Kerckhoff's Principle in Practice: Addressing Security by Obscurity in Secure Hardware

Jan Jancar[1*] Vojtech Suchanek[1*] Jan Kvapil[1]
Petr Svenda[1] Vladimir Sedlacek[2] Łukasz Chmielewski[1]
+ Thanks to Thomas Roche.

CROCS [1]
RUTGERS UNIVERSITY [2]

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Secure hardware

- Smartcards, TPMs, HSMs, U2F tokens, secure elements, …
  - All share hardware/firmware components

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  - Underlying platform for many devices
- **Very secretive**
  - NDAs, hard to obtain samples, no docs

Verifying security

- How can **you** verify security of secure hardware?
  - It's in the name, duh …

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- Secure hardware
  - Be a big fish, sign NDAs, do your own analysis
  - Trust the vendor
  - Security certifications

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Cryptographic theory (primitive & protocol) • Open design • Public review, competitions • Proofs (machine-checked!)	**Rarely fails**
Open-source cryptographic implementations • Public review • Audits • Formal verification	**Vulnerabilities**
Secure hardware • Be a big fish, sign NDAs, do your own analysis • Trust the vendor • Security certifications	**Here be dragons**

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  - Independent lab evaluates

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- **Certifications reward secrecy**
  - *Attack Potential*
  - Non-public information required -> higher score
  - Samples required -> higher score

Vulnerabilities

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  - Factorable RSA keys

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- **EUCLEAK** (2024)
  - Key recovery from EM leakage in ECDSA signing
- All affected certified devices
- All very hard to patch in practice
- Most required recovering non-public information

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
- …

Side-channel attacks

is assumed to be known

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

Side-channel attacks

assumes a white-box evaluator

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

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

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

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attack on the Montgomery-López-Dahab ladder algorithm

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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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[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

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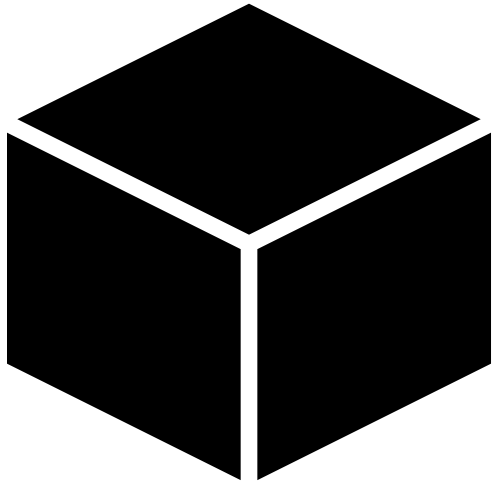
Lots of assumptions!

Reality and the gap

(Kool and the gang)



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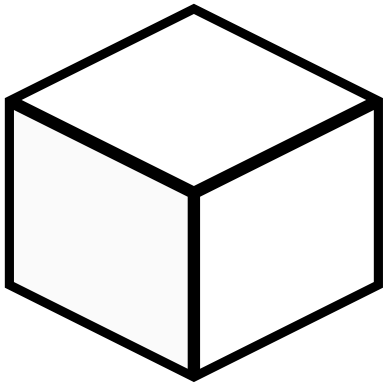
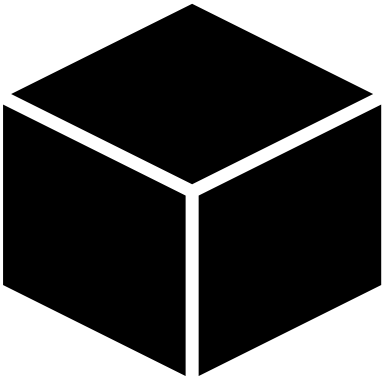


Attacks

???

