Practical white-box topics design and attacks – part 1

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White-Box Cryptography and Obfuscation

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SECURE CONNECTIONS FOR A SMARTER WORLD

What to White-Box?

Standardized crypto

- Comply with current standards / protocols required
  → Focus is on AES / DES

“New” crypto

- Crypto designed to aid certain WB properties

Where is this used in practice?

Original use-case for white-box crypto is
digital right management.

For example: streaming content, protecting DVD’s etc

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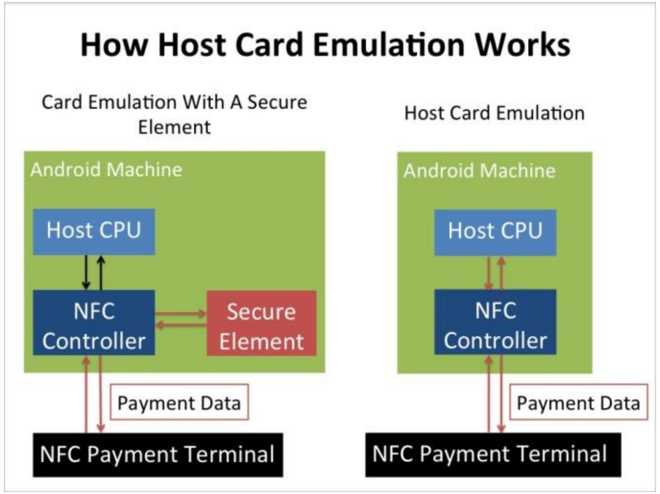


Source: Business Insider

Recent trend

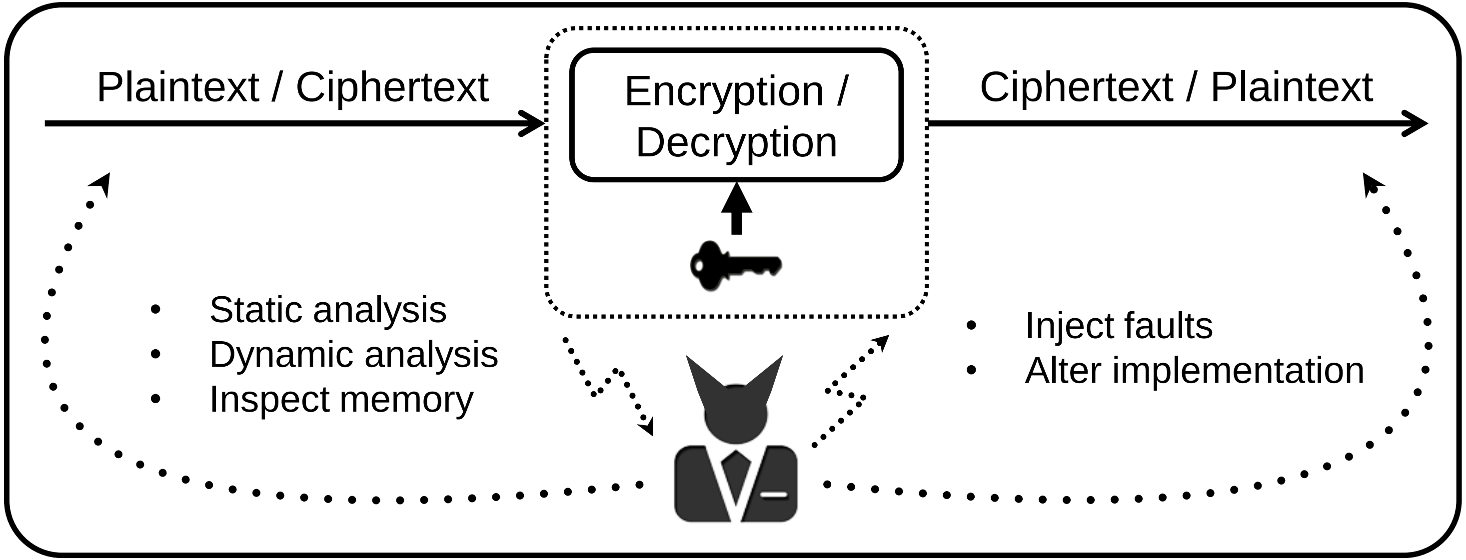
Use *Host Card Emulation* (HCE) to communicate using *Near Field Communication* (NFC)
→ Replace the secure element with software.

Protection of the cryptographic key? How?
White-box implementation!

Huge demand for practical + secure white-box

- 2014: VISA + Mastercard support HCE
- [Berg Insight]: **86%** of the Point of Sale devices in North America and **78%** in Europe will support NFC by 2017.
- [IHS research]: By 2018, 2/3 of all shipped phones will support NFC.
- → the protocols used need to use (and store!) AES / DES keys
  → need to white-box **standardized crypto**.

