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[pietska]

Reverse engineering black-box elliptic curve cryptography via side-channel analysis

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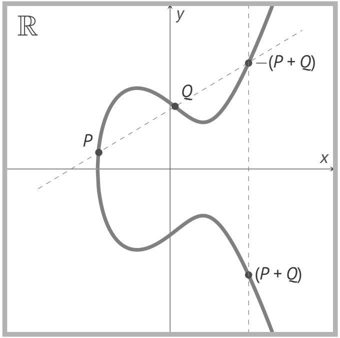
Outline

- Why?
  - Elliptic Curve Cryptography
  - Side-Channel Attacks
- RQ1: Real-world ECC implementations
- RQ2: Space of possible ECC implementations
- RQ3: Reverse-engineering ECC implementations
- Conclusions

Why?

Elliptic Curve Cryptography

- **Elliptic Curve**: $y^2 \equiv x^3 + ax + b$
  - Points $(x, y) \in E(\mathbb{K})$ form an abelian group
  - Scalar multiplication
    $[n] : E(\mathbb{K}) \to E(\mathbb{K})$
    $P \mapsto [n]P = \underbrace{P + P + \ldots + P}_{n \text{ times}}$
  - ECDLP: Find x given $[x]G$ and $G \in E(\mathbb{F}_p)$
    Generally hard when $\mathbb{K} = \mathbb{F}_p$



Short Weierstrass

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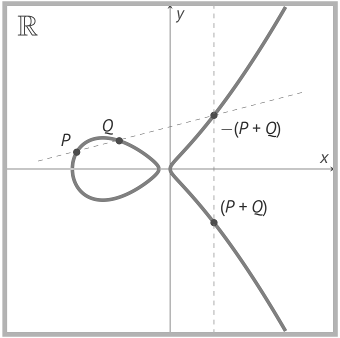

Montgomery

Why?

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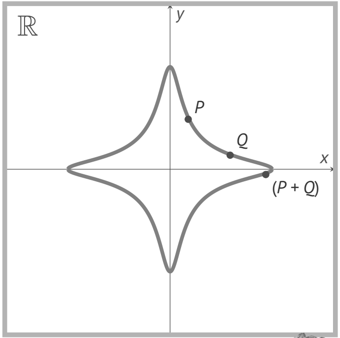

Edwards

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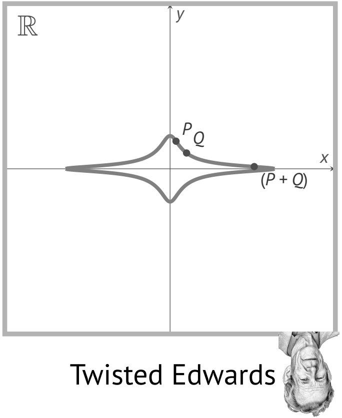

Twisted Edwards

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- **XDH**, **EdDSA**, **...**

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    - (X, Y, Z)
    - $(X, Y, Z, ZZ) \ldots$

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```
Y1Z2 = Y1*Z2
X1Z2 = X1*Z2
Z1Z2 = Z1*Z2
u = Y2*Z1-Y1Z2
uu = u2
v = X2*Z1-X1Z2
vv = v2
vvv = v*vv
R = vv*X1Z2
A = uu*Z1Z2-vvv-2*R
X3 = v*A
Y3 = u*(R-A)-vvv*Y1Z2
Z3 = vvv*Z1Z2
```

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```
U1 = X1*Z2
U2 = X2*Z1
S1 = Y1*Z2
S2 = Y2*Z1
ZZ = Z1*Z2
T = U1+U2
M = S1+S2
R = T2-U1*U2+a*ZZ2
F = ZZ*M
L = M*F
G = T*L
W = R2-G
X3 = 2*F*W
Y3 = R*(G-2*W)-L^2
Z3 = 2*F*F2
```

