Leakage Resilient Cryptography: a Practical Overview

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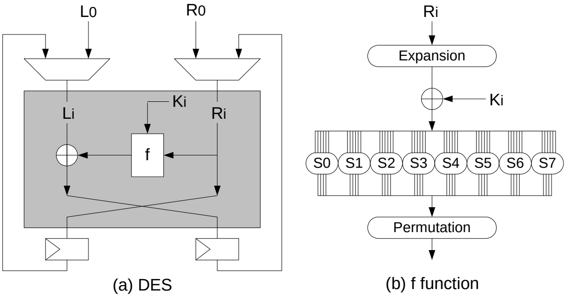
- Moti Yung
- Yu Yu
- ...

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

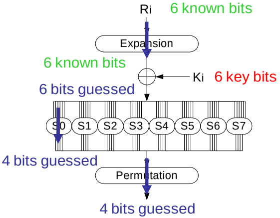
Exemplary attack against the DES

- The Data Encryption Standard
- FPGA implementation, loop architecture



Exemplary attack against the DES

1. Input selection: random plaintexts
2. Internal values derivation
3. Leakage modeling (Hamming weights)



Key[0…5]

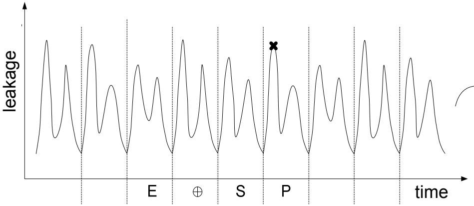
Ri	0	1	**2**	3
0	5	12	**7**	2
1	9	0	**12**	6
2	14	4	**1**	13
3	7	5	**5**	8
4	3	10	**15**	1

Key[0…5]

Ri	0	1	**2**	3
0	2	2	**3**	1
1	2	0	**2**	2
2	3	1	**1**	3
3	3	2	**2**	1
4	2	2	**4**	1

Exemplary attack against the DES

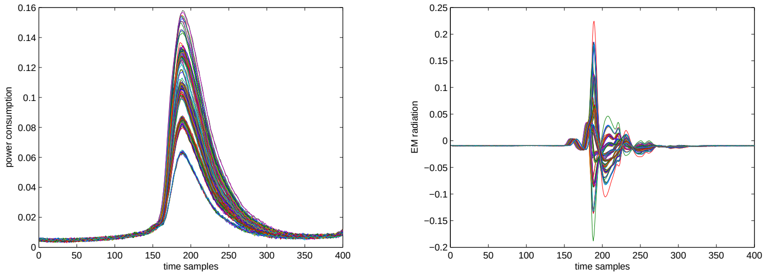
4. Leakage measurement
5. Leakage reduction (select representative samples)



P	R*(L)*
0	1.675
1	1.432
2	1.221
3	1.498
4	1.937

Exemplary attack against the DES

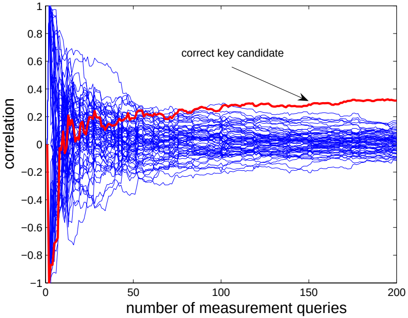
- In practice, power consumption *vs.* EM radiation



Exemplary attack against the DES

6. Statistical test
   - e.g. correlation coefficient

Key[0...5]	0	1	**2**	3
corr	-0.09	0.05	**0.32**	-0.11



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

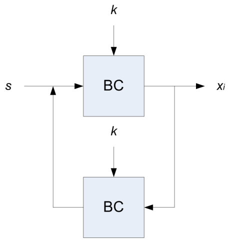
- Implementation level (CHES-like), e.g.
  - Masking
  - Dual-rail logic styles
  - Time randomization
- Cryptographic level (TCC-like), e.g.
  - Physically observable crypto [MR04]
  - Leakage-resilient cryptography [DP08]
  - Bounded retrieval model [CLW06,D06]
  - Auxiliary input model [DKL09]

