Nonce@Once: A Single-Trace EM Side Channel Attack on Several Constant-Time Elliptic Curve Implementations in Mobile Platforms

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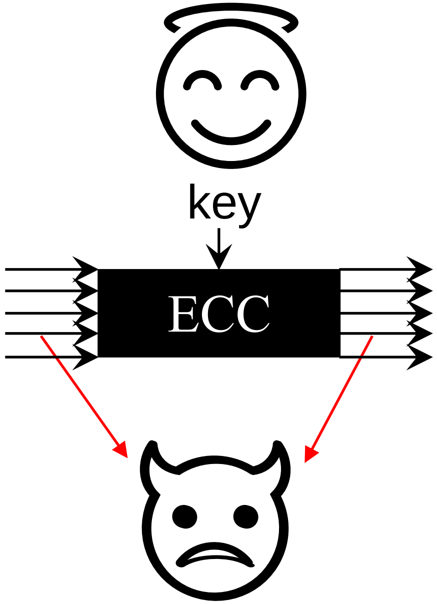
Motivation

- Public key crypto is essential for modern security
  - Secure exchange of session keys
  - Verifying identity of systems and users
  - And much, much more
- Private keys are a highly valuable asset
  - Attackers want to get them
  - But we don’t want them to

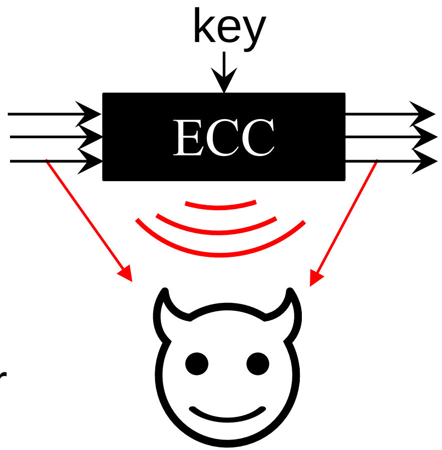
❖Public Key Crypto

- Good public key crypto (e.g. ECC)
  - Designed to make private keys very, very hard to recover



❖Analog Side-Channel Attacks

- But cryptographic implementation runs on real hardware
  - Logic gates switch, causing current flow
  - Currents flowing create changes in surrounding EM field



Most attacks:
Side-channel information helps **eventually** recover the private key

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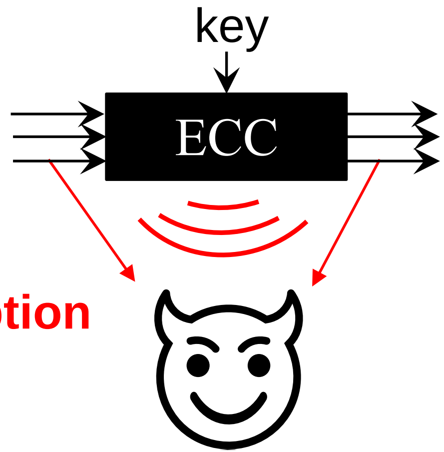


Nonce@Once:
Side-channel information
from only one signing/encryption
operation allows recovery
the private key

❖ECC Digital Signature Algorithm

1. $Q = d \cdot G$, where d is the secret key
2. $z = HASH(msg)$
3. Generate random ephemeral secret k (the “nonce”)
4. $R = k \cdot Q$
5. $r = R \rightarrow x \bmod n$
6. $s = k^{-1}(z + r \cdot d)$
7. Signature=(r, s)

Nonce k must reman secret!