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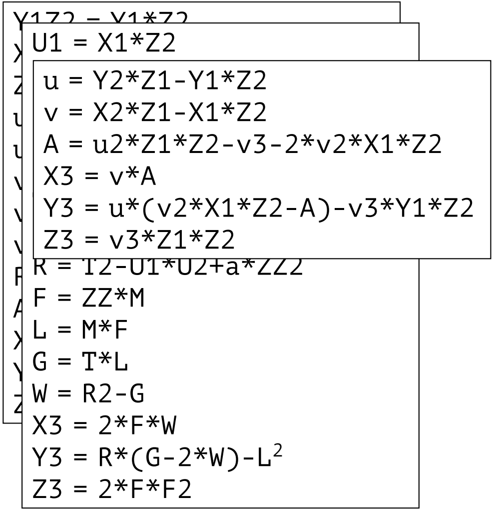

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    - *fixed-base*, *variale-base*, *multi-scalar*

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Algorithm Left-to-right double-and-add

```
function LTR(G, k = (k_l, ..., k_0)_2)
    R = O
    for i = l downto 0 do
        R = dbl(R)
        if k_i = 1 then
            R = add(R, G)
    return R
```

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Algorithm Fixed-window scalar multiplier

function Window($G, k = (k_l, \ldots, k_0)_2$)
  $PrecomuptedTable = [0 * G, 1 * G, \ldots, 2^w - 1 * G]$
  $\hat{k}$ = recode k to w-bit windows
  $T = \mathcal{O}$
  for $i = 1$ **to** $|\hat{k}|$ **do**
    $T = 2^w T$
    $T = T + PrecomputedTable[\hat{k}_i]$
  return T

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    - Reduction: *Barret, Montgomery, …*
    - Inversion: *GCD, Euler*

Why?

Side-Channel Attacks

- Simple Power Analysis
- Differential Power Analysis
- Correlation Power Analysis
- Mutual Information Analysis
- Refined Power Analysis, Zero-value Point Attack, Exceptional Procedure Attack
- Template attacks
- Leakage assessment
- Doubling attack, Collision attacks
- ...

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Why?

Assumptions

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$\mathbb{F}_p$ with $p \neq \{2, 3\}$. The algorithm used for the hardware modular multiplication is assumed to be known to the attacker. Moreover, to simplify the attack

[1] Aurélie Bauer, Eliane Jaulmes, Emmanuel Prouff, Jean-René Reinhard & Justine Wild: Horizontal Collision Correlation Attack on Elliptic Curves

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input to s (“fix class”). (This assumes a white-box evaluator that has access to implementation internals.)

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[2] Oscar Reparaz, Josep Balasch & Ingrid Verbauwhed: Dude, is my code constant time?

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e 6.1 abstractly depicts a side-channel measurement of such an ex-
tion. For the sake of simplicity, I assume it is a binary exponen-

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[3] Johann Heyszl: Impact of Localized Electromagnetic Field Measurements on Implementations of Asymmetric Cryptography

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values may be manipulated when working with points P and $2P$. However this idea only works when using the downward routine.

[4] Pierre-Alain Fouque & Frederic Valette: The Doubling Attack – Why Upwards Is Better than Downwards

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a doubling operation from an addition one. This technique, which allows to eventually recover the secret scalar, is applied to three different atomic formulae on elliptic curves,

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[5] Bo-Yeon Sim & Dong-Guk Han: Key Bit-Dependent Attack on Protected PKC Using a Single Trace

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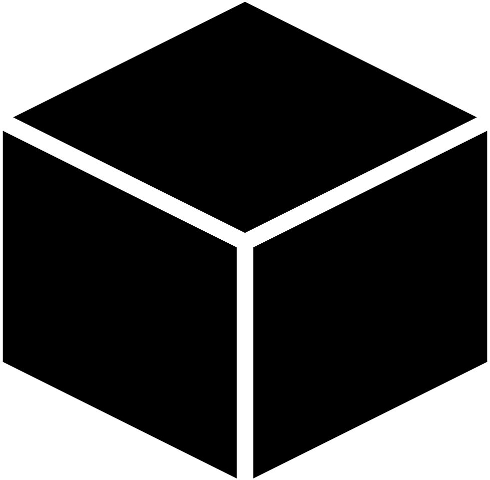
Lots of assumptions you've got there!