Recall: White box model



Adversary owns the device running the software. Powerful capabilities

- ✓ has full access to the source code
- ✓ inspect and alter the memory used
- ✓ perform static analysis
- ✓ alter intermediate results

Security of WB solutions - Theory

White box can be seen as a form of code obfuscation

- It is known that obfuscation of **<u>any</u>** program is impossible

Barak, Goldreich, Impagliazzo, Rudich, Sahai, Vadhan, Yang. On the (im)possibility of obfuscating programs. In CRYPTO 2001

- Unknown if a (sub)family of white-box functions can be obfuscated
- If secure WB solution exists then this is protected (by definition!) to **all** *current* and *future* side-channel and fault attacks!

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Practice

- Only results known for symmetric crypto
  (all academic designs of standard crypto broken)
- Convert algorithms to sequence of LUTs
- Embed the secret key in the LUTs
- Obfuscate the LUTs by using encodings

AES with look-up tables: example, Chow

- The key addition and S-box operations are merged into a single operation (8 bit $\rightarrow 8$ bit table $\rightarrow 256$ byte)

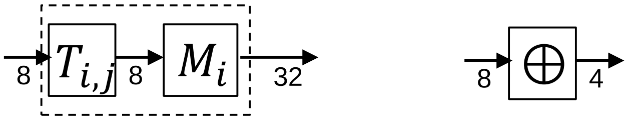
$$b_{i,j} = Sbox(a_{i,j} \oplus k_{i,j}) = T_{i,j}(a_{i,j})$$

- To simplify: we omit ShiftRow operation
  - Corresponds to renumbering of indices

- The MixColumn operation can be split into four byte-to-32-bit (8 bit $\rightarrow 32$ bit table $\rightarrow 1024$ byte) operations:

$$c_j = M_0 T_{0,j}(a_{0,j}) \oplus M_1 T_{1,j}(a_{1,j}) \oplus M_2 T_{2,j}(a_{2,j}) \oplus M_3 T_{3,j}(a_{3,j})$$

- We can now implement a round by only using the following 2 types of lookup tables:



AES (Chow) with look-up tables + obfuscation

- Since S-boxes and matrix M are known, the key can easily be extracted from the lookup tables.
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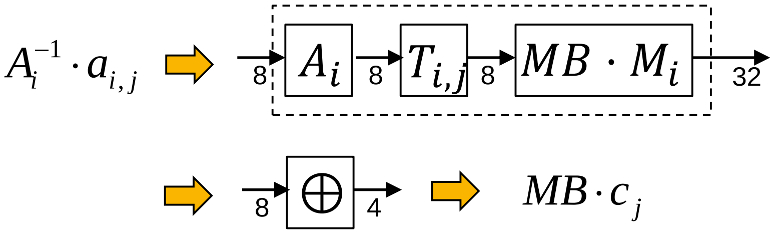
  - A_i: random 8-bit linear mapping
  - MB: random 32-bit linear mapping



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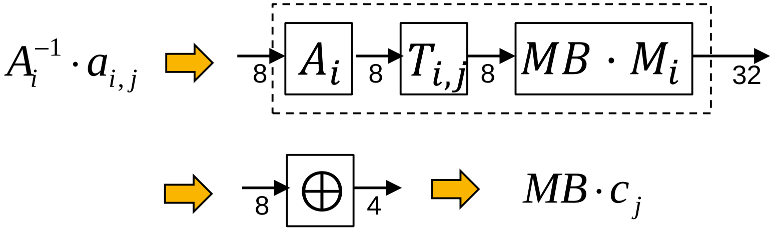


- Matrix MB is removed from the computed output columns.
  Implemented in the same way as the MixColumn operations

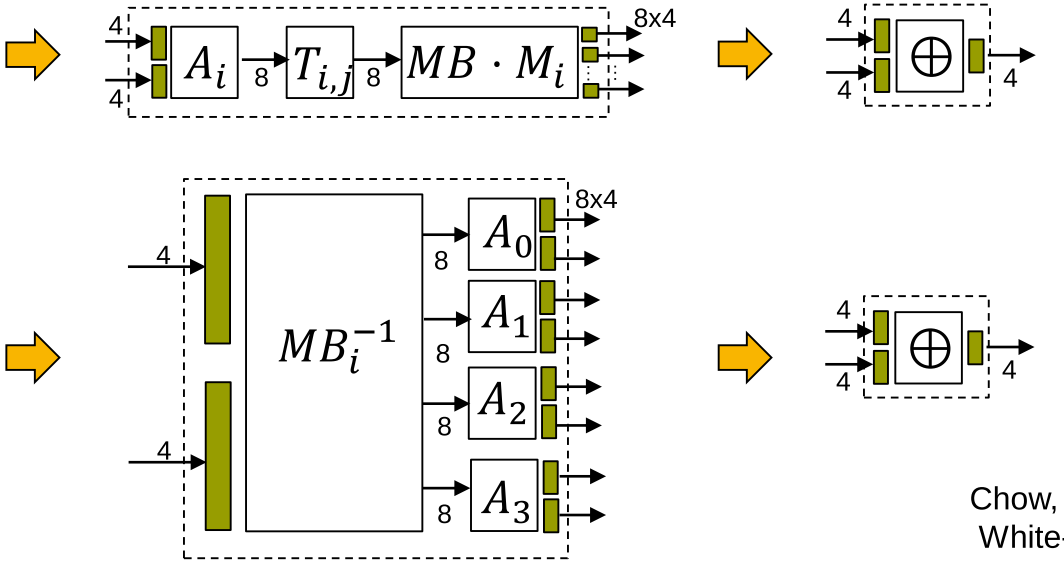
$$MB^{-1}(x) = MB_0^{-1}(x_0) \oplus MB_1^{-1}(x_1) \oplus MB_2^{-1}(x_2) \oplus MB_3^{-1}(x_3)$$

- Merge the MB_i-tables by the linear encodings used in the next round.

