CacheQuote: Efficiently Recovering Long-term Secrets of SGX EPID via Cache Attacks

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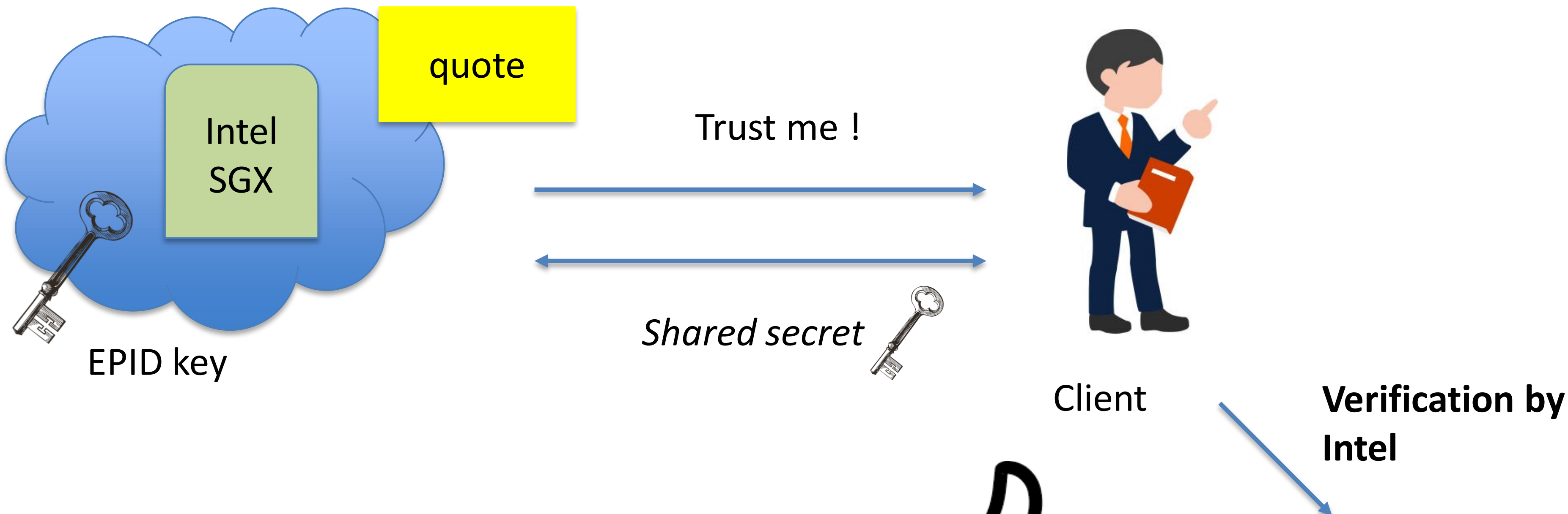
Intel Software Guard Extensions

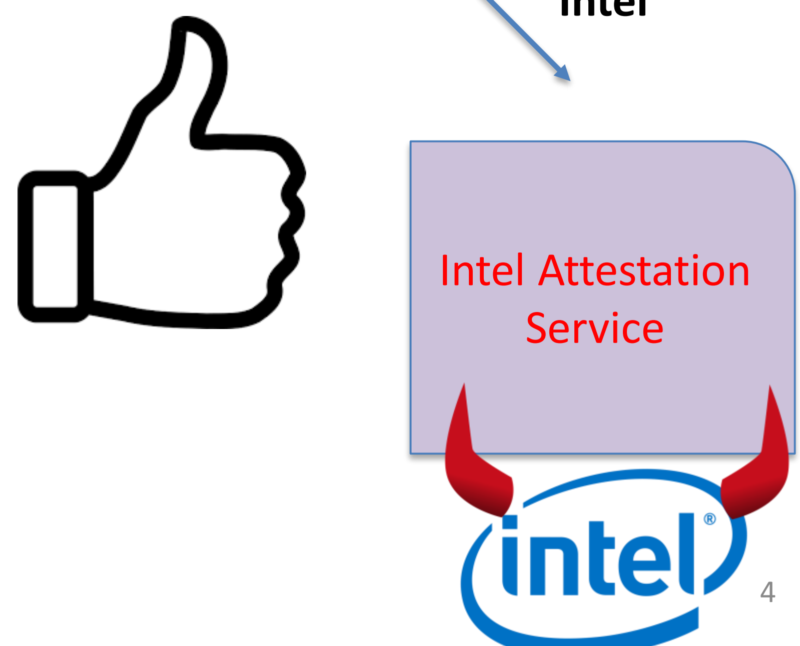
1. Set of instructions aiming to guarantee confidentiality and integrity of applications that run inside untrusted environments.
2. Protects *enclaves* of code and data.

