One&Done: A Single-Decryption EM-Based Attack on OpenSSL's Constant-Time Blinded RSA

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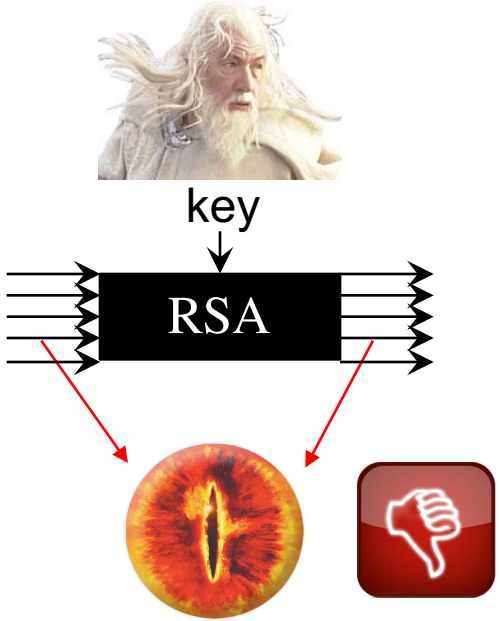
❖Motivation

- Public key crypto is essential for modern security
  - Secure exchange of session keys
  - Verifying identity of systems and users
  - And a lot more
- Private keys are a highly valuable asset
  - So attackers want them
  - And we don't want attackers to get them

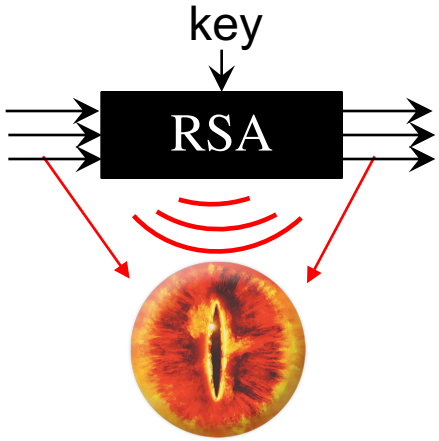
❖Public Key Crypto

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



❖Analog Side-Channel Attacks

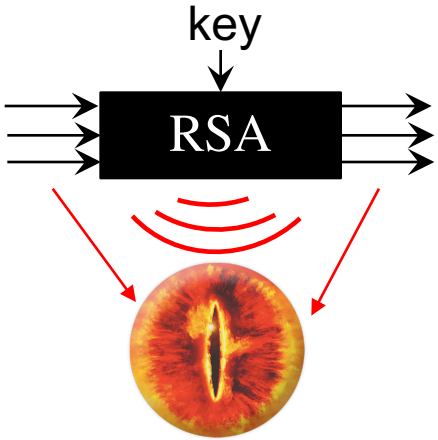
- But cryptographic implementation runs on real hardware
  - Logic gates switch, causing current flow
  - Currents flowing create changes in surrounding EM field



Side-channel information **helps** recover the private key

❖Analog Side-Channel Attacks

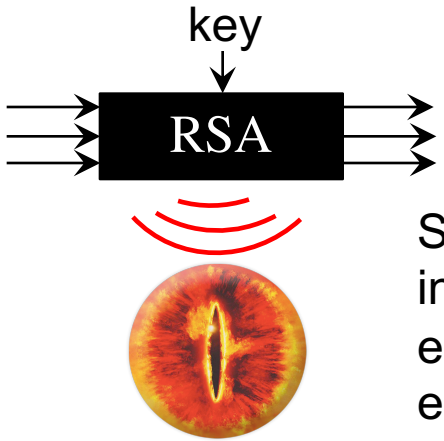
- Message randomization (blinding)
  - Prevents chosen-plaintext and other message-dependent attacks
- But… when message-independent operations use the key



Side-channel information, **alone,**
eventually enables efficient recovery of the private key

❖Analog Side-Channel Attacks

- One&Done
  - Message does not matter (message blinding does not help)
  - Multiple "traces" not needed (exponent blinding does not help)



Side-channel information **alone**, in **a single encryption/signing,** enables efficient recovery of the entire private key