If attacker knows k, a message, and its signature:
$d = (s \cdot k - z)/r \bmod n$

❖Point-by-Scalar Multiplication (R=k·Q)

```
R=Point(0);
// For each bit of nonce k
for(b=nbits-1;b>=0;b--){
        R=2·R;
        if(get_bit(k,b))
                R=R+Q;
}
```

Easy target for side channel attacks, e.g. Flush+Reload

```
R=Point(0);
// For each bit of nonce k
for(b=nbits-1;b>=0;b--){
        R=2·R;
        T=R+Q;
        Swap_Cond(R,T,get_bit(k,b));
}
```

Constant Time Implementation

❖Conditional Swap (RFC 7748)

```
Swap_Cond(A,B,cond){
        mask=0-cond;
        for(i=0;i<nwords;i++){
                Δ = (a[i]^b[i]) & mask;
                a[i]=a[i] ^ Δ;
                b[i]=b[i] ^ Δ;
        }
}
```

11..11 if cond, 00..00 if not cond

For each machine word of an EC point

$$\Delta = \begin{cases} 0, & cond == 0 \\ a\hat{\ }b, & cond == 1 \end{cases}$$

Note this is also Constant-Time!

But… ~ 40 XOR operations with Δ in Swap_Cond

All have a zero operand when cond==0

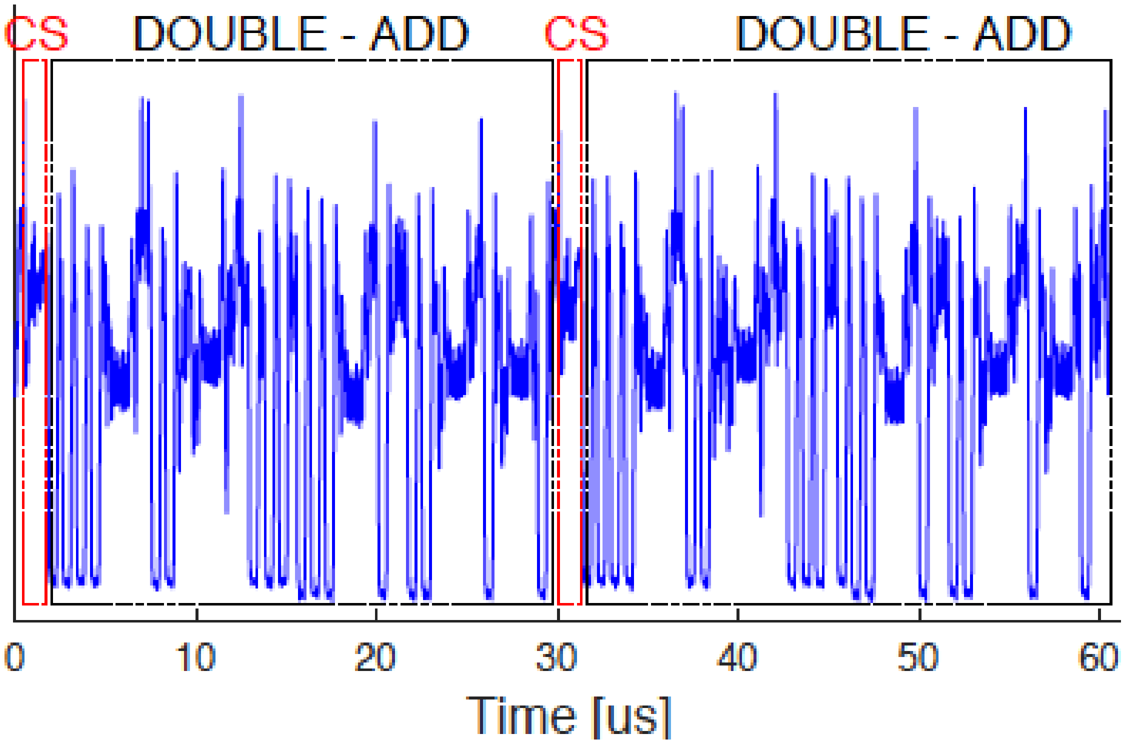
That operand is ~50%-ones when cond==1

❖Measurement Setup

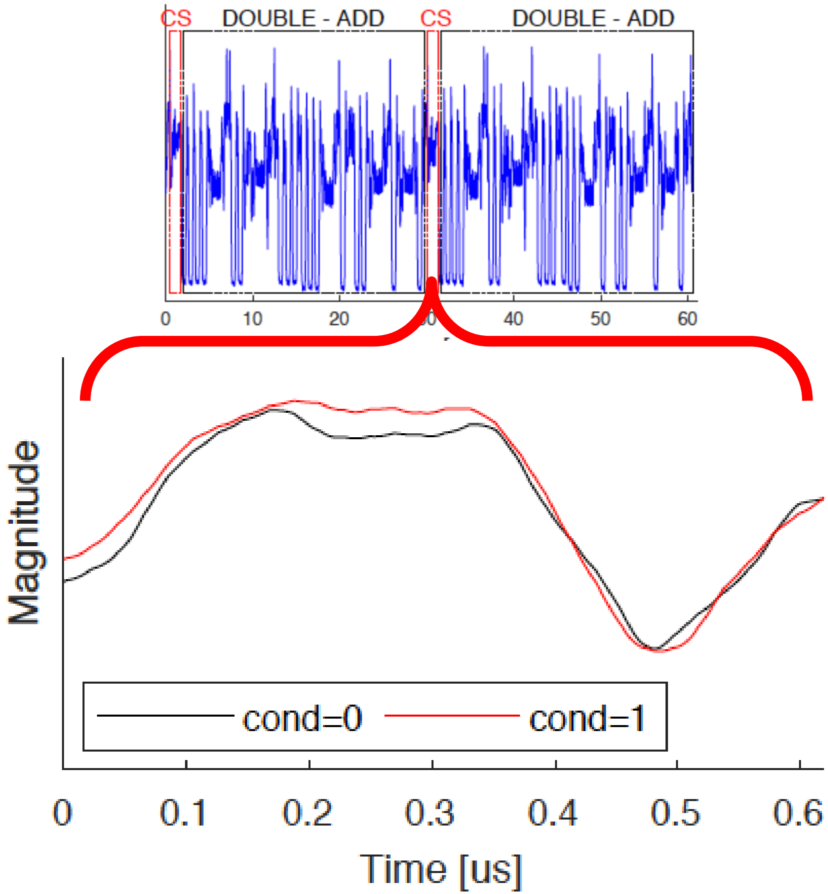
ZTE ZFIVE

Alcatel Ideal

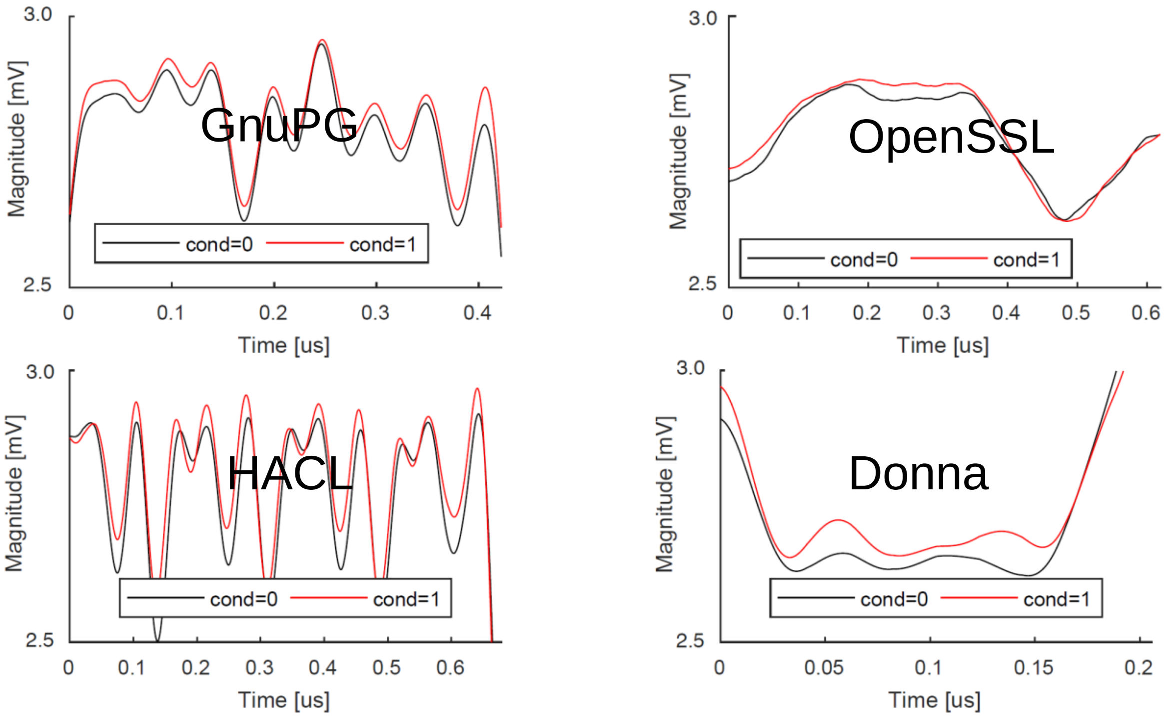
❖Locating the Cond-Swap Signals (OpenSSL)