Why?

Reality



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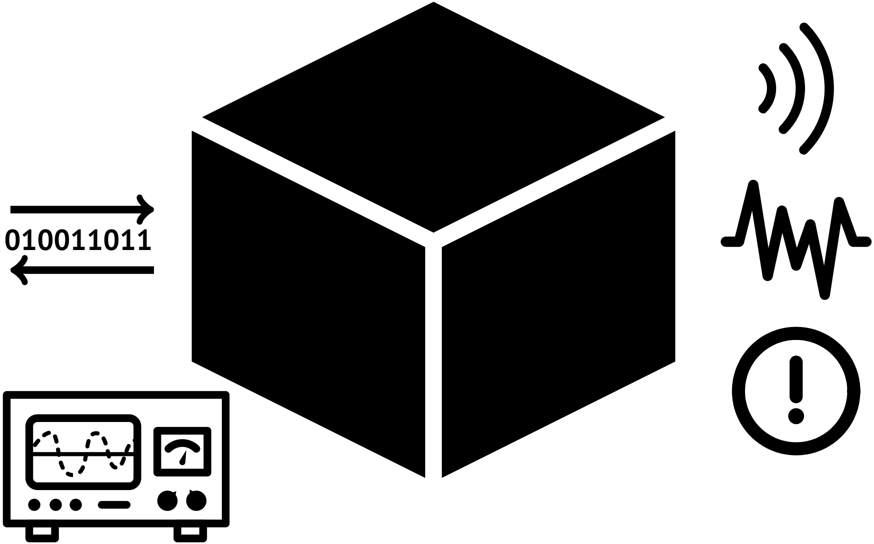

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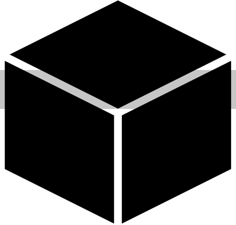

- Real-world cryptographic hardware is usually a black-box
  - TPMs, HSMs, smartcards, ...
- Why?
  - Security by obscurity
  - Certifications encourage information hiding (CC, JIL-SCA)
- Contrast to cryptographic theory space
  - Kerckhoffs's principle
  - Open design, open discussion

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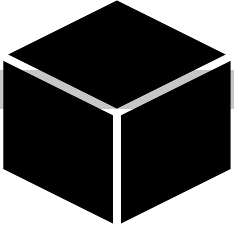

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Auguste Kerckhoffs

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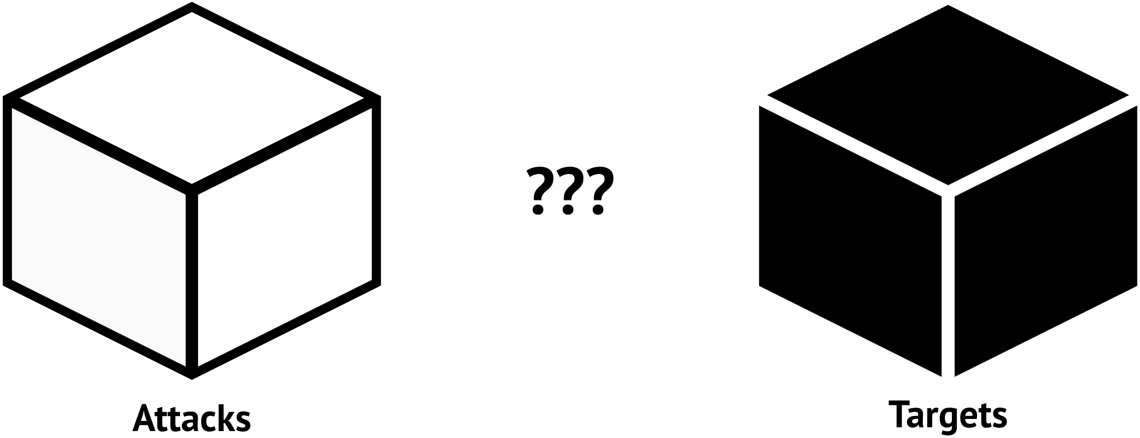
Gap