❖OpenSSL's RSA Implementation

- BN_mod_exp_montgomery_consttime()
  - Computes $\mathbf{x^d \bmod m}$, where **d** is the secret exponent

```
1   b=bits-1;
2   while(b>=0){
3       wval=0;
4       // Scan the window,
5       // squaring the result as we go
6       for (i=0;i<w;i++) {
7           BN_mod_mul(v,v,v,m);
8           wval<<=1;
9           wval+=BN_is_bit_set(d,b);
10          b--;
11      }
12      // Mulitply window's result
13      // into the overall result
14      BN_mod_mul(v,v,ct[wval]);
15  }
```

For each fixed-size "window"

For each bit in the window

Square the result ($\mathbf{v=v^2}$)

Look up one bit of d and add to wval

Multiply result with x^{wval}

Look up precomputed x^{wval}

❖Side-Channel Attacks on OpenSSL's RSA

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For each fixed-size "window"

For each bit in the window

Square the result ($\mathbf{v=v^2}$)

Get bit from d, add to wval

Multiply result with x^{wval}

Look up precomputed x^{wval}

One&Done (new)

Mitigation (new)

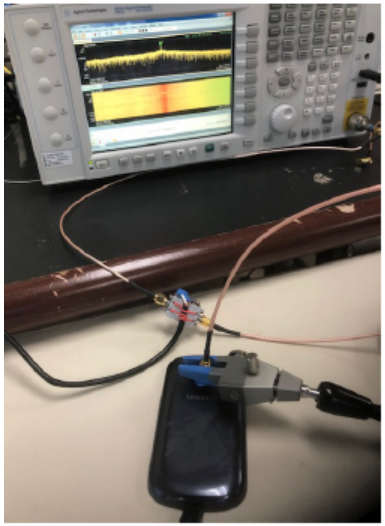
Genkin et al., CHES'15

Message Blinding

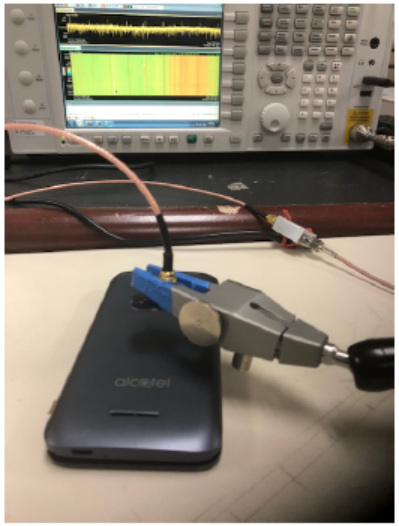
Cache (e.g. Percival)

