Introduction to Side Channel Analysis*

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Outline: Introduction to Side Channel Analysis

Not for distribution!

1. **Introduction: What are Side Channel Attacks?**
2. **Simple Power Analysis (SPA)**
3. **Timing Analysis (TA)**
4. **Differential Power Analysis (DPA)**
5. **Template Attacks**
6. **Differential Fault Analysis (DFA)**
7. **Electromagnetic Analysis (SEMA, DEMA)**
8. **Micro-Architectural Analysis**
9. **Side Channel Attacks — Conclusions**

The Dangerous Bend Sign: to mark any part that is "more obscure than others" with a "special symbol . . . to warn about esoterica" [D. Knuth]

1. Introduction: What are Side Channel Attacks?

The name of the game

> In cryptography, a **side channel attack** is any attack based on information gained from the physical *implementation* of a cryptosystem, rather than the weaknesses in the mathematical algorithms (compare cryptanalysis).
>
> From Wikipedia, the free encyclopedia.

Why are they important?

- Most efficient threats against smart cards, embedded systems and cryptographic hardware
- Much more efficient than classical methods of cryptanalysis
- Resistance to attacks mandatory for security certification (cf. Digital Tachograph / ITSEC E3 high)

Example: Attacks against DES

	Brute Force Search	DPA Analysis
time:	22 h (1999!)	approx. 20 min
hardware:	DES Cracker ($250000), 100000 computers	oscilloscope, standard equipment
Triple DES:	not feasible	approx. 1 h

Theory vs. Practice — What are cryptographic side channels?

Theoretical Cryptography — Algorithm:

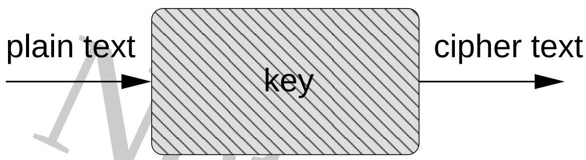
- Mathematical specification of algorithms (exact definition of input, output and attack potential)
- Attacker exploits theoretical weaknesses of algorithm

Practical Cryptography — Implementation:

- Even strong algorithms can be implemented the wrong way
- Attacker gathers additional information from physical *side channels*
  - run-time of operations
  - power consumption
  - electromagnetic radiation
  - behaviour under fault conditions

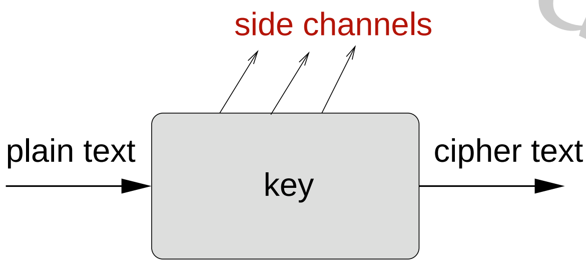
  and exploits them for attacking the implementation
- Meaningful modeling of side channels is difficult

Encryption (Black Box Model)



For state-of-the-art algorithms, brute force search is the most efficient attack method $\Longrightarrow$ Use large key space such that brute force is impractical!

Encryption (Side Channel Model)



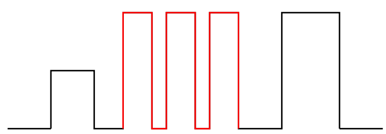
Using side channel information, one can attack interim results which depend only on a few key bits (sub key), i. e., brute force attack on sub keys becomes possible!

Example: Verification of a secret PIN

```
const char top_secret[] = "44250382";
printf("Enter␣PIN:␣");
scanf("%8s", input);
for (i = 0; i < strlen(top_secret); i++)
if (top_secret[i] != input[i]) {
  printf("Wrong␣PIN.\n");
  return FALSE;
}
printf("PIN␣correct.\n");
return TRUE;
```

Possible side channels:

- Run-time between input and response
- Power consumption profile of loop:



Theory: 8-digit PIN, 10 potential trials per digit $\Longrightarrow 10^8$ experiments for brute force search

Practice: unskilled implementation — *perform* 10 *experiments successively per digit*
$\Longrightarrow 10 + \cdots + 10 = 80$ potential experiments

Effort reduction from 100.000.000 to 80!

The most important side channels and their attacks

- **Run-time**
  - **Timing Analysis (TA):** statistical evaluation of run-time variations
  - **Cache Attacks:** information leakage through memory caches
- **Power consumption**
  - **Simple Power Analysis (SPA):** *direct* interpretation of power consumption during *one* cryptographic operation
  - **Differential Power Analysis (DPA):** statistical evaluation of power traces from *many* operations
  - **Template Attacks:** combine techniques from SPA and DPA. Training device (full control of attacker) for exact characterization, *direct key extraction* on target device
- **Electromagnetic fields**
  - **Electromagnetic Analysis (SEMA, DEMA):** evaluation of electromagnetic radiation during cryptographic operations
- **Behaviour under fault conditions**
  - **Differential Fault Analysis (DFA):** exploit faulty results

History of Side Channel Attacks

Cryptography in military/authorities

- Measurement of emissions and application of countermeasures standard practice for a long time
- Focus: correlation between *plain text* and *side channel information*
- Extent of expertise not clear, only a few documents freely available, see TEMPEST

Rediscovery of attack technique by P. Kocher et al.

- 1996 Timing Analysis, 1997 Differential Fault Analysis, 1997 Differential Power Analysis
- Basic idea: find correlation of *key material* with *side channel information*

Status of SCA

- Side channel attacks and countermeasures are active research area
- Many publications about attacks on implementations of common algorithms
- Resistance to side channel attacks is mandatory for security certification with mechanism strength “high”

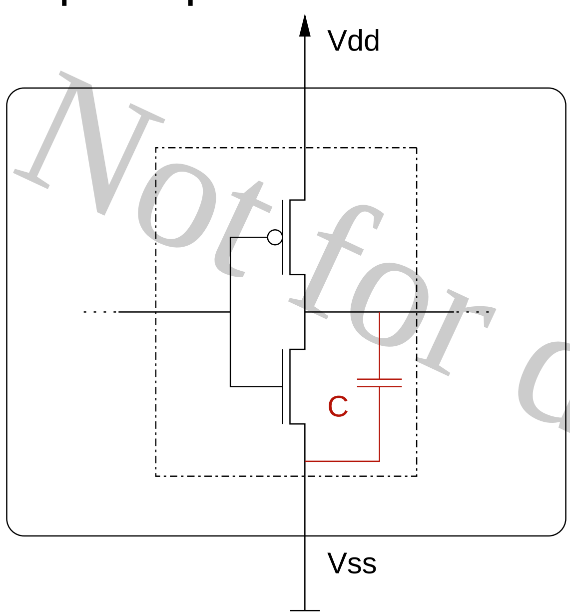
2. Simple Power Analysis (SPA)

Methodology, Assumptions and Goals:

- Collect *one power profile* and *directly extract/compute the secret key*
- Requires oscilloscope and standard equipment $\Rightarrow$ relatively easy to perform
- Normally, the attacker requires *detailed knowledge of implementation* to understand the power profile
- SPA gives information on:
  - data dependent switches, calls of subprograms
  - Hamming weights/Hamming distances of registers as well as data on address and data busses
- Exact power leakage model is architecture dependent!