Obfuscation, obfuscation, obfuscation

- In addition to the *linear* encodings, also add **non-linear** encodings f.

$(f_{0,i}, f_{1,i})A_i^{-1} \cdot a_{i,j}$

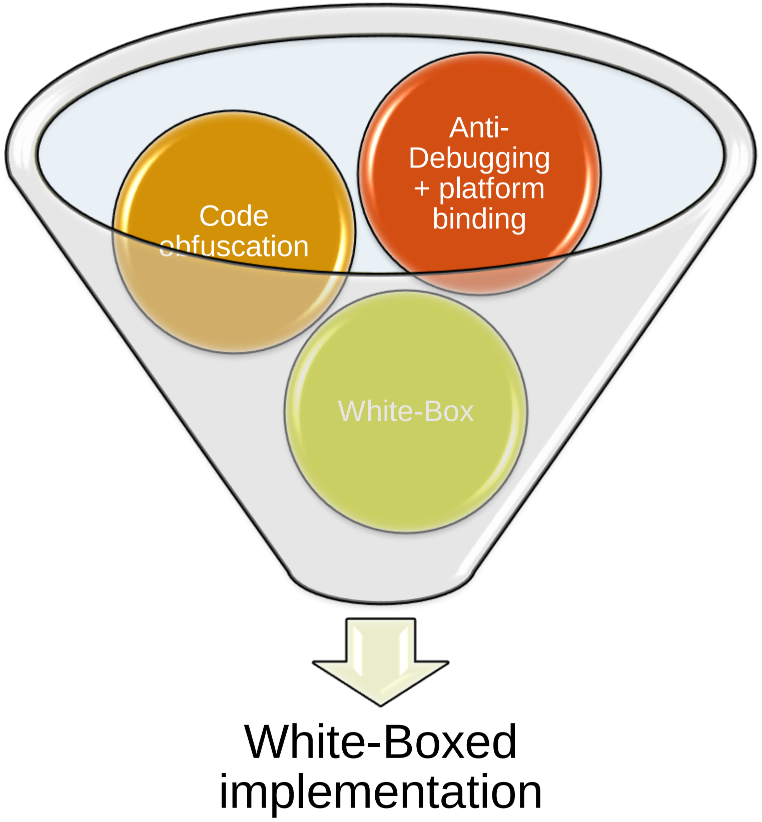


$(f_{0,i}, f_{1,i})A_i^{-1} \cdot c_{i,j}$

Chow, Eisen, Johnson, van Oorschot. White-box cryptography and an AES implementation. In SAC 2002.

Size of implementation: $\approx$ 700 kB

White box crypto - practice



In practice the white box is the most essential but a **small part** of the entire software implementation

- Strong code obfuscation
- Binary is “glued” to the environment
  - Prevent code-lifting
- Support for traitor tracing
- Mechanism for frequent updating

More details see the invited talk at EC 2016 *Engineering Code Obfuscation* by Christian Collberg

Effort and expertise required

Previous effort

Previous WB attacks were WB specific which means knowing

- the *encodings*
- which *cipher operations* are implemented by
- which (network of) *lookup tables*

Attack

1. time-consuming reverse-engineering of the code
2. identify which WB scheme is used + target the correct LUTs
3. apply an algebraic attack

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Our approach

Assess the security of a WB implementation

✓ Automatically and very simply (see CHES challenge)

✓ Without knowledge of any implementation choices

→ only the algorithm itself

✓ Ignores all (attempts) at code-obfuscation

Tracing binaries

- Academic attacks are on open design
- In practice: what you get is a binary blob

Idea: create software traces using *dynamic binary instrumentation* tools

(→ visual representation → use traces to find correlation)

- Record all instructions and memory accesses.

