q_3^{(r,j)}) \circ \overline{AES}^{(r,j)} \circ (P_0^{(r,j)}, P_1^{(r,j)}, P_2^{(r,j)}, P_3^{(r,j)}) \ ,$$

where the mapping $\overline{AES}^{(r,j)}$ *is defined by*

$$\Pi_2^{(r,j)} \circ S^{(r,\pi^{(r)}(j))} \circ \Pi_1^{(r,j)} = \ldots \circ (S,S,S,S) \circ \oplus_{[\bar{k}_i^{(r,j)}]_{0\leq\ldots}}$$

$$\ldots [\bar{k}_i^{(r,j)}]_{0\leq i\leq 3} = \ldots [\bar{k}_i^{(r,\pi^{(r)}(j))}]_{0\leq i\leq 3})$$

$$\mathtt{MC}^{(r,j)} = \ldots \circ \Pi_1^{(r,j)} \ .$$

As a re… algorithm mentioned ab… bite-box adversa… has black-box access … the following structures of each round $R_r|_{r=1,\ldots,10}$:

$$\begin{cases} \mathtt{SR} \circ \bigoplus_{K'_{10}} \circ \{S_{10,i}\}|_{i=0,\ldots,15} \circ \bigoplus_{K_9} \circ \Lambda_9'^{-1} & \text{for } R_{10} \ , \\ \mathtt{MC} \circ \mathtt{SR} \circ \Lambda_r'' \circ \{S_{r,i}\}|_{i=0,\ldots,15} \circ \bigoplus_{K_{r-1}} \circ \Lambda_{r-1}'^{-1} & \text{for } R_r|_{2\leq r\leq 9} \ , \\ \mathtt{MC} \circ \mathtt{SR} \circ \Lambda_1'' \circ \{S_{1,i}\}|_{i=0,\ldots,15} \circ \bigoplus_{K_0} & \text{for } R_1 \ , \end{cases} \quad (5)$$

The second step then implements the function $\tau_{r,i}^k$ in which $\mu_r(n)$ describes the corresponding position of the bit in the output of the t-boxes, and PB is the DES p-box operation:

$$\tau_{r,i}^k(x)(L_r^i, R_r'^i) = \left(\underbrace{\alpha_{r,i}^k(x|_{8\gamma_r(i)}^4, x|_{8\gamma_r(i)+4}, x|_{8\gamma_r(i)+5})}_{\text{depends on } R_{r-1} \text{ only}} \right) \| \left(EP_i \left[PB \left(\underbrace{x|_{\gamma_r(0)}^4 \| x|_{\gamma_r(1)}^4 \| \ldots \| x|_{\gamma_r(11)}^4}_{\text{depends on } R_{r-1} \text{ only}} \right) \oplus \left(\underbrace{x|_{\mu_r(0)} \| \ldots \| x|_{\mu_r(32)}}_{\text{depends on } L_{r-1} \text{ only}} \right) \right] \right)$$

$$\tau_r^k(x) = \tau_{r,0}^k(x) \| \tau_{r,1}^k(x) \| \ldots \| \tau_{r,11}^k(x)$$

ψ_r and ϕ_r are different non-linear bijective encodings on 4-bit blocks, and δ_r

$$\ldots(L,R) = \gamma_r(\mu_r((L|0^{24}), \ldots$$

$$\mu_r(\ldots) = y_0 \ldots y_5 x_{\mu_r^{-1}(0)} x_{\mu_r^{-1}} \ldots x_{\mu_r^{-1}(2)} x_{\mu_r^{-1}(3)} \ldots y_{42} \ldots x_{\mu_r^{-1}(47)}$$

$$\gamma_r(\ldots) = z_{\gamma_r^{-1}(0)} \ldots z_{(\gamma_r^{-1}(\ldots} \ldots z_{(\gamma_r^{-1}(11)+5)} z_{94} z_{95}$$

The o… is

$$T_r'^k(x) = \ldots (x).$$

…e tran…rmed …nction is:

$$E^k(x) = \left[(\lambda^{-1}\delta_n^{-1}\psi_n^{-1}) \cdot \left(\psi_n \delta_n \tau_n^k \phi_n^{-1} \right) \cdot \left(\phi_n T_n^k \psi_{n-1}^{-1} \right) \cdot \ldots \cdot \left(\psi_1 \delta_1 \tau_1^k \phi_1^{-1} \right) \cdot \left(\phi_1 T_1^k \psi_0^{-} \right) \ldots (\psi_0 \ldots \lambda) \right] (x)$$

with

$$\beta(L,R) = L \| EP(R)$$

By setting

$$\tau_r'^k = \begin{cases} \psi_0 \, \delta_0 \, \beta \, \lambda & r = 0 \\ \psi_r \, \delta_r \, \tau_r^k \, \phi_r^{-1} & r = 1, .., n \\ \lambda^{-1} \, \delta_n^{-1} \, \psi_n^{-1} & r = n+1 \end{cases}$$

the resulting encryption operation is

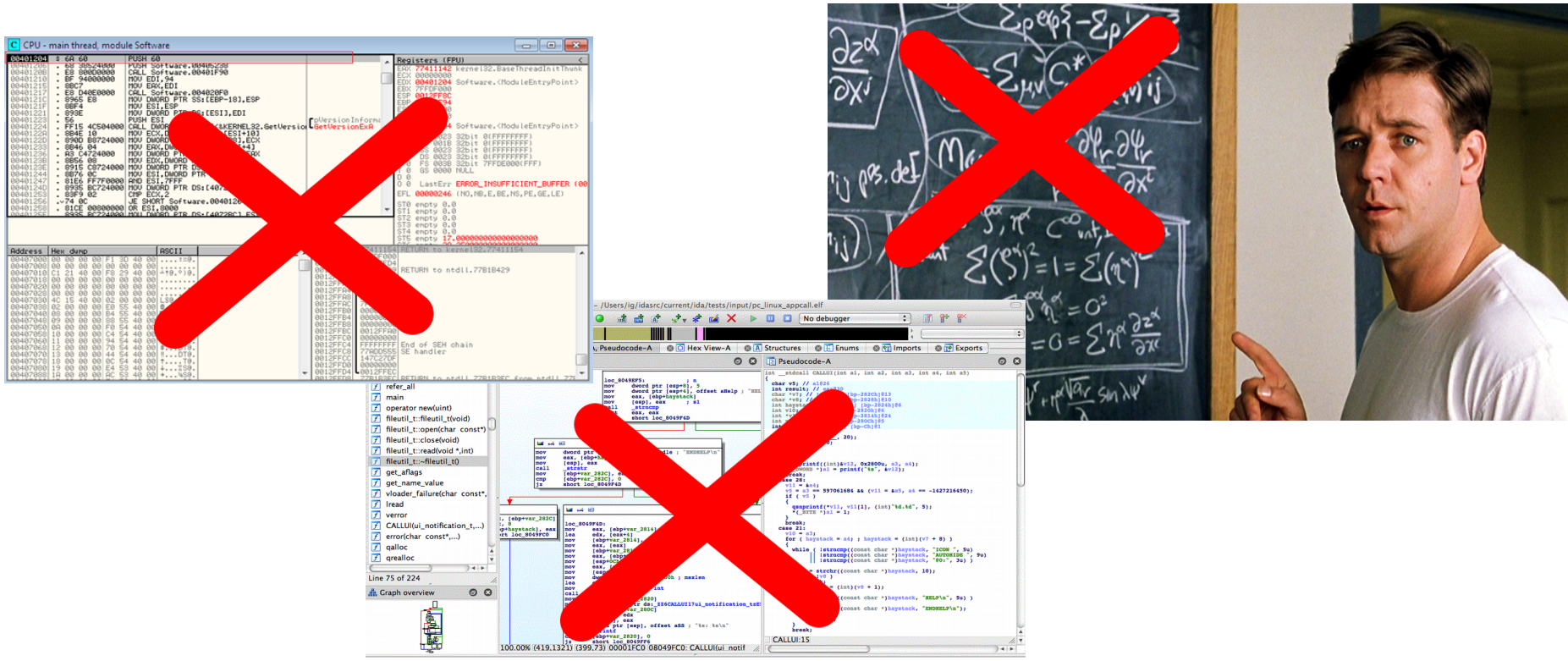
$$E^k(x) = \left[\tau_{n+1}'^k \cdot \left(\tau_n'^k \cdot T_n'^k \right) \cdot \ldots \cdot \left(\tau_1'^k \cdot T_1'^k \right) \cdot \tau_0'^k \right] (x)$$

看起來像天書

Our goal

Recover white-box keys

- without much reverse-engineering effort
- without much intellectual effort ^^



SOFTWARE EXECUTION TRACES

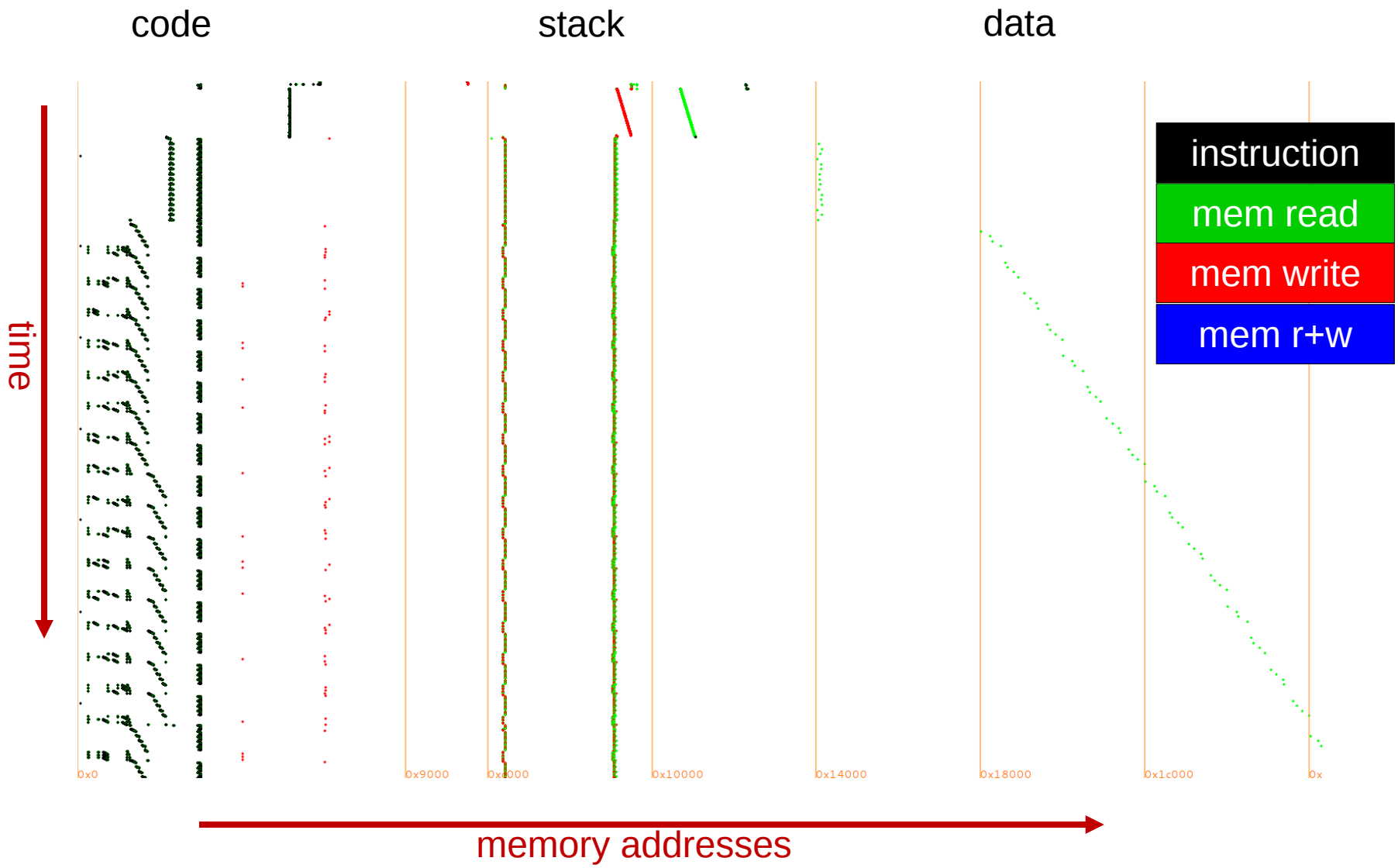
Tracing binaries

Record all instructions and memory accesses

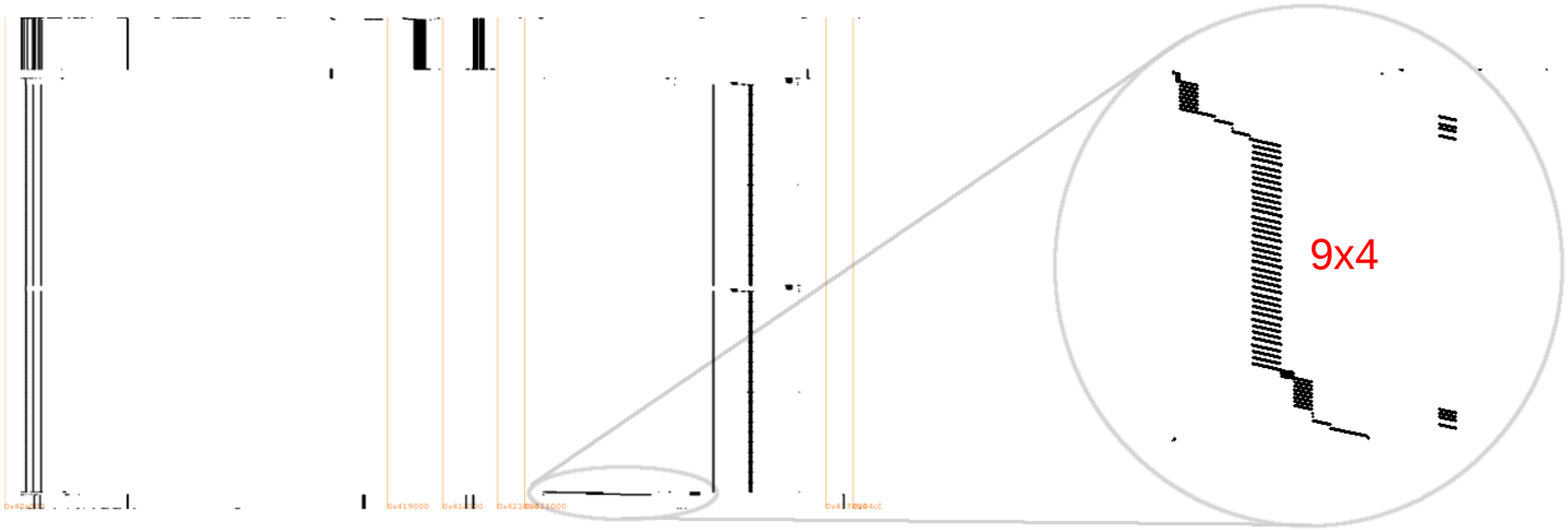
Examples:

- Intel PIN (x86, x86-64, Linux, Windows, Wine/Linux)
- Valgrind (idem+ARM, Android)
- Add hooks to VM (Java, Python,…)
- Add hooks to emulators

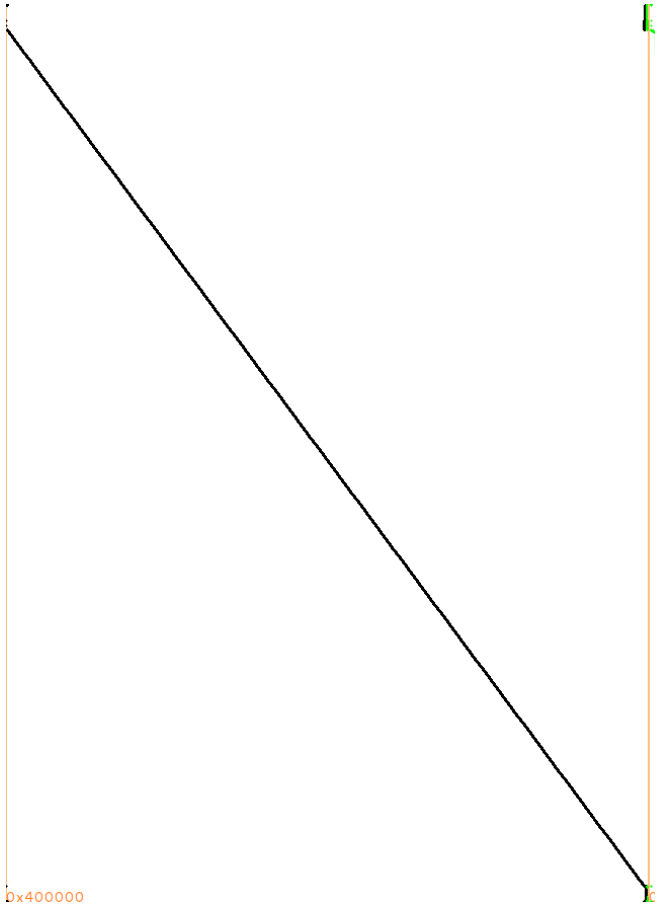
Trace convention: Quarkslab's pTra waterfall