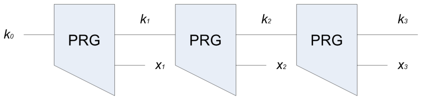
Countermeasures

- 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

$\Rightarrow$ 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

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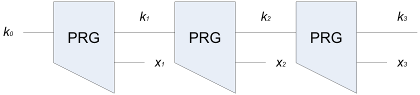
Poly. time vs. AC0 leakage functions

- 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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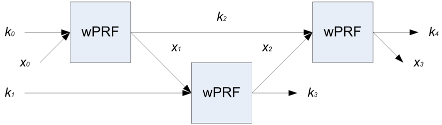
Adaptive leakage functions?

- 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]



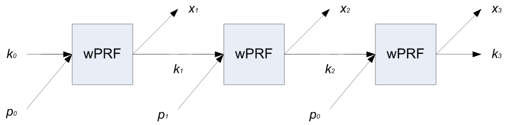
- Not efficient (doubled seed) and looks artificial

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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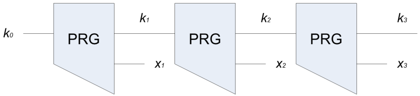
Random oracle based assumptions

- 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?)

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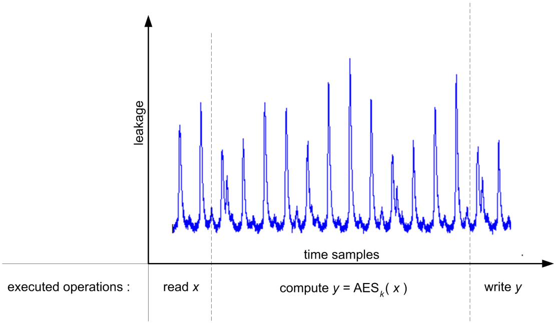
Bounded space

- $y = \mathrm{AES}_k(x) \rightsquigarrow l$ 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

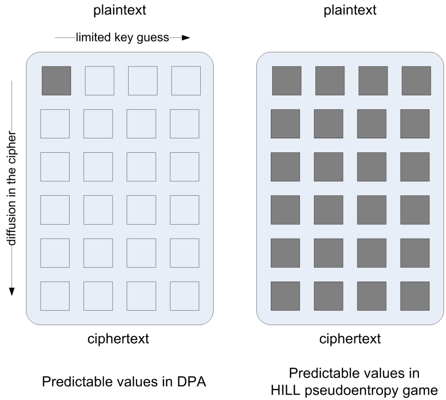
- Informally: $\mathrm{H}^{HILL}_{\epsilon,s}[X|L] \geq n$ if $\exists$ a distribution Y such that $\mathrm{H}_{min}[Y|L] = n$ and Y is hard to distinguish from X with size s and advantage ϵ
- Assumption in [DP08]: $\mathrm{H}^{HILL}_{\epsilon,s}[X|L] \geq n - \lambda$
- Can we guarantee this?
- Let $y_1 = \mathrm{AES}_{k_1}(x) \rightsquigarrow l_1$ and $y_2 = \mathrm{AES}_{k_2}(x) \rightsquigarrow l_2$. Having high HILL pseudoentropy requires that, given l_1, l_2 and k_i, it remains hard to predict i

HILL pseudoentropy

- e.g. $\mathsf{L}(k) = k[0\ldots7]||\mathsf{H}(k)$ implies $\mathrm{H}^{HILL}_{\epsilon,s}[K|L] = 0$
- 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



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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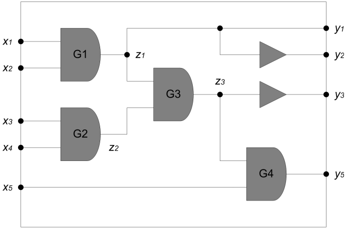
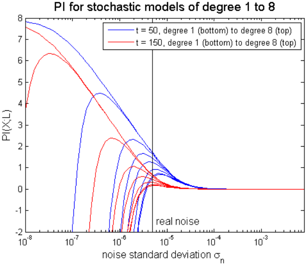
Independent leakages