Security by obscurity



Targets

Reality and the gap

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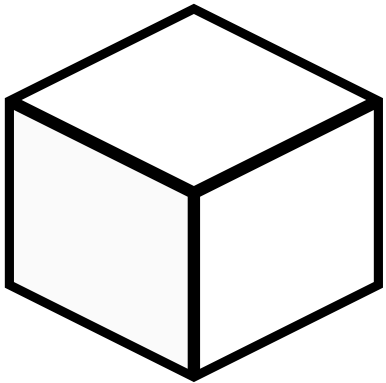

Attacks

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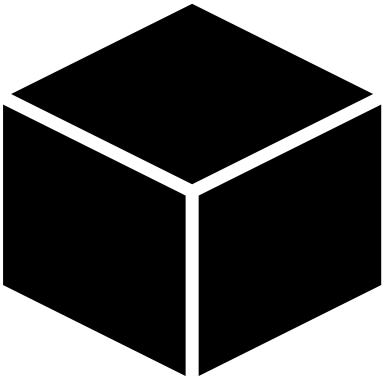
Security by obscurity

How large is the gap?
How hard is it to cross?



Targets

Elliptic curve cryptography

- Many implementation possibilities …

Elliptic curve cryptography

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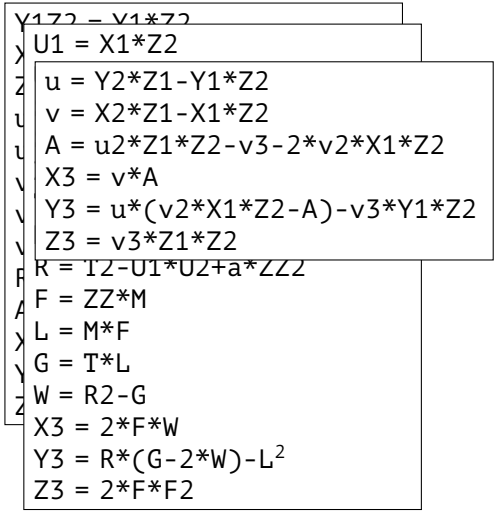
  - Curve model
    - $y^2 \equiv x^3 + ax + b$
    - $x^2 + y^2 \equiv c^2(1 + dx^2y^2)$
    - $ax^2 + y^2 \equiv 1 + dx^2y^2$
    - $by^2 \equiv x^3 + ax^2 + x$

Elliptic curve cryptography

- Many implementation possibilities …
  - Curve model
  - Coordinates
    - (X, Y)
    - (X, Y, Z)
    - (X, Y, Z, ZZ) …

Elliptic curve cryptography

- Many implementation possibilities …
  - Curve model
  - Coordinates
  - Addition formulas



Elliptic curve cryptography

- Many implementation possibilities …
  - Curve model
  - Coordinates
  - Addition formulas
  - Scalar multiplier
    - *LTR*, *RTL*, *Window*, *NAF*, *Comb* …

Fixed-window scalar multiplier

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

Elliptic curve cryptography

- Many implementation possibilities …
  - Curve model
  - Coordinates
  - Addition formulas
  - Scalar multiplier
  - Finite field operations
    - Multiplication: *Toom-Cook, Karatsuba,* …
    - Squaring: *Toom-Cook, Karatsuba,* …
    - Reduction: *Barret, Montgomery,* …
    - Inversion: *GCD, Euler*

Elliptic curve cryptography

- Many implementation possibilities …
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  - Finite field operations
  - Side-channel countermeasures

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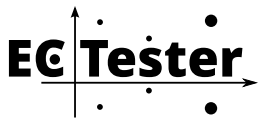
  - Side-channel countermeasures
- …that are used in practice
  - Analyzed 18 open-source crypto libraries
  - Mixed curve models
  - Jungle of scalar multipliers (Comb, fixed window, wNAF, GLV, …)
  - Various coordinate systems
  - Standard and custom addition formulas (more than 100)

Reverse engineering

- How hard is it to cross the gap?

pyecsca

Side-channels



Lying

Reverse engineering via side-channel attacks

- **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.
- ≠ Behavior of different implementations differs under these attacks

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  - ~~Assume knowledge of the impl. and target the key~~
  - Assume knowledge of the key and target the impl.
- ≠ Behavior of different implementations differs under these attacks
- Concretely "*special-point-based*" attacks: **RPA, ZVP, EPA**
  - Can recognize when a special point appears in scalar multiplication
  - Introduce zeros adaptively
  - Zeros detectable via side-channel

