Degenerate Fault Attacks on Elliptic Curve Parameters in OpenSSL

IACR ePrint: 2019/400

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July 2, 2019

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1. Introduction

2. Theory — Singular/Supersingular Curve Point Decompression Attacks

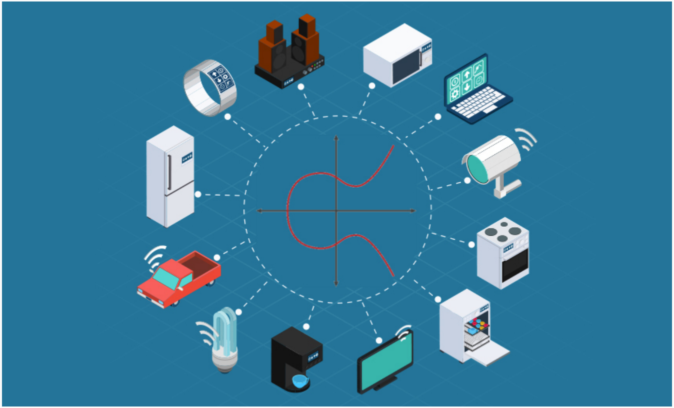
3. Practice — Attacking ECDSA and ECIES in OpenSSL

4. Beyond OpenSSL

5. Conclusion

Introduction

Implementation Attacks against ECC



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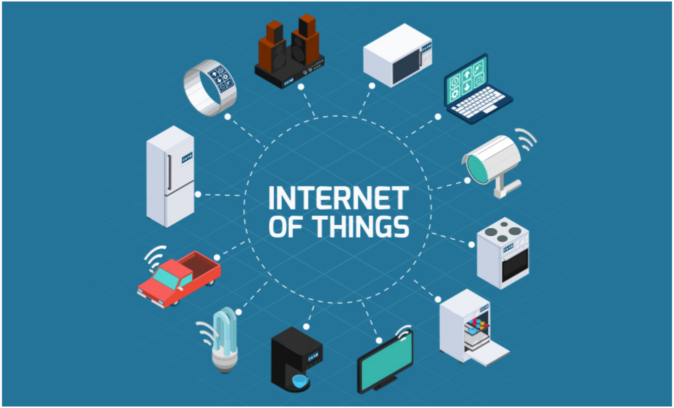

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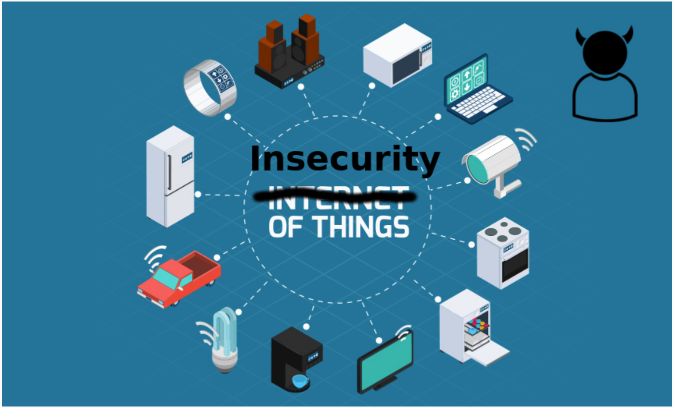

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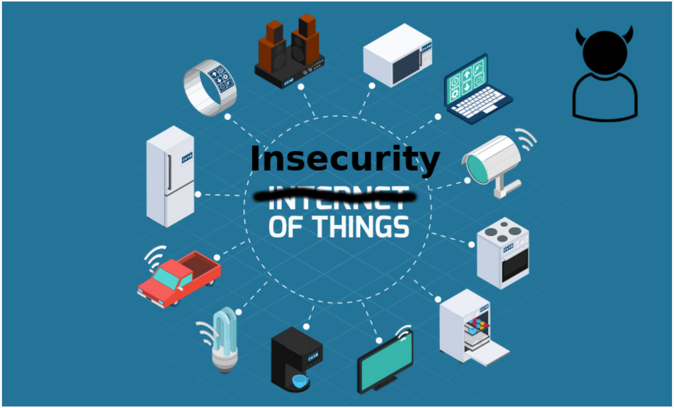

- Elliptic curve crypto is widely used in many devices
- We live in the era of IoT $\approx$ Insecurity of Things!
- Threat of physical attacks on implementations of ECC

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  2. Send $\widetilde{P}$ to the scalar multiplication algorithm
  3. Compute partial bits of the secret scalar k by examining an invalid output $[k]\widetilde{P}$.