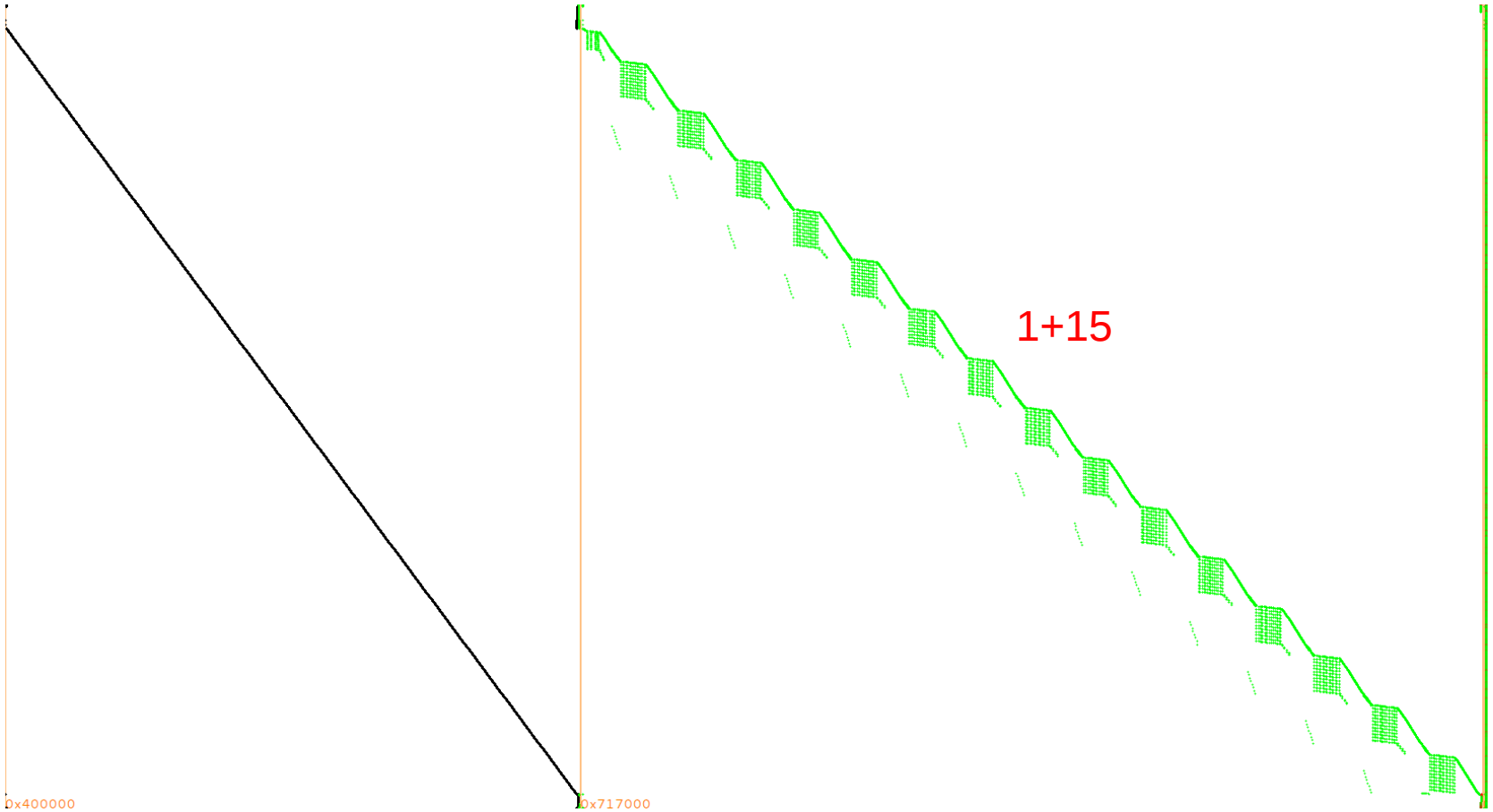
Visual crypto identification: code



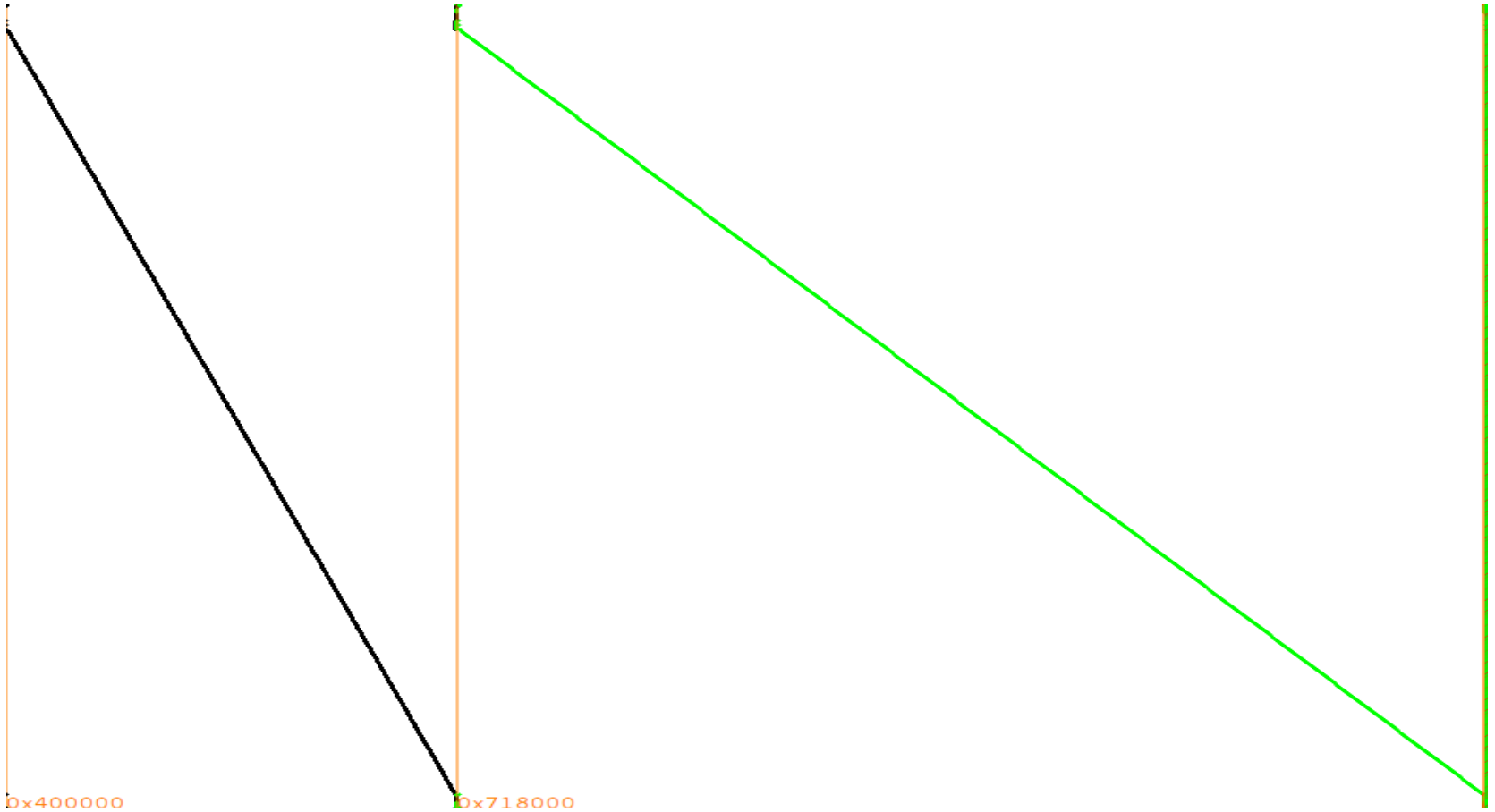
Visual crypto identification: code?



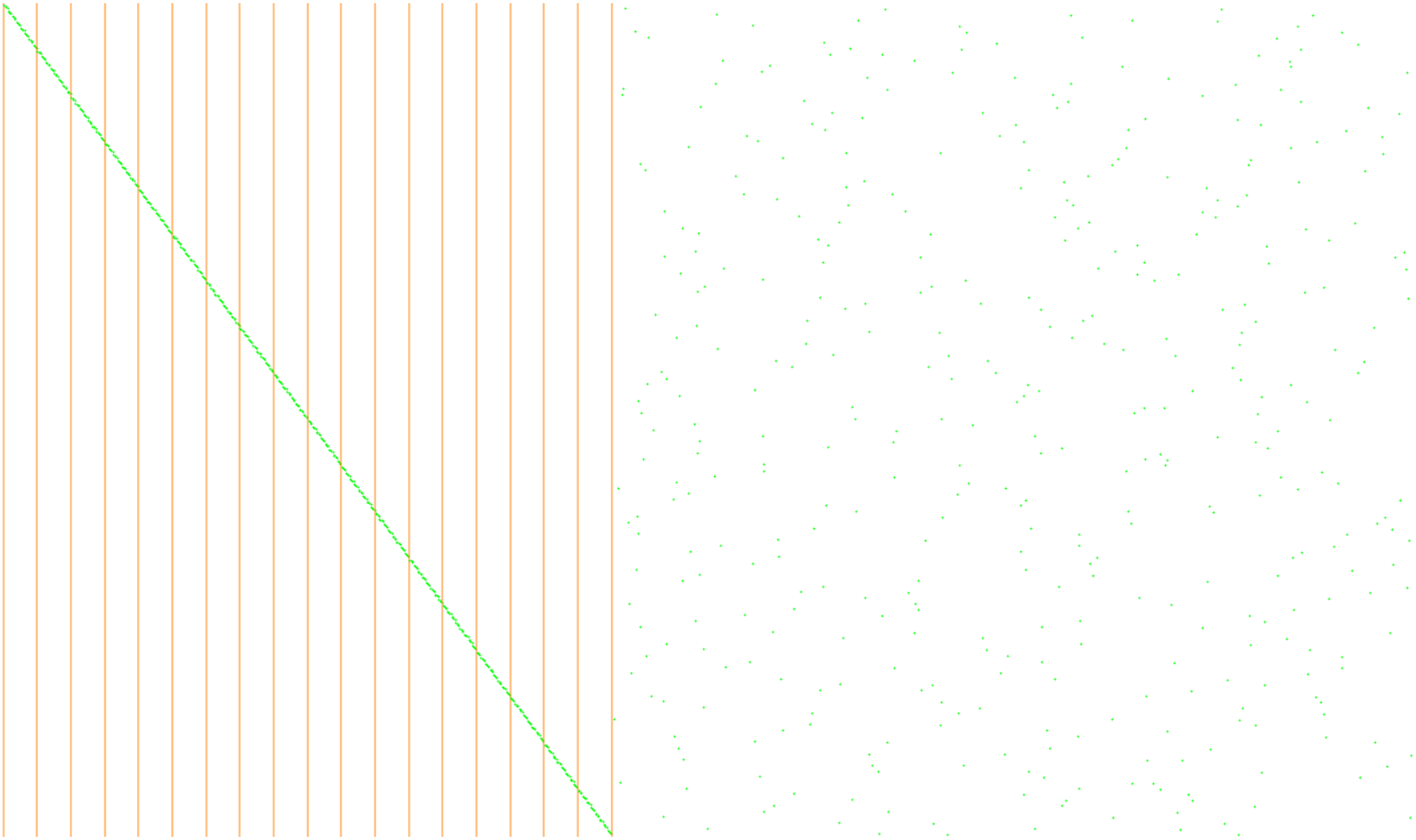
Visual crypto identification: code? data!



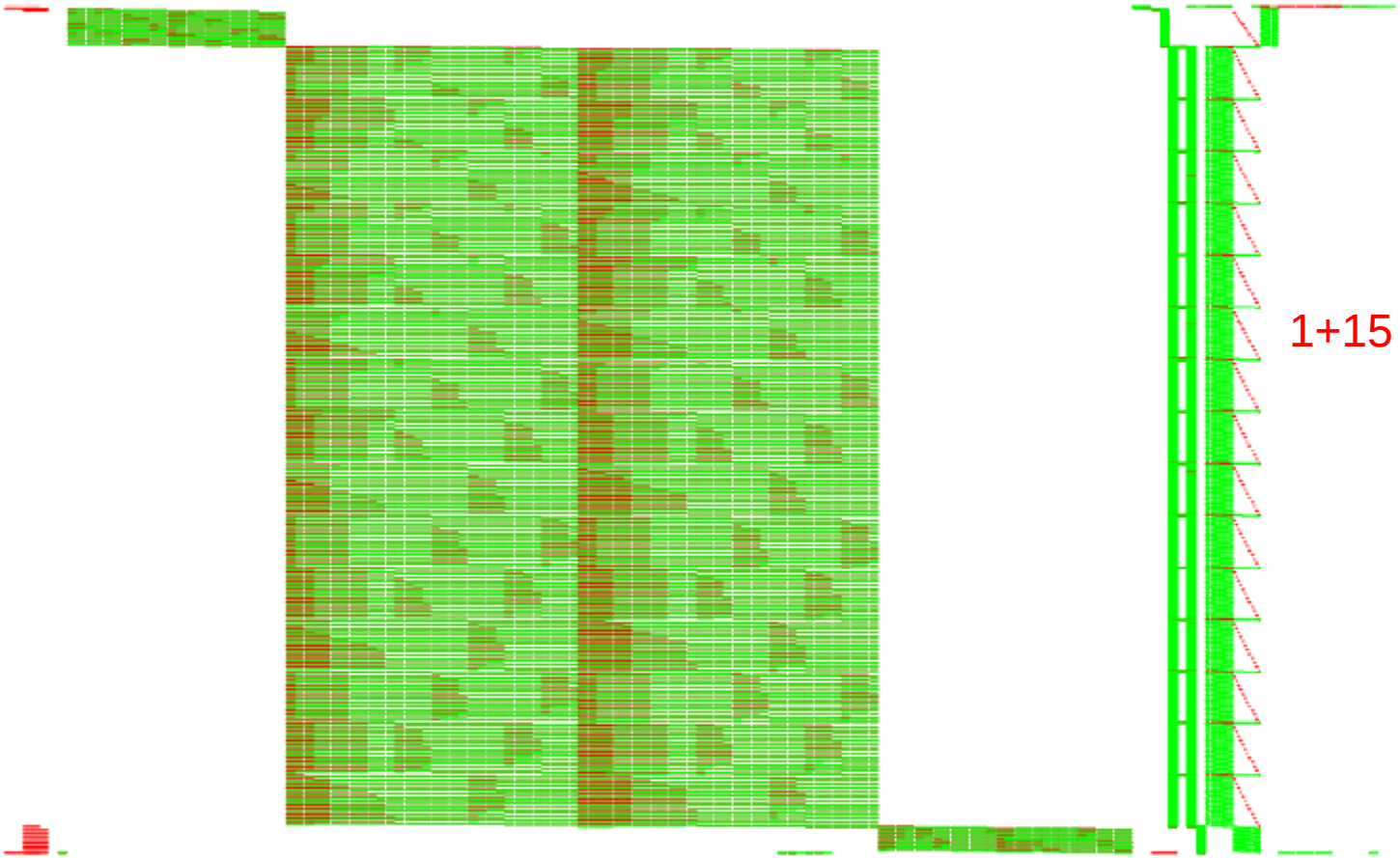
Visual crypto identification: code? data?



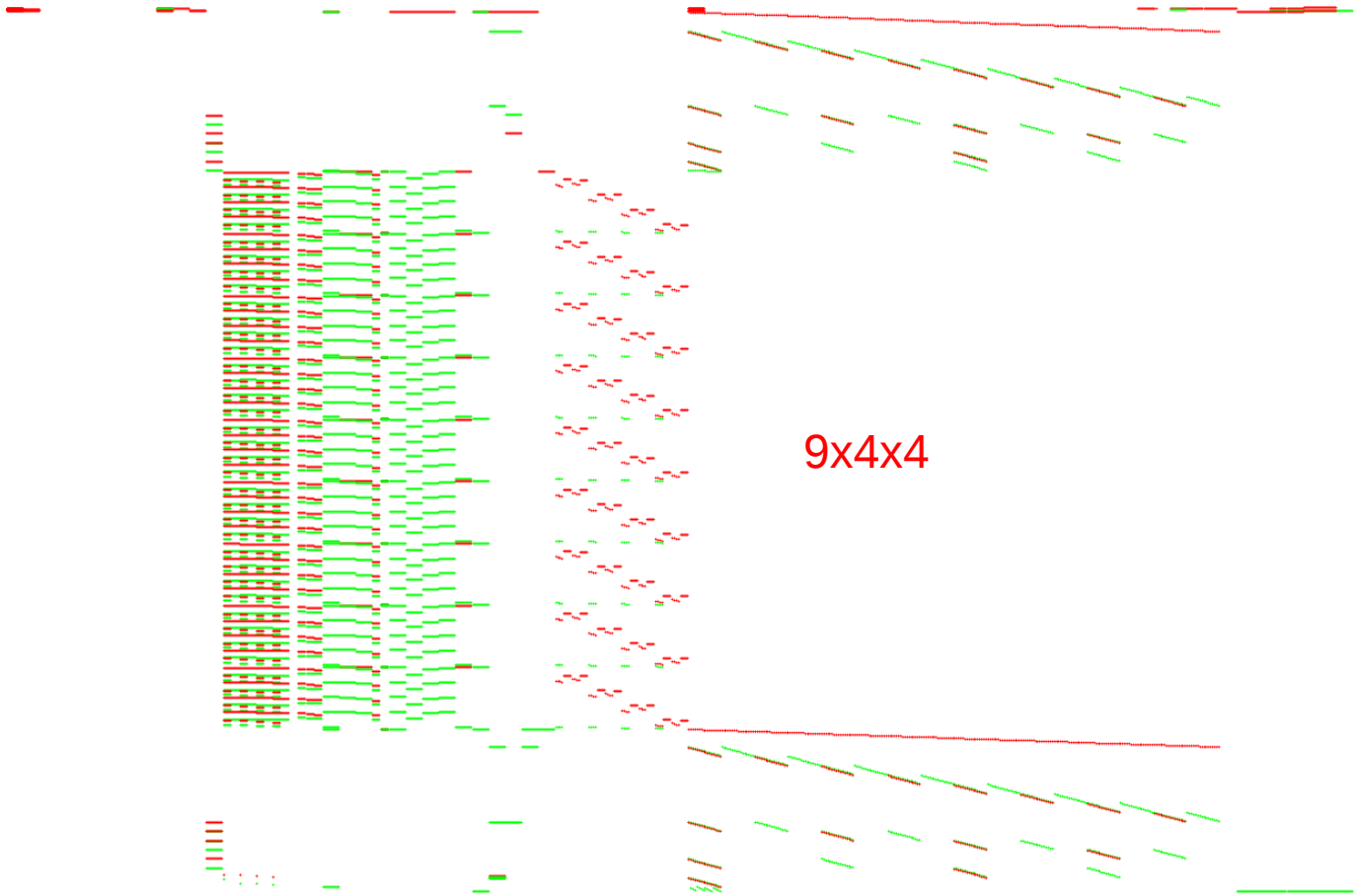
Visual crypto identification: data?