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Target: Static ECDH, $[k]P$ for some known k, can measure power/EM

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  - Build a decision table with the answers

r =	2	3	4	5
LTR	True	True	False	False
RTL	True	False	True	True
Comb	True	False	True	False
Ladder	True	True	True	False
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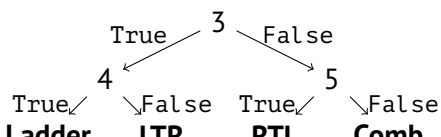

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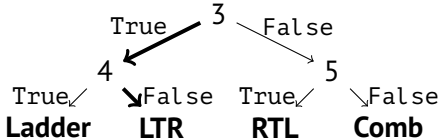

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Works,
but what about countermeasures?

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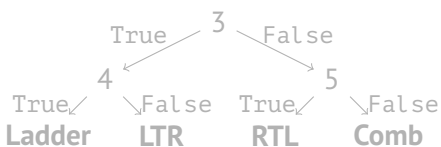

Scalar randomization countermeasures

Group scalar randomization

function Mult(P, k)
  $r \xleftarrow{\$} \{0, 1, \ldots, 2^b\}$
  return $[k + rn]P$

Additive splitting

function Mult(P, k)
  $r \xleftarrow{\$} \mathbb{Z}_n^*$
  return $[k - r]P + [r]G$

Euclidean splitting

function Mult(P, k)
  $r \xleftarrow{\$} \{0, 1, \ldots, 2^{\lfloor \log_2(n)/2 \rfloor}\}$
  $S \leftarrow [r]P$
  $k_1 \leftarrow k \mod r$
  $k_2 \leftarrow \left\lfloor \frac{k}{r} \right\rfloor$
  return $[k_1]P + [k_2]S$

Multiplicative splitting

function Mult(P, k)
  $r \xleftarrow{\$} \{0, 1, \ldots, 2^b\}$
  $S \leftarrow [r]P$
  return $[kr^{-1} \mod n]S$

-> **RPA** will not work

Reverse engineering by lying

- Countermeasures are correct on well-defined curves, what about bad curves?
- JavaCard platform: Allows any short-Weierstrass curve
- **Idea:** Recover the countermeasures based on their (erroneous) behavior

Method $3q$

Target: Static ECDH, $[k]P$ for some known k, no side-channels
+ countermeasures

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$[k]P \quad [k + n]P \quad [k + 2n]P$

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	$[k]P$	$[k + n]P$	$[k + 2n]P$
Group scalar	$\frac{1}{3}$	$\frac{1}{3}$	$\frac{1}{3}$
Additive	$\frac{1}{2}$	$\frac{1}{2}$	0
Multiplicative	$\frac{5}{9}$	$\frac{2}{9}$	$\frac{2}{9}$
Euclidean	1	0	0

Results

Card	Target	Method $3q$			Countermeasure	r bits
NXP 1	Derive	0.34	0.33	0.32	Group scalar	✗
	Sign	0.31	0.31	0.38	Group scalar	160
	Keygen	0.32	0.33	0.35	Group scalar	160
NXP 4	Derive	0.56	0.22	0.22	Multiplicative	64
	Sign	0.54	0.23	0.23	Multiplicative	?
Infineon 2	Derive	0.31	0.36	0.33	Group scalar	✗
	Sign	0.32	0.32	0.36	Group scalar	64
	Keygen	0.32	0.32	0.36	Group scalar	32
⋯	Many more results in the paper ⋯					

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- Consider transparent alternatives
  - opentitan
  - tropicsquare

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Questions?

pyecsca.org
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
- Vojtech Suchanek, Jan Jancar, Jan Kvapil, Petr Svenda, & Łukasz Chmielewski;
  ECTester: Reverse-engineering side-channel countermeasures of ECC implementations

References (cont.)

Attack assumptions

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

- Icons from **Font Awesome** and **Noun Project**

References (cont.)

Vulnerabilities

- Matus Nemec, Marek Sys, Petr Svenda, Dusan Klinec & Vashek Matyas;
  The Return of Coppersmith's Attack: Practical Factorization of Widely Used RSA Moduli
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