RQ1:
What implementation choices are used in real-world open-source ECC libraries?

RQ2:
How large is the space of all possible ECC implementations?

RQ3:
Is it possible to automatically reverse-engineer black-box ECC implementations?

RQ1

What implementation choices are used in real-world open-source ECC libraries?

- Analyzed 18 open-source ECC libraries ( )
- *BearSSL, BoringSSL, Botan, BouncyCastle, fastecdsa, Go crypto, Intel IPP cryptography, libgcrypt, LibreSSL, libsecp256k1, libtomcrypt, mbedTLS, micro-ecc, Nettle, NSS, OpenSSL, SunEC,* and *Microsoft SymCrypt*

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- Full report: https://pyecsca.org/libraries.html

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- **Addition formulas**
  - 112 formula implementations
  - 50 “*standard*” (EFD)
  - 23 out-of-scope
  - 39 “*non-standard*”
  - → Expanded standard formulas from ~200 to ~20000

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Wide range of implementation choices in real-world implementations.

↓

Expect also in black-box implementations.

RQ2

How large is the space of all possible ECC implementations?

- We can enumerate:
  - Curve model
  - Coordinate system
  - Addition formulas
  - Scalar multiplier
  - Misc. options

RQ2

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- Total: 139 489

Curve	Coords	#	Total
$\mathcal{E}_{\mathrm{SW}}$	jacobian	17 136	113 502
	jacobian-0	22 848	
	jacobian-3	28 560	
	modified	2 856	
	projective	9 520	
	projective-1	10 710	
	projective-3	16 660	
	w12-0	476	
	xyzz	1 428	
	xyzz-3	2 856	
	xz	452	
$\mathcal{E}_{\mathrm{M}}$	xz	132	132
$\mathcal{E}_{\mathrm{E}}$	inverted	2 856	14 431
	projective	11 424	
	yz	99	
	yzsquared	52	
$\mathcal{E}_{\mathrm{TE}}$	extended	2 856	11 424
	extended-1	5 712	
	inverted	1 428	
	projective	1 428	

RQ2

How large is the space of all possible ECC implementations?

- We can enumerate:
  - Curve model
  - Coordinate system
  - Addition formulas
  - Scalar multiplier
  - Misc. options
- Total: 139 489

Scalar multiplier	**#**
LTR	9 328
RTL	9 328
Coron	1 166
Ladder	407
SimpleLadder	2 332
DiffLadder	328
BinaryNAF	4 664
WindowNAF	18 656
WindowBooth	18 656
Window	9 328
SlidingWindow	18 656
FullPrecomp	18 656
Comb	9 328
BGMW	18 656

RQ2

How large is the space of all possible ECC implementations?

- We can enumerate:
  - Curve model
  - Coordinate system
  - Addition formulas
  - Scalar multiplier
  - Misc. options
- Total: 139 489

Considerable number of implementation configurations: 139 489.

↓

Worth reverse engineering.

RQ3

Is it possible to automatically reverse-engineer black-box ECC implementations?

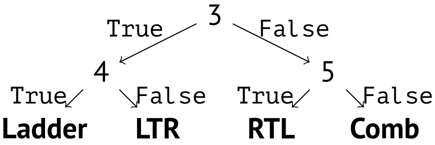
- **Idea:** Use side-channel attacks and turn them around
  - ~~Assume knowledge of the impl. and target the key~~
  - Assume knowledge of the key and target the impl.
- Concretely *"special-point-based"* attacks: **RPA, ZVP, EPA**
- Can recognize when a special point appears in scalar multiplication
- **Idea:** Behavior of different implementations differs under these attacks

RQ3

Is it possible to automatically reverse-engineer black-box ECC implementations?