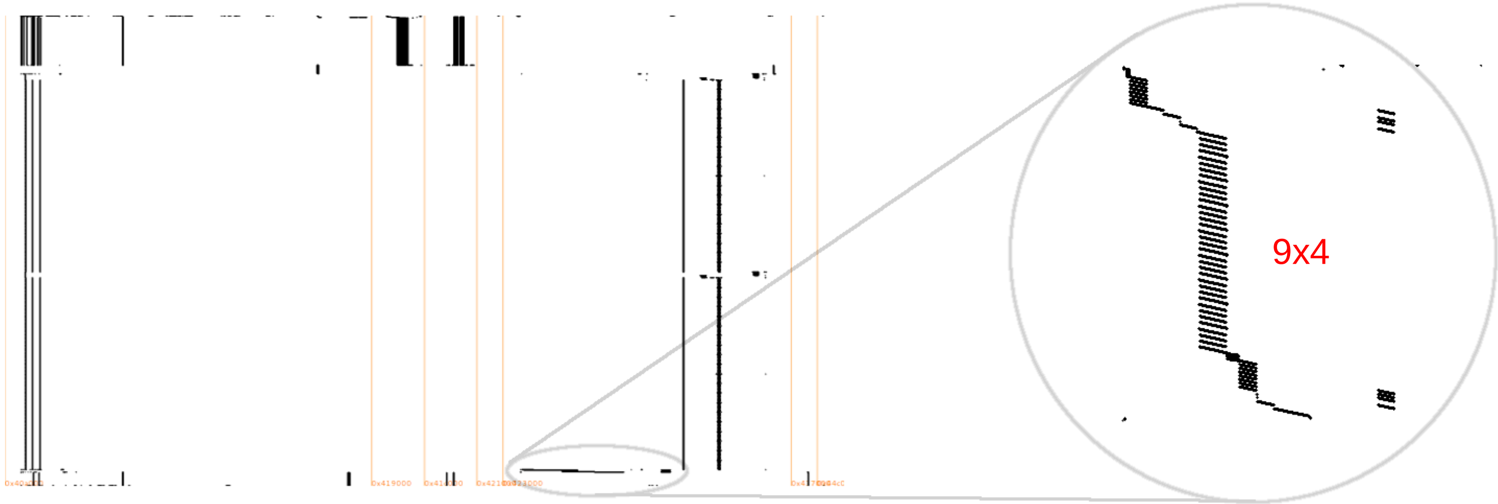
Examples of the tools we extended / modified

- Intel PIN (x86, x86-64, Linux, Windows, Wine/Linux)
- Valgrind (idem+ARM, Android)

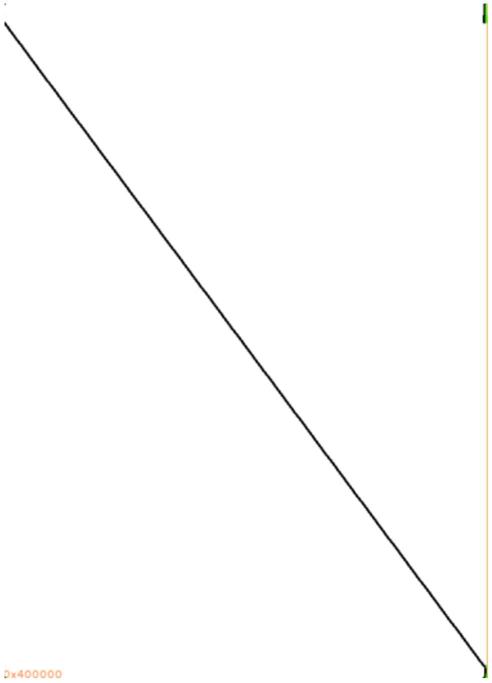
Trace visualization

Based on Ptra, an unreleased Quarkslab tool presented at SSTIC 2014

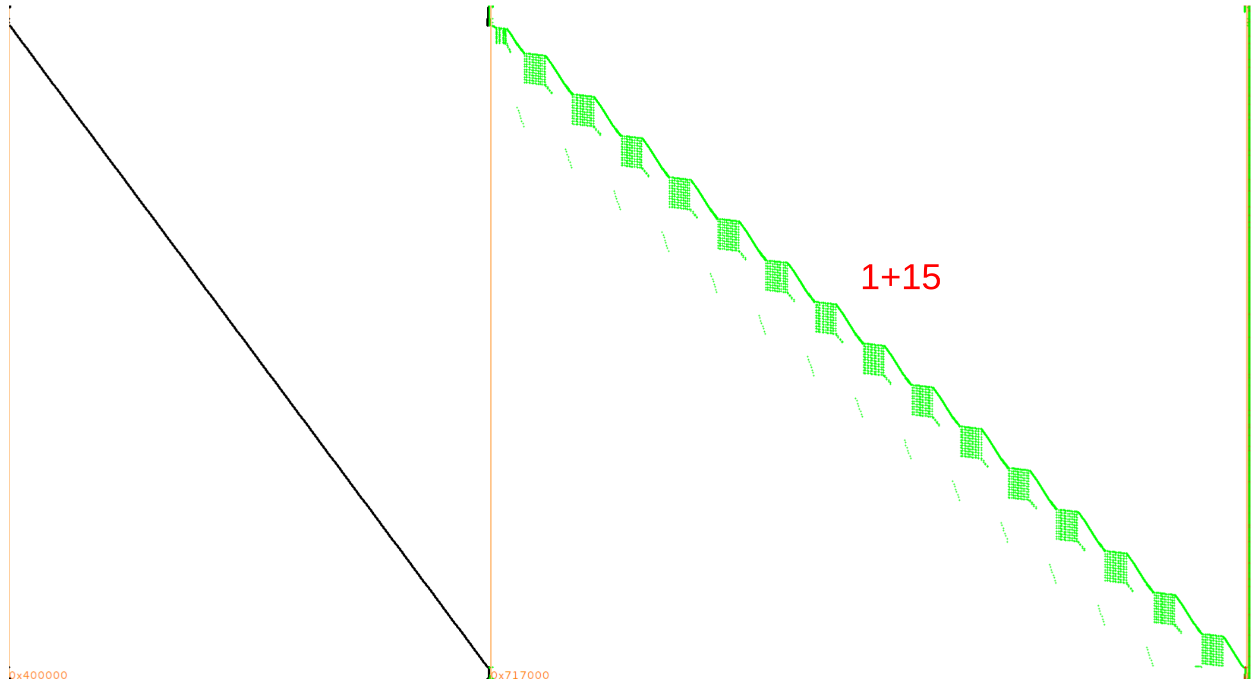
Visual crypto identification: code



Visual crypto identification: code?



