Scan based Attack on Hardware Implementations of Data Encryption Standard

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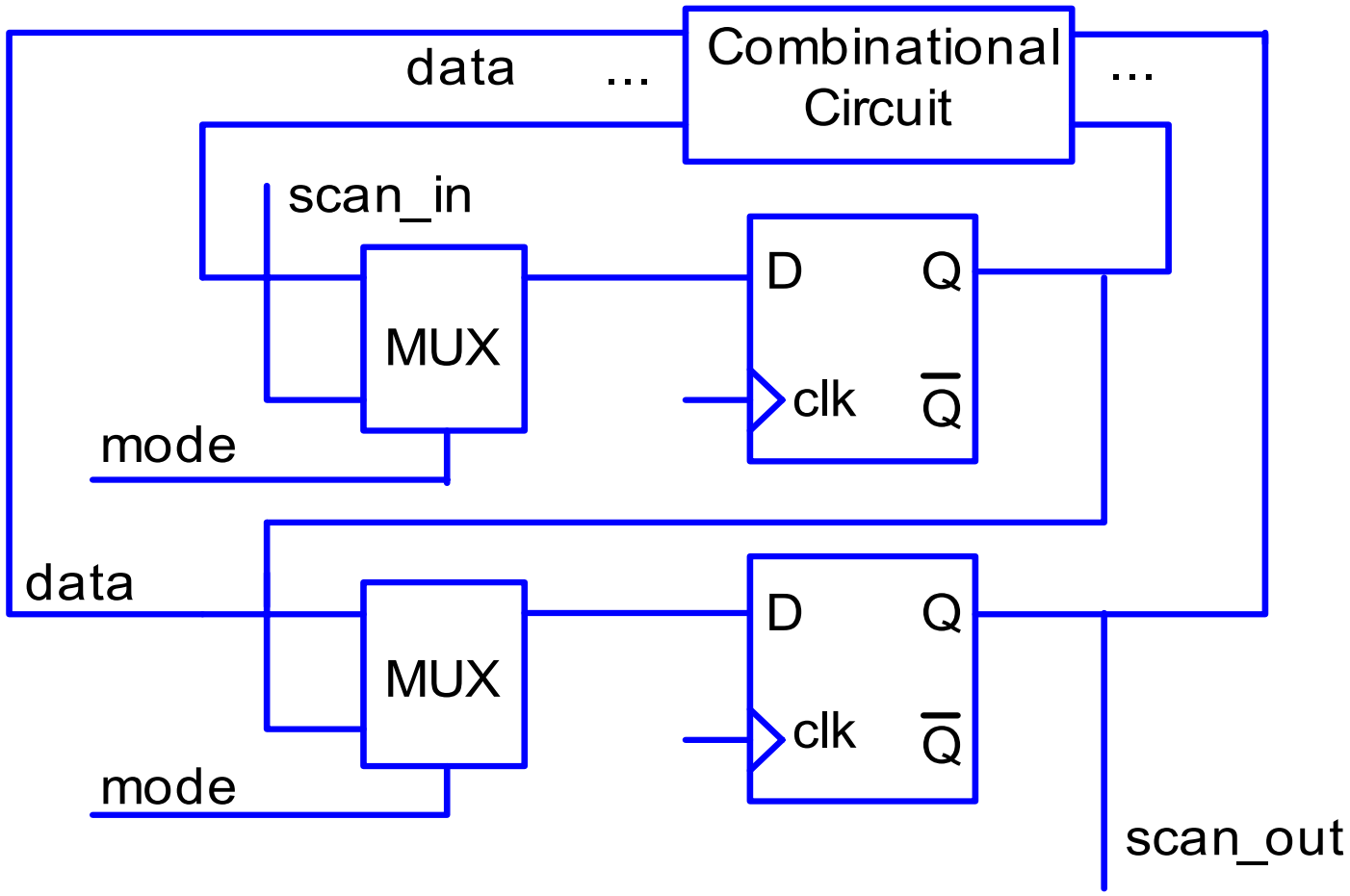
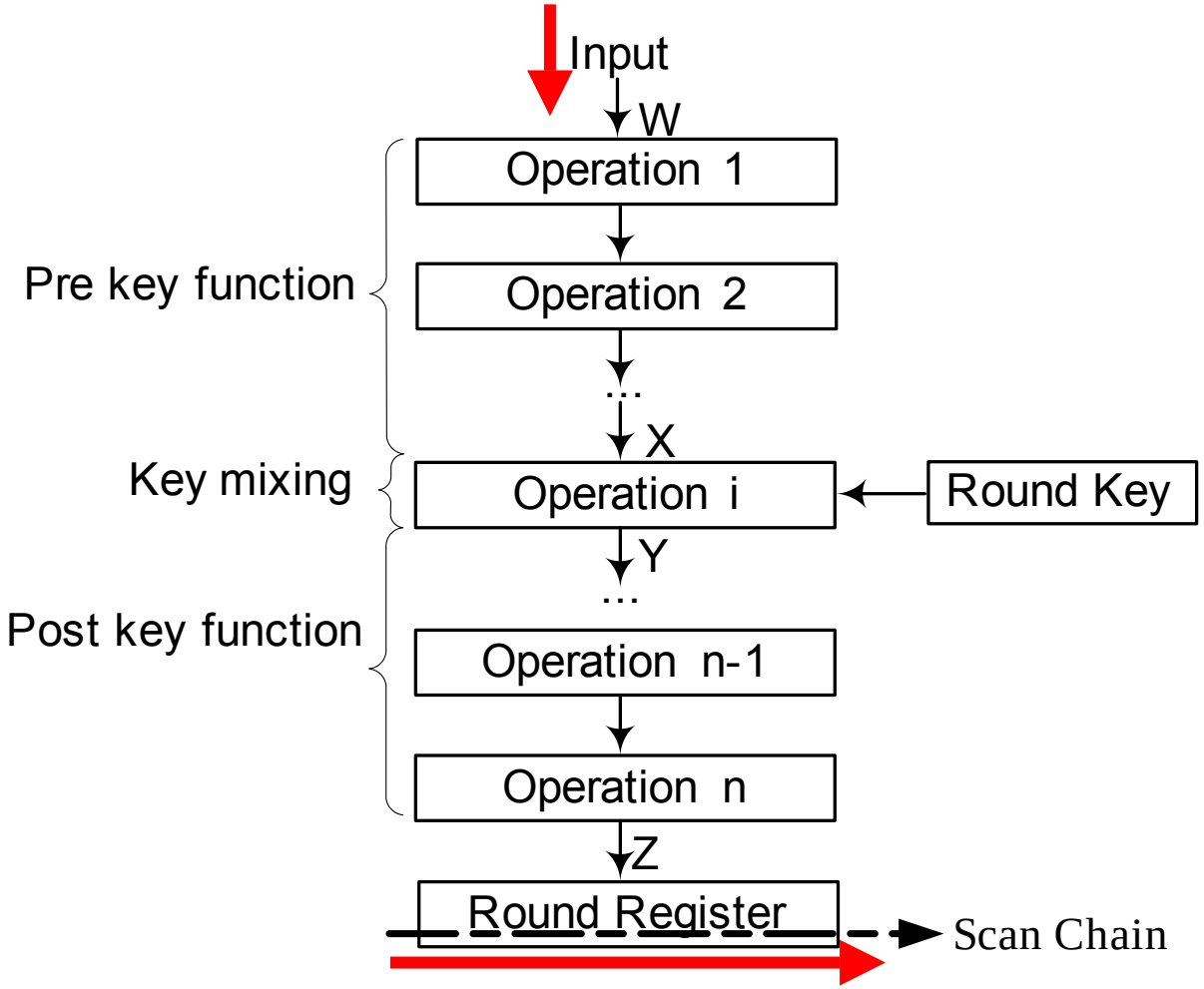
Cryptographic hardware