- Simulate behavior of implementations under the oracle (attack)
  - **RPA**: Is $[r]P$ computed during $[k]P$ computation by the target?
- Build a decision table with the answers
- Build a decision tree, recursively picking the best split

$\mathcal{I}_{\mathsf{RPA}}$:	$[2^{-1}]P_0$	$[3^{-1}]P_0$	$[4^{-1}]P_0$	$[5^{-1}]P_0$
LTR	True	True	False	False
RTL	True	False	True	True
Comb	True	False	True	False
Ladder	True	True	True	False
…		…		



RQ3

Is it possible to automatically reverse-engineer black-box ECC implementations?

- Simulate behavior of implementations under the oracle (attack)
  - **RPA**: Is $[r]P$ computed during $[k]P$ computation by the target?
- Build a decision table with the answers
- Build a decision tree, recursively picking the best split

Method	Curve	Coordinates	Formulas	Multiplier	Scalar	Input point
RPA-RE	chosen	any	any	**target**	known	chosen
ZVP-RE	chosen	**target**	**target**	known	known	chosen
EPA-RE	chosen	**target**	**target**	known	known	chosen

RQ3

Is it possible to automatically reverse-engineer black-box ECC implementations?

- Implemented in the **pyecsca** toolkit
- It works!

				Expected		**Random**	
Method	**Oracle**	$\lvert\mathcal{C}\rvert$	# 🍃	|🍃|	🍃↕	|🍃|	🍃↕
RPA-RE	binary	34	34	1.0	5.0	1.0	5.0
ZVP-RE	binary	214	74	8.7	5.1	5.0	4.0
ZVP-RE	count	214	134	2.4	4.0	1.3	2.5
ZVP-RE	position	214	196	1.2	2.1	1.1	1.8

RQ3

Is it possible to automatically reverse-engineer black-box ECC implementations?

- Implemented in the **pyecsca** toolkit
- It works!

Method	Oracle	$\lvert\mathcal{C}\rvert$	# 🍃	Expected $\lvert$🍃$\rvert$	Expected 🍃↕	Random $\lvert$🍃$\rvert$	Random 🍃↕
RPA-RE	binary	34	34	1.0	5.0	1.0	5.0
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ZVP-RE	count	214	134	2.4	4.0	1.3	2.5
ZVP-RE	position	214	196	1.2	2.1	1.1	1.8

Yes, it is possible.

. . . and much more

pyecsca

pyecsca.org

Python **E**lliptic **C**urve **S**ide **C**hannel **A**nalysis toolkit

- Can enumerate configurations
- Can simulate computation given any configuration
- Can generate C implementations of ECC for micro-processors
- Can perform power and EM-tracing
- Can process collected traces and visualize them
- Can perform known attacks against ECC
- **Can be used to reverse engineer ECC**

Conclusions

- Documented large variety of implementation choices in 18 open-source ECC libraries
  - **Expect similar variety in black-box devices**
- Explored the space of possible implementation choices of ECC
  - **Considerable number of choices, necessary knowledge for an attack**
- Presented several novel attack-based reverse-engineering methods for ECC
  - **Demonstrated effectivenes on two simulation levels**

- Explore our tutorial:

github.com/J08nY/pyecsca-tutorial-ches2024 pyecsca

[pietska]

Reverse engineering black-box elliptic curve cryptography via side-channel analysis

Jan Jancar, Vojtech Suchanek, Petr Svenda, Vladimir Sedlacek, Łukasz Chmielewski

Questions?