- More precisely: $\perp\!\!\!\perp$ computations $\Rightarrow$ $\perp\!\!\!\perp$ 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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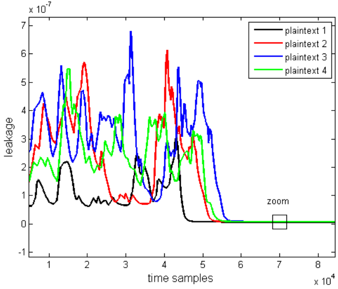
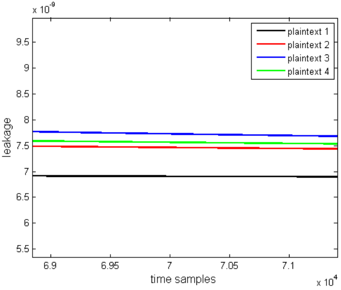
Only computation leaks

- 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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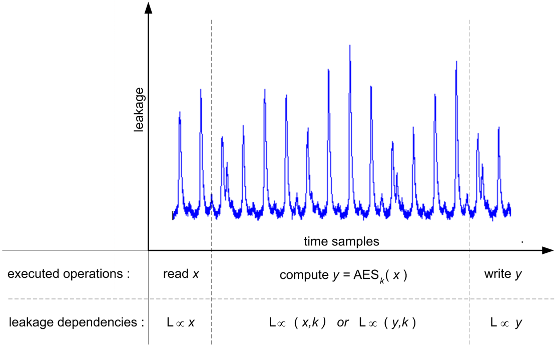
Simulatable leakage

- $\exists$? $SIMU$ such that $AES_k(x) \rightsquigarrow l$, $SIMU(x) \rightsquigarrow l'$ and (l, x) is hard to distinguish from (l', x)?
- A proposal for block ciphers:
  1. Pick up $r' \xleftarrow{R} \{0,1\}^k$;
  2. Perform $y''_0 = \mathrm{AES}_{r'}(0) \rightsquigarrow l_a^{in}||l_a^{out}$;
  3. Compute $x'_0 = \mathrm{AES}_{r'}^{-1}(y'_0)$;
  4. Perform $y'_0 = \mathrm{AES}_{r'}(x'_0) \rightsquigarrow l_b^{in}||l_b^{out}$;
  5. Return $l'_0 = l_a^{in}||l_b^{out}$;
- (requires to concatenate traces)

Simulatable leakage

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



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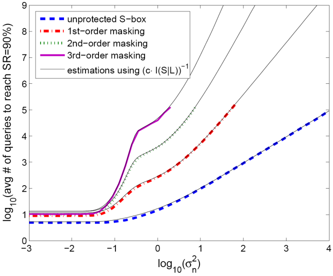
Secure precomputations

- 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: $x \to x \oplus m_1 \oplus m_2 \oplus \ldots$
- Adversary can only recover x from the joint distribution: $(\mathrm{L}(x \oplus M_1 \oplus M_2), \mathrm{L}(M_1), \mathrm{L}(M_2))$
- (so-called higher-order attacks)



Secure precomputations

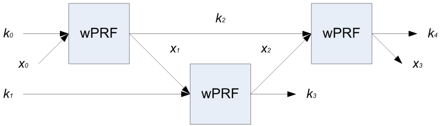
- Now precompute $g_a(x, m) = x \oplus m \oplus a$
- (which requires storing a $2^{2n} \times n$ lookup table)
- The a share is only manipulated during precomputation
- Perfect security if "only computation leaks"

- Can be extended towards complete ciphers
- Not efficient but trivial proofs
- Strong assumption $\Rightarrow$ strong security
- Are there better tradeoffs?