Power side channel is intrinsic to CMOS technology

Example: Simplest circuit = inverter



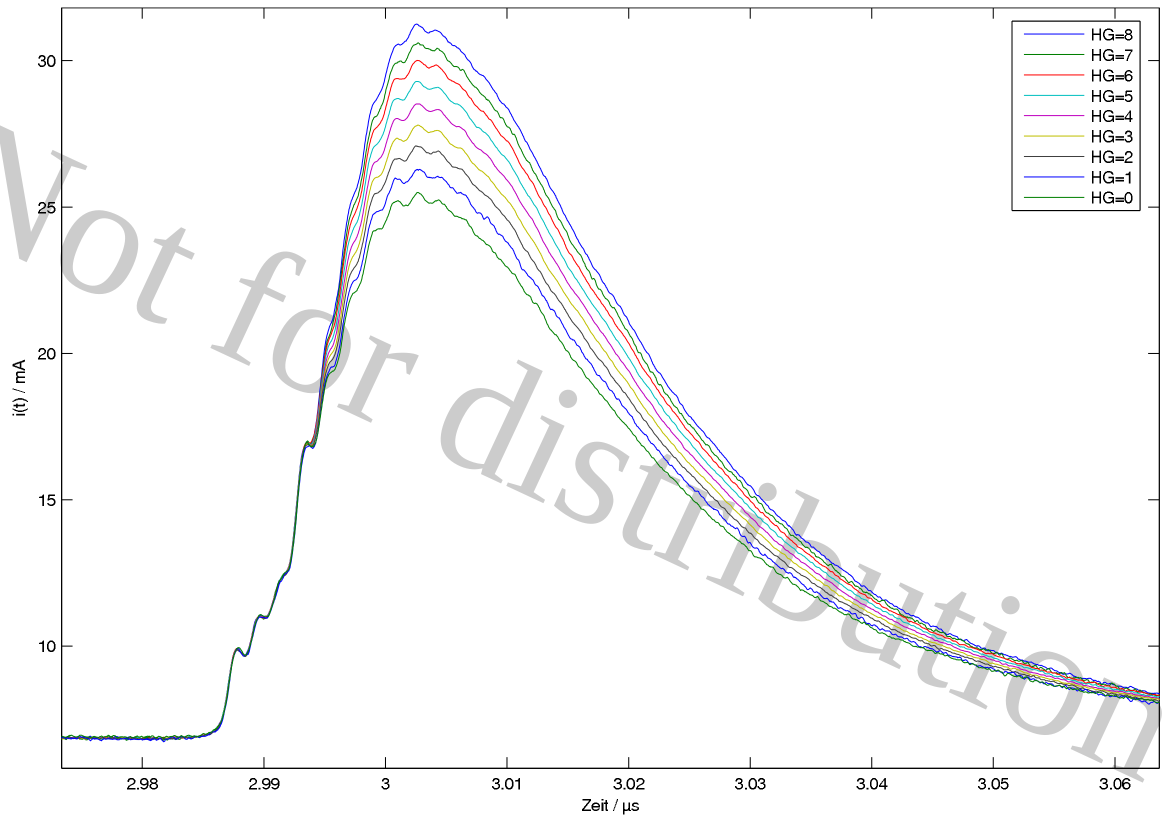
Parasitic capacity C (geometry of wires) results in charging current

Flow through a CMOS-Inverter

transition	current flow
$0 \to 0$	only leakage current
$0 \to 1$	leakage current, short circuit and charging current
$1 \to 0$	leakage current, short circuit current
$1 \to 1$	only leakage current

For different Hamming weights consider above circuit diagram in parallel
$\Longrightarrow$ charging current is data dependent!

Data dependency of power profiles from Hamming weight of data



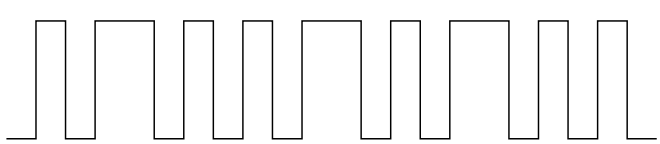
Example: SPA of a simple RSA implementation

RSA implementation with Square-and-Multiply Algorithm (left-to-right binary exponentiation):

$c = b^e \bmod m$, base b, secret exponent $e = (e_1, \ldots, e_k)$, modulus m

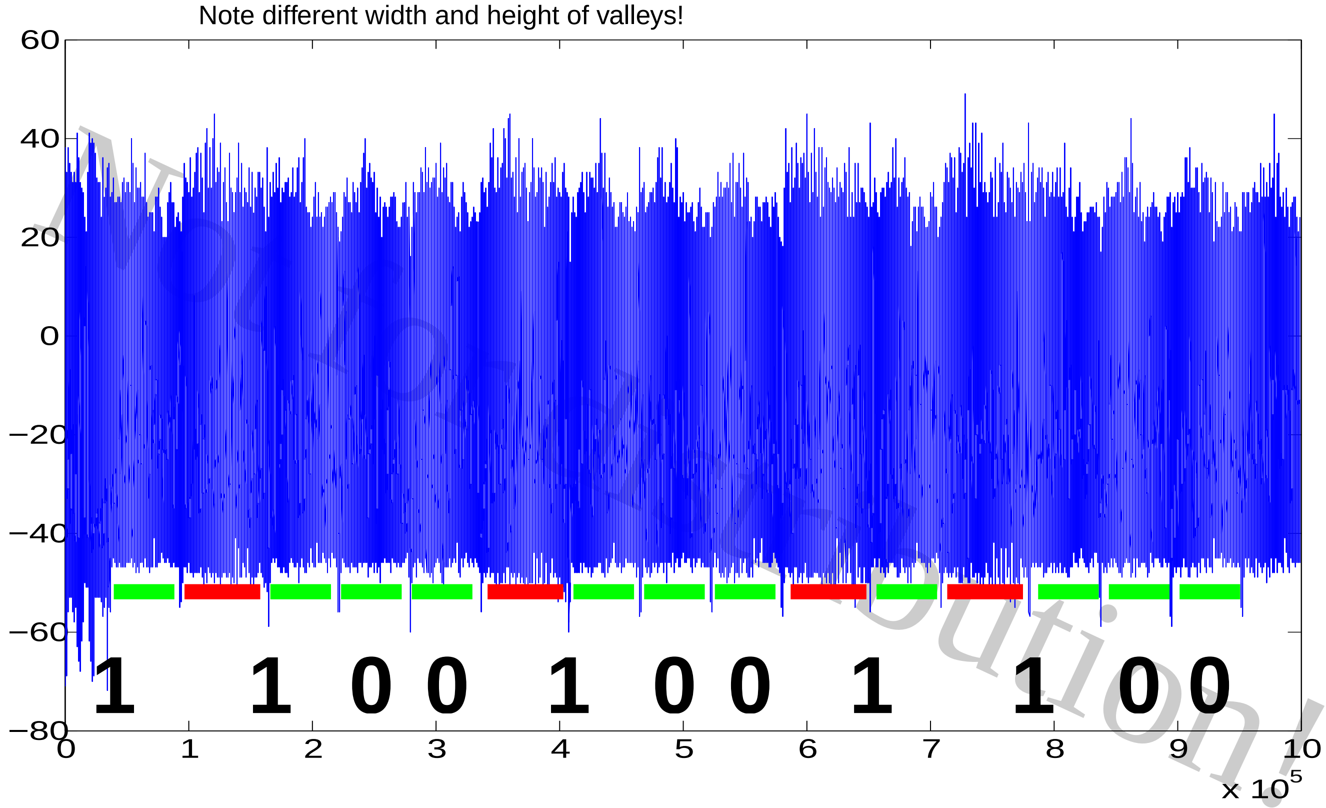
```
c = 1;
for (i = 1; i <= k; i++) {
  c = mod_square(c, m); /* c <- c*c mod m */
  if (e[i] == 1)
    c = mod_mult(c, b, m); /* c <- c*b mod m */
}
```

Schematic power profile for Square-and-Multiply:



Power profile of Square-and-Multiply Algorithm on ST10F168

Note different width and height of valleys!