Scatter-Gather

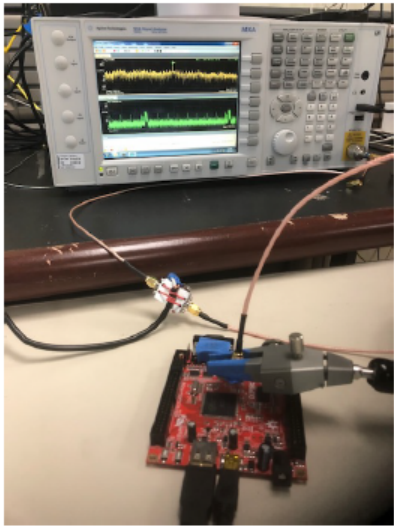
❖Measurement Setup



Samsung Galaxy Centura SCH-S738C



Alcatel Ideal



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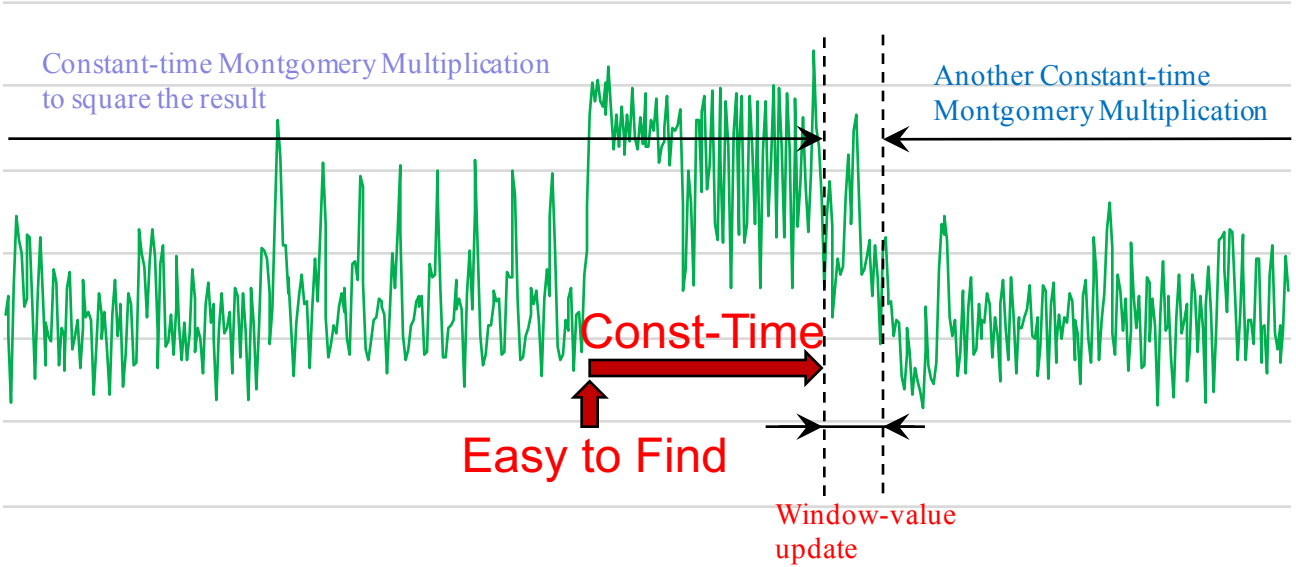
❖Side Channel Analysis

- Recent advances in side-channel-based program monitoring
  - Camelia, our DARPA LADS project
    - Uses analog signals to monitor computational activity to detect control flow deviation and/or execution of unknown code
    - Found that even a single-instruction control-flow can be detected
    - But…
- Constant-time implementation – no key-dependent CF
  - Every encryption has the same CF sequence
    - Can't use CF differences for attack
    - But can use the (very stable and predictable) signal features and timing to tell us **exactly** where in the signal BN_is_bit_set is executing

