Leakage Resilient Cryptography: a Practical Overview

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Side-Channel Attacks

- Take advantage of physical information leakage
- Leakage is device-dependent
- But any device shows leakage
- Less generic but more powerful than computational (e.g., linear, differential) cryptanalysis
Exemplary attack against the DES

- The Data Encryption Standard
- FPGA implementation, loop architecture

(a) DES (b) f function
Exemplary attack against the DES

1. Input selection: random plaintexts
2. Internal values derivation
3. Leakage modeling (Hamming weights)
Exemplary attack against the DES

4. Leakage measurement
5. Leakage reduction (select representative samples)
Exemplary attack against the DES

- In practice, power consumption vs. EM radiation
Exemplary attack against the DES

6. Statistical test
   ▶ e.g. correlation coefficient

<table>
<thead>
<tr>
<th>Key[0…5]</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>corr</td>
<td>-0.09</td>
<td>0.05</td>
<td>0.32</td>
<td>-0.11</td>
</tr>
</tbody>
</table>

![Graph showing correlation between number of measurement queries and correlation]

- correct key candidate
Improved attacks

- Adaptive selection of the inputs
- Pre-processing of the traces (e.g. averaging, filtering)
- Improved leakage models by profiling, characterization
- Exploitation of multiple samples, multivariate statistics
  - Higher-order attacks
  - Template attacks
- Different statistical tests
  - Difference of mean
  - Correlation analysis
  - Bayesian classification
- ...
Countermeasures

- Implementation level (CHES-like), e.g.
  - Masking
  - Dual-rail logic styles
  - Time randomization

- Cryptographic level (TCC-like), e.g.
  - Physically observable crypto [MR04]
  - Leakage-resilient cryptography [DP08]
  - Bounded retrieval model [CLW06,D06]
  - Auxiliary input model [DKL09]
Countermeasures

- Goal: under certain conditions, the attacks’ complexity should increase exponentially with a security parameter

- e.g. masking: security against DPA increases exponentially in the number of shares (given a sufficient amount of noise in the measurements)

- Cryptographic level’s big claim: consider all PT adversaries (rather than some ad hoc ones)

- Note: evaluation ad hoc SCAs is not trivial [SMY09]
Crypto level’s pros

- More formal security guarantee
- Design crypto with SCAs in mind can help, e.g.

ANSI X9.17 PRG vs. stateful PRG

⇒ Ask less to HW designers (protect 1 vs. q iterations)
Open issues in leakage resilience

“Does leakage resilience capture practical SCAs?”

- Issue 1: cost
- Issue 2: assumptions
  - A1. Polynomial time vs. AC0 leakage functions
  - A2. Adaptive vs. non adaptive leakage functions
  - A3. Random oracle based assumptions
  - A4. Limited information leakage
    - Bounded space
    - HILL pseudoentropy
    - Auxiliary input, seed preserving, ...
Open issues in leakage resilience

- Issue 2: assumptions (cont.)
  - A5. Independent leakage
  - A6. Only computation leaks
  - A7. Simulatable leakage
  - A8. Secure precomputations
- Issue 3: instantiation
- Issue 4: initialization
- Issue 5: untight bounds

This talk’s goal: try to formalize engineering constraints
Issue 1: cost
Issue 1: cost

- SCAs are a threat for low cost devices
- We need low cost countermeasures
- Implementation cost usually left out of analysis
- Cryptographers’ (fair) answer:
  “today’s expensive is tomorrow’s low cost”
- Well... let’s leave it out for now...
- (needs to be related to the instantiation issue)
Issue 2: assumptions

A1. Polynomial time vs. AC0 leakage functions
A2. Adaptive vs. non adaptive leakage functions
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Poly. time vs. AC0 leakage functions

- Polynomial time leakage functions [MR04]
  - Overly strong adversaries: allows “future computation attacks”, i.e. leak one bit of $k_3$ while computing $k_1$

- Leakage function in the complexity class AC0 [F+10]
  - Do not capture the actual physics (see slide 34)
  - e.g. no coupling (inner product) possible
Poly. time vs. AC0 leakage functions

- Summarizing: one is too strong, the other too weak
- Leakage functions cannot compute dozens of SHA3
- But they solve Maxwell’s equations!
- e.g. on a standard desktop, simulating the power consumption of a single AES encryption with SPICE is much more complex than encrypting this plaintext
- Bounding the complexity of leakage functions hardly captures the realities of physical implementations
- Leakage functions are not simple, but they perform specific operations (like in the generic group model)
Issue 2: assumptions

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Adaptive leakage functions?

- Makes the adversary even stronger
  - e.g. allows one to accumulate several pieces of information leakage on the same future state
- Implies design tweaks to prevent the attack
  - e.g. alternating structure [DP08], [P09]

- Not efficient (doubled seed) and looks artificial
Adaptive leakage functions?

- In practice, the leakage function is usually a property of the target device (if the measurement setup is fixed)
- Only EM attacks allow moving the antenna on-the-fly
- More critical: the adaptivity of the leakage function anyway has to be prevented during initialization
  - Or full key leakage is possible with reset attacks
- Summarizing: non-adaptive leakages are more realistic
- The possible adaptivity of the meas. setup is better captured by increasing the information leakage (A4)
Adaptive leakage functions?