General countermeasures against SPA

- Decrease signal-to-noise ratio (random noise, dual rail logic, pre-charge logic)
- Hide implementation details
- Avoid key dependent branches, try to achieve uniform behaviour $\Longrightarrow$
  - redundancy: always-square-and-multiply
  - uniform algorithm: Montgomery Powering Ladder
  - defensive programming of branches
- Effective countermeasures (for a medium/high security level) are only possible with hardware and software together

3. Timing Analysis (TA)

- Uses key dependent run-time variations
- Requires *exact emulation of run-time!*
- Easier to implement than DPA, but less powerful

Example: Attack over Ethernet-LAN on OpenSSL = Remote Timing Attack

- D. Boneh/D. Brumley: *Remote Timing Attacks are Practical*, Usenix 2003.
- Based on W. Schindler: *A Timing Attack against RSA-CRT*, CHES 2000.
- Attack on RSA-CRT, Sliding Windows, Montgomery Multiplication, Karatsuba
- Requires for 1024 bit RSA: 1 mio decryptions, 2 h
- Attack can be drastically improved (personal communication with W. Schindler, papers in Statist. Decisions 2002 and 12th ACM Conf. on CCS 2005)

$\Longrightarrow$ Boneh/Brumley paper resulted in a number of Prio 1 Security Advisories e. g. for OpenSSL
$\Longrightarrow$ **Side Channel Resistance is important even for distant servers!!**

Math refresher: Background on stochastic/statistics

Let X be a random variable with cumulative distribution function F_X and probability density function f_X.

Sample: $(x_1, \ldots, x_n)$ realization of random variable $(X_1, \ldots, X_n)$

Standard assumption: random variables X_i, $i = 1, \ldots, n$ are i.i.d. (independent, identically distributed)

Expected value: $\mathrm{E}\,X := \int_{-\infty}^{\infty} x\, dF_X(x)$, continuous $\int_{-\infty}^{\infty} x f_X(x)\, dx$,
discrete $\sum_i x_i P(X = x_i)$

Variance: $\mathrm{Var}\,X := \mathrm{E}(X - \mathrm{E}\,X)^2 = \int_{-\infty}^{\infty} (x - \mathrm{E}\,X)^2\, dF_X(x)$
continuous $\int_{-\infty}^{\infty} (x - \mathrm{E}\,X)^2 f_X(x)\, dx$,
discrete $\sum_i (x_i - \mathrm{E}\,X)^2 P(X = x_i)$

expected value = measure of location, variance = measure of dispersion

Math refresher: Background on stochastic/statistics (2)

- Unbiased estimators for expected value and variance

$$\bar{X} = \frac{1}{n}\sum_{i=1}^{n} X_i \qquad \text{mean}$$

$$\hat{\sigma}^2 = \frac{1}{n-1}\sum_{i=1}^{n} \left(X_i - \bar{X}\right)^2 \qquad \text{sample (empirical) variance}$$

- Normal distribution $N(\mu, \sigma^2)$
  probability density function:

$$f_X(x) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left(-\frac{(x-\mu)^2}{2\sigma^2}\right)$$

$\mathrm{E}\,X = \mu$ expected value, $\mathrm{Var}\,X = \sigma^2$ variance

Example: Timing Analysis Square-and-Multiply (Kocher[96])

Assumption: bits $e_1, \ldots, e_{d-1}$ of exponent are already known, e_d will be attacked

1. Measure run-time T_i for N modular exponentiations with random (known) base b_i, $i = 1, \ldots, N$
$$T_i = T\left(b_i^e \bmod m\right)$$
2. For $e_d = 0$: Compute (via emulation) time $T_{i,d}^0$ until bit e_d is reached
   Compute variance $V_0 := \mathrm{Var}(T_i - T_{i,d}^0)$
3. For $e_d = 1$: Compute (via emulation) time $T_{i,d}^1$ until bit e_d is reached
   Compute variance $V_1 := \mathrm{Var}(T_i - T_{i,d}^1)$
4. Decision rule
$$e_d = \begin{cases} 0 & \text{if } V_0 < V_1, \\ 1 & \text{else.} \end{cases}$$

Why does the attack work?

- **Observation:** Wrong guess of bit e_d leads to increasing empirical variance!
- **Proof:** Elementary operations with variances, see next slide

Proof: Why does the Timing Attack work?

- Time to compute $b_i^e \bmod m$: $T_i = c_i + \sum_{j=1}^{k} t_{i,j}$
- $t_{i,j}$ — time for j-th iteration of exponentiation for base b_i, $\tilde{t}_{i,d}$ — emulated time for step d, c_i — measurement error, noise
- Can be computed via emulation:

$$T_{i,d} = \sum_{j=1}^{d-1} t_{i,j} + \tilde{t}_{i,d} = \sum_{j=1}^{d} t_{i,j} \quad \text{if bit } e_d \text{ is known}$$

- Assumption: run-times are i.i.d. random variables
- Distinction of cases

  Case 1: guess for e_d is correct

$$\begin{aligned}\mathrm{Var}(T_i - T_{i,d}) &= \mathrm{Var}\left(c_i + \sum_{j=1}^{k} t_{i,j} - \sum_{j=1}^{d} t_{i,j}\right) = \mathrm{Var}\left(c_i + \sum_{j=d+1}^{k} t_{i,j}\right)\\ &= \mathrm{Var}(c) + (k-d)\,\mathrm{Var}(t)\end{aligned}$$

Proof: Why does the Timing Attack work? (2)

- Case 2: guess for e_d is wrong

$$\begin{aligned}\mathrm{Var}(T_i - T_{i,d}) &= \mathrm{Var}\left(c_i + \sum_{j=1}^{k} t_{i,j} - (\tilde{t}_{i,d} + \sum_{j=1}^{d-1} t_{i,j})\right)\\ &= \mathrm{Var}\left(c_i - \tilde{t}_{i,d} + \sum_{j=d}^{k} t_{i,j}\right)\\ &= \mathrm{Var}(c) + (k-d)\,\mathrm{Var}(t) + 2\,\mathrm{Var}(t)\end{aligned}$$

Note: $\mathrm{Var}(t) + \mathrm{Var}(-\tilde{t}) = \mathrm{Var}(t) + (-1)^2\,\mathrm{Var}(\tilde{t}) = 2\,\mathrm{Var}(t)$

- **Observation:** Wrong guess of bit e_d leads to increasing empirical variance!

General Countermeasures against TA

- Algorithms with constant run-time
- Random variations of run-time/random wait states
- Masking of data (prohibits emulation of run-times)

  $\Longrightarrow$ “base point blinding” = Chaum’s blind signatures for $c = b^e \bmod m$:

  - Choose random number λ and compute $\mu = (\lambda^{-1})^e \bmod m$
  - Blinding of message $\hat{b} = \lambda b \bmod m$
  - Exponentiation $\hat{c} = \hat{b}^e \bmod m$
  - Unblinding $c = \mu \hat{c} \bmod m$
  - Efficient Updating of (λ, μ) necessary

  Chaum’s blind signatures have been developed for e-Money in 1982
- Masking of exponent and modulus, see DPA

4. Differential Power Analysis (DPA)

Methodology, Assumptions and Goals:

- *Several measurements of power consumption* while performing cryptographic operations and *statistical evaluation* of data dependent variations to extract secret keys
- Requires oscilloscope to acquire power profiles, PC with evaluation software, standard equipment
- *Does not require detailed knowledge of implementation*: It suffices, if certain values are computed at any time somehow or other
- DPA uses statistical methods to increase/amplify the weak signals of individual bits of sub keys in the power traces

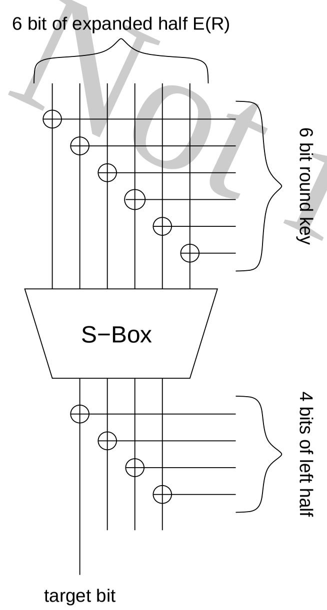
Basic Prerequisites for Differential Power Analysis

1. Physical access to processor/board to measure power consumption during cryptographic operations
2. Known plaintext or known ciphertext
3. **One intermediate result that occurs during the cryptographic operation is a function of the cipher-/plaintext and a small number of key bits.**
4. The power consumption of the device is data dependent.