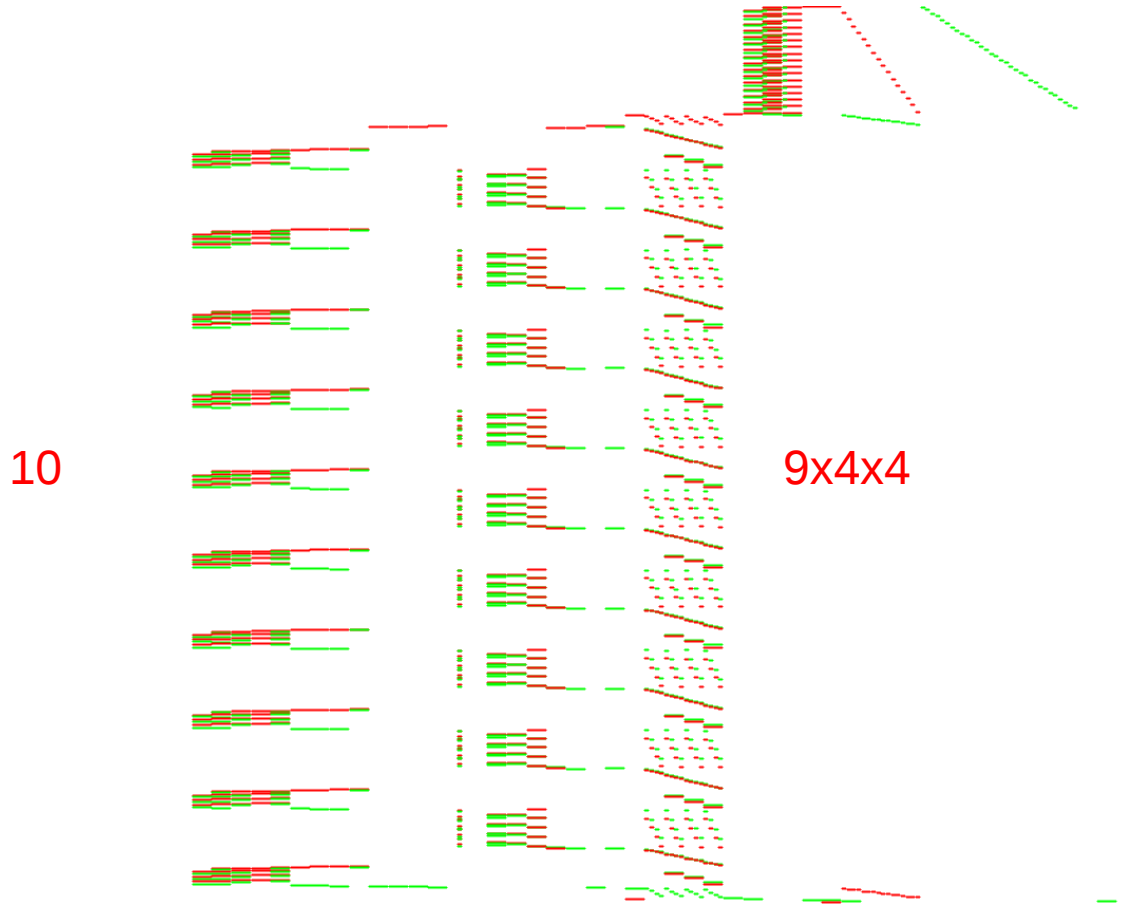
Visual crypto identification: stack!



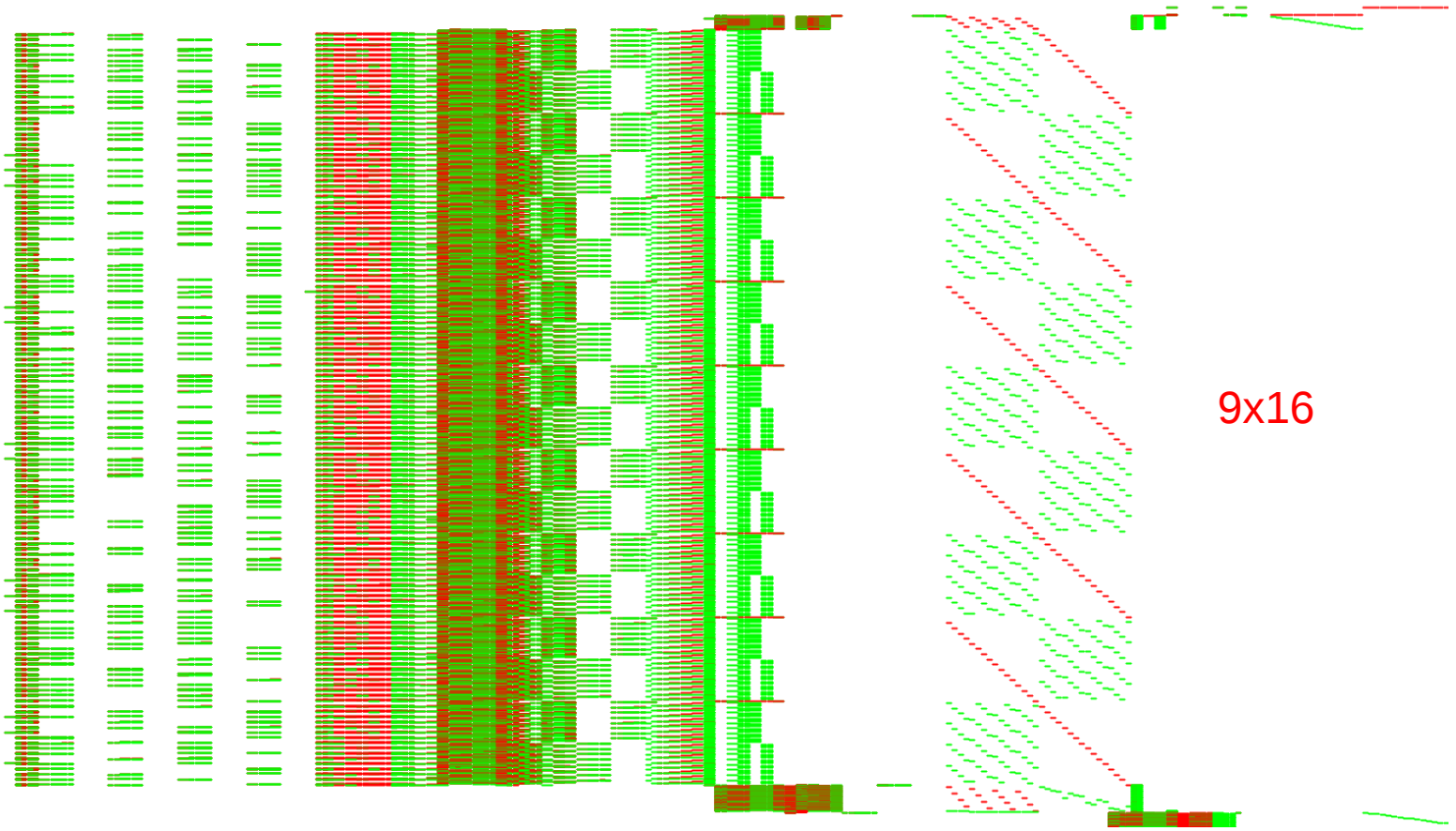
Visual crypto identification: stack!



Visual crypto identification: stack!



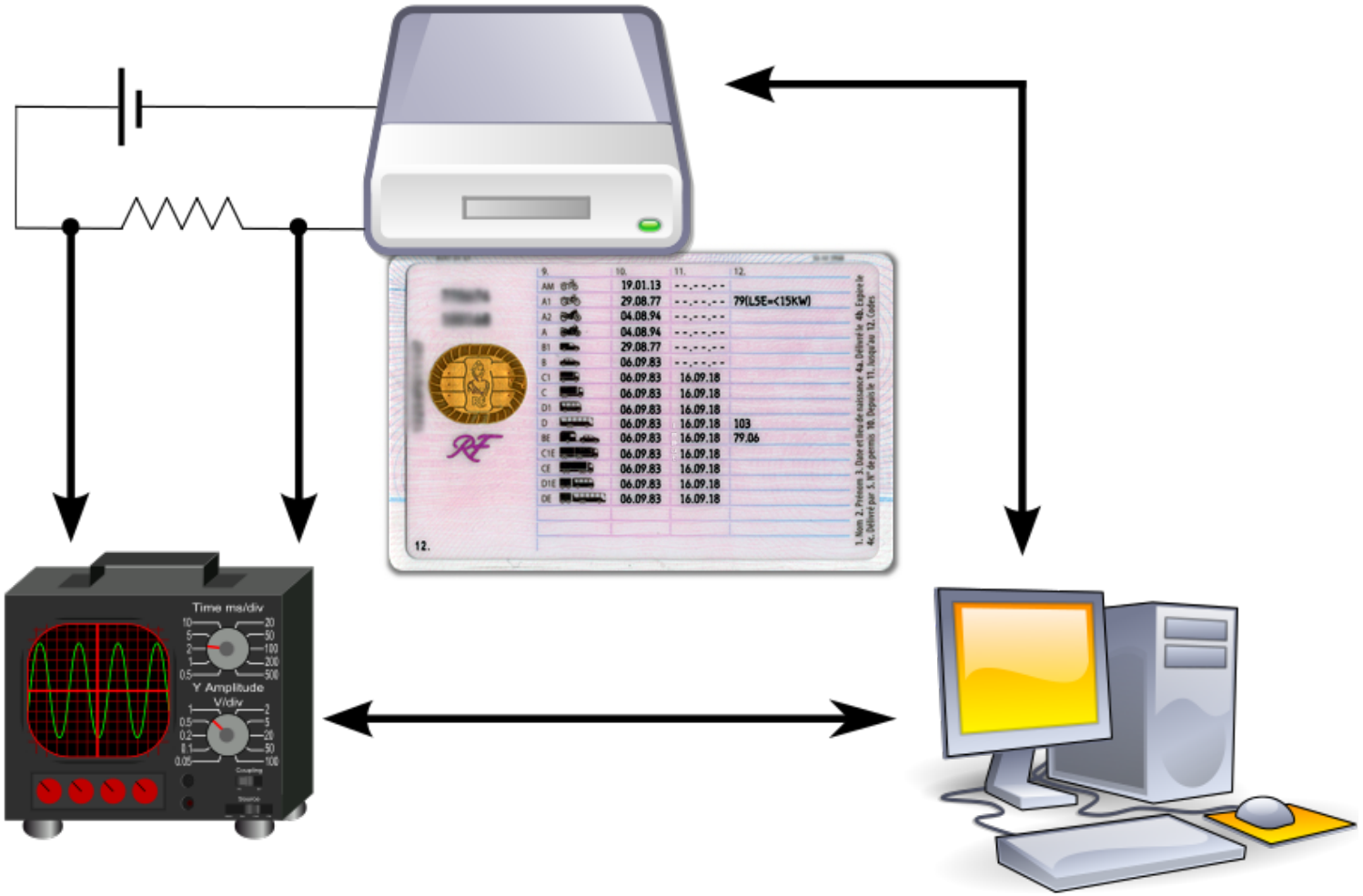
Visual crypto identification: stack!



Where is my key?

DIFFERENTIAL COMPUTATION ANALYSIS

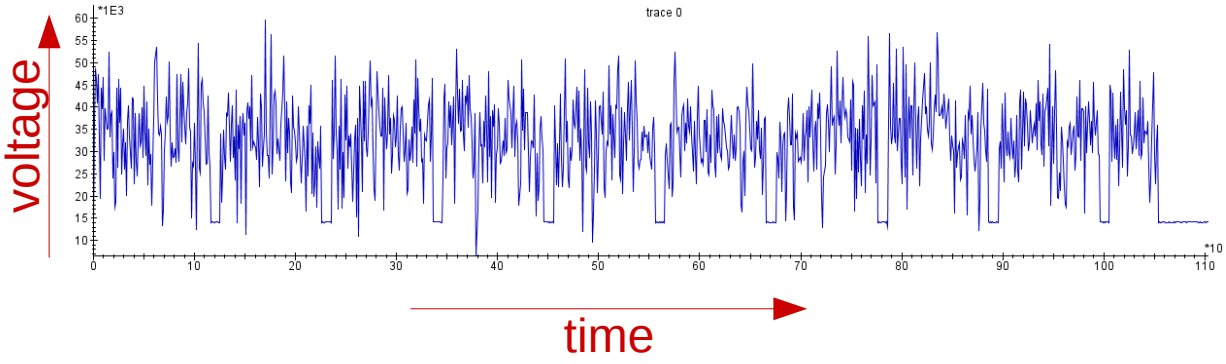
Remember?

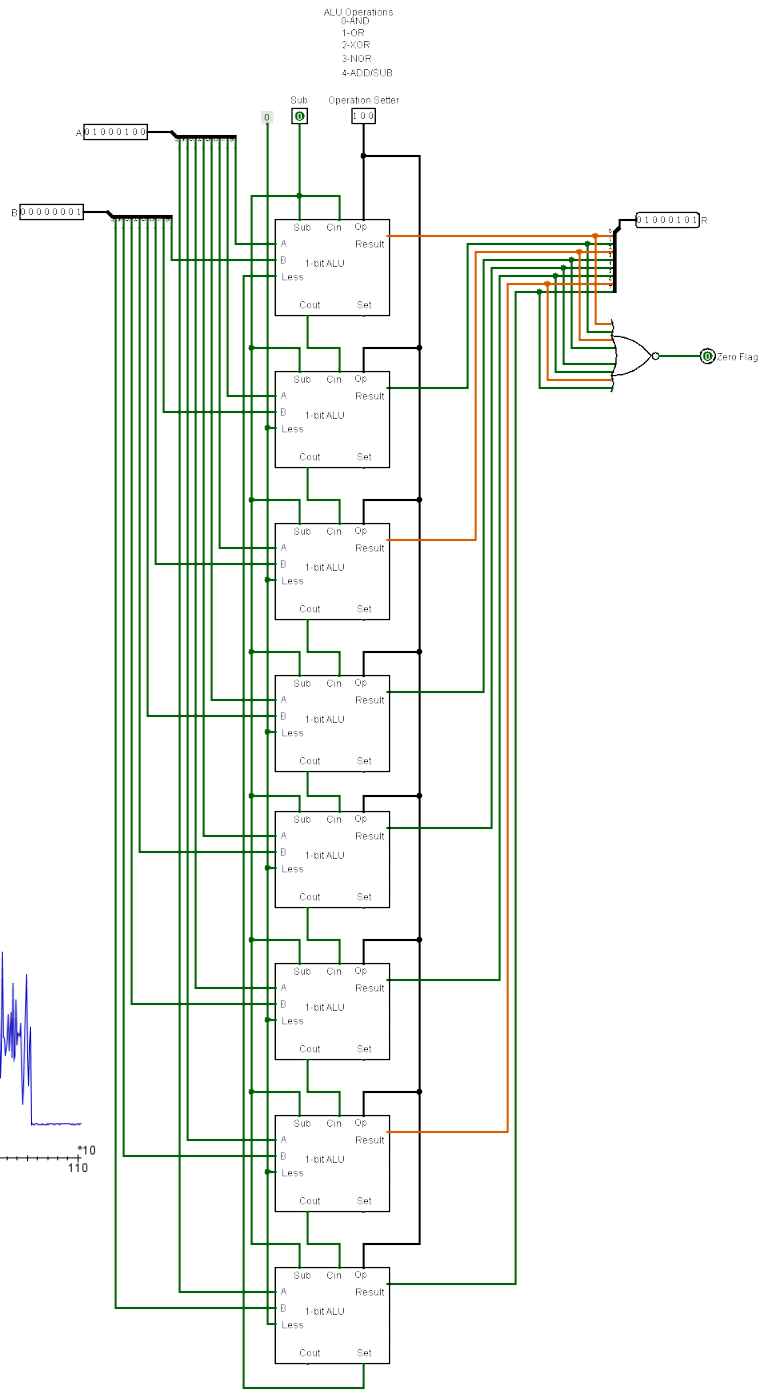


All started with Differential Power Analysis

by P. Kocher et al. (1998)

- Probable correlations:
  power consumption vs.
  Hamming weight of internal values
- Record many traces
  while providing different inputs

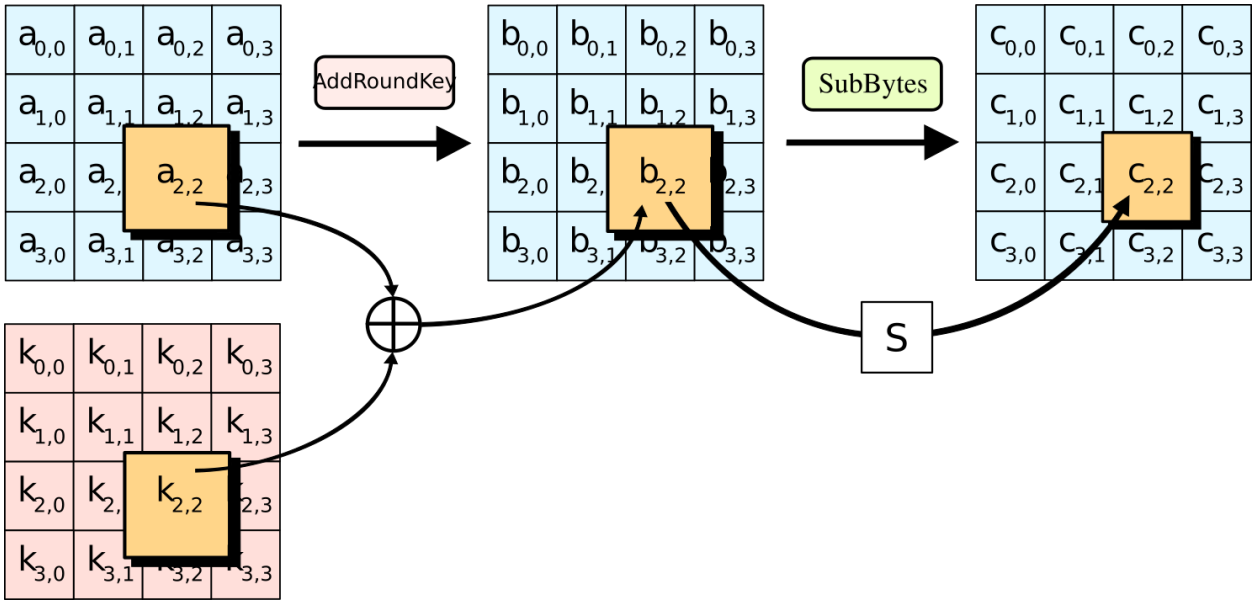




Differential Power Analysis

Some intermediate values in first (or last) round depend only on known data and a fraction of the round key

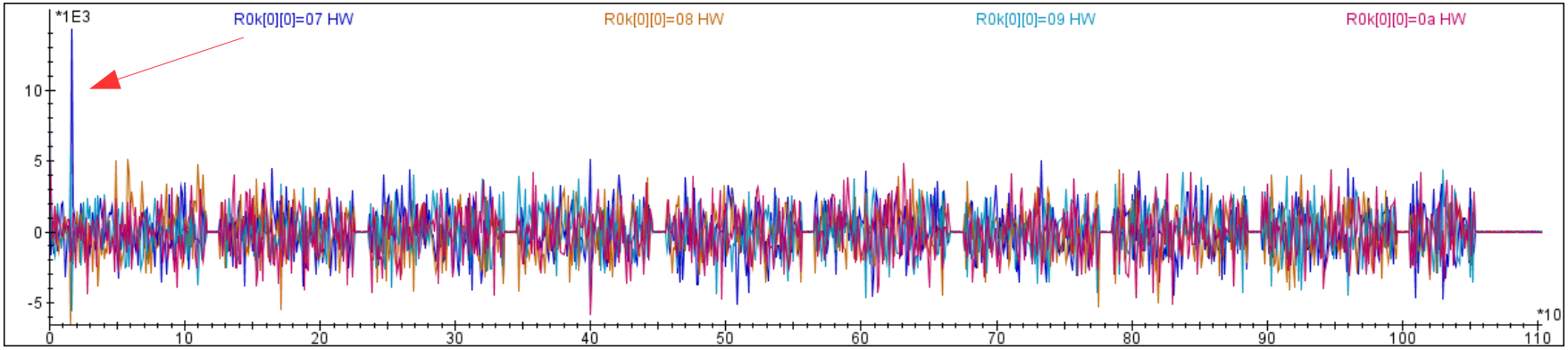
E.g. for AES:



Differential Power Analysis

1) Make a guess on that fraction of key
2) Evaluate targeted intermediate value for each plaintext: 0 or 1?
3) Sort traces accordingly in two buckets and average them
4) Compute differences between those averages

If the key guess is correct, it'll show up:



Differential Power Analysis

Very powerful grey box attack!