- More and more cryptographic algorithms have been implemented in Application Specific Integrated Circuit (ASIC) to provide high throughput.
- Any ASIC has to be tested after fabrication to validate its function.

Scan based test

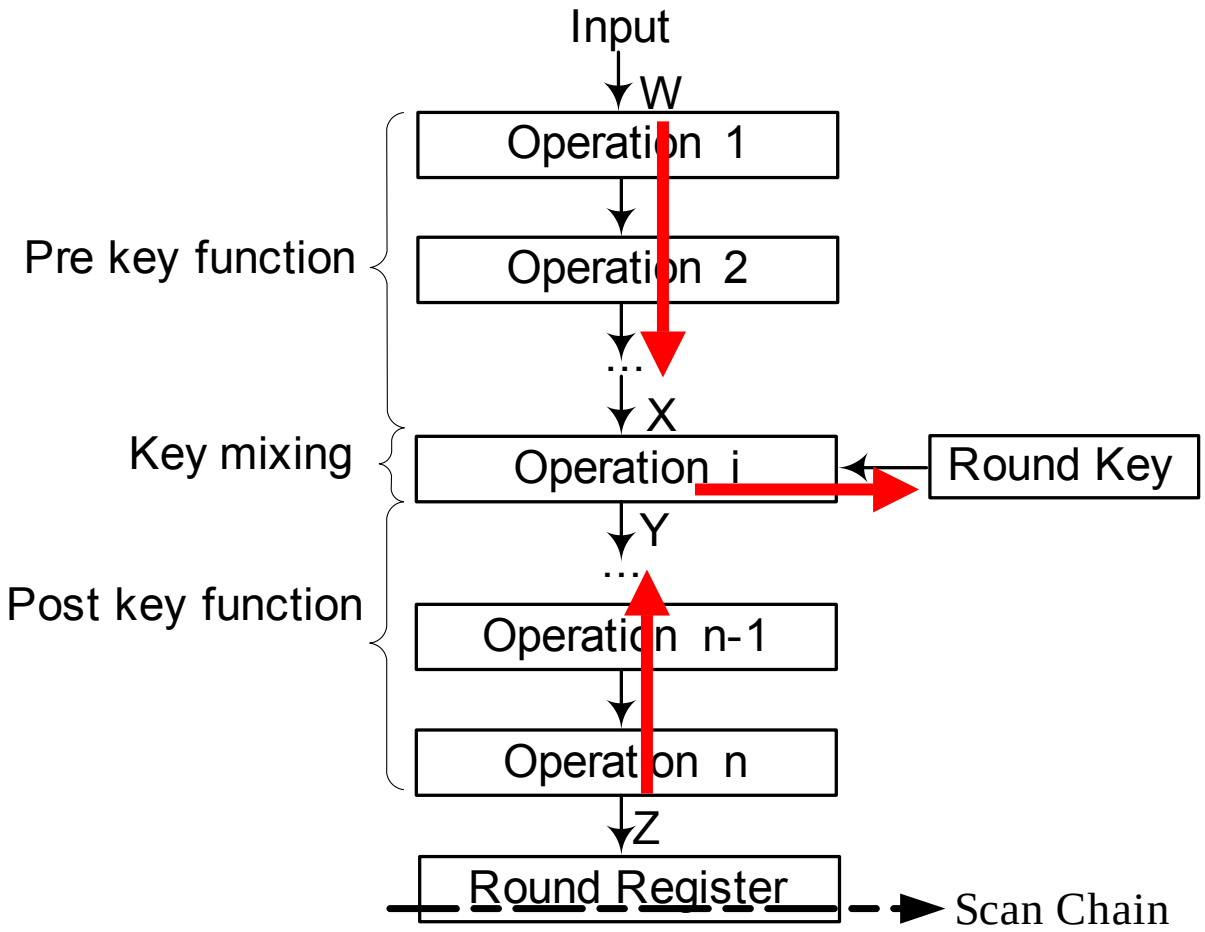


How to mount a scan based attack?