S. Mangard, PhD thesis, 2004

Example: Standard DPA on DES Implementation

Attack first output bit of first S-box in first round of DES Encryption: $(R_0, L_0 \oplus P(S(E(R_0) \oplus K_0)))$



- R_0 and L_0 are known to the attacker (known plaintext attack), trial and error for round key K_0 (only $2^6 = 64$ values!)
- For all possible values of K_0: divide measured power traces into two sets, set C^0 ("target bit is 0") and C^1 ("target bit is 1")
- Compute difference D between mean value of power traces from C^0 and mean value of power traces from C^1
- Value of K_0 with highest peak of D is most probable round key for this S-box
- Repeat attack with other S-boxes

Described attack: difference of means, Kocher attack (1998)

Example: Standard DPA on DES Implementation — detailed —

1. Encrypt N random known plaintexts Y_i, $i = 1, \ldots, N$
   Collect discrete time-power-profile C_i

$$C_{ij} = \{ \text{ power consumption for plaintext } Y_i \text{ at time } t_j \}$$

   Amplification of signal building mean $\bar{C}$

$$\bar{C}_j = \frac{1}{N} \sum_{i=1}^{N} C_{ij}$$

2. Choose target bit, e. g., first output bit of first S-Box in first DES round.
   Note: value b of target bit depends only on 6 sub key bits (and plaintext)!
3. Statistical hypotheses: $H_0 : k_6 = k_6^0$ "guess sub key"
   Important: Under H_0 we can compute b for known plaintext Y_i

$$\text{Classification} \qquad C^0 := \{C_{ij} | b = 0\}, \quad C^1 := \{C_{ij} | b = 1\}$$

Example: Standard DPA on DES Implementation — detailed — (2)

4. Compute mean $\bar{C}^0 = \{\frac{1}{N_0} \sum_{i=1}^{N_0} C_{ij} | b = 0\}$, $N_0 = \#\{C_{i.} | b = 0\}$,
   mean $\bar{C}^1$ analogously

   Case 1: "H_0 is wrong" $\Longrightarrow$ $\bar{C}^0$ and $\bar{C}^1$ are statistically indistinguishable
   (computed value b is wrong in approx. 50%)
   Case 2: "H_0 is correct" $\Longrightarrow$ $\bar{C}^0$ and $\bar{C}^1$ are correlated
   $\Longrightarrow$ high peaks in difference of mean values $\bar{C}^0 - \bar{C}^1$ (bias profile, differential trace)

   Decision rule:
   If $\bar{C}^0$ and $\bar{C}^1$ are with small probability of error statistically indistinguishable $\Longrightarrow$ Reject H_0 and select different hypotheses H_0 (2^6 possible values)
   $\Longrightarrow$ Else "sub key bits k_6^0 found"
5. Repeat steps 1–4 for remaining 7 S-Boxes $\Longrightarrow$ 48 sub key bits found

Consolidation: Some statistics related to Kocher attack

Two sets of power traces = random variables $(X_1, \dots, X_{N_0})$ and $(Y_1, \dots, Y_{N_1})$; X_i and Y_i are independent and identically distributed with unknown cumulative distribution function $X_i \sim F_X$ and $Y_i \sim F_Y$, respectively.
Measured power profiles = realized samples of a random experiment with results x_i and y_i:

$$x_i \in \mathbb{R}^M, i = 1, \dots, N_0 \quad \text{and} \quad y_i \in \mathbb{R}^M, i = 1, \dots, N_1.$$

1. Nonparametric test = no distribution assumption on F_X and F_Y

$$H_0 : F_X = F_Y \quad \Longleftrightarrow \quad H_1 : \exists x : \quad F_X(x) \neq F_Y(x).$$

- If H_0 cannot be rejected, then the hypotheses (sub key guess) was not correct with overwhelming probability.
- If H_0 with probability of error α is rejected, then the measurements come from different distributions and the sub key is found.

Possible statistical tests: Kolmogorov-Smirnov-Test, Wilcoxon-Rank-Sum-Test

Consolidation: Some statistics related to Kocher attack (2)

2. Parametric test, e. g., normal distribution with equal unknown variances $\sigma^2 = \sigma_X^2 = \sigma_Y^2$ and different means μ_X, μ_Y, i.e., $X_i \sim \mathrm{N}(\mu_X, \sigma_X^2)$ and $Y_i \sim \mathrm{N}(\mu_Y, \sigma_Y^2)$.

$$H_0 : \mu_X = \mu_Y \quad \Longleftrightarrow \quad H_1 : \mu_X \neq \mu_Y$$

Check hypotheses with two-sample t-test, test statistics

$$T = \frac{\bar{X} - \bar{Y}}{S_P} \sqrt{\frac{N_0 N_1}{N_0 + N_1}}$$

with

$$S_P^2 = \frac{1}{N_0 + N_1 - 2}((N_0 - 1)S_x^2 + (N_1 - 1)S_y^2),$$

$$S_x^2 = \frac{1}{N_0 - 1} \sum_{i=1}^{N_0} (x_i - \bar{X})^2, \quad S_y^2 = \frac{1}{N_1 - 1} \sum_{i=1}^{N_1} (y_i - \bar{Y})^2.$$

Consolidation: Some statistics related to Kocher attack (3)

- Under H_0 we have $T \sim t_{N_0+N_1-2}$, i. e., rejection of H_0, if $|T| \geq t_{N_0+N_1-2,1-\frac{\alpha}{2}}$
- Kocher attack = neglect S_P, N_0 and N_1 in test statistics T (constant values under assumption of equal variances)
- $\Longrightarrow$ Difference of means
- Difference curve with highest peak comes with overwhelming probability from correct key hypotheses

Alternative method: Correlation Power Attack

- Measurement of N power traces for known plaintext Y_i: $C_{ij}, i = 1, \ldots, N, j = 1, \ldots, M$
- Compute target bit b for all N plaintexts and all 64 key hypotheses:

$$B_{ki}, k = 1, \ldots, 64, i = 1, \ldots, N$$

- Compute Pearson's correlation coefficient $\rho(X, Y) := \frac{\mathrm{Cov}(X,Y)}{\sqrt{\mathrm{Var}(X)\,\mathrm{Var}(Y)}}$:

$$\rho_{kj}(B_{ki}, C_{ij}) = \frac{\mathrm{E}(B_{ki} \cdot C_{ij}) - \mathrm{E}(B_{ki}) \cdot \mathrm{E}(C_{ij})}{\sqrt{\mathrm{Var}(B_{ki}) \cdot \mathrm{Var}(C_{ij})}}$$

- Every row of matrix ρ will be interpreted as correlation curve.
  Correlation curve with highest peak belongs to most probable key!
- Formalization: E. Brier, C. Clavier, F. Olivier: *Correlation Power Analysis with a Leakage Model*, CHES 2004.