Visual crypto identification: code? data!



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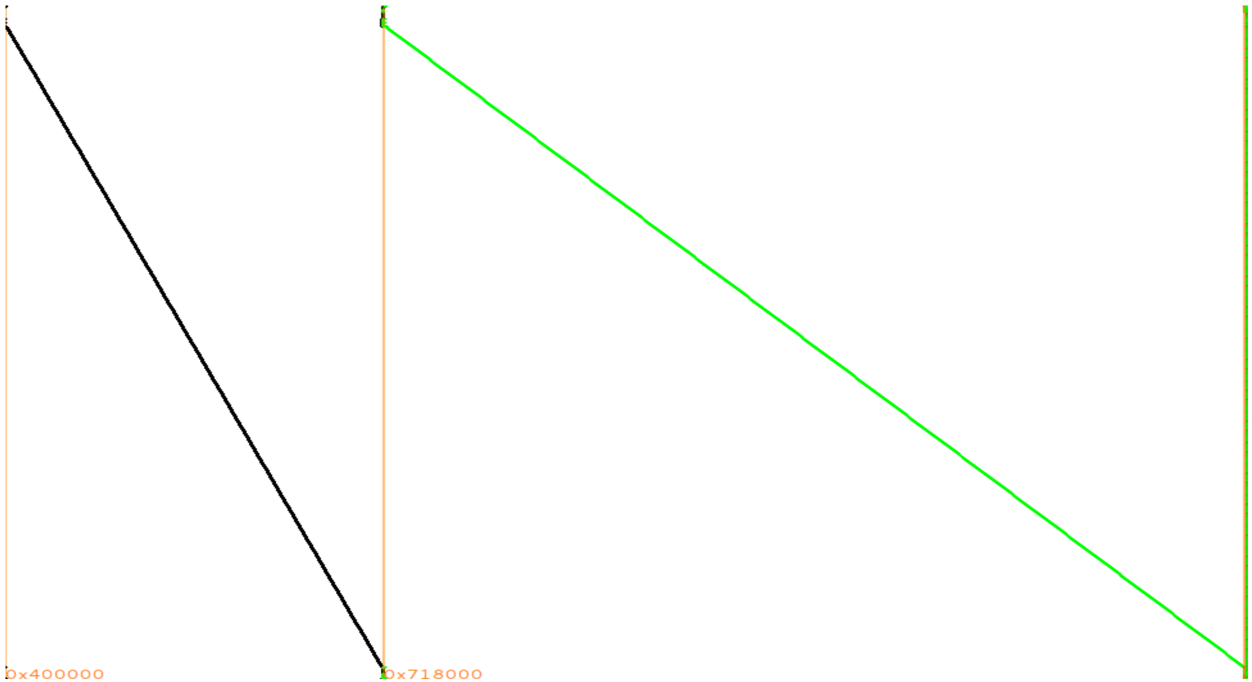
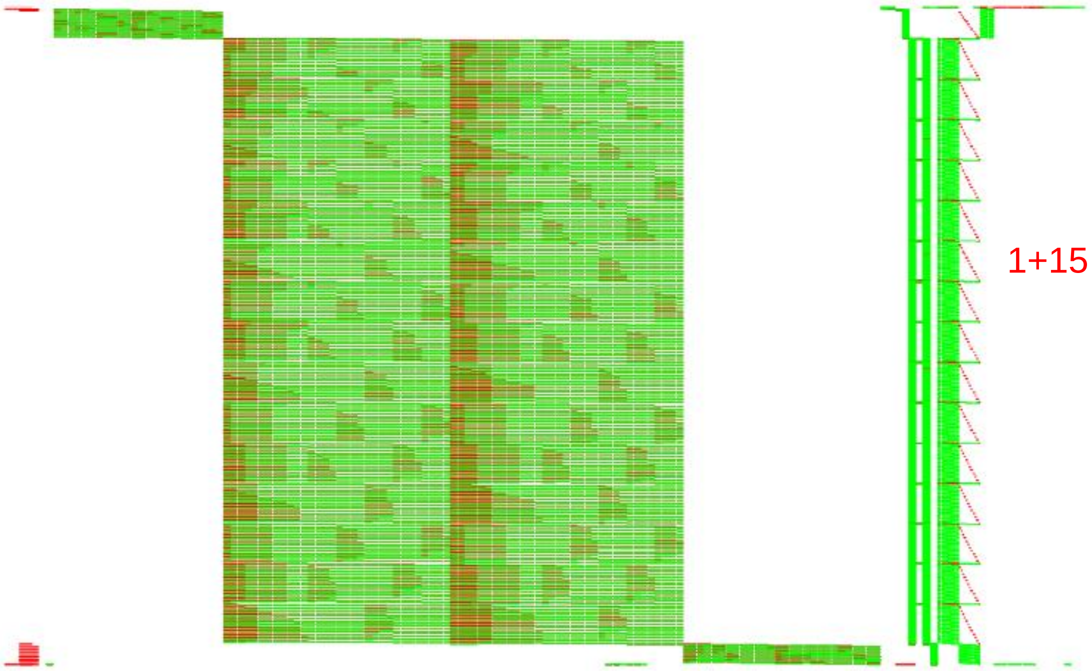


Visual crypto identification: stack!



