


CS 553

CRYPTOGRAPHY

Lecture 9

Linear Cryptanalysis

Instructor
Dr. Dhiman Saha


- ▶ Less effective than Differential Cryptanalysis
- ▶ But is a Known Plaintext Attack (Recall DC is CPA) 
- ▶ Credited to Matsui for applications on DES
- ▶ Earlier references on FEAL-4
 - ▶ By Tardy-Corffdir and Gilbert

Linear Approximation

Basic Idea

Uses a linear relation between inputs and outputs of an encryption algorithm that holds with a certain probability

- ▶ This approximation can be used to assign probabilities to the possible keys and locate the most probable one.

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- Consider the encryption scheme

$$c = m \oplus k \quad c, k, m \in \{0, 1\}^b$$

- Bit expansion

$$\begin{bmatrix} c_0 = m_0 \oplus k_0 \\ c_1 = m_1 \oplus k_1 \\ \vdots \\ c_{b-1} = m_{b-1} \oplus k_{b-1} \end{bmatrix} \rightarrow \begin{bmatrix} k_0 = m_0 \oplus c_0 \\ k_1 = m_1 \oplus c_1 \\ \vdots \\ k_{b-1} = m_{b-1} \oplus c_{b-1} \end{bmatrix}$$

- Vulnerability if k reused  What about KPA?

What did we do here?

Key expressed as a (linear) relation between plaintext and ciphertext

- Consider the following 4-bit cryptosystem

$$c_3 = m_3 \oplus m_1 \oplus m_0 \oplus k_3 \oplus k_1 \oplus k_0$$

$$c_2 = m_2 \oplus m_0 \oplus k_2 \oplus k_0$$

$$c_1 = m_3 \oplus m_2 \oplus k_3 \oplus k_2$$

$$c_0 = m_1 \oplus m_0 \oplus k_1 \oplus k_0$$


$$k_3 = m_3 \oplus c_0 \oplus c_3$$

$$k_2 = m_2 \oplus c_3 \oplus c_1 \oplus c_0$$

$$k_1 = m_1 \oplus c_3 \oplus c_2 \oplus c_1$$

$$k_0 = m_0 \oplus c_3 \oplus c_2 \oplus c_1 \oplus c_0$$

Reiterates the basic aim of LC

Constructing equations that express bits of the key in terms of bits of the message and ciphertext. 

- ▶ Extracting specific bits using the mask vector

$$(1, 0, 0, 0) \times \begin{pmatrix} m_3 \\ m_2 \\ m_1 \\ m_0 \end{pmatrix} = m_3 \quad (1, 0, 1, 0) \times \begin{pmatrix} m_3 \\ m_2 \\ m_1 \\ m_0 \end{pmatrix} = m_3 \oplus m_1$$

- ▶ Linear combination using the mask vector

$$(1, 0, 1, 1) \times \begin{pmatrix} m_3 \\ m_2 \\ m_1 \\ m_0 \end{pmatrix} \oplus (1, 0, 1, 1) \times \begin{pmatrix} k_3 \\ k_2 \\ k_1 \\ k_0 \end{pmatrix} = m_3 \oplus m_1 \oplus m_0 \oplus k_3 \oplus k_1 \oplus k_0$$

The idea of masking

- ▶ Extracting specific bits using the mask vector

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Linear Mask 

Recall the scalar product of vectors in linear algebra

- Recall our 4-bit cryptosystem

$$c_3 = m_3 \oplus m_1 \oplus m_0 \oplus k_3 \oplus k_1 \oplus k_0,$$


$$c_2 = m_2 \oplus m_0 \oplus k_2 \oplus k_0,$$

$$c_1 = m_3 \oplus m_2 \oplus k_3 \oplus k_2, \text{ and}$$

$$c_0 = m_1 \oplus m_0 \oplus k_1 \oplus k_0.$$

- Consider the first equation

$$c_3 = m_3 \oplus m_1 \oplus m_0 \oplus k_3 \oplus k_1 \oplus k_0$$

- With masks α, β this can be written as: 

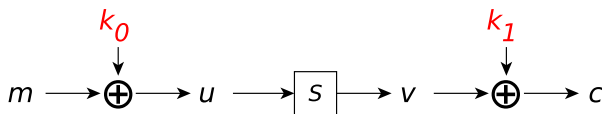
$$\alpha \cdot c = \beta \cdot m \oplus \beta \cdot k, \text{ where } \alpha = \{1, 0, 0, 0\}, \beta = \{1, 0, 1, 1\}$$

- ▶ Sypher00A encrypts 4 bits with two 4 bit keys

S-box 

x	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
S(x)	f	e	b	c	6	d	7	8	0	3	9	a	4	2	1	5