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- Are invalid curve attacks dead? – NO!
    - where there's crypto, there's a risk of fault attacks

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- Various methods:
  - Voltage glitch
  - Clock glitch
  - Optical attacks
  - Temperature attacks
  - Optical attacks
  - Magnetic attacks
  - etc.

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3. Experimentally verified that the attacks reliably work against OpenSSL installed in Raspberry Pi!

Theory — Singular/Supersingular Curve Point Decompression Attacks

SCPD Attacks Overview

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  - Exploit supersingular curves for targets with non-zero j-invariant
  - Achievable with low-cost single fault injection

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- Only the sign of y (i.e. whether y is even or odd in $\mathbb{F}_p$) needs to be stored
- Typically used to compress public keys, but sometimes applied to base points too

Example: secp256k1 Bitcoin curve

Uncompressed base point [Sta10, §2.4.1]

```
04 79BE667E F9DCBBAC 55A06295 CE870B07
   029BFCDB 2DCE28D9 59F2815B 16F81798
   483ADA77 26A3C465 5DA4FBFC 0E1108A8
   FD17B448 A6855419 9C47D08F FB10D4B8
```

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Compressed base point [Sta10, §2.4.1]

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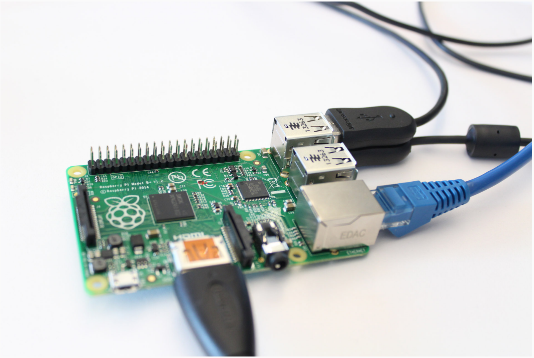

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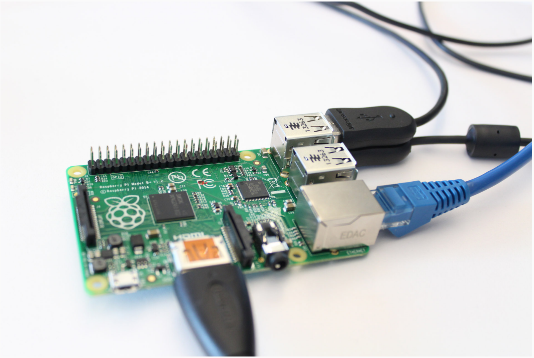

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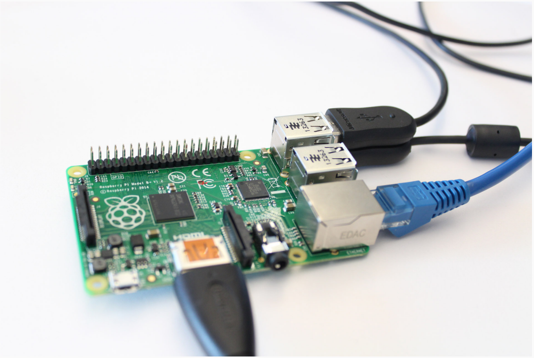

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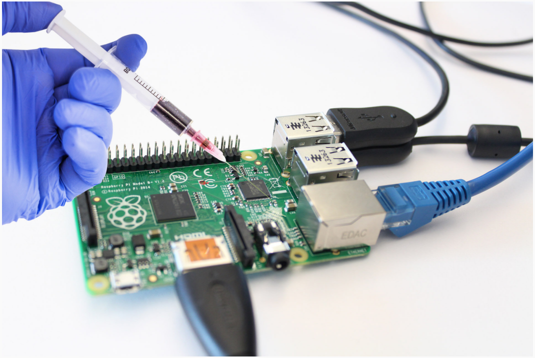

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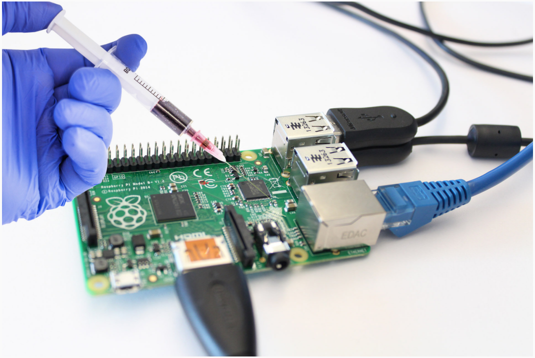

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3. Adversary injects a fault $\rightsquigarrow$ Can skip a few instructions

Instruction Skipping Fault on Base Point Decompression (I)