- X = Pre key function (W) where W is the input to this round
- Y = Key Mixing (X, Round key)
- Z = Post key function (Y) where Z is the round output
- What can we do?
- We can apply different inputs
- We can scan out the value in round register

How to mount a scan based attack?

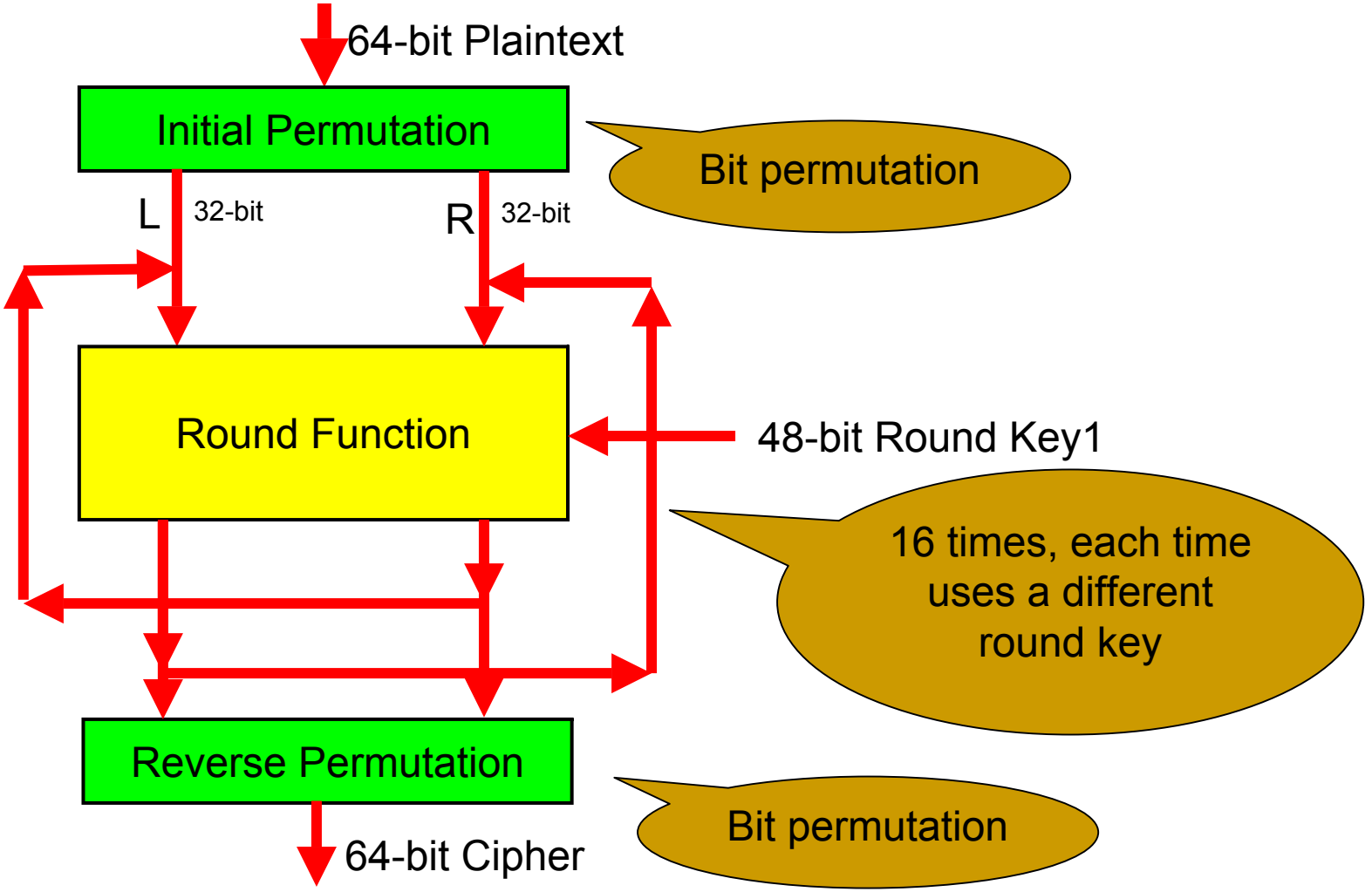


- Can we calculate X from W
- It is easy, because the algorithm is public
- Calculate Y from Z
- It is not easy, because the post key function may be not a bijective function
- Round key can be determined by solving Key mixing function