Requirements:

- Either known input or known output
- Ability to trace power consumption (or EM radiations)
- Some leakage

Differential Computation Analysis

Port the white-box to a smartcard and measure power consumption

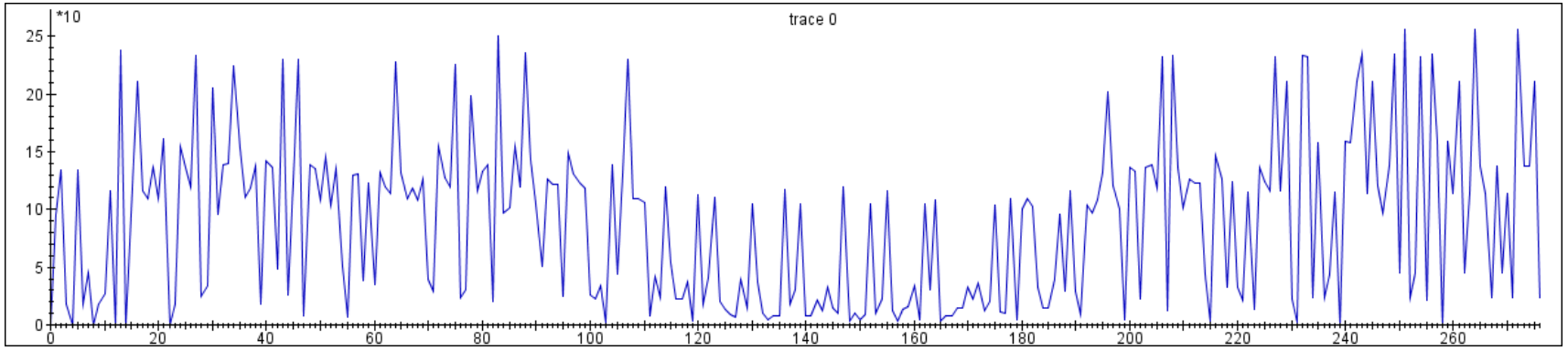
Differential Computation Analysis

~~Port the white-box to a smartcard and measure power consumption~~

Software execution traces → “power traces”

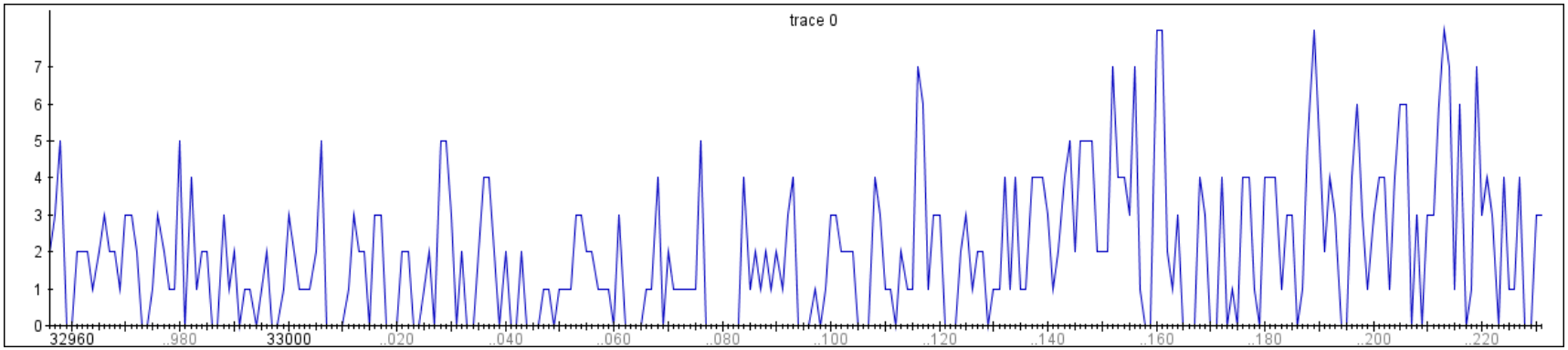
Memory accesses / data / stack writes / …

E.g. build a trace of all 8-bit data reads:



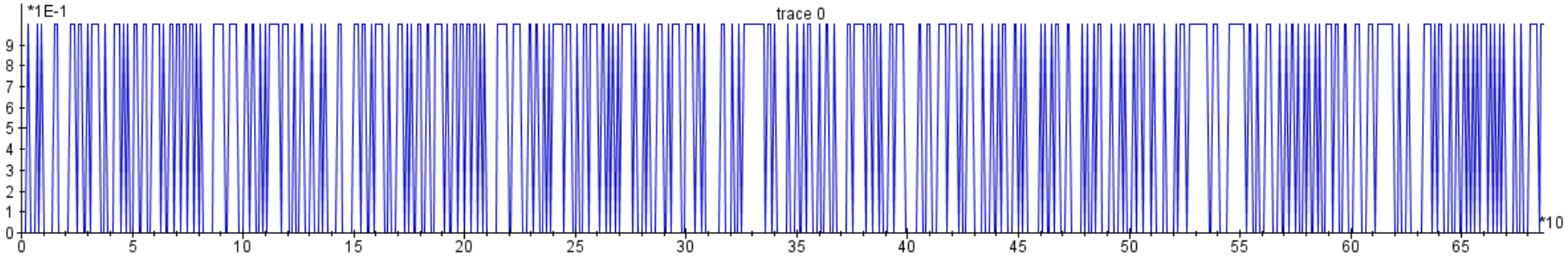
Differential Computation Analysis

→ Build Hamming weight traces?

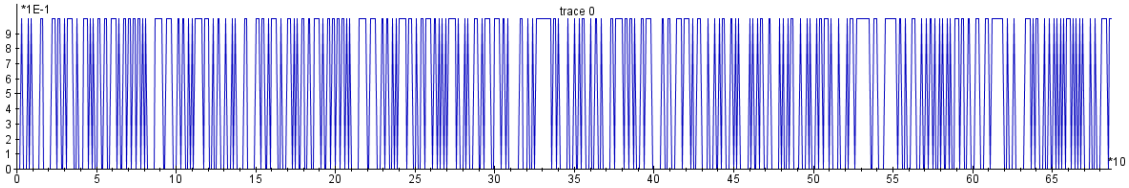


Differential Computation Analysis

→ Serialize bytes in a succession of bits



Differential Computation Analysis



Looks weird but works great!

As if:

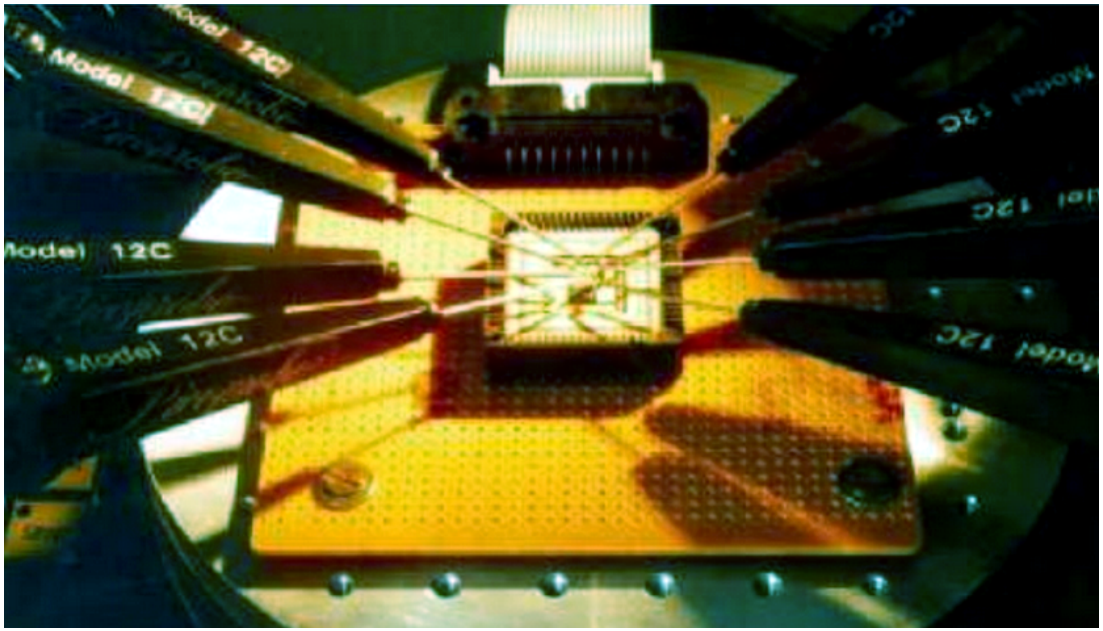


Image source: Brightsight

Next step

Feed traces in your favorite DPA tool

- Riscure Inspector SCA software
- ChipWhisperer opensource software
- Matlab…
- **Daredevil !**

Tips

What to trace?

- Stack writes
- Data reads
- Accessed addresses

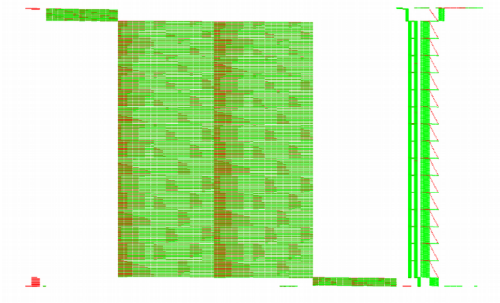
plaintexts and/or ciphertexts

- May require binary instrumentation

Large white-box? Minimize amount of traced information

- Trace only first (or last) round
- Standard deviation analysis to compress the trace

Wyseur challenge



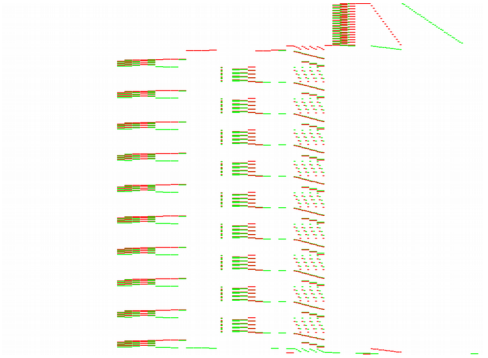
by Brecht Wyseur, 2007

DES implementation based on Chow “plus some personal improvements”

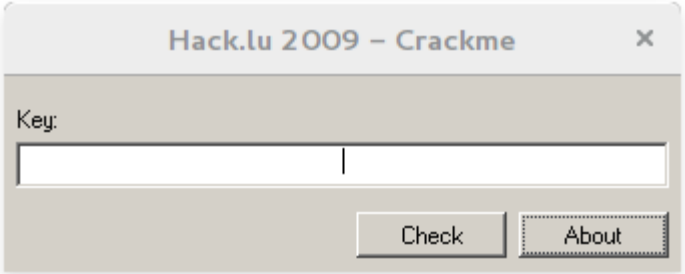
Downloading Linux binary…

1h and 65 traces later (of a full binary execution), key got broken!

Hack.lu 2009 challenge



Windows *crackme* by Jean-Baptiste Bédrune
AES implementation based on Chow



Laziness → Wine/Linux + xdotool (kbd+mouse emulation)

16 traces

(CTF challenge, no internal encodings)

SSTIC 2012 challenge

Python white-box by Axel Tillequin
DES implementation in a marshalled object

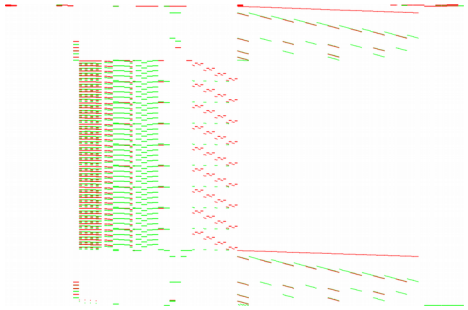
Python + PIN = Boom

→ Instrumenting “Bits” helper class

Again, 16 traces

Again, no internal encodings

Karroumi



Latest academic attempt to “fix” Chow (2011)

Dual Ciphers, i.e. isomorphic AES ciphers:

$$\forall p, k : E_k(p) = f^{-1}\left(E'_{g(k)}(h(p))\right)$$

Our own binary challenge…

2000 traces, 500 traces after some tuning

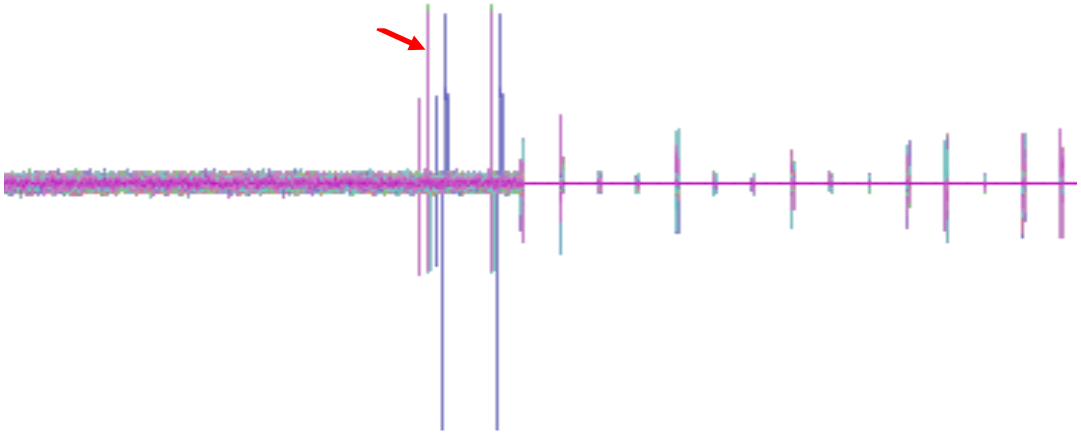
Some proprietary white-boxes

DES & AES

Broken in 200 to 2500 traces

Back to White-Box design

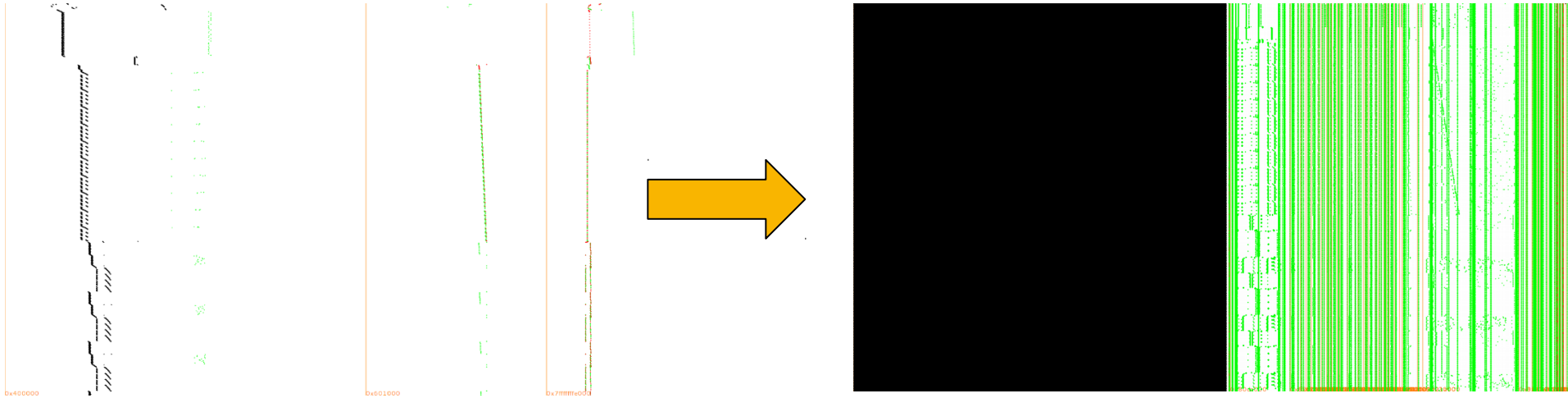
Known key analysis



1) Identify first leaking samples (the original source)
2) Find the corresponding instruction
3) Find the corresponding source code line

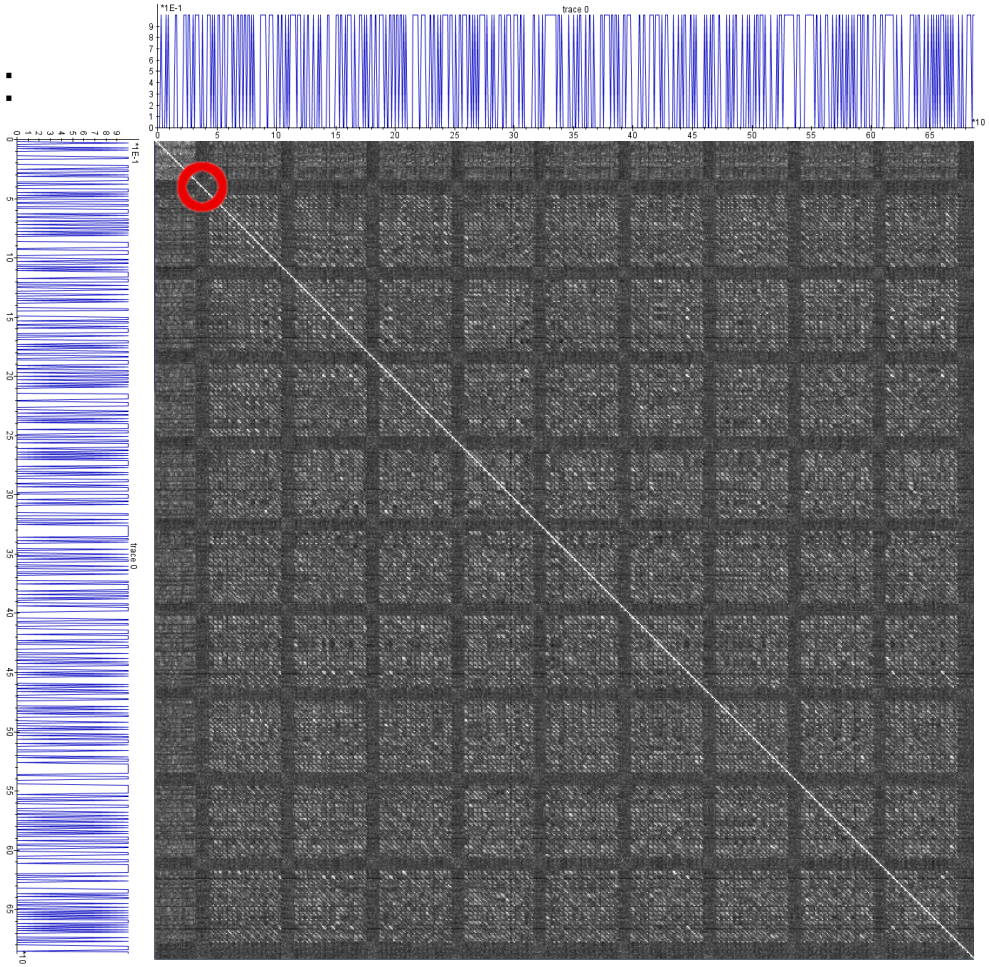
Works also on obfuscated VMs: M/o/Vfuscator2