Algorithm Point Decompression Algorithm

Input: $x \in \mathbb{F}_p$, $\bar{y} \in \{\texttt{0x02}, \texttt{0x03}\}$, A, B, p

Output: $P = (x, y)$: uncompressed curve point

```
y ← x^2
y ← y + A                    ▷ A = 0 for secp k and BN curves
y ← y × x
y ← y + B
y ← ±√y
Validate coordinates: y^2 =? x^3 + Ax + B
return (x, y)
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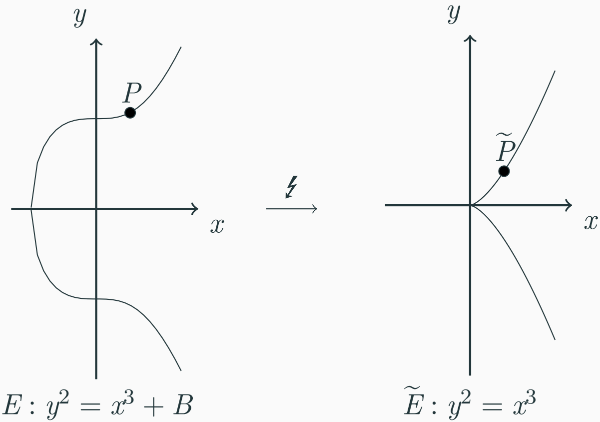
Instruction Skipping Fault on Base Point Decompression (II)

- y-coordinate is incorrectly reconstructed:

$$\widetilde{y}^2 = x^3 \mod p.$$

- The perturbed faulty base point $\widetilde{P} = (x, \widetilde{y})$ is reliably on singular curve $\widetilde{E}$!



Isomorphism between Singular Curve and Additive Group $\mathbb{F}_p^+$

Theorem

Let $\mathbb{F}_p^+$ be the additive group of $\mathbb{F}_p$ and $\widetilde{E}(\mathbb{F}_p)$ be the set of nonsingular $\mathbb{F}_p$-rational points on $\widetilde{E}$ including the point at infinity $O = (0 : 1 : 0)$. Then the map $\phi : \widetilde{E}(\mathbb{F}_p) \to \mathbb{F}_p^+$ with

$$(x, y) \mapsto x/y$$
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- k can be simply recovered by computing $(\widetilde{y}\widetilde{x}_k)/(x\widetilde{y}_k)$ in $\mathbb{F}_p$

What if $A \neq 0$? (New observation)

Theorem (MOV attack)

Let E' be a supersingular curve over $\mathbb{F}_p$, $p \geq 5$. Then there exists an injective, efficiently computable group homomorphism

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- The DLP on E' is no harder than the DLP in the multiplicative group $\mathbb{F}_{p^2}^*$.
- Tractable for most standardized parameters

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Can SCPD attacks be more practical?

Practice — Attacking ECDSA and ECIES in OpenSSL

- OpenSSL's `ecparam` command allows users to generate EC key files with:

```
akira@akira-HP-EliteDesk-800-G2-TWR:~$ openssl ecparam
Field Type: prime-field
Prime:
    00:ff:ff:ff:ff:ff:ff:ff:ff:ff:ff:ff:ff:ff:ff:
    ff:ff:ff:ff:ff:ff:ff:ff:ff:ff:ff:ff:ff:fe:ff:
    ff:fc:2f
A:    0
B:    7 (0x7)
Generator (compressed):
    02:79:be:66:7e:f9:dc:bb:ac:55:a0:62:95:ce:87:
    0b:07:02:9b:fc:db:2d:ce:28:d9:59:f2:81:5b:16:
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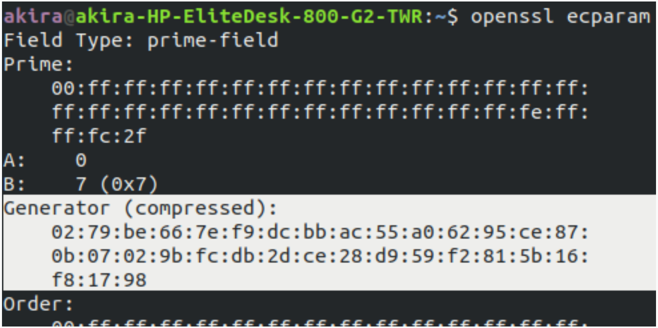

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    ff:fc:2f
A:    0
B:    7 (0x7)
Generator (compressed):
    02:79:be:66:7e:f9:dc:bb:ac:55:a0:62:95:ce:87:
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  - Compressed public key (`-conv_form compressed`)

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How to Attack with a Single Fault