Encryption



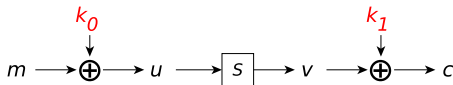
- ▶ Same as Sypher001 in DC but different Sbox

- ▶ Linear approximation of $S[\cdot]$

To find some (α, β) such that

$$\Pr\left[\alpha \cdot x = \beta \cdot S[x]\right] \neq \frac{1}{2} \quad \triangle$$

- ▶ Implication:
 - ▶ XOR of certain bits of the input to S equals
 - ▶ XOR of certain bits in the output of S
 - ▶ With a probability “different from the random case”



► Note:

$$\alpha \cdot m = \alpha \cdot k_0 \oplus \alpha \cdot u \quad \rightarrow \text{Holds with prob. } 1 \quad (1)$$

$$\alpha \cdot u = \beta \cdot v \quad \rightarrow \text{Holds with prob. } p \quad (2)$$

$$\beta \cdot v = \beta \cdot k_1 \oplus \beta \cdot c \quad \rightarrow \text{Holds with prob. } 1 \quad (3)$$

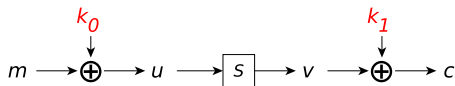
► Adding Eqn. (1 – 3):

$$(\alpha \cdot m) \oplus (\alpha \cdot u) \oplus (\beta \cdot v) = (\alpha \cdot k_0) \oplus (\alpha \cdot u) \oplus (\beta \cdot v) \oplus (\beta \cdot k_1) \oplus (\beta \cdot c)$$

Simplifying

Holds with prob. p

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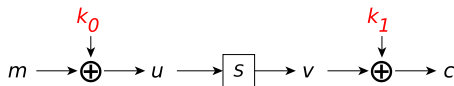
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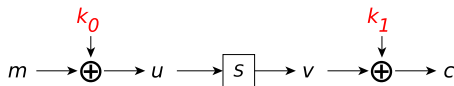
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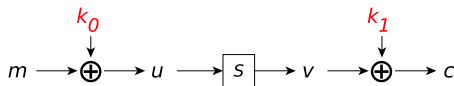
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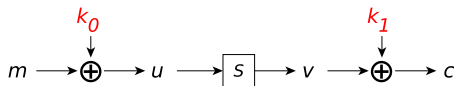
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Simplifying

Holds with prob. p

$$(\alpha \cdot m) \oplus (\beta \cdot c) = (\alpha \cdot k_0) \oplus (\beta \cdot k_1)$$

$$p = 1$$

$$\forall s$$

$$p = 0$$

Holds with prob. p

$$(\alpha \cdot m) \oplus (\beta \cdot c) = (\alpha \cdot k_0) \oplus (\beta \cdot k_1)$$

- ▶ $p = 0$ or $p = 1$, equally useful for attacker
- ▶ if $p = 1$, attacker recovers a key-bit using multiple (m, c)
 - ▶ Recall this a KPA
- ▶ if $p = 0$, attacker uses the same strategy with

$$(\alpha \cdot m) \oplus (\beta \cdot c) \oplus 1 = (\alpha \cdot k_0) \oplus (\beta \cdot k_1)$$

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- ▶ Worst-case scenario for attacker: $p = \frac{1}{2}$
- ▶ Attacker gets no extra info about key-bit
- ▶ 0/1 is equally probable
- ▶ Ideal from designer's perspective

Non-zero Bias

Aim of LC

Choose masks α and β so that equations in linear approximation hold with probability

$$p = \frac{1}{2} + \epsilon$$

where ϵ , which is known as the bias is non-zero (“non-negligible”)

- ▶ Target: $0 < |\epsilon| \leq \frac{1}{2}$
- ▶ Larger $|\epsilon| \implies$ better attack

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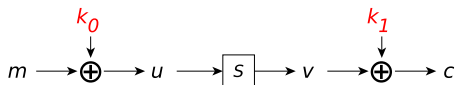
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$$\alpha = (1, 0, 0, 1), \beta = (0, 0, 1, 0)$$

Example (Sypher00A)



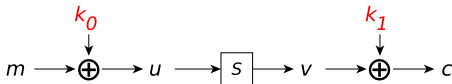
x	0	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
S[x]	f	e	b	c	6	d	7	8	0	3	9	a	4	2	1	5
$\alpha \cdot x$	0	1	0	1	0	1	0	1	1	0	1	0	1	0	1	0
$\beta \cdot S[x]$	1	1	1	0	1	0	1	0	0	1	0	1	0	1	0	0

$p = ?$

$$\Pr[\alpha \cdot x = \beta \cdot S[x]] = \frac{2}{16}$$

or

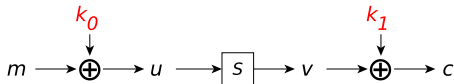
$$\Pr[\alpha \cdot x \oplus 1 = \beta \cdot S[x]] = \frac{14}{16}$$