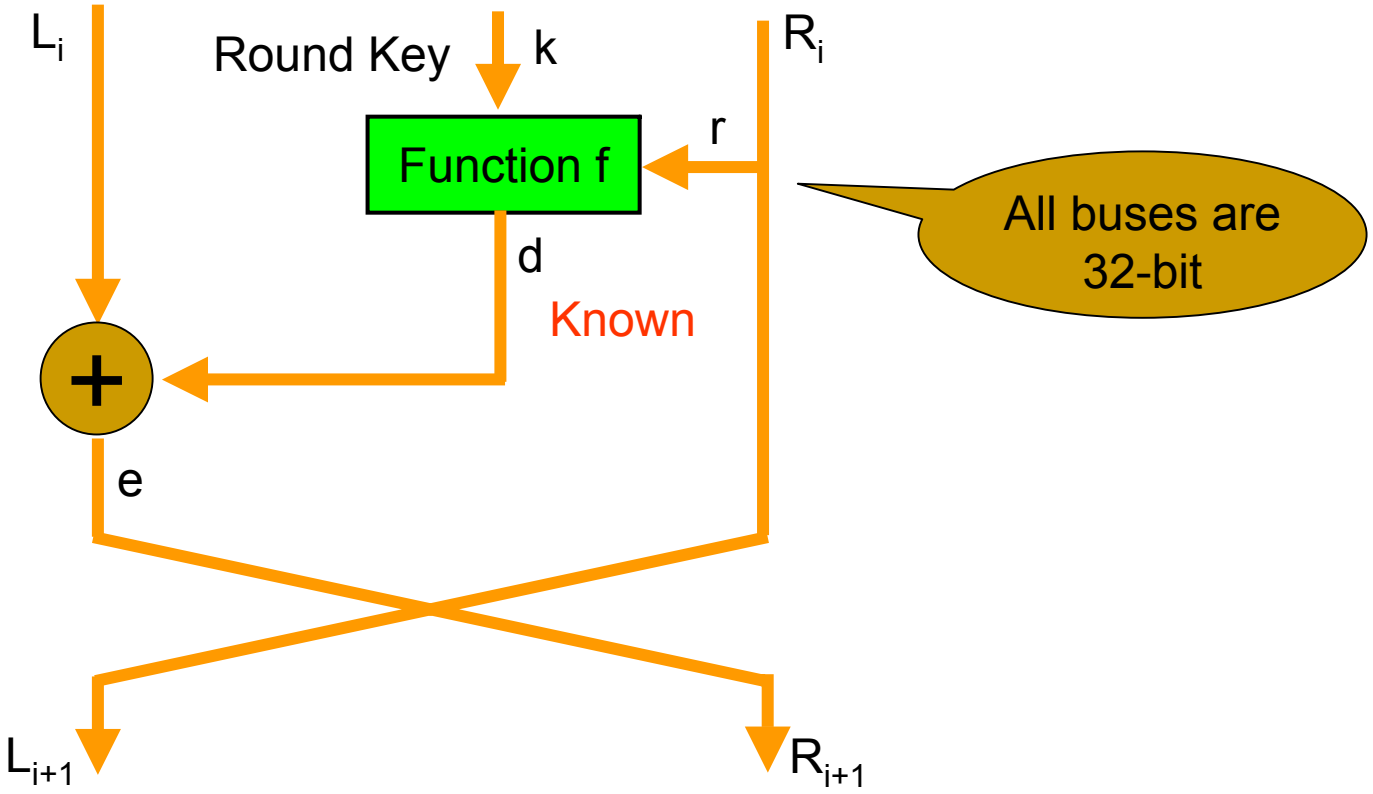
Data Encryption Standard

- The Data Encryption Standard (DES) is a symmetric encryption algorithm developed in the 1970s by IBM.
- DES encrypts 64-bit data blocks under the control of a 56-bit user key.
- DES decryption is the inverse of DES encryption and uses the same user key.
- Sixteen 48-bit round keys are generated from 56-bit user key by key schedule algorithm.