Input: Domain parameters in raw binary formats

Output: Domain parameters in `BIGNUM` type

$p \leftarrow$ `BN_bin2bn`(p_{bin})

$A \leftarrow$ `BN_bin2bn`(A_{bin})

$B \leftarrow$ `BN_bin2bn`(B_{bin})

$x \leftarrow$ `BN_bin2bn`(x_{bin})

$P \leftarrow$ `Decomp`$(\bar{P} = (x, \bar{y}), p, A, B)$

Validate $y^2 \stackrel{?}{=} x^3 + Ax + B$

return (p, A, B, P)

- `BIGNUM`: OpenSSL's data structure representing a multiprecision integer
- `BN_bin2bn()`: utility function which converts a raw byte array to a `BIGNUM` object

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5: $\widetilde{P} \leftarrow$ `Decomp`$(\bar{P} = (x, \bar{y}), p, A, B)$ ⚡SCPD fault

6: Validate $y^2 \stackrel{?}{=} x^3 + Ax + B$ ⚡SCPD fault

7: **return** $(p, A, B, \widetilde{P})$

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2: $A \leftarrow$ `BN_bin2bn`(A_{bin})

3: $0 \leftarrow$ `BN_bin2bn`(B_{bin}) ⚡Our fault

4: $x \leftarrow$ `BN_bin2bn`(x_{bin})

5: $\widetilde{P} \leftarrow$ `Decomp`$(\bar{P} = (x, \bar{y}), p, A, 0)$

6: Validate $y^2 \stackrel{?}{=} x^3 + Ax + 0$

7: **return** $(p, A, 0, \widetilde{P})$

- `BIGNUM`: OpenSSL's data structure representing a multiprecision integer
- `BN_bin2bn()`: utility function which converts a raw byte array to a `BIGNUM` object

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- Actual fault attack targets a certain CPU instruction

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        beq         .L351
.L330:

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.L334:
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        ldrb        r2, [r3]
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        sub         r5, r5, #1
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- Actual fault attack targets a certain CPU instruction
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- Quick experiment: comment out each target line ⇝ the function returned 0!

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Algorithm ECDSA signature generation [JMV01]

Input: P: base point of prime order n, $d \in \mathbb{Z}/n\mathbb{Z}$: secret key, $Q = [d]P$: public key, $M \in \{0,1\}^*$: message to be signed

Output: a valid signature (r, s)

1: $k \xleftarrow{\$} \mathbb{Z}/n\mathbb{Z}$
2: $(x_k, y_k) \leftarrow [k]P$
3: $r \leftarrow x_k \mod n$
4: $h \leftarrow H(M)$
5: $s \leftarrow k^{-1}(h + rd) \mod n$
6: **return** (r, s)

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Once k is obtained, the secret key d is directly exposed:

$$d = (\widetilde{s}k - h)/\widetilde{r} \mod n$$

Effect on SM2-ECIES (for OpenSSL ver. $\geq 1.1.1$)

Algorithm SM2-ECIES encryption [SL14]

Input: $Q \in E(\mathbb{F}_p)$: public key, $M \in \{0,1\}^*$: plaintext

Output: ciphertext (C_1, C_2, C_3)

1: $k \leftarrow_{\$} \mathbb{Z}/n\mathbb{Z}$

2: $C_1 = (x_k, y_k) \leftarrow [k]P$

3: $(x', y') \leftarrow [k]Q$

4: $K \leftarrow \mathsf{KDF}(x'||y', |M|)$

5: $C_2 \leftarrow M \oplus K$

6: $C_3 \leftarrow H(x'||y'||M)$

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- Once K is obtained, the plaintext can be recovered:

$$M = C_2 \oplus K.$$

Practical Experiment

- Target:
  - Raspberry Pi Model B
  - OpenSSL 1.1.1: latest release as of November 2018
  - ECDSA/SM2-ECIES over secp256k1

Practical Experiment

- Target:
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  - ECDSA/SM2-ECIES over secp256k1
- ChipWhisperer-Lite side-channel/fault analysis evaluation board

Experimental Setup (I)