Differential Power Analysis and friends

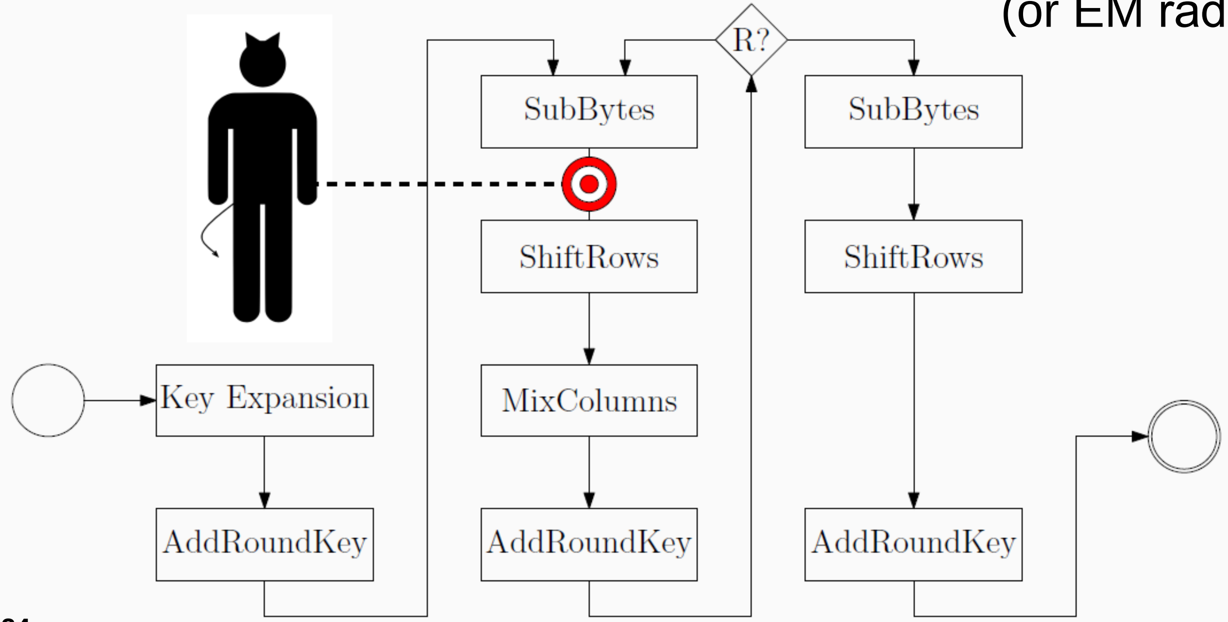
P. C. Kocher, J. Jaffe, and B. Jun: *Differential power analysis*. CRYPTO'99

Very powerful grey box attack!

Requirements

- known input or known output
- ability to trace power consumption (or EM radiations, or …)