Modifications of Kocher Attack

Multiple Bit DPA

- Consider 4 target bits $b = (b_1, \ldots, b_4)$
- Build sets C^i depending on the Hamming weight of b:

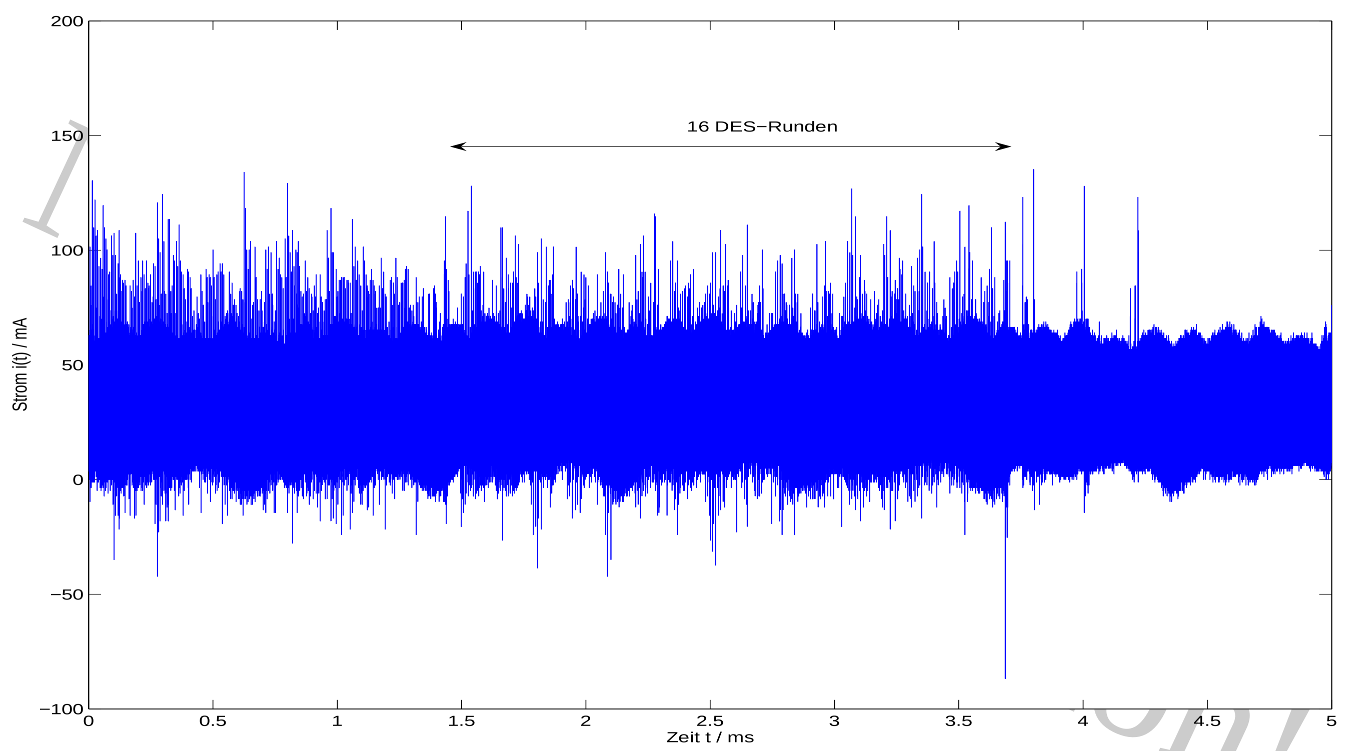
$$C^0 := \{C_{ij} | \operatorname{hw}(b) \leq l\}, C^1 := \{C_{ij} | \operatorname{hw}(b) \geq u\}, C^2 := \{C_{ij} | l < \operatorname{hw}(b) < u\}$$

- C^2 will be discarded: Multiple Bit DPA needs more samples $\Longrightarrow$ but better for low signal-to-noise ratio

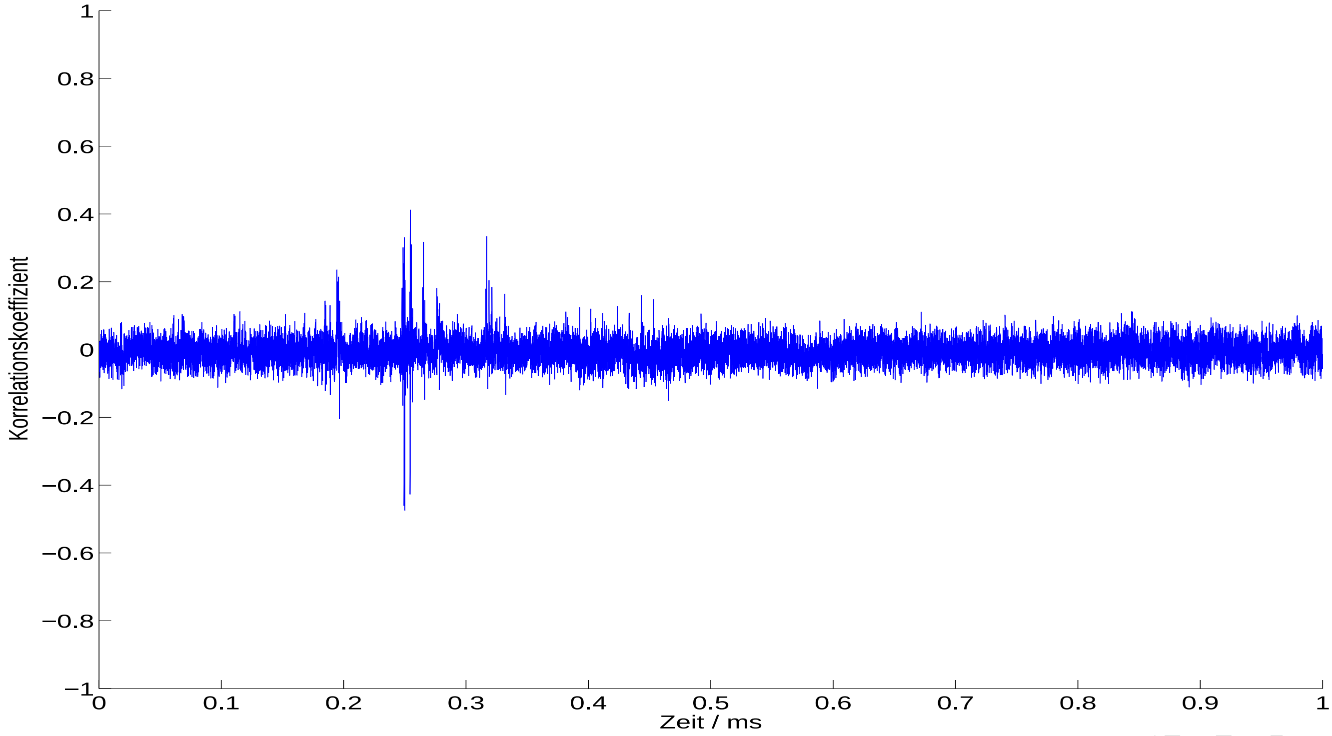
Higher Order DPA

- All attacks presented so far are first order attacks, i. e., one evaluation point / target bits is attacked, no detailed knowledge about implementation is necessary.
- Improvement: Second and Higher Order DPA
  - Attack, e.g., target bits of different rounds together
  - Requires detailed knowledge of implementation
  - Can overcome masking countermeasures, see later
  - Example: Thomas Messerges, *Using Second-Order Power Analysis to Attack DPA Resistant Software*, CHES 2000.