Enclaves

- Enclaves are isolated from the software running on the computer.
- SGX controls the entry to and exit from enclaves.

Remote attestation: EPID



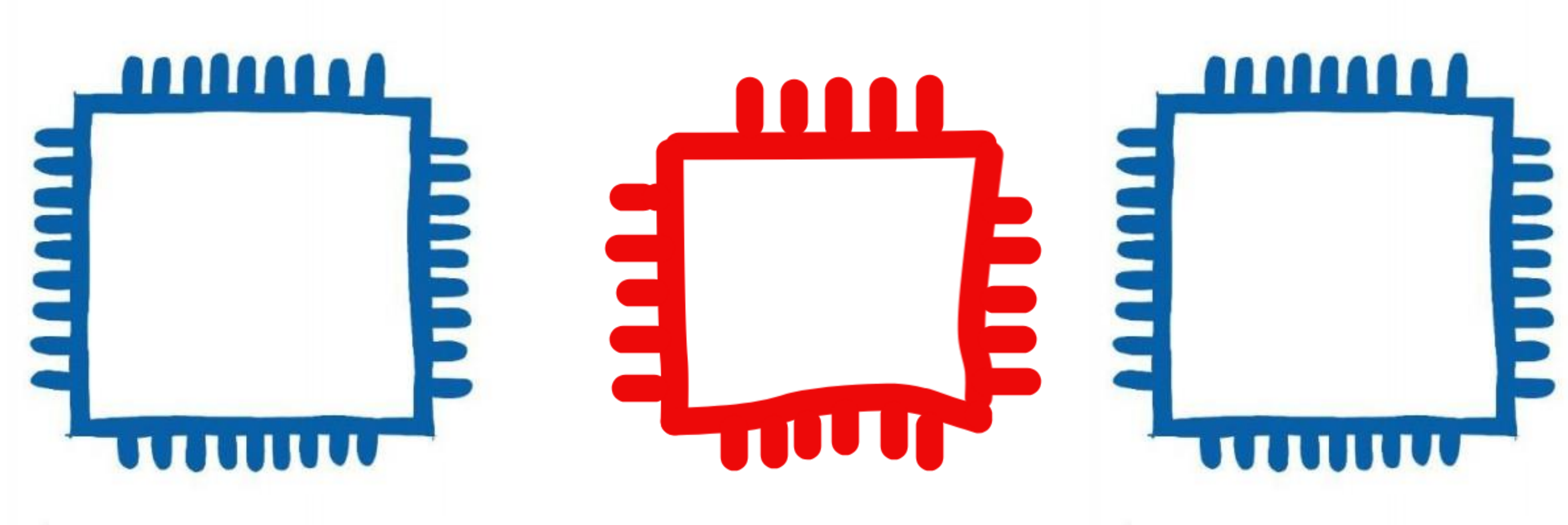


Trust is based on the EPID key!

Why need IAS ? Revocation !
All quotes are encrypted by SGX.