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jan@neuromancer.sk

References

- Jan Jancar, Vojtech Suchanek, Petr Svenda, Vladimir Sedlacek & Łukasz Chmielewski;
  pyecsca: Reverse-engineering black-box elliptic curve cryptography via side-channel analysis

References (cont.)

Attack assumptions

1. Aurélie Bauer, Eliane Jaulmes, Emmanuel Prouff, Jean-René Reinhard & Justine Wild: Horizontal Collision Correlation Attack on Elliptic Curves
2. Oscar Reparaz, Josep Balasch & Ingrid Verbauwhed: Dude, is my code constant time?
3. Johann Heyszl: Impact of Localized Electromagnetic Field Measurements on Implementations of Asymmetric Cryptography
4. Pierre-Alain Fouque & Frederic Valette: The Doubling Attack – Why Upwards Is Better than Downwards
5. Bo-Yeon Sim & Dong-Guk Han: Key Bit-Dependent Attack on Protected PKC Using a Single Trace
6. Jean-Luc Danger, Sylvain Guilley, Philippe Hoogvorst, Cédric Murdica & David Naccache: A synthesis of side-channel attacks on elliptic curve cryptography in smart-cards

Other

- https://hyperelliptic.org/EFD/
- Icons from **Noun Project** & **Font Awesome**

References (cont.)

ECC attack and countermeasure surveys

- Junfeng Fan, Xu Guo, Elke De Mulder, Patrick Schaumont, Bart Preneel & Ingrid Verbauwhede; State-of-the-art of secure ECC implementations: A survey on known side-channel attacks and countermeasures
- Junfeng Fan & Ingrid Verbauwhede; An updated survey on secure ECC implementations: Attacks, countermeasures and cost
- Jean-Luc Danger, Sylvain Guilley, Philippe Hoogvorst, Cédric Murdica & David Naccache; A synthesis of side-channel attacks on elliptic curve cryptography in smart-cards
- Rodrigo Abarzúa, Claudio Valencia Cordero & Julio Cesar López-Hernández; Survey on performance and security problems of countermeasures for passive side-channel attacks on ECC

References (cont.)

Special-point-based attacks

- Louis Goubin; A Refined Power-Analysis Attack on Elliptic Curve Cryptosystems
- Toru Akishita, Tsuyoshi Takagi; Zero-value point attacks on elliptic curve cryptosystem
- Tetsuya Izu, Tsuyoshi Takagi; Exceptional procedure attack on elliptic curve cryptosystems
- Vladimir Sedlacek, Jesús-Javier Chi-Domínguez, Jan Jancar, Billy Bob Brumley;
  A formula for disaster: a unified approach to elliptic curve special-point-based attacks

References (cont.)

Side-channel-based disassembly

- Jean-Jacques Quisquater & David Samyde;
  Automatic code recognition for smart cards using a Kohonen neural network
- Dennis Vermoen, Marc F. Witteman & Georgi Gaydadjiev;
  Reverse engineering Java Card applets using power analysis
- Thomas Eisenbarth, Christof Paar & Björn Weghenkel;
  Building a side channel based disassembler
- ...and much more (see the paper)

References (cont.)

Side-channel-based reverse engineering

- Christophe Clavier;
  Side channel analysis for reverse engineering (SCARE) – an improved attack against a secret A3/A8 GSM algorithm
- Rémy Daudigny, Hervé Ledig, Frédéric Muller & Frédéric Valette;
  SCARE of the DES
- Manuel San Pedro, Mate Soos & Sylvain Guilley;
  FIRE: Fault injection for reverse engineering
- Frederic Amiel, Benoit Feix & Karine Villegas;
  Power analysis for secret recovering and reverse engineering of public key algorithms
- ...and some more (see the paper)

References (cont.)

Manual reverse engineering

- Thomas Roche, Victor Lomné, Camille Mutschler & Laurent Imbert;
  A Side Journey to Titan
- Thomas Roche;
  EUCLEAK: Side-Channel Attack on the YubiKey 5 Series