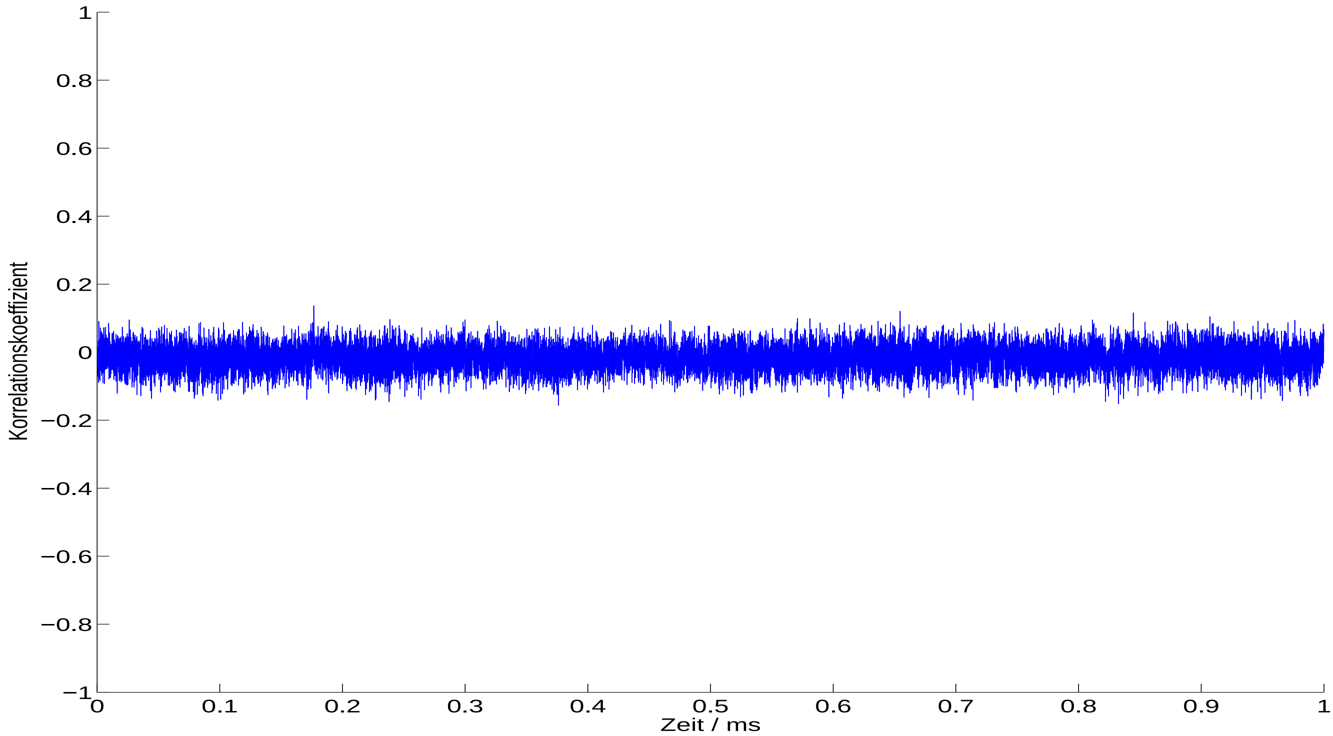
Example: Power trace of a DES computation on ST10F168



Correlation curve, 1000 measurements (insecure implementation)



Correlation curve, 1000 measurements (secured implementation)



Example: Masking of DES due to Akkar/Giraud

Unsecured DES:

$$L_{i+1} = R_i \quad \text{and} \quad R_{i+1} = L_i \oplus P\left(S\left(E\left(R_i\right) \oplus K_i\right)\right)$$

Secured DES due to Akkar/Giraud [2001]:

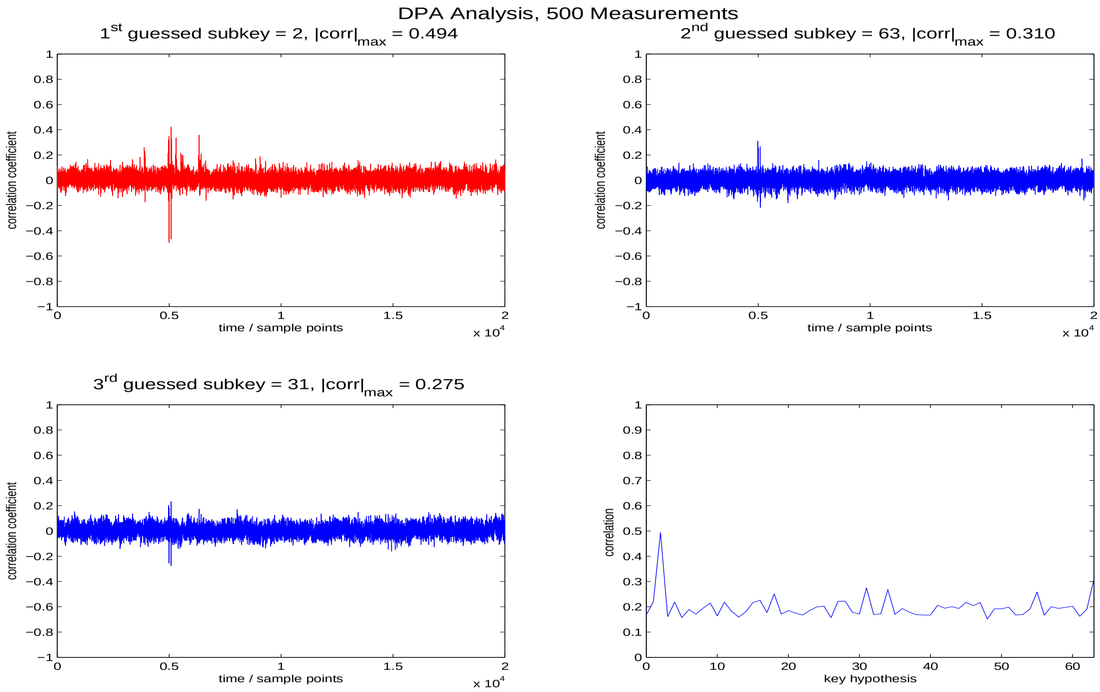
- Generate two random 32-Bit masks X_L and X_R; $L'_1 = L_1 \oplus X_L$, $R'_1 = R_1 \oplus X_R$
- Modified round function
  $L'_{i+1} = R'_i \oplus (X_L \oplus X_R) \quad \text{and} \quad R'_{i+1} = L'_i \oplus P\left(SM\left(E\left(R'_i\right) \oplus K_i\right)\right)$
- Masked S-Box:
  $$SM(A) = S(A \oplus E(X_R)) \oplus P^{-1}(X_L \oplus X_R)$$
- Every round is masked by the same value, i. e.,
  $L'_i = L_i \oplus X_L$, $R'_i = R_i \oplus X_R$
- After the last round the mask has to be removed, i. e.,
  $L_{16} = L'_{16} \oplus X_L$, $R_{16} = R'_{16} \oplus X_R$
- Main problem: modified S-Box is variable, i. e., RAM instead of SP-Box in ROM

General countermeasures against DPA

- Decrease signal-to-noise ratio $\Longrightarrow$ more measurements required
- Random Wait States $\Longrightarrow$ make alignment of power traces on time scale more difficult $\Longrightarrow$ signal processing to overcome
- Randomization = De-correlate processed data from known inputs/outputs
  - Randomization of Algorithms (random addition/subtraction chains, etc.) $\Longrightarrow$ not very powerful
  - Randomization of data/Masking
    - Compute $b^{e+\text{rand}\,\varphi(m)} \bmod m$ instead of $b^e \bmod m$ for RSA
    - Use projective coordinates for elliptic curves
    - mask input for DES and AES
- In general: hardware and software countermeasures together required