Encryption Algorithm

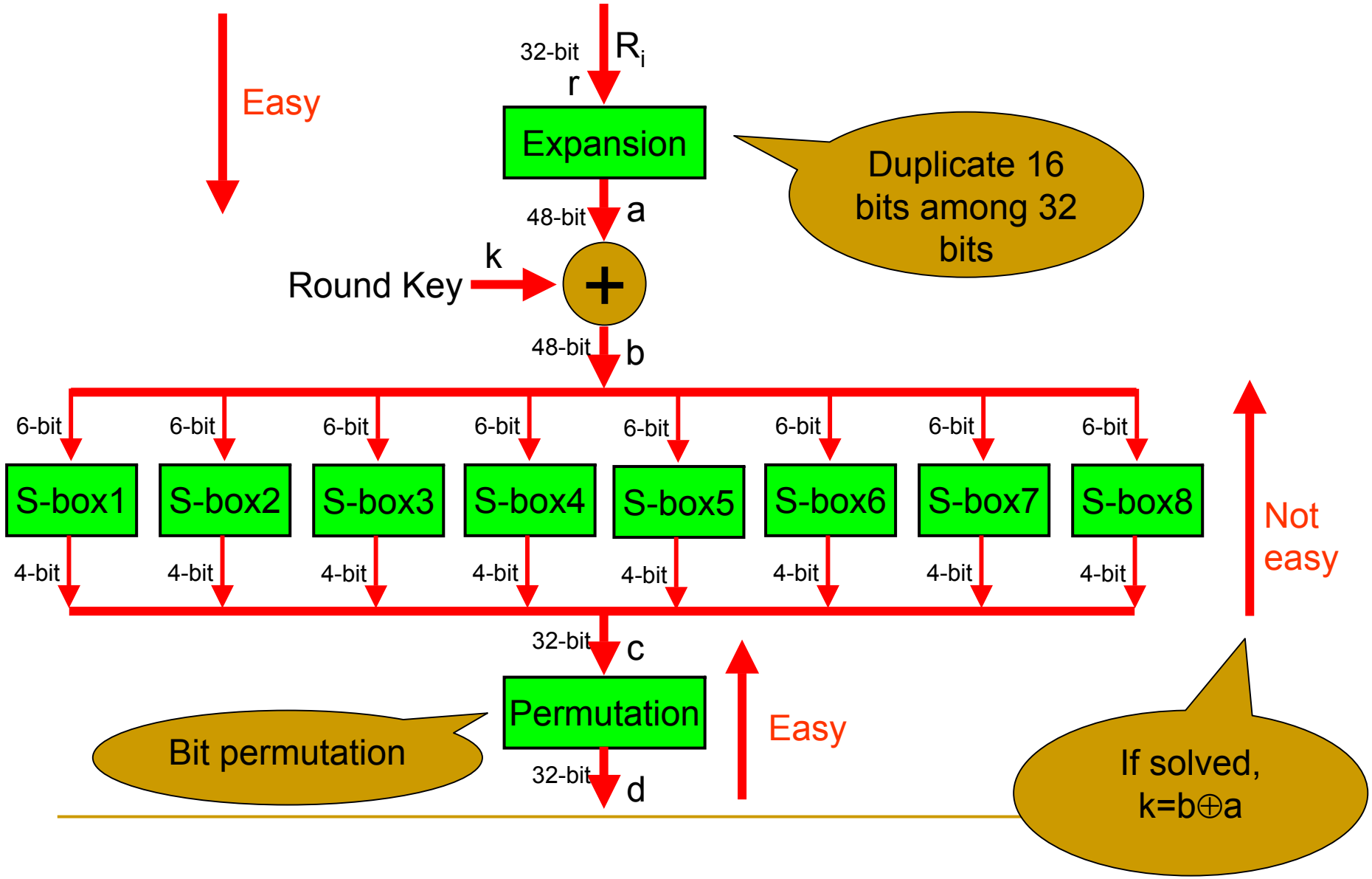


Round Function

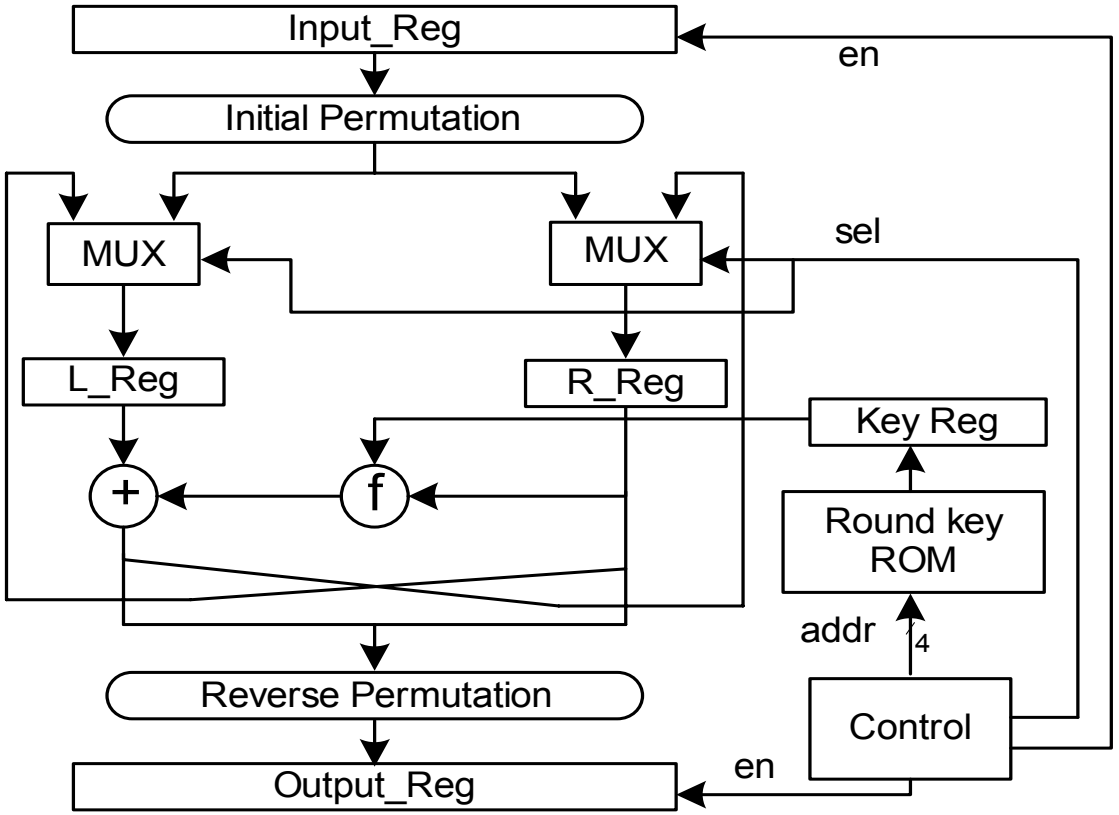


- If R_i, L_i and R_{i+1} are known, what will happen?
- If we can solve d=f(k,r), then k is retrieved.