For example in AES: $SubBytes(p \oplus \kappa)$



Differential Computation Analysis

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

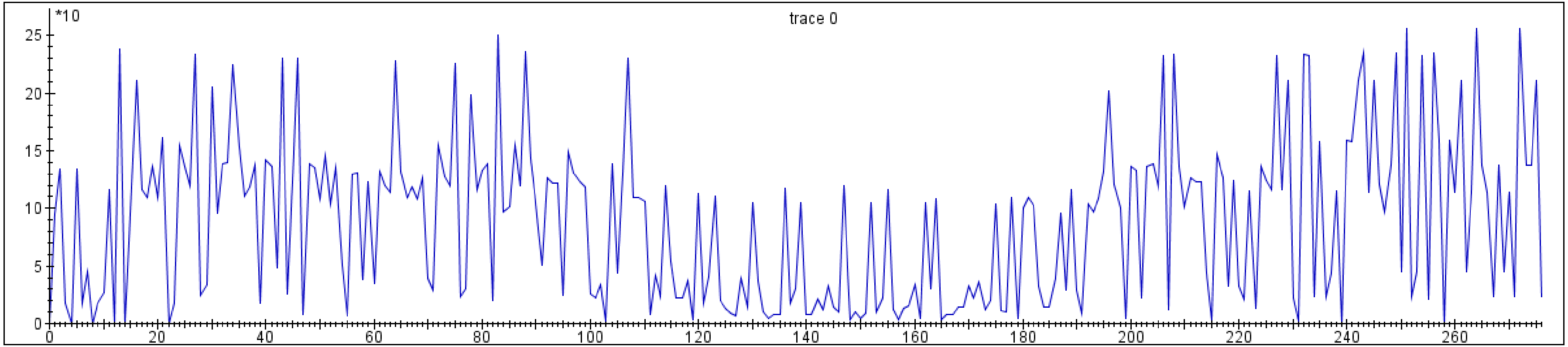
Differential Computation Analysis

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

Make pseudo power traces from our software execution traces

→ this are lists of memory accesses / data + stack writes / …

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

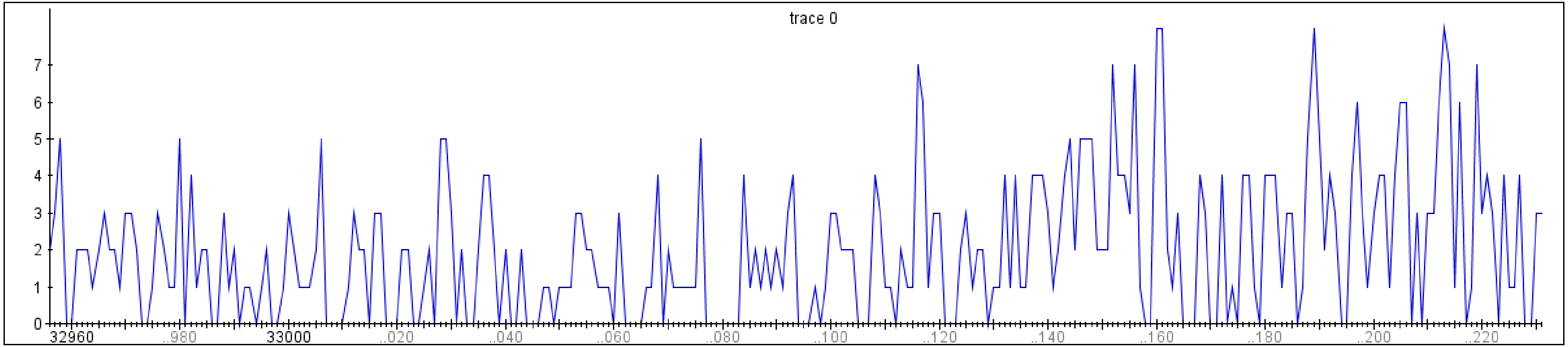


→ 256 possible discrete values

Differential Computation Analysis

256 possible discrete values but bit values dominated by the MSB

→ Build Hamming weight traces?



→ 8 possible discrete values

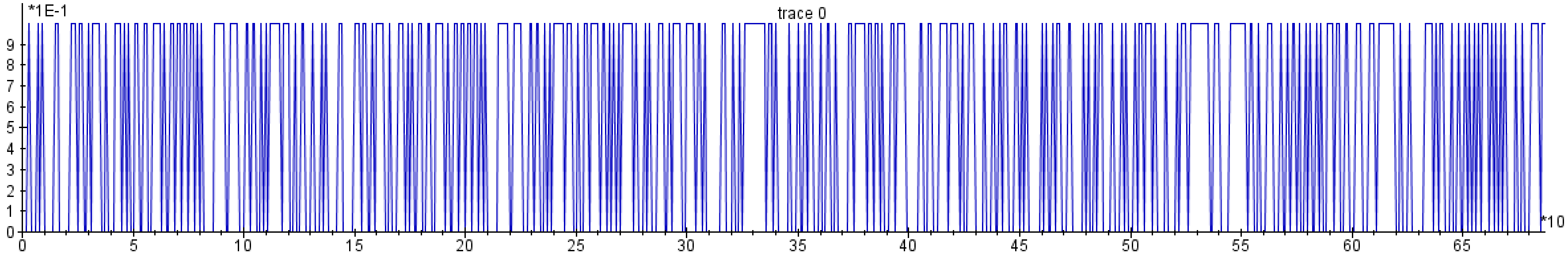
That works but we can do better…

recall: Hamming weight was a **hardware model** for combined bit leaks

Differential Computation Analysis

Each bit of those bytes is equally important
address bits represent a different way to partition the look-up tables

→ Serialize bytes in a succession of bits



→ 2 possible discrete values: 0's and 1's

DCA: DPA on software traces

HW analogy: this is like probing each bus-line individually ***without any error***