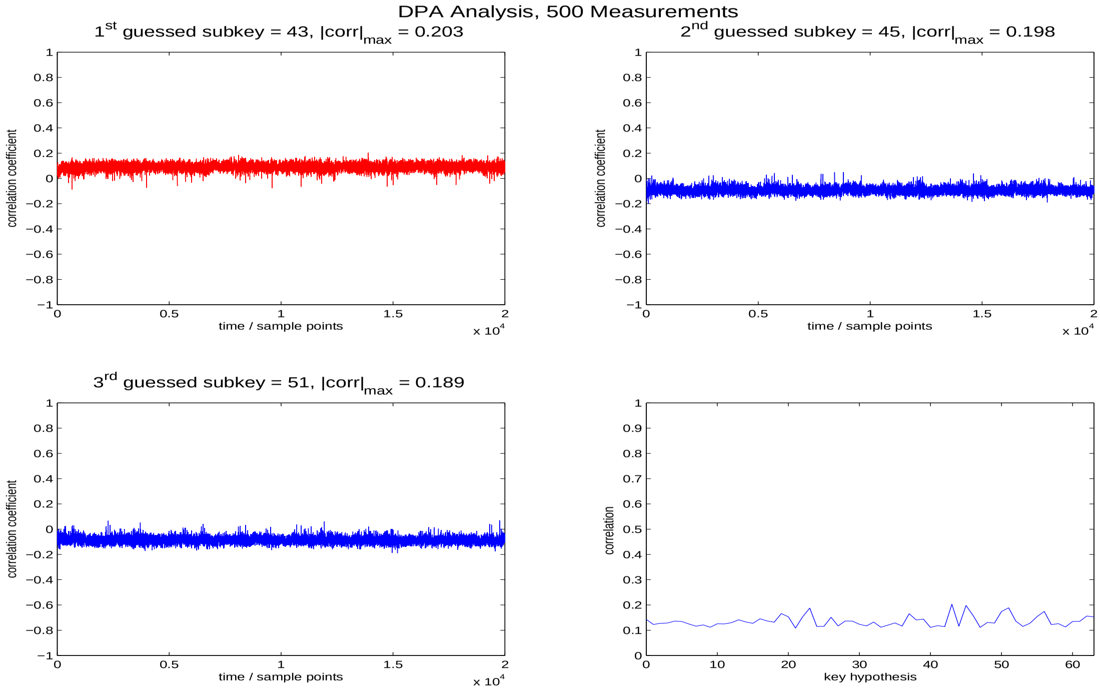
It's demo time!

Demo: Correlation Power Attack on DES implementation



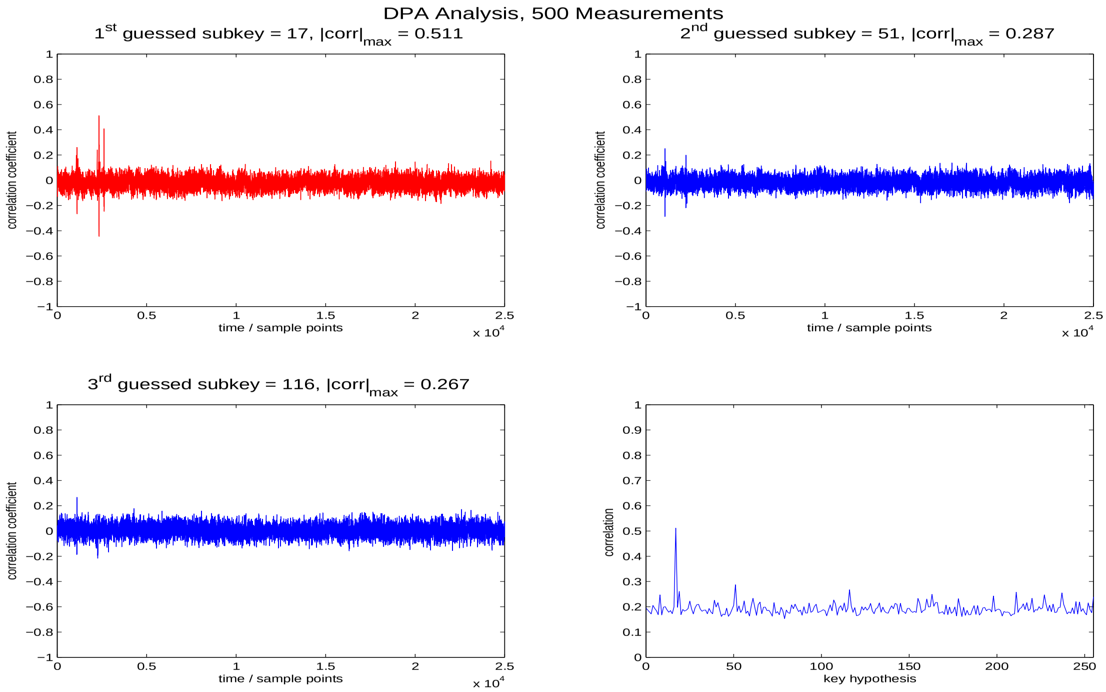
Insecure DES implementation on ST10F168 processor, 500 measurements, Source: ©Siemens CT

Demo: Correlation Power Attack on secured DES implementation



Secured DES implementation on ST10F168 processor, 500 measurements, Source: ⓒSiemens CT

Demo: Correlation Power Attack on AES implementation



Insecure AES implementation on ST10F168 processor, 500 measurements, Source: ⓒSiemens CT

5. Template Attacks

Methodology, Assumptions and Goals:

- Template Attacks combine techniques from SPA and DPA, they build a noise model and use this model during the attack
  $\Longrightarrow$ optimal attack in an information theoretical sense
- Prerequisite: Access to Training Device
- **Training Device — Profiling Step**
  - Identical to target device except the secret cryptographic key used
  - Under "full control" of attacker, i. e., key is known or can be loaded
  - Training Device is used to characterize the power leakage model with statistical methods (estimation/learning methods)
- **Target Device — Key Extraction Step**
  - Contains unknown secret key
  - Direct interpretation of *one measurement* to extract key utilizing the model from first step
    $\Longrightarrow$ can be used even for ephemeral keys or masked keys

Template Attacks (2)

Stochastic Model:

Target of evaluation: block cipher without masking

$x \in \{0,1\}^p$ known plaintext or ciphertext

$k \in \{0,1\}^s$ sub key, t time

$$\underbrace{I_t(x,k)}_{\text{random variable}} = \underbrace{h_t(x,k)}_{\text{deterministic part}} + \underbrace{R_t}_{\text{random variable, } E(R_t)=0}$$

Statistical standard notation: X, I, R, K random variables; x, i, r, k realizations/samples of random variable

Profiling Step: Use known x and k to characterize $h_t(x,k)$ and distribution of R_t for $t = t_1, t_2, \ldots, t_m$

Naïve Approach: Estimate $E(I_t(x,k))$ independently for all $(x,k) \in \{0,1\}^p \times \{0,1\}^s$

Key Extraction: Use characterization of $h_t(.,.)$ and noise distribution to find unknown key k

Template Attacks (3)

Some Well-known Template Attacks

- Chari/Rao/Rohatgi [2003]: estimate $\mathrm{E}(I_t(x,k))$ and covariance matrix of noise $\mathrm{Cov}(R_t)$
- Schindler [2005]: linear stochastic model for $h_t(x,k)$; estimator in low-dimensional (optimal) sub-spaces, details see CHES 2005 paper, Attention, statistics!
- CHES 2006: Lemke-Rust et al. *Templates vs. Stochastic Methods*, Standaert et al. *Template Attacks in Principal Subspaces*

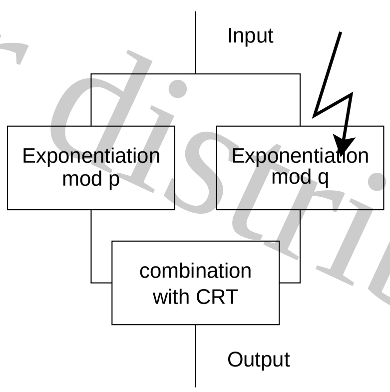
Template Attacks — Conclusions

- More efficient than SPA and DPA, statistical countermeasures against DPA can be overcome $\Longrightarrow$ give attacker no full control even on training device, e.g., no control over masking
- Today besides higher order DPA and micro-architectural side channel attacks most active research area in SCA community.

6. Differential Fault Analysis (DFA)

- Exploit faulty results which have been (actively) induced by errors
- Sources of errors: x-rays and ion beams, UV- and laser light, voltage glitches, temperature, electromagnetic induction, etc.