Applied on a standard AES implementation



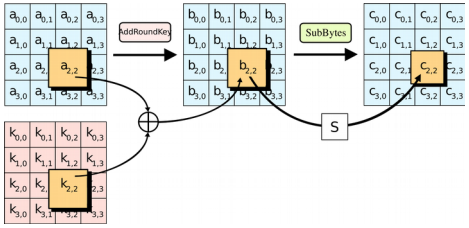
M/o/Vfuscator2 on AES

Auto-correlation reveals structure:



Huge traces, compressed by looking at standard deviation
4Mb -> 6.6kb

First round Sbox output



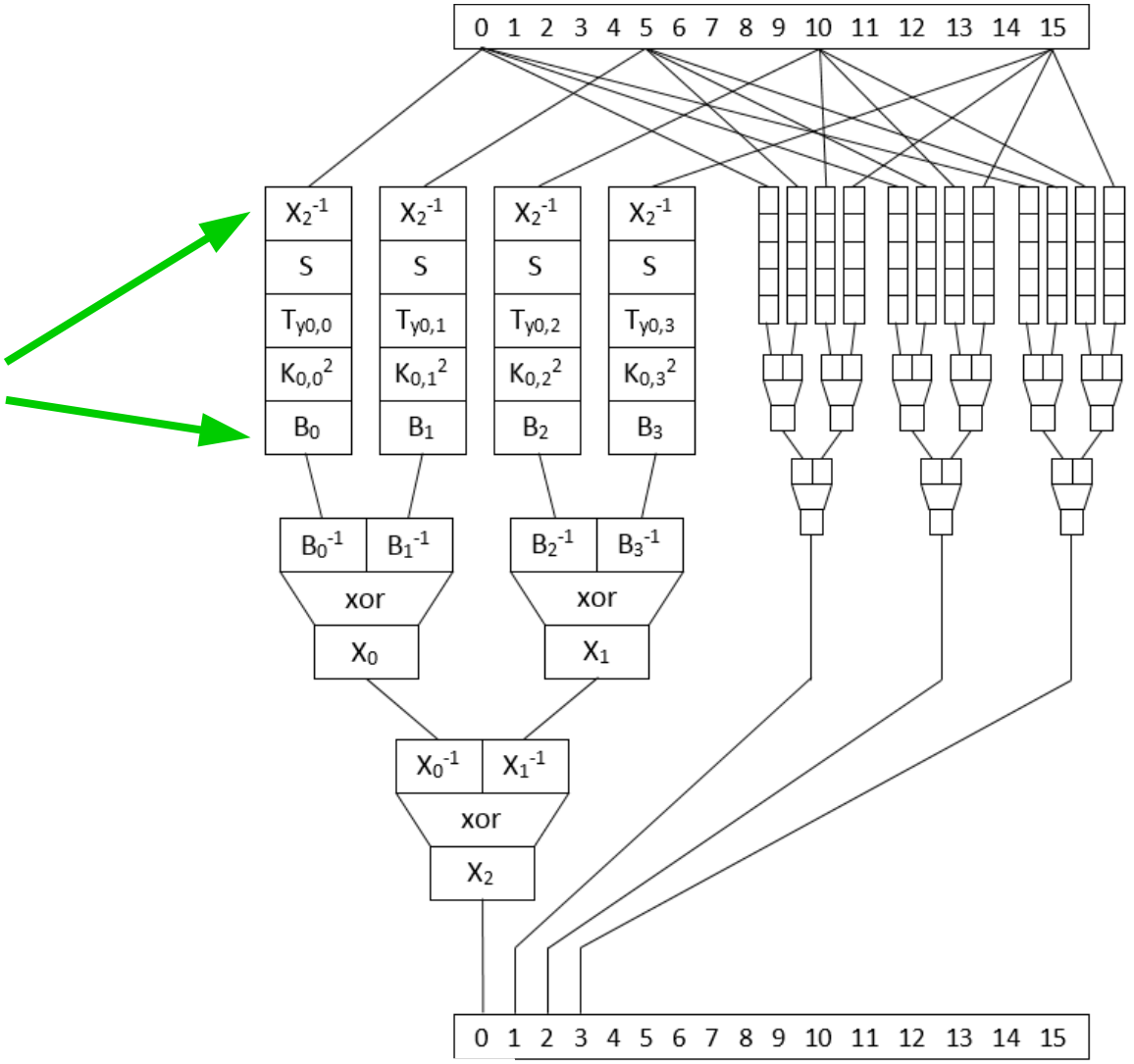
20 – 30 traces

http://wiki.yobi.be/wiki/MoVfuscator_Writeup

Can DCA fail?

Yes!

Wide intermediate non-linear encodings (8x8) blind the SBox non-linerarity



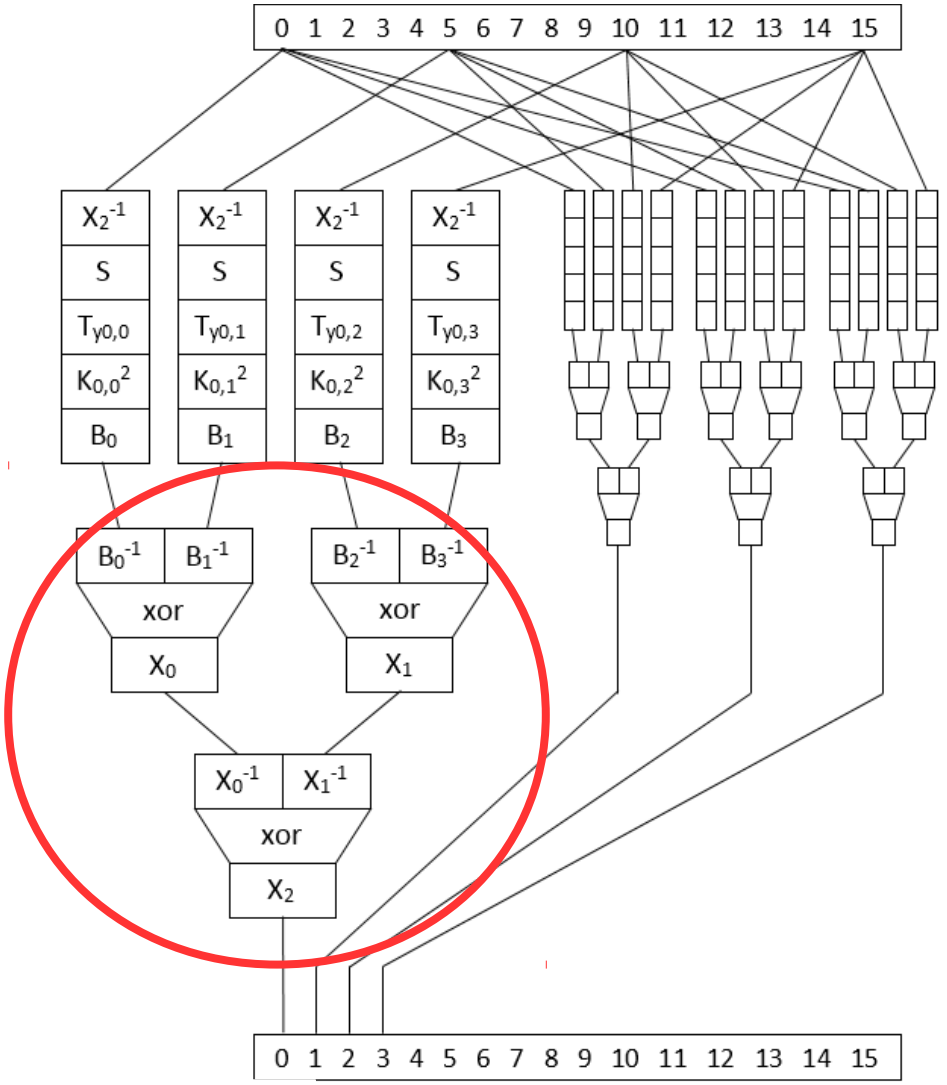
Can DCA fail?

Yes!

Wide intermediate
non-linear encodings (8x8)
blind the SBox non-linearity

But very large tables!

→ Trend to reuse those tables
→ reuse encodings
→ other types of attack



cf my write-ups of
NoSuchCon 2013 and CHES 2015
http://wiki.yobi.be/wiki/CHES2015_Writeup

Other countermeasures?

Runtime randomness?

- Here, no trustworthy TRNG available

Runtime random delays?

- Trace instructions → realign

Building proper white-box technology is a delicate matter…
Forget about “perfect” security, but if cost of an attack is larger than the benefit for the attacker, you achieved your goal.

Oops, it seems our cheap attack raised the bar...

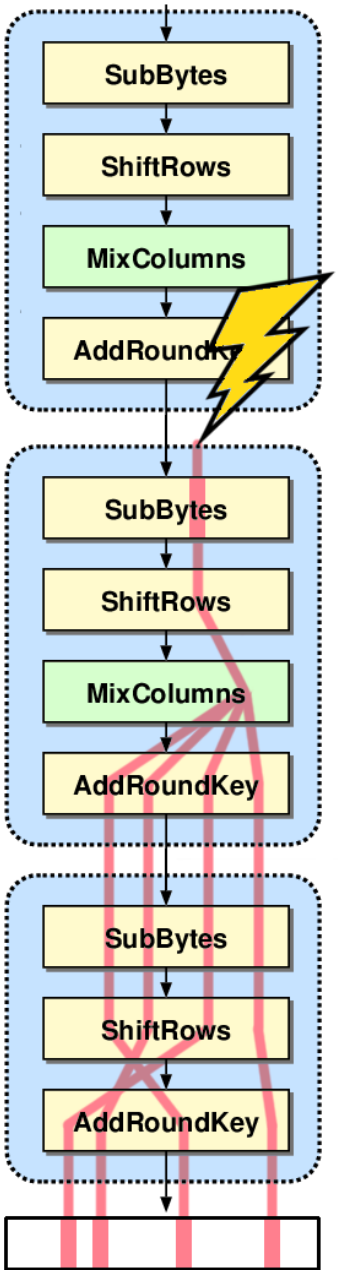
Other grey box attacks within reach: Higher order DPA, CPA, DFA,…

DFA, let's talk about it...

Differential Fault Analysis on AES (Dusart et al. 2003)

- Prerequisite: replay input, see clear output
- Injection: source ; bin statically ; bin dynamically
- Blind injection
- 8 "good" faults are enough (on AES-128 enc or dec)
- Analysis time: a few seconds

Detailed blog post will be published soon, stay tuned!



Take also care of code lifting, inversing f(),...

“Now this is not the end.
It's not even the beginning of the end.
But it is, perhaps, the end of the beginning.”

Side-Channel Marvels

https://github.com/SideChannelMarvels

Tracer
- TracerGrind
- TracerPIN
- TraceGraph

Deadpool
- White-boxes
- Attacks automation

Daredevil
- Side-channel analysis (CPA)

JeanGrey
- Fault analysis (DFA)

Side-Channel Marvels

https://github.com/SideChannelMarvels

Charles Hubain (Quarkslab)

Joppe Bos (NXP)

Michael Eder (TUM, Fraunhofer AISEC)

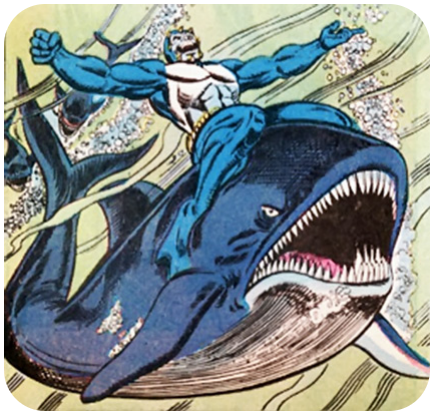
Paul Bottinelli (EPFL)

Philippe Teuwen (Quarkslab)

Van Huynh Le (U.Twente, NXP)

Wil Michiels (NXP, TU/e)

But also...



Orka
- images Docker

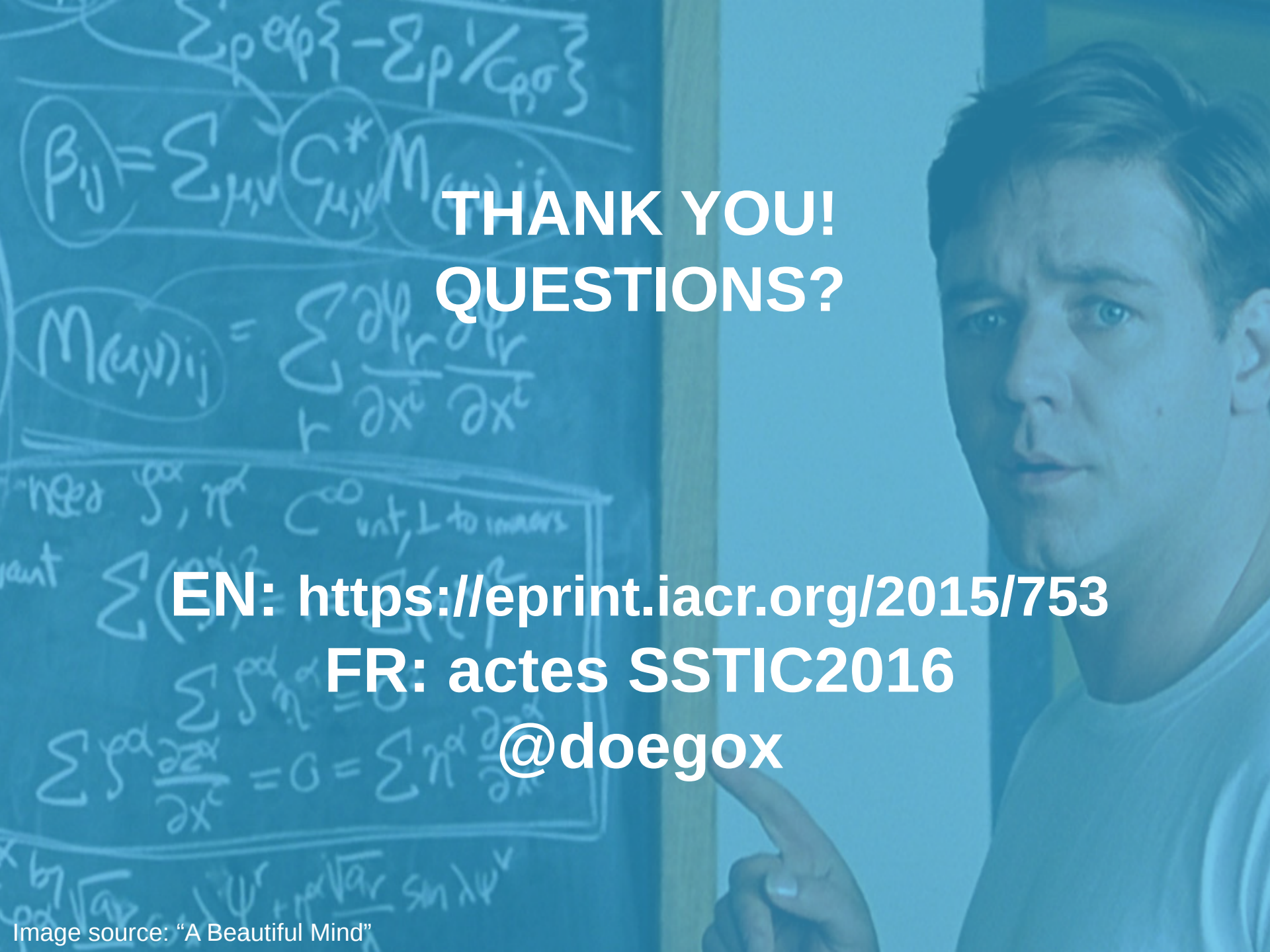
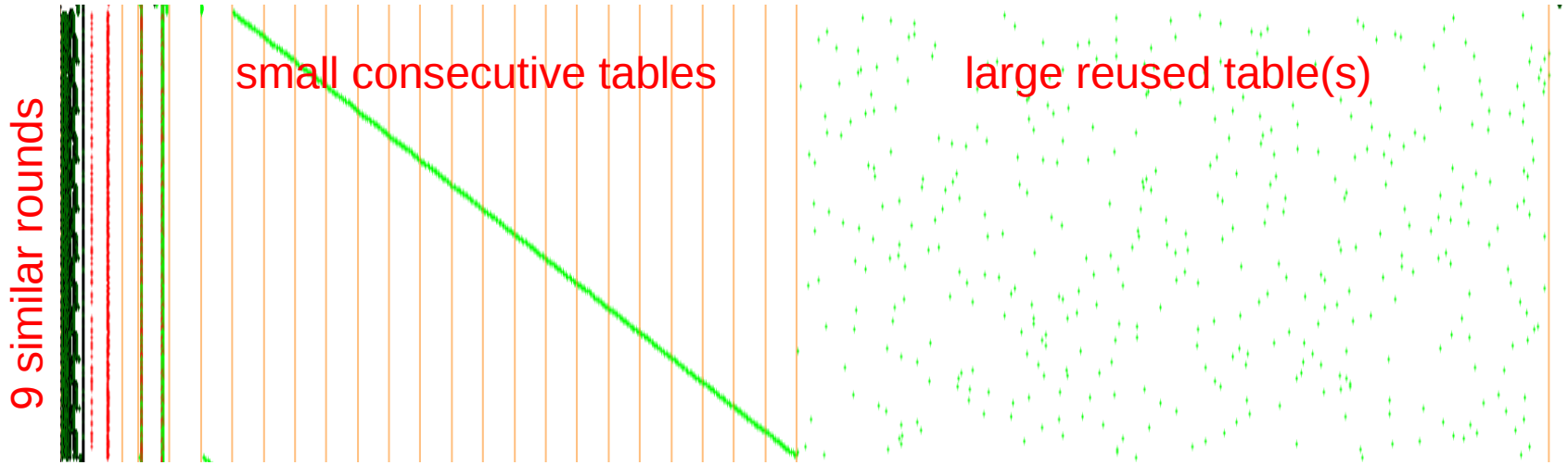


Image source: “A Beautiful Mind”