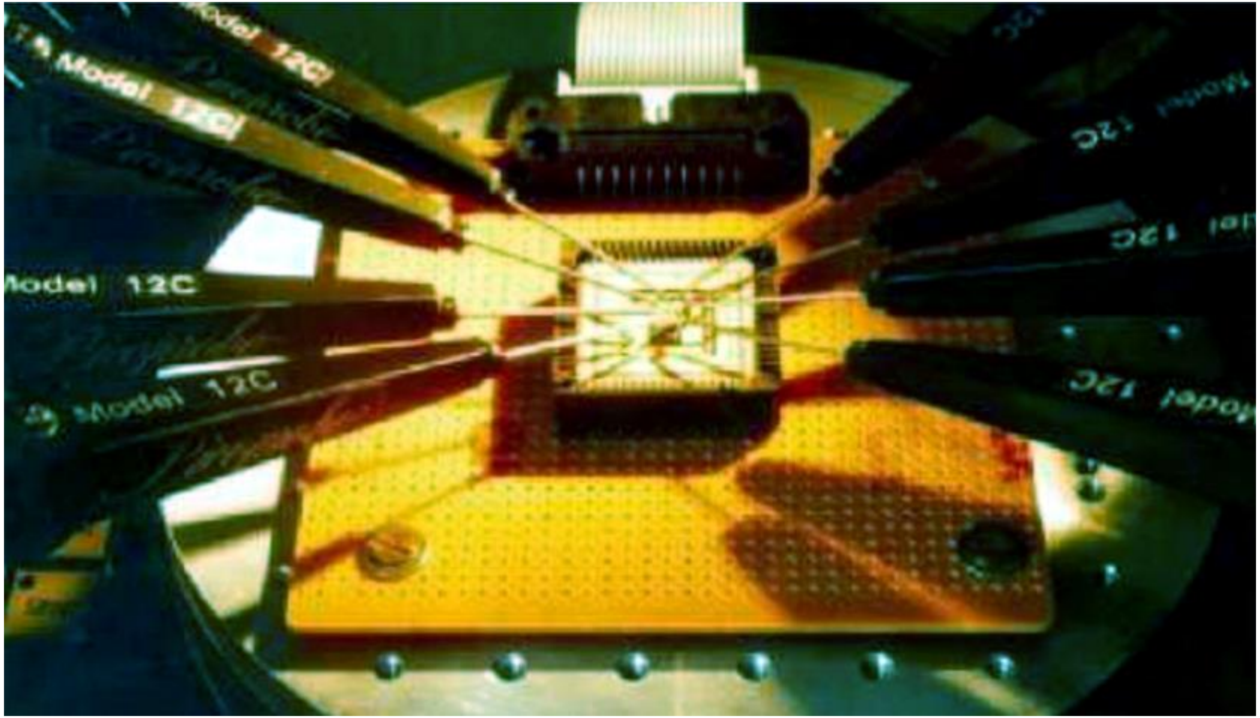


Image source: Brightsight

Results

WB implementations should not leak any side-channel information (by definition of the WB attack model): let's check!

WB implementation	Algorithm	#traces
Wyseur challenge, 2007	DES (Chow+)	65
Hack.lu challenge, 2009	AES (Chow)	16 (no encodings)
SSTIC challenge, 2012	DES	16 (no encodings)
Klinec implementation, 2013	AES (Karroumi, dual ciphers)	2000 → 500

Intuition why this works:
Encodings do not sufficiently hide correlations when the correct key is used.

See also: P. Sasdrich, A. Moradi, and T. Güneysu. White-box cryptography in the gray box - a hardware implementation and its side channels. In FSE 2016.

Countermeasures?

Academic remedies

- Cannot rely on random data in the white-box attack model
- Use static random data within the white-box itself?
- DCA might fail when using large encodings → either impractically large tables or simplified schemes → easy to break with algebraic attacks
- Use ideas from threshold implementation?
  - masking scheme based on secret sharing and multi-party computation

    S. Nikova, C. Rechberger, and V. Rijmen. Threshold implementations against side-channel attacks and glitches. In Information and Communications Security, 2006.

Practical remedy

- strengthen other measures
  - anti-debug / detect DBI frameworks, code-obfuscation (?), integrity checks, platform binding, etc

Side-Channel Marvels

SCA-related projects

https://github.com/SideChannelMarvels

Any help to complete our collection of open whitebox challenges and attacks or to improve our tools is highly appreciated!

Deadpool — C ★ 25 ⑂ 6

Repository of various public white-box cryptographic implementations and their practical attacks.

Updated 10 days ago

Tracer — C++ ★ 25 ⑂ 7

Set of Dynamic Binary Instrumentation and visualization tools for execution traces.

Updated on Apr 24

JeanGrey — Python ★ 0 ⑂ 0

A tool to perform differential fault analysis attacks (DFA).

Updated on Apr 18

Orka — ★ 4 ⑂ 1

Repository of the official Docker image for SideChannelMarvels.

Updated on Apr 14

Daredevil — C++ ★ 10 ⑂ 4

A tool to perform (higher-order) correlation power analysis attacks (CPA).

Updated on Apr 11

Conclusions and future work

- Software-only solutions are becoming more popular
  - white-box crypto
- Besides traditional (DRM) also other use-cases (HCE) such as payment, transit, …
- Level of security / maturity of many (all?) WB schemes is questionable
  - Open problem to construct asymmetric WB crypto
  - Industry keeps design secret
- DCA is an *automated* attack (no expertise needed!)
  - Counterpart of the SCA from the crypto HW community
- What if DCA fails, can we do better? What about software FA, CPA, higher-order attacks etc?
  - **See the next presentation!**
    Riscure was the first show DFA works as well, see our online repo for an implementation

References

- Joppe W. Bos, Charles Hubain, Wil Michiels, and Philippe Teuwen: *Differential Computation Analysis: Hiding your White-Box Designs is Not Enough*. CHES 2016.
- Eloi Sanfelix Gonzalez, Cristofaro Mune, Job de Haas: *Unboxing the White-Box: Practical Attacks Against Obfuscated Ciphers*. Black Hat Europe 2015.

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