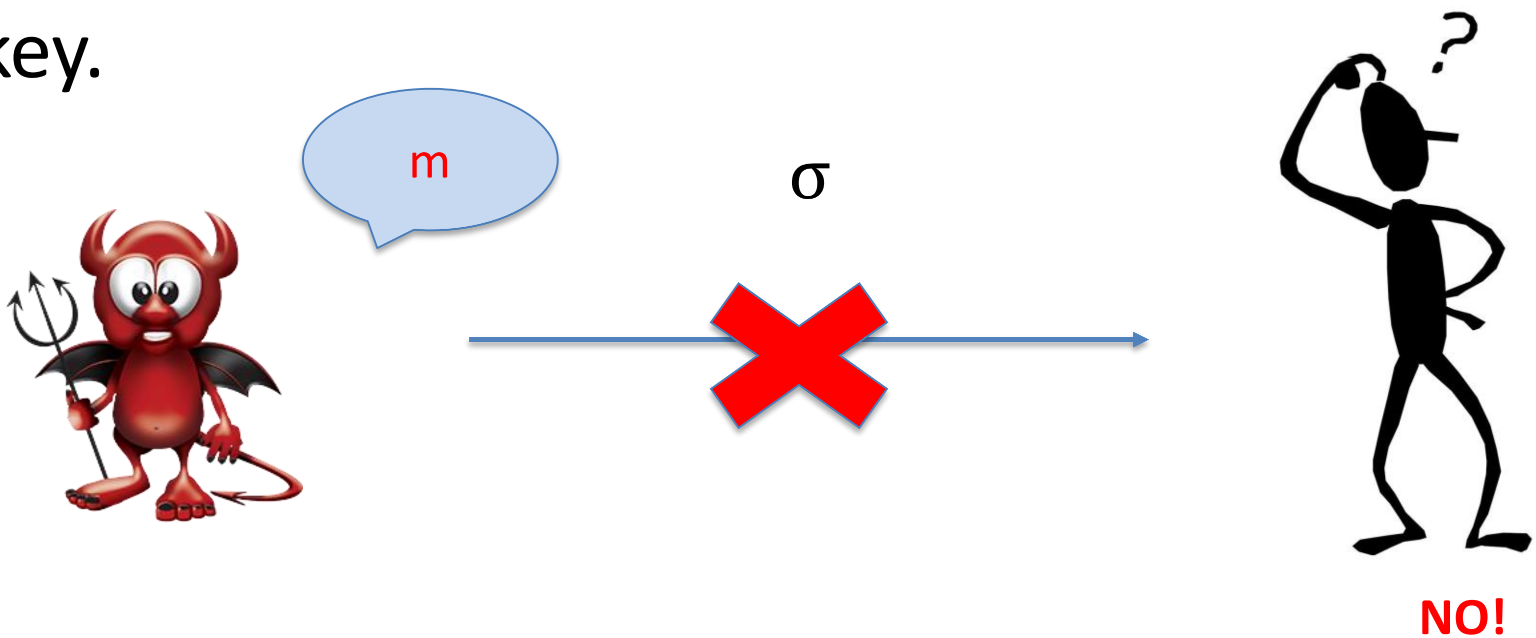
Unlinkability

➡ impossible to identify the platform that produced a signature on some message m.



Unforgeability

impossible for an attacker to forge a valid signature on some previously-unsigned message, without knowing a non-revoked secret key.