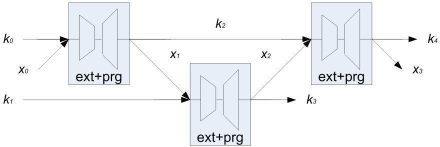
Issue 3: instantiation

Issue 3: instantiation

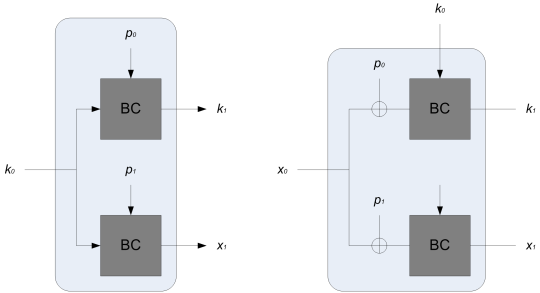
- wPRF-based stream cipher [P09]



- Extractor+PRG-based stream cipher [DP08]



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 λ 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:

$$\mathsf{PRG}: \{0,1\}^n \mapsto \{0,1\}^{3n} : x \mapsto \Big(\mathsf{AES}_x(c_1), \mathsf{AES}_x(c_2), \mathsf{AES}_x(c_3)\Big)$$

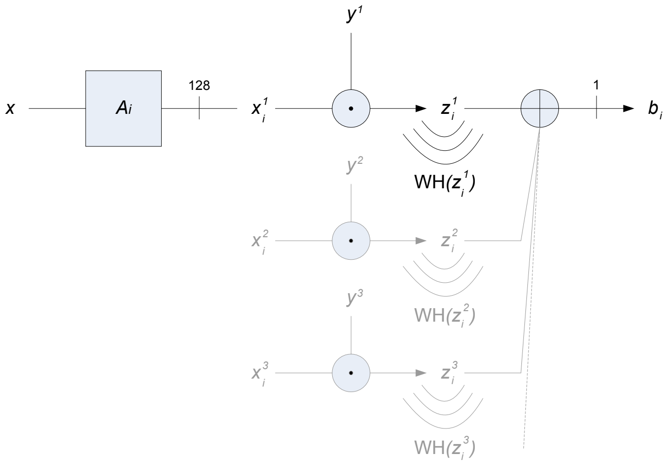
   - Extractor can be instantiated, *e.g.* with Vazirani 1987.
   - (*i.e.*, we extract 128 bits from two 196-bit sources)
2. 8-bit device, Hamming weight leakages, Gaussian noise

$\Rightarrow$ 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

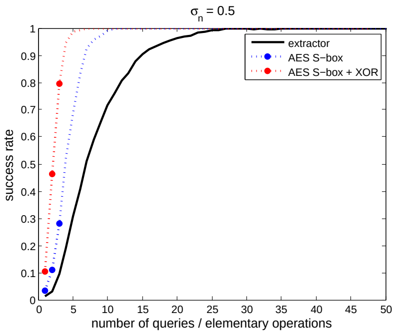


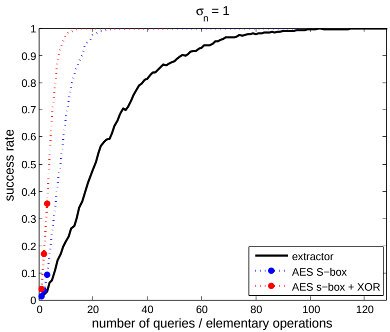
Main observations

- 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





Summarizing

- λ-bit per AES iteration $<<$ λ-bit per Ext. iteration
- [DP08] has better security bounds then [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)

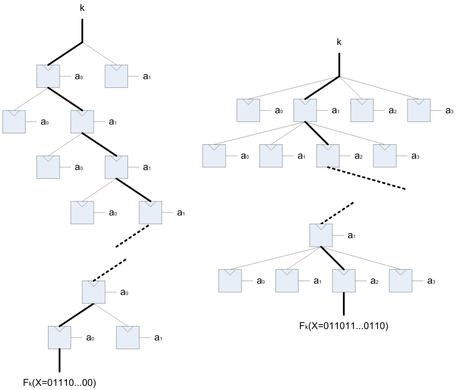
Summarizing

- 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 λ-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

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?