VISUAL RE

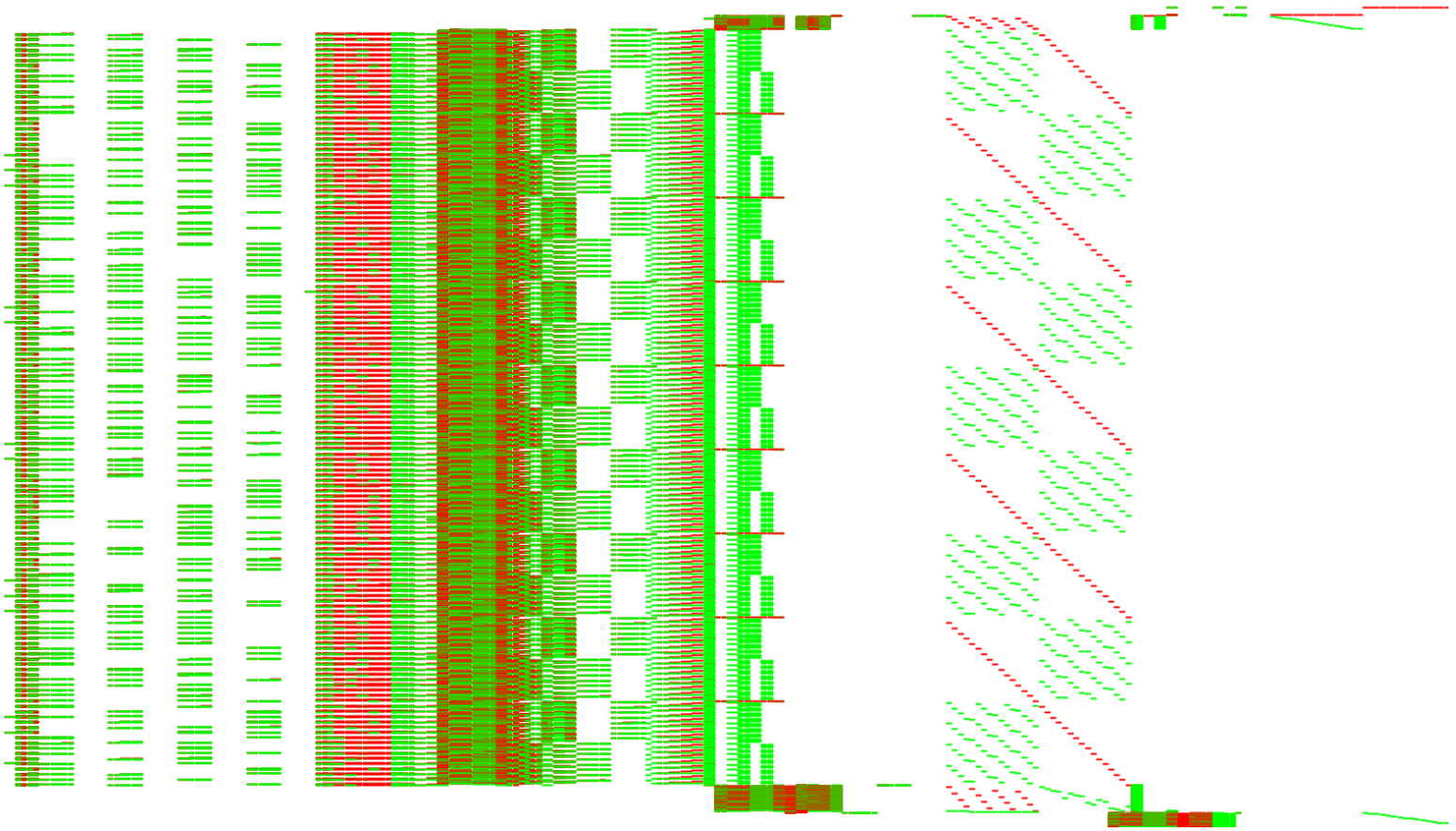
Case study 1



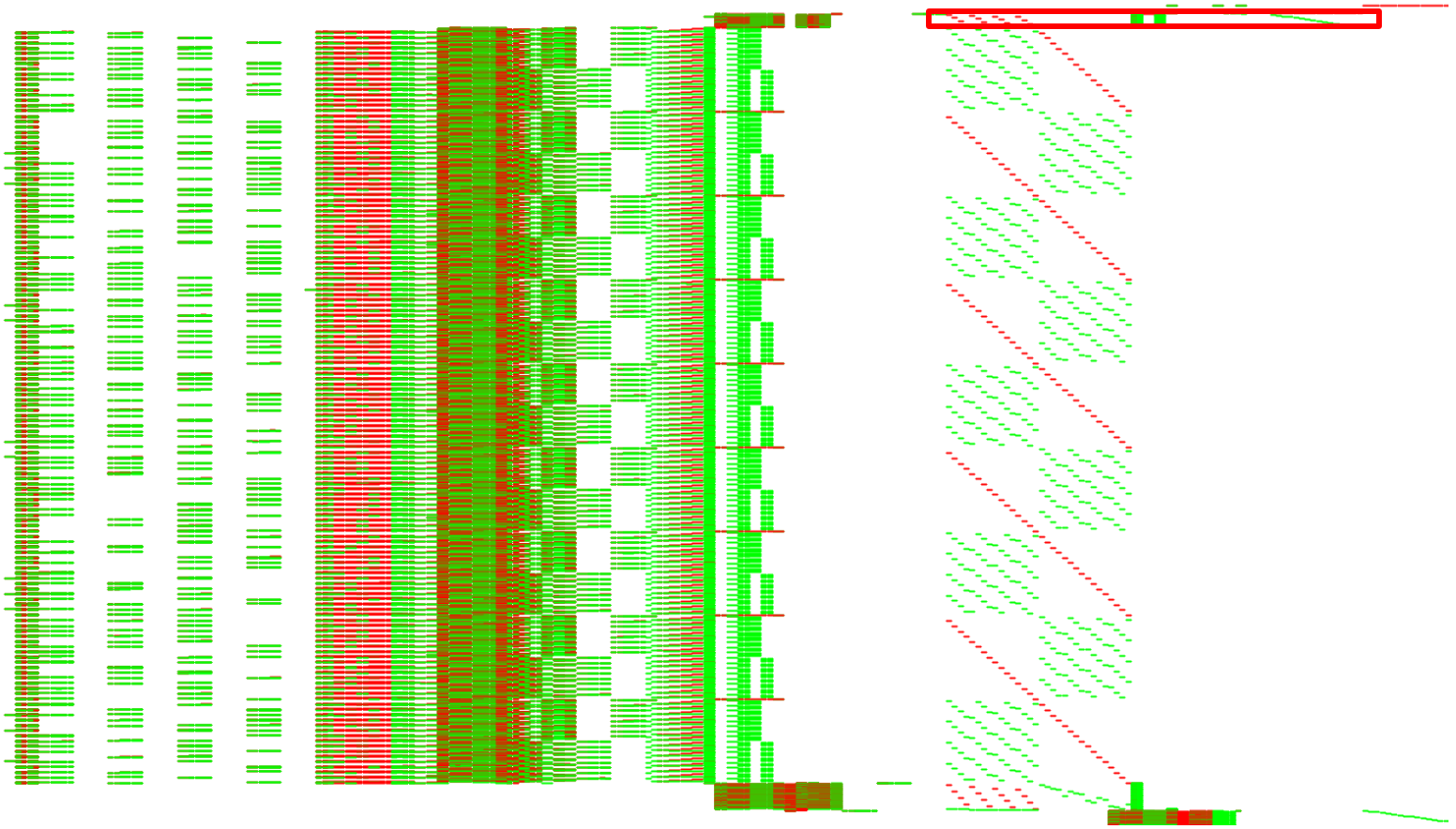
Context implies AES-128 decryption…

Case study 1

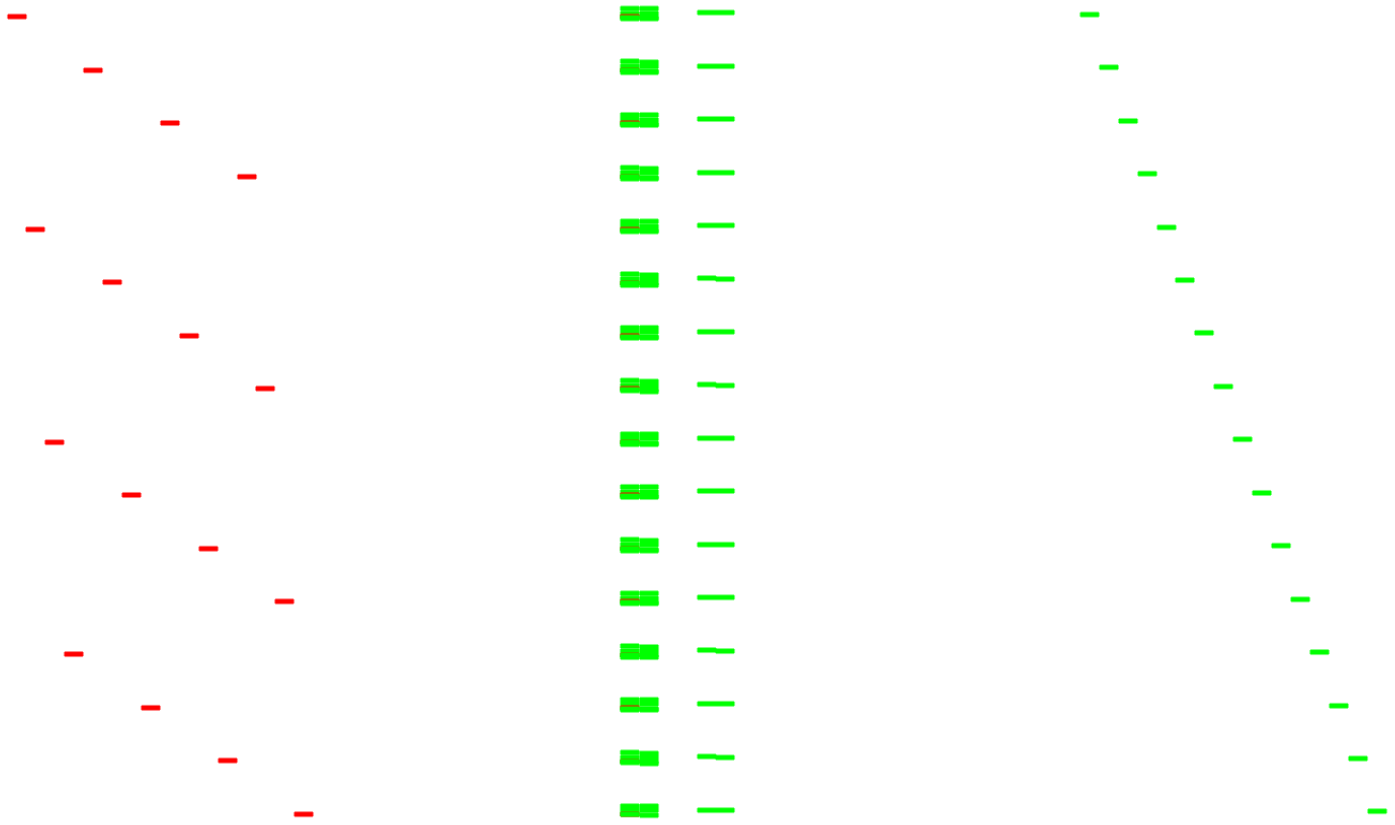
Case study 1: stack



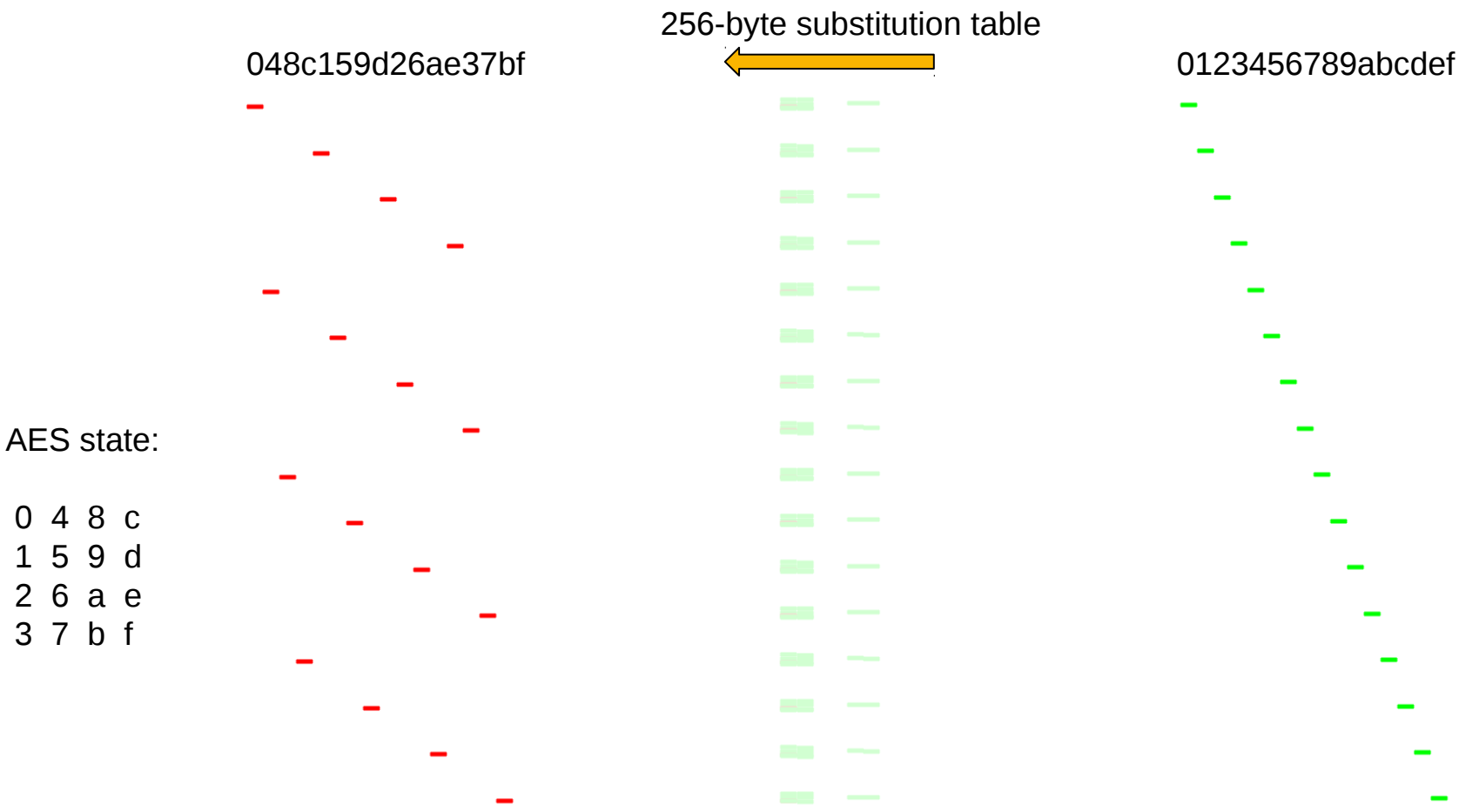
Case study 1: before rounds



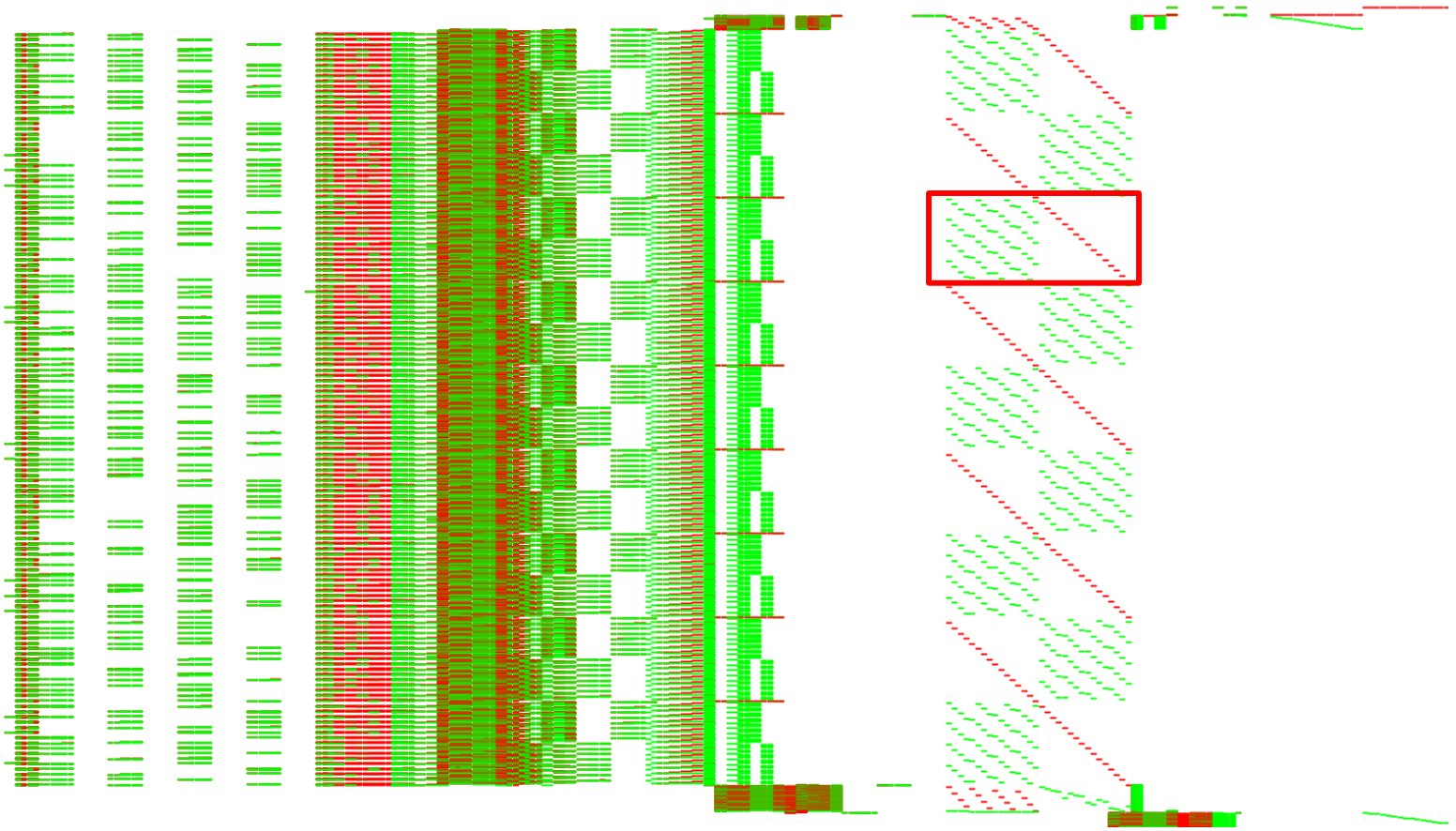
Case study 1: before rounds



Case study 1: before rounds

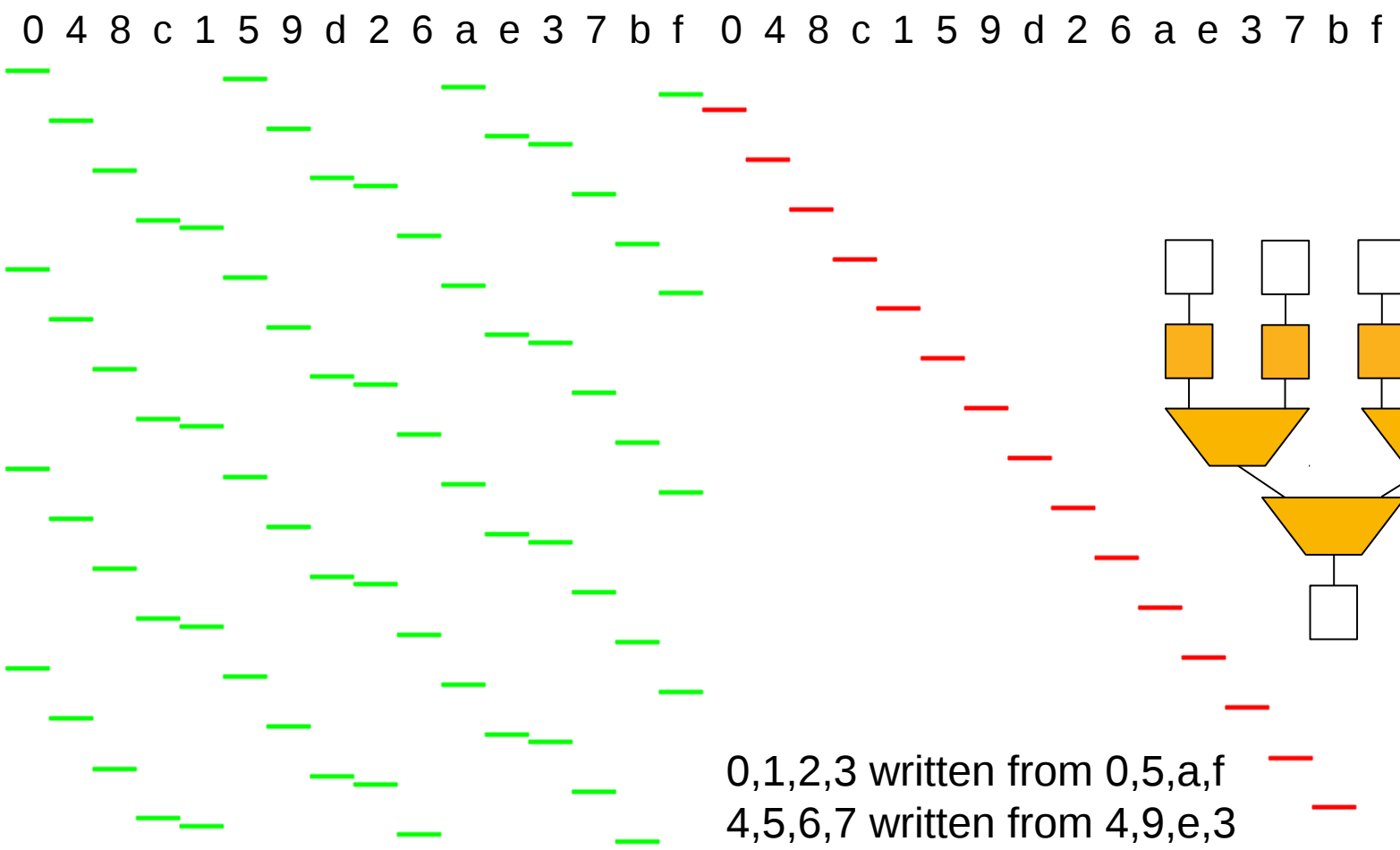


Case study 1: one round



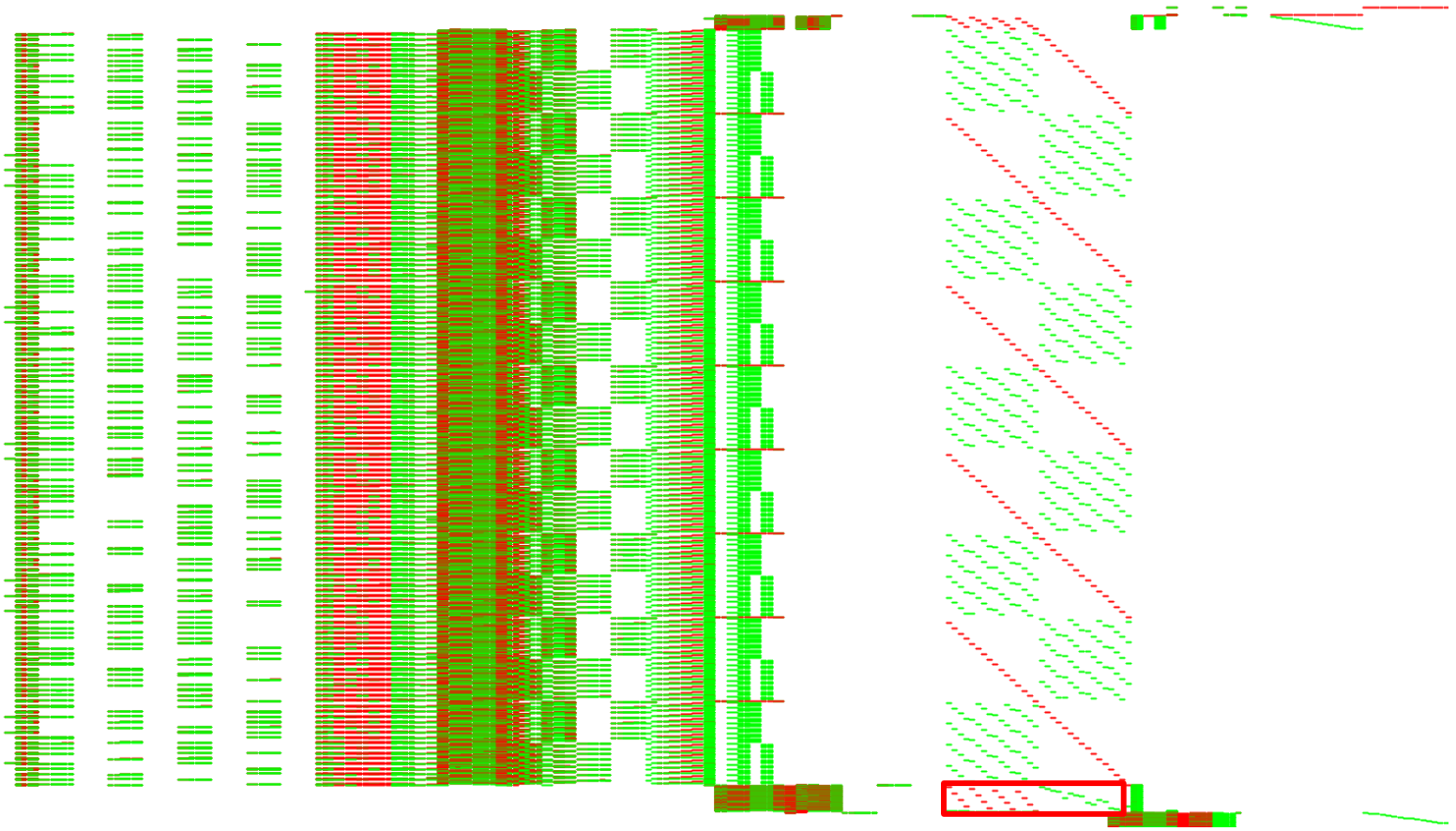
Case study 1: one round

with 64 reads from 64 256-byte tables
and 48 reads from 3 65536-byte tables

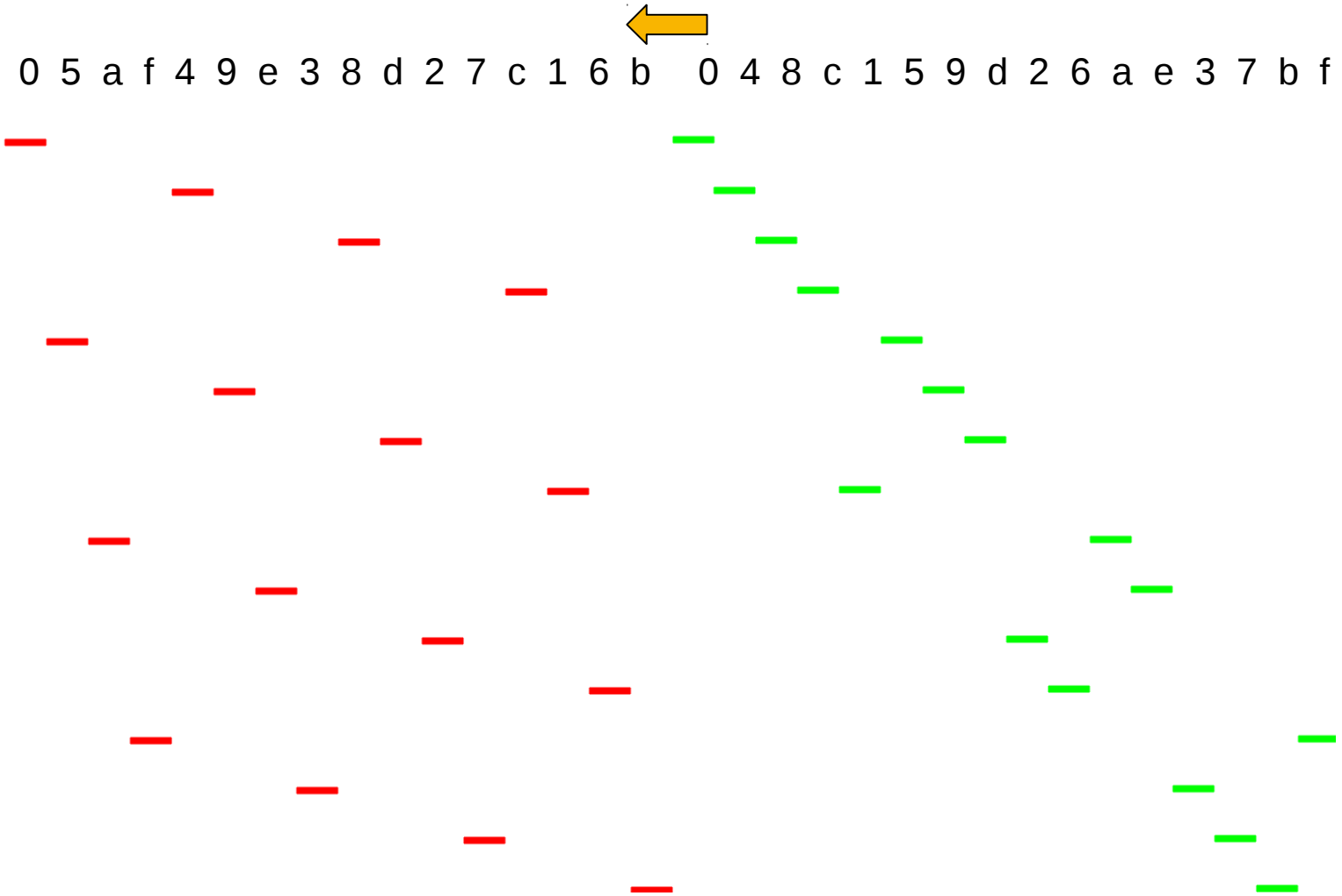