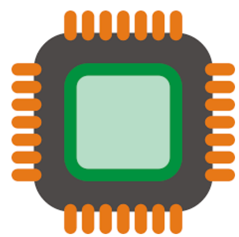


Our results

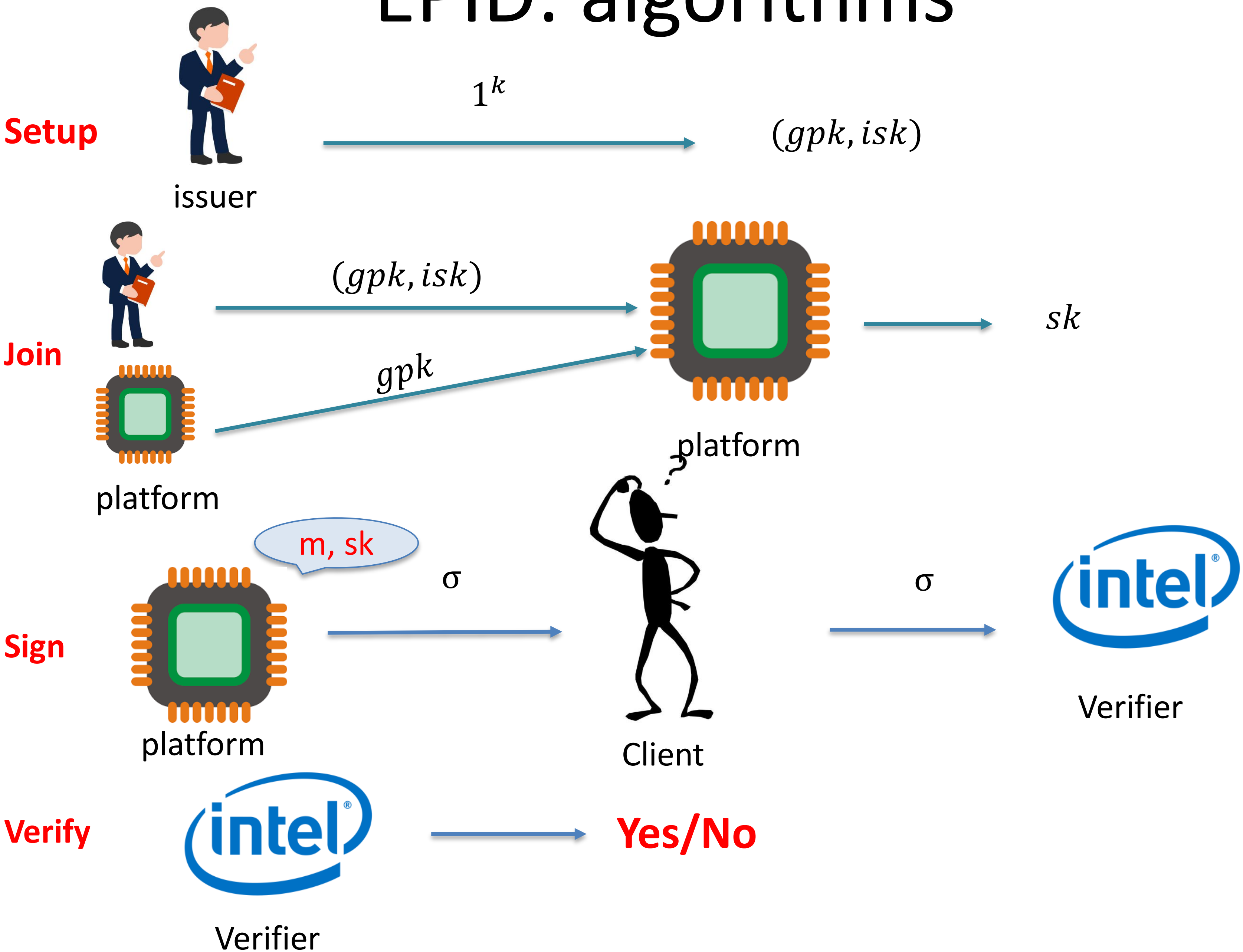
- First cache attacks on Intel’s EPID protocol implemented inside SGX.

- Recover part of the enclave’s long term secret key.
- Malicious attestation server (Intel) can break the unlinkability guarantees of SGX’s remote attestation protocol.

EPID: setup

- An issuer: 
- A revocation manager: 
- A platform: 
- A verifier: intel

EPID: algorithms



The signing algorithm

- Secret key: f + Intel's signature on f
- Randomly choose: $B \in G$ and compute

$$K := B^f$$

- How to sign ?

Non-interactive zero knowledge proof of knowledge:

"I know an unrevoked f such that $K := B^f$*"*

- Requires computing A^r , where A is some value.
- Signature σ has the values *K, B* and *s* $\leftarrow r + Hf$

Attack idea

- Recover side-channel information about the length of the nonce r from A^r.

- After many observations, use length data to mount a lattice attack to recover the value of f.

- Break unlinkability.

How unlinkability is broken?

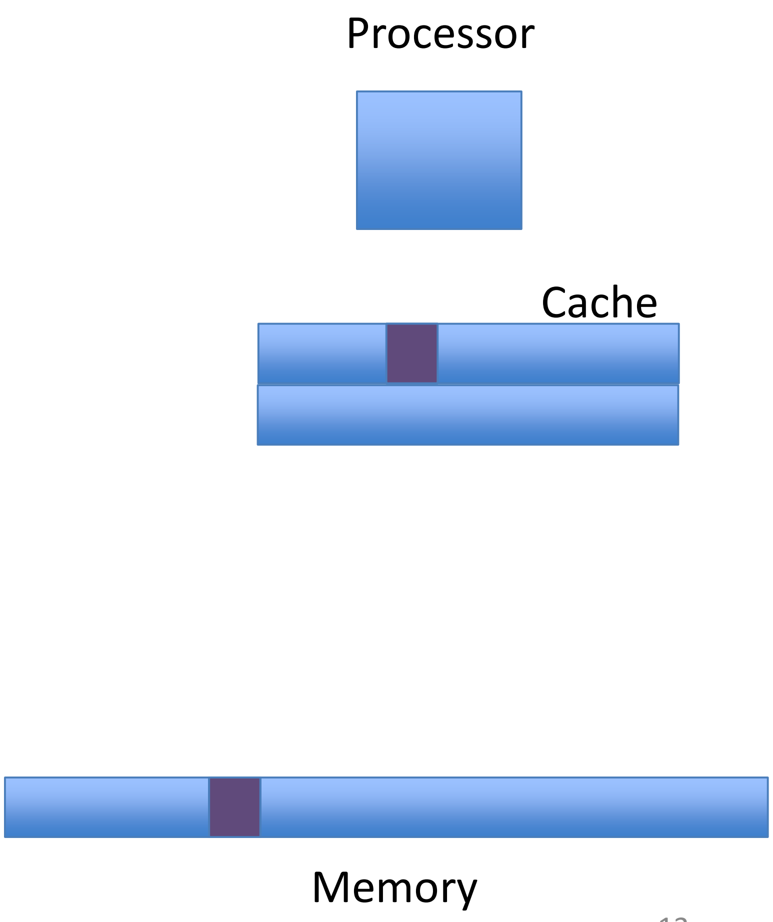
- f is unique per platform and private.
- The attacker knowns a signature $\sigma = (K, B, \dots)$ on some message m and f.
- He can check if $K = B^f$.
- If yes, then the signature was issued by the platform whose key is f.