Function f


Easy
32-bit
R_i
r
Expansion
Duplicate 16 bits among 32 bits
48-bit
a
k
Round Key
+
48-bit
b
6-bit
S-box1
S-box2
S-box3
S-box4
S-box5
S-box6
S-box7
S-box8
4-bit
Not easy
32-bit
c
Permutation
Bit permutation
Easy
32-bit
d
If solved, k=b⊕a

Iterative DES architecture



- All 16 rounds use the same hardware
- If the L and R Register can be scanned out, then L_i and R_i are known. Then K_i will be retrieved

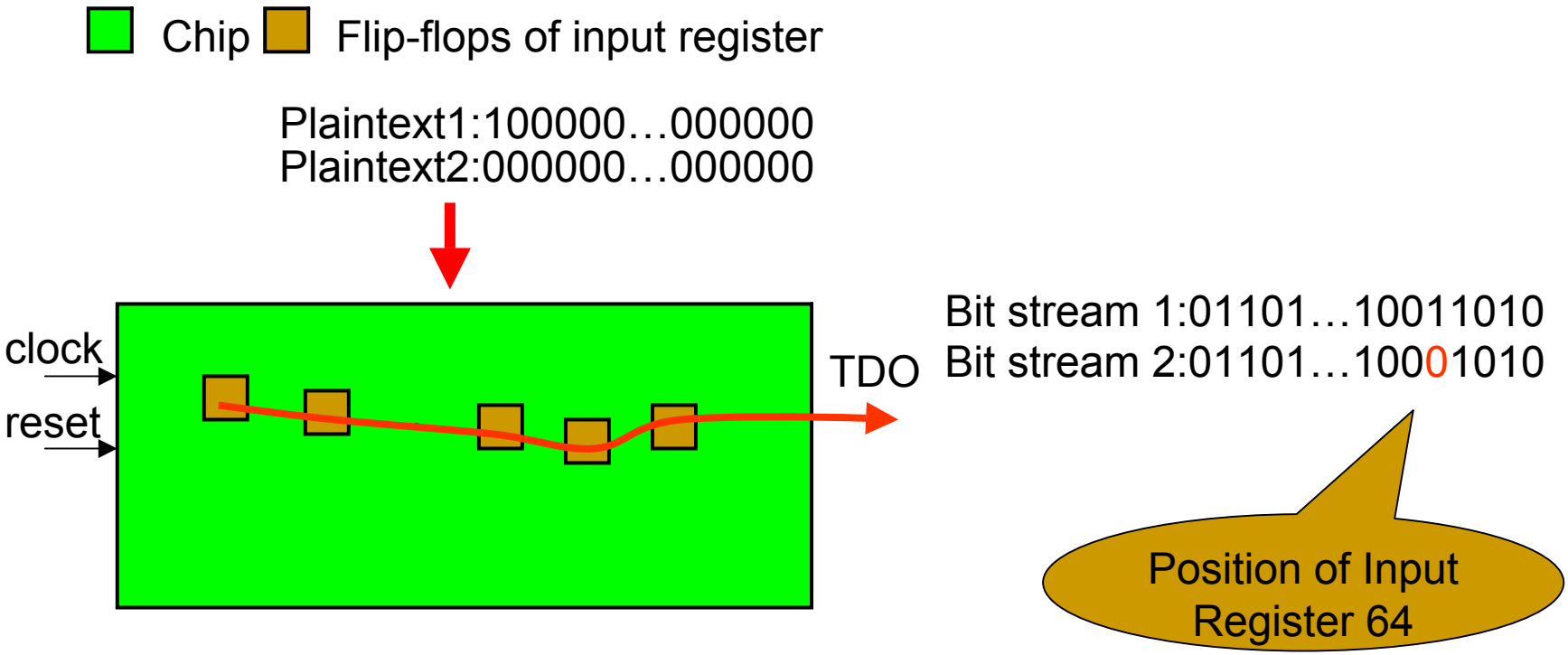
Two-step scan based attack

- The positions of flip-flops of L and R register should be determined in the scan chain. Then we can get the value of L and R register in the scanned out bit stream.
- Using L_0, R_0, L_1 and R_1 to discover Round Key1

Some Assumptions

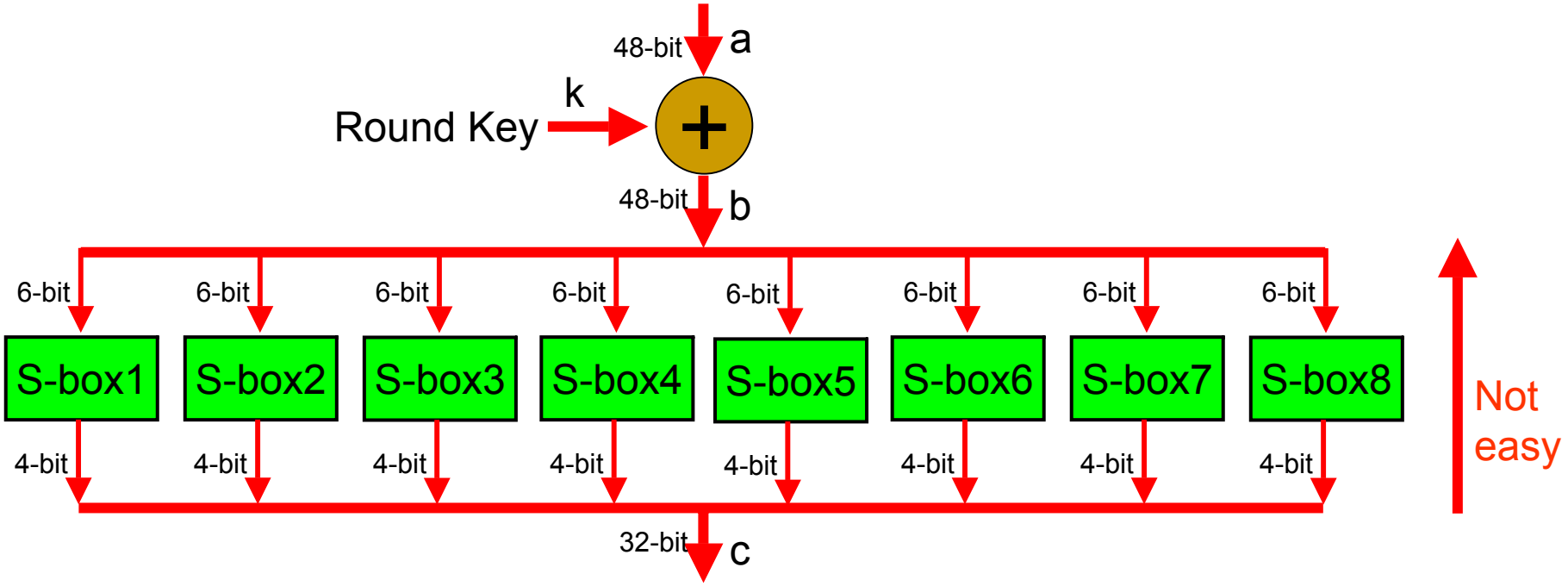
- The attack knows the algorithm (it is public)
- The attacker has access to high level timing diagrams provided by DES ASIC vendor
- Round keys are stored in a secure RAM/ROM
- The attacker has access to scan chains via the JTAG port
- Round key registers are not included in the scan chain; otherwise it will be easy to scan out the round key