0,1,2,3 written from 0,5,a,f
4,5,6,7 written from 4,9,e,3
8,9,a,b written from 8,d,2,7
c,d,e,f written from c,1,6,b

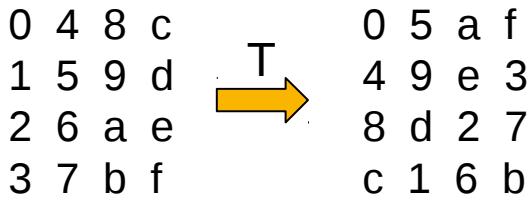
Case study 1: last round



Case study 1: last round



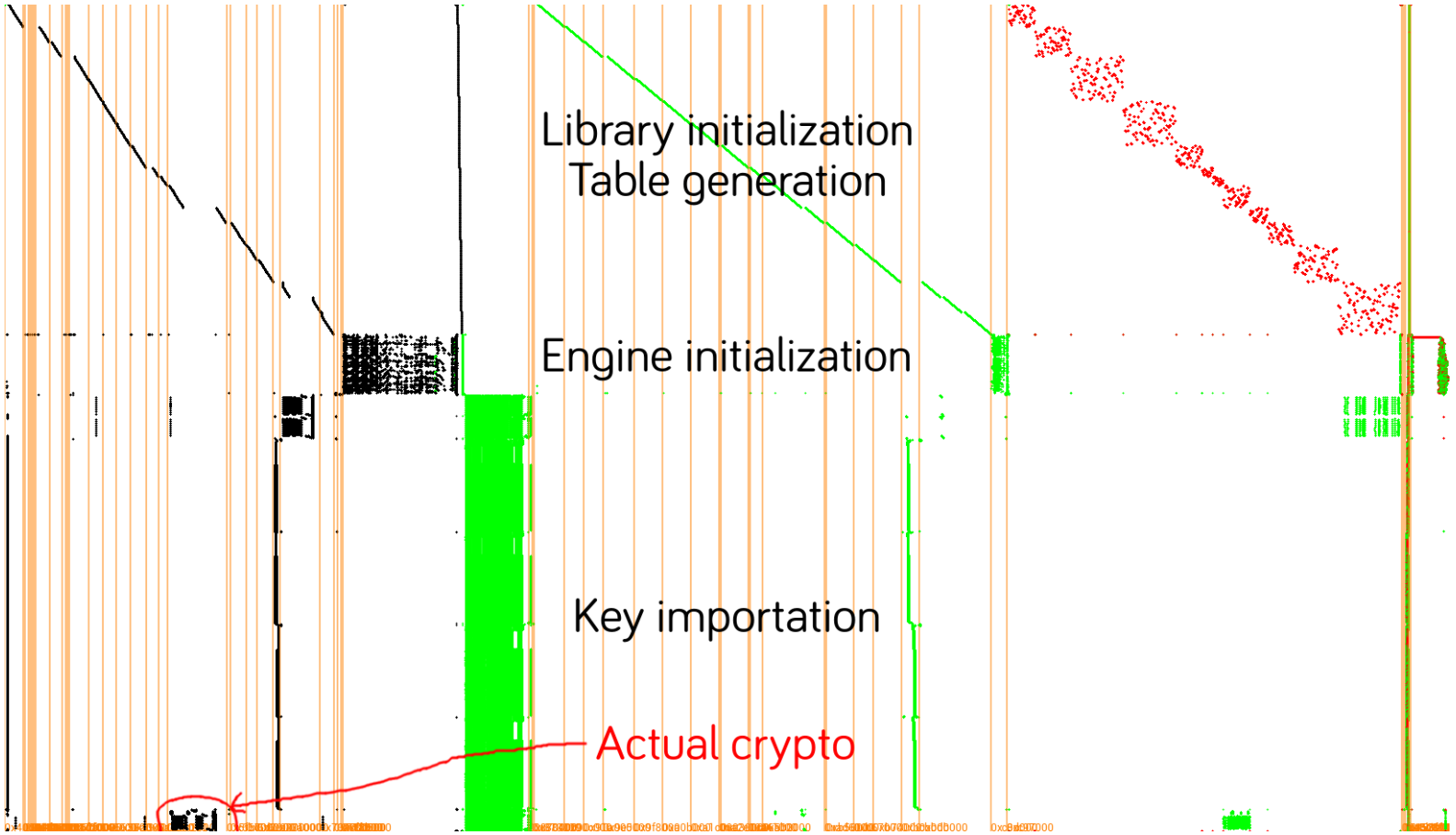
Case study 1: last round



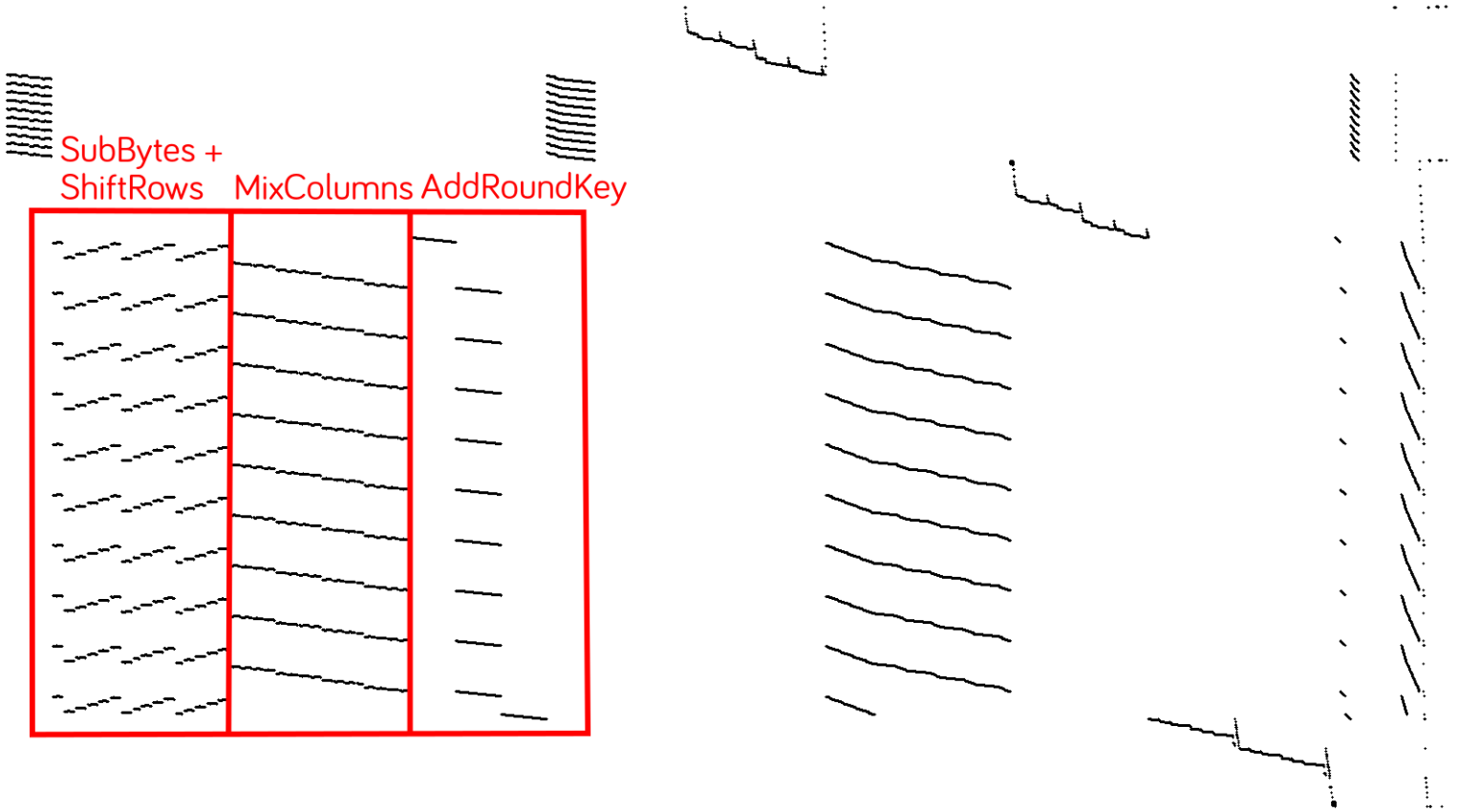
- Only one explanation for this reordering:
  ShiftRow followed by *Transpose* (to restore natural output order)
- This means AES *encryption*, not decryption!
- Next step: table-lifting
  - Correct boundaries?
    Check statistical distribution of extracted tables
    (here we got 2+14 bytes missing every 0x4000 bytes -> secondary table)