❖Recovering value of cond (OpenSSL)



❖Recovering value of cond

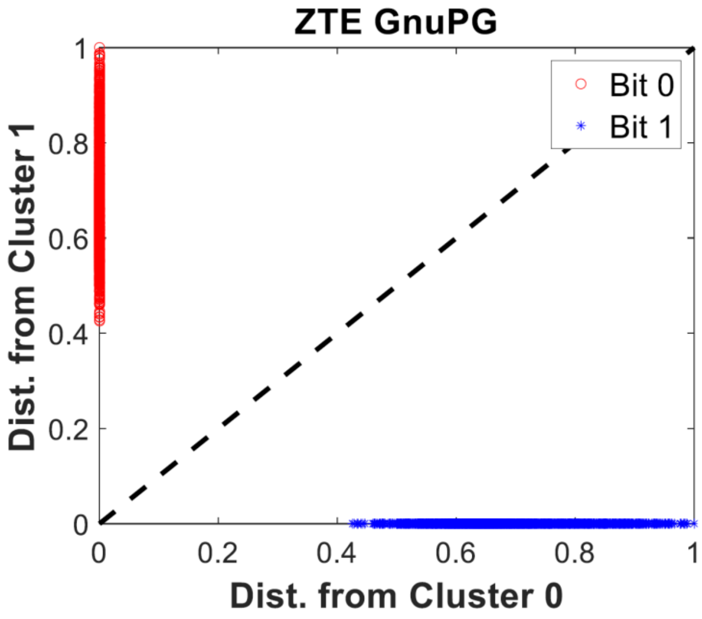


❖Nonce Recovery Algorithm

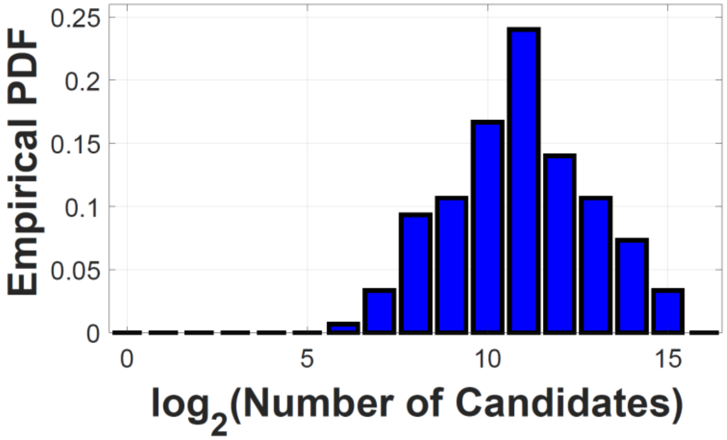
- Training
  - Record signal while signing with a few known nonces on device of same kind (but different instance of the device)
  - Cluster training Cond_Swap signals (K-Means)
  - Keep centroid and label (0 or 1) of each cluster
- Attack
  - Record signal from target device
  - Identify Cond_Swap snippets
  - Label each snippet (closest cluster)
  - Brute-force labels of “missing” snippets

❖Nonce Recovery (GnuPG on ZTE)

Bit Recovery - Clusters



Erasure Recovery – Brute Force



Mitigation

- Fundamental enabler of the attack
  - Leakage amplification
    - XOR with zero or non-zero operand leaks a little about the operand
    - But same leakage repeated 40 times in each Cond_Swap!
- Mitigation – randomization to avoid amplification