CPU vs memory

Caches are used to bridge the gap.

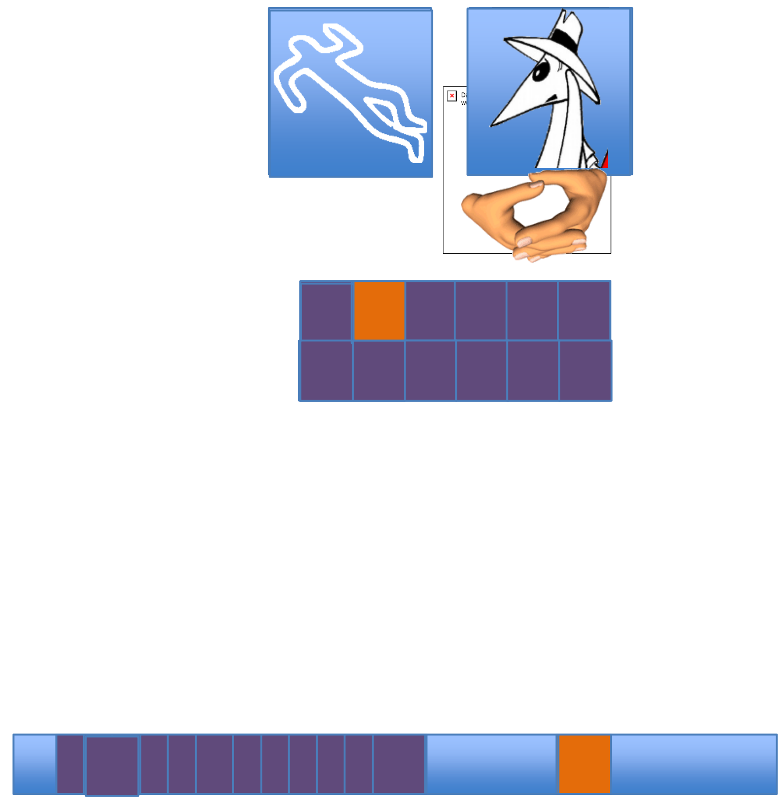
- Divides memory into *lines*
- Stores recently used lines

- In a *cache hit*, data is retrieved from the cache
- In a *cache miss*, data is retrieved from memory and inserted to the cache



The Prime+Probe Attack

- Allocate a cache-sized memory buffer
- *Prime:* fills the cache with the contents of the buffer
- *Probe:* measure the time to access each cache set
  - Slow access indicates victim access to the set



In our attack

- The signing algorithm requires computing A^r.
- Exponentiation uses some variant of square and multiply with fixed windows of bits.
- Quoting enclave recodes the nonce r to have fewer non-zero bits.