- ▶ In terms of Sypher00A $\rightarrow \Pr[\alpha \cdot u \oplus 1 = \beta \cdot v] = \frac{14}{16}$
- ▶ i.e., $\Pr[(\alpha \cdot m) \oplus (\beta \cdot c) \oplus 1 = (\alpha \cdot k_0) \oplus (\beta \cdot k_1)] = \frac{14}{16}$

Procedure

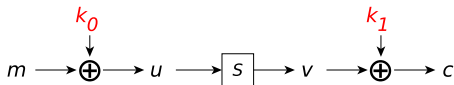
- ▶ Initialize counters T_0 and T_1 to 0
- ▶ Request the encryptions of N known plaintexts.
- ▶ For each plaintext-ciphertext pair, we compute the **left-hand side** of the equation: $(\alpha \cdot m) \oplus (\beta \cdot c) \oplus 1$,
 - ▶ Which is either 0 or 1.
- ▶ Gives an estimate for the value of $(\alpha \cdot k_0) \oplus (\beta \cdot k_1)$
- ▶ T_0++ if LHS evaluates to 0; T_1++ if LHS evaluates to 1



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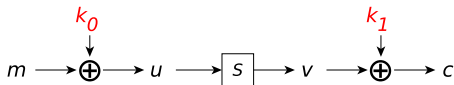
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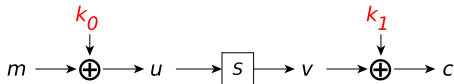
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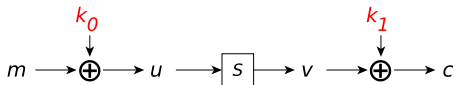
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- ▶ $(\alpha \cdot k_0) \oplus (\beta \cdot k_1) \stackrel{?}{=} 0/1$
- ▶ Key-bit estimation correct with prob. $\frac{14}{16}$
- ▶ What to expect at T_0/T_1 after N KP encryptions

$$\text{If } (\alpha \cdot k_0) \oplus (\beta \cdot k_1) = 1$$

$$T_0 \leftarrow \frac{2N}{16}$$

$$T_1 \leftarrow \frac{14N}{16}$$

$$\text{If } (\alpha \cdot k_0) \oplus (\beta \cdot k_1) = 0$$

$$T_0 \leftarrow \frac{14N}{16}$$

$$T_1 \leftarrow \frac{2N}{16}$$

- ▶ Verifying any one counter say, T_0 for $\frac{2N}{16}$ or $\frac{14N}{16}$
 - ▶ Reveals one bit $\rightarrow (\alpha \cdot k_0) \oplus (\beta \cdot k_1)$
 - ▶ Increase $N \rightarrow$ better success prob.

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- ▶ $s \rightarrow$ value of RHS of target equation involving secret key
- ▶ Counters $\rightarrow T_s, T_{s \oplus 1}$
- ▶ Expected values after using N texts

$$T_s \leftarrow pN \quad T_{s \oplus 1} \leftarrow (1 - p)N$$

- ▶ For $p \neq \frac{1}{2}$ and enough N
 - ▶ Possible to determine s
 - ▶ Correspondingly recover 1 bit of key info.

The Linear Approximation Table

	1	2	3	4	5	6	7	8	9	a	b	c	d	e	f
1	-2	.	2	.	-2	4	-2	2	4	2	.	-2	.	2	.
2	2	-2	.	-2	.	.	2	2	4	.	2	4	-2	-2	.
3	4	2	2	-2	2	.	.	.	.	2	-2	-2	-2	.	4
4	.	-2	2	2	-2	.	.	-4	.	2	2	2	2	.	4
5	-2	2	.	2	4	.	2	-2	4	.	-2	.	2	-2	.
6	-2	.	2	.	2	4	2	2	-4	2	.	2	.	-2	.
7	.	.	.	4	.	-4	.	.	.	.	4	.	4	.	.
8	.	-2	2	-4	.	2	2	-4	.	-2	-2	.	.	2	-2
9	-2	-6	.	.	2	-2	.	2	.	.	-2	-2	.	.	2
a	-2	.	-6	-2	.	2	.	-2	.	2	.	.	-2	.	2
b	.	.	.	2	-2	2	-2	.	.	-4	-4	2	-2	-2	2
c	.	.	.	-2	-2	-2	-2	.	.	4	-4	2	2	-2	-2
d	-2	.	2	2	.	-2	.	-2	.	2	.	.	-6	.	-2
e	2	-2	.	.	2	2	-4	-2	.	.	2	-2	.	-4	-2
f	-4	2	2	-4	.	-2	-2	.	.	-2	2	.	.	-2	2

How to interpret it¹ ?

¹Will be discussed in details in next class