❖Mitigation

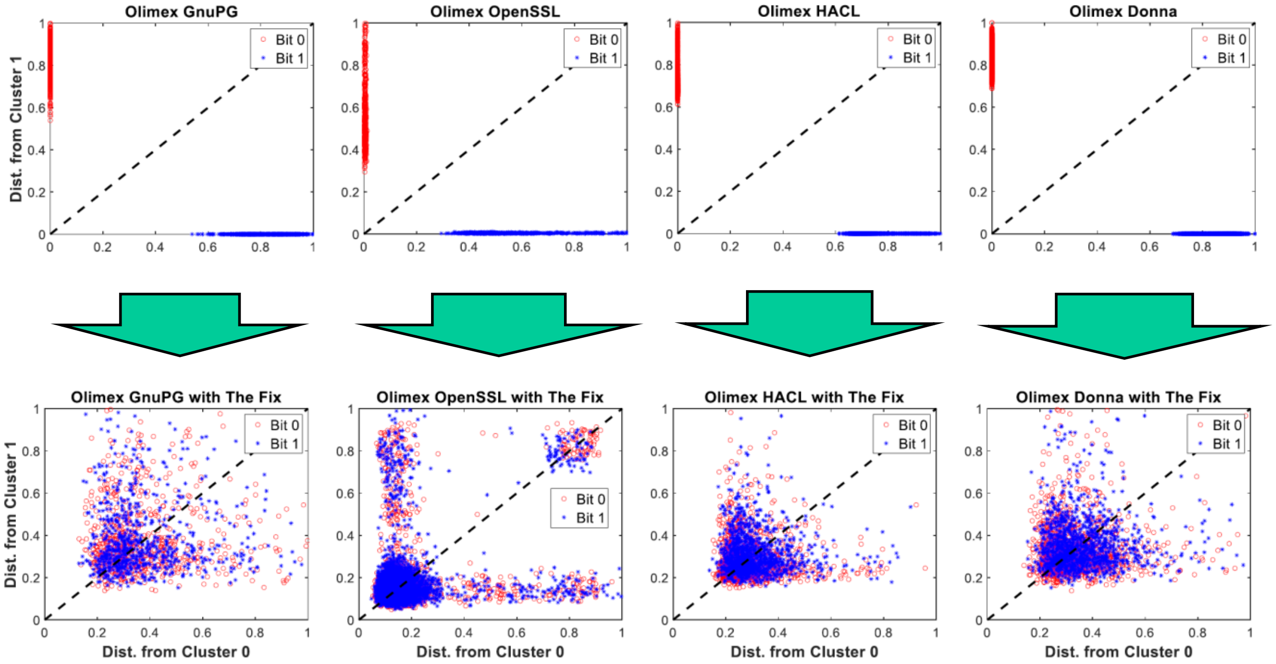
```
Swap_Cond(A,B,cond){
    mask=0-cond;
    for(i=0;i<nwords;i++){
        Δ = (a[i]^b[i]) & mask;
        a[i]=a[i] ^ Δ;
        b[i]=b[i] ^ Δ;
    }
}
```

```
Swap_Cond(A,B,cond){
    mask=0-cond;
    rand=random_word();
    for(i=0;i<nwords;i++){
        Δ′ = (a[i]^b[i]) & mask;
        Δ = Δ′ ^ rand;
        a[i]=a[i] ^ Δ ^ rand;
        b[i]=b[i] ^ Δ ^ rand;
    }
}
```

Problem: Mitigation optimized-out by compiler

Ask/trick the compiler not to do this (see paper)

❖Mitigation's Effect on the Attack



❖Conclusions

- Analog side-channel attack on constant-time ECC implementations that use conditional swap (RFC 7748)
  - Highly accurate thanks to leakage amplification
  - Successful on OpenSSL, GnuPG, HACL*, and Curve25519-donna
- ECC private key recovered from only one use of that key
- Mitigation: randomization in Cond_Swap
  - Removes leakage amplification
  - Very low performance overhead

Thank you!

Questions?