Scalar multiplication algorithm

MultPoint(point P, window size w , scalar r):

Initialize P : $P_0 \leftarrow O$

For $i \leftarrow 1$ to 2^{w-1} do:

$\quad P_i \leftarrow P \cdot P_{i-1}$

$i \leftarrow \max(j : r_j \neq 0)$ ← Start with MSB $\neq 0$

$s \leftarrow P_{r_i}$

$i \leftarrow i - 1$

Main loop:

While $i \geq 0$ do:

$\quad s \leftarrow r^{2^w}$ ← w squaring operations

$\quad s \leftarrow s \cdot P_{r_i}$ ← Multiplication with precomputed value P_{r_i} (selected in constant-time)

$\quad i \leftarrow i - 1$

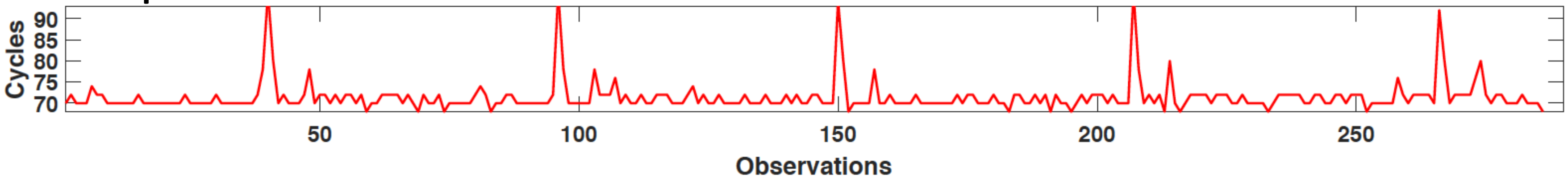
End while

Output: s

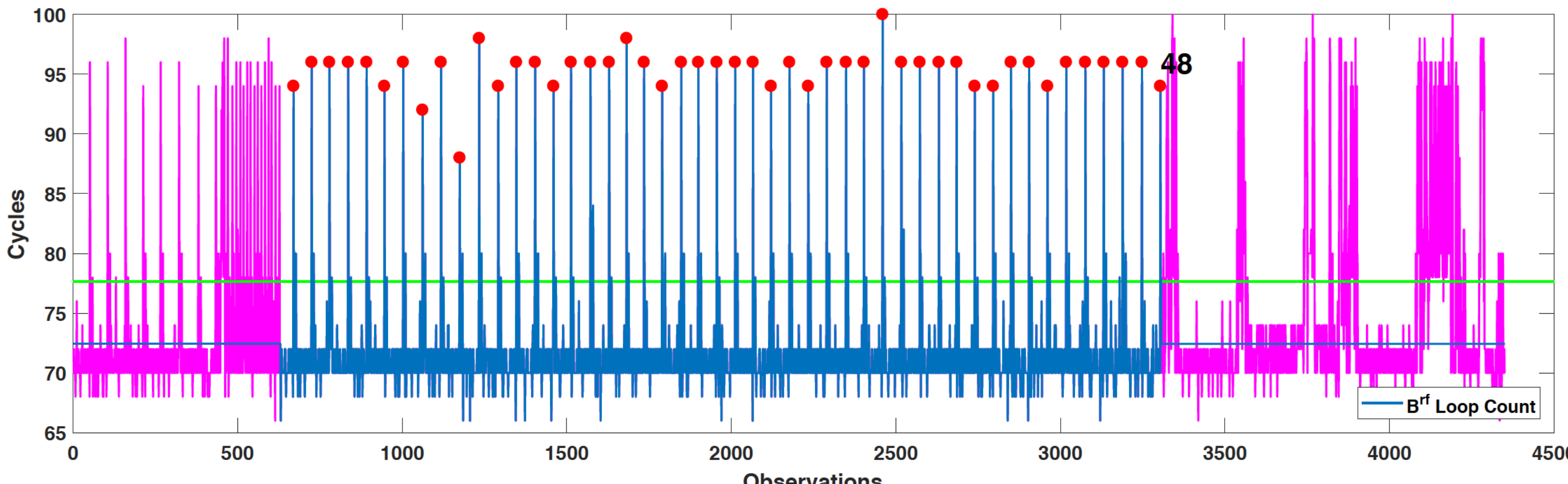
- Scalar of length 256 bits ⇨ recoded scalar of length 52 ⇨ 51 loop iterations.
- Bits 256 and 255 are 0 ⇨ recoded scalar of length 51 ⇨ 50 loop iterations.

Counting loops

- Monitor cache access patterns during the computation of the main loop.



- One period corresponds to one loop iteration.
- Number of periods gives us information on the number of iterations.



A lattice attack

Side channel ⟶ information about the length of r.

Goal: Solve for f.

- Many samples $\{(s, H)\}_i$ such that:

$$s \equiv r + Hf \bmod p$$

- Information about the number l_i of most significant zero bits in r_i.
- We learn $|s_i - H_i f| = |r_i| < \frac{p}{2^{l_i}}$

⟶ hidden number problem and obtain *f*.