Attack step 1: determine the scan chain structure



- Similarly, all the flip flops in Input register, L register and R register are determined.

Attack step 2: recover round key 1



- As we discussed, if we can figure out the input of S-box from the output of s-box, the round key can be recovered.
- Why is it not easy to determine?
- Each S-box compresses 6-bit input into 4-bit output, so it is not a bijective function.

Look into S-box structure: S1

Address	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	14	4	13	1	2	15	11	8	3	10	6	12	5	9	0	7
1	0	15	7	4	14	2	13	1	10	6	12	11	9	5	3	8
2	4	1	14	8	13	6	2	11	15	12	9	7	3	10	5	0
3	15	12	8	2	4	9	1	7	5	11	3	14	10	0	6	13

- Compresses 2^6 to 2^4. Each row has 16 different numbers ranging from 0 to 15
- Input is $b_{48\text{-}43}$, among which $b_{48}b_{43}$ is row address and $b_{47}b_{46}\,b_{45}b_{44}$ is column address
- For example, if $c_{32\text{-}29}$ is $(0100)_2$, $b_{48\text{-}43}$ can be either $(000010)_2$ or $(000111)_2$ or $(100000)_2$ or $(101001)_2$.

Apply the second input?

Address	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	14	4	13	1	2	15	11	8	3	10	6	12	5	9	0	7
1	0	15	7	4	14	2	13	1	10	6	12	11	9	5	3	8
2	4	1	14	8	13	6	2	11	15	12	9	7	3	10	5	0
3	15	12	8	2	4	9	1	7	5	11	3	14	10	0	6	13

- If $c_{32}c_{31}c_{30}c_{29}$ is $(0100)_2$, $b_{48}b_{47}b_{46}\,b_{45}b_{44}b_{43}$ can be either $(000010)_2$ or $(000111)_2$ or $(100000)_2$ or $(101001)_2$.
- Suppose we apply $b_{48}b_{47}b_{46}\,\overline{b_{45}}b_{44}b_{43}$
- the output will be 15 if $b_{48}b_{47}b_{46}\,b_{45}b_{44}b_{43}$ is $(000111)_2$
- the output will be 14 if $b_{48}b_{47}b_{46}\,b_{45}b_{44}b_{43}$ is $(100000)_2$
- the output will be 1 if $b_{48}b_{47}b_{46}\,b_{45}b_{44}b_{43}$ is $(000010)_2$ or $(101001)_2$
- We still can not determine the input according to the output

Apply three inputs

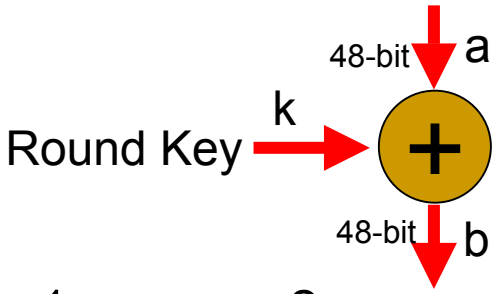
Address	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
0	14	4	13	1	2	15	11	8	3	10	6	12	5	9	0	7
1	0	15	7	4	14	2	13	1	10	6	12	11	9	5	3	8
2	4	1	14	8	13	6	2	11	15	12	9	7	3	10	5	0
3	15	12	8	2	4	9	1	7	5	11	3	14	10	0	6	13

We apply input $b_{48}b_{47}b_{46}\,b_{45}b_{44}b_{43}$, then $b_{48}b_{47}b_{46}\,\overline{b_{45}}b_{44}b_{43}$ and finally $b_{48}b_{47}b_{46}\,b_{45}b_{44}\overline{b_{43}}$

- If the output sequence is 4→15 →1, $b_{48}b_{47}b_{46}\,b_{45}b_{44}b_{43}$ is $(000111)_2$
- If the output sequence is 4→14 →15, $b_{48}b_{47}b_{46}\,b_{45}b_{44}b_{43}$ is$(100000)_2$
- If the output sequence is 4→1 →15, $b_{48}b_{47}b_{46}\,b_{45}b_{44}b_{43}$ is $(000010)_2$
- If the output sequence is 4→1 →13, $b_{48}b_{47}b_{46}\,b_{45}b_{44}b_{43}$ is $(101001)_2$
- Input is determined