▶ + non adaptive leakage functions allow limiting the tweaks to face future computation attacks
▶ e.g. by using two public values $p_0, p_1$ chosen independently of the leakage function [YSPY10]

▶ Also needed in PRF constructions [S+09,DP10]
Issue 2: assumptions

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Random oracle based assumptions

- Assume PRG is a random oracle that can be queried by the adversary but not by the leakage function
- Allow proving “natural” constructions

- (with empirically verifiable assumptions, see later)
- (even with tight bounds [S+09], [YSPY10])
Random oracle based assumptions

- Summarizing: ROs are undesirable in theory
- But we use them differently than in black box proofs
  - + ROs allow capturing many physical intuitions
  - + they discriminate good and bad re-keying schemes
- Useful as a preliminary step (or more?)
Issue 2: assumptions

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Bounded space

- \( y = \text{AES}_k(x) \sim l \) with \(|l|\) bounded
- But Adv. typically acquires data in the Gs/s rate
- \( \exists \) as many traces as there are \( x \) and \( k \)’s
Bounded space

- Summarizing: completely unrealistic
- Intuitively, leakages can be made of Gbits of data, but exploiting them may still be difficult...
HILL pseudoentropy

- Informally: $H_{\epsilon, s}^{HILL}[X|L] \geq n$ if $\exists$ a distribution $Y$ such that $H_{min}[Y|L] = n$ and $Y$ is hard to distinguish from $X$ with size $s$ and advantage $\epsilon$

- Assumption in [DP08]: $H_{\epsilon, s}^{HILL}[X|L] \geq n - \lambda$

- Can we guarantee this?

- Let $y_1 = AES_{k_1}(x) \rightsquigarrow l_1$ and $y_2 = AES_{k_2}(x) \rightsquigarrow l_2$. Having high HILL pseudoentropy requires that, given $l_1, l_2$ and $k_i$, it remains hard to predict $i$
HILL pseudoentropy

- e.g. $L(k) = k[0 \ldots 7]||H(k)$ implies $H^{HILL}_{\epsilon,s}[K|L] = 0$

- But it typically corresponds to a practical SCA, where the adversary predicts 8 bits (out of $n$) and the remaining bits constitute “algorithmic noise” (leakage that depends on a too large part of the key to be exploited in a divide-and-conquer attack)

- Summarizing: very hard to guarantee in practice
Intuitively

- Requires to secure the implementation against adversaries with infinite guessing power

![Diagram showing plaintext and ciphertext diffusion and limited key guess](image-url)
Auxiliary input / unpredictability

- Given $L(k)$ it remains difficult to predict (one bit of) $k$
- Most natural type of assumptions
- Closely connects to actual SCAs
- But does not allow proving useful constructions (e.g. stream ciphers) in the standard model (up to now)
- Alternative: combine seed-preserving leakages with a RO based assumption [S+09], [YSPY10]
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Independent leakages

- More precisely: \( \perp \) computations \( \Rightarrow \perp \) leakage
- Not correct at the gate level (to appear in EC2011)
- \( L(x) = \sum \alpha_i x[i] + \sum \beta_{i,j} x[i] x[j] + \ldots (\neq AC0) \)
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Only computation leaks

- Formally incorrect as devices scale below 65nm
- But static leakage still orders of magnitude smaller
- Summarizing: would be nice to include in the model
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Simulatable leakage

- \( \exists \text{ SIMU} \) such that \( \text{AES}_k(x) \sim l, \text{SIMU}(x) \sim l' \) and \((l, x)\) is hard to distinguish from \((l', x)\)?

- A proposal for block ciphers:
  1. Pick up \( r' \leftarrow \{0, 1\}^k \);
  2. Perform \( y'_0 = \text{AES}_{r'}(0) \sim l'_a||l'_a \);
  3. Compute \( x'_0 = \text{AES}^{-1}_{r'}(y'_0) \);
  4. Perform \( y'_0 = \text{AES}_{r'}(x'_0) \sim l'_b||l'_b \);
  5. Return \( l'_0 = l'_a||l'_b \);

- (requires to concatenate traces)
Simulatable leakage

- Harder to achieve than seed-preserving $L$
- But easier to achieve than HILL pseudoentropy
- Is it useful?