❖ Attack Approach

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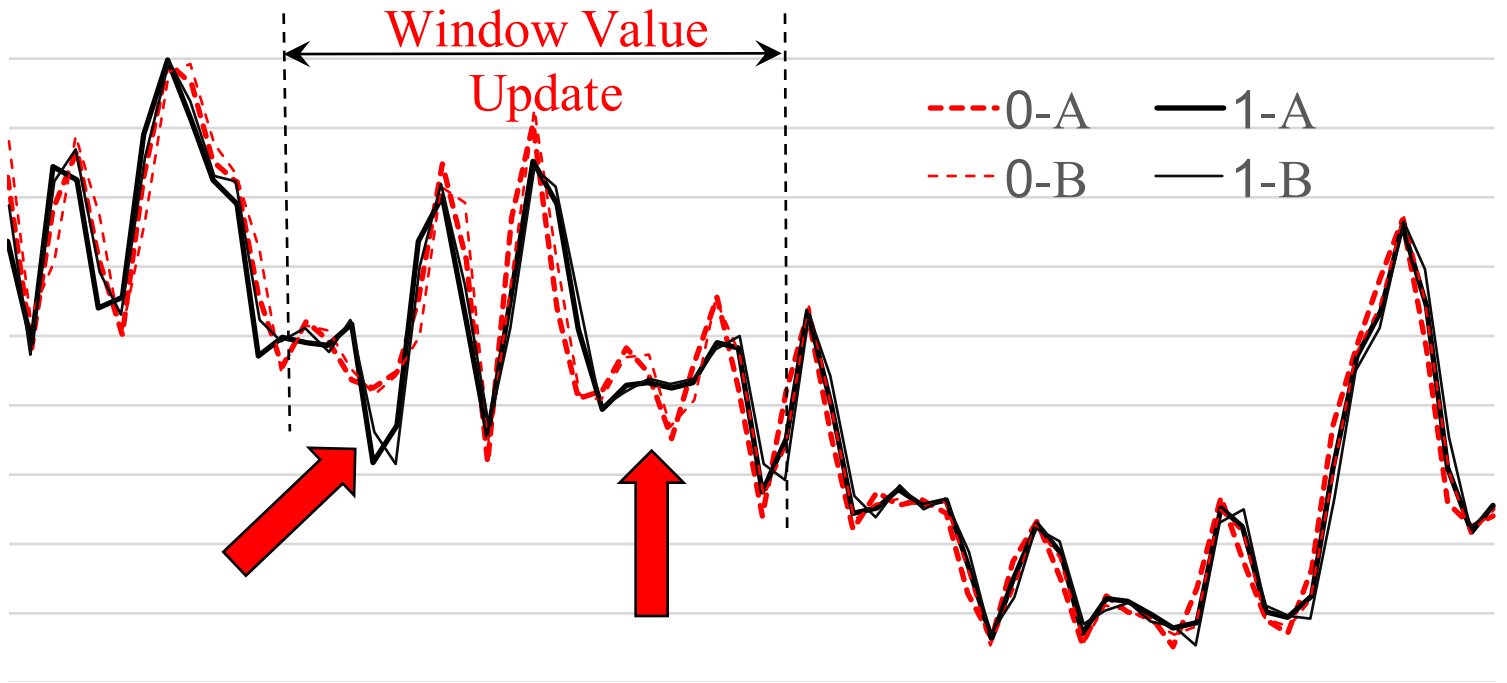
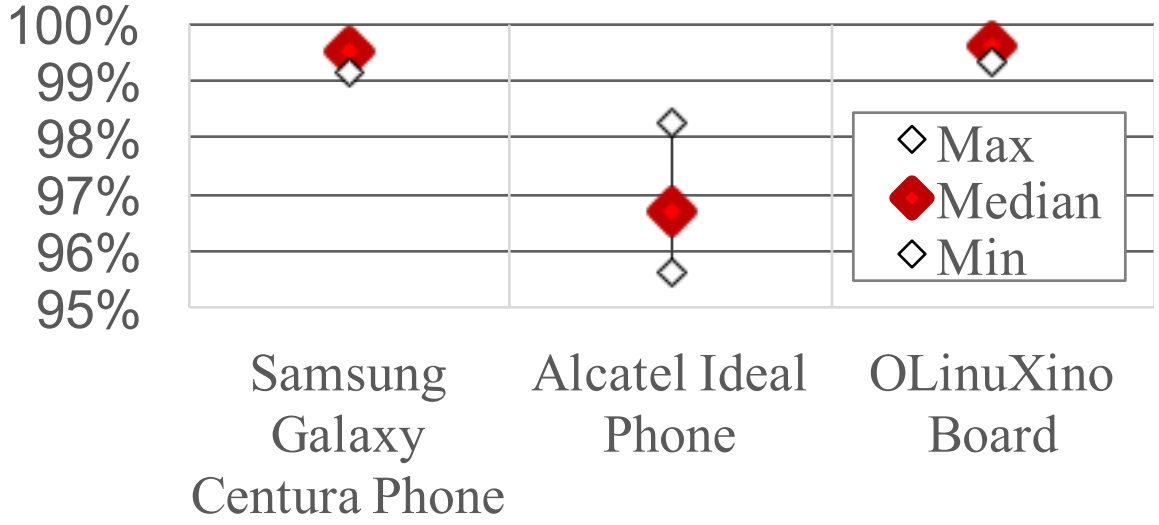
```

❖Relevant Part Zoom-In



How well does this recover bits of $<d_p,d_q>$?

- Training on 15 private-key RSA decryptions
- Recover bits of secret exponents using only **one** decryption



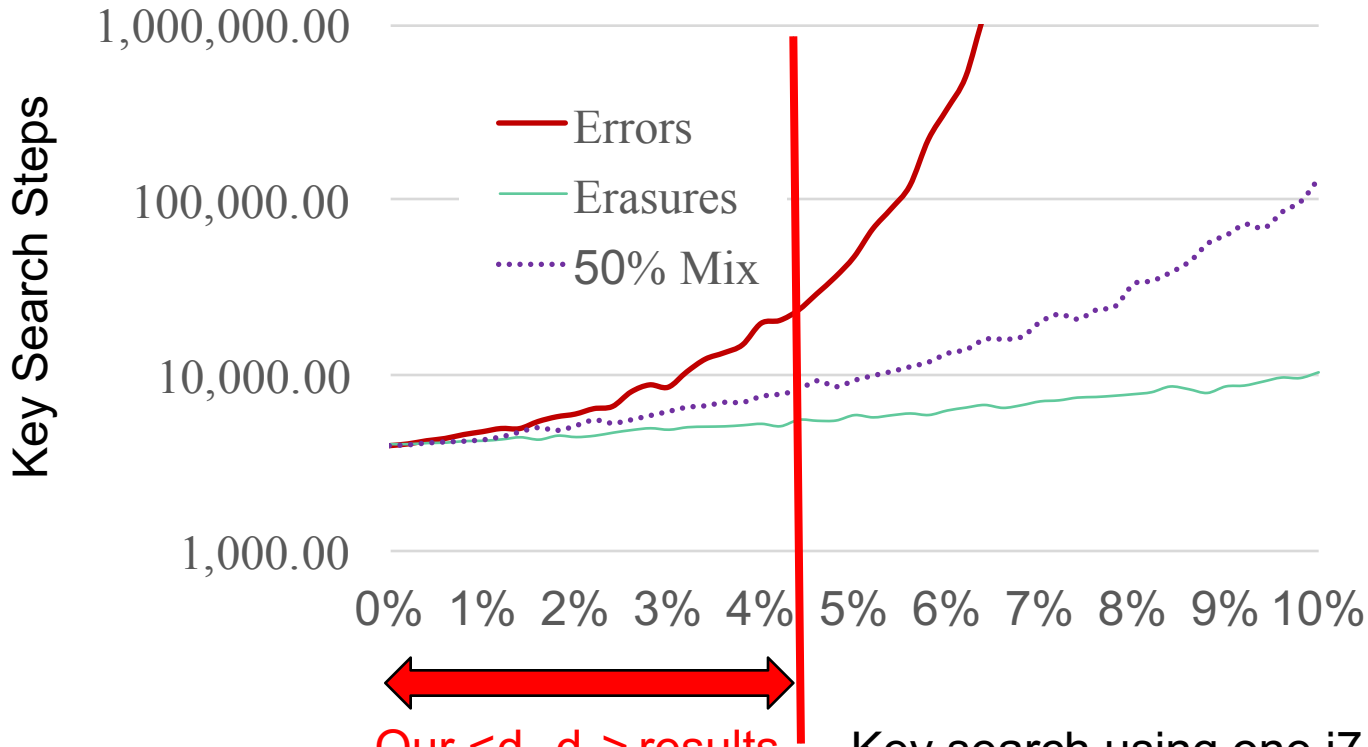
❖Full RSA Key Recovery

- We have dp and dq but with
  - Erasures – could not find where the bit's signal is
  - Errors – found the bit's signal, but misclassified it (0 vs. 1)
- Existing branch-and-prune algorithms
  - Prune partial solutions when group of bits has too many errors
    - Assumes errors are uniformly distributed
    - Our errors often occur in bursts
    - Does not explicitly handle erasures
  - Prune partial solutions that disagree with known bits of $<d_p,d_q>$
    - Can't handle errors (no bits truly "known")

❖Full RSA Key Recovery

- We have dp and dq but with
  - Erasures – could not find where the bit's signal is