Famous Example: Bellcore Attack on RSA in CRT-Mode



Details on Bellcore Attack

Garner's Algorithm on RSA in CRT-Mode

$N = pq, S = m^d \bmod N, ed = 1 \bmod (p-1)(q-1)$

Precomputation: $d_p = d \bmod p-1, d_q = d \bmod q-1, P_q = p^{-1} \bmod q$

Exponentiation: $S_p = m^{d_p} \bmod p, S_q = m^{d_q} \bmod q$

Combination: $S = S_p + [((S_p - S_q) \times P_q) \bmod p] \times q$

Attack: faulty medium result $\tilde{S}_q \Longrightarrow$ faulty end result $\tilde{S}$

It holds: $S - \tilde{S} \neq 0$, but $S - \tilde{S} = 0 \bmod q$

$\Longrightarrow$ Factorization

$$\gcd\left(\left(m - \tilde{S}^e\right) \bmod N, N\right) = q$$

= Lenstra Attack [1997]

Differential Fault Analysis — Conclusions

Reconstruction of private signature key possible through (transient fault model):

- Boneh/DeMillo/Lipton [1997]: one wrong signature, one correct signature
- Lenstra [1997]: one wrong signature, original message

Biham/Shamir [1997]: Extension to symmetric methods, persistent fault model

General Countermeasures against DFA

- Introduce redundancies/invariants
- Comparison of results:
  - after encryption try decryption
  - after signature generation try signature verification
  - compute back-wards some/all rounds
- Special methods for RSA-CRT
- Many proposals for ECC countermeasures
- Note! Simple repetition of calculation is often not sufficient!

7. Electromagnetic Analysis (SEMA, DEMA)

Methodology, Assumptions and Goals:

- Measure electromagnetic field during cryptographic operations
- Analysis in simplest case as in SPA and DPA

  Differences:
  - No galvanic connection necessary, only contact-less measurement in near and far field
  - Measurement can be performed at any place in the field (interesting regions on chips as busses, crypto coprocessors, etc.)
  - Lots of data, but, in general, bad signal-to-noise ratio
  - Additional dimension per measurement: TA: scalar; SPA/DPA: time dependent vector; SEMA/DEMA: time dependent three-dimensional information
- Efficient usage of this information difficult, but large potential (signal processing know-how)

8. Micro-Architectural Analysis

- Newly evolving area of side-channel cryptanalysis
- Studies the effects of common processor components and their functionalities on the security of software cryptosystems
- Especially dangerous for virtualization technologies as Intel's LaGrande Technology (LT) and Vanderpool Technology (VT), AMD's Pacifica, ARM's Trustzone, and software based virtualization mechanisms like VMWare
- Two important classes of MA attacks, both utilize data dependent run-time

  1. cache analysis
  2. branch prediction analysis

Micro-Architectural Analysis — Cache Analysis

- Access times to different types of processor memory differ by several order of magnitudes
  $\Longrightarrow$ cache architectures, e. g., L1 code & data cache, L2 cache, Translation Lookaside Buffer
  $\Longrightarrow$ data depending timing differences due to cache access
- Fast AES implementations, for example, Barreto's method with four 1024-byte tables T_i, use table lookups, i. e., variable-index array lookups like $T_0[k[0] \oplus p[0]]$
- Main misconception: "Table lookup: not vulnerable to timing attacks" (NIST, 2001)
- But: above instruction leaks information about key $\Longrightarrow$ unprotected implementations can be broken in several milliseconds

Short history of cache attacks

- D. Page, *Theoretical Use of Cache Memory as a Cryptanalytic Side-Channel*, 2002.
- Y. Tsunoo et al., *Cryptanalysis of DES implemented on computers with cache*, CHES 2003.
- D.J. Bernstein, *Cache-timing attacks on AES*, 2004–2005.
- D.A. Osvik, A. Shamir, E. Tromer, *Cache Attacks and Countermeasures: The Case of AES*, CT-RSA 2006.
- M. Neve, *Cache-based Vulnerabilities and SPAM Analysis*, PhD Thesis, UCL, July 2006.

Micro-Architectural Analysis — Branch Prediction Analysis

- Modern pipelined processors use branch predictors, i. e., guess whether a conditional branch will be taken or not
- Timing information from branch prediction can be used in a classical timing analysis
  $\Longrightarrow$ Branch Prediction Analysis (many measurements)
- Spy process running simultaneously with crypto algorithm
  $\Longrightarrow$ analyze CPU's Branch Predictor states
  $\Longrightarrow$ *single crypto operation* reveals most key bits, e.g., 500 from 512 RSA key bits
  $\Longrightarrow$ Simple Branch Prediction Analysis

Short history of branch prediction analysis

- O. Aciiçmez, J.P. Seifert, C.K. Koç, *Predicting secret keys via branch prediction*, CT-RSA 2007.
- O. Aciiçmez, C.K. Koç, J.P. Seifert, *On the Power of Simple Branch Prediction Analysis*, 2006.
- O. Aciiçmez, W. Schindler, *A Major Vulnerability in RSA Implementations due to MicroArchitectural Analysis Threat*, 2007.

Micro-Architectural Analysis — Countermeasures and Conclusion

- Use logical operations instead of table lookups: very slow
- Preload tables: not always possible; masking and hiding: possible
- Normalize cache: very CPU specific
- Use vendor specific secured AES commands:
  Intel introduces new AES instructions for next generations processors, [Rev. 2.0, April 2009]
  - four instructions (`AESENC`, `AESENCLAST`, `AESDEC`, and `AESDELAST`) for encryption and decryption; two instructions (`AESIMC` and `AESKEYGENASSIST`) for key expansion
  - run in data independent time and do not use table lookups $\Longrightarrow$ secure against MAA
  - substantial performance speedup, especially in parallelizable modes of operation
- Micro-Architectural Analysis = essentially timing attack variant, but with much smaller effects caused by Micro-Architecture
- Difficult to protect without detailled processor knowledge
- Breaks many assumptions on compartments etc. in virtualized systems

9. Side Channel Attacks — Conclusions

Side Channel Attacks are todays most efficient threat against smart cards, embedded systems, and cryptographic hardware!

- Side Channel Analysis can be performed with standard equipment
- Without special countermeasures most implementations of cryptographic methods are vulnerable
- Efficient countermeasures are possible, but only as interaction between hardware and software
- Countermeasures cost performance and memory
- Many attacks and countermeasures are not published
- Difficult patent situation
- Secure implementation of cryptographic algorithms is experts work

Side Channel Analysis — Further Information

- E. Hess; N. Janssen; B. Meyer; T. Schütze:
  Information Leakage Attacks Against Smart Card Implementations of Cryptographic Algorithms and Countermeasures – A Survey. Proceedings of EUROSMART Security Conference 2000,
  `http://www.torsten-schuetze.de/reports/leakage.pdf`
- M. Aigner; E. Oswald: *Power Analysis Tutorial*, Technical report, IAIK Graz, 2000,
  `http://www.iaik.tu-graz.ac.at/aboutus/people/oswald/papers/dpa_tutorial.pdf`
- J. J. Quisquater; F. Koeune:
  State-of-the-art regarding side channel attacks, Technical report, Oct 2002,
  `http://www.ipa.go.jp/security/enc/CRYPTREC/fy15/doc/1047_Side_Channel_report.pdf`
- YongBin Zhou; DengGuo Feng:
  Side-Channel Attacks: Ten Years After Its Publication and the Impacts on Cryptographic Module Security Testing. NIST Physical Security Testing Workshop, Hawaii, Sep 2005.
  `http://csrc.nist.gov/cryptval/physec/physecdoc.html`
- Proceedings of CHES Conferences (Cryptographic Hardware and Embedded Systems)
- S. Mangard; E. Oswald; T. Popp:
  Power Analysis Attacks: Revealing the Secrets of Smart Cards. Springer, April 2007,
  `http://www.dpabook.org`