![Graph showing leakage over time samples]

<table>
<thead>
<tr>
<th>Executed operations</th>
<th>Leakage dependencies</th>
</tr>
</thead>
<tbody>
<tr>
<td>read $x$</td>
<td>$L \propto x$</td>
</tr>
<tr>
<td>compute $y = AES_k(x)$</td>
<td>$L \propto (x,k)$ or $L \propto (y,k)$</td>
</tr>
<tr>
<td>write $y$</td>
<td>$L \propto y$</td>
</tr>
</tbody>
</table>
### Issue 2: assumptions

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Secure precomputations

- Assume that the target device is sometimes operated in a secure environment, for refreshing
- e.g. one-time programs [GKR08]
- (or recent FOCS models [BKKV10,DHLW10])
- Can give rise to very simple intuitions
Secure precomputations

- e.g. Boolean masking: $x \rightarrow x \oplus m_1 \oplus m_2 \oplus \ldots$
- Adversary can only recover $x$ from the joint distribution: $(L(x \oplus M_1 \oplus M_2), L(M_1), L(M_2))$
- (so-called higher-order attacks)
Secure precomputations

- Now precompute $g_a(x, m) = x \oplus m \oplus a$
- (which requires storing a $2^n \times n$ lookup table)
- The $a$ share is only manipulated during precomputation
- Perfect security if “only computation leaks”
- Can be extended towards complete ciphers
- Not efficient but trivial proofs
- Strong assumption $\Rightarrow$ strong security
- Are there better tradeoffs?
Issue 3: instantiation
Issue 3: instantiation

- **wPRF-based stream cipher [P09]**

  ![Diagram of wPRF-based stream cipher]

- **Extractor+PRG-based stream cipher [DP08]**

  ![Diagram of Extractor+PRG-based stream cipher]
AES-based wPRF and PRG
Summary

- 2 constructions
- [DP08] as significantly tighter reductions than [P09]
- Both are proven leakage resilient in the standard model, if the leakage per iteration is bounded to $\lambda$ bits

- Open question: is an instance of [DP08] indeed more resistant against a standard DPA than an instance of [P09]? Or: how does the leakage of an extractor compare to the one of the wPRF and PRG?
Case study

1. [DP08] stream cipher components:
   - Length tripling PRG instantiated with AES:
     \[ \text{PRG} : \{0, 1\}^n \mapsto \{0, 1\}^{3n} : x \mapsto (\text{AES}_x(c_1), \text{AES}_x(c_2), \text{AES}_x(c_3)) \]
     - Extractor can be instantiated, e.g. with Vazirani 1987.
     - \((i.e., \text{we extract 128 bits from two 196-bit sources})\)

2. 8-bit device, Hamming weight leakages, Gaussian noise
   \( \Rightarrow \) Which one is the weak point in the stream cipher?
AES implementation

- Well known target for SCA
- PRG runs three AES computations
- Standard DPA: typically exploits one/two leaking points per AES computation (e.g. the key addition and/or S-box computation in the first round)
Leaking extractor implementation

\[ A_i \]

\[ \begin{array}{c}
  x \\
  x_i^1 \\
  x_i^2 \\
  x_i^3 \\
\end{array} \]

\[ \begin{array}{c}
  128 \\
  y^1 \\
  y^2 \\
  y^3 \\
\end{array} \]

\[ \begin{array}{c}
  z_i^1 \\
  z_i^2 \\
  z_i^3 \\
\end{array} \]

\[ WH(z_i^1), WH(z_i^2), WH(z_i^3) \]

\[ b_i \]
Main observations

- AES: 2 exploitable operations per key byte
- Extractor: 128 exploitable operations per secret byte
- AES: extensive use of bitwise XOR
- Extractor: extensive use of bitwise AND
Attack results

\( \sigma_n = 0.5 \)

\( \sigma_n = 1 \)

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0 5 10 15 20 25 30 35 40 45 50

success rate

number of queries / elementary operations

0 20 40 60 80 100 120

success rate

number of queries / elementary operations

extractor

AES S-box

AES S-box + XOR

extractor

AES S-box

AES S-box + XOR
Summarizing

- $\lambda$-bit per AES iteration $\ll \lambda$-bit per Ext. iteration
- [DP08] has better security bounds than [P09]
- . . . but it is easier to attack with standard DPA
- The use of extractors can be paradoxical
- Similar to the general problem of trading security parameters (e.g. $(\epsilon^{1/3}, s)$ vs. $(\epsilon, s^{1/3})$-secure PRGs)
Summarizing

- Results do not invalidate theoretical analyzes
- But show that their relevance to practice is limited
- Eventually, a useful construction needs to face the full complexity of side-channel attacks
  - i.e., not only assume $\lambda$-bit leakage but also find algorithms and implementations for which small leakages can be obtained: instantiation matters
- More research on extractors needed
- What about NIZK?
Issue 4: initialization

Stream ciphers need to be securely initialized

Only known solution is GGM tree [S+09,DP10]
**Issue 4: initialization**

- Stream ciphers need to be securely initialized
- Only known solution is GGM tree [S+09,DP10]
Issue 5: tight bounds
Issue 5: tight bounds

- Bounds in leakage-resilience are not tight \((\epsilon^{1/4}, \epsilon^{1/12})\)
- Security guarantees vanish with the iterations
- Summarizing: present proofs validate constructions but do not allow determining security parameters
- (excepted with RO-based assumptions)
Conclusions

- Cryptographer’s approach is too disconnected
- But implementation leakage and specificities are very difficult to capture with theoretical analysis
- Most problems remain open - no present solution is perfectly satisfying in theory and practice
- (we should not give up now)
Further research

- Always instantiate the proposed constructions
- If possible, implement (complexity matters!)
- Use empirically verifiable assumptions
- Find efficient initialization mechanisms
- Obtain tight bounds
THANKS

Questions?