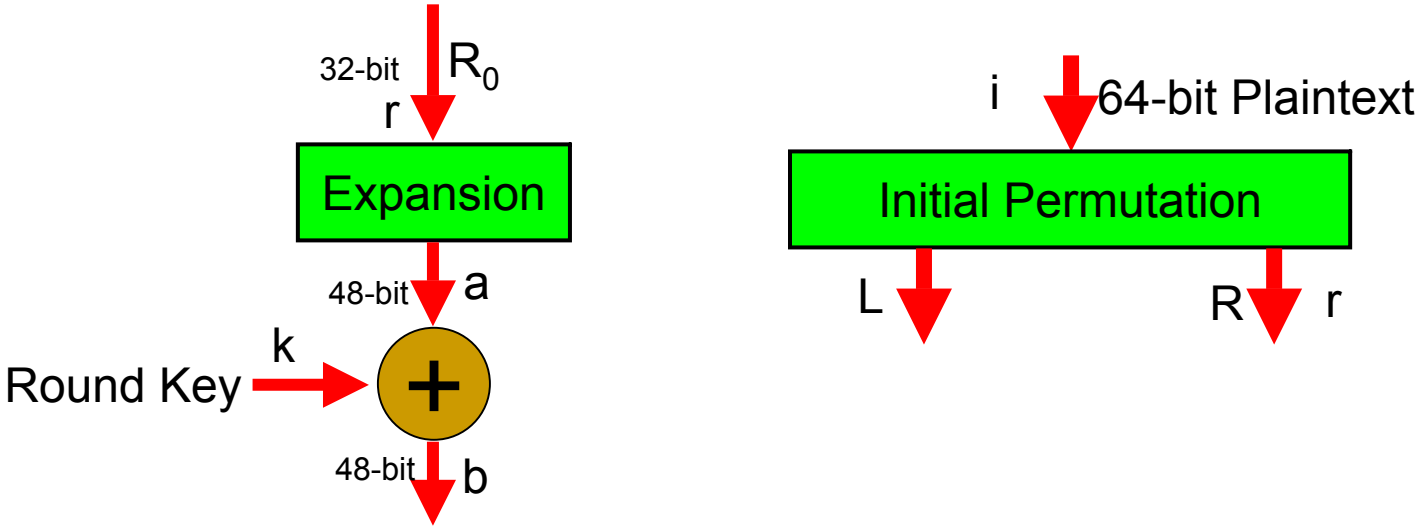
How to apply plaintexts?

- If we apply the three inputs:
  - $b_{48}b_{47}b_{46}\,\overline{b_{45}}b_{44}b_{43}$
  - $b_{48}b_{47}b_{46}\,\overline{b_{45}}b_{44}\overline{b_{43}}$
  - $b_{48}b_{47}b_{46}\,b_{45}b_{44}\overline{b_{43}}$



- According to the sequence of $c^1_{32\text{-}29}$, $c^2_{32\text{-}29}$ and $c^3_{32\text{-}29}$, we can determine $b_{48}b_{47}b_{46}\,b_{45}b_{44}b_{43}$. Then $k_{48}k_{47}k_{46}\,k_{45}k_{44}k_{43}$ can be calculated.
- Now the problem is: Can we apply three plaintexts to generate required input sequence of S1?

Trace back to plaintext



- Since b=a⊕k and k is unchanged, $\overline{a}_{45} \rightarrow \overline{b}_{45}$
- According to Expansion, $\overline{r}_{30} \rightarrow \overline{a}_{45}$
- According to Initial Permutation, $\overline{i}_{24} \rightarrow \overline{r}_{30}$
- Similarly, $\overline{i}_{40} \rightarrow \overline{r}_{43}$
- So we can control plaintext to apply required inputs to S1

Summary of attack step 2

- We can random pick up a plaintext i^1
- Switch its 24^{th} bit as i^2
- Switch its 40^{th} bit as i^3
- Calculate $c^1_{32\text{-}29}$, $c^2_{32\text{-}29}$ and $c^3_{32\text{-}29}$ from R_1 and L_1.
- Determine $b_{48}b_{47}b_{46}\,b_{45}b_{44}b_{43}$ from $c^1_{32\text{-}29}$, $c^2_{32\text{-}29}$ and $c^3_{32\text{-}29}$
- Calculate $a_{48}a_{47}a_{46}\,a_{45}a_{44}a_{43}$ from R_0
- Calculate $k_{48}k_{47}k_{46}\,k_{45}k_{44}k_{43}$ from $a_{48}a_{47}a_{46}\,a_{45}a_{44}a_{43}$ and $b_{48}b_{47}b_{46}\,b_{45}b_{44}b_{43}$
- Attend this method to other S-box, we can recover Round Key 1

Totally using 3 plaintext in attack step 2

- If we discover the Round Key 1 by attack S-box one by one, we need 24 plaintexts.
- By exhaustively simulating, we find we can use only 3 plaintexts that work for all 8 S-boxes simultaneously.
- For example:
  - i^1: $(0000000000000000)_{16}$
  - i^2: $(0000550000005500)_{16}$
  - i^3: $(5500400110000401)_{16}$.

Discover user key

- Similarly, we can discover Round Key 2 and Round Key 3.
- From these three round key, we can discover the user key by key schedule algorithm.

Conclusions

- We develop a two step attack to DES hardware implementations that use scan test
- First, we determine the positions of flip flops in the round register in the scan chain.
- By using the temporary round results, we can discover the corresponding round key.