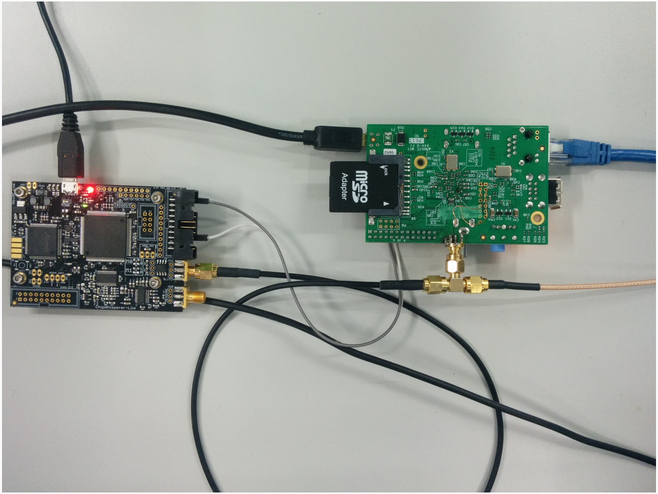


Figure 1: ChipWhisperer-Lite evaluation board connected to Raspberry Pi Model B

Experimental Setup (II)

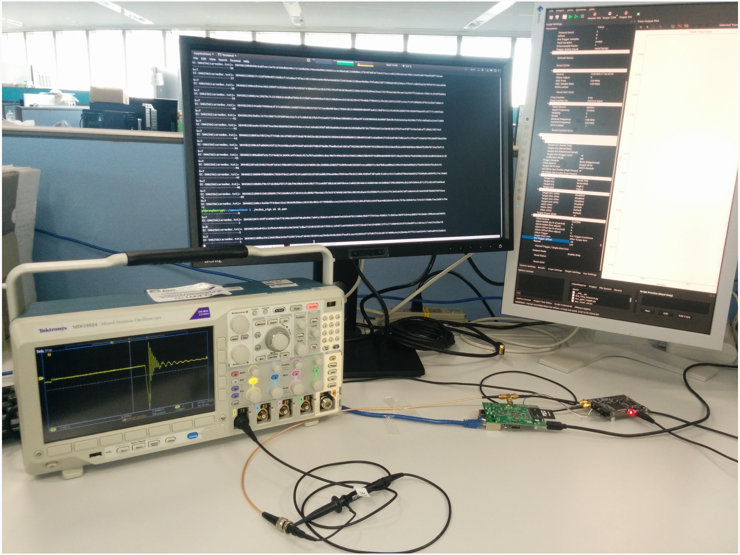
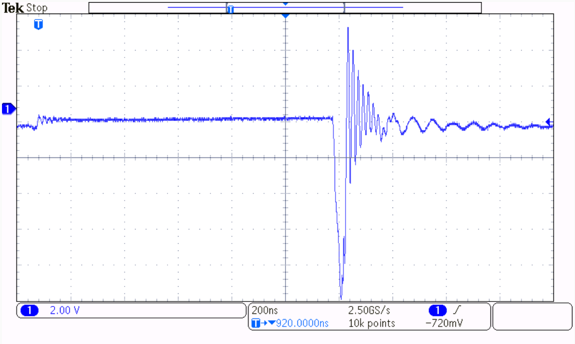


Figure 2: Overview of the experimental setup

Experimental Setup (III)



- Inserted a single voltage glitch

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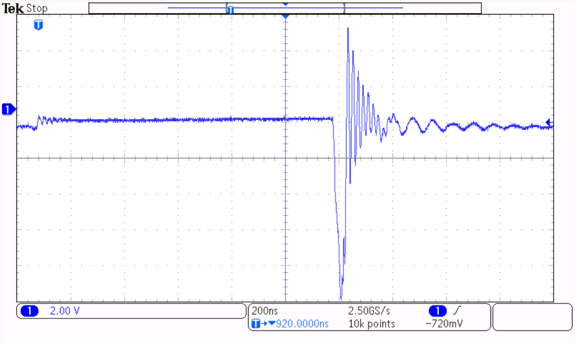

- Inserted a single voltage glitch
- Found the suitable parameters causing reliably reproducible misbehavior of Raspberry Pi:
  - Enable-only glitches repeated 127 times
  - Offset 10 clock cycles

Experimental Result

Success	No effect	Program crash	OS crash	Total
95	813	89	3	1000

- $\approx 10\%$ success rate
- Still serious enough since the adversary requires only one successful instance to recover the secret

Beyond OpenSSL

Bitcoin Wallets

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- We investigated several major open-source bitcoin wallet implementations
- Turned out they do not use decompression technique for base points:
  - ✓ libsecp256k1
  - ✓ Trezor
  - ✓ Ledger
- More exhaustive evaluation will be required!
  - Some PoC implementation does use the compressed BP

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- Demonstrated the attacks in a practical scenario
    - OpenSSL installed in Raspberry Pi
- Lesson: Never apply point compression/decompression to base points!

Countermeasure & Future Work

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  - Investigate more cryptocurrency wallets/libraries

Tack!

`https://ia.cr/2019/400`

Questions?

AARHUS UNIVERSITET

NTT

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