Recovering *f*

10 600 signatures required if only using 49-loop samples to get 37 error-free samples.

Signatures	48-loop	49-loop	50-loop	BKZ block size	BKZ time
10300	2	35	0	2	0.1s
10000	2	31	10	20	0.2s
9000	2	29	21	30	1.4s
8000	2	25	35	30	4.5s

- Use samples of different loop lengths

- Reduce the number of signatures with manual inspection: less than 7 500 observed signatures to obtain enough 49-loop observations for a full key recovery.

Conclusion

- We finally have *f*.
- Limitations: we can’t run the attack ourselves as all the EPID signatures are encrypted with Intel’s public key !
- A malicious Intel could break the unlinkability guarantee.
- Thank you !

Thank you !

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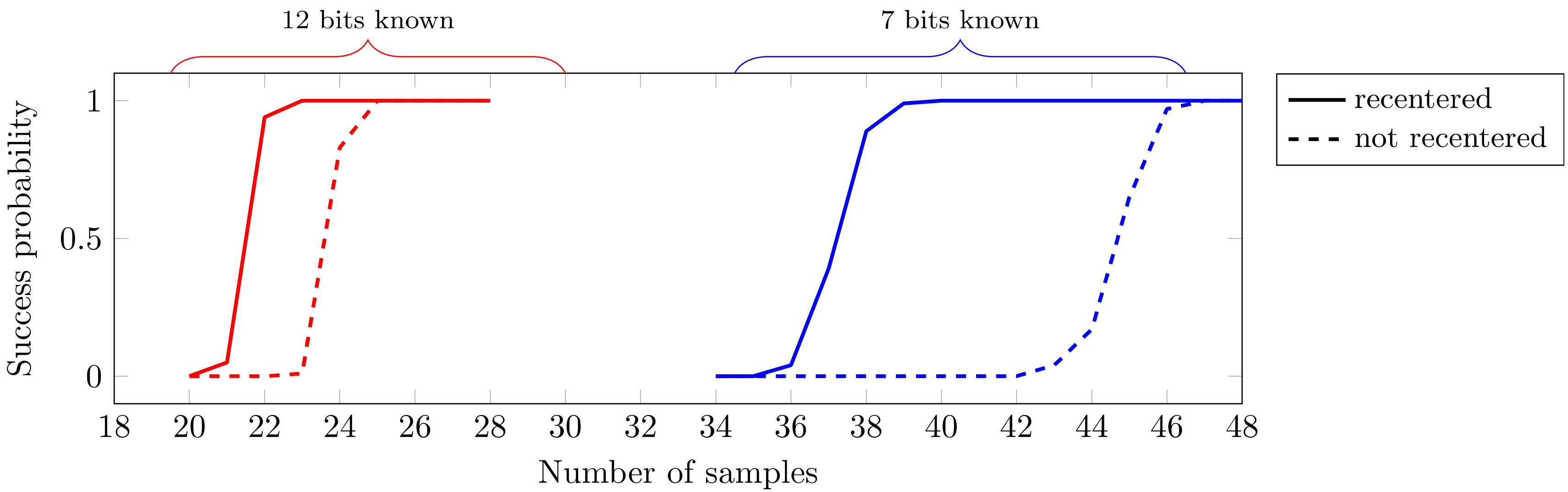
Key recovery with the hidden number problem



In our experiments, 8000 signatures necessary to enough error-free samples for key recovery.

Recoding the nonces

- Non-adjacent form (NAF) encoding:

  a. no two sequential non-zero digits.

  b. signed digits
- Example:

  a. binary: $(0,1,1,1) = 2^2 + 2^1 + 2^0 = 7$

  b. 2-NAF: $(1,0,0,-1) = 2^3 - 2^0 = 7$

- Generalization to *w*-NAF: work in base 2^w.
- The quoting enclave *recodes* the scalar r_f using some variant of *w*-NAF.

$r_f = (r_1, \cdots r_n)$ s.t.:

1. $r_f = \sum_i 2^{w \cdot i} r_i$
2. $-2^w - 1 \leq r_i \leq 2^w - 1.$

- Example: $(0, 0, 1, -25) = 2^{5 \cdot 1} \cdot 1 + 2^{5 \cdot 0} \cdot (-25) = 7$