  - Errors – found the bit's signal, but misclassified it (0 vs. 1)
- Our algorithm
  - Take partial solution with fewest disagreement overall
    - Known-to-be-unknown bits (erasures) not counted
  - Expand that partial solution by one bit position
    - Prune expansions that violate relationships between p,q,n,dp,and dq
    - Efficient implementation, nearly all checks use only scalars (not BNs)
  - Repeat

❖Recover RSA key from <d_p,d_q> with errors



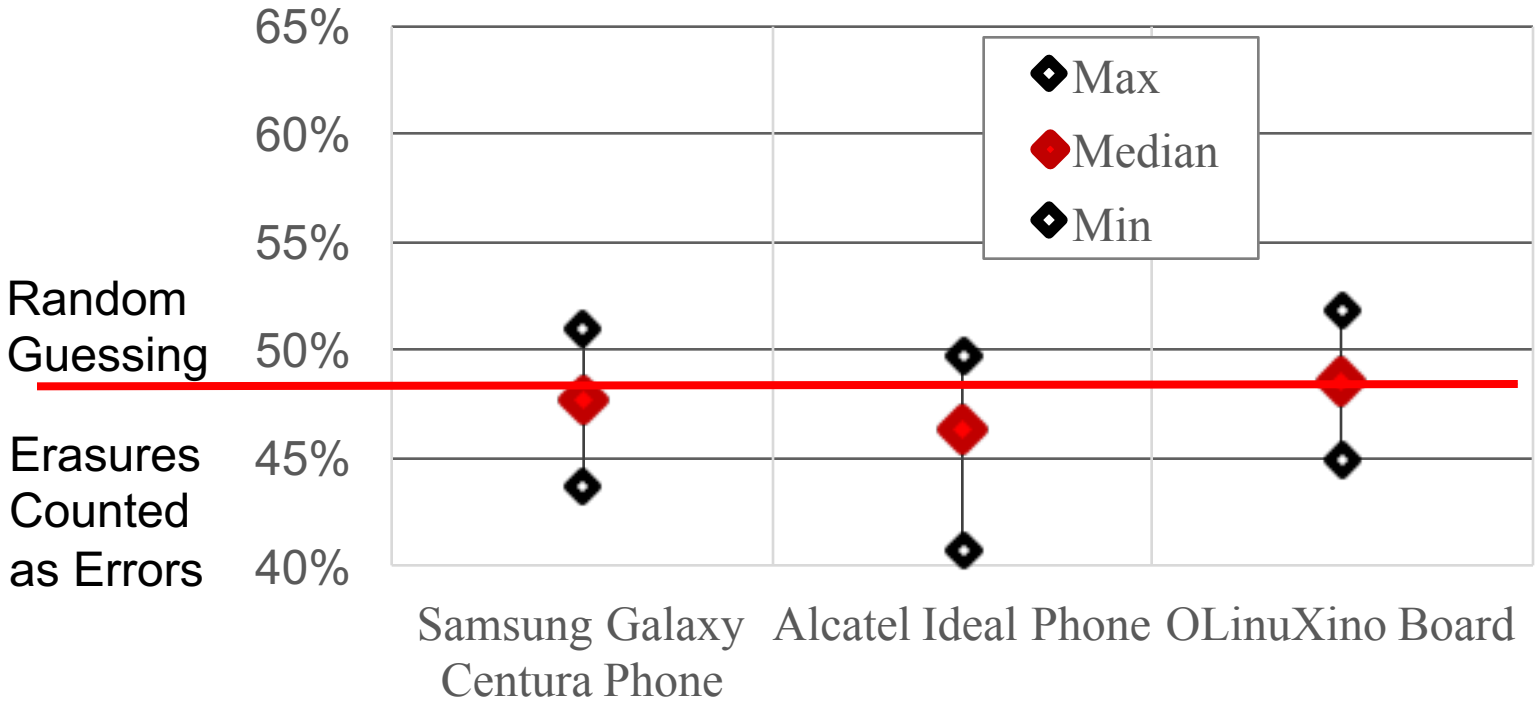
❖More in the paper

- Train on one device, attack another
  - Only slightly worse than same-device (still 100% key recovery)
- Similar attack on sliding-window implementation
  - Used in prior versions of OpenSSL
    - Prior attacks extract enough bits to sometimes allow full-key recovery
  - One&Done recovers nearly all bits in one private-key encryption, recovered full key every time

❖Mitigation

- Fundamental enabler of the attack
  - Several instructions have very few possibilities for their operands
    - BN_is_bit_set returns either 0 or 1
- No need to get bits one at a time
  - A 5-bit fixed window needs 5 consecutive bits
    - Don't have to get them one at a time and shift into wval
  - So we take an entire word's worth of bits each time, mask to window-size only before wval is needed
  - Takes only a little longer than getting one bit!
  - But done only once per window!

❖Results after mitigation



❖Conclusions

- Analog side-channel attack on OpenSSL's constant-time modular exponentiation implementation
  - Precise timing thanks to constant-timeness of the implementation
  - Highly accurate thanks to one-secret-bit-at-a-time implementation
- Entire private key recovered from only one use of that key
- Attack not affected by blinding
  - Attack directly obtains exponent bits, message bits not relevant
  - Exponent blinding does not help agains single-trace attacks
- Mitigation: look up groups of secret bits, not individual bits

Thank you!

Questions?