REUSING INTERMEDIATE ENCODINGS

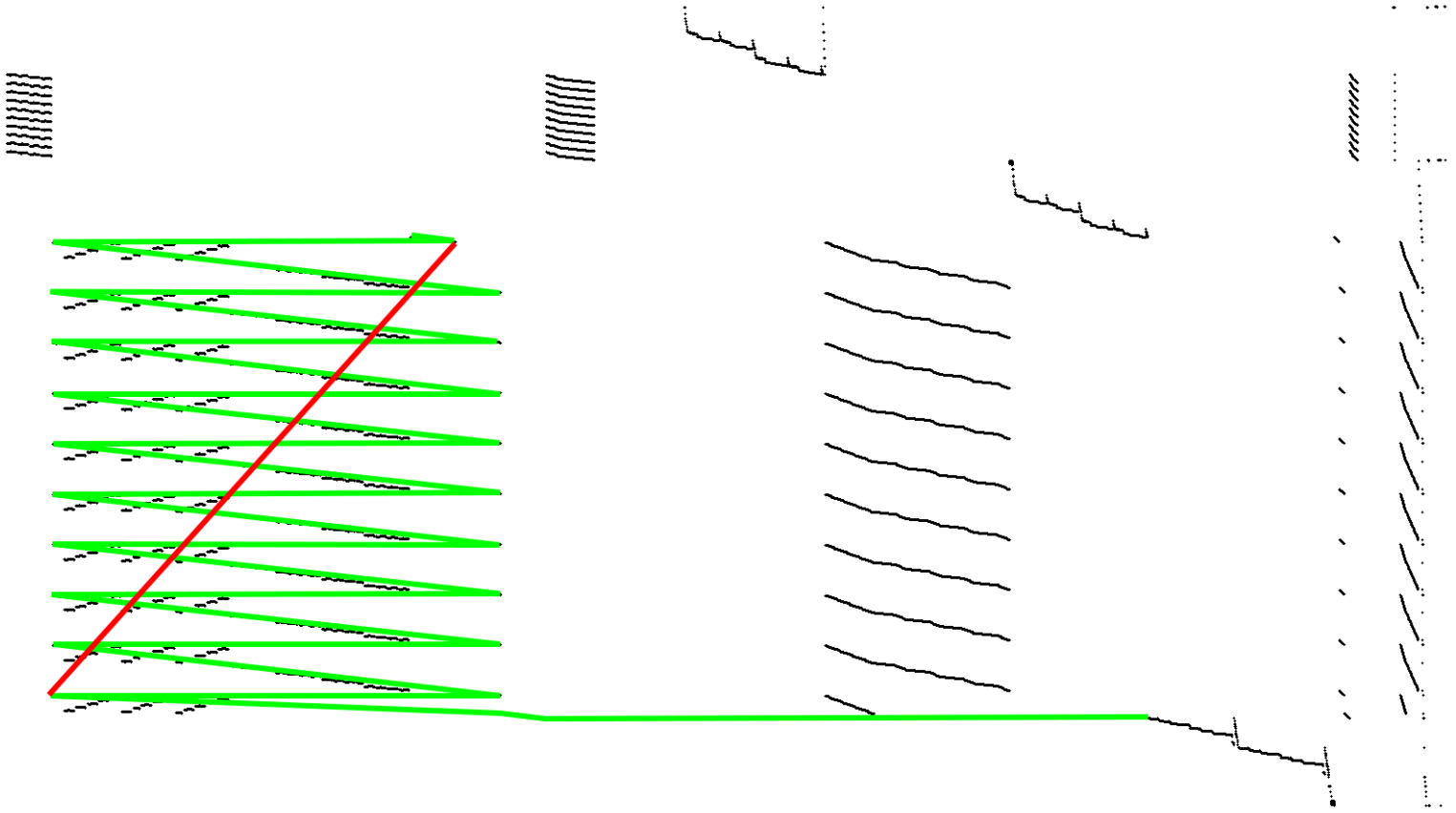
Case study 2: plaintext & ciphertext accessible



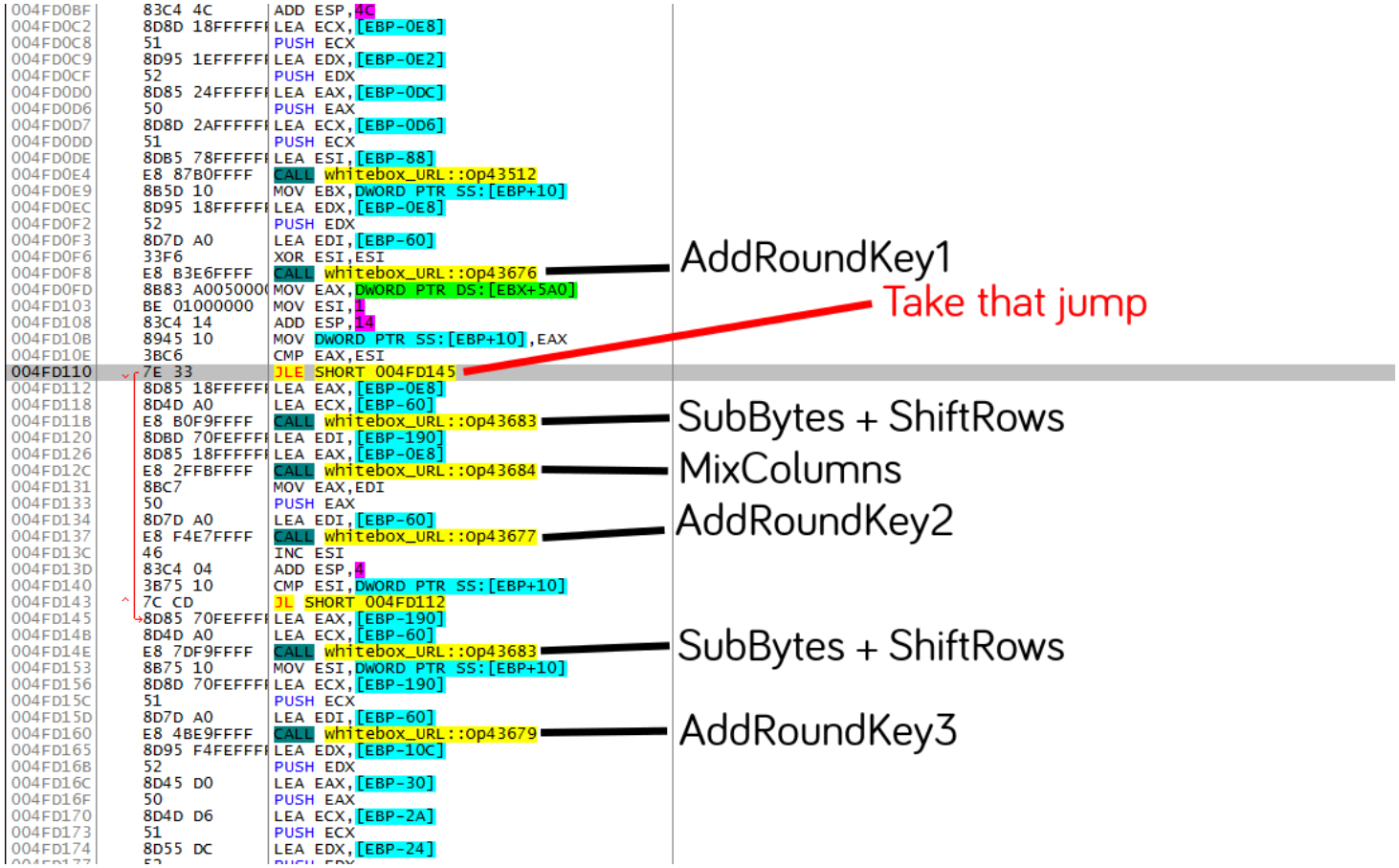
Case study 2



Case study 2



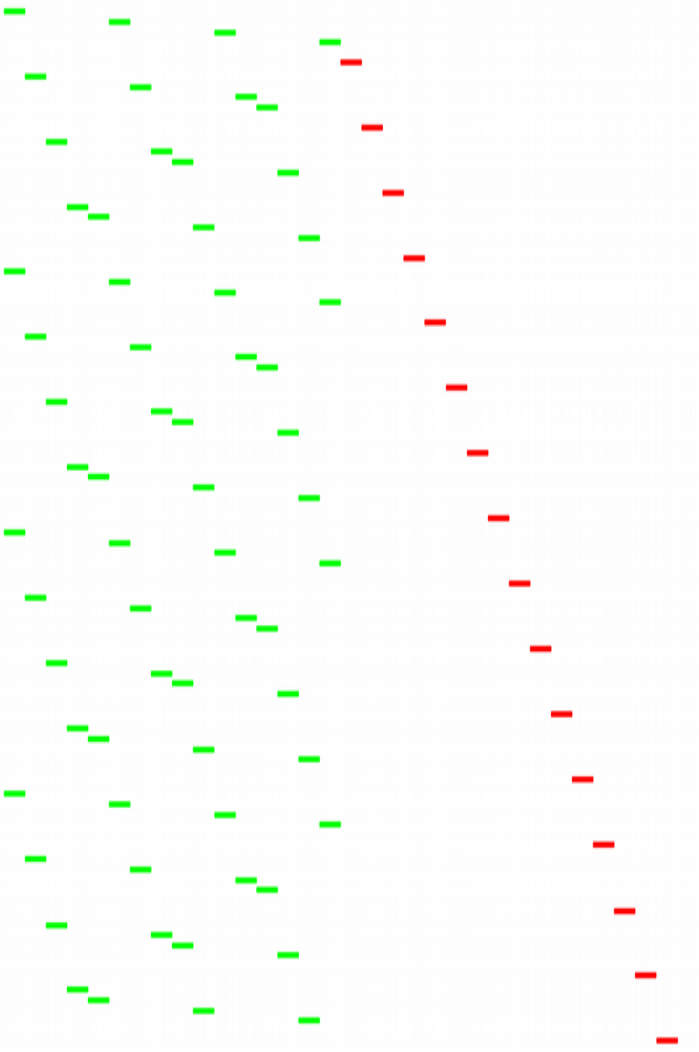
Case study 2

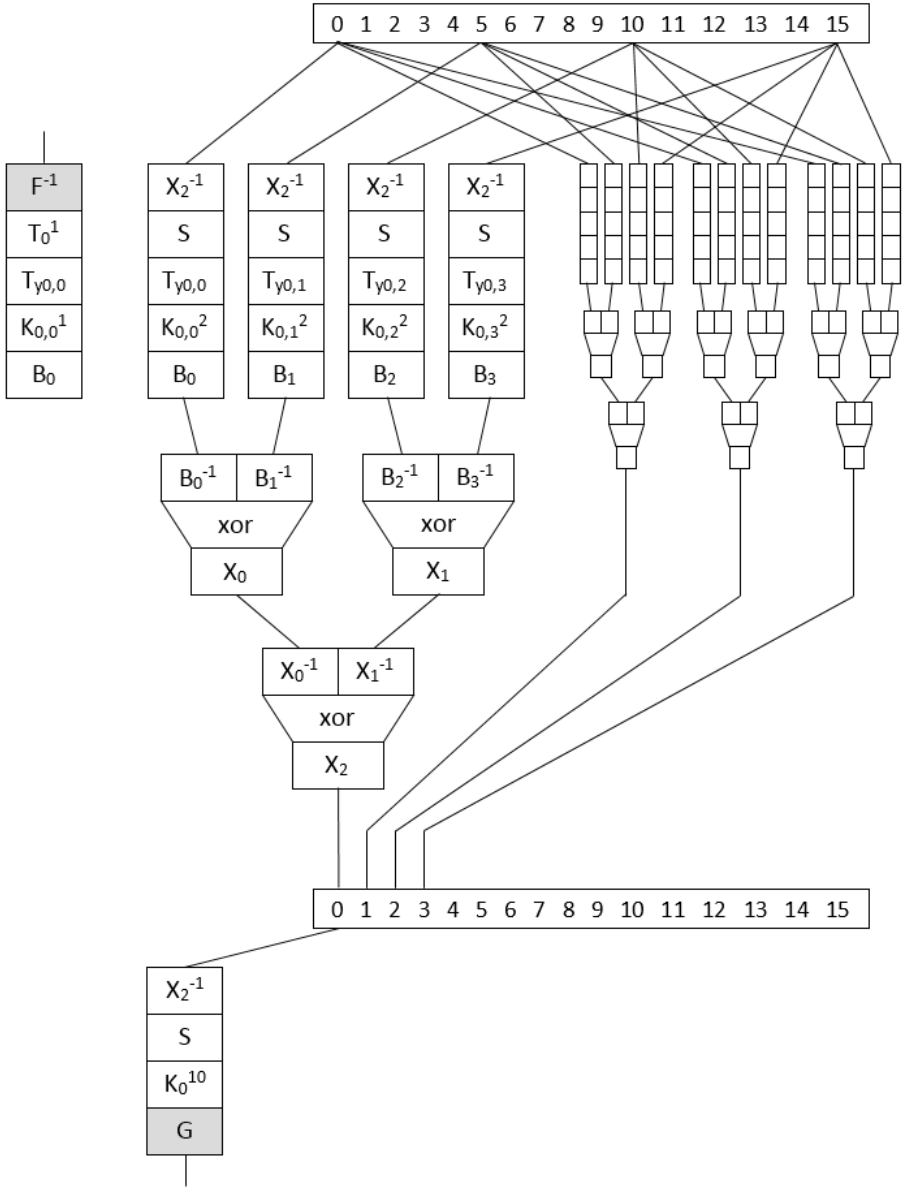


Then break a 2-round AES…

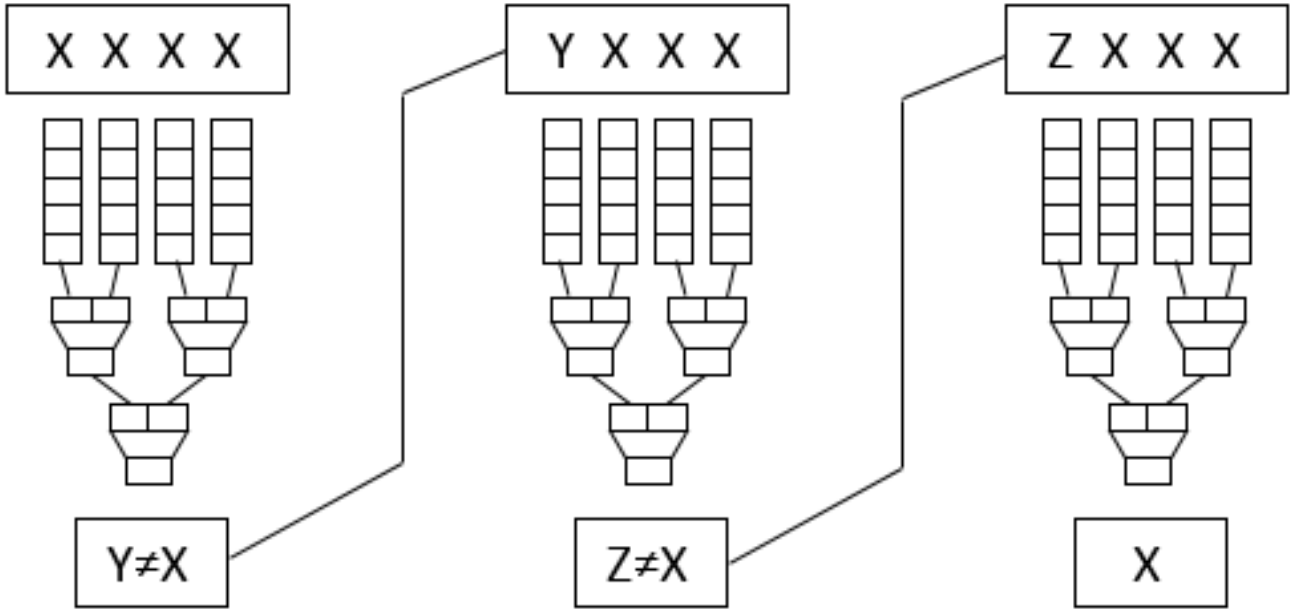
This requires access to the clear plaintexts & ciphertexts

Case study 3




0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
F-1
T0 1
Ty0,0
K0,0 1
B0
X2-1
S
Ty0,0
K0,0 2
B0
X2-1
S
Ty0,1
K0,1 2
B1
X2-1
S
Ty0,2
K0,2 2
B2
X2-1
S
Ty0,3
K0,3 2
B3
B0-1
B1-1
xor
X0
B2-1
B3-1
xor
X1
X0-1
X1-1
xor
X2
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
X2-1
S
K0 10
G

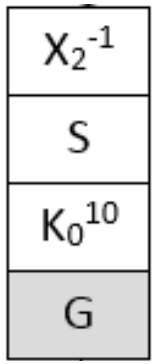
Case study 3



- Make a guess on encoding of 1 byte value (e.g. 0x00 => X=0xAB)
- Check for each key byte: which candidates with same # of iterations?
- Make second guess on encoding of another byte (e.g. 0x01 => X=0xCD)
- Check for each key byte: which compatible candidates?
- Iterate, backtrack if no candidate left for this set of encodings
- At the end we get the round key and the intermediate encoding map
- Reverse key scheduling

Doesn’t require access to plain/ciphertext or knowledge of external encodings
Takes about 3s max

Case study 3



If G(), the external encoding of output, is known, it's even easier:

- Choose arbitrarily an output byte value
- Make a guess for the corresponding round key byte
- Propagate output byte till getting the corresponding clear input byte and encoded input byte -> dictates one X2 entry
- Use same input for the next byte table -> only one possible key byte
- Go on for all Round 10 key bytes -> one round key -> one AES key
- At the end, 256 candidates for the AES key
  -> bruteforce with one plaintext/ciphertext pair

Takes 0.12s max